

AN ABSTRACT OF THE THESIS OF

David E. Garland for the degree of Master of Science in Fisheries Science
presented on November 29, 1993.

Title: Effect of Ageing Errors on Estimates of Growth, Mortality and Yield-per-
Recruit for the Chilean Sardine (*Sardinops sagax*).

Abstract

Redacted for Privacy

approved: _____

Richard A. Tubb

Ageing errors produce important changes in the estimates of different fishery models and can result in different management decisions for the same stock. The effect of using two different ageing methods on the estimation of growth, mortality and yield-per-recruit was explored for the management of the Chilean sardine fishery. A sample of 1,161 sardines (*Sardinops sagax*) taken from September 1985 until August 1986 were aged using daily growth increments. During the same period, the Chilean government (IFOP) used otolith annual-ring counts to estimate age for the same stocks. From these two sources of age data growth, mortality and yield-per-recruit parameter were estimated. The maximum age for *S. sagax* was 5 years for UNAP and 9 years for IFOP. The age determination using annual-ring counts was almost two times greater than the age estimated using daily growth increment. Sardines off northern Chile grew faster than previously estimated by annual ring count. From the 3rd to the 6th year, two hyaline rings are deposited each year: the first

in winter at the time of the main spawning period, and the second during secondary spawning in summer. It is probable that the rings count method misidentified secondary rings for annual rings and different methods of age assignation were used. The consequences of these age overestimations together with size - age data organization used in the fitting of von Bertalanffy growth equation were reflected in the underestimation of mortality and yield-per-recruit parameters. Under the assumption of Beverton and Holt yield-per-recruit model and the management point of view it is possible to reach very different management decisions for the same stock depending on the yield-per-recruit isopleth, which depends on different ageing methods and size - age data organization. Sardine stock off northern Chile during 1985 - 1986 was probably underexploited.

EFFECT OF AGEING ERRORS ON ESTIMATES OF GROWTH, MORTALITY
AND YIELD-PER-RECRUIT FOR THE CHILEAN SARDINE
(*SARDINOPS SAGAX*)

by

David E. Garland

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed November 29, 1993
Commencement June 1994

APPROVED:

Redacted for Privacy

Richard A. Tubb, Professor of Fisheries in charge of major

Redacted for Privacy

Richard A. Tubb, Head of Department of Fisheries and Wildlife

Redacted for Privacy

Dean of Graduate School

Date thesis is presented: November 29, 1993

Typed by: Researcher

"Nature has a way of giving us embarrassing reminders of how easily our best laid plans can come unstuck; fisheries is no exception, especially when some of our plans have not been that well laid."

Ray J.H. Beverton, 1983.

To my wife Myriam
and daughters
Melanie and Cynthia

ACKNOWLEDGEMENTS

I would like to acknowledge my major professor and friend Dr. Richard A. Tubb, Professor of Fisheries, for his guidance and support during the course of this research and for his allowing me the freedom to work in areas of research that were of interest to me and my country. The efforts of my other committee members, Drs. David B. Sampson, Assistant Professor of Fisheries and Wildlife, and Frederick J. Smith, Professor of Agriculture and Resource Economics, are also gratefully acknowledged. A special acknowledgement goes to Dr. David B. Sampson for his helpful and friendly suggestion not only in focusing the research and editing the manuscript but also in give me the philosophies and conceptual basis of the fish stock assessment. I further recognition and acknowledge to Dr. James D. Hall, Professor of Fisheries who gave me valuable suggestions during the first step of this thesis.

I am indebted to Dr. Patricio Bernal, Director of the Instituto de Fomento Pesquero (IFOP) of Chile for supplying the age-length-key, catch-at-age and weight-length data considered in this study. I would also like to thanks Miguel Araya, Patricio Pavez and Dr. Eleuterio Yañez for supplying important bibliographic references. My gratitude to Dr. Oscar M. Brandt for starting my study of Chilean fisheries. I also want to give special thanks to: Gonzalo Castillo and Paul Crone, friends and classmates at OSU, Raúl Berrios, a friend at University of Washington and Dr. Antonio Torres for their comments and input to this work.

Rwangano Felician, Chris Sinnet, Bob Steidl, Silvana Roncagliolo and Wido Contreras, friends at OSU, deserve credit for their computer assistance during the

initial stages of this thesis. I also like to acknowledge to Fisheries and Wildlife administrative staff, in particular Jan Mosley, Charlotte Vickers, LaVon Mauer, Robin Sether and Kelly Wildman for their constant help and friendships. Finally, I would like to thank to my friends Rosa Steinbrecher, Nestor Rojas, Samuel Ortega and Tom Cope for their constant encouragement, friendships, and concern throughout my graduate studies at OSU.

I wish to thank my sponsors Agencia de Cooperación Internacional del Ministerio de Planificación Nacional (MIDEPLAN), Chile and the Universidad Arturo Prat - Iquique for their interest, and financial support.

I would also to express my eternal love to Myriam, Melanie and Cynthia for their sacrifices, understanding and love during these year of study and dedication.

TABLE OF CONTENTS

I. Introduction	1
1.1. Objectives	3
II. Theoretical Background	5
2.1. Effects of ageing error on fisheries management	5
2.2. Validation studies in age determination	5
2.3. Ageing errors in <i>Sardinops</i>	6
2.4. Age determination for <i>Sardinops sagax</i>	8
III. Materials and Methods	12
3.1. IFOP sampling procedures and data generation	12
3.2. UNAP sampling procedures and data generation	17
3.3. Determination of von Bertalanffy growth parameters	23
3.4. Determination of mortality parameters	27
3.4.1. Instantaneous rate of natural mortality	27
3.4.2. Instantaneous rate of fishing and total mortality	32
3.5. Evaluation of the Beverton and Holt yield-per-recruit model	33
IV. Results and Discussion	35
4.1. Populations parameters for the Chilean sardine	35
4.1.1. Growth of <i>Sardinops sagax</i>	35
4.1.2. Instantaneous rate of natural mortality for <i>Sardinops sagax</i>	42
4.1.3. Instantaneous rate of total fishing mortality of <i>Sardinops sagax</i>	42
4.2. Potential yield	47
4.3. Comparison of the Chilean sardine population parameters with respect to other species of <i>Sardinops</i>	58
4.3.1. Comparison of growth of <i>Sardinops sagax</i> with other studies	58
4.3.2. Comparison of mortality of <i>Sardinops sagax</i> with other studies	65
4.3.3. Growth and mortality of <i>Sardinops</i> in relation to fishing	68
4.3.4. Re-evaluation of <i>Sardinops sagax</i> life history characteristics	74
4.4. Fishery management	78
V. Conclusion	89
VI. Bibliography	92
VII. APPENDICES	
Appendix I	104
Appendix II	107
Appendix III	109

LIST OF FIGURES

Figure 1. Fisheries zones of northern Chile, including Arica, Iquique, and Antofagasta landing ports.	13
Figure 2. Length frequency distribution obtained by IFOP in the landing ports of Arica, Iquique, Antofagasta and northern Chile.	15
Figure 3. Age frequency distribution determined by IFOP in the landing ports of Arica, Iquique, Antofagasta and northern Chile.	16
Figure 4. Length frequency distribution obtained by IFOP and UNAP in the landing ports of Iquique and northern Chile.	18
Figure 5. Block diagram of the different methods applied in this thesis. * ¹ IFOP: Instituto de Fomento Pesquero. * ² UNAP: Universidad Arturo Prat.	24
Figure 6. Estimated von Bertalanffy curve in total length for pairs of observed age and length frequency in number of fish for (A) IFOP total and (B) UNAP total.	37
Figure 7. Estimated von Bertalanffy curve in total weight for pairs of observed age and weight frequency in number of fish for (A) IFOP total and (B) UNAP total.	38
Figure 8. Estimated von Bertalanffy curve in total length for pairs observed of averaged age and averaged length for (A) IFOP average and (B) UNAP average.	39
Figure 9. Estimated von Bertalanffy curve in total weight for pairs observed of averaged age and averaged weight for (A) IFOP average and (B) UNAP average.	40
Figure 10. Age composition of <i>Sardinops sagax</i> sampled by (A) IFOP and (B) UNAP during 1985-1986 in northern Chile.	43
Figure 11. Catch curves based on age determination made by (A) IFOP and (B) UNAP.	44
Figure 12. Catch curves based on frequency length distribution calculated using compleat ELEFAN by (A) IFOP data and (B) UNAP data.	46
Figure 13. Plot of yield-per-recruit against age at entry for (A) IFOP total with $F = 1.386$ and (B) UNAP total with $F = 1.877$	48

Figure 14. Plot of yield-per-recruit against age at entry for (A) IFOP average with $F = 1.318$ and (B) UNAP average with $F = 1.693$	49
Figure 15. Plot of yield-per-recruit against fishing mortality for (A) IFOP total with $t_c = 2$ and (B) UNAP total with $t_c = 2$	50
Figure 16. Plot of yield-per-recruit against fishing mortality for (A) IFOP average with $t_c = 2$ and (B) UNAP average with $t_c = 2$	51
Figure 17. Yield-per-recruit isopleth for (A) IFOP total and (B) UNAP total. Asterisk indicate the actual position of the fishery and dotted line is the eumetric curve.	53
Figure 18. Yield-per-recruit isopleth for (A) IFOP average and (B) UNAP average. Asterisk indicate the actual position of the fishery and dotted line is the eumetric curve.	54
Figure 19. Plot of relative yield-per-recruit against fishing mortality estimated using ELEFAN for (A) IFOP and (B) UNAP.	57
Figure 20. (A) Size composition of catch ∇ : modal size and (B) age composition of catch for different species of <i>Sardinops</i> around the world, ∇ : maximum age and ? are problems in ageing (modified from Rosa and Laevastu 1960).	60
Figure 21. General biological characteristics for <i>Sardinops</i> species according to Beverton (1963). (A) M versus K and (B) Z versus K . (symbols in appendix III).	70
Figure 22. General biological characteristics for <i>Sardinops</i> species according to Beverton (1963). (A) L_m and L_∞ and (B) E and Γ . (symbols in appendix III).	72
Figure 23. Yield-per-recruit versus fishing mortality, showing the position of $F_{0.1}$, F_{MSY} , and actual F of the fishery based on (A) IFOP total and (B) UNAP total.	80
Figure 24. Yield-per-recruit versus fishing mortality, showing the position of $F_{0.1}$, F_{MSY} , and actual F of the fishery based on (A) IFOP average and (B) UNAP average.	81

LIST OF TABLES

Table 1. Comparison of length frequency distributions for IFOP and UNAP samples. "Z" values for Mann-Whitney test are not significant ($\alpha = 0.05$)	14
Table 2. Age-length keys obtained by IFOP for northern Chile	19
Table 3. Age-weight keys obtained by IFOP for northern Chile.	20
Table 4. Age-length keys obtained by UNAP for Iquique.	21
Table 5. Age-weight keys obtained by UNAP for Iquique	22
Table 6. Von Bertalanffy growth parameter in length for different data source and method of data organization for IFOP and UNAP	36
Table 7. Von Bertalanffy growth parameter in weight for different data source and method of data organization for IFOP and UNAP.	36
Table 8. Hotelling's T^2 values for von Bertalanffy parameter in length and weight between IFOP and UNAP. Hotelling's T^2 values are significant ($p < 0.01$).	41
Table 9. Population parameters estimated using complete ELEFAN	42
Table 10. Natural mortality parameter calculated using different methods. "t" test values are significant at $p = 0.05$	45
Table 11. Parameter used in the Beverton and Holt yield-per-recruit analysis. . .	52
Table 12. Maximum yield-per-recruit for IFOP and UNAP when t_c was maintained constant.	52
Table 13. Maximum yield-per-recruit for IFOP and UNAP when F was maintained constant	56
Table 14. Maximum yield-per-recruit values with respect to t_c and F values. Numbers in parentheses correspond to calculated values.	56
Table 15. Von Bertalanffy growth in length parameters for <i>Sardinops sagax</i> off Chile, Perú and, Ecuador.	61
Table 16. Von Bertalanffy growth in length parameters for different species of <i>Sardinops</i>	62

Table 17. Von Bertalanffy growth in weight parameter for <i>Sardinops sagax</i> off Chile, Perú and, Ecuador.	64
Table 18. Instantaneous mortality parameters for <i>S. sagax</i> estimated by different authors. M: natural mortality, F: fishing mortality and Z: total mortality.	68
Table 19. Instantaneous mortality parameters for different species of <i>Sardinops</i> . M: natural mortality, F: fishing mortality and Z: total mortality.	71
Table 20. Idealized life history characteristics of fishes under the r and K selection theory. (From Pianka 1974 and Adams 1980).	77
Table 21. Fishing mortality values at levels of $F_{0.1}$, F_{MSY} and, $F_{fishery}$. The corresponding yield-per-recruits values are in parentheses.	82
Table 22. Fishing mortality values at levels of $F_{0.1}$, F_{MSY} and, $F_{fishery}$. $\triangle F$ and $\triangle Y/R$ are the change in F and Y/R relative to F_{MSY} and $F_{0.1}$	83

Effect of Ageing Errors on Estimates of Growth, Mortality and Yield-per-Recruit for the Chilean Sardine (*Sardinops sagax*)

I. Introduction

For most of the last 25 years, sardine species from the genera *Sardinops* or *Engraulis* have supported the world's largest fisheries, and *Sardinops* is presently the largest component of the world's fish harvest (Parrish et al. 1989). Pelagic *Sardinops* and other pelagic fishery activity in Chile, represents 80% of the country's landed seafood, and fishmeal and fishoil exports from these fisheries have been the third most important export of the country, generating nearly \$250 million per year (Serra 1983). The sardine (*Sardinops sagax*) has dominated the pelagic ecosystem off northern Chile from 1973 - 1991. If the fishery is to continue as an important contributor to the Chilean economy, it is imperative that improved stock assessment information be made available to fishery managers responsible for the resource. Some of the uncertainties associated with current stock assessment are due to discrepancies in the estimates of age composition of the sardine population.

In Chile, total allowable catches (TACs) are determined annually through prescribed repeated empirical processes that establish age-length keys, and annual catch-at-length and catch-at-age (age composition) data for all major exploited species. This monitoring work is usually performed in national laboratories such as "Instituto de Fomento Pesquero" (IFOP), a centralized government research institute responsible for stock assessment. The total catch-at-age data for each major species are used in

stock assessment procedures, such as the Virtual Population Analysis (VPA), yield-per-recruit, and stock-recruit analysis (Serra et al. 1988; Zuleta and Serra 1985). These analyses are performed by scientists from IFOP and "Subsecretaria de Pesca" (SUBPES, Undersecretary for Fisheries). In Chile, almost all stock management recommendations are based on annually updated catch-at-age data provided by IFOP and SUBPES.

The age and growth characteristics of sardines are primarily determined by analyzing ring formations deposited on hard parts, such as sagittal otoliths and scales. Additionally, length frequency distributions as well as von Bertalanffy growth equations are utilized at particular stages during the age and growth determination process. One problem that currently precludes effective management of the sardine fishery in Chile, and other fisheries throughout the world as well, is evaluating contradictory results from different research studies. For example, Trautmann (1980) and Trautmann and Aguayo (1980) working for IFOP, determined sardine ages using sagittal otoliths from fish collected in northern Chile and found that the maximum age was 11 years. However, research conducted at Universidad Arturo Prat (UNAP) by Garland (1988) and Garland and Araya (1988) on samples from the same fishery zone found that the maximum sardine age was 6 years when determined using daily growth lines. This discrepancy was due to different ageing and validation methodologies. In comparison to ageing methods based on daily growth ring formation (Garland 1988), the traditional age determination techniques, based on yearly growth ring evaluation (Trautmann 1980; Trautmann and Aguayo 1980), may fail to detect "false" annuli,

such as ring deposition due to spawning. Additionally, in these two age determination methods birth dates were based on a different criteria, i.e., January 1 (yearly growth ring method) and date of birth for each fish (daily growth ring method). The results generated from stock assessment procedures are directly influenced by the age information itself. Inconsistencies in the age data from different research sources may have a considerable impact on stock management decisions recommended by a fishery agency.

Ageing errors produce important changes in the estimates of different fishery models and can result in different management decisions for the same stock. The goal of this research was to study the effect of using two different ageing methods on the estimation of growth, mortality and yield-per-recruit in the Chilean sardine fishery. The use of two different methods of ageing Chilean sardines can produce important differences in age composition and result in different estimates of growth, mortality and yield-per-recruit parameters, with important implications for the management of this resource.

1.1. Objectives

The specific objectives of this research were:

1. To determine population parameters such as: von Bertalanffy growth parameters, instantaneous rate of mortality and, age at first capture, and age at recruitment for fishes in the stock.

2. To compare the parameter estimates from the two ageing methods.
3. To evaluate the results of using the two sets estimates in the yield-per-recruit model of Beverton and Holt and to analyze potential management impacts of ageing errors.

II. Theoretical Background

2.1. Effects of ageing error on fisheries management

The effects of ageing error on fisheries management have been reported by Mathews (1974), Mortera and Levi (1982) and Tyler et al. (1989). Fournier and Archibald (1982) found that large year classes appeared smaller and, perhaps more seriously, the smallest year classes appeared larger. Under estimation of age can result in an overestimation of mortality rates, and the masking of important strong year-classes could result in overfishing (Beamish and McFarlane 1983b; Powers 1983; Lai and Gunderson 1987). Management based on ages from scale estimators appears to have resulted in overfishing, whereas management strategies based on updated age information have resulted in a stable fishery (McFarlane et al. 1985). Beamish and McFarlane (1983a) illustrate the financial cost and management consequences of underestimating the age of older fish for the Pacific ocean perch fishery off the west coast of Canada.

2.2. Validation studies in age determination

An increasing number of studies indicate that application of "routine" methods of age determination have resulted in important misunderstanding of the age composition of populations (Beamish and Harvey 1969; Leaman and Beamish 1984; Beamish 1979; Beamish and Chilton 1982; Chilton and Beamish 1982). The differences in age determination in different species of fishes resulted from using

different structures such as scales and otoliths and hyalin rings versus daily growth increments. Sectioned otoliths usually result in higher age estimates (Carlander 1974).

Reliable age determinations are essential for almost all aspects of fishery research, particularly for studies of growth, production, and population structure and dynamics. It is imperative that the validity of the age determination method be established in each population study. Checks on scales, opercular, or other bony tissues are insufficient, and caution must be exercised because it is easy to tentatively assume a method is valid, and retrospectively to obtain apparent confirmation (Hellawell 1974).

2.3. Ageing errors in *Sardinops*

Mosher and Eckles (1954) investigated the age composition of adult California sardines (*Sardinops caerulea*) and concluded that fish length-at-age, with ages determined by otoliths, were not significantly different from length-at-age determined by scales. However, the variability of the mean lengths of fish with age determined from otoliths was less than the variability of lengths of the fish with age determined from scales. Kimura (1970) and Kimura and Sakagawa (1972) reared individuals of Pacific sardine from hatching through the first year of life to determine growth in length and weights and the formation of accessory rings and annuli on scales, and compared these measurements with those for field-captured fish. The examination of the scales of laboratory-reared fish was insufficient to distinguish between accessory

rings and annuli. Therefore, extreme caution must be exercised in ageing because of the presence of accessory marks on scales. A significant finding was the observation that early readers (between 1934 to 1943) probably aged sardines correctly, whereas later readers (between 1944 to 1957) probably underestimated age II and older fish (Kimura and Sakagawa 1972). They concluded that a bias was present in published age-compositions of the Pacific sardine catch, which in turn, probably affected studies of population dynamics of the Pacific sardine. Ramirez and Uraga (1986) working with Monterrey sardine *Sardinops sagax caerulea* suggest there is a relationship between the two spawning periods and the periodic hyaline and opaque bands of the otoliths. The possibility that these bands occur with a frequency of six months is put forward.

Blackburn (1949, 1950) studied age, rate of growth, and general life-history of the Australian sardine (*Sardinops neopilchardus*) in the waters off New South Wales and concluded that ring pattern is complex, involving yearly, spawning, and secondary rings. One yearly and one spawning ring are usually formed. Biological growth patterns should therefore, be considered in the fishery management. Davies (1958) determined the age composition of the commercial catches of sardine (*Sardinops ocellata*) off the West coast of the South Africa using scales and concluded that two rings are formed on the scales of sardine each year. Thomas (1984) noted wide variations in the published age compositions of southern African sardine and concluded that part of the variation may be explained by differences in growth in different areas and periods. For the Japanese sardine (*Sardinops melanosticta*),

Aikawa (1940) reported that two rings were formed on the scales per year, one in the summer and one in the winter. Spring catch indicated the oldest individual usually had 6 rings on the scale which correspond to a 3 year life span. Individuals with 7 or more rings on the scale were scarce among Japanese catches.

2.4. Age determination for *Sardinops sagax*

The age and growth of adult sardines in Chile, Perú and Ecuador have been studied by different authors. Methods used have included reading of rings in scales of sardines from Antofagasta - Chile (Alberti and Larrañeta 1966). Also used is the reading of hyalin rings in sagittal otolith in Chile (Trautmann and Aguayo 1980; Aguayo et al. 1983; Aguayo et al. 1987), in Perú (Samamé 1977; Cardenas 1983, 1987), and in Ecuador (Saldaña 1983). Daily growth lines in sagittal otolith also were used for ageing sardine in Chile (Garland 1988, Garland and Araya 1988). In Chile, Vidal (1967, 1985) used modal progression of length frequency and in Perú Cárdenas and Mendo (1985) fitted the von Bertalanffy model for length at age.

Specialists in age and growth studies of pelagic species associated with official stock assessment institutions from Chile (IFOP: Instituto de Fomento Pesquero), Perú (IMARPE: Instituto del Mar del Perú) and Ecuador (INP: Instituto Nacional de Pesca) met in 1982 to analyze and standardize the ageing methods used by each country. The goal was to generate consistent and accurate information for the successful management of pelagic species (SELA 1982). However, there are still differences in average length for the same age caused by differences in ring measurement. In Perú,

the radius is measured from the focus to the caudal margins of the opaque ring and in Chile, measurements are taken from the focus to the caudal edge of the hyalin ring. Identification of the first ring is also a problem. Samples from Chile, Perú and Ecuador, exhibit a wide range of formation periods and with differences in intensity of the rings. Finally, a different birth date is used for the assignation of age. Chile uses January 1 (traditional method) and Perú uses July 1. The information used to generate age-length keys and the distances from focus to each ring are not comparable. Another important issue in age studies of chilean sardines is age assignation. For instance, Aguayo et al. (1983, 1987) used January 1 while Garland and Araya (1988) used date of birth for each fish. Date of birth was determined using the date of capture and age in days. Differences noted in the estimation of age and growth between traditional (reading otoliths) and progression of length frequency methods led to a 1987 agreement between certain fisheries companies (Coloso S.A. and Guanaye, Ltda., Iquique, Chile) and the Universidad Arturo Prat to conduct sardine age validation studies based on daily growth increments. In 1987 an agreement was signed for age validation of sardine using daily growth increment between the fisheries companies and Universidad Arturo Prat because of the differences in the estimation of age and growth between traditional methods (reading otoliths) and progression of length frequency methods.

In Chile, three captivity experiments were used to determine the periodicity of the microincrement formation by studying the otolith's hourly growth (Garland 1988 and Garland and Araya 1988). Daily growth increments were used for validating

annuli by recording the time between estimated date of hatching and the end of each winter and by counting the daily lines between the different hyaline rings. Consistent estimates were found with both methods but not with the traditional methods used by IFOP. From the third to sixth years of life two rings were deposited for each annual cycle. The first was correlated with winter season plus principal spawning (between July to September), and the second ring was correlated with a secondary spawning (between February to March). Spawning rings were also characterized using daily growth increments. A close relationship between spawning events and the deposition of daily growth lines was found. Spawning rings were characterized by daily growth lines more refringent and brighter than normal microincrements (Garland 1988 and Garland et al. 1988). The maximum age was almost 6 years, rather than 11 years determined by Trautmann (1980) and Trautmann and Aguayo (1980) and Aguayo et al. (1983, 1987).

Methods used for ring validation in a typical age and growth study involve the analysis of the otolith edge through the frequency of the type of otolith edge (hyalin or opaque), marginal increments, and the relationship between otolith radius and fish length (Dannevig 1933; FAO 1982; Huang and Walters 1983). These methods are common and have been used with Chilean sardine (Trautmann 1980; Aguayo et al. 1983, 1987). However, the interpretations of data obtained by these methods are ambiguous, especially when the type of otolith edge and marginal increments are separated by ages groups. The frequency of hyalin or opaque edge is similar in different seasons and the average of marginal increments is not representative because

the variance is not homogeneous (Garland and Araya 1988). For these reasons these techniques were not appropriate to validate annulus in Chilean sardine and must be used with caution and supported by other methods, e.g. daily growth increments.

Different methods of annuli validation and age determination together with age assignation used by IFOP (Aguayo et al. 1983, 1987) and UNAP (Garland and Araya 1988; Garland 1990) can produce important changes in the results of different fishery models especially yield per recruit and stock - recruit. Different ageing methods produce different information and lead to different management decisions for the same stock.

III. Materials and Methods

The data sources for this research came from stock assessments conducted regularly by IFOP and published work completed by Garland (1988) at UNAP. Of particular interest were ageing determinations for *S. sagax* caught in northern Chile between September 1985 and August 1986.

