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INTERGRATION OF TAGGING AND POPULATION DYNAMICS MODELS IN FISHERIES STOCK ASSESSMENT

by

Mark Nicholas Maunder

A dissertation submitted in partial fulfillment of the
requirements for the degree of

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Abstract

Integration of Tagging and Population Dynamics in Fisheries Stock Assessment

by Mark Nicholas Maunder

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An integrated tagging and population dynamics model is developed, tested, and applied to the SNA1 snapper (*Pagrus auratus*) stock off the east coast of the North Island of New Zealand. An Integrated Model (IM) is a model that combines two analyses that are usually carried out separately into one analysis, by incorporating the raw data directly into the fitting procedure of the population dynamics model. When tagging data is integrated with a catch-at-age model, it is called an Integrated Tagging and Catch-at-Age ANalysis (ITCAAN). The integrated approach has a number of advantages over traditional methods: it includes all information from the data, standardizes dynamics and parameters for all analyses, automatically incorporates correlation between parameters, allows detailed investigation of the model fit, and allows the incorporation of any dynamics. The main disadvantage of the integrated modeling approach is the complexity of the models needed to implement it. This complexity can lead to confounding between parameters, problems with model misspecification, and high computational demands. Movement between sub-stocks is a main dynamic that is included in the models used in this dissertation. Incorporation of movement in the analysis is very important, if management of individual sub-stocks is required. The results of the Integrated Model applied to the SNA1 snapper stock are more pessimistic than results from the current assessment. The initial fishing mortality rate in 1970 is a critical parameter of the model, and model misspecification caused problems in estimating this parameter. The integrated

modeling approach can be applied to a number of other applications in fisheries and other fields.

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GLOSSARY

Integrated Model. Is a model that combines two analyses, that are usually carried out separately into one analysis, by incorporating the raw data directly into the fitting procedure of the population dynamics model.

ITCAAN. An Integrated Tagging and Catch-at-Age ANalysis model is a model that integrates tagging data into a catch-at-age model.

LIST OF ABBREVIATIONS

BoP. Bay of Plenty

CPUE. Catch per Unit Effort

CRI. Crown Research Institute

DSNLR. Dynamic Structural Nonlinear Regression

EN. East Northland

HG. Hauraki Gulf

IM. Integrated Model

ITCAAN. Integrated Tagging and Catch-at-Age Analysis

ITQ. Individual Transferable Quota

NZFIB. New Zealand Fishing Industry Board

QMA. Quota Management Area

QMS. Quota Management System

SNA1. Snapper QMA1 located off the east coast of the North Island of New Zealand

TACC. Total Allowable Commercial Catch

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DEDICATION

The author wishes to dedicate this dissertation to all the families around the world that have suffered due to the economic collapse of major fisheries.

Chapter 1: Introduction

1.1 History of integrating data into population dynamics models

The methods historically used in fisheries stock assessment were developed based on the main types of data available from a fishery. For example, virtual population analysis was the preferred method when a long time series of catch-at-age data was available. These analyses typically did not use other auxiliary data that were available. Described below and summarized in Table 1.1 are the main types of analyses historically used and the data they require (details of these methods can be found in Hilborn and Walters 1992).

TABLE 1.1: Data usage for the main historical assessments. “I” indicates that the data is used as an input into the analysis. “O” indicates that the data is an output of the analysis.

	Data									
Method	C@A	Total Catch	Effort	Survey Index	M	Recruit-ment	Stock size	Tagging	F	Growth
VPA	I				I	O	O		O	
SP		I	I	I			O		O	
YPR					I					I
SR						I	I			
Petersen							O	I	O	
Grow								I		O

VPA: virtual population analysis
SP: surplus production modeling
YPR: yield per recruit analysis
SR: stock recruitment analysis
Petersen: Petersen tagging analysis
Grow: growth analysis based on tagging data

Cohort analysis (Pope 1972) uses a time series of catch-age-data to follow the catch taken from a cohort as it ages over time. When the cohort size becomes very small, indicated by negligible catch from the cohort in the catch-at-age data, the sum of the catch from that cohort can be used in conjunction with the rate of natural mortality to calculate the initial numbers in the cohort. Virtual Population Analysis (VPA, Gulland 1965) uses cohort analysis on multiple cohorts to calculate the historic total population size. There are a number of problems with VPA, and it is well known that VPA is unreliable unless auxiliary information is used in the analysis (Rivard 1989, Pope and Stokes 1989). The output of VPA (recruitment and biomass) is often used as inputs for stock-recruitment analysis (described below).

Surplus production models (Schaefer 1954; Pella and Tomlinson 1969) use a time series of catch and effort data to reconstruct the biomass trajectory of the population. These methods traditionally do not model age-structure, but model changes in biomass as a simple function of biomass in the year before.

Stock-recruitment analysis (Ricker 1954; Beverton and Holt 1957; Ricker 1975) attempts to estimate the relationship between stock and recruitment using estimates of stock size and the size of recruitment for a number of years. Stock-recruitment analysis is most often used for salmonids. The output of VPA (recruitment and biomass) is often used as inputs for stock-recruitment analysis.

Yield per recruit analysis (Beverton and Holt 1957) uses information about natural mortality, growth rates, and fishery selectivity to determine optimal harvest rates and optimal age at entry into the fishery. These estimates are independent of any stock-recruitment relationship and are often compared to exploitation rate estimates (e.g. from age or length frequency data).

Tagging data has historically been used in two ways. Petersen tagging analysis (Petersen 1896) uses the number of tag releases, the number of individuals sampled, and the number of recoveries to calculate population size using simplifying assumptions. Tagging growth analysis uses growth increments that are calculated from tagging data to estimate growth rates.

Most of the methods listed above use different data. When there was more than one type of data available, analysts would often use a number of these methods and compare the results (e.g. results from a VPA compared with results from a surplus production model). Some of these methods are used to generate input for the other methods. For example, VPA is used to generate stock and recruitment data for stock-recruitment analysis.

Despite some obvious connections between these methods, it has only been in the last 20 years that researchers have started combining the different data types in these analyses. Some examples are summarized in Table 1.2.

TABLE 1.2. Data usage for the models that incorporate many different kinds of data. “I” indicates that the data is used as an input into the analysis. “O” indicates that the data is an output of the analysis.

	Data									
Method	C@A	Total Catch	Effort	Survey Index	M	Recruit-ment	Stock size	Tagging	F	Growth
Tuned VPA	I		I	I	I	O	O		I/O	
SRA		I	I	I	I	I	I/O		I/O	I/O
Stat C@A	I		I	I	I/O	I/O	I/O		I/O	I/O
Sim Tag		I	I		I/O		O	I	O	

Tuned VPA: tuned virtual population analysis
SRA: stock reduction analysis
Stat C@A: statistical catch-at-age analysis
Sim Tag: simulation tagging analysis

The methods that combine different data types range in complexity. A simple method that combines relative abundance indices into a catch-at-age assessment is Tuned VPA (Pope and Stokes 1989). Tuning a VPA involves changing parameters of a VPA to get a better correspondence to the relative abundance indices. Stock reduction analysis (Kumura 1988) is a method that combines multiple data sources when catch-at-age data is not available. Stock reduction analysis combines a stock-recruitment relationship with an age-structured model and then fits the model to a relative abundance index. The most sophisticated approach is statistical catch-at-age analysis (Fournier and Archibald 1982; Deriso et al. 1985; Methot 1990). Statistical catch-at-age analysis uses an age-structured model to predict data that is observed from the fishery; the parameters of the model are then changed to determine the best fit between the model predictions and the observed data. The best fit is defined using a mathematical representation based on statistical assumptions about the data. The data used in the analysis includes catch-at-age data and auxiliary information (e.g. fishing effort, trawl survey indices of abundance).

Simulation tagging analysis is one method that combines tagging data with other information (Hilborn 1990). A model is used to simulate the dynamics of the tagged population over time and predicted recoveries from the model are compared with observed recoveries to estimate the model parameters. This technique has been used to estimate exploitation rates, the rate of natural mortality, movement, and population size.

A number of researches have outlined general approaches to include all types of information into the stock assessment model (Fournier and Archibald 1982; Deriso et al. 1985; Methot 1990). Hilborn and Walters (1992) state that these techniques are the "state of the art in analysis of fisheries data." These approaches have been developed for populations that have catch-at-age data, but the general methodology can be applied in other situations. The methodology is called statistical catch-at-age analysis (Hilborn and Walters 1992) because it is based on the statistical properties of the data. Statistical catch-at-age analyses uses a population dynamics model to predict quantities that have been observed from the fishery; the parameters of the population dynamics model are then changed to give the best fit between the model predictions and the observed data. The best fit is determined by a mathematical representation of the error in the relationship between the observed data and the model predictions. Stock synthesis (Methot 1990) is the most general implementation of statistical catch-at-age analysis, and it can use most types of data available from a fishery. The data that can be used in stock synthesis includes CPUE (or catch and effort) data, commercial catch-at-age data, commercial catch-at-length data, survey catch-at-age data, and survey catch-at-length data.

Even in the sophisticated statistical catch-at-age analyses, the raw data is often processed before it is included in the fitting procedure of the population dynamics model. For example, CPUE (catch per unit effort) data is usually standardized for factors like area and month of capture using a general linear model before it is used in the fitting procedure. The processing of raw data often results in the loss of information that could help in estimating the parameters of the population dynamics model. In addition, the uncertainty in the estimates of parameters obtained from processing the raw data is often not transferred to the population dynamics model fitting process. Recently, Bayesian posteriors or likelihood profiles from the analysis used to process the raw data have been used to represent uncertainty by being included as priors in the population dynamics model fitting procedure. Unfortunately, with multi-parameter models it gets complicated to incorporate the correlation between parameters. In many applications only the marginal posteriors or likelihood profiles are used, and correlation between parameters is ignored. Integrating the raw data into the population dynamics model would allow all the information from the data to help estimate the parameters of the population dynamics model, avoids the problems with representing uncertainty, and to allows the incorporation of correlation between parameters.

1.2 The integrated modeling approach

The integrated modeling approach goes one step beyond the general concept developed by Methot (1990) in stock synthesis. The integrated modeling approach combines two analyses by incorporating the raw data and additional model structure into the fitting procedure of the population dynamics model. The main difference between the Integrated Modeling approach and stock synthesis is that the integrated modeling approach merges model structure from two analyses into one analysis, whereas stock synthesis generally uses the existing population dynamics model structure to predict quantities that can be compared to additional data.

As mentioned above, many fisheries stock assessments involve a two-step procedure: 1) first raw data is analyzed to derive summary statistics and then 2) the summarized data is used as inputs or data for a population dynamics model that calculates quantities used in management advice. This two-step procedure has a number of disadvantages:

1) *Information is lost in the summarization process.* There may be additional information contained in the raw data that is useful for estimating the parameters of the population dynamics model; this information is lost in the summarization process.
2) *Inconsistencies in assumptions.* The two analyses may use different parameter values or different model structures. For example, the tagging model of Anganuzzi et al. (1994) used selectivity estimates from a catch-at-age analysis to estimate parameters that were then used in the same catch-at-age analysis to re-estimate the selectivity parameters.

3) *Difficulty in determining error structure*. The error structure that should be used to incorporate the summarized data into the fitting procedure may be more difficult to determine than the error structure for the raw data. For example, Xiao (1998) suggests that it is difficult to represent the error structure of the ratio of catch divided by effort.
4) *Difficulty in including uncertainty*. It is difficult to incorporate uncertainty from the analysis that summarizes the raw data into the fitting procedure of the population dynamics model, if there is high correlation between parameters. The representation of correlation between parameters requires the use of joint distributions which are harder to represent than the marginal distributions that are commonly used.
5) *Reduced diagnostic ability*. A major technique used to evaluate the fit of a model to the data is to view the residuals (difference between the observed data and the values predicted by the model). If summarized data is used in the fitting procedure, the analyst is unable to determine if a lack of fit is due to the summarization procedure or the population dynamics model fitting procedure.

The above problems can be overcome by integrating the two analyses, which allows for shared dynamics and parameters, and by including the raw data into the fitting procedure of the population dynamics model.

Definition 1: An Integrated Model is a model that combines two analyses that are usually carried out separately into one analysis, by incorporating the raw data directly into the fitting procedure of the population dynamics model.

The integrated modeling approach can be demonstrated by the simple example of fitting a surplus production model to a standardized abundance index based on catch per unit effort data (CPUE). The commonly used approach requires a two-step procedure: 1) First, a standardized index of annual CPUE is calculated using a general linear model to standardize the CPUE for factors such as month, area and gear (e.g. Maunder and Starr 1995a); 2) a surplus production model is then fit to the standardized abundance index by estimating the parameters of the surplus production model (e.g. Maunder and Starr 1995b). The parameters estimated include a catchability coefficient (q) that relates the population biomass to the standardized CPUE index. These two steps can be combined into one integrated analysis by using the raw CPUE data in the model fitting procedure and including a separate catchability parameter for each factor that the index is standardized for. For example, the CPUE data in year y for January in area A caught by long line ($CPUE_{y,Jan,A,LL}$) is related to biomass in year y (B_y) by multiplying the biomass by the overall catchability coefficient (q_{total}) and the catchability coefficients for January (q_{Jan}), for area A (q_A) and for long line (q_{LL}). The parameters of the surplus production model and all the catchability parameters are estimated at the same time integrating the standardization process with the model fitting. A similar approach to the one described above is used by Xiao (1998) to fit a surplus production model to catch and effort data while standardizing for factors like gear and area.

$$CPUE_{y,Jan,A,LL} = B_y q_{total} q_{Jan} q_A q_{LL} e^{\varepsilon}$$

where ε is the error.

1.3 Integrated tagging and population dynamics models

One characteristic of the use of tagging data in stock assessments is the two-step procedure outlined above. The tagging data is analyzed independent of the population dynamics model to determine a number of quantities (e.g. total biomass, exploitation rates, natural mortality, movement rates) that are then used as inputs or data for the fitting of a population dynamics model. For example, first a Petersen analysis is used to estimate the total population size from the tagging data and then a population dynamics model is fit to the total biomass estimate.

Hilborn et al. (1995) suggest that integrating tagging data into the population dynamics model would overcome the problems of having different assumptions between the tagging analysis and the population dynamics model. Recent studies have integrated tagging data into population dynamics models in fairly simplistic ways. Richards (1991) developed an integrated model to assess a Canadian lingcod stock. The term composite model was used to describe the integrated model. Essentially the same equations were used to model the tagged and total populations and the effect of sharing parameters between the two models was investigated. The model used was very simple with no age or spatial structure. The integrated modeling approach can easily be extended to the more complex general catch-at-age models (Fournier and Archibald 1982; Deriso et al. 1985; Methot 1990) or more importantly to migratory catch-at-age analysis (Quinn II et al. 1990). Punt and Butterworth (1995) and Porch et al. (1995) used an integrated migratory VPA fit to area-structured tagging data to assess the North Atlantic bluefin tuna. Neither of these models used age- or size-structured tagging data because of the small number of recoveries. Gove (1997) showed that catch-at-age data is insufficient to estimate the parameters of a likelihood-based model and found that combining a Petersen type tagging likelihood with the catch-at-age likelihood enabled the parameters to be estimated. She also showed how a multinomial likelihood for telemetry data could be combined with the catch-at-age likelihood. The Integrated Model applied to tagging data in a fully age-structured context may provide solutions to problems encountered when the tagging analysis is separated from the population dynamics model.

The Integrated Model presented in this dissertation combines the recently developed simulation tagging model (Hilborn 1990) and a population dynamics model into one analysis. Both tagged and total populations are modeled sharing the same dynamics and parameter values. The total population is simulated forward over the period of interest, which may include the total exploitation history. Each tag release stratum (i.e. area of release, time of release) is modeled as a separate population. The tagged populations are simulated starting from the time of release and predicted recoveries in each stratum are compared to the observed recoveries. Other data observed from the fishery (e.g., catch-at-age data) can also be compared with the model's predictions using maximum likelihood. The sum of the negative log of these likelihoods is used to estimate the parameters of the model using a minimization routine. When tagging data and catch-at-age data are incorporated into the model the technique is termed an Integrated Tagging and Catch-at-Age ANalysis (ITCAAN).

Definition 2: An ITCAAN (Integrated Tagging and Catch-at-Age ANalysis) model is a model that integrates tagging data into a catch-at-age model.

The Integrated Model is a generalized concept and any type of population dynamics can be incorporated in the model. Any of the models described in this chapter can be used in the integrated modeling framework. For example, the tagging models described in this dissertation focus on movement between sub-stocks.

1.4 Goals of the dissertation

This dissertation describes the development and application of an integrated tagging and population dynamics model. The motivation for development of the Integrated Model comes from the problems associated with analyzing tagging data for a snapper (*Pagrus auratus*) population off the east coast of the North Island of New Zealand (this population is referred to as SNA1). Previous assessments have used a two step procedure where the raw tagging data is analyzed using a Petersen estimator to estimate total biomass and then a population dynamics model is fit to these biomass estimates. This two step procedure reduces the amount of information that can be derived from the tagging data. Integrating the raw tagging data into the population dynamics model allows for full use of the information contained in the tagging data and may help overcome or identify the problems in the current SNA1 assessments.

This dissertation has three main goals:

1) Development of an integrated tagging and population dynamics model that is useful for fisheries stock assessment
2) Evaluation of the performance of the integrated tagging and population dynamics model
3) Application of the integrated tagging and population dynamics model to the SNA1 snapper stock off the east coast of the North Island of New Zealand to help overcome problems in the current assessment.

This chapter (Chapter 1) has outlined the integrated modeling approach in a general context. Chapter 2 describes in detail the Integrated Model that I have developed, which combines tagging data with a population dynamics model. Chapter 3 looks at using simulation tests to evaluate the Integrated Model and compare it with the two-step procedure currently used for SNA1. Chapter 4 describes the SNA1 stock, describes the available data, outlines recent assessments and identifies the problems with these assessments. Chapter 5 applies the Integrated Model to the SNA1 stock. Chapter 6 describes the current assessment of the SNA1 stock, which uses a two step procedure where the tagging data is analyzed separately from the population dynamics model. Chapter 7 summarizes, compares and makes overall conclusions about the results obtained from this dissertation.

Chapter 2: Integrated Model of Tagging and Population Dynamics

2.1 Introduction

The Integrated Tagging and Catch-at-Age Analysis presented in this chapter is an extension of recent advances in tagging models. Historically, stock assessments involving tagging data separate the tagging analysis from the population dynamics model. A Petersen analysis is used to derive a best estimate of population biomass from the tagging data and the population dynamics model is fit to this estimate. Recently, more complicated models have been introduced into the fisheries literature which simulate the tagged population over a short period and fit to groups of recoveries (Hilborn 1990; Kleiber and Hampton 1994). These models are often called simulation models (Hilborn 1990; Anganuzzi et al. 1994). I propose to integrate the tagging simulation method with a population dynamics model using a maximum likelihood technique in an attempt to derive better estimates of stock status and productivity in terms of reduced bias and variance in point estimation. The method differs from previous studies in that it simulates the population over the total (or partial) history of the fishery rather than just the time period of the tagging study. The new model will be termed an Integrated Model and can be used in a similar way to integrate other raw data (i.e. catch per unit effort data) into a population dynamics model. When the Integrated Model uses both age-specific tagging data and catch-at-age data it is termed an Integrated Tagging and Catch-at-Age Analysis (ITCAAN).

2.2 Tagging Models

Alternative approaches of abundance estimates are special cases of a general form (J.R. Skalski, School of Fisheries, University of Washington, Seattle, WA 98195, USA, pers comm.) where closed population estimators can be described as follows:

$$\hat{N} = \frac{r}{\hat{p}}$$

where $\hat{N}$ is the estimate of the population size, r is the catch index and $\hat{p}$ is the estimated probability that an individual is captured. Estimators differ in how $\hat{p}$ is estimated and range from simple two sample Petersen estimators (Petersen 1896) to complex dynamic structural nonlinear regressions (Hilborn 1990).

2.2.1 Petersen

The nature of commercial fisheries restrict recoveries to single sightings as each recovery is not returned to the population. In a simple situation, when there is a single release period and a single recapture period, the Petersen (1896) method (also known as the Lincoln index) is frequently used. The Petersen method is based on the assumption that, due to random mixing of tagged animals in the population, the ratio of tagged to total individuals in the recovery sample is the same as in the population.

$$\frac{m}{n_2} = \frac{n_1}{N}$$

where n_1 is the number of individuals tagged, n_2 is the sample size for the recovery data of which m are tagged and N is the total population size.

This relationship can be used to estimate the population size (N), which is the only unknown quantity.

$$\hat{N} = \frac{n_1 n_2}{m}$$

In this simple estimator the probability of being caught is the number of tagged animals recaptured divided by the number of tagged animals released.

$$\hat{p} = \frac{m}{n_1}$$

and the catch index is equal to the size of the recover sample $r = n_2$.

The same result is achieved when using maximum likelihood techniques based on the binomial or hypergeometric distributions. Chapman (1951) gave an approximately unbiased estimator for the case when $n_1 + n_2 \geq N$.

$$\hat{N} = \frac{(n_1 + 1)(n_2 + 1)}{m + 1} - 1$$

The assumptions made in the Petersen estimation are (see Seber 1982):

1) All individuals have equal probability of capture within a sampling period
2) Tagging does not effect catchability
3) Individuals do not loose their tags
4) All tags are reported
5) The population is closed

If assumption 5 is violated the estimates are still valid in two cases specific cases. If the population is closed $\hat{N}$ estimates N. If there is mortality only, $\hat{N}$ estimates the population size at the time of the first sample. If there is recruitment only, $\hat{N}$ estimates the population size at the time of the second sample. If both recruitment and mortality are occurring, $\hat{N}$ is biased.

The data can be stratified into categories to reduce bias, but requires observed recoveries in all strata. There is also a variance-bias tradeoff associated with stratification (Chapman 1951). More complex stratified-Petersen methods can be used when there is a need to model movement between strata (Schwarz and Taylor 1998).

2.2.2 Dynamic Structural Non-Linear Regression (DSNLR)

Recently there has been development of more complex methods to determine the probability of capture in situations when there is more detailed data (Hilborn 1990). Often there are a number of recapture periods or stratification of data into groups that have interactions. The population dynamics of the tagged individuals is modeled over time to calculate the population size in any strata at any time. The recovery sampling is modeled to give a prediction of the probability of capture. The model is used to predict recoveries, which are compared with observed recoveries. An optimization routine is then used to estimate the parameters of the model.

Bailey (1951, 1952) used a simple model to simulate the tagged population over time and predict recoveries. The exponential model was used to represent the dynamics of the tagged population and gave estimates of the population size in three time periods. In this estimator, the probability of being caught in time t is:

$$\hat{p}_t = \frac{m_t}{n_1 e^{Z_t}}$$

where Z_t is the total mortality rate between the tagging sample and the recovery sample in time t.

m_t is the number of tagged individuals in the recovery sample at time t

If total mortality is the same for the tagged and untagged populations, and there is no recruitment, then this gives an estimate of the initial population size at the time of tagging.

The bases of Bailey's and the more recent method described by Hilborn (1990) is modeling the populations dynamics of the tagged individuals over time to calculate the probability of survival and probability of capture. These quantities can then be used to predict the recoveries and compare them with the observed recoveries. Parameters can be estimated by finding the best fit to the observed data given some fitting criteria (i.e. least squares or maximum likelihood). The parameters that are estimable depend on the data available and the structure of the model.

Models similar to that of Bailey, but more complex, have recently been introduced into the fisheries literature. Ishii (1979) and Sibert (1984) appear to be the first to use this method for fisheries tagging applications (Hilborn 1990). These methods model the population (usually the tagged population) over a short period and fit to groups of recoveries. Hilborn (1990) proposed a general framework for using simulation models for analyzing tagging data. Some authors term this technique simulation modeling because the models simulate the dynamics of the tagged population over time (Hilborn 1990; Anganuzzi et al. 1994; Kleiber and Hampton 1994), but this method is more accurately described as dynamic structural nonlinear regression (DSNLR).

Modeling the population over time gives the ability to fit to recoveries from a number of different time periods of recovery data. The releases are aggregated into categories (i.e. area and time of release) and are modeled through time. The resulting distributions of release groups within recovery groups are compared to the observed recovery data. These new methods typically fit to the recovery data using observation error and a likelihood function (Hilborn 1990; Deriso et al. 1991; Sibert and Fournier 1991). This observation error maximum likelihood method is the same that is suggested for fitting population dynamic models to abundance indices (Polacheck et al. 1993).

The DSNLR method is much more general than the traditional Jolly-Seber (Jolly 1965; Seber 1965) and Brownie et al. (1985) models used for analyzing tagging data with multiple recapture periods. The DSNLR method allows for the incorporation of structural assumptions that increase the estimability of the parameters. For example the capture probability can be related to the fishing effort and age-specific capture probabilities can follow a functional form reducing the number of parameters needed. These structural assumptions are similar in nature to assuming constant survival or capture probabilities over time when the data is insufficient to estimate all the parameters of a Jolly-Seber or Brownie models. These structural assumptions are often based on population dynamics theory or empirical data from other studies. The structural assumptions used in the DSNLR are useful in fisheries stock assessment because the tagging data is often more sporadic compared to other wildlife applications.

Significant advances in tagging studies due to the development of tagging DSNLR models have come from the literature analyzing tuna movement. Movement of individuals from one sub-population to another creates a complex system that cannot be analyzed by simple models. Sibert and Fournier (1991) suggest that there are few population dynamic models in the fisheries literature that consider movement and the estimation of movement parameters. This may be because traditional methods found in the wildlife literature that estimate movement from mark-recapture studies are not suitable for fisheries applications because they require marked fish that are recaptured to be returned alive (e.g. Arnason 1972; Schwarz and Arnason 1990). The DSNLR approach is ideal to model situations with interacting sub-populations because complex dynamics can be easily modeled and incorporate structural constraints that increase parameter estimability.

Modeling movement introduces a large number of parameters and it is often necessary to make additional assumptions to reduce the number of parameters. For example, movement in some directions is ignored based on data or other evidence (e.g. Kleiber and Fonteneau 1991; Anganuzzi et al. 1994). Typically, the sub-populations are assumed to make a single closed population so movement out of the area, which usually cannot be estimated, is not modeled. Movement is often seasonal and Deriso et al. (1991) found that models including seasonal movement fit the data better for yellowfin tuna. Incorporating seasonal movement requires additional parameters to be estimated. These parameters can be separate for each season (i.e., Sibert and Fournier 1991) or introduced through a functional form to reduce the number of parameters. Kleiber and Fonteneau (1991) used a cosine function to induce seasonal movement that cycles in direction and intensity. Movement can be simplified by assuming that it occurs as a discrete event at the start of the year. In a sensitivity analysis Hilborn et al. (1995) assumed that fish moved instantly on tagging and remained in the area until recaptured. Residuals from the analysis suggested that this assumption may be violated and continuous movement was occurring. For the same data, Anganuzzi et al. (1994) assumed that movement occurred annually and showed that their model produced a better fit to the data. In some situations more complex movement dynamics need to be incorporated into the analysis and Deriso et al. (1991) modeled movement velocity differently for large and small fish. It is likely that age or size-specific movement is important for many species, but will be difficult to estimate unless recovery sample sizes are large.

Growth, natural mortality and fishing mortality are also commonly incorporated in tagging DSNLR models. These processes are implemented using the structure of population dynamics models typically used in stock assessments. The processes modeled depend on the structure of the model chosen and the importance of these processes to the population's dynamics. The dynamics of the simulation model are often divided into discrete events to simplify the analysis rather than modeling continuous simultaneous processes (e.g., Deriso et al. 1991; Anganuzzi et al. 1994). The use of discrete events makes the assumption that fishing takes place in a short period and does not interact with natural mortality or movement.

Growth can be modeled in a number of ways and the method used to represent growth depends on the model structure. An age-structured model usually incorporates growth through incrementing the age of each cohort and assuming a fixed length for each age. Length-structured models can explicitly incorporate growth at length and variation of length at age. Growth rates often differ between sub-populations causing problems when modeling the interactions between the sub-populations. In age-structured models, weight-at-age of an individual will be determined by it's current sub-population and the weight-at-age of that individual will instantaneously change (including decrease in weight) when it enters a new sub-population. This inconsistency can be overcome using a length-structured model if growth is environmentally driven rather than genetic. Fish enter the new population at the correct length and growth is based on length. It is possible that growth may be both age and length dependent which would require an age-length-structured model. The short term models used for tagging studies often do not incorporate growth because the limited growth occurring over the period modeled does not change the important characteristics of the individuals represented in the model. Kleiber and Hampton (1994) for example, modeled natural mortality, harvest and movement, but not growth because they were focusing on movement patterns in respect to Fish Aggregation Devices (FADs) and the behavior of tuna was not thought to change due to the growth in the short time period of the study.

Fishing mortality is often modeled using the seperability assumption, where fishing mortality for an age or size-class is divided into a year component and an age or size component. The age or size selectivity is typically represented by a selectivity curve allowing a reduction in the number of parameters to be estimated (i.e., Anganuzzi et al. 1994). Anganuzzi et al. (1994) modeled selectivity as being different in different areas and found that this model fitted the data better than a model with selectivity fixed at estimates from a catch-at-age analysis.

Natural mortality is often modeled as a single quantity independent of time, age or size. In cases where natural mortality is assumed to change with age or time, a similar seperability approach can be used for natural mortality as used for fishing mortality (Anganuzzi et al. 1994). Deriso et al. (1991) suggest that natural mortality can be estimated from tagging data when reliable fishing effort measures are available, but found high residual variations.

2.3 Integrated Model

The Integrated Model combines a DSNLR tagging model and a population dynamics model into one analysis. The total population is projected forward over its exploitation history from an unexploited population size. The tagged population is modeled starting from it's release period and the number of recoveries predicted in each strata are compared to the observed recoveries. The tagged and total populations share the same dynamics and parameters. Other data observed from the fishery (i.e. catch-at-age data) can also be compared with the models predictions using maximum likelihood. The sum of the negative log of the combination of these likelihoods is used to estimate the parameters of the model using a minimization routine. The key of the Integrated Model is that all the parameters are estimated simultaneously while fitting to all the data.

The integrated method allows for the combination of all data in one framework and allows the tagging data to simultaneously give information on all parameters. Often information in the tagging data (e.g. age or size-structure, temporal stratification of recoveries) is lost because it is used in a processed form. Tag recovery data, in its simplest form, is catch-at-age data (or catch-at-length) with the addition that you often know (or have an estimate of) what the starting tagged population size and age-structure was. It is therefore logical that you should incorporate tagging and catch-at-age data in the same way. Catch-at-age data, typically, has too much influence on abundance trends and using tagging data in its raw form may overcome this problem. The integrated approach follows the trend to integrate all data in the same framework (i.e., stock synthesis, Methot 1990).

The integrated approach is the logical next step in the development of tagging models. For example Kleiber and Fonteneau (1991) used the DSNLR approach for the tagged population and then use the estimated parameters in a similar (with the addition of a recruitment sub-model), but separate, model for the untagged population. It would be a simple process to combine these two models. Hilborn et al. (1995) analyzed movement of juvenile Pacific Halibut using a model that fixed selectivity-at-age using estimates from a separate analysis on commercial catch-at-age data. Anganuzzi et al. (1994) criticized this method because sub-legal untagged fish were returned to the water while sub-legal tagged fish could be kept and therefore exploitation rates on the tagged sub-legal fish would be different from untagged sub-legal fish. Anganuzzi et al. attempted to derive size selectivity using the tagging data rather than fixing selectivity. These two types of data could be combined in the same analysis to generate results that are more consistent.

Integrated models have recently been used to assess some stocks where tagging data is available. Richards (1991) developed an integrated model to assess a Canadian lingcod stock. The term composite model was used to describe the integrated model. Essentially the same equations were used to model the tagged and total populations and the effect of sharing parameters between the two models was investigated. The model used was very simple with no age or spatial structure. The integrated modeling approach can easily be extended to the more complex general catch-at-age models (Fournier and Archibald 1982; Deriso et al. 1985; Methot 1990), or more importantly, migratory catch-at-age analysis (Quinn II et al. 1990). Punt and Butterworth (1995) and Porch et al. (1995) used an integrated migratory VPA fit to area structured tagging data to assess the North Atlantic bluefin tuna. Neither of these models used age or size-structured tagging data because of the small number of recoveries. Gove (1997) showed that catch-at-age data was insufficient to estimate the parameters of an age-structured model and that auxiliary information is needed to estimate the parameters. Gove combined a Petersen type tagging likelihood to the multinomial catch-at-age likelihood to enable parameter estimation of an age-structured model with simplifying assumptions. She also used a multinomial telemetry likelihood.

Often some parameters in population dynamics models are confounded and using the additional information in the raw tagging data may overcome this problem. Some researchers suggest that it is likely to be difficult to estimate fishing mortality and selectivity simultaneously when using tagging data (*see* Dorazio and Rago 1991) although Anganuzzi et al. (1994) suggest it may be possible to estimate both if there are releases every year. Recent assessments of the SNA1 snapper fishery in New Zealand (reported in Annala and Sullivan 1997) have found that selectivity and recruitment estimates are confounded when using catch-at-age data and it is better to fix either of these sets of parameters. There will also be a confounding between movement and exploitation rate, because high estimates of either can explain high recovery rates in areas away from the release site (Deriso et al. 1991) and it is necessary to have tag releases in all areas and estimates of total removals. It may be possible to separate the confounding effects using the integrated model.

The following text describes a simple age-structured Integrated Model that will be tested against artificial data sets. The total population is simulated forward from a virgin state as in stock reduction analysis. The tagged population is simulated from time of release and the number of recoveries predicted in each strata are compared to the observed recoveries using maximum likelihood. A difference equation model is used and assumes catch is taken at the start of the year. The model structure is similar to that used by Maunder and Starr (1998). Movement is simplified by assuming that it occurs as a discrete event at the start of the year, assumes a closed population and is constant over all ages.