3.1. IFOP sampling procedures and data generation

A standard sampling protocol was used by IFOP from September 1985 to August 1986 for stock assessment. Sardines landed in Arica ($18^{\circ}21'$ - $19^{\circ}30'S$), Iquique ($19^{\circ}30'$ - $21^{\circ}30'S$) and Antofagasta ($21^{\circ}30'$ - $24^{\circ}00'S$), Chile (Fig. 1) during September 1985 to August 1986 were sorted into 0.5 cm size classes. Five females and 5 males were selected from each size class for otolith analysis. Otoliths were mounted in block plates with Canadian balsam, sent to a central laboratory in Santiago, and processed following standard techniques (Aguayo et al. 1983, 1987). Data on length, weight, sex, landing port and catch were used to build length-key tables, length and weight relationships. The length frequency distribution plus age-length keys together with the ratio of weight of catch and weight of sample were used to build catch-at-age (age composition in number). Samples were collected and differentiated on a monthly and landing port basis and summed to produce quarterly, semiannual and annual reports. Age I fish, landed in Iquique during July 1985, were included in length-key and catch-at-age tables to obtain more representative data.

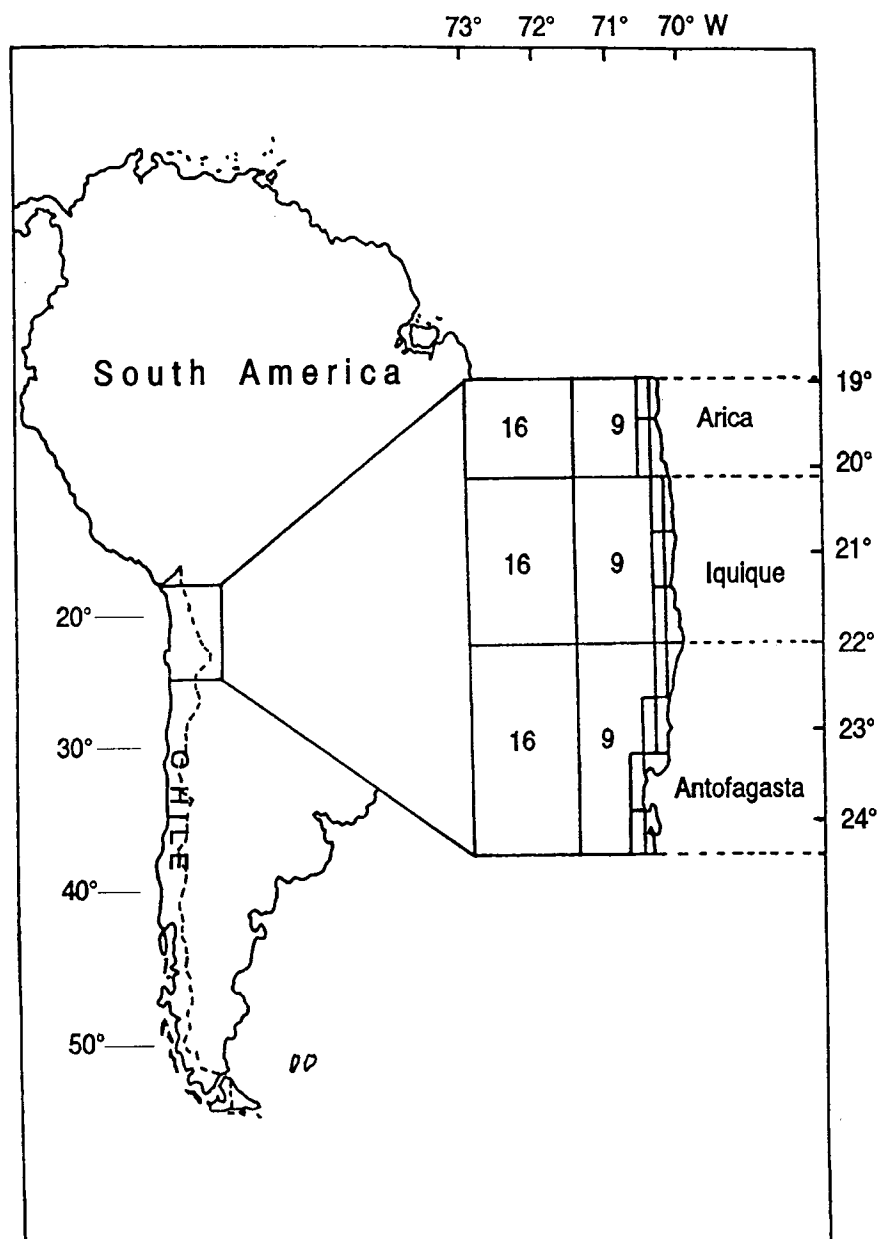


Figure 1. Fisheries zones of northern Chile, including Arica, Iquique, and Antofagasta landing ports.

Frequency distribution of length and age composition among Arica, Iquique and Antofagasta exhibited no significant differences (Mann-Whitney test, $\alpha = 0.05$) from September 1985 to August 1986 (Fig 2, 3 and Table 1). Data agreed with IFOP and SUBPES stock definition of sardine for management purposes and separate and annual reports were combined to produce length-key tables for all of northern Chile between September 1985 to August 1986. The absence of differences allowed the pooling data in order to produce age-length-key tables for all of northern Chile sardines between September 1985 to August 1986.

Table 1. Comparison of length frequency distributions for IFOP and UNAP samples. "Z" values for Mann-Whitney test are not significant ($\alpha = 0.05$).

	Arica	Iquique (IFOP)	Antofagasta	Northern Zone	Iquique (UNAP)
Arica		0.443	0.234	0.680	1.788
Iquique			-0.261	0.154	1.168
Antofagasta				0.381	1.599
Northern Zone					1.110

Parameter **a** and **b** the relationships of length and weight, by months for Arica, Iquique and Antofagasta from September 1985 to August 1986 were averaged, obtaining **a** = 0.0105 (S.D. = 0.00507) and **b** = 2.975 (S.D. = 0.161). These parameters together with a table of age-length, were used for building a table of age-weight. Both tables correspond to the starting point of the standard stock assessment procedures (Tables 2 and 3).

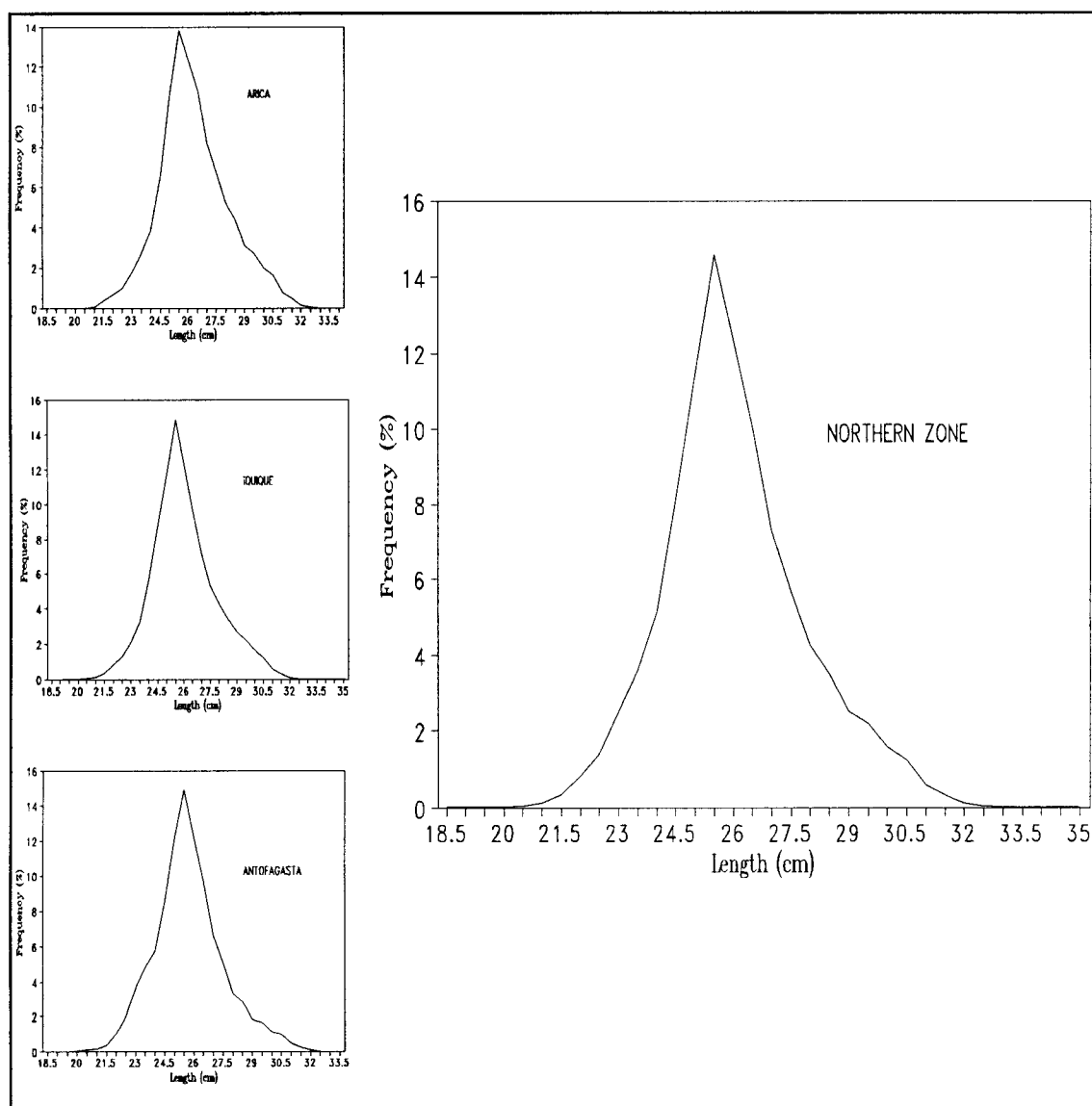


Figure 2. Length frequency distribution obtained by IFOP in the landing ports of Arica, Iquique, Antofagasta and northern Chile.

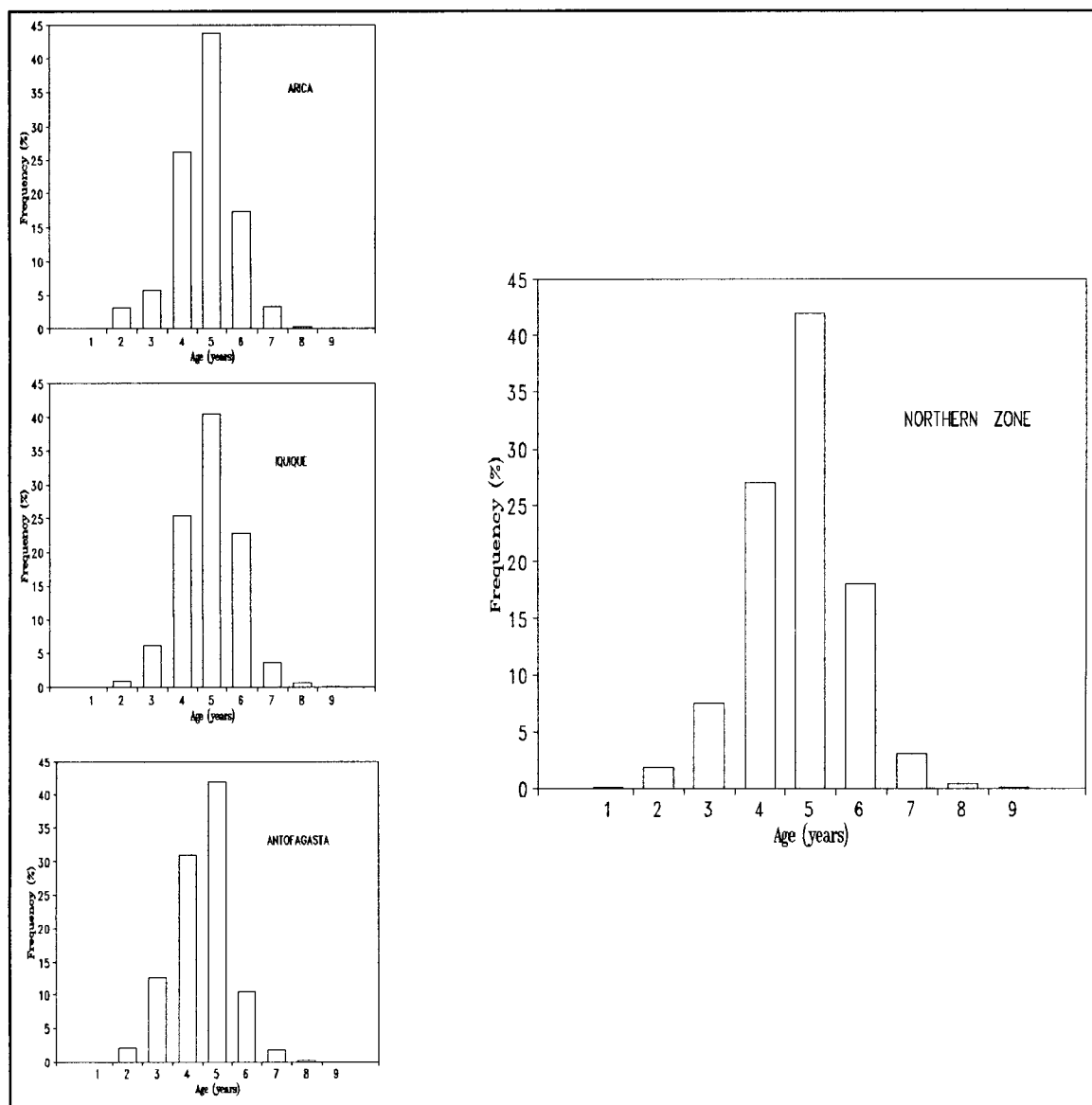


Figure 3. Age frequency distribution determined by IFOP for the landing ports of Arica, Iquique, Antofagasta and northern Chile.

3.2. UNAP sampling procedures and data generation

Samples from the Iquique fishery zone were obtained in conjunction with the staff from UNAP. From September 1985 to August 1986, individual Chilean sardines were sampled at the landing sites (Coloso Co., Iquique, Chile) by choosing different vessels that had fished in the Iquique zone. Samples were taken daily each week, from one boat. Each sample consisted of fish collected at intervals of 5 minutes during discharge of fish from the vessels to avoid bias from possible stratification within the catch. The total monthly sample was tabulated as a length frequency histogram; each interval of size was considered a stratum and proportional random sub-samples were taken to obtain otoliths.

From the 13,888 sardines sampled, 1,161 were randomly subsampled to determine age. Two hundred were used for age validation using the daily increment technique, considering age range (1 to 5 years), year classes (1980 to 1984) and, time of sampling (months). Age and length data in addition to the parameter $a=0.004911$ and $b=3.16$ for the length-weight relationship were used for building age-length key tables (Tables 4 and 5).

The length frequency distribution for northern Chile obtained by IFOP and the length frequency distribution for Iquique obtained by UNAP and IFOP exhibited no significant differences (Mann - Whitney test $\alpha = 0.05$) (Fig 4 and Table 1) indicating that samples obtained by UNAP were representative for all northern Chile and that the age compositions estimated by IFOP and UNAP were comparable. The only differences in the age-length keys were, therefore due to ageing method

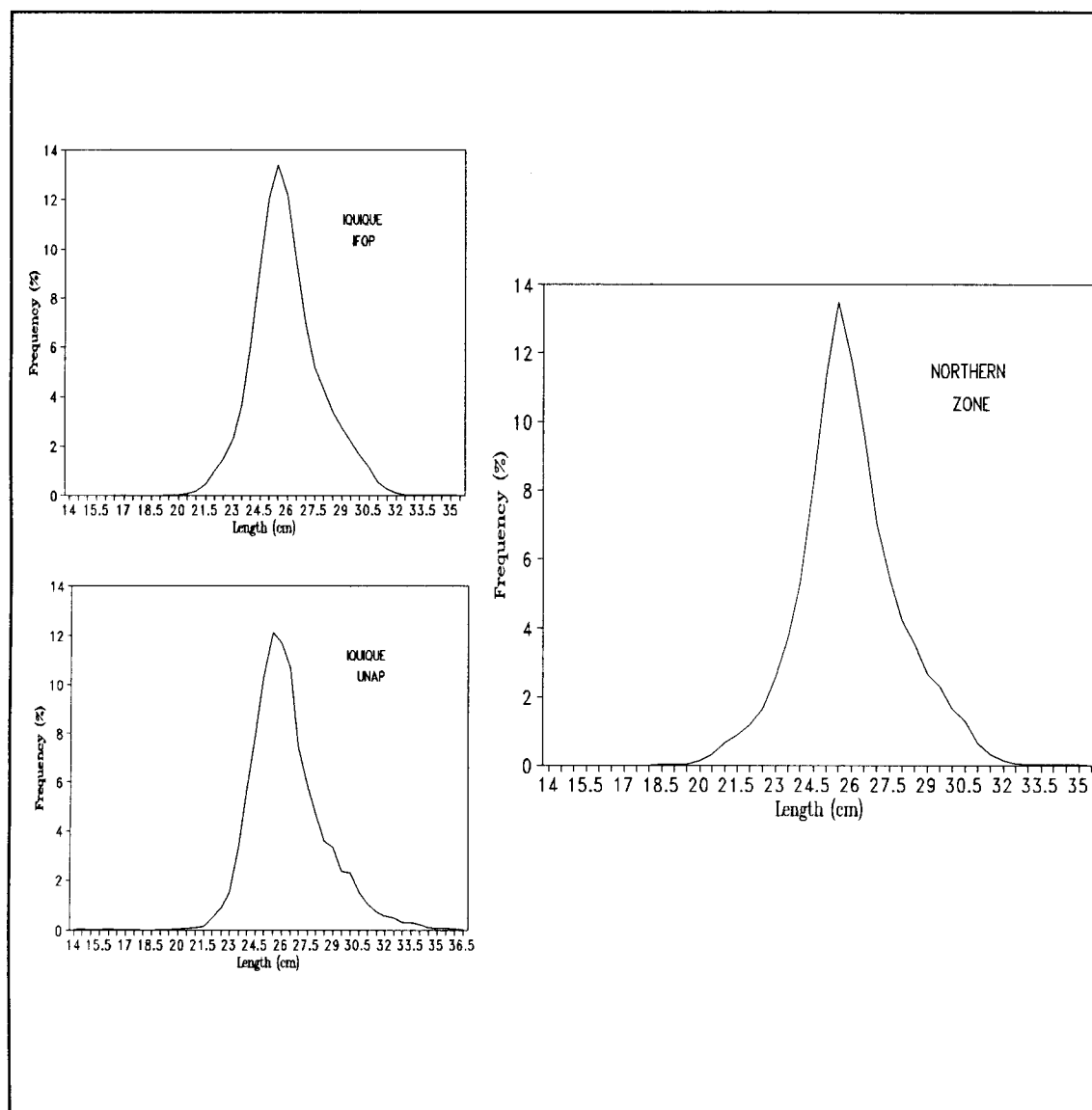


Figure 4. Length frequency distribution obtained by IFOP and UNAP in the landing ports of Iquique and northern Chile.

Table 2. Age-length keys obtained by IFOP for northern Chile.

Length (cm)	I	II	III	IV	V	VI	VII	VIII	IX
15	1								
15.5	1								
16	1								
16.5	1								
17									
17.5									
18									
18.5	1	4							
19		4							
19.5		13							
20		19							
20.5		17	4						
21		18	19						
21.5		24	24						
22		23	29						
22.5		18	38	5					
23		8	51	24					
23.5		7	53	60	4				
24		1	47	92	34	2			
24.5			30	103	76	10			
25			20	94	97	25			
25.5			8	98	106	26			
26			6	74	112	45	1		
26.5			1	73	106	58			
27				54	108	72	4		
27.5				41	111	74	12		
28				11	114	89	19	1	
28.5				11	81	112	27	5	
29					69	114	43	3	
29.5					44	121	58	7	
30					24	115	73	14	2
30.5					12	97	92	16	2
31						84	82	26	2
31.5						45	71	34	6
32						8	62	25	3
32.5						2	15	22	2
33						1	10	15	2
33.5							3	10	1
34								7	1
34.5								2	1
35								1	1
Avg.	16.300	21.215	23.206	25.298	26.844	27.737	30.420	31.574	32.000
Var.	1.825	1.552	1.530	1.736	2.558	3.027	1.670	1.781	1.818
N.	5	156	330	740	1098	1100	572	188	23

Table 3. Age-weight keys obtained by IFOP for northern Chile.

Weight (gr)	I	II	III	IV	V	VI	VII	VIII	IX
33.1	1								
36.5	1								
40.1	1								
44.0	1								
48.1									
52.4									
57.0									
61.8	1	4							
66.9		4							
72.3		13							
77.9		19							
83.9		17	4						
90.1		18	19						
96.7		24	24						
103.5		23	29						
110.7		18	38	5					
118.1		8	51	24					
125.9		7	53	60	4				
134.1		1	47	92	34	2			
142.6			30	103	76	10			
151.4			20	94	97	25			
160.6			8	98	106	26			
170.1			6	74	112	45	1		
180.0			1	73	106	58			
190.3				54	108	72	4		
201.0				41	111	74	12		
212.1				11	114	89	19	1	
223.5				11	81	112	27	5	
235.4					69	114	43	3	
247.7					44	121	58	7	
260.4					24	115	73	14	2
273.5					12	97	92	16	2
287.1						84	82	26	2
301.1						45	71	34	6
315.5						8	62	25	3
330.4						2	15	22	2
345.8						1	10	15	2
361.6							3	10	1
377.9								7	1
394.6								2	1
411.9								1	1
Avg.	43.108	93.817	122.309	158.063	189.032	231.558	272.806	304.769	317.095
Var.	125.568	262.752	373.018	610.114	1126.45	1647.89	1148.98	1446.22	1647.39
N.	5	156	330	740	1098	1100	572	188	23

Table 4. Age-length keys obtained by UNAP for Iquique.

Length (cm)	I	II	III	IV	V
14.5	2				
15					
15.5	2				
16					
16.5	2				
17					
17.5					
18					
18.5					
19					
19.5					
20		1			
20.5		6			
21		6			
21.5		2			
22		6	1		
22.5		9	3		
23		6	7		
23.5		10	18	1	
24		11	18	1	
24.5		23	31	2	
25		28	49	3	
25.5		38	32	2	
26		28	61	2	
26.5		28	40	3	
27		27	52	4	
27.5		17	47	5	
28		8	31	5	
28.5		10	32	7	1
29		5	38	8	2
29.5		2	28	4	
30		6	29	14	3
30.5		1	35	8	1
31		3	18	8	1
31.5		4	20	13	1
32		1	18	7	1
32.5		4	12	6	
33			14	5	
33.5			12	11	
34			10	9	1
34.5		1	7	5	
35			1		1
35.5			5	2	
36					2
36.5				1	
37				1	
Avg.	15.500	25.867	27.961	30.555	31.607
Var.	0.8	5.705	8.162	7.9	6.815
N.	6	290	669	137	14

Table 5. Age-weight keys obtained by UNAP for Iquique.

Weight (gr)	I	II	III	IV	V
23.0	2				
25.6					
28.4	2				
31.3					
34.5	2				
38.0					
41.6					
45.5					
49.6					
54.0					
58.6					
63.4		1			
68.6		6			
74.0		6			
79.7		2			
85.7		6	1		
92.1		9	3		
98.7		6	7		
105.6		10	18	1	
112.9		11	18	1	
120.5		23	31	2	
128.4		28	49	3	
136.7		38	32	2	
145.4		28	61	2	
154.4		28	40	3	
163.8		27	52	4	
173.6		17	47	5	
183.7		8	31	5	
194.3		10	32	7	1
205.3		5	38	8	2
216.7		2	28	4	
228.5		6	29	14	3
240.7		1	35	8	1
253.4		3	18	8	1
266.6		4	20	13	1
280.2		1	18	7	1
294.3		4	12	6	
308.8			14	5	
323.8			12	11	
339.3			10	9	1
355.4		1	7	5	
371.9			1		1
388.9			5	2	
406.5					2
424.6				1	
443.3				1	
Avg.	28.623	147.244	189.559	248.981	275.399
Var.	26.869	1972.67	3994.501	4819.487	5583.301
N.	6	290	669	137	14

differences. The age-length keys derived from each ageing techniques separately (IFOP versus UNAP) were used to estimate growth and mortality rates for *S. sagax*; and the rates were then compared statistically. Data for the sexes were combined to facilitate comparison with past studies.