2.4 Model equations

This section describes the equations of the Integrated Model. The model parameters and symbols used are defined in table 2.1.

TABLE 2.1. Description of model parameters.

Parameter	Description
$N_{y,a,l}$	Number at age a in year y and location l at the start of the year.
$\dot{N}_{y,a,l}$	Number at age a in year y and location l after movement.
$p_{x \to l}$	Probability that a fish in location x moves to location l
$S_{y,l}$	Spawning biomass in year y and location l
$S_{0,l}$	Virgin spawning biomass in location l
$R_{0,l}$	Virgin recruitment in location l
h	Steepness of the Beverton-Holt stock recruitment relationship
$f_{a,l}$	Fecundity of a fish age a in location l
$\varepsilon_{y,l}$	Recruitment anomaly for year y and location l
M	Instantaneous natural mortality rate
$C_{y,a,l}$	Total number of fish caught in location l of age a in year y
$u_{y,l}$	Annual exploitation rate in location l and year y
$v_{a,l}$	Vulnerability at age in location l
$C^{*}_{y,l}$	Total weight of the catch in location l and year y
$B_{y,l}$	Exploitable biomass in location l at the start of year y, after movement
$w_{a,l}$	Weight of an age a fish in location l
$\hat{r}^{k}_{y,a,l}$	Number of predicted recoveries of age a from release group k in location l and year y
$T^{k}_{y,a,l}$	Number of age a tagged fish from release k in location l at the start of year y
$\dot{T}^{k}_{y,a,l}$	Number of age a tagged fish from release k in location l after movement during year y after movement
$R^{k}_{y,a,l}$	Number of age a tag releases from release k in location l and year y

2.4.1 Movement

Movement is assumed to occur at the start of the year and is modeled following a Markov process (Deriso et al. 1991): the probability of being in area l after movement depends only on the current location, x. This probability is represented by a movement matrix.

$$\dot{N}_{y,a,l} = \sum_{x} p_{x \to l} N_{y,a,x}$$

$N_{y,a,l}$ is the number at age a in year y and location l at the start of the year.

$\dot{N}_{y,a,l}$ is the number at age a in year y and location l after movement.

$p_{x \to l}$ is the probability that a fish in location x moves to location l

Constraints are added to the movement parameters to keep them in the appropriate range. The constraints reduce the number of movement parameters estimated in the model. The proportion of individuals not moving is calculated as one minus the proportion of individuals moving to all other areas.

$$0 \le p_{x \to l} \le 1$$

$$\sum_{l} p_{x \to l} = 1$$

2.4.2 Recruitment

Recruitment follows the Beverton-Holt stock-recruitment relationship formulated with a steepness parameter, h, the proportion of the virgin recruitment that is realized at a spawning biomass level 20% of the virgin spawning biomass (Francis 1992). In the example used in this paper, the steepness parameter is common to all sub-populations, but steepness can be sub-population specific if required. Annual recruitment is log-normally distributed with mean equal to the stock recruitment relationship and is implemented using the log-normal bias correction. The bias correction makes the virgin recruitment equal to the mean recruitment rather than the median recruitment.

$$N_{y+1,1,l} = \frac{S_{y,l}}{\alpha_l + \beta_l S_{y,l}} \exp(\varepsilon_{y,l} - \frac{\sigma_r^2}{2})$$

$$\alpha_l = \frac{S_{0,l}(1-h)}{4hR_{0,l}}$$

$$\beta_l = \frac{5h-1}{4hR_{0,l}}$$

$$S_{y,l} = \sum_{1}^{a_{max}} \dot{N}_{y,a,l} f_{a,l}$$

$S_{y,l}$ is the spawning biomass in year y and location l

$S_{0,l}$ is the virgin spawning biomass in location l

$R_{0,l}$ is the virgin recruitment in location l

h is the steepness of the Beverton-Holt stock recruitment relationship

$f_{a,l}$ is the fecundity of a fish age a in location l

$\varepsilon_{y,l}$ is normally distributed with mean zero and variance σ_r^2

2.4.3 Mortality

Fishing and natural mortality are modeled using a difference equation that assumes catch is taken at the start of the year after movement.

$$N_{y+1,a+1,l} = (\dot{N}_{y,a,l} - C_{y,a,l})e^{(-M)}$$

M is the instantaneous natural mortality rate

$C_{y,a,l}$ is the total number of fish caught in location l of age a in year y

The final age-class (*amax*) is used as a plus group to accumulate old fish.

$$N_{y+1,a\max,l} = (\dot{N}_{y,a\max-1,l} - C_{y,a\max-1,l})e^{(-M)} + (\dot{N}_{y,a\max,l} - C_{y,a\max,l})e^{(-M)}$$

Catch at age is calculated using a separability assumption, which splits the exploitation rate into a year and an age component reducing the number of parameters to be estimated.

$$C_{y,a,l} = \dot{N}_{y,a,l} u_{y,l} v_{a,l}$$

$u_{y,l}$ is the annual exploitation rate in location l and year y

$v_{a,l}$ is the vulnerability at age in location l

The exploitation rate in year y is calculated as the catch divided by the vulnerable biomass, $B_{y,l}$. This assumes that the total catch is known without error and reduces the number of parameters to be estimated.

$$u_{y,l} = \frac{C^{*}_{y,l}}{B_{y,l}}$$

$$B_{y,l} = \sum_{a=1}^{a_{max}} \dot{N}_{y,a,l} v_{a,l} w_{a,l}$$

$C^{*}_{y,l}$ is the total weight of the catch in location l and year y

$B_{y,l}$ is the exploitable biomass in location l at the start of year y, after movement

$w_{a,l}$ is the weight of an age a fish in location l

2.4.4 Tagged population

The tagged population, T, is modeled assuming the same behavior and parameters as the untagged population with the only difference being recruitment to the tagged population is by releases and can occur at any age. Each set of releases, k, that can be uniquely identified in the recoveries is modeled as a separate population.

$$\dot{T}^{k}_{y,a,l} = \sum_{x} p_{x\to l|a} T^{k}_{y,a,x}$$

$$T^{k}_{y+1,a+1,l} = (\dot{T}^{k}_{y,a,l} - \sum_{m} \hat{r}^{k}_{y,a,l}) e^{(-M)} + R^{k}_{y,a,l}$$

$$\hat{r}^k_{y,a,l} = \dot{T}^k_{y,a,l} u_{y,l} v_{a,l}$$

$\hat{r}^k_{y,a,l}$ is the number of predicted recoveries of age *a* from release group *k* in location *l* and year *y*

$T^k_{y,a,l}$ is the number of age *a* tagged fish from release *k* in location *l* at the start of year *y*

$\dot{T}^k_{y,a,l}$ is the number of age *a* tagged fish from release *k* in location *l* after movement during year *y* after movement

$R^k_{y,a,l}$ is the number of age *a* tag releases from release *k* in location *l* and year *y*

2.4.5 Initial conditions

The population is assumed to be initially in equilibrium with regard to natural mortality, movement, and virgin recruitment. The initial population is generated by simulating each cohort over the number of years corresponding to its age in the initial population using only movement and natural mortality. The plus group is more complex and is approximated by summing up the individuals that would be alive in cohorts from the maximum age to age 200.

$$N_{1,1,l} = R_{0,l}$$

$$\dot{N}_{1,a,l} = \sum_x p_{x\to l} N_{1,a,l}$$

$$N_{1,a+1,l} = \dot{N}_{1,a,l} e^{-M}$$

2.5 Likelihoods

Maximum likelihood is used to estimate the parameters of the Integrated Model. Maximum likelihood has become the standard technique for parameter estimation in the fisheries literature when using non-linear regression (*see* Polacheck et al 1993, Hilborn and Mangel 1997) and is the preferred estimation technique.

2.5.1 Tagging likelihood

In a simple, single-mark and single-recapture, experiment the number of recoveries follows a hypergeometric distribution and this can be approximated by the binomial distribution for large samples. After a fraction of the population is tagged there are two types of individuals in the population, tagged and non-tagged. Recoveries occur in the commercial fishery without replacement. This is modeled by the hypergeometric distribution. Fishery assessment typically involves large populations so removing an individual from the population does not significantly change the probability of recapturing a tagged or untagged individual. Therefore, sampling with replacement can be assumed without significant error (if the ratio of the sample over the total population is much less than 0.1, Seber 1982) and the binomial distribution can be used to represent the number of recoveries.

The multinomial likelihood function is appropriate when there are more than two types of outcomes. In many studies the release and recovery data is divided into different strata based on area, age, size, time or other factors. There are two reasons for this, the first is to generate better estimates of the population size when capture probabilities are heterogeneous between strata and the abundance estimate will be biased if stratification is not used. The second reason is that separate estimates for each strata are needed, for example age-structured models may require abundance estimates by age. In an experiment that includes multiple recovery types (i.e. tagged in population one, tagged in population two, or not tagged) the number of recoveries follows a multivariate hypergeometric distribution and is approximated by the multinomial distribution for large samples.

There are two ways of looking at tagging data using the multinomial likelihood function. 1) Each tag release of an individual is a trial and the multinomial likelihood models which recovery strata the tagged individual is recovered in. 2) Each individual caught is a trial and the multinomial likelihood models what strata the individual was tagged in. The form of the likelihood is dependent on whether the likelihood is conditional or unconditional. An unconditional likelihood is used when the sample sizes are random variables (e.g. there is a fixed amount of effort in the sampling phase rather than a fixed sample size) and the likelihood includes a term for the sample size. A conditional likelihood is used when the sample sizes are fixed (also used to describe when a model parameter is fixed). If the parameters of the model are uninformative about the sample size, then the likelihood should be conditioned on that sample size (Edwards 1992).

The multinomial likelihood function is the most commonly used likelihood function when there are more than two types of recoveries possible (i.e. Deriso et al 1991; Kleiber and Fonteneau 1991; Anganuzzi et al. 1994; Kleiber and Hampton 1994). The Poisson likelihood function has been used in some analyses (i.e. Kleiber and Hampton 1994) and it is suggested that the multinomial and the Poisson likelihoods give essentially the same results in the mean (Hilborn 1990; Deriso et al. 1991). The Poisson likelihood will give different variance estimates compared to the multinomial because in the Poisson the variance is equal to the mean. The Poisson probability distribution is used for tagging studies because it models rare events that occur randomly and independently in time, but the multinomial is more appropriate for tagging data.

The Multinomial likelihood function with each tag release as a trial is used in this analysis. The likelihood function from one release period and multiple recapture periods is given below. The constants are left out of the likelihood because they do not add to the estimation of parameters (or to likelihood ratio tests or Bayes posterior calculations).

$$L(\text{parameters} \mid \text{tag\_data}) = \prod_{a'} \left[\left(1 - \sum_{t,l} \hat{p}_{y'+t,a'+t,l} \right)^{\left(R_{a'} - \sum_{t,l} r_{y'+t,a'+t,l} \right)} \prod_{t,l} \hat{p}_{y'+t,a'+t,l}{}^{r_{y'+t,a'+t,l}} \right]$$

$$\hat{p}_{y'+t,a'+t,l} = \frac{\hat{r}_{y'+t,a'+t',l}}{R_{a'}}$$

$\hat{r}_{y,a,l}$ is the model predicted recoveries in year y and location l that are age a.

a' is the age at release

y' is the year of release

t is the time after release in years

l is the location of recapture

Because likelihoods are usually very small numbers it is convenient to use the negative of the logarithm of the likelihood to avoid computational over and underflows (Hilborn and Mangel 1997, Gelman et al. 1995). The negative log likelihood from other release periods or independent auxiliary information can be added to the total negative log likelihood.

2.5.2 Catch-at-age likelihood

Catch-at-age data is commonly included in the joint likelihood using a multinomial likelihood. If we assume that the catch-at-age data is independent from the tagging data then we can simply add the negative log likelihood from the catch-at-age data to the total negative log likelihood. The likelihood less the constant terms is given below.

$$L(\text{prameters} \mid \text{C@A\_data}) = \prod_{l} \prod_{y} \prod_{a} p'_{y,a,l}{}^{C^{S}_{y,a,l}}$$

$$p'_{y,a,l} = \frac{\dot{N}_{y,a,l} v_{a,l}}{\sum_{a} \dot{N}_{y,a,l} v_{a,l}}$$

$C^{S}_{y,a}$ is the number of fish of age a in the catch at age sample from year y

The catch-at-age data is usually not independent from the tagging data, but because the sample size of catch-at-age data and the number of tagged recoveries are both small there is very little interaction between the two.

2.5.3 Recruitment residual prior

When the annual recruitment parameters are estimated, a penalty based on the log-normal distribution is added to the negative log-likelihood function. This is essentially a prior distribution on recruitment variation and makes the analysis Bayesian. The mode of the joint posterior distribution is used for point estimation of parameters in the same manner as the maximum likelihood estimate. This technique is similar to the concept of support described by Edwards (1992). The term added to the total negative log-likelihood (ignoring constants and using a fixed value for σ_r) is:

$$-\ln P(\text{paramters} \mid \text{prior}) \propto \sum_{y,l} \frac{\varepsilon^2_{y,l}}{2\sigma^2_r}$$

$\varepsilon_{y,l}$ is the recruitment anomaly in year y and location l.

σ_r is the standard deviation of the natural logarithm of the annual recruitment anomalies

2.6 Estimation

The parameters of the model are estimated using an iterative minimization routine to minimize the total negative log-posterior probability given below:

Total negative log-posterior probability =

$-\ln L(\text{parameters} \mid \text{tag\_data}) - \ln L(\text{parameters} \mid \text{C@A\_data}) - \ln \text{Prior}(\varepsilon)$

$$L(\text{parameters} \mid \text{tag\_data}) = \prod_{k}\prod_{a'}\left[\left(1-\sum_{t,l}\hat{p}^{k}_{y'+t,a'+t,l}\right)^{\left(R^{k}_{a'}-\sum_{t,l} r^{k}_{y'+t,a'+t,l}\right)}\prod_{t,l}\hat{p}^{k}_{y'+t,a'+t,l}{}^{r^{k}_{y'+t,a'+t,l}}\right]$$

$$L(\text{prameters} \mid \text{C@A\_data}) = \prod_{l}\prod_{y}\prod_{a} p'_{y,a,l}{}^{C^{S}_{y,a,l}}$$

$$-\ln \text{Prior}(\varepsilon) \propto \sum_{y,l}\frac{\varepsilon^{2}_{y,l}}{2\sigma^{2}_{r}}$$

where:

$$\hat{p}^{k}_{y'+t,a'+t,l} = \frac{\hat{r}^{k}_{y'+t,a'+t,l}}{R^{k}_{a'}}$$

k is the release group (i.e. area and year of release)

$r^{k}_{y,a,l}$ is the number of observed recoveries of age a from release group k in location l and year y

$\hat{r}^{k}_{y,a,l}$ is the number of predicted recoveries of age a from release group k in location l and year y

R^{k}_{a} is the number of age a tag releases from release k

a' is the age at release

y' is the year of release

t is the time after release in years

l is the location of recapture

$$p'_{y,a,l} = \frac{\dot{N}_{y,a,l} v_{a,l}}{\sum_{a} \dot{N}_{y,a,l} v_{a,l}}$$

$C^{S}_{y,a}$ is the number of fish of age a in the catch at age sample from year y

$v_{a,l}$ is the vulnerability at age in location l

$\dot{N}_{y,a,l}$ is the number at age a in year y and location l after movement.

$\varepsilon_{y,l}$ is the recruitment anomaly in year y and location l.

σ_r is the standard deviation of the natural logarithm of the annual recruitment anomalies

The auto differentiation method supplied with AD Model Builder (© Otter Research) is used in the analyses presented in this dissertation to estimate the model parameters by minimizing the negative log-posterior probability.

Chapter 3: Testing the Integrated Model

The robustness of the Integrated Model to different population characteristics is tested using simulated data. The results of the Integrated Model are compared with results from the traditional method of fitting a population dynamics model to biomass estimates from a Petersen analysis. The Integrated Model performs well with no bias in estimates of production and current status. Variance is large for estimates of sub-population productivity compared to variance for estimates of productivity for the total population and compared to results when fitting to Petersen estimates of biomass, but variance can be reduced with the addition of catch-at-age data and estimation of annual recruitment residuals. The Petersen method produces highly biased estimates of sub-population production and sub-population current status because the population dynamics model does not incorporate movement between the sub-populations.