3.3. Determination of von Bertalanffy growth parameters

Von Bertalanffy growth curves were estimated following the methodologies suggested by Sparre (1987) and Sparre et al. (1989), who commented that the von Bertalanffy growth function has become one of the cornerstones in fishery biology because it is used routinely as a submodel in more complex models for describing fish population dynamics. The von Bertalanffy growth function in length is described by the equation:

$$L_t = L_{\infty} (1 - e^{-k(t-t_0)}) \quad \text{eq. 1.}$$

where t = age, k = a growth constant, L_{∞} = average asymptotic length, L_t = length at age, and t_0 = age when $L_t = 0$. The procedures suggested by Sparre (1987) were used to estimate the growth parameters L_{∞} , k and t_0 . The parameter were estimated using: (a) pairs of observed age (t_i) and length frequency (L_i) in number of fish (Total) ($t_i/L_i * n_i + L_{i+1} * n_{i+1} + \dots + L_{i+m} * n_{i+m}$) and, (b) pairs of averaged age (t_i) and averaged length (L_i) (Average or Aver.) (t_i/L_i) (Fig 5). In order to obtain estimated von Bertalanffy parameters that were comparable between IFOP and UNAP, I used annual age-length keys of northern Chile

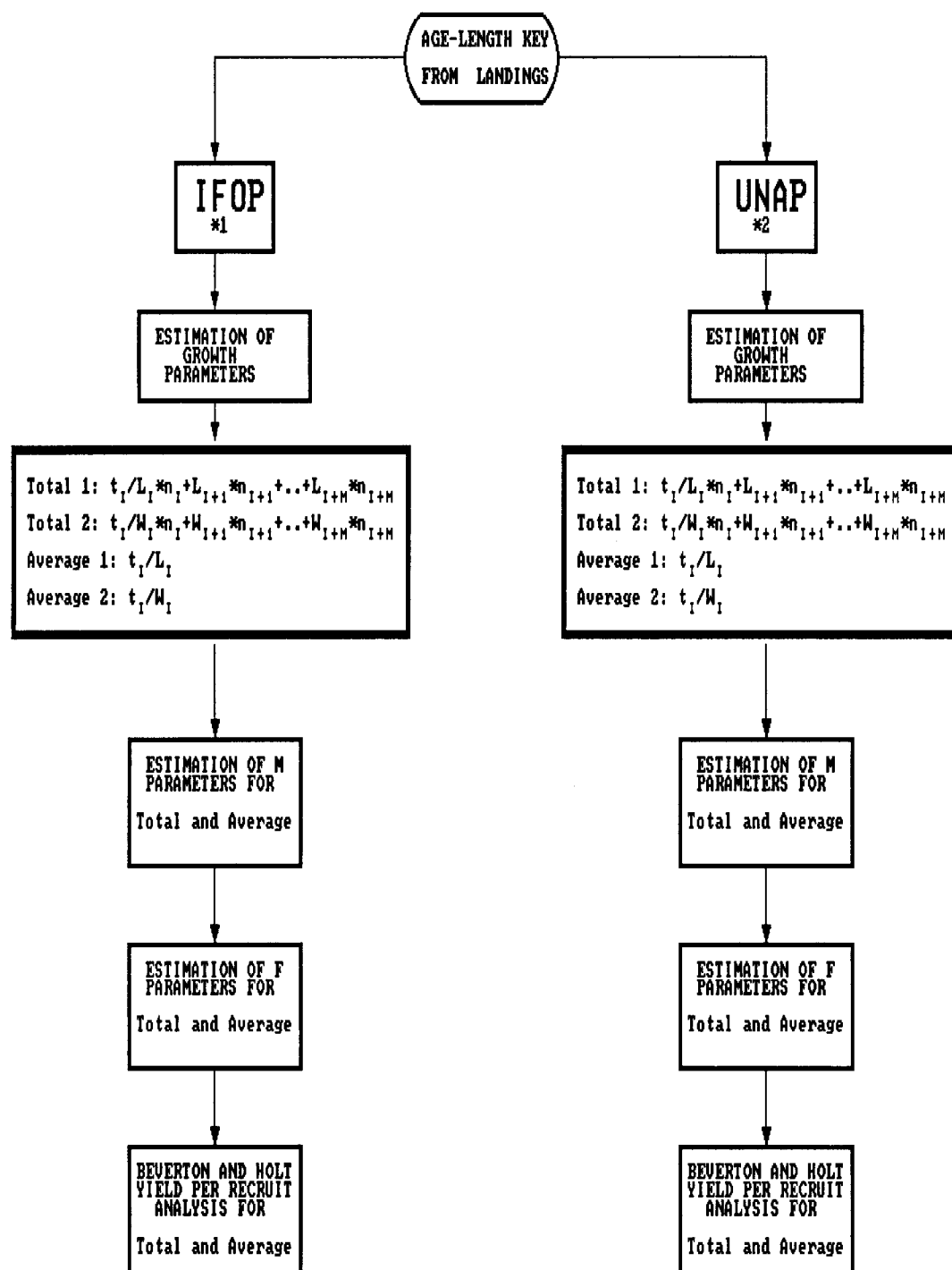


Figure 5. Block diagram of the different methods applied in this thesis.

*1 IFOP: Instituto de Fomento Pesquero.

*2 UNAP: Universidad Arturo Prat.

samples, between September 1985 and August 1986 (Bernal and Barrias 1992; Garland 1988). The von Bertalanffy growth models were fitted to the length at age data using a nonlinear regression routine (NLIN) of SAS (Statistical Analysis System Institute Inc., Cary, NC, U.S.A., version 6.04). The routine estimates L_{∞} , k and t_0 by minimizing the sum of squared deviations (SSD) between the observations and the estimated growth curve, so that the sum:

$$SSD = \sum_{i=1}^n (L_i - L_{\infty} (1 - e^{-k(t-t_0)}))^2 \quad \text{eq. 2.}$$

is minimized (Kimura 1980 and Sampson pers. com.). The fitting procedure was iterative and begins with a search for suitable initial values for the parameter estimates. The parameters estimated by Aguayo et al. (1987) for the IFOP data and by the Ford-Walford method (Ricker 1975) for the UNAP data were used as starting points for the initial searching procedure. The von Bertalanffy growth parameters for weight were estimated from age-weight tables using the same SAS nonlinear routine. Von Bertalanffy growth curves in length and weight for the two data sets were compared using Hotelling's T^2 as a test for differences between the two sets of von Bertalanffy growth parameters (L_{∞} , k and t_0) (Bernard 1981). Hotelling's T^2 statistic is derived from the joint probability distribution for several normally distributed random variables and is based on vectors of parameter values (P_{IFOP} and P_{UNAP}) and the variance - covariance matrix for each set of estimates. The nonlinear regression procedure produced parameter estimates with

asymptotic standard errors, and the correlation matrix for the parameter estimates. The correlation matrices were used to calculate the variance - covariance matrices. The calculated T^2 statistics were used to test the hypothesis that the IFOP parameters are equal to the UNAP parameters. Because T^2 is related to 't', the tabulated F statistic with some modification is used to determine the significance of a T^2 value (Bernard 1981).

The complete ELEFAN routine (Pauly 1987) was used to estimate population parameters from the length compositions and data for August 1985 to September 1986. The von Bertalanffy growth parameter were calculated by identifying the "best" combination of growth parameters through response surface analysis i.e. many (say, a thousand) different growth curves are examined to find the best combinations of parameters. These values were improved by using an automatic search procedure, which tested alternative growth curves until one produced the highest R_n (goodness of fit test) (ELEFAN I). In order to compare the von Bertalanffy growth parameter estimated with ELEFAN I, I used the Munro phi prime test (Φ') (Munro and Pauly 1983, Pauly and Munro 1984) who suggested that the "overall growth performance" is reflected by:

$$\Phi' = \ln k + 2 * \ln L_{\infty} \quad \text{eq. 3.}$$

where L_{∞} and k are parameter of von Bertalanffy growth function. These authors found that species within the same family have similar Φ' values which are normally distributed.

3.4. Determination of mortality parameters

3.4.1. Instantaneous rate of natural mortality

There are several methods for estimating the instantaneous rate of natural mortality (M). Sparre et al. (1989) commented that most of the methods for estimating M, perhaps all, rank no higher than intelligent guesses. Since direct measurements of M are difficult to obtain, Sparre et al. (1989) suggested obtaining or identifying quantities that can be assumed proportional to M and that are easier to measure (or estimate). I used five methods to obtain estimates of the natural mortality rate:

(a) Method of Taylor (1960)

Natural mortality should be related to L_{∞} or the maximum weight of the species, W_{∞} , since large fish have fewer predators than small fish, maybe because big fish swim faster or because big prey imply big predator. Taylor (1960) found an empirical relationship between growth parameters and temperature and these appeared to be related with longevity and mortality. Therefore, Taylor (1958, 1959) suggested that for certain animal groups M can be predicted from body size using the following equations:

$$A_{0.95} = \left(\frac{2.996}{k} \right) + t_0 \quad \text{eq. 4.}$$

$$M = \frac{2.996}{A_{0.95}} \quad \text{eq. 5.}$$

where:

$A(0.95)$ = age when length is 95% of L_{∞}

k and t_0 = von Bertalanffy growth parameters in length.

For my application of this method to the Chilean sardine data, I used sets of growth parameters derived from the two ageing methods for each estimation of growth.

(b) Method of Rikhter and Efanov (1976)

Empirical studies concluded that fish with a high natural mortality usually mature early in life. They compensate for the high M by earlier reproduction.

Based on this idea Rikhter and Efanov (1976) found the following expression:

$$M = \frac{1.521}{tm_{50}^{0.72}} - 0.15 \quad \text{eq. 6.}$$

where:

tm_{50} = age when 50% of the population is mature.

For my application of this method I assumed that *S. sagax* during 1985-86 mature at 26 cm of total length (TL) (Martinez et al. 1987). This length

corresponded to 5 years and 3 years when was transformed to age using the length at age tables from IFOP and UNAP.

(c) Method of Pauly (1980 and 1983)

Pauly made a regression analysis with data from 175 different fish stocks, and estimated the following empirical relationship.

$$\ln M = -0.0152 - 0.279 \ln L_{\infty} + 0.6543 \ln k + 0.463 \ln T \quad \text{eq. 7.}$$

where:

L_{∞} and k = parameter of von Bertalanffy growth function.

T = average annual temperature at sea surface in Celsius degrees.

Applying Pauly's method to the Chilean sardine data, I used sets of growth parameters derived from the two ageing methods for each estimation of growth. The average temperature for 1985-86 was 18°C (Fuenzalida pers. com.).

For schooling fish Pauly (1983) suggested multiplying equation (7) by 0.8. The equation (7) is transformed as follows:

$$\ln M = 0.8 (-0.0152 - 0.279 \ln L_{\infty} + 0.6543 \ln k + 0.463 \ln T) \quad \text{eq. 8.}$$

(d) Method of Peterson and Wroblewski (1984)

This method is based on similar assumptions as Taylor's method but is specific for pelagic fishes. The method assumes that mortality is primarily due to predation and is size-dependent. Peterson and Wroblewski (1984) derived the following expression:

$$M_{wd} = 0.2 (1.92 \text{ yr}^{-1}) W_w^{-0.25} \quad \text{eq. 9.}$$

where:

Wd = dry weight in average for all size classes

Ww = wet weight

For my application of this method I assumed that $Ww = aL^b$, where L = modal length for 1985-86 and **a** and **b** are parameters of the relationship between weight and length calculated for both IFOP and UNAP.

(e) Method of Gunderson and Dygert (1988)

These authors added more species to the analysis of Gunderson (1980). They carried out an evaluation of the relation between reproductive effort and natural mortality rate for 20 fish stocks using a multiple regression analysis and showed that wet gonad somatic weight index (WGSi) was superior to any of the other life history parameters evaluated (k , L_∞ , age at maturity and maximum

age) in predicting natural mortality. Gunderson and Dygert estimated the following relationship between M and $WGSI$.

$$M = 0.03 + 1.68 WGSI \quad \text{eq. 10.}$$

The wet gonad somatic weight index is the ratio of wet gonad weight over body weight. In my application of this method I used monthly values of gonad weight from September 1985 to August 1986 (Martinez et al. 1987).

$$WGSI = \frac{\sum_{x=1}^{x=12} (GW / 2) / BW}{12} \quad \text{eq. 11.}$$

where:

GW = gonad weight

BW = body weight

x = September 1985 to August 1986.

I transformed modal length to monthly body weight using **a** and **b** parameters for IFOP and UNAP. Because *S. sagax* has two periods of spawning each year the gonad weight was divided by two in order to approximate annualized estimates (Gunderson and Dygert 1988).

For each growth estimate I computed an average for all estimations of M , because in the yield-per-recruit equation of Beverton and Holt (1957) only one

value of M is used. The yield-per-recruit analysis assumes that M is constant over the fishable lifespan of the stock and is independent of the size of adult stock (see appendix I). Instantaneous natural mortality rates were compared using a "t" test for different in means with variances not homogeneous (Dixon and Massey 1969).

3.4.2. Instantaneous rate of fishing and total mortality

Total instantaneous mortality Z is equal to $F + M$, where F is the instantaneous fishing mortality rates and M is the instantaneous natural mortality rate. I calculated instantaneous fishing mortality rates by subtracting M from the instantaneous rates of total mortality (Z) which I estimated by applying the linearized catch curve to catch-at-age data (population size at each age) from the IFOP and UNAP age data (Robson and Chapman 1961; Ricker 1975). This analysis corresponds to fitting a straight line to the plot of the natural logarithms of catch versus age. The slope of the line corresponds to minus the instantaneous rate of total mortality (Z). Sparre et al. (1989) noted that the catch curve is a graphical representation of numbers of survivors plotted against age. This method assumes that the recruitment remains constant every year and that F and M are constant over the range of ages observed in the catch. In this case all cohorts have the same age structure.

In the case of IFOP data, the last age was not considered in the regression because its low frequency (0.008%) could bias the estimates of Z (Chapman and Robson 1960; Robson and Chapman 1961 and Sampson pers. com.). Total

instantaneous mortality rates derived from the IFOP and UNAP data sets were compared using a partial F test for regression lines (Neter and Wasserman 1974).

3.5. Evaluation of the Beverton and Holt yield-per-recruit model

Various authors have studied the sensitivity of the Beverton-Holt model for yield-per-recruit to ageing errors and errors in M. They have demonstrated that bias or inaccuracies can have important effects on the management advice derived from the model (Mathews 1974; Lai and Gunderson 1987; Tyler et al. 1989).

Megrey and Wespestad (1988) described the dynamic pool model of Beverton and Holt as a mixing of three equations. The first is the growth model of von Bertalanffy. The second is a slight modification of the exponential survival model that incorporates a pre-exploited phase as well an exploited phase. The third and final equation is the Baranov catch equation that is used in many fishery models.

The yield-per-recruit equation is:

$$\frac{Y}{R} = F e^{-M(t_c - t_p)} W_{\infty} \sum \frac{U_n e^{-n k (t_c - t_p)}}{F + M + n k} \quad \text{eq. 12.}$$

where:

Y/R = yield -per-recruit

F = instantaneous fishing mortality coefficient

M = instantaneous natural mortality coefficient

W_{∞} = asymptotic weight (von Bertalanffy parameter)

U_n = summation parameter: $U_0=1$, $U_1=-3$, $U_2=3$, $U_3=-1$

- t_c = age at first capture
- t_r = age at recruitment
- t_0 = hypothetical age at size zero (von Bertalanffy parameter)
- k = rate of weight growth (von Bertalanffy parameter)

Age at first capture (t_c) was based on the legal minimum size, 20 cm of total length, (Serra et al. 1988). This total length was transformed to age (t_c) using age-length key for IFOP and UNAP resulting in age II for IFOP and UNAP. Age at recruitment (t_r) was considered to be the youngest age in the catch, which corresponded to age I in both cases. Equation 12 was solved using the computer program B-H3 of the Fishery Science Applications System, FSAS (Saila et al. 1988).

The yield-per-recruit model of Beverton and Holt (1957) has been one of the models used in assessments of the Chilean sardine stock. I used this model with both the IFOP and UNAP data. The von Bertalanffy growth parameters estimated using averaged age and length data (method b in section 3.3) was the traditional method used by IFOP for stock assessment. In this analysis I estimated the yield per recruit for Chilean sardine using the age data sets of IFOP and UNAP. The yield-per-recruit analyses were generated in parallel (Fig 5).

IV. Results and Discussion

4.1. Populations parameters for the Chilean sardine

4.1.1. Growth of *Sardinops sagax*

Estimation of growth parameters of length and weight for *Sardinops sagax* using IFOP and UNAP data resulted in different von Bertalanffy parameters for the same kind of length and age data (Table 6 and 7). The L_{∞} and W_{∞} parameters for the IFOP data were higher than those for UNAP, except for W_{∞} with UNAP total data. The UNAP k and t_0 parameters for length and weight were higher than the IFOP parameters, except for t_0 in UNAP total for weight. The goodness of fit statistics was measured using the coefficient of determination (R^2) (Kvalseth 1985) from the ANOVA table generated by the SAS NLIN procedure. In all cases, the R^2 values were significant at the 1% level. There were significant non-linear goodness of fit statistics for length/weight and age data, but data for intermediate ages gave better a fit than for younger and older fish because in the intermediate ages there were greater numbers (Fig 6, 7). The distribution and dispersion of data points for the different length, weight and age averaged data for IFOP and UNAP were also analyzed (Figures 8, 9).

Growth curves corresponding to the same kind of length/weight (total and average) and age data for IFOP and UNAP were compared using Hotelling's T^2 . There were significant differences between the IFOP and the UNAP von Bertalanffy growth estimates (Table 8). The length at age curves for the UNAP

data indicated faster growth than those for the IFOP data (Fig 6, 8). The most important differences were in the estimates for k . The values for the IFOP age-length data were 4.4 and 4.5 times those for the UNAP data.

Table 6. Von Bertalanffy growth parameter in length for different data source and method of data organization for IFOP and UNAP.

Data source	Method	\hat{L}_{∞}	\hat{k}	\hat{t}_0	N	R^2
IFOP	Total	48.813	0.080	-5.038	4212	0.997
UNAP	Total	34.875	0.349	-1.735	1117	0.990
IFOP	Average	35.896	0.202	-2.130	9	0.999
UNAP	Average	31.588	0.909	0.248	5	0.998

Table 7. Von Bertalanffy growth parameter in weight for different data source and method of data organization for data for IFOP and UNAP.

Data source	Method	\hat{W}_{∞}	\hat{k}	\hat{t}_0	N	R^2
IFOP	Total	904.463	0.095	-4.505	4212	0.975
UNAP	Total	1186.674	0.107	-4.679	1117	0.898
IFOP	Average	484.667	0.180	-2.492	9	0.999
UNAP	Average	290.901	0.764	0.039	5	0.987

The asymptotic lengths (L_{∞}) from the UNAP data were less than those for the IFOP data by between 4.3 and 15.3 cm. The weight curves showed similar differences. The weight at age curves for the UNAP data showed faster growth than the weight at age curves for the IFOP data. The k values for the UNAP

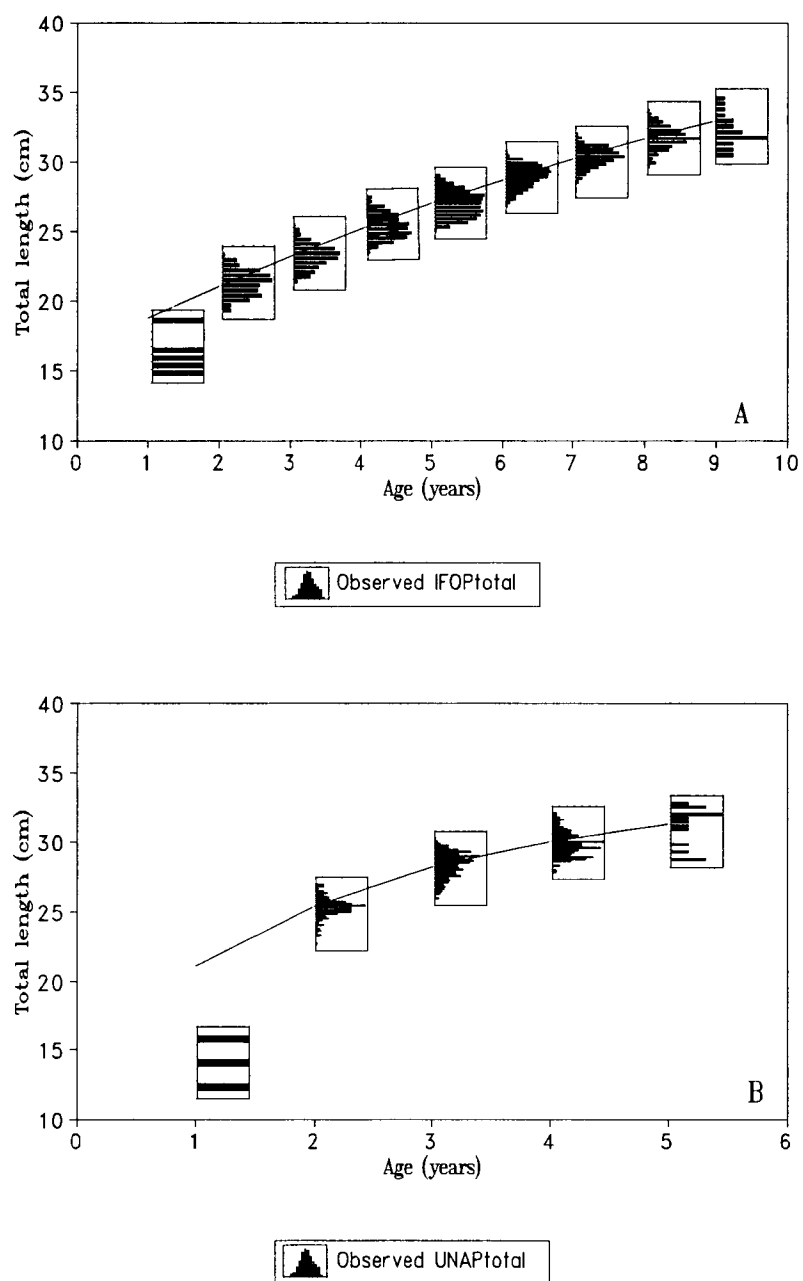


Figure 6. Estimated von Bertalanffy curve in total length for pairs observed age and length frequency in number of fish for (A) IFOP total and (B) UNAP total.

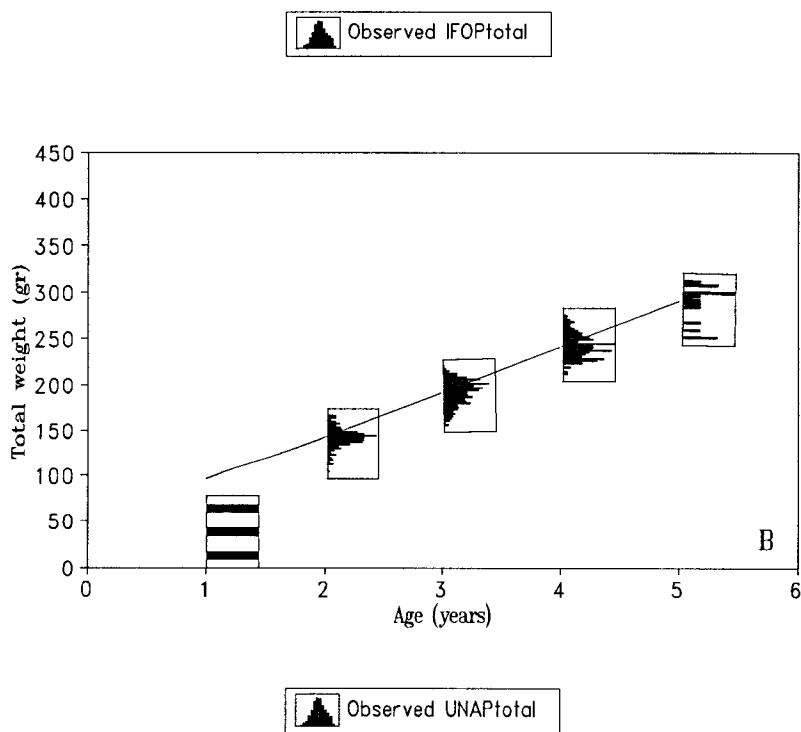
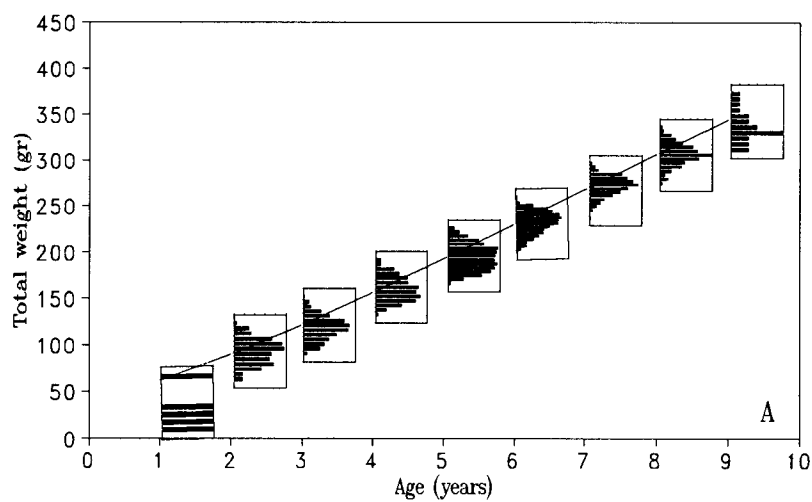
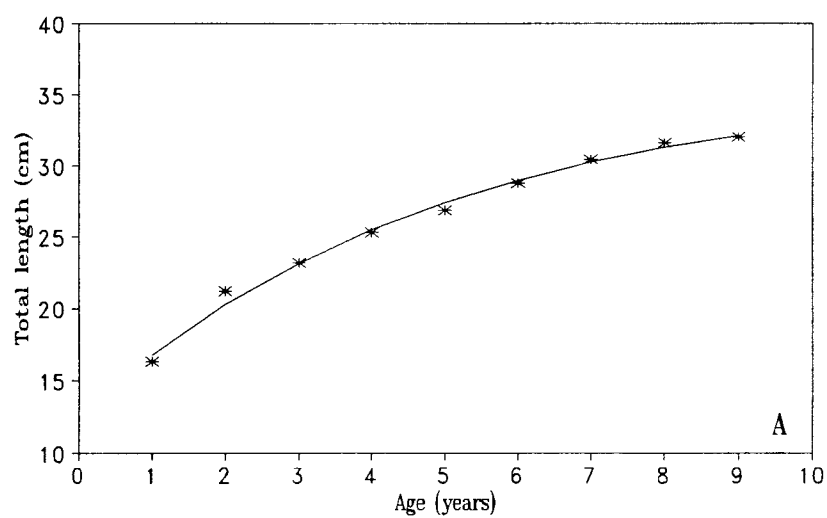
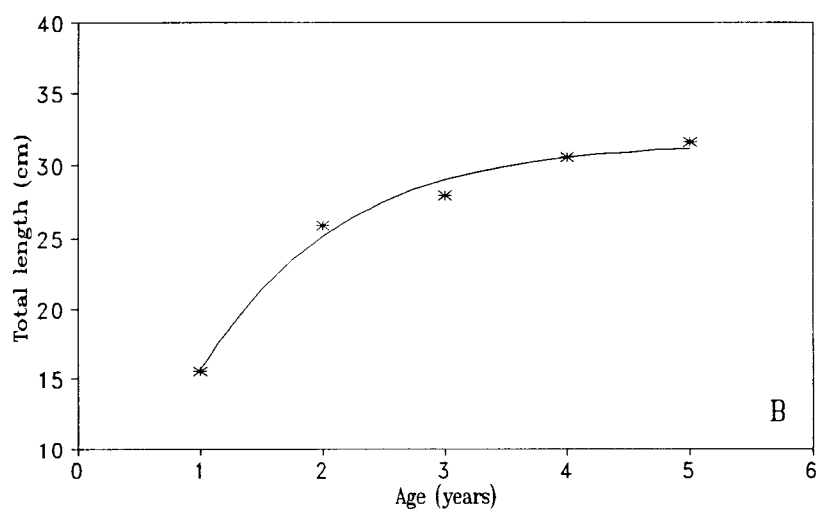


Figure 7. Estimated von Bertalanffy curve in total weight for pairs observed age and weight frequency in number of fish for (A) IFOP total and (B) UNAP total.

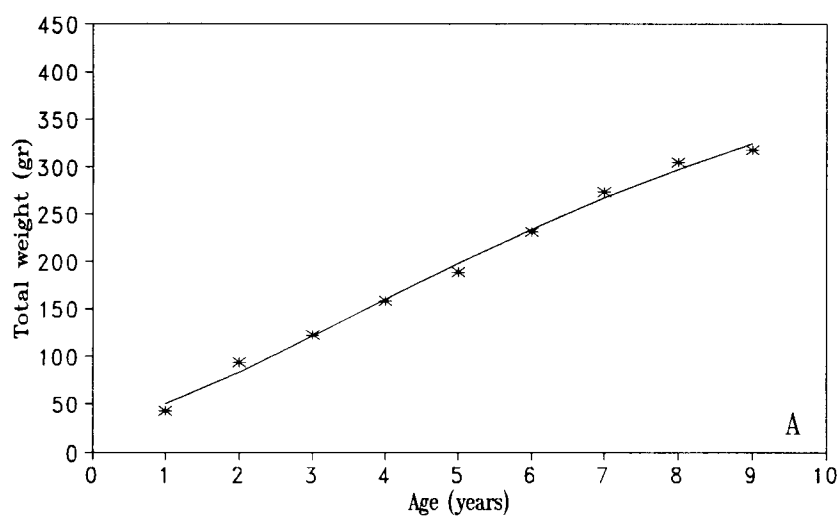


* Observed IFOPaver

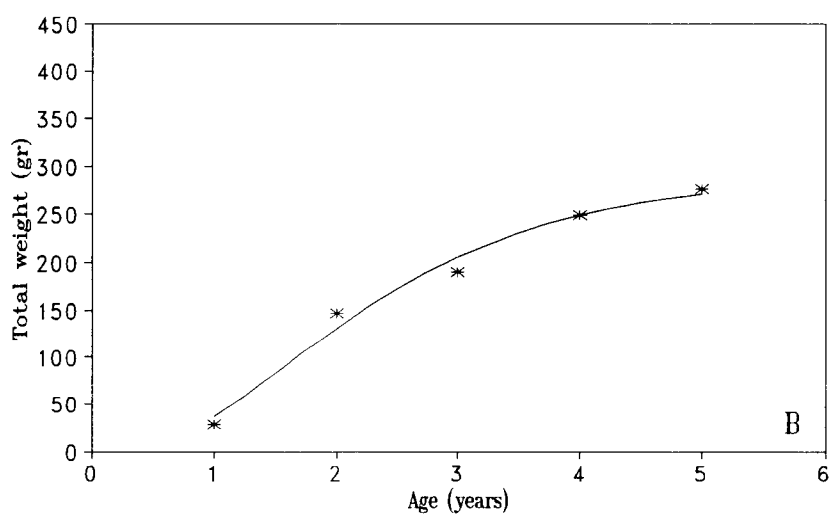


* Observed UNAPaver

Figure 8. Estimated von Bertalanffy curve in total length for pairs of averaged age and averaged length for (A) IFOP average and (B) UNAP average.



* Observed UNAPaver



* Observed UNAPaver

Figure 9. Estimated von Bertalanffy curve in total weight for pairs observed of averaged age and averaged weight for (A) IFOP average and (B) UNAP average.

data were 1.1 and 4.2 times higher and the differences in W_{∞} were 282.2 to 193.8 gr (Table 7).

Table 8. Hotelling's T^2 values for von Bertalanffy parameter in length and weight between IFOP and UNAP. Hotelling's T^2 values are significant ($p < 0.01$).

Data source	Method	T^2_{length}	T^2_{weight}
IFOP (N=4212)	Total	135259.8	66409.8
UNAP (N=1117)			
IFOP (N=9)	Average	275.910	95.995
UNAP (N=5)			

The von Bertalanffy growth parameters estimated using ELEFAN I are presented in Table 9. The annual length frequency distributions for the IFOP and UNAP data showed no significant differences (Table 1 section 3.1), but the monthly length frequency data indicated some differences. For instance, IFOP monthly length frequency data ranged between 18 - 35 cm with an average mode of 23 cm in comparison with the UNAP data, which ranged between 17 to 36.5 cm with an average mode of 25.5 cm. In general, the von Bertalanffy growth parameters for IFOP and UNAP together with Munro phi prime test (Φ') (Munro and Pauly 1983, Pauly and Munro 1984) showed little difference (Table 9).

4.1.2. Instantaneous rate of natural mortality for *Sardinops sagax*

Averaged natural mortality parameter calculated from different methods and derived from IFOP and UNAP ages showed that estimates of M ranged between 0.168 - 0.236 for IFOP and between 0.356 - 0.541 for UNAP data. Instantaneous natural mortality rates (M) corresponding to the same kind of length and age data for IFOP and UNAP showed significant differences ($\alpha = 0.05$) (Dixon and Massey 1969) (Table 10). These results reflected the same trend as the calculated von Bertalanffy growth parameters in length because the different method of estimate M depend on growth parameter previously estimated. This was particularly true for the methods of Taylor (1960), Rikhter and Efanov (1976) and Pauly (1980, 1983).

Table 9. Population parameters estimated using complete ELEFAN.

Data source	\hat{L}_{∞}	k	Φ'	M	Z	F_{fishery}	$F_{0.1}$	F_{MSY}
IFOP	31.2	0.315	5.72	0.676	0.69	0.014	0.0074	
UNAP	32.04	0.384	5.97	0.764	0.84	0.076	0.0098	0.63

4.1.3. Instantaneous rate of total fishing mortality of *Sardinops sagax*

Catch-at-age data (Fig 10) were used to obtain catch curves for IFOP and UNAP data (Fig 11). The descending right hand sides of the linearized catch curves appeared linear, indicating no evidence for violations of the assumptions of similar age specific mortality, uniform recruitment, and equal vulnerability to the

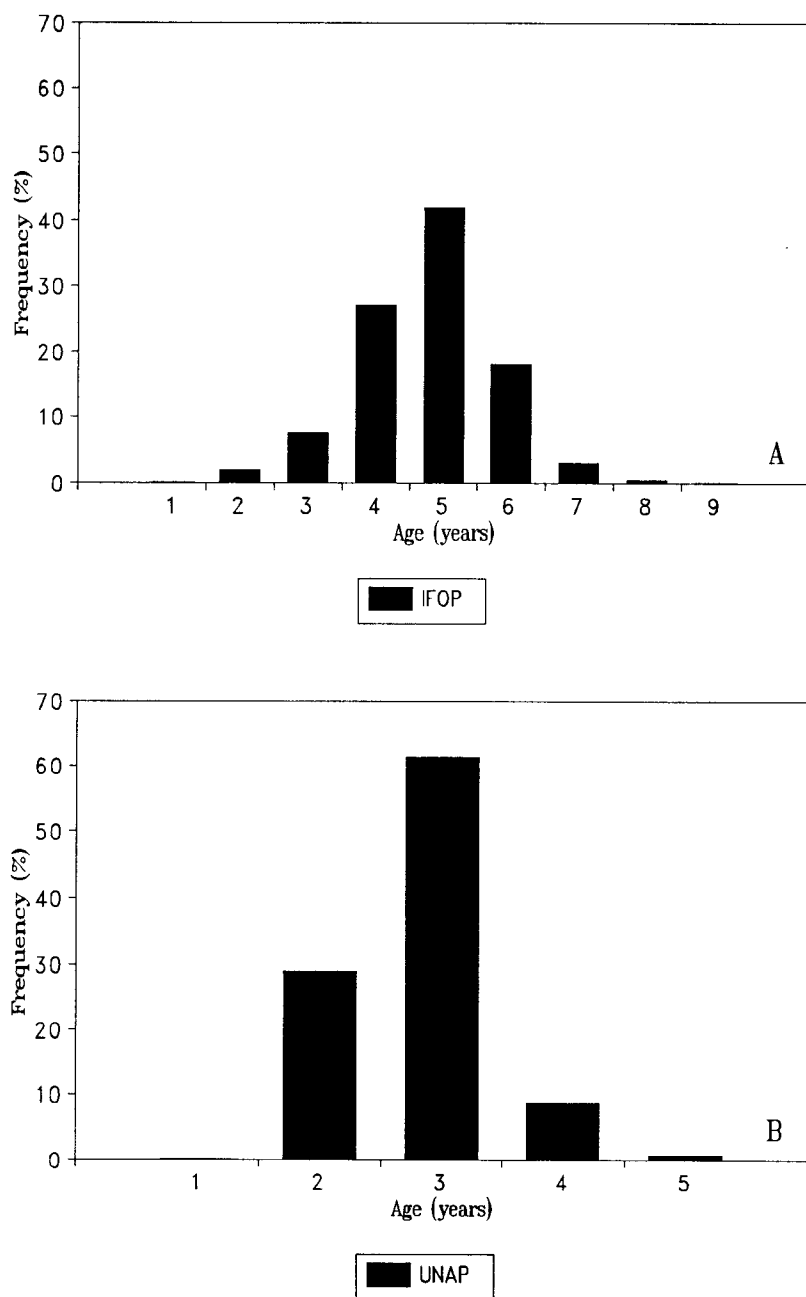


Figure 10. Age composition of *Sardinops sagax* sampled by (A) IFOP and (B) UNAP during 1985-86 in northern Chile.

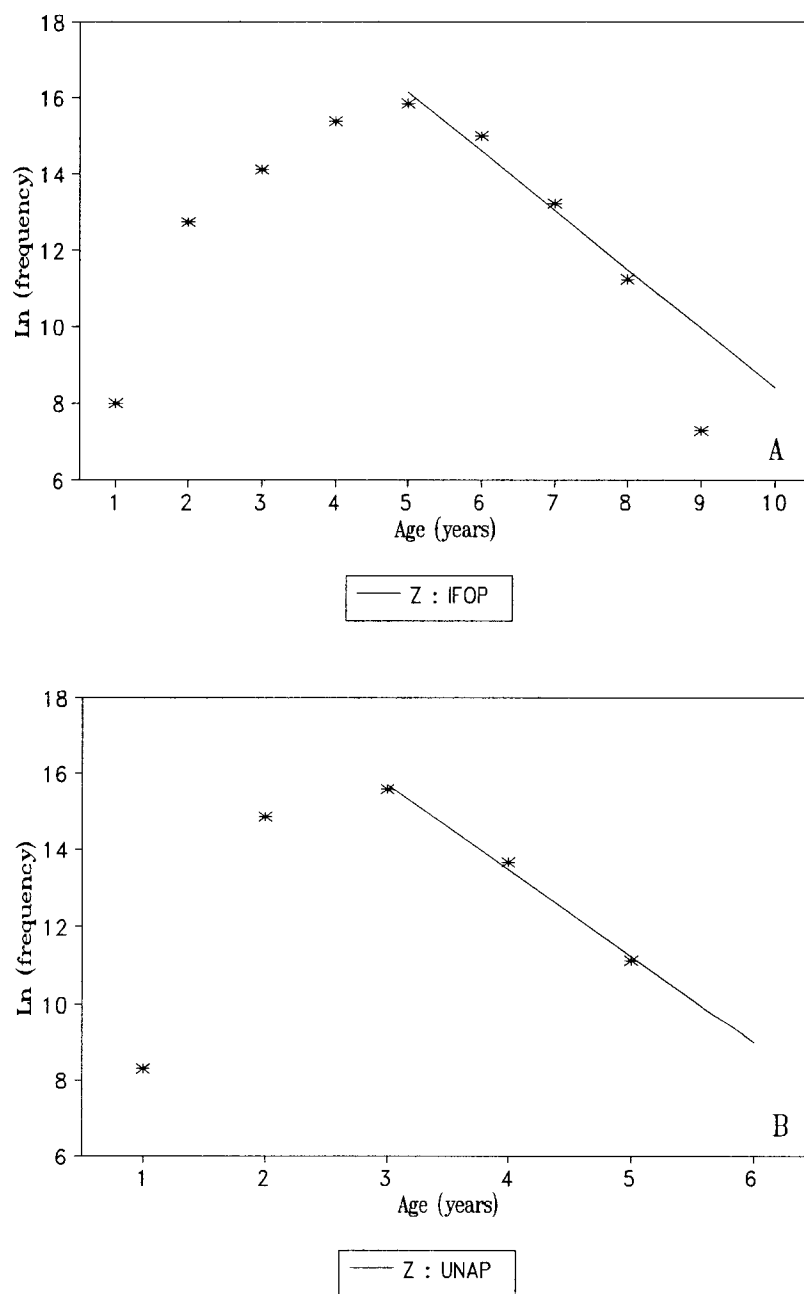


Figure 11. Catch curves based on age determination made by (A) IFOP and (B) UNAP.

sampling gear of all fully recruited age groups (Ricker 1975; Chapman and Robson 1960; Robson and Chapman 1961). The instantaneous rate of total mortality (Z) for IFOP and UNAP followed the same pattern as the von Bertalanffy growth parameters and natural mortality coefficient, i.e. UNAP estimates are larger than IFOP. There is strong evidence of significant differences between the estimates of Z for the IFOP ($Z = 1.554$) and UNAP ($Z = 2.234$) data sets ($p\text{-value} = 0.00844$ partial F test).

Catch curves based on length were used to estimate instantaneous total mortality (Z) (Fig 12), and instantaneous natural mortality (M) (Table 9). The length data were analyzed using the ELEFAN II procedure and equation 7 instead of equation 8 (to see section 3.4.1.).

Table 10. Natural mortality parameter calculated using different methods. "t" test values are significant at $p = 0.05$.

Data source	Method	M ₁	M ₂	M ₃	M ₄	M ₅	\bar{x}	Std. Dev.	"t" test
IFOP	Total	0.092	0.322	0.194	0.109	0.124	0.168	0.094	1.78
UNAP	Total	0.437	0.535	0.560	0.114	0.135	0.356	0.216	
IFOP	Average	0.236	0.322	0.388	0.109	0.124	0.236	0.122	1.53
UNAP	Average	0.845	0.535	1.077	0.114	0.135	0.541	0.426	

M₁: Taylor (1960)

M₂: Rikhter and Efanov (1976)

M₃: Pauly (1980, 1983)

M₄: Peterson and Wroblewski (1984)

M₅: Gunderson and Dygert (1988)

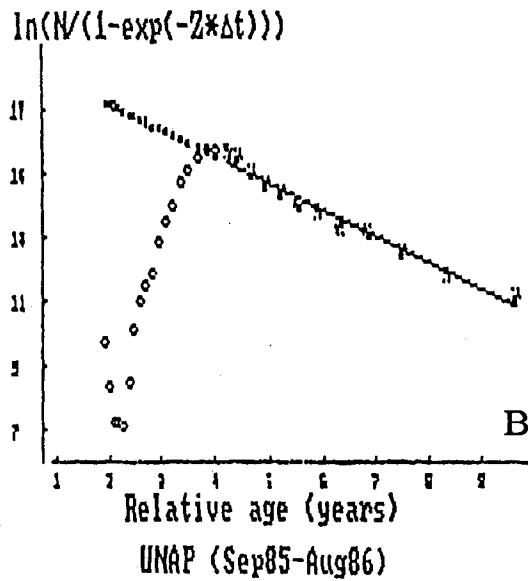
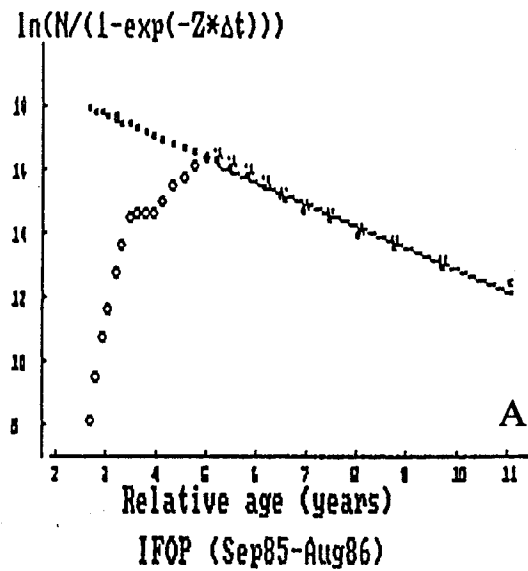
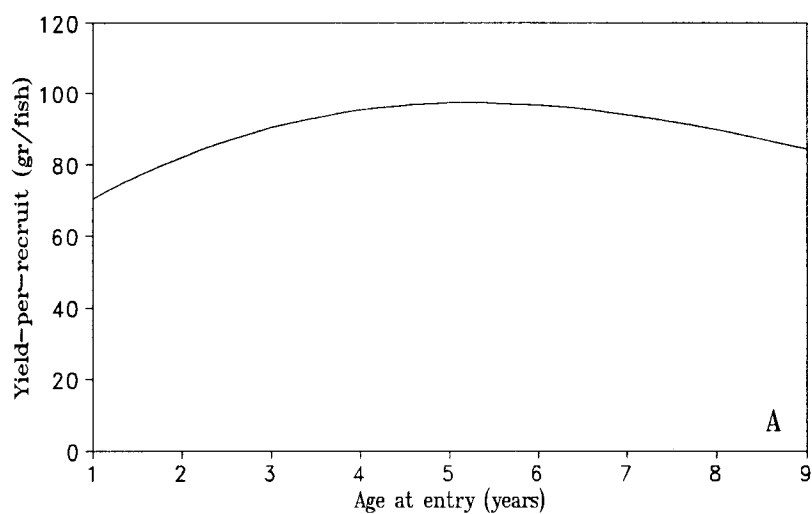


Figure 12. Catch curves based on frequency length distribution calculated using compleat ELEFAN by (A) IFOP data and (B) UNAP data.

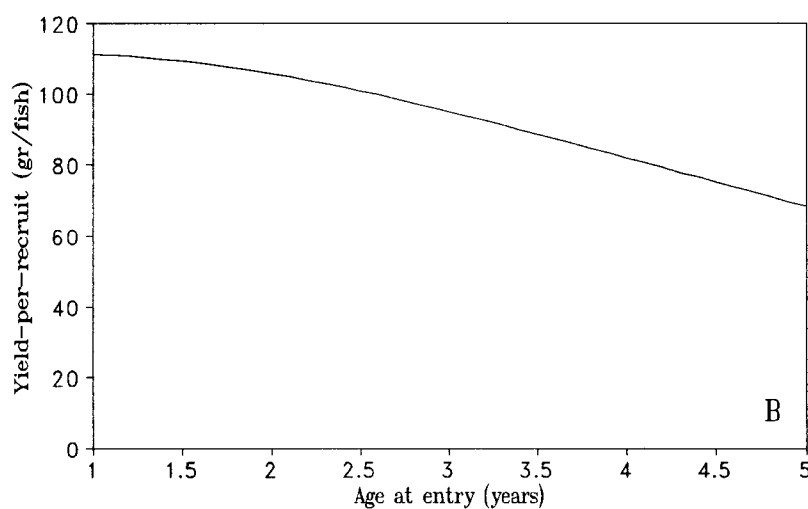
4.2. Potential yield

The potential yield was estimated using the Beverton and Holt model for yield-per-recruit (Y/R) and the parameters calculated previously (Table 11). The specific values of t_c and F used in the graphs (Fig. 13, 15, 23 and 24) corresponded to the estimates in section 3.5. for t_c and section 4.1.3. for F (Fig 14, 16). The relationship between Y/R and t_c is parabolic with a maximum of Y/R when t_c is equal to the age when the cohort reach the maximum biomass at the specified level of instantaneous fishing mortality. This relationship for IFOP total and IFOP average are rather flat (Fig 13a, 14a). The behavior of the same variables for UNAP total was different since the Y/R decreases rapidly with increases in t_c (Fig 13b). For UNAP average data the Y/R increases rapidly with increases in t_c and then decreases rapidly (Fig 14b). Maximum Y/R for UNAP was a little larger than IFOP for the totals, but the situation was reversed for the averages (Table 12 and 13).

The graphs of Y/R versus F for IFOP total, and IFOP average with $t_c = 2$ years increased rapidly to a maximum and then declined slowly (Fig 15a, 16a). In contrast the graphs for UNAP total and UNAP average with $t_c = 2$ year (Fig 15b, 16b) increased more slowly than the corresponding IFOP curves. For UNAP total the graph had no maximum for finite values of F . The maximum value of Y/R for UNAP was larger than IFOP for total and averaged data (Table 14).



— IFOPtotal: $F=1.386$



— UNAPtotal: $F=1.877$

Figure 13. Plot of yield-per-recruit against age at entry (A) IFOP total with $F=1.386$ and (B) UNAP total with $F=1.877$.

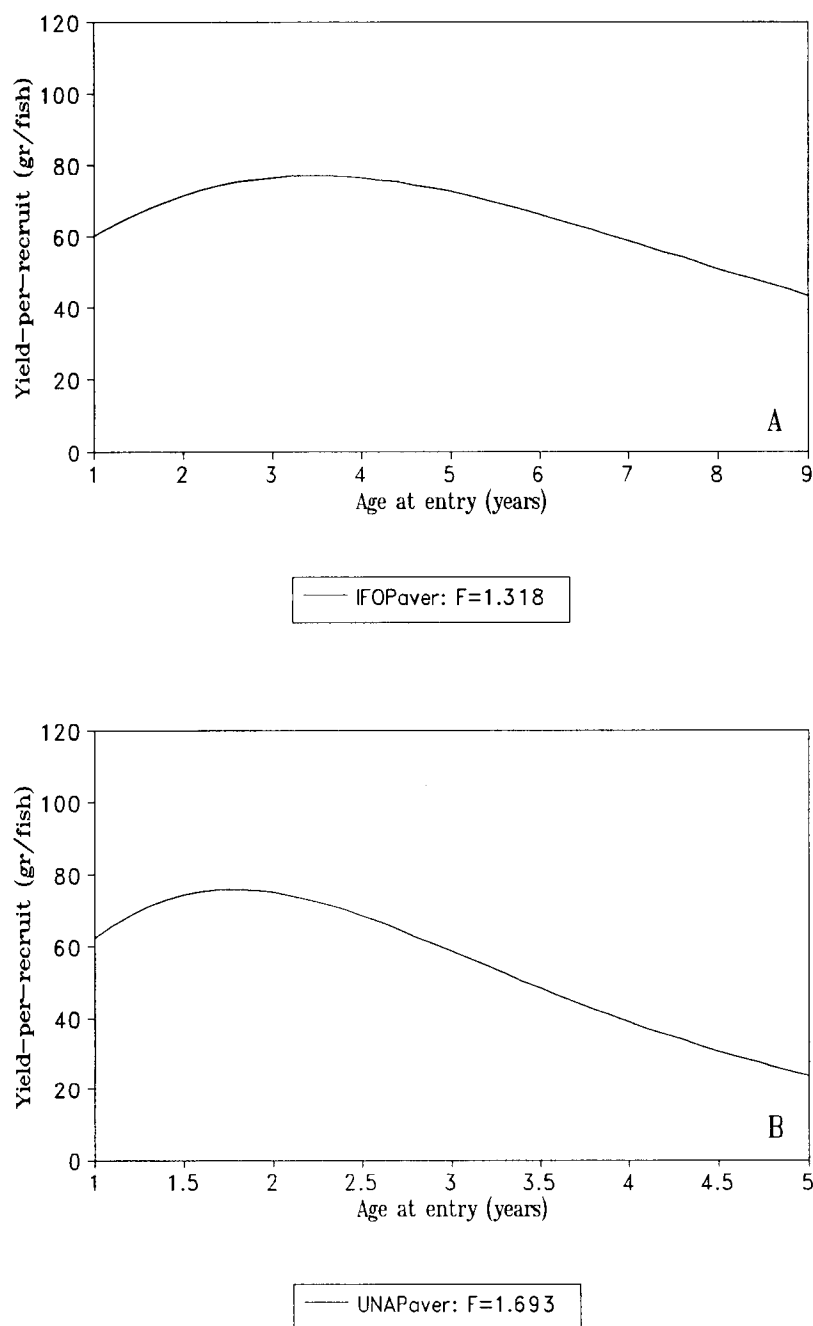


Figure 14. Plot of yield-per-recruit against age at entry for (A) IFOP average with $F=1.318$ and (B) UNAP average with $F=1.693$.