3.1 Introduction

It is important to test the effectiveness of new assessment methods before applying them to real populations. The impracticality of performing experiments on real fish populations has made tests against simulated artificial data sets become the accepted way of evaluating assessment methods (e.g. National Research Council 1998). Ludwig and Walters (1985) suggest that all estimation schemes should be tested using simulated data. These tests are used to calculate the bias and variance of parameter estimates. Simulation of artificial data relies on constructing a mathematical representation of the population and simulating its dynamics forward in time. This mathematical representation is termed the operating model and can be used to produce observational data that is used in the estimation methods. The observational data includes a stochastic representation of observation error and the results of the estimation procedures using this data can then be compared to the true dynamics represented by the operating model. Many studies use the estimation model being tested to also generate the artificial data sets (e.g. de la Mare 1986; Sullivan et al. 1990; Hampton 1991a). Hilborn and Mangel (1997) suggest that all assessments should be fit to deterministic data generated from the same model as used to estimate the parameters. This test is used to check for programming errors and can sometimes indicate confounding, or estimability problems with the parameters of interest. Hilborn and Mangel then suggest adding error to the deterministic data to test the estimation model. Hilborn (1979) suggests using a model more complicated than the one being tested. Other authors suggest using many different models as robustness tests (i.e., Punt 1992; Cooke 1995). Cooke (1995) suggests that a simple model should be used to generate the artificial data in initial tests and any estimation models that perform poorly should be abandoned. In this first analysis of the Integrated Model, I use the same underlying formulation of the Integrated Model for the simulation algorithm, to produce the artificial data sets, as I do for the estimation algorithm.

3.2 Methods

3.2.1 Structure of simulated data

To create artificial data sets, the Integrated Model is used to simulate three interconnected sub-populations forward ten years starting from an unexploited population using a fixed exploitation history (Table 3.1). In the tenth year a single mark recovery experiment is carried out in all areas (releases are given in Table 3.2) and the dynamics are simulated for another ten years. The observation data generated are age-specific tag recoveries and catch-at-age data over the last ten years of the simulation. The main population characteristic that is modeled is movement between the three sub-populations. Error in the simulated data is introduced as process error in recruitment for the total population and the natural mortality, movement and exploitation rate of tagged fish. Fecundity-at-age was set equal to weight-at-age which follows the von Bertalanffy growth equation with the usual length weight relationship. Selectivity by the gear was made knife-edge with a given age at first selectivity, a_{vuln}. Parameters used in the creation of the artificial data sets and also assumed known in the estimation procedure given in Table 3.3.

TABLE 3.1: Annual exploitation rates (y^{-1}) used to generate the artificial data sets. The exploitation rates are based on a fishery that is fished to over exploitation and then allowed to rebuild.

Year	Exploitation Rate
1	0.05
2	0.05
3	0.05
4	0.05
5	0.1
6	0.1
7	0.1
8	0.1
9	0.2
10	0.2
11	0.3
12	0.3
13	0.1
14	0.1
15	0.1
16	0.1
17	0.1
18	0.1
19	0.1
20	0.1

3.2.2 Random Errors

Log-normal variation with a σ_r of 0.6 ($\sigma_r \approx$ coefficient of variation and is based on an average for many species) is incorporated into annual recruitment and recruitments used to generate the initial age-structure of the total population. The plus group is assumed to have no variation because fluctuations are averaged out over many cohorts.

$$R'_{y,l} = R_{y,l} \exp(\varepsilon^r_{y,l} - 0.5\sigma^2_r)$$

where $R'_{y,l}$ is the recruitment in year y and location l

$R_{y,l}$ is the underlying deterministic recruitment in year y and location l based on the stock-recruitment relationship.

$\varepsilon^{r}_{y,l}$ is the recruitment anomaly for year y and location l

σ_r is the variance of the recruitment distribution.

TABLE 3.2: Releases by age for each sub population used to generate the artificial data sets.

Age	Releases
4	1000
5	740
6	548
7	406
8	301
9	223
10	165
11	122
12	90
13	67
14	49
15	36
16	27
17	20
18	14
19	11
20	8
21	6
22	4
23	3
24	2
25	1
26	1
27	1

TABLE 3.3: Model parameters assumed known for the simulation tests. These parameters are used in both the simulation model to generate the artificial data and in the estimation model.

$Amax$	50
M	0.2
H	0.75
a_{vuln}	4
A	1
B	3
K	0.1
L_{inf}	10
T_0	0

Log normal variation with a σ_u of 0.3 is incorporated into the exploitation rate on the tagged fish affecting both the dynamics of the tagged population and the observed recoveries. This implementation for the variation in exploitation rate assumes that individuals tagged in the same strata and of the same age have the same exploitation rate, which is consistent with species that school by age. To keep the recoveries as integers, the Binomial distribution is used to randomly determine the number of recoveries from a given exploitation rate and size of the tagged population. This is similar to the individual based approach used by Hampton (1991b). The use of the Binomial distribution adds binomial variance only to the recovery data.

$$r_{y,a,l}^{k} \sim \text{binomial}\left(n = T_{y,a,l}, p = u_{y,l} v_{a,l} \exp(\varepsilon_{y,a,l}^{u} - 0.5\sigma_u^2)\right)$$

where

$\varepsilon_{y,a,l}^{u}$ is the exploitation rate anomaly for year y, age a and location l

σ_u is the variance of the exploitation rate distribution.

To keep the recoveries as integers, natural mortality and movement for the tagged population are modeled as binomial and multinomial events, respectively. The observed catch-at-age data is generated using a multinomial distribution with a sample size of 500.

3.2.3 Tests

The artificial data sets are used to investigate the robustness of the Integrated Model to different characteristics of the population's structure. The population characteristics investigated are outlined below and summarized in Table 3.4. The exploitation history used to generate the artificial data sets (Table 3.1) is based on a typical fishery that is over exploited and then allowed to rebuild. When there is equal movement between all the sub-populations a movement rate of 10% is used (i.e. 80% of the individuals will remain in the same sub-population each year). The movement used when there is unequal movement between the populations is given in Table 3.5.

TABLE 3.4: The different population characteristics used in the simulation model to create the artificial data sets for the five tests. The exploitation rate column gives a multiplier that scales the exploitation history given in Table 3.1.

Population	Virgin Recruitment			Exploitation			Movement
Scenario	1	2	3	1	2	3	
1	1000	1000	1000	1	1	1	Equal
2	500	1000	1500	1	1	1	Equal
3	1000	1000	1000	1	1	1	Unequal
4	1000	1000	1000	0.5	1	2	Equal
5	500	1000	1500	0.5	1	2	Unequal

TABLE 3.5: Annual movement rates (y^{-1}) between sub-populations when movement is unequal.

		To		
		1	2	3
From	1	1	0	0
	2	0	0.9	0.1
	3	0.1	0.2	0.7

The five different population characteristics used to generate the artificial data sets to test the Integrated Model are listed below:

1) Three populations with equal recruitment and the same exploitation history and equal movement
2) Three populations with <u>different recruitment</u> and the same exploitation history and equal movement
3) Three populations with equal recruitment and the same exploitation history with <u>unequal movement</u>
4) Three populations with equal recruitment and <u>different exploitation</u> history and equal movement
5) Three populations with <u>different recruitment</u> and <u>different exploitation</u> history with <u>unequal movement</u>

For each of the different population characteristics, 500 independent artificial data sets are generated and the results of the Integrated Model analysis are compared to the underlying "real" data. R_0 and the movement parameters are estimated when fitting to the age and area specific tagging data. The benefit of including catch-at-age data and estimating annual recruitment is investigated (this is referred to as the ITCAAN model). The results of the Integrated Model are compared to a traditional method of fitting a population dynamics model to a Petersen estimate of abundance (based on Chapman 1951 see below) using least squares constrained to a narrow set of assumptions.

$$B_l = \frac{(b1_l + 1)(b2_l + 1)}{(m_l + 1)} - 1$$

where B_l is the estimated biomass in location l

$b1_l$ is the biomass of the individuals tagged in location l

$b2_l$ is the biomass of the individuals examined for tags in location l

m_l is the biomass of the individuals examined for tags location l which had tags.

In the Petersen analysis R_0 is the only parameter estimated, there is no movement between sub-populations and the Petersen total (or sub-population) biomass estimate is the only data used. Two Petersen analyses are used; 1) a single estimate of the three sub-populations combined (referred to as the Total Petersen method) and 2) separate estimates of each sub-population (referred to as the Individual Petersen method). There is no movement between the release and capture phase in the Petersen analysis.

3.2.4 Performance Indicators

The two main aspects of a fishery available from a stock assessment are the status of the stock (the current population size relative to the optimal or virgin population size) and the available production (related to the sustainable yield). These two characteristics can be described by two quantities, the current biomass as a fraction of the initial biomass (B_{cur}/B_I) which indicates the status of the stock and virgin recruitment (R_0), which scales the productivity of the stock. Production is a complicated relationship between growth, natural mortality and recruitment. If growth and natural mortality are known, recruitment is the main parameter that scale production. These two values, for the total combined population and for individual sub-populations, will be compared to the true vales giving the bias and variance of the estimates.

3.3 Results

Graphical results are presented as boxplots of the relative error. Relative error is defined as the estimation error (estimate minus the true value) divided by the true value. The upper and lower bounds of the box represent the interquartile range (i.e. the middle 50% of the data), the mid point line is the median, and the whiskers extend to the furthest point excluding outliers. Each figure includes a cluster of boxplots, each cluster representing the results from one of the tests described above. In the following discussion of the results, the term variance is used to describe how the relative error in an estimated quantity differs within the 500 simulations carried out for a particular test, and the term bias refers to how the mean relative error for an estimate from all the 500 simulations for a particular test differs from zero.

3.3.1 Virgin Recruitment (R_0)

Estimates of R_0 for each sub-population are unbiased, but they have high variance compared to the variance for the combined total R_0 (Figure 3.1). The high variance for the sub-population R_0s is caused by interaction between the populations and a confounding between movement and sub-population R_0. Variation in sub-population R_0 and movement cancel each other out in the calculation of initial biomass (B_I) reducing it's variance (Figure 3.2).

When the three interacting sub-populations have different levels of virgin recruitment (test 2) the variance in the estimates of R_0 decreases as virgin recruitment increases. When movement rates differ between the sub-populations (test 3), sub-population one has the lowest variance because it has the least interaction with the other sub-populations.

3.3.2 Current biomass as a proportion of virgin biomass (B_{cur}/B_0)

There is no bias in the estimates of B_{cur}/B_I (Figure 3.3). Variance in the estimates of sub-population B_{cur}/B_I is much smaller than estimates of R_0, but slightly higher than the variance in estimates of B_I (Figure 3.2). Variance in the estimates of total combined B_{cur}/B_I are only slightly smaller than for the for individual sub-populations estimates.

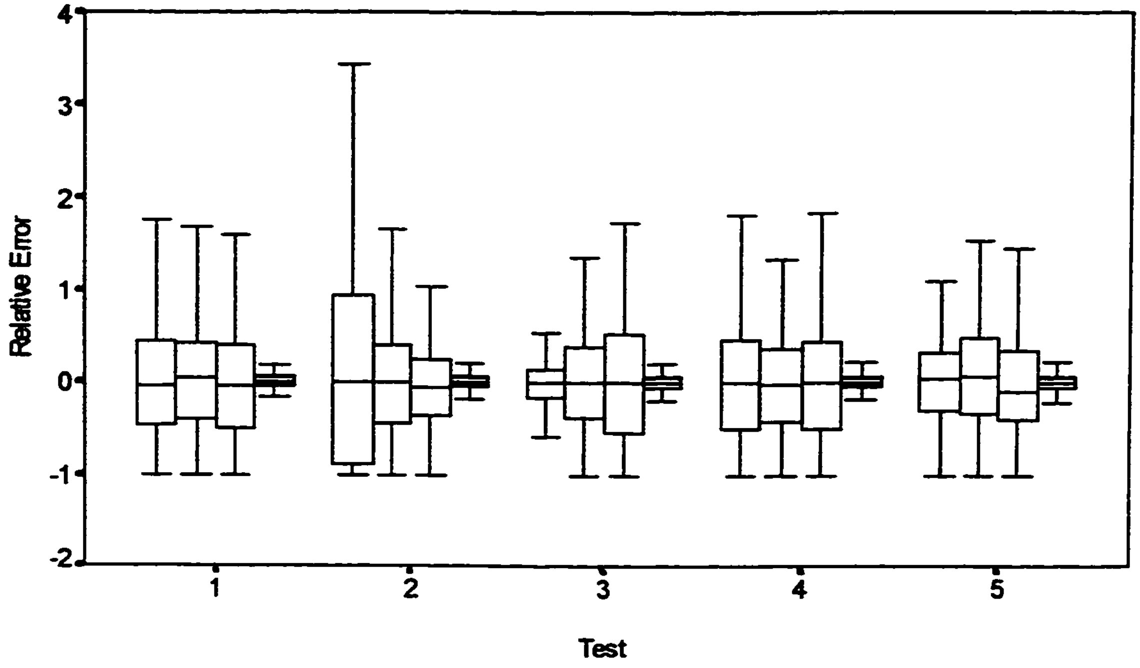

FIGURE 3.1: Relative error in the estimation of virgin recruitment ($[\hat{R}_0 - R_0]/R_o$). The first three boxplots in each cluster represent estimates for each sub-population. The last boxplot in each cluster represents the total R_0, that is the sum of the sub-population R_0s. Variance in the estimates for sub-populations is much larger than for the combined total population.

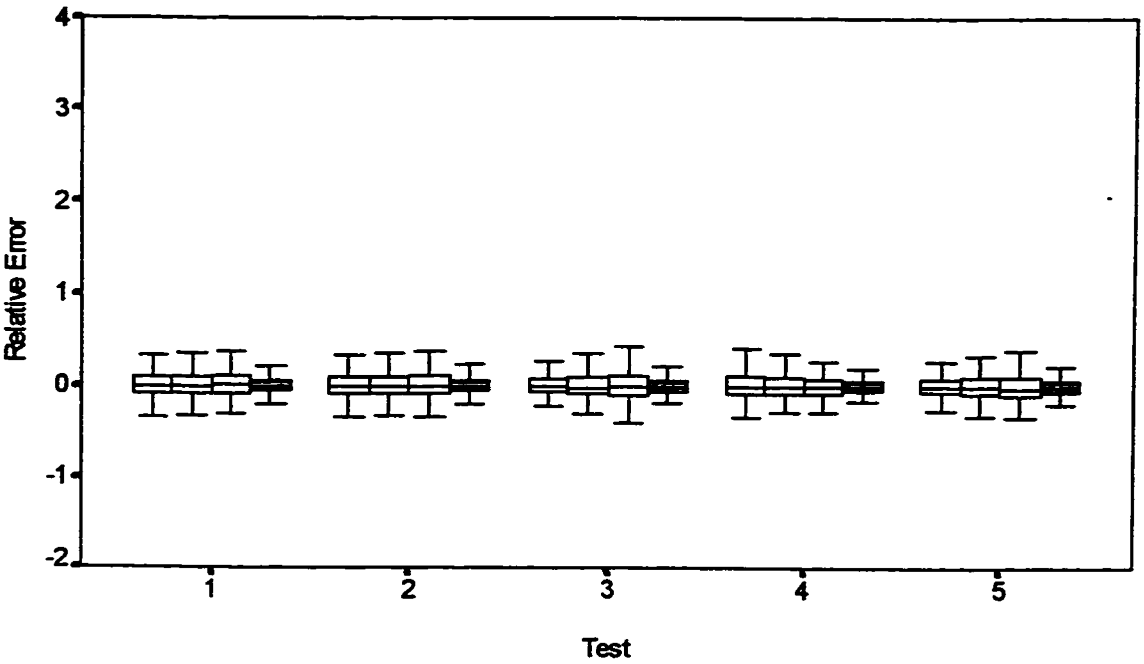

FIGURE 3.2: Relative error in the estimation of initial biomass ($([\hat{B}_1 - B_1]/B_1)$). The first three boxplots in each cluster represent estimates for each sub-population. The last boxplot in each cluster represents the total B_1, that is the sum of the sub-population B_1s.

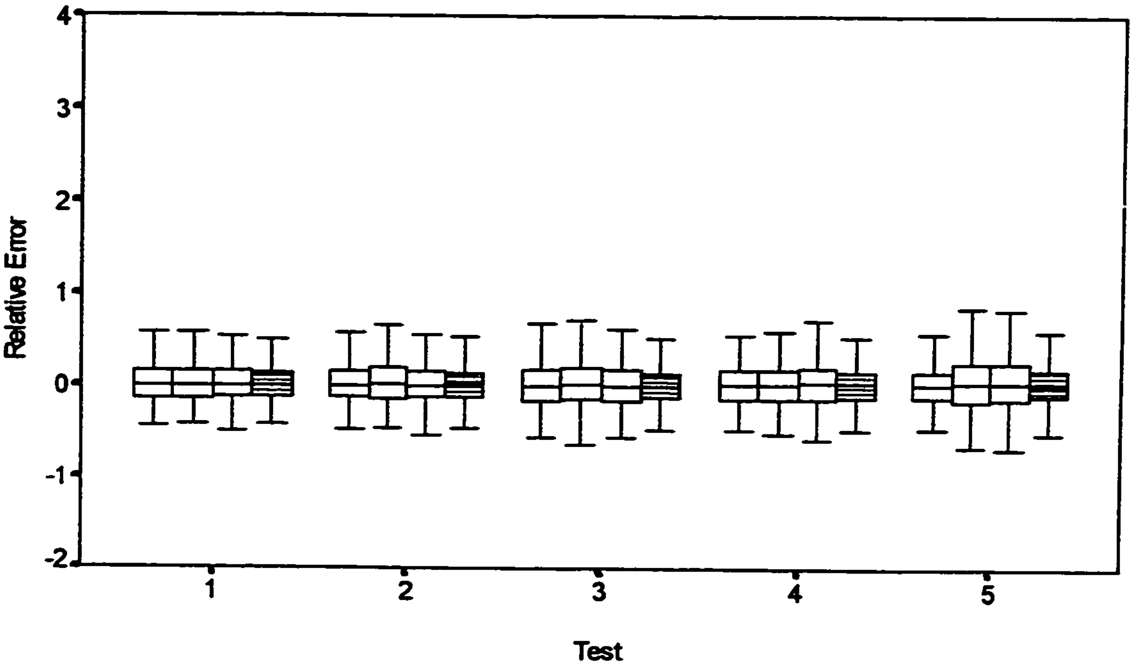

FIGURE 3.3: Relative error in the estimation of current status ($([\hat{B}_{cur}/\hat{B}_1 - B_{cur}/B_1]/[B_{cur}/B_1])$. The first three boxplots in each cluster represent estimates for each sub-population. The last boxplot in each cluster represents the total B_{cur}/B_1, that is the sum of the sub-population B_{cur}/B_1s.