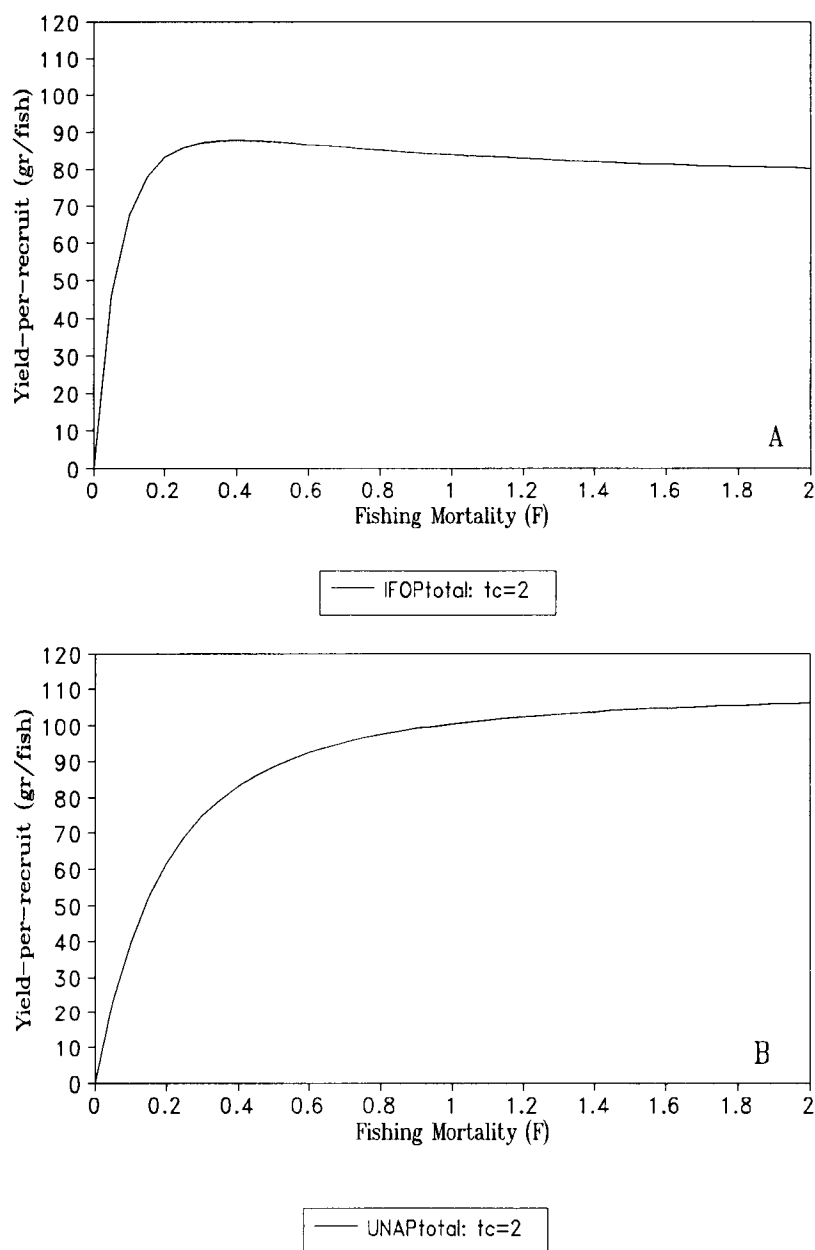


Figure 15. Plot of yield-per-recruit against fishing mortality for (A) IFOP total with $t_c=2$ and (B) UNAP total with $t_c=2$.

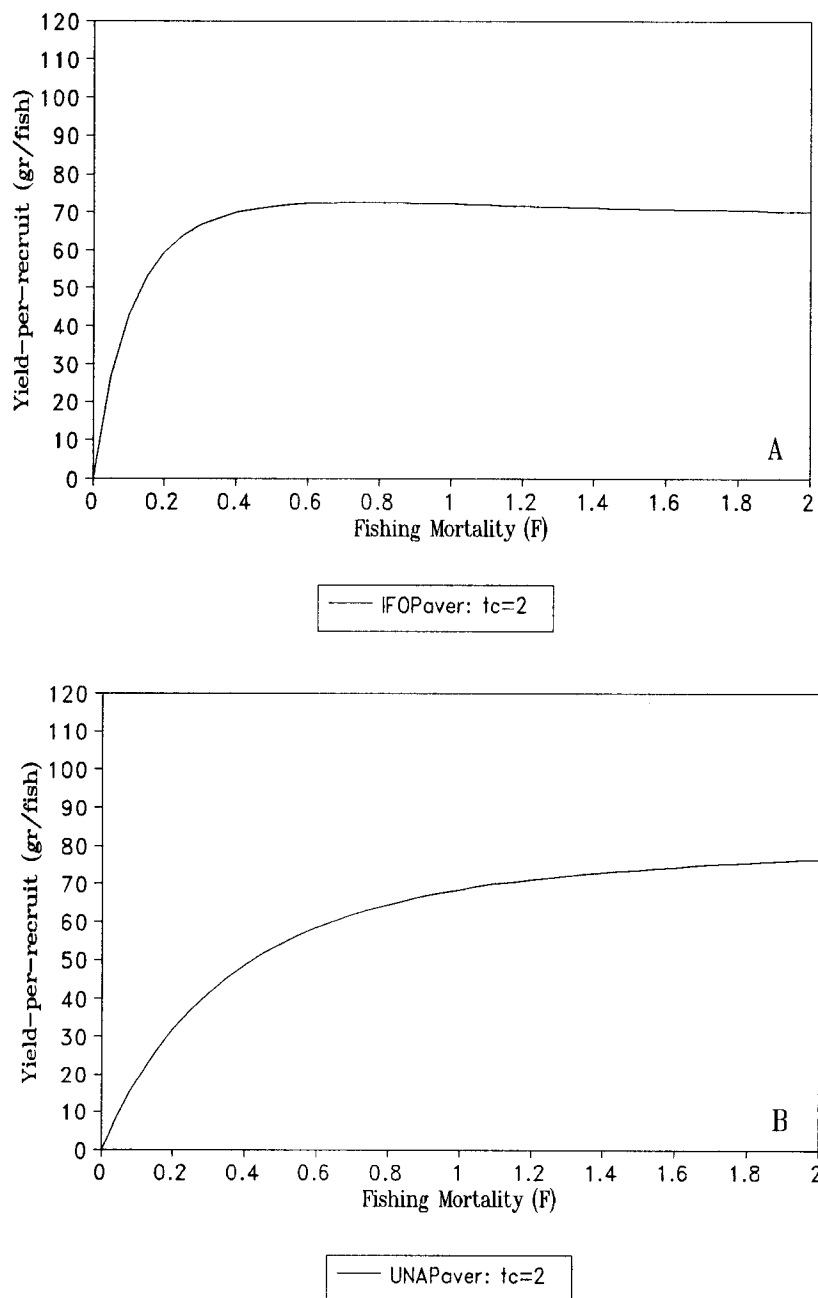


Figure 16. Plot of yield-per-recruit against fishing mortality for (A) IFOP average with $t_c=2$ and (B) UNAP average with $t_c=2$.

Table 11. Parameter used in the Beverton and Holt yield-per-recruit analysis.

Data source	Method	\hat{W}_∞	\hat{k}	\hat{t}_0	t_c	t_r	\bar{M}	F
IFOP	Total	904.463	0.095	-4.505	2	1	0.168	1.386
UNAP	Total	1186.674	0.107	-4.679	2	1	0.356	1.877
IFOP	Average	484.667	0.180	-2.492	2	1	0.236	1.318
UNAP	Average	290.901	0.764	0.039	2	1	0.541	1.693

Table 12. Maximum yield-per-recruit for IFOP and UNAP when t_c was maintained constant.

Data source	Method	t_c	Y/R_{\max}
IFOP	Total	2	87.724
UNAP	Total	2	106.034
IFOP	Average	2	72.457
UNAP	Average	2	76.267

The behavior of Y/R with respect to F and t_c was substantially different for IFOP and UNAP. Therefore, I followed the standard practice of using yield-per-recruit isopleth to analyze the influence of both factors acting simultaneously with a combination of t_c between 1 to 9 and F between 0 to 2 for IFOP, and with t_c between 1 to 5 and F between 0 to 2 for UNAP. Yield isopleths for IFOP (Fig 17a and 18a) had values between 10 and 96 gr/recruit and the yield-per-recruit - reached a maximum (isopleth of 96) when fish were first taken at an age between

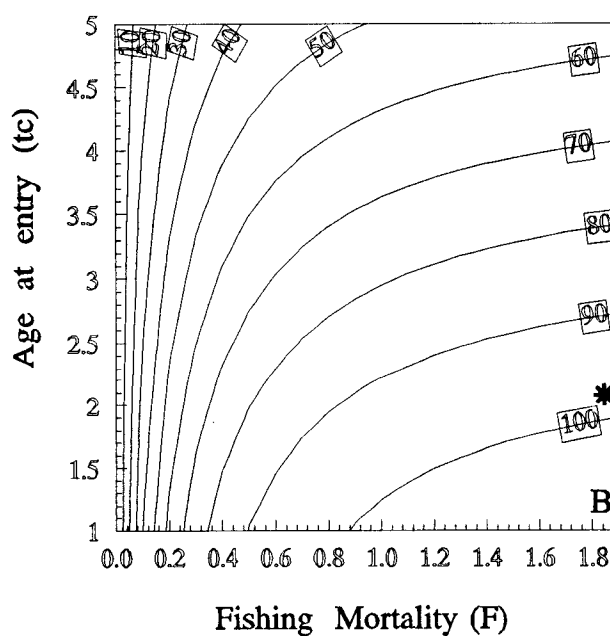
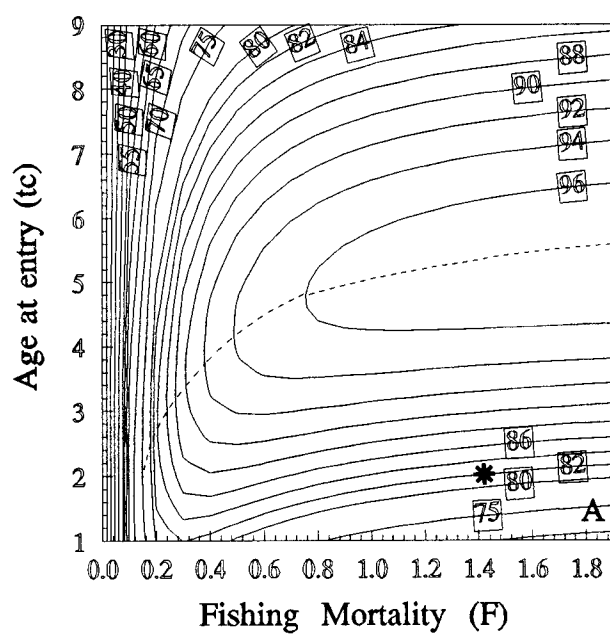


Figure 17. Yield-per-recruit isopleth for (A) IFOP total and (B) UNAP total. Asterisk indicates the actual position of the fishery and the dotted line is the eumetric curve.

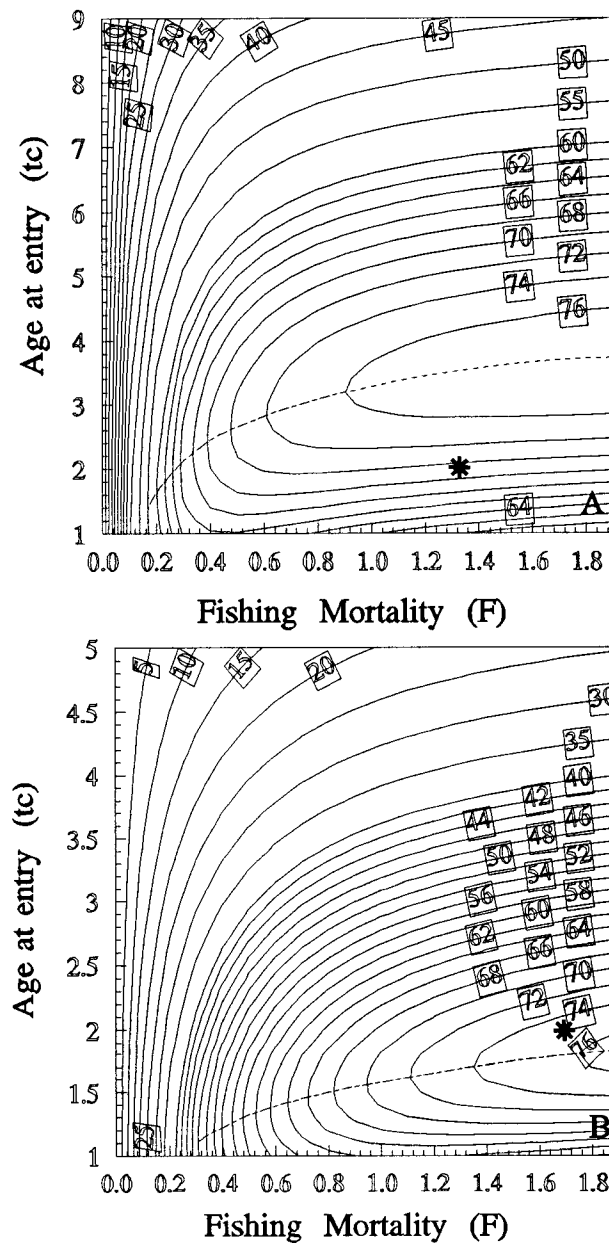


Figure 18. Yield-per-recruit isopleth for (A) IFOP average and (B) UNAP average. Asterisk indicates the actual position of the fishery and the dotted line is the eumetric curve.

4 and 5 (specifically at age 4.8 year) with a F value of 0.76 or greater (Fig 17a). In the case of UNAP (Fig 17b and 18b), the yield values ranged between 5 and 76 gr/recruit and reach a maximum at $Y/R \approx 76$ gr/recruit at age 1.8 year with a F value of 1.76 or greater (Fig 17b). The comparison of maximum Y/R values between IFOP total and UNAP total is not very clear because the eumetric fishing line (least cost combination (smallest F) of F and t_c that produces a given yield) for the UNAP total is outside the range of values for F and t_c (Fig 17b) and the eumetric curve could not therefore, be established. In the case of averaged data, the maximum Y/R values for UNAP data were larger than for the IFOP data (Table 12 and 13). Also the range of values for the age at entry (t_c) for the UNAP data were smaller than the values for IFOP, although the range of values for F were the same for both IFOP and UNAP.

ELEFAN II was used to compute relative yield-per-recruits (Y'/R) which corresponded to a more general version of the Y/R model of Beverton and Holt (1957). Monthly length frequency distributions and the ELEFAN V procedures (Pauly 1987) were used to compute Y/R . The input parameters were L_c/L_∞ and M/k , which had been previously determined using ELEFAN I and II. The L_c parameter is analogous to the t_c parameter used in the traditional model of Beverton and Holt (1957). I used values of 19.48 and 15.19 cm for the IFOP and UNAP data. The relationship between Y'/R versus F for IFOP did not show a maximum value, but for the UNAP data the maximum Y'/R was 0.032 at $F = 0.63$ (Fig 19 a, b).

Table 13. Maximum yield-per-recruit for IFOP and UNAP when F was maintained constant.

Data source	Method	F	Y/R_{\max}
IFOP	Total	1.386	97.215
UNAP	Total	1.877	111.110
IFOP	Average	1.318	77.055
UNAP	Average	1.693	75.781

Table 14. Maximum yield-per-recruit values with respect to t_c and F values. Numbers in parentheses correspond to calculated values.

Data source	Method	t_c	F	Y/R_{\max}
IFOP	Total	5.4	1.9	96(97.479)
UNAP	Total	1	1.9	111.145*
IFOP	Average	3.6	1.9	76(77.610)
UNAP	Average	1.8	1.9	76(76.522)

∴It is not really a maximum.

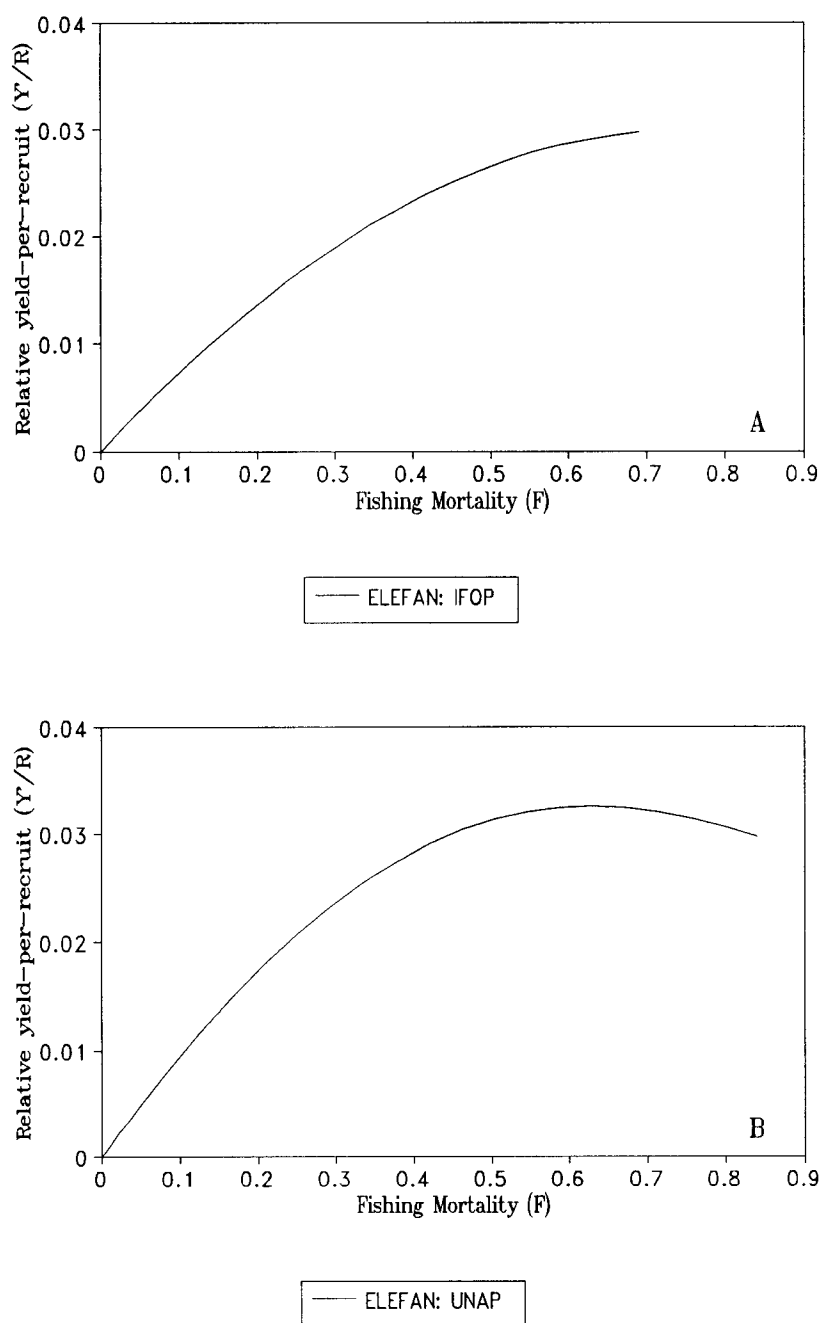


Figure 19. Plot of relative yield-per-recruit against fishing mortality estimated using ELEFAN for (A) IFOP and (B) UNAP.

4.3. Comparison of the Chilean sardine population parameters with respect to other species of *Sardinops*.

4.3.1. Comparison of growth of *Sardinops sagax* with other studies

The differences in the relationship between age-length and age weight, based on two different ageing methods, resulted in significative differences in the estimation of the von Bertalanffy growth parameters (VBGP). When I compared estimates of VBGP for IFOP data with estimations done by IFOP using averaged length-age data, I observed that the estimated L_{∞} was lower than the IFOP's estimation (Serra et al. 1979, Trautmann and Aguayo 1980, Aguayo et al. 1983 and Aguayo et al. 1987). The estimation of VBGP based on daily growth increments (DGI) was in the range of other estimates for *S. sagax* in the South-Eastern Pacific (Table 15). The estimate for parameter k , was exactly the same as the estimate published in Aguayo et al. (1987) and also was in the range of other estimates (Table 15). Although the IFOP totals data (data source from IFOP and fitting method used was length frequency distribution at each age) are not exactly comparable with other estimates, L_{∞} from the IFOP totals was the largest estimate not only with respect to IFOP's estimates, but also with other estimates for *S. sagax* (Table 15). In the case of the parameter k , the opposite situation occurred, because k of IFOP totals was the lowest estimation. By comparing VBGP for IFOP (totals and average) with another species of *Sardinops* it was possible to see that estimates for both L_{∞} and k were larger and smaller respectively than the others (Table 16). Although *S. caerulea*, *S. ocellata* and *S.*

sagax inhabit similar environments (Eastern Boundaries Currents), the three species exhibited different growth patterns. The methods of age analysis, i.e. (a) rings count versus daily growth increment and (b) fit average length-at-age versus fit all the individual length-at-age data, may be a factor in growth pattern differences. For UNAP estimations, in particular, the estimate for parameter k using the totals and averages were very close to the estimates for the different species (Table 16).

With respect to parameter L_{∞} , both data sets, IFOP and UNAP, and both methods for data organization, totals and averages, showed larger values than the other species of *Sardinops*, because *S. sagax* is the biggest sardine (Fig 20). The VBGP estimates using UNAP's data were in the range of the other estimates for *S. sagax* (Table 15) except for k based on average length-at-age ($k = 0.909$) which was larger than other estimates but was not too different from the estimates for *S. melanosticta* (Kondo 1980) and *S. ocellata* (Thomas 1985) (Table 16). The UNAP estimates of VBGP using UNAP data showed important differences with respect to the other estimates for *S. sagax* off Chile. The UNAP estimates for L_{∞} were smaller and k was larger than other estimates. The fact that the VBGP based on UNAP data averages and totals data were close to the estimates for others species of *Sardinops* (particularly the more recent estimates by Kondo (1980) and Thomas (1985)), may be an indicator of mistakes in the ageing methods used by IFOP (Serra et al. 1979, Trautmann and Aguayo 1980,

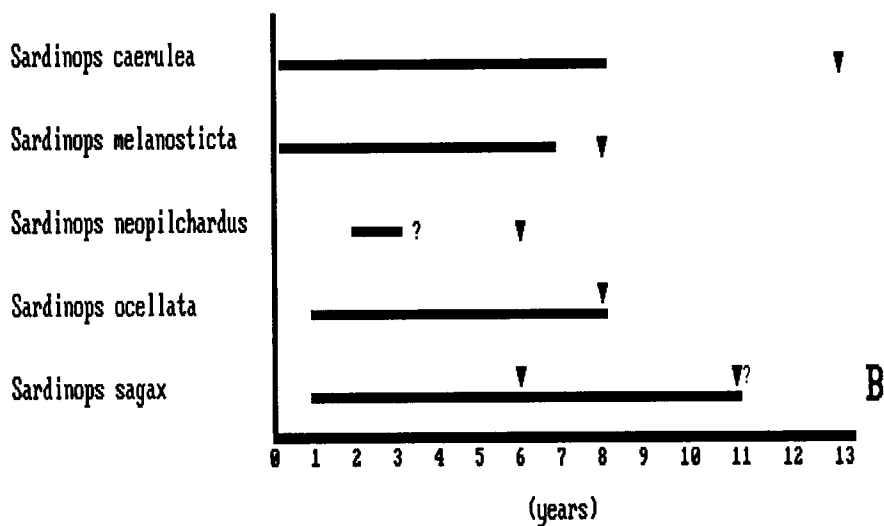
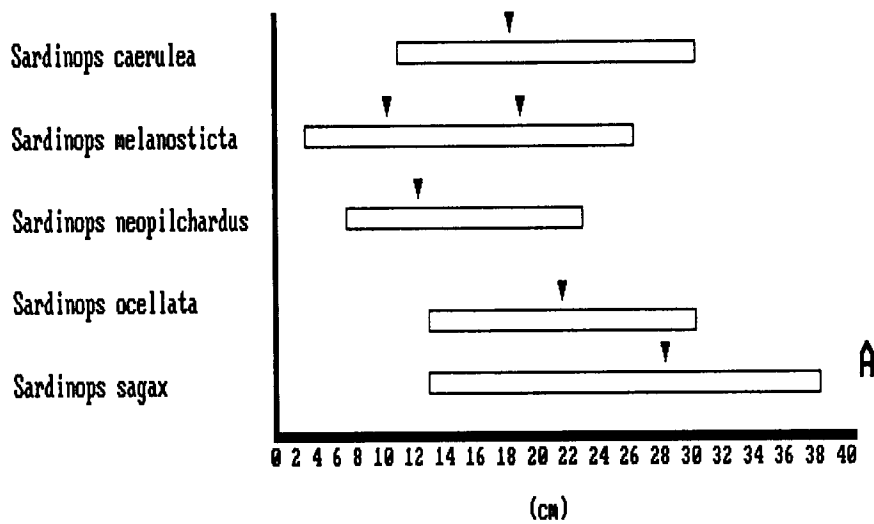


Figure 20. (A) Size composition of catch, ▼: modal size and (B) age composition of catch for different species of *Sardinops* around the world, ▼: maximum age and ? are problems in ageing (modified from Rosa and Laevastu 1960).

Table 15. Von Bertalanffy growth in length parameters for *Sardinops sagax* off Chile, Perú and, Ecuador.

Author's	Sex	\hat{L}_{∞}	k	\hat{t}_0
Alberti and Larrañeta (1966)	M ⁵ + F ⁵	38.3 ¹	0.439	
Vidal (1967) ²	M + F	37.28	0.5	0.121
Samamé (1977) ³ +	males	33.79	0.326	-0.389
Samamé (1977) ³ +	females	32.39	0.322	-0.724
Serra et al. (1979) +	M + F	38.6	0.207	-2.160
Trautmann and Aguayo (1980) +	M + F	48.06	0.145	-0.972
Aguayo et al. (1983) +	M + F	40.0	0.205	-0.916
Cardenas (1983) ³ +	M + F	41.58	0.19	-1.43
Cardenas (1983) ³ + +	M + F	38.51	0.25	-0.54
Saldaña (1983) ⁴ +	M + F	31.2	0.437	-0.932
Saldaña (1983) ⁴ + +	M + F	34.0	0.347	-0.612
Vidal (1985) ²	M + F	37.73	0.459	0.287
Cárdenas and Mendo (1985) ²	M + F	41.0	0.252	
Cárdenas (1987) ³ +	M + F	39.8	0.22	-0.84
Cárdenas (1987) ³ + +	M + F	37.49	0.25	-0.71
Aguayo et al. (1987)	M + F	40.26	0.202	-0.934
IFOP total ⁶ +	M + F	48.813	0.080	-5.038
UNAP total ⁶ + + +	M + F	34.875	0.349	-1.735
IFOP average ⁶ +	M + F	35.896	0.202	-2.130
UNAP average ⁶ + + +	M + F	31.588	0.909	0.248

- *1 Fork length
 *2 Length frequency
 *3 *S. sagax* (Perú)
 *4 *S. sagax* (Ecuador)
 *5 M = males and F = females
 *6 Estimates in this thesis
 + Rings count
 + + Back calculation
 + + + Daily growth increment

1987) (Table 17). The difference was caused by different methods of fitting the von Bertalanffy growth function (non-linear versus Ford-Walford or Beverton-Holt). Similar explanations are possible when examining the ranges for the other estimates for *S. sagax* (Table 17). Due to ageing differences together with different methods of fitting von Bertalanffy growth weight function the UNAP estimates of parameter W_{∞} for weight based on UNAP totals data and parameter k based on UNAP average data were larger than the other estimates. The parameter W_{∞} based on the UNAP average and k based on UNAP totals were lower than the other estimates (Table 17).

The VBGP estimate derived using the complete ELEFAN were similar for both the IFOP data and the UNAP data. This result was expected since ELEFAN Table 15. Von Bertalanffy growth in length parameters for *Sardinops sagax* off Chile, Perú and, Ecuador is based on length frequency and both sets of length frequency observation came from the same population. In the particular case of L_{∞} , estimates from both data sets were less than the estimates reported in Vidal (1967 and 1985) and Cárdenas and Mendo (1985), which were also derived using length frequency data. In the case of k , both values were in the range reported by Vidal (op. cit.) and Cárdenas and Mendo (op. cit.).

Age and growth based on the DGI data indicated that the sardine off northern Chile grew faster than indicated from estimates derived from annual

growth rings. It is probable that the other studies misidentified secondary rings for annual rings in age determinations, since no corroborative growth studies were

Table 17. Von Bertalanffy growth in weight parameter for *Sardinops sagax* off Chile, Perú and, Ecuador.

Author's	Sex	\hat{W}_∞	\hat{K}	\hat{t}_0
Samamé (1977) ¹ +	males	424.19	0.3187	
Samamé (1977) ¹ +	females	373.56	0.3144	
Serra et al. (1979) +	M ³ + F ³	550.6	0.2	-2.014
Trautmann and Aguayo (1980) +	M + F	1141.7	0.137	-0.817
Aguayo et al. (1983) +	M + F	612.2	0.205	-0.917
Aguayo et al. (1987) +	M + F	680.5	0.185	-1.131
IFOP total ² +	M + F	904.463	0.095	-4.505
UNAP total ² + +	M + F	1186.674	0.107	-4.679
IFOP average ² +	M + F	484.667	0.180	-2.492
UNAP average ² + +	M + F	290.901	0.764	0.039

*1 *S. sagax* (Perú)

*2 Estimates in this thesis

*3 M= males and F= females

+ Rings count

+ + Daily growth increment

done and different methods of age assignation were used. The sardine off northern Chile apparently grew much faster than previous studies have indicated. This age - growth correction produced important changes in the estimates of the yield-per-recruit and resulted in different interpretations of the appropriate management policy for this stock.

4.3.2. Comparison of mortality of *Sardinops sagax* with other studies

The differences in the VBGP between IFOP and UNAP resulted in significative differences in the estimation of the instantaneous natural mortality (M) and total mortality (Z) parameter for the totals and the averages data. The natural mortality coefficient has been estimated for *S. sagax* using different methods, such as Rikhter and Efanov (1976), Roff (1984) and Pauly (1980) being latter more used. A range values of M from 0.28 to 0.51 was reported for *S. sagax* (Table 18), with M= 0.4 the value used in management. The 0.4 value was used for the *S. caerulea* by Murphy (1966) and MacCall (1979). In my study the estimate for \bar{M} based on IFOP data are outside the range of estimates mentioned above, but the estimates using averaged data and Pauly's method is close to the value used for management in Chile and was close to the estimates for *S. caerulea* and *S. melanosticta* (Table 19). The averaged instantaneous natural mortality based on the total data and Pauly's method are the lowest value not only for *S. sagax* but also with respect to other species of *Sardinops* (Table 19). The estimates of \bar{M} using UNAP data are in the range of the estimates for both *S. sagax* and for other species in the genus *Sardinops*.

There are no studies related to the causes of natural mortality in *S. sagax*, however, predation is a potential factor that could account for changes in mortality. There are several studies in Perú that show the presence of sardine in the diets of mackerel (*Scomber japonicus peruanus*) and jack mackerel (*Trachurus murphy*), bonito (*Sarda chiliensis*), fur seal (*Arthrocephalus australis*), dorado

(*Coryphaena hippurus*), pelican (*Pelecanus thagus*), piquero (*Sula variegata*) and cormorant (*Phalacrocorax sp.*). Of these predators mackerel and jack mackerel eat juvenile sardines less than 20 cm. Jack mackerel may account for a considerable predation when they carry out their migration along the coast during the Austral Spring and Summer (several authors in Serra and Tsukayama 1988). Santander et al. (1983 in Serra and Tsukayama 1988) found predation of sardine eggs by anchovy and cannibalism by sardines, which can be an important factor of natural mortality. The "El Niño" events and other physical factors play important but unquantified roles in regulating mortality, principally in the larval stage. During "El Niño" in 1982 -83 the nursery grounds were reduced, concentrating the eggs and larvae and attracting predators (Mujica et al. 1985). During the "El Niño" events of 1982 and 1983 the total sardine biomass declined by almost 20% due to loss of body weight and increased natural mortality (Arntz 1986).

The mortality parameters estimated using length data and the complete ELEFAN were very different from comparable estimates based on IFOP and UNAP age data. However the data available for running ELEFAN corresponded to only 12 monthly observations, which were not adequate to obtain reliable results.

Instantaneous total mortality (Z) for IFOP and UNAP followed the same pattern as the von Bertalanffy growth parameters and the natural mortality coefficients, that is, the UNAP parameter estimate was significantly higher than IFOP. In fact the estimate of Z for UNAP data was higher than other estimations

for other *Sardinops* species (Table 18) but it was close to the estimated value for Z reported for *S. sagax* from northern Chile in 1978 ($Z = 1.52$) (Serra and Tsukayama 1988). The total mortality coefficient for UNAP based on DGI age readings was higher even than the Z estimated for IFOP in 1982 ($Z = 2.05$ in Serra and Tsukayama op. cit.). It was also higher than estimates for other *Sardinops* species (Table 18 and 19).

Fishing mortality coefficients can be expressed in terms of an exploitation rates (E), which define the fraction (in numbers) of an age class that will be caught during its fishable life span (E : number caught/number dying of all causes, $E = F/Z$), or the fraction of deaths caused by fishing (Sparre et al. 1989). The exploitation rate based on the IFOP data, both the total and average data, were 89.2% and 84.8%, which were higher than the corresponding UNAP estimates (84.2% and 75.8%). According to Gulland (1971) fishing mortality in a stock that is optimally exploited should be approximately equal to natural mortality, or $F_{opt} \approx M$ which corresponds to $E_{opt} \approx 0.5$. The 0.5 value is less than the estimated exploitation rates based on the data from IFOP and UNAP. The degree of exploitation for *S. sagax* off northern Chile for 1985 - 1986 was higher than the value recommended by Gulland (op. cit.) and much higher than the exploitation rate of 0.2 recommended by Caddy and Csirke (1983), stocks like sardine that are low in the food chain.

Table 18. Instantaneous mortality parameters for *S. sagax* estimated by different authors. M: natural mortality, F: fishing mortality and Z: total mortality.

Author's	\hat{M}	\hat{F}	\hat{Z}
Serra and Zuleta (1982)	0.4		
Serra and Zuleta (1986)	0.28		
Serra and Zuleta (1986) ¹		0.86 - 2.07	
Serra and Zuleta (1986) ²		0.45 - 1.53	
Vidal (1983)		0.8	0.95
Patterson et al. (1992) ³		0.32	
Vidal (1967)			0.87 - 0.89
Vidal (1985)	0.51		
Serra and Tsukayama (1988)			
IFOP total ⁴	0.168	1.386	1.554
UNAP total ⁴	0.356	1.878	2.234
IFOP average ⁴	0.236	1.318	1.554
UNAP average ⁴	0.541	1.693	2.234
Ecuador (1978 - 1982)	0.4	1.0	1.4
Perú (1978 - 1982)			
North	0.3	0.56	0.86
Center	0.3	0.4	0.7
South	0.3	0.49	0.79
Chile (1974 - 1982)	0.3	0.88	1.18

*¹ Serra and Zuleta (1986), catch curve

*² Serra and Zuleta (1986), Virtual Population Analysis.

*³ Patterson et al. (1992), *S. sagax* from Perú

*⁴ Estimates in this thesis

4.3.3. Growth and mortality of *Sardinops* in relation to fishing

Beverton and Holt (1959) reviewed the lifespans, mortality rates and their relation to growth and other physiological characteristics for different species of fishes in order to understand the fishery dynamics. Holt (1960) and Beverton

(1963) made a more detailed studies which included the population parameters of Clupeid and Engraulid stocks. These studies provide preliminary estimates of the population parameters for *Clupeidae* stocks for which biological data are not available.

There is a general tendency for a high values of k to be associated with a low values of L_{∞} for both inter-specific and intra-specific comparisons. This general tendency was exhibited by sardines (Table 15 and 16). Species with high k and low L_{∞} values generally have short life spans and high natural mortalities (M) (Holt 1960). The ratio of M/k , establishes the relative rate of change in the biomass of a year-class during its exploited life (Beverton 1963). The UNAP average estimates for *S. sagax* were always in the extreme upper right of this relationship (Fig 21). Estimates that used IFOP data were in the lower left extreme (Fig 21a), and also in the middle range on the estimates for all *Sardinops* species (Fig 21b).

The relationship between growth and maturity, in particular the graph of length at maturity (L_m) versus L_{∞} (Fig 22 a) shows that L_m increases directly with L_{∞} . The ratio of L_m/L_{∞} is the proportion of the maximum length that an animal achieves at maturity. Growth is often reduced once an animal reaches maturity because energy is diverted from growth to reproduction. My estimates for *S. sagax*, where L_m was constant, were between 0.53 and 0.72 for the IFOP data and between 0.75 and 0.82 for the UNAP data. The estimates based on UNAP

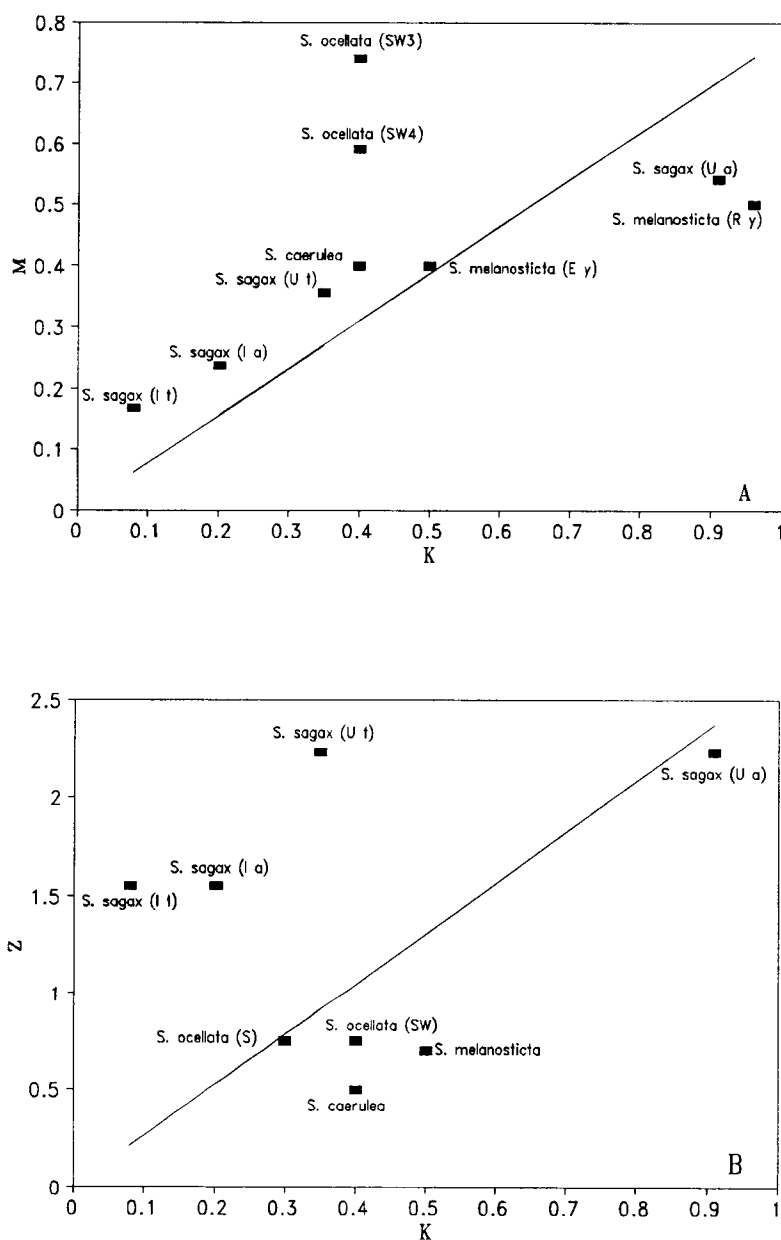


Figure 21. General biological characteristics for *Sardinops* species according to Beverton (1963). (A) M versus K and (B) Z versus K . (symbols in appendix III).

Table 19. Instantaneous mortality parameters for different species of *Sardinops*. M: natural mortality, F: fishing mortality and Z: total mortality.

Specie	\hat{M}	\hat{F}	\hat{Z}
<i>Sardinops caerulea</i>	0.4 ^{*1} (0.3-0.7) ^{*2}		0.5 ^{*6}
<i>Sardinops melanosticta</i>			0.7 ^{*6}
Early years	0.3 - 0.5 ^{*3}		
Recent years	0.4 - 0.6 ^{*4}		
<i>Sardinops neopilchardus</i>			
<i>Sardinops ocellata</i>			
S. West Africa			
1957 - 1960	0.74 ^{*5}		
1963 - 1966	0.59 ^{*5}		

^{*1} Murphy (1966)

^{*2} Yamanaka (1960)

^{*3} Yamanaka (1960)

^{*4} Nakai (1960)

^{*5} Newman (1970)

^{*6} Beverton (1963)

data imply that sardines rapidly approach their asymptotic size (high k), and mature at a size that is large in relation to the size they ultimately attain.

The ratio of the growth parameter k , and the natural mortality M (M/k) can be used for determining the probability that a fish will complete most of its potential growth before dying of natural causes. If M/k is small, as the UNAP data (0.6 - 1.02) suggest, then the stock (in the absence of fishing) will probably contain many relatively large fish, which will result in better yields from a given recruit level, and a high size at first capture (Gulland 1974). When M/k is large, as the IFOP data (1.2 - 2.1) suggest, then many fish die before attaining their

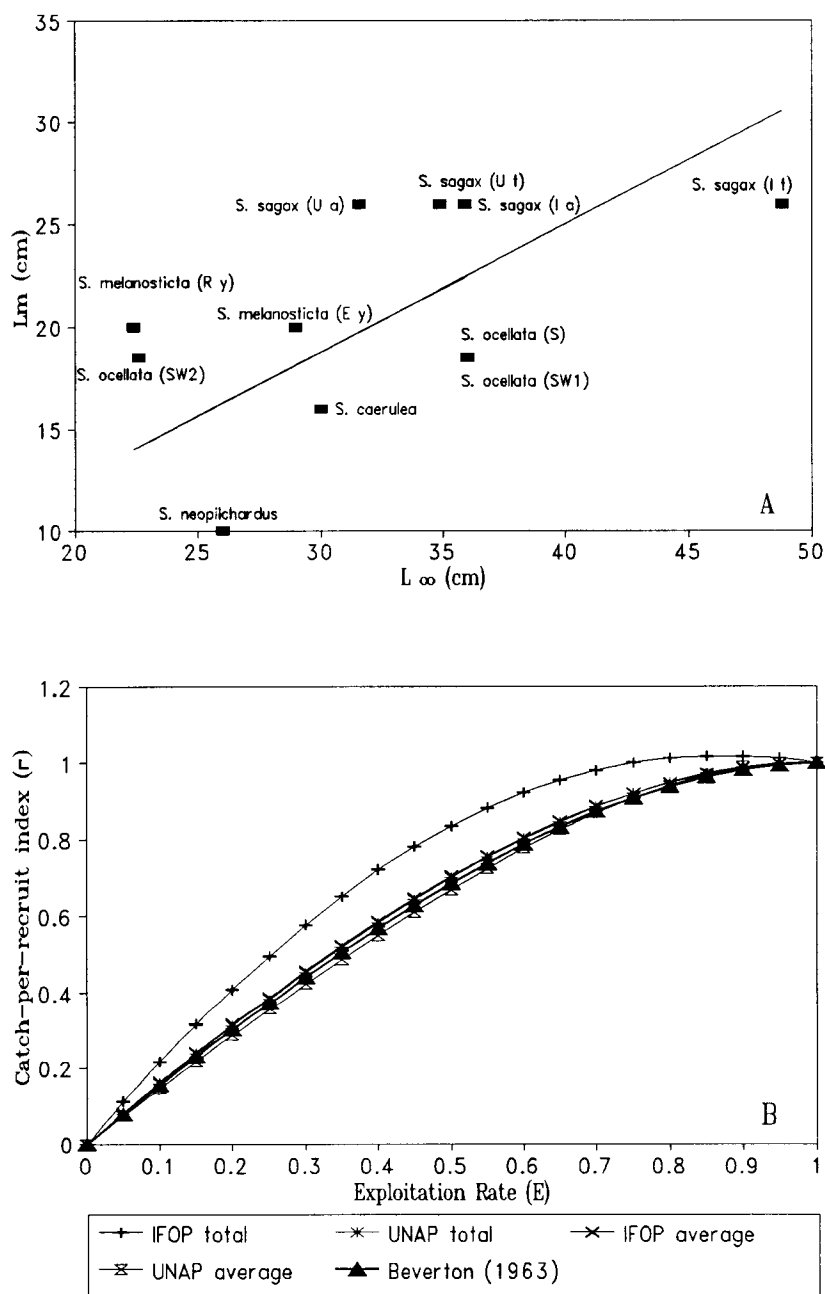


Figure 22. General biological characteristics for *Sardinops* species according to Beverton (1963). (A) L_m and L_∞ and (B) E and Γ . (symbols in appendix III).

maximum size and the size at first capture should be set at relatively small size to obtain a good yield-per-recruit.

According to Beverton and Holt (1957) and Beverton (1963) the potential yield-per-recruit from a stock depends essentially on the magnitude of three characteristics: natural mortality, growth, and the size at which fish first enter the exploited phase.

In order to compare the results from this study with data for another species of *Sardinops* and to examine the effects on a fishery from different values for the estimates of growth, mortality and reproduction parameters I calculated values of a catch-per-recruit index (Γ), which was developed by Beverton (1963). It is a modified version of the yield-per-recruit equation of Beverton and Holt (1957). This index is useful for comparing different stocks because it includes a relative measure of fishing pressure (E), a relative rate of change in the biomass of a year class during its exploited life ($1/(M/k)$), and a proportion of the potential growth span remaining when fish enter the exploited phase ($1-L_m/L_\infty$).

The relative catch-per-recruit was calculated using the estimates of k , L_m , L_∞ , and M for *S. sagax* based on the IFOP and UNAP data. It is unlikely that errors in age determination cause serious distortion in the general pattern because these errors would affect the estimates of k and Z in the same direction (Beverton 1963). The estimated catch per recruit depends on the ageing method used (DGI versus IFOP reading) and on the method for organizing the length - age data (total versus average length-at-age) (Fig 22 b). Only the IFOP total

catch-per-recruit curve has a maximum value. The IFOP total had the highest Γ followed by IFOP average together with UNAP total, then UNAP average (Fig 22b). Compared to results in Beverton (1963) the catch-per-recruit curves for IFOP average, UNAP total, and UNAP average close to the general trends for *Sardinops* species.

The Beverton and Holt (1957) yield-per-recruit model (appendix I) and the estimated yield-per-recruit isopleth developed in this analysis suggested different management decisions. The yield-per-recruit estimate is a function of the size-age methodology. Assuming the UNAP ageing method was accurate, the sardine stock of northern Chile during 1985 - 1986 was underexploited. However, if the IFOP ageing method was correct, then this sardine stock was overexploited during 1985 - 1986.

4.3.4. Re-evaluation of *Sardinops sagax* life history characteristics

Fishery managers often assume that species will respond to an increase in mortality in a compensatory manner (Tyler and Galluci, 1980). However, the response of the stock to fishing depends on the life history characteristics of the particular stock. Under the population parameters estimated from the UNAP data, the Chilean sardine was fast-growing, short-lived fish with a high natural mortality rate. A fast growing stock differs remarkably from a slower growing stock with a longer life span and low natural mortality (as indicated by the IFOP data). Accurate estimates of population parameters are therefore crucial to

management, particularly when harvest is intensive. Comparison of the different estimations of population parameters for Chilean sardine can be done by employing r and K selection theory (Pianka 1974 and Adams 1980). It was assumed that this theory provides a general but useful comparison between species occupying similar roles in the ecosystem.

The theory r and K selection assumes that there is a positive relationship between the amount of resources spent on an offspring and the fitness of that offspring, and for any species there is a fixed amount of available resources (Pianka 1974 and Adams 1980). The second part of the theory concerns the relationship between these life history strategies and the habitat the species occupies (Southwood et al. 1974; Southwood and Comins 1976). According to Adams (1980) if mortality is dominated by environmental or unpredictable factors then the best strategy would be to place maximal resources into reproduction and produce as many offspring as possible (r selection). The contrasting situation is where mortality factors are stable and/or predictable. In stable environments the optimal strategy is to produce offspring with substantial competitive ability (K selection), which implies the production of fewer offspring. Therefore, specific combinations of population parameters are characteristic of an r strategist, while other combinations are characteristic of a K strategist (Table 20).

From the stand point of yield per recruit analysis there are specific differences in fisheries for r or K selected species. In fisheries based on K selected species, the maximum yield per recruit occurs at a lower level of fishing

mortality and at a later age at first entry than in fisheries based on **r** selected species. The Y/R curves also indicate that **K** selected species are more sensitive to overfishing both in terms of fishing mortality and age at first entry (Adams 1980). In general Y/R is maximized at low values of F in the case of **K** selected species with long life span and low natural mortality but **r** selected species of fish require high values of F to maximize Y/R (Adams 1980 and Pauly 1984).

The biological characteristics that determine whether an animal is an **r** or **K** strategist (Table 20) are related to age. Therefore, the classification of a specific species or stock as an **r** or **K** strategist relative to some other species or stocks will depend on the ageing methods. The two different ageing methods indicated two different life history strategies based on **r** and **K** selection theory. The IFOP data indicates that the Chilean sardine is a more **K** strategist and the UNAP data indicates it is a more **r** strategist. This theory also makes predictions about the relationship between a species life history strategy and the habitat occupied by the species. In this context is important to remark that the Chile - Perú current system has high physical variability (Bernal et al. 1982, 1983 and Bernal 1986) with quick changes in the weather, upwelling, high productivity and unstable oceanographical conditions. According to Adams (1980) the best life history strategy in an upwelling zone is to produce a high number of offspring (**r** strategy) such as a sardine (136,102 eggs/kilo/batch in 1981, Retamales and Gonzalez 1982). Compare this with the Atlantic cod (5,000 egg/kilo, Garrod 1977). Sardines have, however, an extended spawning season, from July to March

with two peaks, the most important are during August - September and a secondary one in February - March (Serra et al. 1979 and Martinez et al. 1984).

Table 20. Idealized life history characteristics of fishes under the **r** and **K** selection theory. (From Pianka 1974 and Adams 1980).

r strategist	K strategist
(1) low age at first maturity	(1) high age at first maturity
(2) rapid growth rates (high k^1)	(2) reduced growth rates (low k^1)
(3) production of larger numbers of offspring at a given parental size.	(3) production of fewer numbers of offspring at a given parental size
(4) maximum production of offspring at early age	(4) maximum production of offspring at late age
(5) small body size (small L_∞^1)	(5) large body size (high L_∞^1)
(6) high mortality rates (high M^2)	(6) low mortality rates (low M^2)
(7) shorter life span	(7) longer life span

1: parameter for von Bertalanffy growth function for length

2: rate of instantaneous natural mortality.