3.3.3 Catch-at-age data (ITCAAN)

The addition of catch-at-age data reduces variance in the estimates of total combined (Figure 3.4) and sub-population (Figure 3.5) B_{cur}/B_1. This reduction in variance is expected because of the information on recruitment strength. The ITCAAN model also greatly reduces the variance in estimates of sub-population R_0 (Figure 3.6) at the expense of slightly increasing the variance in the estimates of the total combined R_0 (Figure 3.7).

3.3.4 Petersen

The estimates of sub-population R_0 when fitting to Individual Petersen estimates of biomass show large bias when there are any differences in recruitment, in exploitation rate or in movement between the populations (Figure 3.8). Any runs where the estimated parameters caused the exploitation rate to exceed one were not included in the results. Exploitation rates greater than one mean that the catch is greater than the biomass and are impossible, indicating that the parameter estimates are incorrect. By removing these results from the figures, the figures indicate the bias and variance in results that would appear to the analyst as possible solutions. By comparing the number of simulations that were not included in the graphs with the total number of simulations you can get an idea of the probability of getting an answer that appears incorrect. Figure 3.8 gives the number of runs included in the results. When the exploitation rate was increased in a sub-population (test 4), there were only 55 runs (out of 500) that could have a biomass in the tenth year equal to the Petersen estimate and not have the exploitation rate exceed one in following years. Variance in the estimates of sub-population R_0 are much smaller from the Individual Petersen method. The estimates of total R_0, from either the Total Petersen

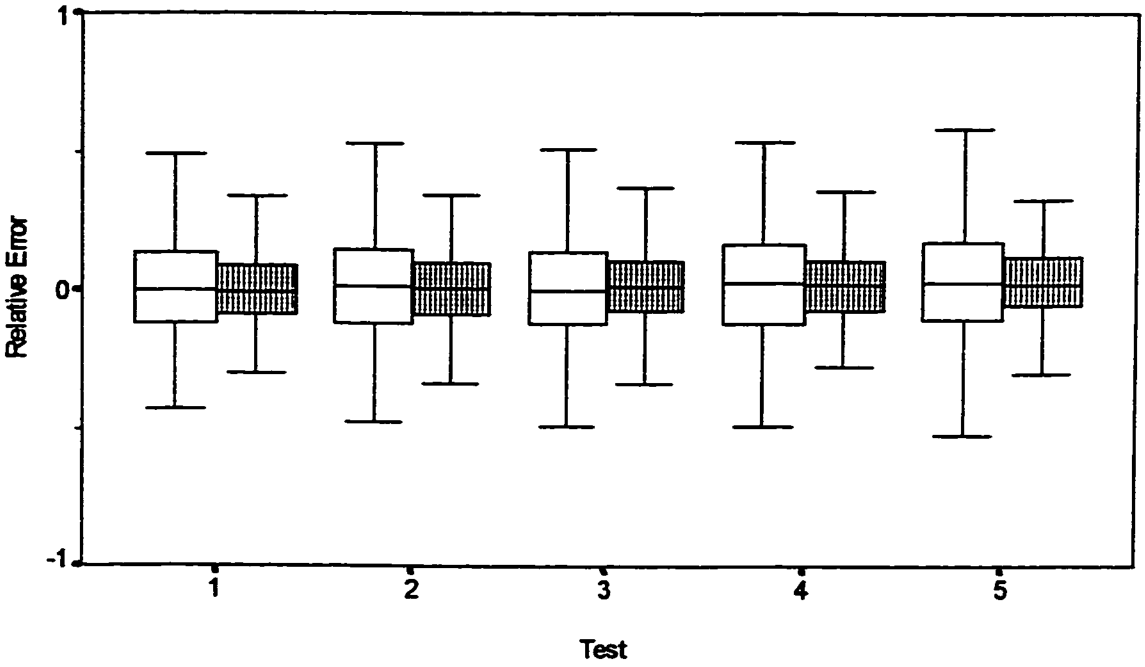

FIGURE 3.4: Relative error in the estimation of total combined current status($[\hat{B}_{cur}/\hat{B}_1 - B_{cur}/B_1]/[B_{cur}/B_1]$), with and without catch-at-age data. The first boxplot in each cluster represent estimates without catch-at-age data and the last boxplot represents estimates with catch-at-age data. Inclusion of catch-at-age data reduces the variance in the estimates.

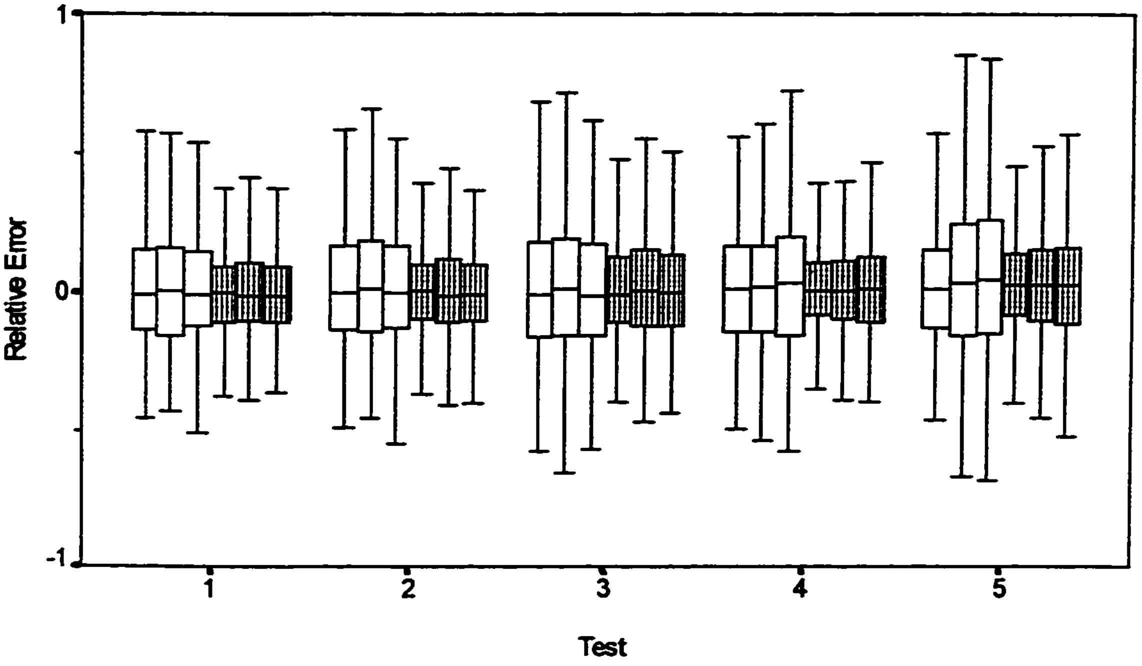

FIGURE 3.5: Relative error in the estimation of individual sub-population current status ($[\hat{B}_{cur} / \hat{B}_1 - B_{cur} / B_1]/[B_{cur} / B_1]$), with and without catch-at-age data. The first three boxplots in each cluster represent estimates for each sub-population without catch-at-age data. The last three boxplots in each cluster represents estimates for sub-populations with catch-at-age data. Inclusion of catch-at-age data reduces the variance in the estimates.

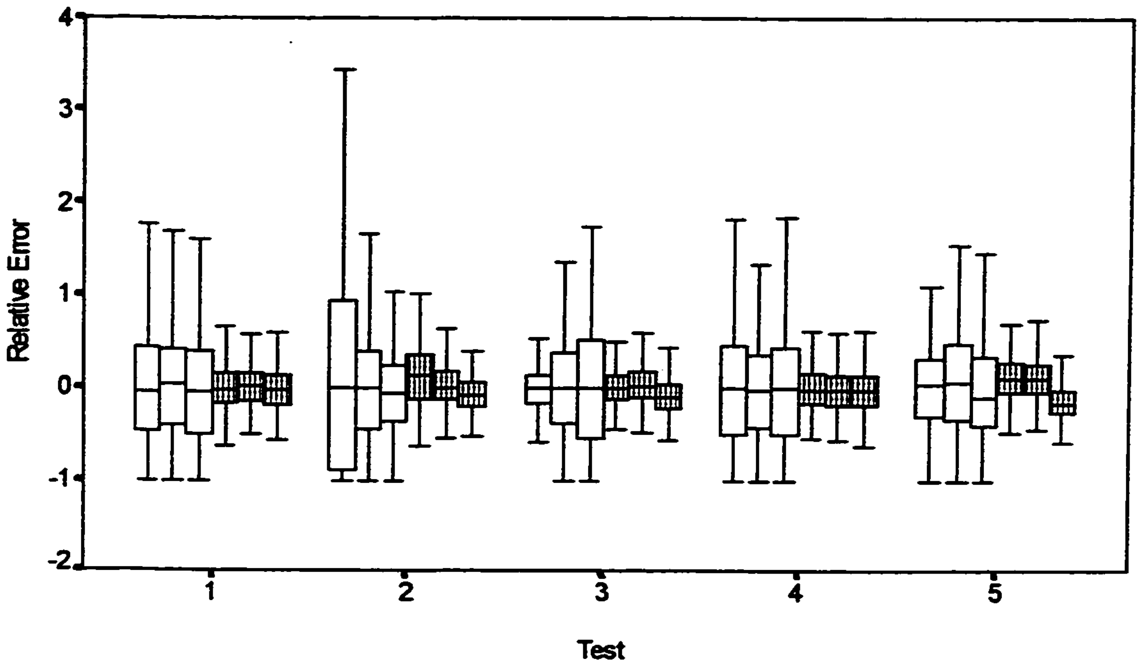

FIGURE 3.6: Relative error in the estimation of individual sub-population virgin recruitment ($[\hat{R}_0 - R_0]/R_o$), with and without catch-at-age data. The first three boxplots in each cluster represent estimates for each sub-population without catch-at-age data. The last three boxplots in each cluster represent estimates for each sub-population with catch-at-age data. Inclusion of catch-at-age data reduces the variance in the estimates.

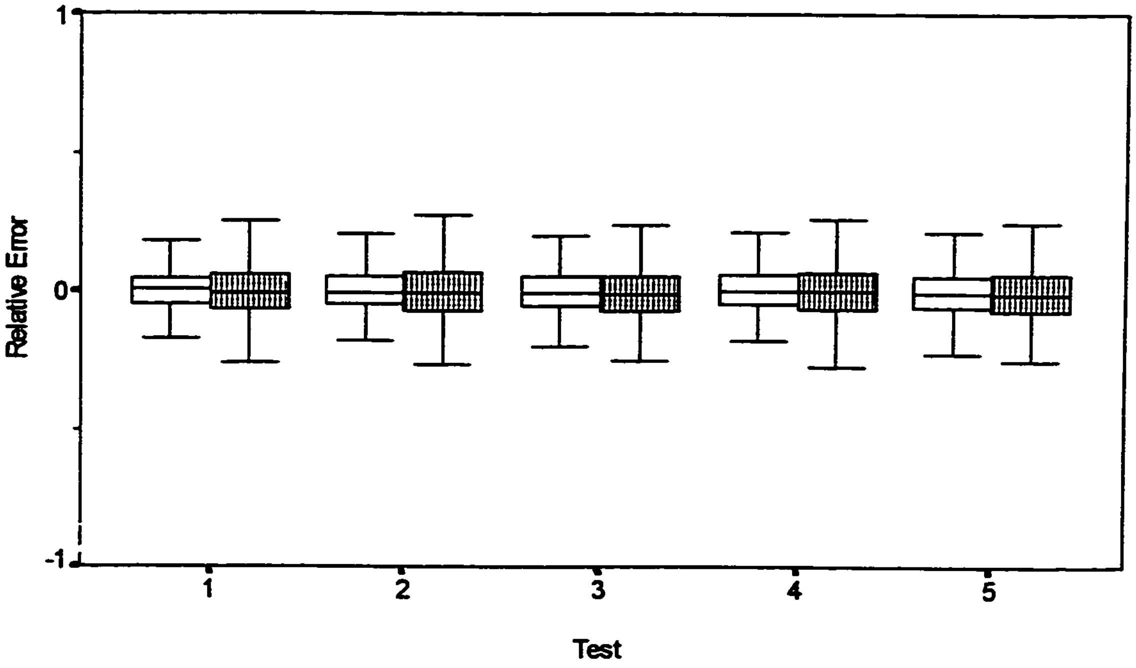

FIGURE 3.7: Relative error in the estimation of total combined virgin recruitment ($[\hat{R}_0 - R_0]/R_o$), with and without catch-at-age data. The first boxplot in each cluster represent estimates without catch-at-age data and the last boxplot represents estimates with catch-at-age data.

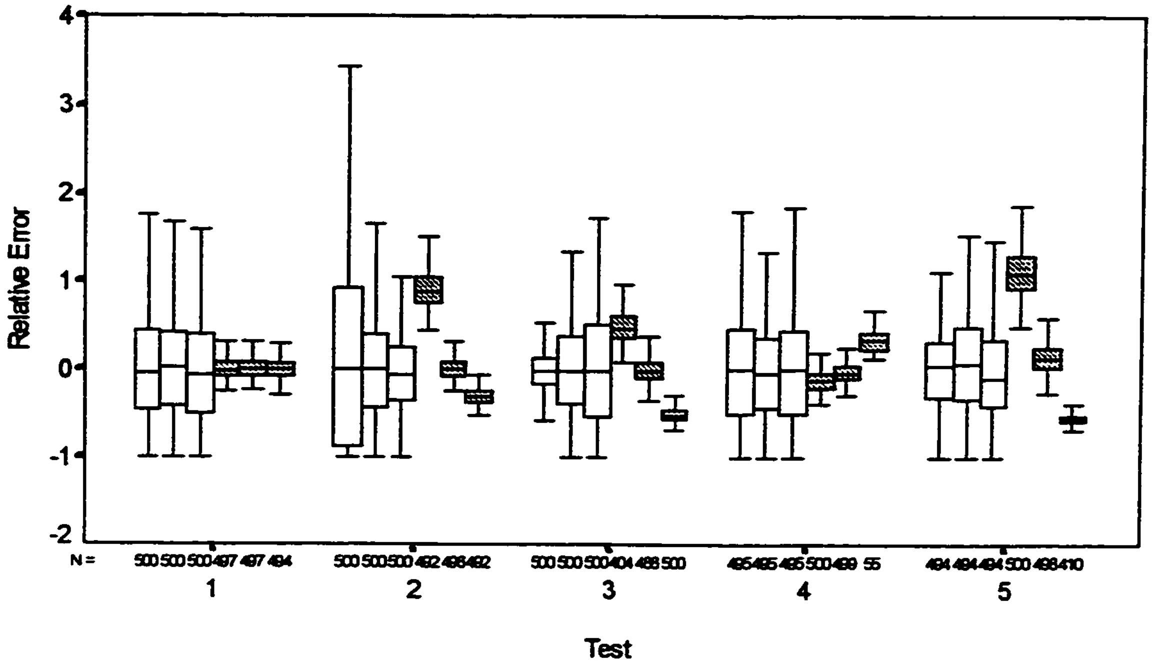

FIGURE 3.8: Comparison of relative error in the estimation of individual sub-population virgin recruitment ($[\hat{R}_0 - R_0]/R_o$), between the Integrated Model and the Individual Petersen model. The first three boxplots in each cluster represent estimates for each sub-population from the Integrated Model. The last three boxplots in each cluster represents the estimates for each sub-population from the Individual Petersen method. The estimates from the Individual Petersen method are biased when there is any difference between the sub-populations.

method or by combining the sub-population estimates from the Individual Petersen method, only show a small bias when there is a difference in exploitation rates (Figure 3.9, tests 4 and 5) and the variances are only slightly higher than the Integrated Model.

The estimates of sub-population B_{cur}/B_I from the Petersen analysis show bias when there are differences in movement or differences in exploitation rates (Figure 3.10, tests 3 and 4). Variance estimates are slightly higher than the Integrated Model. Results for total B_{cur}/B_I are similar to those for R_0 (Figure 3.11).