Because the intrinsic characteristics of the sardine habitat, a life history close to a **r** strategist is expected. The life history of an **r** species is also suggested by the biological parameter derived from the UNAP data. Management of an **r** selected species assumes that the yield-per-recruit is large and that exploitation can be more intense than when managing a **K** selected species. The analysis of yield-per-recruit for the UNAP data produced higher Y/R than the result from the corresponding IFOP data, which supports a management decision for a higher rate of exploitation on this sardine stock.

4.4. Fishery management

The effects over fishery management policies of the two ageing techniques and the two methods for estimating the growth parameters were examined using yield-per-recruit analysis of the IFOP and UNAP data. The policy for selecting a target exploitation rate was the $F_{0.1}$ harvest policy for selecting a target level for fishing. The $F_{0.1}$ corresponds to the point at which the marginal yield-per-recruit from an additional unit of effort is 0.1 the marginal yield-per-recruit at very low levels of fishing (Gulland 1983). The $F_{0.1}$ policy is recommended when economic data on the performance of a fishery are lacking (Gulland and Boerema 1973; Pauly 1984). The $F_{0.1}$ concept may be viewed as a simple alternative to fishing for the maximum economic yield (MEY), which corresponds to the maximum difference between gross value of the catch and cost of fishing (Gulland and Boerema 1973 and Pauly 1984). The $F_{0.1}$ was determined using the difference between two succeeding Y/R values and then divided by ten as an approximation of the slope of the yield-per-recruit curve between the two values in question (Pauly 1984). The $F_{0.1}$ normally is compared with F_{MSY} and the actual position of the fishery ($F_{fishery}$). The F_{MSY} it is the instantaneous fishing mortality rate that produces the maximum yield-per-recruit at a specific age at entry (t_c). The MSY corresponds to the long run maximum yield-per-recruit associated with the instantaneous fishing mortality level (F_{MSY}) at a specific age at entry (t_c). The relative position of the F values showed different patterns for data from IFOP and UNAP. The estimates based on IFOP data had the following sequence $F_{0.1}$, F_{MSY} ,

and F_{fishery} , but estimates based on UNAP data had the pattern, $F_{0.1}$, F_{fishery} , and F_{MSY} (Table 21 and Fig 23 and 24). The important difference between the patterns was that Y/R was maximized at low values of F for estimates based on IFOP data when compared to estimates derived from UNAP data, except for UNAP total for which Y/R has no maximum value over the range of F examined (Table 21).

The actual position of F in the Chilean sardine fishery was far greater than $F_{0.1}$ and F_{MSY} for both data sets and methods for combining the length (weight) at age data. To increase the Y/R to the MSY level when F is less than F_{MSY} is not economical because near the MSY level the yield changes slowly with changes in fishing mortality (Gulland 1983). A reasonable management policy would be to decrease fishing mortality to the $F_{0.1}$, since fishing at greater intensities than $F_{0.1}$ produces smaller yields with increasing effort and cost. Based on IFOP data to reduce F from current levels to $F_{0.1}$ and F_{MSY} would require a reduction between 76.9% to 85.7% for $F_{0.1}$ and between 42.3% to 71.4% for F_{MSY} . If the UNAP data were used the required reduction would be 52.9% (UNAP average) to 77.3% (UNAP total) for $F_{0.1}$ and -435.3% for F_{MSY} (Table 22). This reduction in F , with respect to $F_{0.1}$, reduces Y/R by 6.7% for the IFOP data, and between 7.2% to 20% for the UNAP data. Based on the traditional fishery management used in Chile (estimation of von Bertalanffy parameter with ages averaged), F would have to be reduced to 42.3% to attain the F_{MSY} level for the IFOP data and increased by 435.3% for the UNAP data, respectively. To attain $F_{0.1}$ would require a

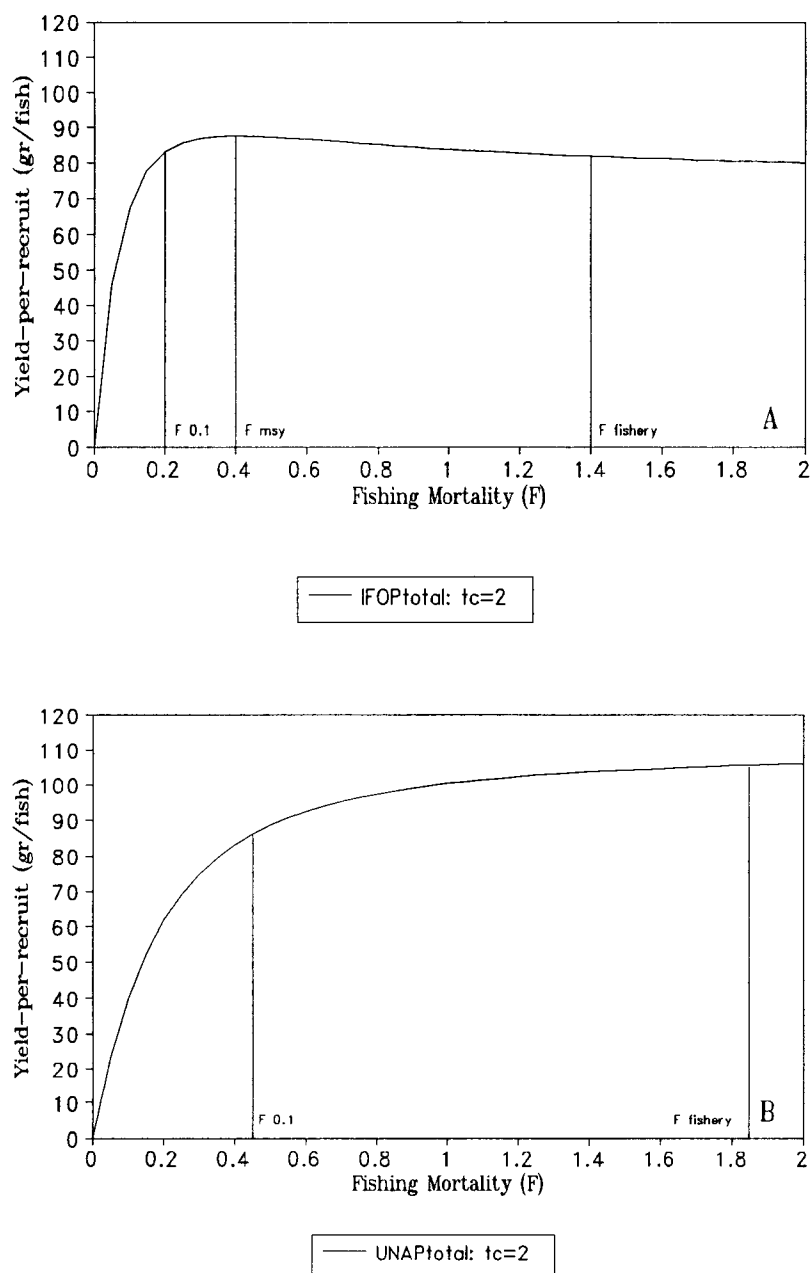


Figure 23. Yield-per-recruit versus fishing mortality, showing the position of $F_{0.1}$, F_{MSY} and actual F of the fishery based on (A) IFOP total and (B) UNAP total.

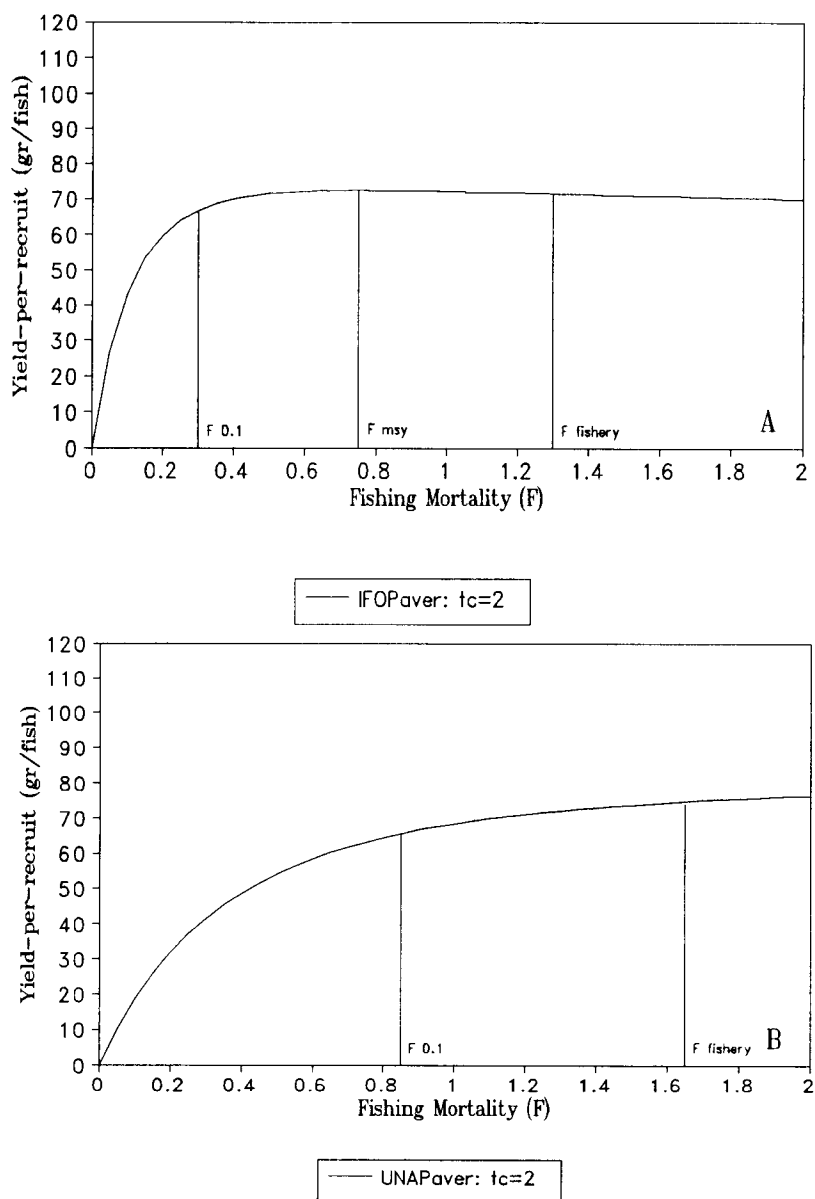


Figure 24. Yield-per-recruit versus fishing mortality, showing the position of $F_{0.1}$, F_{MSY} and actual F of the fishery based on (A) IFOP average and (B) UNAP average.

reduction in F of 76.9% and 52.9% for the IFOP and UNAP data, respectively (Table 22).

Table 21. Fishing mortality values at levels of $F_{0.1}$, F_{MSY} and, $F_{fishery}$. The corresponding yield-per-recruits values are in parentheses.

Data source	Method	$\hat{F}_{0.1}$	\hat{F}_{MSY}	$\hat{F}_{fishery}$
IFOP	Total	0.2 (83.1)	0.4 (87.7)	1.4 (81.9)
UNAP	Total	0.42(84.7)	large number	1.85 (105.6)
IFOP	Average	0.3 (66.7)	0.75 (76.5)	1.3 (71.5)
UNAP	Average	0.8 (64.4)	9.1 (79.8)	1.7 (74.9)

When comparing the yield-per-recruit isopleths of IFOP and UNAP, it is important to note that although the scale for F is the same for IFOP and UNAP, the t_c scale of UNAP was almost half the scale of IFOP. The large differences in appearance between the yield-per-recruit isopleths were largely due to the different scaling. Although in theory the eumetric curve extends from F of 0 to ∞ , values over a limited range, from $F = 0$ to 1.9 were examined. The actual position of the fishery ($F = 1.386$ and $t_c = 2$ years) was far from the eumetric curve. With a significant reduction in F together with an increase in t_c to 2.7 years, the fishery would have reached a larger Y/R at a much lower cost (Fig 17 a). In

the case of the UNAP total (Fig 17 b) there was no eumetric curve over the given range of values for t_c and F with which to compare the curve for the IFOP total. The actual position of the fishery ($F = 1.318$ and $t_c = 2$ years) was far from the eumetric curve based on the IFOP average data. With a significant reduction in F combined with an increase in t_c to 1.75 years, the fishery would have produced a

Table 22. Fishing mortality values at levels of $F_{0.1}$, F_{MSY} and, $F_{fishery}$. ΔF and $\Delta Y/R$ are the change in F and Y/R relative to F_{MSY} and $F_{0.1}$.

Data source	Method	$\hat{F}_{0.1}$	ΔF	$\Delta Y/R$	\hat{F}_{MSY}	ΔF	$\Delta Y/R$	$\hat{F}_{fishery}$
IFOP	Total	0.2	85.7%	1.5%	0.4	71.4%	7.1%	1.4
UNAP	Total	0.42	77.3%	-20%				1.85
IFOP	Average	0.3	76.9%	-6.7%	0.75	42.3%	7%	1.3
UNAP	Average	0.8	52.9%	-14%	9.1	-453.3%	6.5%	1.7

larger Y/R with a much lower cost. In the case of UNAP averages (Fig 18 b) the fishery ($F = 1.693$ and $t_c = 2$ year) has a position near the eumetric curve.

Management measures could shift the sardine fishery to a more efficient yield by decreasing the mesh size to decrease t_c by 0.2 years, without any change in the fishery mortality rate (F).

The relative yield-per-recruit (Y'/R) for the IFOP data calculated using ELEFAN V program had no maximum at values of F inferior to the range of F values considered, and it was thus impossible to calculate the F_{msy} . Therefore, $F_{0.1}$ values were compared with $F_{fishery}$. The value for $F_{fishery}$ was extremely low because the natural mortality (M) estimate from which $F_{fishery}$ was derived was very high

(see section 3.4.1.). The procedure (eq. 7) used to calculate M has been reported to overestimate M by approximately by 20% (Pauly 1983). Consequently the estimate for the natural mortality rate and total mortality (Z) rate were very similar. In the case of the UNAP data the situation was almost the same. The F_{fishery} was low relative to F_{msy} (Table 21). This was probably a result of using only 12 months of length compositions. The ELEFAN method requires a longer series of monthly length compositions. Another point is that the total mortality (Z) and natural mortality (M) estimates calculated from the frequency length data were similar and produced low estimates of F . The Compleat ELEFAN results do not appear to be representative of the Chilean sardine population dynamics during 1985 - 1986.

According to Y/R analysis for the IFOP data the sardine fishery during 1985 - 1986 was growth overfishing because a reduction in F would produce an increase in Y/R , which means that fish were being caught at too low an age at first capture relative to the amount of fishing mortality. The most important issue regarding the Y/R for the IFOP and UNAP data was the intense fishing pressure (except in UNAP average where F was near to the eumetric curve). When fishing mortality is larger than natural mortality the stocks are over exploited (Gulland 1988). Intense fishing pressure was evident for all cases studied in this thesis, but particularly for the IFOP data where the actual position of the fishery (F_{fishery}) or open access equilibrium point was far from F_{MSY} or $F_{0.1}$.

Economically, the effect of this overfishing decreases the average revenue to the point of zero profit and beyond if the stock can tolerate such a fishing effort. *Sardinops sagax* was one of the most important fishery resources in northern Chile during the 1980's and contributed a significant portion of the gross national product. When this kind of fishery reaches the open access equilibrium point and the stock has not collapsed, existing boats will not expand the effort and new vessels will not profitably enter the fishery. A practical consequence of the open access equilibrium point is high competition and many vessel owners may find that they can no longer compete successfully. Owners must then decide whether to build bigger, more efficient vessels and continue participating in a declining fishery or to switch to another resource, or abandon this economic activity. These decisions have important regional consequences where fishing is the principal economical activity. There are social, as well as economic costs and the situation is more dramatic in the semi-industrial companies (Smith pers. com.). The yield-per-recruit model and the bioeconomic model derived from it assume that recruitment and prices are constant and the open access equilibrium point is unstable depending on recruitment and prices level. Costs can increase or decrease. Growth overfishing can affect the spawning stock and produce recruitment overfishing which is difficult to detect (Gulland 1988). In an unpredictable environment sardine recruitment can fail and produce a rapid collapse of the fishery (Csirke 1988).

Limited entry might be a long term solution to the problem of controlling the fishing effort (Gulland 1974 and Cummingham et al. 1985). Controlling entry of fishermen, vessels, or both into the fishery can adjust fishing to take an allowable catch. A second method is to set quotas for individual vessels or fishermen, the sum of which is equal to the maximum sustainable yield (MSY) or the maximum economic yield (MEY). Another method is to place a tax on gear or on catch to make entry to the fishery unattractive beyond the point of MEY or MSY. Limited entry appears to be the preferable alternative.

The Chilean sardine fishery during the 1970's was unregulated until 1981 when SUBPES made an analysis for determining the state of pelagic resources in northern Chile, in order to prevent overharvest and optimize the catch of sardines (SUBPES 1981, Serra 1981). A high risk fishery was predicted since sardine catches were increasing rapidly and the catches per unit effort and modal size were decreasing. The SUBPES analysis estimated an exploitation rate of 43%, for sardine, which was considered excessive in accordance to the criterion defined as the adequate level of exploitation, ($F=M$), as indicated by empirical evidence of various similar fisheries in the world (Troadek et al. 1980 in SUBPES 1981 and Serra 1981). The SUBPES concluded that it was necessary to adopt management measures, to decrease the exploitation rate and increase the abundance (Serra 1983). Regulations were enacted on minimum size, no fishing zones in coastal spawning and nursery areas, and an annual allowable catch of 1,300,000 tons was specified (appendix II). These management measures produced strong reactions

from the sardine fishery community. Industrial companies did not feel that accurate methodology was used for estimating the fishery parameters (Vidal 1983, 1985 and Cañon 1990). According to Serra (1983) the large alteration in the spawning stock and the high mortality on larvae and juveniles would likely reduce the sardine recruitment during subsequent years. Because sardine have a short life cycle with recruitment between the second and third year, sardines remain in the fishery for 5 to 6 years with few age groups supporting the fishery. It is probable that the combined effects of poor recruitment, during the "El Niño" of 1982 - 1983, combined with overfishing caused the near collapse of the Chilean sardine during the 1990's. A similar situation occurred in the anchoveta fishery off Perú between 1972 - 1973 (Csirke 1988). Unfortunately, the most successful form of fishery regulation, limited entry, was not applied to the sardine fishery until 1991 when the new fishery law was promulgated, but by this time the sardine fishery was near collapsed.

Management Chilean objectives were: "to provide an effective protection and overall benefit of the hydrobiological resources, to avoid recruitment overfishing and to protect recruitment strength which will permit resguard the future spawning population, not only in volume (biomass) but also in the age composition of the resources" (SUBPES 1981). These objectives implies efficient management processes and decisions which are a function of the analysis of biologically accurate information (Hueth and Smith 1983). The collapse of the

sardine fishery was caused by a number of factors, but a more accurate ageing technique might have helped by alerting managers to the potential problems.

V. Conclusion

1. The differences in the relationship between length-at-age and weight-at-age, based on the two different ageing methods used by IFOP and UNAP, resulted in significant differences in the estimated parameter for the von Bertalanffy growth function. The growth parameters also varied significantly depending on whether total or average size-at-age data were used in the estimation process.
2. Analysis of age structure indicated that the sardines off northern Chile grow faster than previous estimates predicted. It is probable that the IFOP analysis misidentified secondary rings for annual rings in age determinations, because no corroborative independent growth studies were done and different methods of age assignation were used.
3. The differences in the von Bertalanffy growth parameters between IFOP and UNAP resulted in significant differences in the estimates of the instantaneous natural mortality (M) and total mortality (Z) coefficients. The estimates also varied significantly depending on whether total or average size-at-age data were used in the estimation process.

4. Total size-at-age must be used in the future estimation of growth and mortality parameters of *Sardinops sagax* because it includes the variability of size for each specific age present in the stock.
5. Under the assumption of the yield-per-recruit model and the assumption that the UNAP ageing method was correct it is probable that the sardine stock of northern Chile during 1985 - 1986 was underexploited. The yield-per-recruit was maximized at low values of F for estimates based on IFOP data when compared with estimates based on the UNAP data.
6. Under the assumptions of r and K selection theory and the growth, mortality and reproductive parameters obtained using the UNAP data for *S. sagax* and in combination with the highly variable ocean habitat off northern Chile, it is possible to expect that Chilean sardines have a life history closer to an r strategist and a higher yield-per-recruit than suggested from the IFOP data.
7. Using the result of the yield-per-recruit models as the basis for management policy, it appears that F must be reduced between 42.3 to 71.4% to attain to MSY and F must be reduced between 76.9% to 85.7% to attain $F_{0.1}$. If the UNAP data were used the required reduction would be -453.3% for MSY and between 52.9% to 77.3% for $F_{0.1}$. This reduction in F with respect to $F_{0.1}$ represents a reduction in Y/R of 6.7% for IFOP data and between 7.2% to 20% for UNAP data.

8. From the point of view of social objectives the management of the Chilean sardine fishery during the 1980's was not efficient because the use of inappropriate ageing methods led to incorrect management decisions. The lack of controls over fishing effort produced a near collapse of the sardine off northern Chile with important social and economic effects.

9. Because of the influence on stock assessments, the methods used for age determination must be improved by increasing the precision and accuracy of the validation methods, and the consistency between otolith readers. Improved ageing methods and more accurate age data can produce important benefits to fishery management in the long term.

VI. Bibliography

- Adams, P.B. 1980. Life history patterns in marine fishes and their consequences for fisheries management. Fish. Bull. U.S. 78:1-12.
- Aguayo, M., V. Erbs, E. Estay, R. Gili and H. Steffens. 1983. Elaboración de claves edad-talla de sardina española jurel, anchoveta y caballa para el año 1982. (AP 83-33) IFOP-Chile. Informe 84 p.
- Aguayo, M., R. Gili and V. Erbs. 1987. Estudio de edad y crecimiento en sardina (*Sardinops sagax*) del norte de Chile. Invest. Pesq. (Chile) 34:85-98.
- Aikawa, H. 1940. On the age and race of the Japanese sardine *Sardinia melanosticta* (Temminck and Schlegel). Rec. Oceanogr. Works. Jap. 2(1):81-112.
- Alberti, V., M.G. Larrañeta. 1966. Sobre mediciones y crecimiento de la sardina (*Sardinops sagax* Jen.) en la costa de Antofagasta, p.11-37. Cuaderno 1. Ciencias del Mar, Universidad Católica Valparaíso. Chile.
- Arntz, W.E. 1986. The two faces of El Niño 1982-83. Meeresforschung Reports on Marine Research, Sonderdruck aus Bd. 31(1986), H.1-46, Hamburgo N.E.
- Beamish, R. 1979. New information on the longevity of Pacific ocean perch (*Sebastes alutus*). J. Fish. Res. Board. Can. 36:1395-1400.
- Beamish, R. and D. Chilton. 1982. Preliminary evaluation of a method to determine the age of sablefish (*Anoplopoma fimbria*). Can. J. Fish. Aquat. Sci. 39:277-287.
- Beamish, R. and H. Harvey. 1969. Age determination in white sucker. J. Fish. Res. Board. Can. 26:633-638.
- Beamish, R.J. and G.A. McFarlane. 1983a. Validation of age determination estimates: The forgotten requirement. NOAA Tech. Rep. NMFS 8:29-33. Proceedings of the international workshop on age determination of oceanic pelagic fishes: Tunas, Billfishes, and Sharks.
- Beamish, R.J. and G.A. McFarlane. 1983b. The forgotten requirement for age validation in fishery biology. Trans. Am. Fish. Soc. 112(6):735-743.
- Bernal, P. 1986. La oceanografía del sistema de corrientes de Chile-Perú en relación a sus pesquerías, p. 17-29. In OLDEPESCA/SELA 1986 Bases

biológicas y marco conceptual para el manejo de los recursos pelágicos en el Pacífico Suroriental. OLDEPESCA. Documento de Pesca 1.

Bernal, P. and P. Barrias, P. 1992. Personal communication. IFOP.

Bernal, P., F.L. Robles and O. Rojas. 1982. Variabilidad física y biológica en la región meridional del sistema de corrientes Chile-Perú, p. 15-25. *In* Seminario - Taller bases biológicas para el uso y manejo de recursos naturales renovables: Recursos biológicos marinos, estudios de casos en el Pacífico Oriental. Univ. Católica, Santiago.

Bernal, P., F.L. Robles and O. Rojas. 1983. Variabilidad física y biológica en la region meridional del sistema de Corrientes Chile-Perú. *In* G.D. Sharp and J. Csirke (eds.) Proceedings of the expert consultation to examine changes in abundance and species of neritic fish resources. San Jose, Costa Rica. FAO Fish. Rep. 291(2):683-711.

Bernard, D. 1981. Multivariate analysis as a means of comparing growth in fish. *Can. J. Fish. Aquat. Sci.* 38:233-236.

Beverton, R.J.H. 1963. Maturation, growth and mortality of Clupeoid and Engraulid stocks in relation to fishing. *Rapp. P. v. Reún. Cons. Int. Explor. Mer.* (154):44-67.

Beverton, R.J.H and S.J. Holt 1957. On the dynamics of exploited fish populations. *Fish. Invest. Minist. Agric. Fish. Food G.B.* (2 Sea Fish.), 19:533p.

Beverton, R.J.H. and S.J. Holt. 1959. A review of the lifespans and mortality rates of fish in nature, and their relation to growth and other physiological characteristics, p. 142-180. *In* G.E.W. Wolstenholme and M. O'Connor (eds.) CIBA Foundation, colloquia on ageing Vol.5. The lifespan of animals, London, Churchill.