3.3.5 Movement

Estimates of movement parameters have no bias and small variance (90% interval of the relative error from the simulation tests ranges from –20% to 20%). Addition of catch-at-age data produces a slight bias of around 1% to 2% and reduced variance (90% interval from –15% to 15%).

3.4 Discussion

The results from testing the Integrated Model against artificial data sets indicate that the integrated approach is a promising method to incorporate tagging data into fisheries stock assessments. None of the results showed any bias in the estimation of model parameters (movement and virgin recruitment) or current status under the assumptions set out in the tests. There is very little variance in the estimates of production (virgin recruitment) for the total population, but greater variance in estimates of production for individual sub-populations. The addition of catch-at-age data and estimation of annual recruitment residuals in the ITCAAN model greatly reduces the variance in estimates of virgin recruitment for individual sub-populations. Variance in the estimates of individual sub-population current status (B_{cur}/B_I) are small compared to the variance in estimates of production and this variance can be further reduced with the addition of catch-at-age data in the ITCAAN model. The Integrated Model out performs the traditional Petersen methods in estimating production and current status of individual sub-populations. The better performance is a result of estimating movement between the sub-populations.

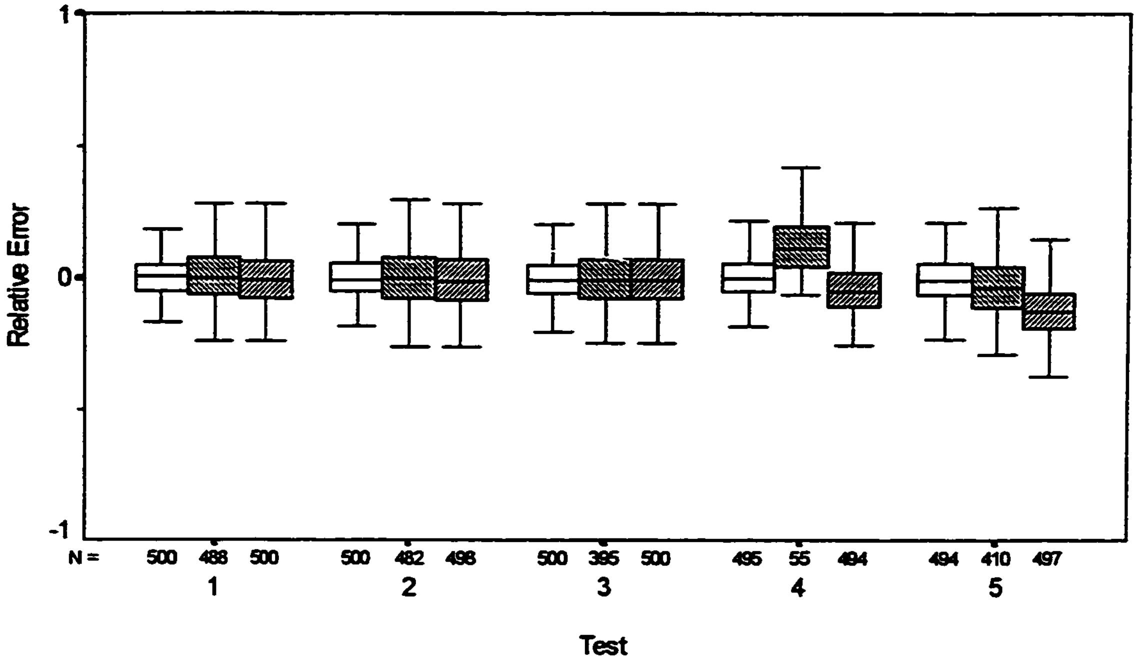

FIGURE 3.9: Comparison of relative error in the estimation of total combined virgin recruitment ($[\hat{R}_0 - R_0]/R_o$), between the integrated model and the Petersen models. The first boxplot in each cluster represent estimates from the integrated model. The second boxplot represents estimates from summing the estimates from sub-populations using the Individual Petersen method. The last boxplot represents estimates from the Total Petersen method.

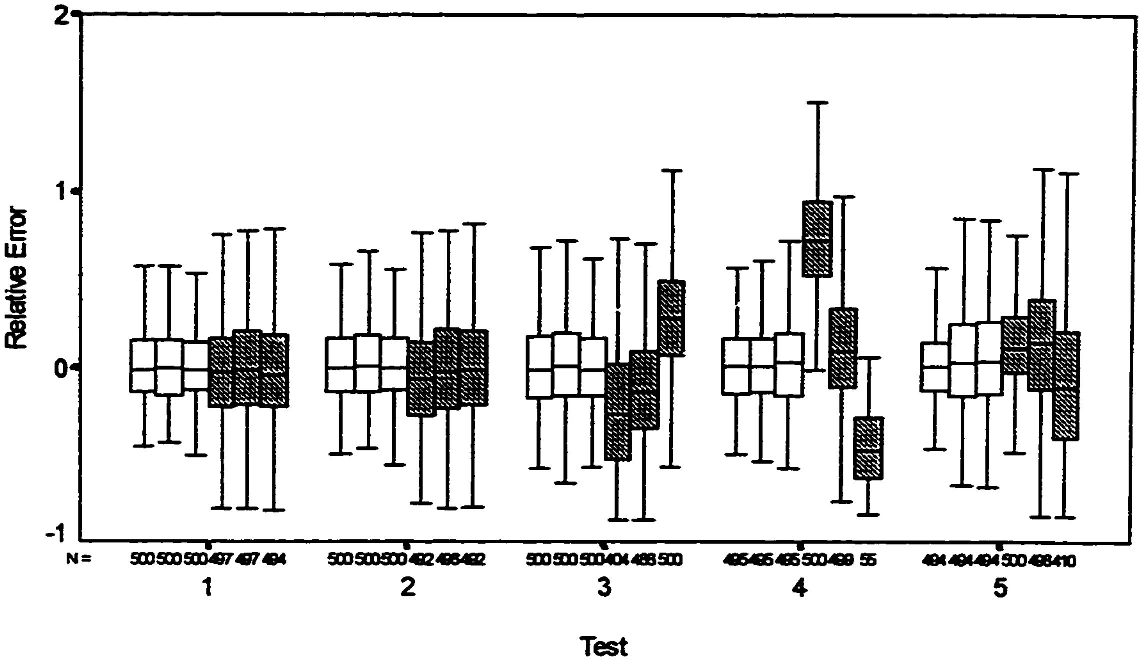

FIGURE 3.10: Comparison of relative error in the estimation of individual sub-population current status ($[\hat{B}_{cur}/\hat{B}_1 - B_{cur}/B_1]/[B_{cur}/B_1]$), between the Integrated Model and the Individual Petersen model. The first three boxplots in each cluster represent estimates for each sub-population from the Integrated Model. The last three boxplots in each cluster represents the estimates for each sub-population from the Individual Petersen method.

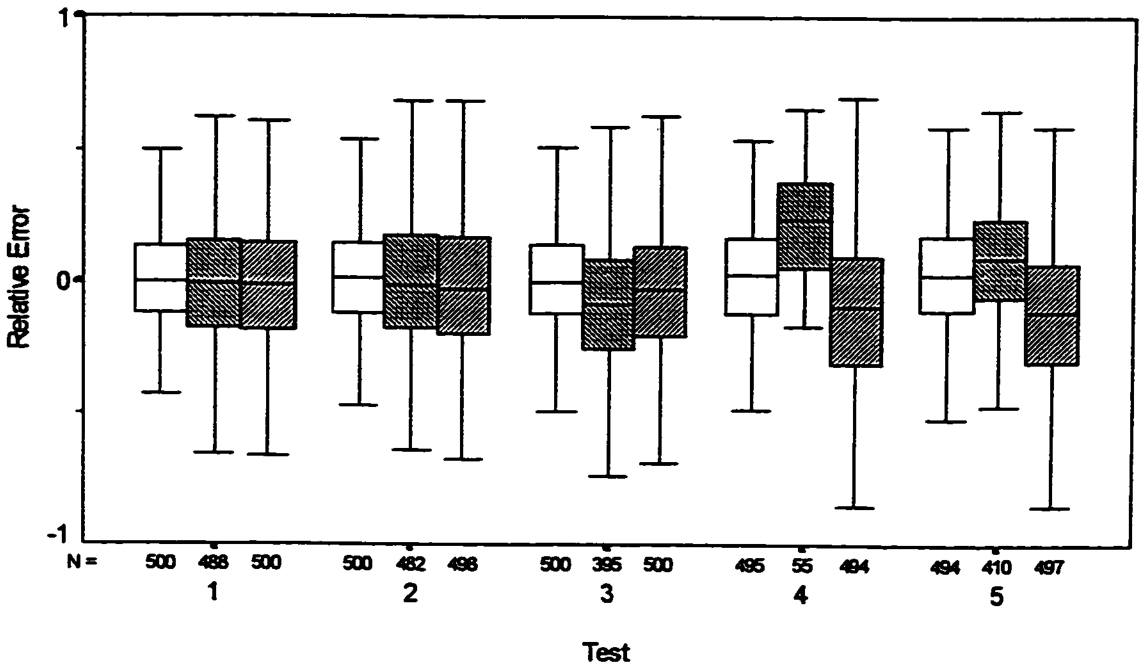

FIGURE 3.11: Comparison of relative error in the estimation of total combined current status ($[\hat{B}_{cur} / \hat{B}_1 - B_{cur} / B_1]/[B_{cur} / B_1]$), between the Integrated Model and the Petersen methods. The first boxplot in each cluster represent estimates from the Integrated Model. The second boxplot represents estimates from summing the estimates from sub-populations using the Individual Petersen method. The last boxplot represents estimates from the Total Petersen method.

Individual estimates of virgin recruitment for each sub-population are very sensitive to small changes in the movement rates. This sensitivity is due to compounding of the movement effect in the equilibrium unexploited population size. The estimates of total recruitment summed over all sub-populations and the individual sub-population virgin population size are much less sensitive to movement, indicating a confounding affect between movement and individual sub-population virgin recruitment. The addition of catch-at-age data and estimation of annual recruitment residuals in the ITCAAN model appears to remove the confounding. This is a promising characteristic and the ITCAAN model may also remove confounding between estimates of recruitment and selectivity. The simplifying assumption that movement rates are constant over age may not be appropriate for many applications and age-dependent movement should be investigated. In many species movement may only occur in a few age-classes, which should be apparent from the tagging data.

Estimates of current status (B_{cur}/B_0) are only moderately variable despite annual variation in recruitment. This leaves little room for catch-at-age data to reduce the variance. Increased recruitment variability or higher dependence of population size on recruitment (i.e., higher natural mortality rates) will increase variability in current status. In these cases the inclusion of catch-at-age data will be more important for reducing variance in estimates of current status. Because recruitment is independent between sub-populations, movement will average out recruitment fluctuations. Real populations may show correlation in annual recruitment strength between sub-populations which could increase variance in estimates of current status.

Estimates of movement parameters have variances comparable to estimates of total combined virgin recruitment. The precise estimation is probably due to the accumulated effect of movement on the unexploited population. Small changes in movement have a large effect on the starting population size of each sub-population.

The results suggest that a tagging study with a single release period and multiple recovery periods may be adequate to assess a recently exploited fishery that is based on interacting sub-populations. The method can be compared to cohort analysis (Pope 1972) with the additional information that the population size and age-structure of the tagged population are known at the time of tagging. For this reason, the Integrated Model should be superior to a simple VPA that uses only catch-at-age data. Any comparisons should consider sample size limitations based on the costs of the tagging study. Additional biases caused by the inherent problems in tagging studies (reporting rates, tag shedding, tagging mortality, etc.) and problems with aging fish also need to be investigated.

Fitting a population dynamics model to biomass estimates from a Petersen analysis produced biased estimates of sub-population productivity and current status in the simulation tests. The biased estimates were caused by interactions between the sub-populations and the lack of movement in the population dynamics model. Stratified-Petersen estimates (Schwarz and Taylor 1998) could be used to incorporate movement, but the integrated approach would be a more flexible framework to use. In the artificial data sets, there was no movement between the release and recapture phases for the Petersen analysis. In a real situation, where there is movement between the sub-populations, the Petersen estimates of biomass would be biased because the assumption of a closed population would be violated. The variance for estimates of individual R_0 were much smaller giving a false sense of security if bias is not taken into account.

The model used to generate the artificial data uses binomial and multinomial distributions to keep recoveries as integers. Hampton (1991b) used a similar technique by modeling the fate of each individual tagged fish. Using real numbers for the recapture data would produce underestimation of the variance in parameter estimates and is not appropriate for the multinomial likelihoods used. Truncation or rounding of the recoveries causes problems because of fractional recoveries in many area/age strata due to low movement rates. Predicted recoveries in many strata will be set to zero even though there is a reasonable probability of at least a single recovery. Increasing the number of releases in the simulation would overcome this problem, but would cause the under estimation of variance compared to a real application. Analyses with truncated and rounded recoveries produced large biases in estimates of sub-population virgin recruitment when there was different movement or exploitation rates between sub-populations. Sibert and Fournier (1991) also found biases when they truncated their recaptures at 0.1.

A main assumption of the likelihood function is that the fate of each tagged animal is independent of other tagged animals (Anganuzzi et al. 1994). Kleiber and Hampton (1994) suggest that likelihoods that assume independence may be inappropriate because tags are not independent due to the schooling behavior of fish. To overcome this schooling effect, a number of studies start recording recoveries after a given time to allow mixing of tags (e.g., Kleiber and Fonteneau 1991). In my analysis, errors introduced into the tag recovery data assumed that fish school by age. Results indicate that there will be no bias in point estimates caused by schooling if there is random fishing on these schools. It is likely that schooling increases the variance of parameter estimates because recoveries will come in groups.

The population dynamics model described in this paper is very simple, but the integrated modeling framework allows for the incorporation of more complex dynamics. The population dynamics model could be extended to include age-specific movement, multiple fishing methods, sub-population specific selectivites, or a different time frame. The framework can also be used with a length-based model, which may be more appropriate because it is difficult (if not impossible) to age releases. The use of the ITCANN model shows that it is easy to incorporate additional data into the likelihood function (i.e., recruitment or relative abundance indices). There is also the possibility to estimate additional parameters (i.e. natural mortality, gear selectivity or stock recruitment steepness) or start from an exploited population size. Data that is usually analyzed separately to produce abundance indicies could be incorporated into the Integrated Model as raw data in a similar fashion to the tagging data.

Chapter 4: Introduction to the SNA1 snapper fishery

The SNA1 snapper stock provides a major inshore fishery off the east coast of the North Island of New Zealand. In this chapter I discuss different aspects of this fisher to provide a background for the application of the Integrated Catch-at-Age Analysis (ITCAAN) to the SNA1 stock that is presented in the next chapter. First I describe the history of New Zealand fisheries management and the current assessment-management system to put the SNA1 snapper assessment in context. Next I describe the SNA1 fishery and the available data. Then I describe the historic assessments used to assess the SNA1 fishery. Finally I discuss the problems with the current assessment.

4.1 History of New Zealand Fisheries Management

The history of New Zealand fisheries science and management has been very influential in producing the relatively highly technical assessments used for the SNA1 stock. The formation of New Zealand's Exclusive Economic Zone (EEZ) in 1978 greatly increased the resource base under New Zealand's control. New Zealand needed to produce resource assessments to successfully manage these stocks. The 1986 introduction of the Quota Management System (QMS) and Individual Transferable Quotas (ITQs) provided the incentive for fishers to protect their resource and become interested in the science and management of their fisheries (see Annala 1996 for a detailed review and discussion of the New Zealand QMS). The QMS is based on an output control of Total Allowable Catch (TAC) and requires quality assessments to determine sustainable yields in absolute terms. Once the TAC has been determined, provisions are made for other interest groups (recreational and customary) and a Total Allowable Commercial Catch (TACC) is determined. Initially each fisher was given a quota of absolute tonnage based on catch history, which required the Government to buy back catch when the TACC was reduced. In 1990 the ITQs were converted into proportional ITQs. In the case of proportional ITQs, each quota holder owns a proportion of the TACC rather than an absolute tonnage. If the TACC is reduced, the fishers absolute tonnage is automatically reduced as well. Quota holders still did not have total security in the ownership of the resource because allowances had to be made for recreational and customary catch. Insecurity about property rights reduces Industries willingness to invest in science and management. In 1992 the Treaty of Waitangi Settlement Act removed that uncertainty about what fishing rights could be claimed by Maori (the pre-European people of New Zealand). The Government gave Maori 50% of the largest fishing company and 20% of all new species brought into the QMS. This agreement prevents any further claims from Maori giving all quota holders much more security in their property right. The only major remaining concern associated with property rights is the increasing pressure by recreational fishers. This is particularly a concern with SNA1 snapper, which has a high level of recreational catch (around 35-40% of the total removals).

Recently there have been changes that have put more emphasis on the payment of research and management by quota holders and consequently the quota holder want to be involved in the research and management. In 1963, the Government formed the New Zealand Fishing Industry Board (NZFIB). This quasi Government organization provides services to the industry and is funded by levies posed on all Industry participants. Services provided by the NZFIB include information gathering and dissemination, marketing, scientific investigation and resource management. A main resource management aspect of the NZFIB is that the Government is required by law to consult them about any proposed management changes. The NZFIB employs in-house scientists who attend all stock assessment working group meetings, run industry organized data collection programs (e.g. Starr and Vignaux 1997), collaborate with Government scientists on assessments (Breen et al 1994), and conduct alternative or additional assessments (e.g. Maunder and Starr 1998). The NZFIB also employs consultants to carryout stock assessments on the major species including SNA1 snapper (e.g. the assessment presented in Chapter 6). The NZFIB (recently renamed the New Zealand Seafood Industry Council, SeaFIC) has funded the research presented in this dissertation including the current assessment of the SNA1 snapper stock presented in Chapter 6.

In 1994 the Government introduced Cost Recovery which required quota holders to pay for a majority of scientific research and management costs. In 1995 the research section of the Ministry of Fisheries and Agriculture that deals with fisheries research (MAFfish) was restructured into a Crown Research Institute (CRI). This restructuring caused the separation of the policy and research branches of fisheries management. The policy group became the Ministry of Fisheries (MoF) and the formation of the CRI was a precursor to the 1997 introduction of Contestable Research. Contestable Research means that the Government owned CRI is not the only organization that can be contracted by the Government to do research. Each year the research projects go up for tender and the best bids get the contracts. In the first year of contestable research, the Industry won a large research contract for rock lobster. This contract included both stock assessment and data collection. Winning the rock lobster contract highlights the quality of the Industries scientific work and the motivation of industry to be involved in science.

4.2 The New Zealand Assessment and Management Process.

New Zealand has a very structured format for translating research into management actions (Annala 1996). The process starts with a series of meetings to review proposed research and to prioritize research. The projects that have been selected are then put up for tender. The tender winners collect data and produce assessments. The assessments are reviewed and developed through a set of working group meetings. The working group meetings are attended by all interest groups including Government policy, commercial, recreational, Maori, and environmental. The final outcome of the working group meetings is a working group report, which is the groups consensus on the status of the stock relative to a set of reference points. No TAC recommendations are made in the working group report. The working group report is then presented at a public Plenary session that is attended by a wider audience. The plenary session agrees on a final revised version of the working group report (e.g. Annala and Sullivan 1998) that is used as the basis for making management decisions. Each interest group uses the plenary report to develop their own position statement that recommends TACC changes. MoF and the Minister hold a number of meetings (TACC Council Meetings) where each interest group presents their position statement and other interest groups are allowed to respond. Through this process MoF also develops a position statement. Finally the Minister makes a decision about TACC changes taking into consideration all aspects concerning the stock.

The process described above is very open (Annala 1996) and has a clear split between scientific research and policy. This openness allows industry and other interest groups to be successfully involved in research and assessment process (Starr et al. 1998). The industry has been involved in the development of assessments for SNA1 (e.g. Maunder and Starr 1998).

4.3 The SNA1 Snapper Fishery

Snapper (*Pagrus auratus*) is one of the most valuable commercial inshore fisheries and the most important recreational finfish in New Zealand (Annala 1995). Its high value to multiple sectors has given SNA1 a high political profile and fueled resources for research. The large amount of data for this fishery and the high involvement of industry has resulted in one of the most complex models used in NZ. A number of documents form the main source of information required to develop assessment models of the SNA1 snapper fishery. Catch statistics, biological information and stock assessment summaries can be found in reports from the annual Fishery Assessment Plenary (e.g. Annala and Sullivan 1998). Details of assessment procedures are reported in the New Zealand Fisheries Assessment Research Document (FARD) series which is internally pair reviewed. Detailed data are published in the New Zealand Fisheries Data Report series (e.g. Davies and Walsh 1995).

New Zealand waters are divided into six areas for the management of snapper. The management area SNA1 on the east coast of the North Island produces the majority of commercial snapper catch (Figure 4.1). The total commercial catch of snapper in the 1996-97 (October 1 1993 to September 31 1994) fishing year was 7,176t with 5,049 t coming from SNA1 (Annala and Sullivan 1998, Table 4.1). SNA1 has been exploited since the mid 1800's with the greatest catches coming from the mid 1960's to the mid 1980's (Gilbert 1994). The quota management system was introduced in 1986, and a TACC 4,710 t was set for SNA1 to allow for stock rebuilding (Annala and Sullivan 1998). Decisions from the Quota Appeal Authority allowed the TACC to increase to

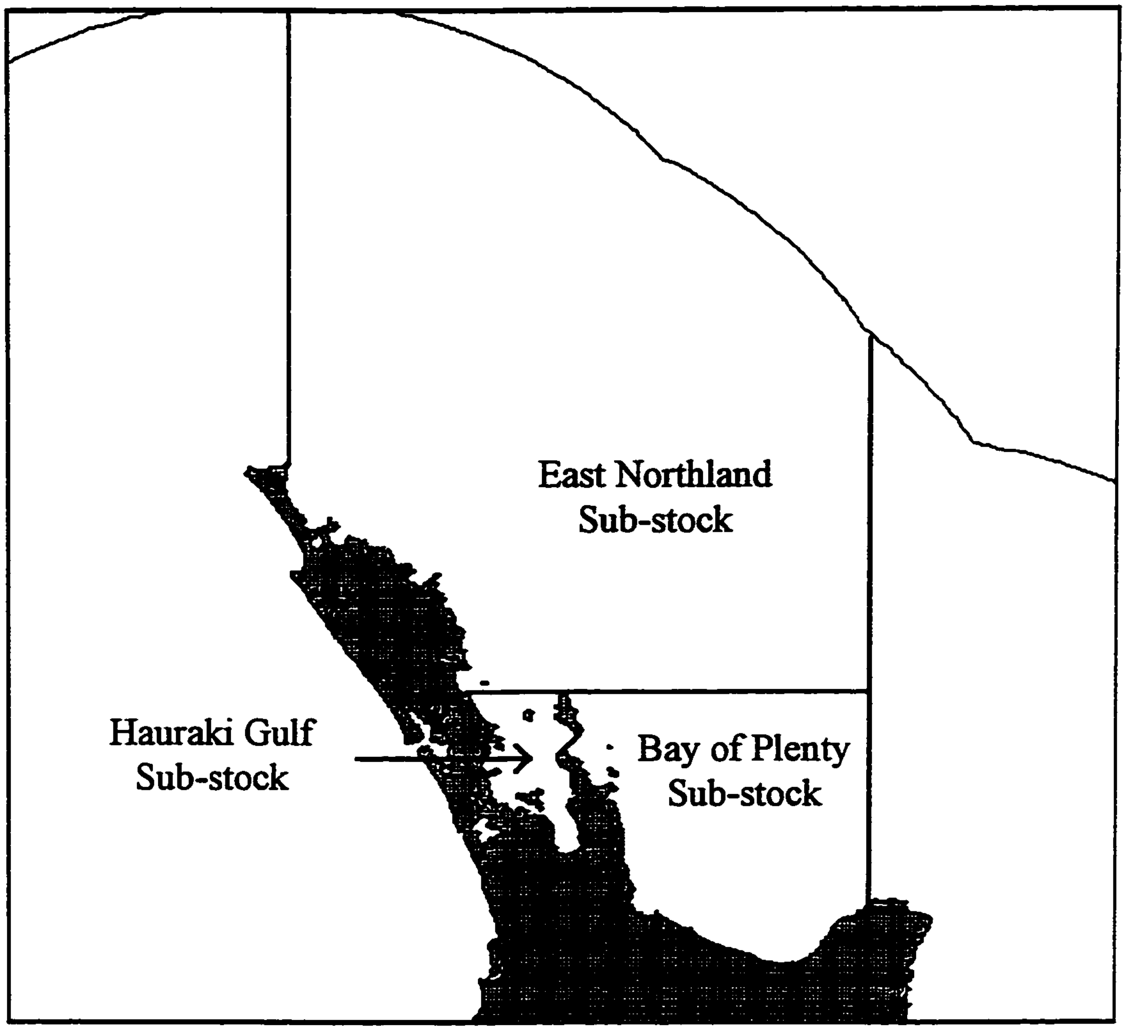

FIGURE 4.1: Map of the SNA1 fishery and its sub-stocks.

6,010 t by the 1991-92 fishing year (Annala and Sullivan 1998). For the 1992-93 fishing year the TACC was reduced to 4,900 t (Annala and Sullivan 1998). The TACC was again cut in both the 1995-96 and 1996-97 fishing years to 3,000 t, but appeals by the commercial interests reversed both these decisions (Annala and Sullivan 1997). In 1997-98 the TACC for SNA 1 was reduced to 4500 t with an overall Total Allowable Catch (TAC) of 7550 t which includes commercial, recreational and customary catch (Annala and Sullivan 1998).

TABLE 4.1: Commercial catch and TACC in SNA1 since the Quota Management System was introduced (Annala and Sullivan 1998).

Fishing Year	Catch (t)	TACC (t)
1986–87	4,016	4,710
1987–88	5,061	5,098
1988–89	5,793	5,614
1989–90	5,826	5,981
1990–91	5,315	6,002
1991–92	6,191	6,010
1992–93	5,423	4,904
1993–94	4,846	4,928
1994–95	4,831	4,938
1995–96	4,941	4,938
1996–97	5,049	4,938
1997-98	N/A	4,500

"The 1987 National Marine Recreational Survey showed that snapper was the most important finfish species sought by recreational fishers" (Annala 1995). In addition to snapper being the most important recreational fish, SNA1 is situated adjacent to Auckland, the largest city in New Zealand. Recent estimates of recreational catch in SNA1 are over half the total SNA1 commercial catch (Annala, 1995). During 1994-95, in an effort to reduce recreational catch, managers reduced the bag limit from 15 to 9 (as of 1 October 1995) and increased the minimum legal size from 25 to 27 cm (as of 1 December 1994, Annala and Sullivan 1997). The commercial minimum legal size has remained at 25cm.

The SNA1 fishery is divided into three sub-stocks for assessment purposes (Figure 4.1) based on biological evidence (movement between sub-stocks and differences in age-structure). The sub-stocks are East Northland (EN), Hauraki Gulf (HG) and Bay of Plenty (BoP). HG is the largest and most researched of the three sub-populations, and contributes most to the overall status of the SNA1 stock. Due to observations of large movements between HG and BoP, current assessments combine the HG and BoP sub-stocks into a single stock (Annala and Sullivan 1998). These current assessments conclude that the HG-BoP stock is below the biomass level that would produce maximum sustainable yield (B_{MSY}), but current removals are probably sustainable. The EN sub-stock is estimated to be above B_{MSY} and will remain above B_{MSY} for the next 20 years under current removals and average conditions (Annala and Sullivan, 1998).

Due to its value to both recreational and commercial sectors the SNA1 fishery has a high political profile (Maunder 1998). There are conflicts between recreational fishers, the commercial sector, environmental groups, charter operators and between sectors of the commercial fishery. One outcome of this political pressure is the emphasis of research into this fishery making it one of the most researched New Zealand fish species.

4.4 Data

4.4.1 Natural mortality

Historically the instantaneous rate of natural mortality was estimated as 0.06 yr^{-1} based on age-structure data collected from a lightly exploited population on the west coast of the North Island (SNA8) in the mid 1970s (Annala and Sullivan 1996). Re-examination of this data increased the estimate to 0.075 (Annala and Sullivan 1997), but this value is very uncertain with indication of age-specific natural mortality rates. Snapper can live up to 60 years or more and they mature at age four in SNA1 (Annala and Sullivan 1996).

4.4.2 Growth

Snapper have a strong seasonal growth pattern with rapid growth during November to May and a slowing or cessation of growth form June to September (Annala and Sullivan 1996). Growth rates vary around New Zealand (Annala and Sullivan 1997) and age-length data suggest that growth rates differ between the three SNA1 sub-stocks (Davies and Walsh 1995).

Growth of the first few cohorts in the fishery has been shown to vary annually (Maunder and Starr 1998). For example, length-at-age data shows that less than half of the 4 year olds in the HG during 1984 exceeded 25cm, but the proportion is much higher in other years (Annala and Sullivan 1997). It is possible that inter-annual variation in water temperature or intra-cohort density dependence causes this variability.

The length weight relationship used in current assessments was derived from a large sample in the early 70s (Paul 1976). Length at age is represented by the von Bertalanffy growth equation with parameters estimated for each of the three sub-stocks.

4.4.3 Movement

Paul (1967), Crossland (1976) and Crossland (1982) described the movement of snapper. During spring snapper congregate in inshore areas before moving offshore to spawn, and during summer there is a movement into bays and harbors. During autumn there is movement into the deep and there is a possibility of movement to other sub-stocks during winter. Historic information has suggested that snapper do not move great distances (Paul 1967, Crossland 1976, Tong 1978, Crossland 1982), but recent tagging studies provide evidence suggesting that there is a large amount of movement between HG and BoP. Over 10% of the recoveries from fish released in HG in 1984 were recovered in BoP (Sullivan et al. 1988). Thirty percent of recoveries from fish tagged in the BoP during 1993 were recovered in the HG (Annala and Sullivan 1997). There appears to be much less movement associated with EN. Crossland (1982) suggests there is movement from HG to EN in Summer and from HG to BoP in Summer and Autumn. There is very little published data on movement into HG due to most of the early tagging studies releasing fish only in HG.

4.4.4 Commercial catch

The SNA1 fishery is one of the oldest in New Zealand and significant catches have been observed since 1850. Commercial catch has been officially reported from 1931 for the total SNA1 stock. Total catch by gear and sub-stock has been recorded since 1984-85 and estimated for earlier years by Gilbert et al (1996). Designation of the sub-stock for the earlier catch is based on port of landing, except for 1960 to 1973 which is based on recorded area fished. Catch prior to 1931 has been assumed (Gilbert 1994).

During the 1960s and 70s there were significant levels of unrecorded catch by Japanese longline vessels. Current assessments assume cumulative removals of 30,000 t between 1960 and 1977 (Annala and Sullivan 1997). This assumed catch increases linearly to a peak of 2202 t in 1968 and then declines linearly to 1978. The catch is split evenly between the combined HG-BoP stock and EN.

Catch-at-age data has been periodically collected since 1989 for all three sub-stocks and the three main gear types. The three main gear types are longline, single trawl and Danish seine (Davies and Walsh 1995). Additional catch-at-age data is available for Danish seine in HG during 1970 to 1973. This 70s data only represents a few trips and is less reliable than the 90s data, which is based on a much larger number of trips.

Selectivity in recent assessments has been estimated from tagging data (Annala and Sullivan1996, Annala and Sullivan 1997). Alternatively, it may be possible to estimate selectivity from catch-at-age data within the assessment model, but recent analyses found selectivity to be confounded with recruitment estimates causing estimation problems (Annala and Sullivan 1997).

4.4.5 Recreational catch

Estimates of recreational catch (t) were calculated from tagging data in the mid 80's and from diary surveys in the mid 90's (Annala and Sullivan 1997, Gilbert et al. 1996, Table 4.2).

TABLE 4.2: Recreational catch estimates for SNA1 by sub-stock (Annala and Sullivan 1997, Gilbert et al. 1996).

Year	HG	BoP	EN
1983		400	
1984	830		370
1993-94	1289	782	751
1996	1471[1]	[1]	581

[1] the 1996 estimate combines HG and BoP sub-stocks

In 1994 there was an increase in the minimum legal size for recreational caught fish from 25cm to 27cm and in 1995 a reduction in the bag limit from 15 to 9. The bag limit was estimated to decrease recreational catch by 8% (Annala and Sullivan 1997).

No other reliable information is available on recreational catch. This lack of information on recreational catch and the large contribution that recreational catch has to the total removals is a major problem in estimating the yields of this fishery from historical data.

4.4.6 Illegal catch

A 20% non-reporting rate has been assumed for reported domestic catch prior to 1986 and 10% since the QMS was introduced in 1986 (Annala and Sullivan 1997).

4.4.7 1983-84 tagging

A tagging study was carried out in the Bay of Plenty sub-stock during 1983-84 (see Hore et al. 1986 for details). A total of 8,452 tagged fish were released by longline and trawl vessels during November and December 1983. A total of 1,058 tags were returned by commercial and recreational fishers during 1984. The non-commercial sector returned 30% of the tag recoveries by weight. A Petersen analysis of the data provided an estimate of 6,600 t for the total exploitable biomass above 25cm in the Bay of Plenty assuming no under reporting of tag recoveries. Sullivan et al. (1988) revised the estimate of fish greater than 45 cm to produce an estimate of 7300 t for the total exploitable biomass. The 1992-93 assessment includes an assumption of 15% for under reporting in the biomass estimates (Gilbert and Sullivan 1994) and the 1998 assessment includes a correction for growth (Annala and Sullivan 1998).

In all previous assessments the biomass estimate from this study has been used as an estimate of the 1985 biomass to allow for the combination of BoP and HG sub-stocks in the assessments.