Blackburn, M. 1949. Age, rate of growth, and general life-history of the Australian pilchard (*Sardinops neopilchardus*) in New South Wales waters. *Bull. Coun. scien. Ind. Res. Melb.* (242):1-86.

Blackburn, M. 1950. Studies on age, growth, and life history of the pilchard, *Sardinops neopilchardus* (Steindachner), in southern and western Australia. *Australian Journal of Marine and Freshwater Research* 1(2):221-258.

Blackburn, M. 1960. Synopsis of biological information on the Australian and New Zealand sardine, *Sardinops neopilchardus* (Steindachner), p. 245-264. *In* H.

- Rosa and G. Murphy. (eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol II. Species Synopses. FAO 1960.
- Caddy, J.F. and J. Csirke. 1983. Approximation to sustainable yield for exploited and unexploited stocks. *Oceanogr. Trop.* 18(1):3-15.
- Cañon, J.R. 1990. Regulaciones pesqueras aplicadas al recurso sardina española. Chile Pesquero Agosto - Septiembre 1990:36-41.
- Cárdenas, G. 1983. Estudios de la edad y el crecimiento de sardina (*Sardinops sagax sagax*) de la región central del Perú, p.25-33. In Proyecto de Evaluación de los recursos sardina, jurel y caballa en el Pacífico Sur Oriental. Taller de Dinámica de Poblaciones, Guayaquil, 1983.
- Cárdenas, G. 1987. Estudios de la edad y el crecimiento de sardina (*Sardinops sagax sagax*) de la región central del Perú. Bol. Inst. Mar Perú, 11(3):118-145.
- Cárdenas, G. and J. Mendo. 1985. Preliminary length-based growth parameter estimates of Peruvian sardine (*Sardinops sagax sagax*). ICLARM Fishbyte 3(3):10-11.
- Carlander, K. 1974. Difficulties in ageing fish in relation to inland fishery management, p. 200-205. In T.B. Bagenal.(ed.). The proceedings of an international Symposium on the ageing of fish. Unwin Brothers, Surrey. England.
- Chapman, D.G. and D.S. Robson. 1960. The analysis of a catch curve. *Biometrics* 16(3):354-368.
- Chilton, D. and R. Beamish. 1982. Age determination methods for fishes studied by the Groundfish Program at the Pacific Biological Station. Can. Spec. Publ. Fish. Aquat. Sci.60, 120p.
- Csirke, J. 1988. Small shoaling pelagic fish stocks, p. 271-302. In J. Gulland (ed.). Fish populations dynamics, John Wiley & Sons.
- Cunningham, S., M.R. Dunn and D. Whitmarsh. 1985. Fisheries economics: an introduction. Mansell Publishing Limited London. St. Martin's Press.372p.
- Dannevig, A. 1933. On the age and growth of the cod (*Gadus callarias* L.) from the Norwegian Shagerrack Coast. Rep. Norw. Fish and Mar. Inv. 4(1):145.

- Davies, D.H. 1958. The South African pilchard (*Sardinops ocellata*): preliminary report on the age composition of the commercial catches, 1950 -55. Investl. Rep. Div. Fish. Un. S. Afr. (33):1-20.
- Dixon, W.J. and F.J. Massey. 1969. Introduction to statistical analysis. McGraw-Hill, Inc. 638 p.
- Du Plessis, C.G. 1960. Trends in the pilchard fishery of the Union of South Africa, 1943-58, p. 631-666. In H. Rosa and G. Murphy (eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol III. Stock and Area Paper 2. FAO 1960.
- FAO, 1982. Report of the technical consultation on methodologies used for age-reading. FAO Rapp/FAO Fish. Rep. 257:104 p.
- Fournier, D. and P. Archibald 1982. A general theory for analyzing catch at age data. Can. J. Aquat. Sci. 39:1195-1207.
- Garland, D.E. 1988. Validación de la lectura de edades por el método de incrementos diarios en la sardina española (*Sardinops sagax musica*) en el norte de Chile. Informe final, presentado ante las Sociedades Pesqueras Coloso S.A. y Guanaye Ltda. 411 p.
- Garland, D.E. 1990. Incrementos de crecimiento diarios: Una herramienta para validar *annulis* en otolitos sagitales de sardina española (*Sardinops sagax musica*) del norte de Chile, p. 74-87. In M.A. Barbieri(ed.). Perspectivas de la actividad pesquera en Chile. Escuela de Ciencias del Mar, U.C.V.
- Garland, D.E. and M. Araya. 1988. Validación de la lectura de edades por el método de incrementos diarios en la sardina española (*Sardinops sagax musica*) en el norte de Chile. Memorias del Simposio Internacional de los Recursos Vivos y las Pesquerías en el Pacífico Sudeste Chile, Viña del Mar, CPPS Rev.Pacífico Sur (Número especial):327-340.
- Garland, D., G. Herrera, M. Diaz and C. Padilla 1989 Estimación de la talla y edad de la primera madurez sexual en *Sardinops sagax musica* del norte de Chile utilizando incrementos de crecimiento diarios en sus otolitos sagitales. Congreso Latinoamericano de Ciencias del mar, Cumana, Venezuela.
- Garrod, D.J. 1977. The North Atlantic cod, p. 216-242. In J.A. Gulland (ed.) Fish population dynamics. John Wiley & Sons.

- Gulland, J.A. 1971. The fish resources of the ocean. Surrey, Fishing News (Books) Ltd., for FAO, 255 p. Rev. ed. of FAO Fish. Tech. Pap. (97):425 p.
- Gulland, J.A. 1974. The management of marine fisheries. Seattle, University of Washington Press. 198 p.
- Gulland, J.A. 1983. Fish stock assessment: a manual of basic methods. Chichester, U.K., John Wiley Interscience, FAO/Wiley series on food and agriculture, (1):223.
- Gulland, J.A. 1988. Fish population dynamics: the implications for management. Chichester, John Wiley and Sons Ltd., 422.
- Gulland, J.A. and L.K. Boerema 1973. Scientific advice on catch levels. Fish. Bull. U.S. 71(2):325-336.
- Gunderson, D.R. 1977. Population biology of Pacific ocean perch, (*Sebastes alutus*) off Washington-Queen Charlotte Sound region, and their response to fishing. Fish. Bull. U.S. 75:369-403.
- Gunderson, D.R. 1980. Using r-K selection theory to predict natural mortality. Can. J. Fish. Aquat. Sci. 37:2266-2271.
- Gunderson, D.R. and P.H. Dygert 1988. Reproductive effort as a predictor of natural mortality rate. J. Cons. CIEM. 44:200-209.
- Hellawell, J. 1974. The problems of protracted check formation and the validity of the use of scales in age determination exemplified by two populations of dace *Leuciscus leuciscus* (L.), p. 173-180. In T.B. Bagenal.(ed.).The proceedings of an international Symposium on the ageing of fish. Unwin Brothers, Surrey. England.
- Holt, S.J. 1960. A preliminary comparative study of the growth, maturity and mortality of sardine, p. 553-561. In H. Rosa and G. Murphy (eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol II. Subject synopses paper 2.FAO 1960.
- Huang, B. and C. Walters. 1983. Cohort analysis and populations dynamics of large yellow croaker in the China sea. North American Journal of Fisheries Management 3:295-305.
- Hueth, D.L. and F.J. Smith. 1983. Rational fisheries management an opportunity for South America, p. 431-437. In P. Arana(ed.). Proceedings of the international conference on Marine resources of the Pacific.

- Kimura, D. 1980. Likelihood method for the von Bertalanffy growth curve. Fish. Bull. U.S. 77(4):765-776.
- Kimura, M. 1970. Formation of a false annulus on scales of Pacific sardines of known age. Calif. Mar. Res. Comm. CalCOFI Rept., 13:73-75.
- Kimura, M. and G. Sakagawa. 1972. Observation on scale patterns and growth of the Pacific sardine reared in the laboratory. Fis. Bull. U.S. 70(3):1043-1051.
- Kondo, K. 1980. The recovery of the Japanese sardine: the biological basis of stock size fluctuations. Rapp. P. v. Reun. Cons. Explor. Mer 177:332-354.
- Kvalseth, T.O. 1985. Cautionary note about R^2 . Am. Stat. 39:279-285.
- Lai, H.L., and D.R. Gunderson. 1987. Effects of ageing errors on estimates of growth, mortality and yield per recruit for walleye pollock (*Theragra chalcogramma*). Fish. Res. 5:287-302.
- Leaman, B. and R. Beamish. 1984. Ecological and management implications of longevity in some northeast Pacific groundfishes. Int. North. Pac. Fish. Comm. Bull. 42:85-97.
- MacCall, A.D. 1979. Population estimates for the waning years of the Pacific sardine fishery. CalCOFI Rep. (20):72-82.
- Martinez, C., A. Aranís, C. Estrada and P. Barria. 1987. Situación actual de la pesquería de sardina española (*Sardinops sagax musica*) en la zona norte de Chile, p. 115-132. In P. Arana(ed.). Manejo y desarrollo pesquero. Escuela de Ciencias del Mar, Facultad de Recursos Naturales, Universidad Católica de Valparaíso.
- Martinez, C., C. Salazar, G. Bohm, A. Aramis, J. Mendieta and A. Torres. 1984. Análisis de las pesquerías pelágicas 1978-1983. Corporación de fomento de la producción. Gerencia de desarrollo (ap84-26). Inst. Fom. Pesq., Santiago Chile. 138 p.
- Mattews, J.P. 1960. Synopsis on the biology of the South West African pilchard (*Sardinops ocellata* Pappé). p. 118-135. In H. Rosa and G. Murphy (eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol II. Species synopsis No. 8. FAO 1960.
- Mathews, C. 1974. An account of some methods of overcoming errors in ageing tropical and subtropical fish populations when the hard tissue growth markings are unreliable and the data sparse, p. 158-166. In T.B.

- Bagenal(ed.).The proceedings of an international Symposium on the ageing of fish. Unwin Brothers, Surrey. England.
- McFarlane, G., W. Shaw and A. Tyler. 1985. Sablefish: coastwide stock assessment, p. 163-186. *In* A. Tyler and G. McFarlane(eds.). Groundfish stock assessment off the west coast of Canada in 1984 and recommended yield options for 1985. Canadian Manuscript Report of Fisheries and Aquatic Sciences 1813.
- Megrey, B.A. and V.G. Wespestad. 1988. A review of biological assumption underlying fishery assessment models, p. 31-69. *In* W.S. Wooster (ed.).Fishery science and management: objectives and limitations. Lectures notes on coastal and estuarine studies 28. Springer-Verlag.
- Mortera, J. and D. Levi 1982. Bias in age reading and consequences on age/length key, on growth curve and in virtual population analysis, p. 72-81. *In* FAO.Report of the technical consultation on methodologies used for age-reading. FAO Rapp/Fish. Rep. 257.
- Mosher, K. and H. Eckles 1954. Age determination of Pacific sardine from otoliths. Res. Rep. U.S. Fish. Wild. Serv. (37):40p.
- Mujica, A. O. Rojas and A. Araniz 1985. Aspectos reproductivos de la sardina española (*Sardinops sagax* Jenys) en la zona norte de Chile y su variación durante el fenómeno El Niño 1982-83. Invest. Pesq. (Chile) 32:153-160.
- Munro, J.L. and D. Pauly. 1983. A simple method for comparing growth of fishes and invertebrates. ICLARM Fishbyte 1(1):5-6.
- Murphy, G.I. 1966. Population biology of the Pacific sardine (*Sardinops caerulea*). Proc. Calif. Acad. Sci. 34:1-84.
- Nakai, Z. 1960. Changes in the population and catch of the Far East sardine area, p. 807-853. *In* H. Rosa and G. Murphy(eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol III. Stock and Area Paper 5. FAO 1960.
- Neter, J. and W. Wasserman. 1974. Applied linear statistical models, Richard D. Irwin, Inc., Illinois. 842.
- Newman, G.G. 1970. Stock assessment of the pilchard *Sardinops ocellata* at Walbis Bay, South West Africa. Investl. Rep. Div. Sea. Fish. S. Afr. 85:13.

- Parrish, R.H., R. Serra and W.S. Grant. 1989. The monotypic sardines, *Sardina* and *Sardinops*: their taxonomy, distribution, stock structure and zoogeography. Can. J. Fish. Aquat. Sci. (46):2019-2036.
- Patterson, K.R., J. Zuzunaga, and G. Cárdenas. 1992. Size of the South American sardine (*Sardinops sagax*) population in the northern part of the Peru upwelling ecosystem after collapse of anchoveta (*Engraulis ringens*) stocks. Can. J. Aquat. Sci. 49:1762-1769.
- Pauly, D. 1980. On the interrelationship between natural mortality, growth parameters and mean environmental temperature in 175 fish stocks. J. Cons. CIEM, 39(2):175-192.
- Pauly, D. 1983. Some simple methods for the assessment of tropical fish stocks. FAO Fish. Tech. Pap. (234):52p.
- Pauly, D. 1984. Fish populations dynamics in tropical waters: a manual for use with programmable calculators. ICLARM Stud. Rev. (80):325p.
- Pauly, D. 1987. A review of the ELEFAN system for analysis of length - frequency data in fish and aquatic invertebrates. ICLARM Conf. Proc. (13):7-34.
- Pauly, D. and J.L. Munro 1984. Once more on the comparison of growth in fish and invertebrates. ICLARM Fishbyte 2(1):21.
- Peterson, I. and S.J.Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem. Can. J. Fish. Aquat. Sci. 41:1117-1120.
- Pianka, E.R. 1974. Evolutionary ecology. Harper and Row, N.Y. 356p.
- Powers, J. 1983. Some statistical characteristics of ageing data and their ramification in populations analysis of oceanic pelagic fishes. NOAA Tech. Rep. NMFS 8: 19-24. Proceedings of the international workshop on age determination of oceanic pelagic fishes: Tunas, Billfishes, and Sharks.
- Retamales, R. and L. Gonzalez. 1983 Fecundidad de sardina española (*Sardinops sagax musica*). Corporación de Fomento de la Producción. Santiago, Chile, Instituto de Fomento Pesquero, 27p.
- Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. B. of Canada 191:382p.

- Rikhter, V.A. and V.N. Efanov. 1976. On one of the approaches to estimation of natural mortality of fish population. ICNAF Restricted doc. Serial No (3777): 12p.
- Robson, D.S. and D.G. Chapman. 1961. Catch curve and mortality rates. Trans. Amer. Fish. Soc. 90:181-189.
- Roff, D.A. 1984 The evolution of life history parameters in Teleosts. Can. J. fish. Aquat. Sci. 41(6):989-1000.
- Rosa, H. and T. Laevastu. 1960. Comparison of biological and ecological characteristics of sardines and related species: a preliminary study, p. 521-552. In H. Rosa and G. Murphy(eds.). Proceedings of the world scientific meeting on the biology of sardines and related species. Vol II. Species Synopsis: Paper 1.FAO 1960.
- Saila, S.B., C.W. Recksie, and M.H. Prager. 1988. Basic fishery science programs: a compendium of microcomputer programs and manual operation. Elsevier, Amsterdam. 230 p.
- Saldaña, Y. 1983. Estudio preliminar de la estimación de la edad y crecimiento de *Sardinops sagax sagax* (Jenyns). Rev. Cien. Mar. Limn. 2(1):97-108.
- Samamé, M. 1977. Determinación de la edad y el crecimiento de la sardina (*Sardinops sagax sagax*). Bol. Inst. Mar Perú 3(3):95-112.
- SELA, 1982. Evaluación de los recursos sardina, jurel y caballa en el Pacífico Sur Oriental. Taller para la estandarización de métodos de estudios de edad y crecimiento. Santiago, Chile. 50 p.
- Serra, R. 1981. Situación de los recursos pelágicos de la zona Norte, p. 26-37. In III Jornadas en pesquerías chilenas. Valparaíso, Escuela de ciencias del mar U.C.V.
- Serra, J.R. 1983. Changes in the abundance of pelagic resources along the Chilean Coast. In G.D. Sharp and J. Csirke (eds.) Proceedings of the expert consultation to examine changes in abundance and species of neritic fish resources. San Jose, Costa Rica. FAO Fish. Rep. 291(2):255-284.
- Serra, J.R., M. Aguayo, O. Rojas, F. Inostroza and J. Cañon. 1979. Sardina española *Sardinops sagax musica*, De Buen Teleostomi: clupeiformes, Clupeidae, p.1-37p. In Estado actual de las principales pesquerías nacionales, tomo I peces.

- Serra, J.R., P.Barria and A. Zuleta. 1988. Estado de situación de la sardina y estimación de una captura total permisible para 1988. Instituto de Fomento Pesquero, Boletín. 32
- Serra, J.R. and I. Tsukayama. 1988. Sinopsis de datos biológicos y pesqueros de la sardina *Sardinops sagax* (Jenyns, 1842) en el Pacífico Suroriental. FAO Sinopsis sobre la pesca (13) Rev.1:60p.
- Serra, R. and A. Zuleta. 1982. La pesquería chilena: antecedentes. In J.C. Castilla(ed.) Segundo seminario taller. bases biológicas para el uso y manejo de recursos naturales renovables: recursos biológicos marinos. Monogr. Biol. 2:19-37.
- Serra, J.R. and A. Zuleta. 1986. Dinámica poblacional de las especies pelágicas y estimación de parámetros vitales. Sardina. OLDEPESCA Doc.Pesca, (1): 133-139.
- Southwood, T.R.E. and H.N. Comins. 1976. A synoptic population model. J. Anim. Ecol. 45:949-965.
- Southwood, T.R.E., R.M. May, M.P. Hassell, and G.R. Conway. 1974. Ecological strategies and population parameter. Am. Nat. 108:791-804.
- Sparre, P. 1987. Computer programs for fish stock assessment. FAO Fish. Tech. Pap. 101(2):218.
- Sparre, P., E. Ursin, and S. Venema. 1989. Introduction to tropical fish stock assessment. Part 1 - Manual. FAO Fish.Tech.Paper 306/1 Rome, FAO 337 p.
- SUBPES, 1981. Fundamentos técnicos de los decretos No 458, 459 y 460 del ministerio de economía, fomento y reconstrucción. Subsecretaría de pesca, Archivo. Serie DD/4. 12 p.
- Taylor, C.C. 1958. Cod growth and temperature. J. Cons. int. Explor. Mer, (23):366-370.
- Taylor, C.C. 1959. Temperature and growth - the Pacific razor clam. J. Cons. int. Explor. Mer, (25):93-101.
- Taylor, C.C. 1960. Temperature, growth and mortality - the Pacific cockle. J. Cons. CIEM, 26:117-124.

- Thomas, R. 1984. A method of age determination for the South West African pilchard *Sardinops ocellata*. S. Afr. J. Mar. Sci. 2:63-70.
- Thomas, R.M. 1985. Age studies on pelagic fish in the south-east Atlantic, with particular reference to the South African pilchard *Sardinops ocellata*. Ph.D. thesis, University of Cape Town: XI+289p.
- Trautmann, S. 1980. Determinación de la edad y el crecimiento de la sardina española (*Sardinops sagax musica*) para la zona de Iquique. Seminario de Titulo Ing. Ejec. Acuicultura, Universidad de Chile, Depto. Mat. Cien. Nat. Sede Osorno. 75 p.
- Trautmann, S. and M. Aguayo. 1980. Edad y crecimiento de sardina española (*Sardinops sagax musica*). In Investigaciones del recurso sardina española (*Sardinops sagax*). Aspectos biológicos. Inst. Fom. Pesq. AP 80. 43 p.
- Tyler, A.V., R.J. Beamish and G.A. McFarlane. 1989. Implications of age determination errors to yield estimates, p.27-35. In R.J. Beamish and G.A. McFarlane (eds.) Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Can. Spec. Publ. Fish. Aquat. Sci. 108.
- Tyler, A.V. and V.F. Galluci. 1980. Dynamics of fished stocks, p 111-147. In R.L. Lackey and L.A. Nielsen (eds.) Fisheries Management. John Wiley and Sons, N.Y.
- Vidal, J. 1967. Some populations dynamics of the spanish sardine (*Sardinops sagax musica*) in Antofagasta, Chile. Thesis for degree of Master of Science, University of Washington, USA. 77p.
- Vidal, J. 1983. Comentarios sobre la fijación de cuota para la sardina española en la zona norte, p. 189-226. In P.Arana (ed.) Análisis de las pesquerías chilenas. Escuela de Ciencias del Mar, Universidad Católica de Valparaíso.
- Vidal, J. 1985. Estimaciones de edad y crecimiento para la sardina española (*Sardinops sagax musica*) en la zona norte de Chile basadas en el método de Petersen, p. 189-226. In P. Arana (ed.) Análisis en Pesquerías Chilenas. Escuela de Ciencias del Mar, UCV, Valparaíso.
- Yamanaka, I. 1960. Comparative study of the populations size of Japanese and California sardine, p. 1151-1191. In H. Rosa and G. Murphy (eds.) Proceedings of the world scientific meeting on the biology of sardines and related species. Vol III. Experience Paper 19. FAO 1960.

- Zuleta, A. and R. Serra. 1985. The management of Chilean pelagic fisheries with emphasis on the spanish sardine (*Sardinops sagax musica*). FAO Fish. Rep. 289(3):457-470.

VII. APPENDICES

Appendix I: Model's Assumptions.
Megrey and Wespestad (1988)

1. Harvest Function

- a) The catchability of the gear is constant, that is one unit of fishing effort catches the same percentage of the stock. This assumption holds regardless of when and where the effort is applied. The relationship between fishing effort and fishing mortality is independent of stock size.
- b) Catchability is independent of age and time.
- c) Units of effort are independent of how much effort there already is or of effort on other fish stocks (i.e. there is no gear interference or saturation).
- d) The fishery is operating on a single stock over its entire geographic.
- e) The fish population is uniformly distributed.
- f) All fish in the stock are available to the fishery throughout their life and are equally vulnerable to the gear as they age.
- g) Fishing and natural mortality take place simultaneously throughout the year.
- h) Catch and effort statistics are accurate.
- i) The main human influence on the abundance of recruits is the amount of fishing.
- j) There has been no change in gear or vessel efficiency over the period that fisheries data are available.

2. Growth

- a) Growth parameters do not vary with age, time or size of the adult stock.
- b) The processes of catabolism and anabolism are solely a function of weight.

3. Catch-Equation

- a) Those for Harvest Functions (see above)
- b) Growth parameters do not vary with age, time or size of the adult stock.
- c) The rate at which fish are caught is proportional to the numbers present.
- d) Fishing and natural mortality take place simultaneously throughout the year and are independent of each another (Type II fishery, Ricker (1975, p. 11)).
- e) All removals from the population are accounted for in the catch (resulting from directed effort), except for losses due to natural mortality.

3. Yield-per-recruit

- a) Growth parameters do not vary with age, time or size of the adult stock. The processes of catabolism and anabolism are solely a function of weight.
- b) The rate of natural mortality is typically assumed to be known. In conventional use M does not vary with age, time or size of the adult stock.
- c) Those associated with the Catch Equation (see above).
- d) All age-specific parameters and vital population rates are assumed to be constant over the fishable lifespan of the stock and independent of the size of adult stock. Natural mortality does not vary with age or time.

- e) The age-structure of the population is an important feature of natural populations.
- f) recruitment is constant.
- g) Fish of the same age always have the same weight, have the same natural mortality schedule and have the same susceptibility to the gear.

Appendix II: Sardine fishery regulation for 1982
Serra (1983 and Zuleta and Serra (1983)

a) Fixation of a minimum size for sardine (20 cm. total length).

The minimum size was estimated on the base of the criterion of critical age, to make a more efficient use of the growth of species (overfishing by growth) at the same time increasing the expectation of an individual to reach adulthood (Decree Law No. 458).

b) Prohibition of the use of purse-seines with nets over 20 fathoms deep and a mesh size equal to or less than 38 mm., along a costal fringe of one nautical mile (Decree Law No. 459).

Knowledge on the spacial distribution of anchovy, mackerel and sardine indicates that their breeding areas lie along the coastal fringe. Thus, the recruiting force is protected.

c) Determination of a quota of allowable catches for sardine in the northern zone for 1982. The allowable catch quota was calculated using the catch equation of Baranov and assuming that the biomass existing in 1982 was the same as in 1981.

First a projection was made of sardine catches for 1981, based on available data up to September of that year and on seasonal patterns observed during 1978, 1979 and 1980. Then a 39% exploitation rate was established as a gradual

approximation to the adequate level of 30%, which results when $F=M$ and $M=0.4$. The quota calculated was of 1,300,000 tons.

Finally, it is necessary to explain that the application of an allowable catch quota caused conflicts because it was completed before the end of the period for which it had been established. Consequently, the quota was supplemented with 116,000 tons (Decree Law No. 263), which represents the establishment of a 42% exploitation rate, in accordance with the estimates made. This supplement was also completed before the end of the fishing season.

Appendix III: Symbols used in Figure 21 and 22a.

SW1: L_{∞} and k for *S. ocellata* from South West Africa (Mathews 1960)

SW2: L_{∞} and k for *S. ocellata* from South West Africa (Thomas 1985)

SW3: M for *S. ocellata* from South West Africa since 1957 - 1960 (Newman 1970)

SW4: M for *S. ocellata* from South West Africa since 1963 - 1966 (Newman 1970)

S: L_{∞} and k for *S. ocellata* from South Africa (du Plessis 1960)

It: IFOP total data

Ia: IFOP average data

Ut: UNAP total data

Ua: UNAP average data

Ey: *S. melanosticta* from early years (Yamanaka 1960)

Ry: *S. melanosticta* from recent years (Kondo 1980)