Unfortunately, the raw data from this tagging program are not available. The only available information is that presented in summary reports. For population modeling purposes, total biomass estimates as presented in published reports have to be used at face value or the data ignored totally.

4.4.8 1984-85 tagging

A tagging study was carried out in the HG and EN sub-stocks during 1984-85 (described in Sullivan et al. 1988). A total of 24,197 (16,002 in HG and 8,195 in EN) tagged fish were released by longline and single trawl vessels using a two stage release design during November and December 1984. Lock-on loop style Floy tags were applied immediately in front of the dorsal fin. Ten percent of the fish were double tagged to determine tag loss. Annual tag loss was around 35% (Gilbert et al. 1996). Unvented snapper (venting is the deflation of a fishes swim bladder using a needle) had lower return rates than vented snapper and trawl released fish had lower return rates than longline released fish (Sullivan et al 1988). Corrections to release numbers for initial tagging mortality were made based on a mortality experiment. Returns were made by commercial and recreational fishers. Under reporting was thought to be in the range of 10-15% (Sullivan et al. 1988). The total exploitable biomass above 25cm in November 1984 was calculated using a Petersen analysis. The estimates are 32,300 and 21,800 t for HG and EN respectively with no allowance for under reporting (Sullivan et al. 1988). The 1992-93 assessment (Gilbert and Sullivan 1994) included an assumption of 15% for under reporting in the biomass estimates and the 1998 assessment includes a correction for growth (Annala and Sullivan 1998).

4.4.9 1993-94 tagging

A comprehensive tagging study was carried out in all three SNA1 sub-stocks during 1993-94 (see Annala 1995 and Gilbert et al. 1996 for details). In the last quarter of 1993, a total of 30,477 fish were tagged using trawl and longline throughout SNA1. Fish were tagged with an internal binary coded wire and tag recoveries were made at commercial fish sheds by research staff. Recoveries were taken from February 1994 to February 1995 with a total of 1300 t of commercial catch examined for tags. The length and age of the fish was recorded for each tag recovered. Only the main commercial methods from each sub-stock were sampled (HG - trawl, Danish seine, longline; BoP - trawl, Danish seine, longline; EN - longline). Releases were corrected for initial tagging mortality obtained from analyzing mortality experiments from the 1992 west coast tagging program and additional experiments carried out for this program. Tag loss was assumed to be small (0.02) but could not be estimated from double tagging experiments because of detection problems of multiple tags when collecting samples (Gilbert et al. 1996). Seeding experiments produced an estimate of 0.851 for the mean probability of miss-detecting tags by the electronic scanning equipment (Gilbert et al. 1996).

Estimates of biomass from the 1993-94 tagging program have varied from assessment to assessment depending on the assumptions made about which gears to include in the analysis and which estimation procedure is used. The variation in assumptions is caused by discrepancies in tag recovery rates between the different gears. Gilbert et al. (1996) gave ranges of 23,501-30,341, 7,897-8,284 and 13,817-15,022 t for HG, BoP and EN respectively.

4.4.10 Recruitment index

Water temperature plays an important role in the success of recruitment each year with warm years producing strong cohorts (Paul 1976). Abundance estimates of age 1+

snapper in the Hauraki Gulf trawl surveys have a positive relationship with sea surface temperatures from the Leigh Marine Laboratory (Francis 1993, Francis et al. 1997). The correlation has been extended to include air temperatures recorded at Albert Park and Owairaka (Gilbert 1994). Catch-at-age analysis has shown that the relationship carries through to recruitment into the fishery at around age 4 (Maunder and Starr 1998). This temperature recruitment correlation has been used to generate an index of relative recruitment strength for input into stock assessment models (Gilbert 1994, Gilbert and Sullivan 1994). The use of this temperature recruitment correlation has highlighted a number of problems in the SNA1 assessment as summarized by Maunder (1998).

Catch-at-age data show similar relative recruitment strength between HG and BoP (Davies and Walsh 1995). Relative recruitment indicated in catch-at-age data show some differences between HG and EN (Davies and Walsh 1995). Notably the 1982 and 1986 year classes appear strong in EN but not in HG (Davies and Walsh 1995).

4.5 Historic assessments

There have been four recent assessments of the SNA1 fishery based on age-structured models (Maunder 1998, see below). Models one and two were presented by Government scientists and incorporate a recruitment index derived from pre-recruit trawl surveys and a temperature relationship. The third model was presented by industry scientists (New Zealand Fishing Industry Board) and uses catch-at-age data rather than the recruitment index. The forth model combines the long term (model 1) and catch-at-age (model 3) models and has been developed form collaboration between Government and industry scientists.

The four models can be briefly summarized as follows:

1. Total catch history model (Gilbert 1994). This model projects the fishery from its virgin state in 1850 using the total exploitation history of the fishery. Annual recruitment strengths are determined by the temperature recruitment relationship

and an average recruitment parameter is estimated to determine absolute recruitment. All other model parameters are assumed known.

2. 1985-94 model (Gilbert & Sullivan 1994). This model projects the fishery from a fixed population size and age structure in 1985 based on tagging data. Annual recruitment strengths are determined by the temperature recruitment relationship and an average recruitment parameter is estimated to determine absolute recruitment. All other model parameters are assumed known.

3. Catch-at-age model (Maunder and Starr 1998). This model is similar to the 1985-94 model (2) except that it uses catch-at-age data to estimate recruitment and a limited number of selectivity parameters.

4. Long term catch-at-age model (reported in Annala and Sullivan 1997). This model projects the fishery from its virgin state in 1850 using the total exploitation history of the fishery. Catch-at-age data is used to estimate recruitment and/or selectivity parameters.

The current assessment (reported in Annala and Sullivan 1998 and described in Chapter 6) uses the mid-term model suggested by Maunder (1998). This model is similar to the long-term catch-at-age model (4), except that it starts at an exploited population size in 1970. This mid-term model overcomes some of the problems associated with making assumptions about historic recruitment.

The historical assessments of SNA1 have been based on two biomass estimates; one estimates biomass in 1985 and the other in 1994. The biomass estimates are calculated from tagging data, and the tagging data is analyzed independently from the population dynamics model that is used in the stock assessments. These biomass estimates have been calculated using a length stratified Petersen method (Gilbert et al. 1996). More recently an observation error estimator (Gilbert et al. 1996) based on the method of Hilborn (1990) has been used as an alternative to the Petersen analysis. This method simulates the tagged population over time. The observation error estimator is very flexible and has been used to incorporate movement and stochastic seasonal growth.

4.6 Problems with the assessment

Historical assessments of the SNA1 snapper stock have had four major problems associated with the tagging data; 1) discrepancies in return rates, 2) the failure to incorporate growth between release and recapture, 3) ignoring movement between sub-stocks and 4) estimation of selectivity. In addition to the problems with the tagging data there are problems associated with assumptions of historic recruitment.

4.6.1 Discrepancies in return rates

The recovery rates for each growth adjusted length strata (tags recovered per tonne of fish sampled) declined over time for Danish seine recoveries in HG from the 1993-94 tagging program (Gilbert et al 1996). The recovery rates for Danish seine are also much higher than for the other gears. It is possible that this effect could be due to the nature of the Danish seine method and clumping of tags in schools. Because of this discrepancy the Danish seine and single trawl recaptures were removed from the HG base case estimate presented in Gilbert at al. (1996). Gilbert et al. included all methods in a sensitivity analysis giving a HG biomass estimate 22% less than when using longline recaptures only. Longline recoveries showed higher recovery rates of trawl released fish than of longline released fish (Annala and Sullivan 1997). Hook shyness has been suggested as a hypothesis to describe this difference in recovery rates (pers com. J. McKenzie, National Institute of Water and Atmospheric Research, Auckland, New Zealand). In the 1997 analysis (Annala and Sullivan 1997) two sets of data were used; 1) longline releases only and all gear recoveries and 2) all releases and all recoveries for BoP and EN, and all releases and only longline recoveries for HG.

Recovery rates also differed between methods for the 1984-85 program (Gilbert et al 1996). As with the 1993-94 program, longline recoveries showed higher recovery rates of trawl released fish than of longline released fish (pers com. J. Mckenzie, National Institute of Water and Atmospheric Research, Wellington, New Zealand). In addition there is a seasonal difference in the recovery rates (Gilbert et al 1996). Because of these problems, the working group agreed that the 1984-85 program was not as reliable as the 1993-94 program and assigned it a cv of 0.3 compared to the cv of 0.2 for the 1993-94 program (Annala and Sullivan 1998). The cv estimates calculated using Seber's variance equation and a Monte Carlo procedure (Gilbert et al. 1996) are thought to be biased low and the cvs presented above have been arbitrarily increased to reflect the scientists perception of the error in the biomass estimates.

4.6.2 Growth between release and recovery

The stratified Petersen estimation method stratifies the releases and recoveries into length classes (Gilbert et al. 1996). Each length class is used separately to estimate the biomass in that length class. This method ignores the possibility for growth into or out of a length class occurring between the time of recapture and the time of release. For the 1984-85 tagging program each tag recapture can be associated with its release length, therefore growth is only a problem with the length structure of the total fish sampled for tags. Because of the inability to uniquely identify each fish with its release details, the 1993-94 tagging program has the additional problem of growth of recaptured fish. It is possible to convert recapture lengths into release lengths using a growth curve overcoming the problem of growth into and out of different strata (Gilbert et al. 1996). Growth for snapper is very seasonal and can have high inter-annual variation. This makes it difficult to incorporate growth into the tagging analysis. Growth is the highest for young individuals. This high growth rate of young individuals can cause a large number of fish that were not included in the smallest length class at tagging to be represented in that length class at recovery. This growth would cause the number of fish in the smallest length class sampled for tags to be over estimated resulting in a positive bias in the biomass estimate. Gilbert et al. (1996) present a simulation tagging model that incorporates the effect of growth. They showed that there was around a 20% overestimation of biomass for the growth rates investigated.

4.6.3 Movement between sub-stocks

As mentioned earlier, there is evidence for significant movement between HG and BoP sub-stocks. For this reason, HG and BoP have been combined in the current tagging biomass estimates and stock assessment models (Annala and Sullivan 1998). There is also evidence for a smaller amount of movement between EN and the other two sub-stocks. It is unknown what effect this movement has on the assessment of the SNA1 fishery. Movement between sub-stocks violates one of the assumptions of the Petersen method. Gilbert et al. (1996) presented biomass estimates based on a Petersen type analysis that incorporated movement between sub-stocks. The results from the movement analysis were the same as the no movement analysis for HG, and only 7% lower for EN and 5% higher for BoP. There has been no analysis to determine the effect of movement in the population dynamics model on the estimates of current status and yield.

4.6.4 Estimation of selectivity

Despite the large amount of catch-at-age data, estimation of selectivity has been difficult. The Maunder and Starr (1998) model was the first method used to estimate selectivity for the SNA1 assessment. They limited their estimates to the annual selectivity of age 4 and 5 year olds, which varies greatly from year to year. Other efforts have been taken to estimate selectivity, but in all cases is has been impossible to estimate selectivity curves for the three main gears and recruitment at the same time (Annala and Sullivan 1997). Therefore, selectivity has been estimated independently from the tagging program data. There is a discrepancy between the estimated selectivity from the 1984-85 and 1993-94 tagging programs. In the current assessment the estimates from the two tagging programs have been cobbled together into a single estimate of selectivity (Annala and Sullivan 1998).

4.6.5 Historic Recruitment

Recruitment in the HG has been related to water temperature and this relationship has been used to predict historical recruitment used in stock assessments. Total catch-history models have used this relationship to determine recruitment levels as far back as 1910 (Gilbert 1994). The use of the temperature-recruitment index has caused two main problems in the assessments (Maunder 1998); 1) assumptions about historic levels of recruitment have a large influence on the estimates of the current status of the population (Gilbert 1994), 2) assumptions about the period of historic recruitment used to calculate future recruitment influence yield calculations. The temperature-recruitment relationship is calculated only over a short period starting in 1993, but the relationship is applied to water temperatures since 1967 and air temperatures since 1910. To further complicate the situation, in the series of air temperatures used in estimating recruitment there is a positive trend over time and in the series of water temperatures used in estimating recruitment there is a negative trend over time. Given these problems, it is undesirable to use a total catch history model that starts in 1850 as has been used in previous assessments (Gilbert 1994). On the other hand, short term models (Gilbert and Sullivan 1994; Maunder and Starr 1998) produce results that have such high variance they are of little use to policy makers (Maunder 1998). Maunder (1998) suggests that a mid-term model may be the best choice.

Chapter 5: Application of the Integrated Model to the SNA1 snapper stock

5.1 Introduction

This chapter applies the Integrated Tagging and Catch-at-Age Analysis (ITCAAN) the SNA1 stock. The SNA1 snapper stock provides a major inshore fishery off the east coast of the North Island of New Zealand. Historically the SNA1 snapper stock has been assessed using a two step procedure. 1) abundance estimates are derived using tagging data and then 2) a population dynamics model is fit to the abundance estimates. The two step procedure permits inconsistencies in model structure and parameter values between the different analyses used in each of the steps. The Integrated Modeling approach is applied to the SNA1 stock in order to eliminate these inconsistencies and include all the information from the tagging data in the population model fitting process. In addition to the integration of tagging data with the population dynamics model, movement between the three SNA1 sub-stocks is modeled.

The main differences from previous assessments (summarized in Maunder 1998, see Chapter 4) and the model developed here have been included to address some of the problems associated with previous assessments and are listed below:

1) Integration of tagging data with the population dynamics model. This allows the inclusion all the information from the tagging data in the population model fitting process and may help overcome confounding between selectivity and recruitment and some of the discrepancies in tag return rates.
2) Starting from an exploited population in 1970. This removes the assumptions about historic recruitment and catch.
3) Modeling the interactions between the three sub-populations. This directly addresses the movement between sub-stocks that is observed in the tagging data.
4) Seasonal time structure. Allows for the incorporation of seasonal data and estimation of seasonal movement parameters.

5.2 Model structure

The model developed in this chapter is based on the ITCAAN Integrated Model presented in Chapter 2, but is much more complex. The model in Chapter 2 is modified to include the five different gear groupings used in the SNA1 fishery, namely the longline, single trawl, Danish seine, other commercial, and recreational gear types. The group "other commercial" is made up from many different gears that only have a small contribution to the total catch. The exception is pair trawl, which has had large catches in some years, but there is no catch-at-age data or data from the 1993-94 tagging program for this method. Another modification to the model is the inclusion of a quarterly seasonal-time-structure. This seasonal time structure allows for the inclusion of seasonal tag recoveries and seasonal catch-at-age data.

5.2.1 Starting from an exploited population in 1970

The starting point of 1970 is chosen to avoid or reduce assumptions about Japanese catch, recruitment fluctuations based on air temperatures, and regime shifts associated with a total catch-history model starting in 1950 (Maunder 1998). This starting point is also used in the current assessment (Annala and Sullivan 1998, see Chapter 6). Starting the modeling from an exploited population results in additional parameters to be estimated. These parameters describe the population size and age-structure in 1970. Total catch history models (Gilbert 1994) allow the assumption of unexploited equilibrium conditions to start the model. There is no direct data for the 1970 age-structure so numbers at age must be estimated. There is also very little data to estimate the age-structure so some simplifying assumptions have to be made. For this model, the starting biomass and age-structure are assumed to be in equilibrium with constant recruitment and a constant exploitation rate estimated for each sub-stock. Only one extra parameter, the initial fishing mortality rate, needs to be estimated for each sub-stock. By estimating these extra parameters rather than starting from an unexploited population level, uncertainty in historical recruitment is included in the estimation process rather than making assumptions about historical recruitment. Previous sensitivity analysis show that the population size in 1970 relative to its virgin state is the important factor in determining the outcome of the assessment rather than the fine detail of the age structure.

This is because individuals from the initial population in 1970 will have grown into the plus group by the mid 1980s when the first major set of data is used. Therefore, the simplifying assumption of equilibrium conditions under a constant fishing mortality rate should not have a large influence on the results.

5.2.2 Modeling the interaction between sub-stocks

An additional complexity included in the model is the simultaneous modeling of the three interconnected sub-stocks, Hauraki Gulf (HG), Bay of Plenty (BoP) and East Northland (EN). These sub-stocks are allowed to interact and the tagging data provides information on movement rates.

Many reports have suggested that there is very little movement of snapper between sub-stocks. Crossland (1982) cited Paul (1967), Crossland (1976) and Tong (1978) as reporting "that generally snapper do not move long distances". This conclusion has come from tag releases in HG. But, the two most recent tagging studies suggest that there is significant exchange between HG and BoP and for this reason HG and BoP are combined into one stock in recent assessments (Annala and Sullivan 1997). The 1984-85 tagging program suggests that there is significant movement from HG to BoP (Table 5.1). Unfortunately the raw data from the 1983-84 BoP tagging program is unavailable to determine movement from BoP to HG. There is some movement from HG to EN, but only a small amount of movement from EN to the other two sub-stocks. The 1993-94 tagging program gives similar results (Table 5.2) and also suggests significant movement from BoP to HG.

TABLE 5.1: Indication of movement rates from the 1984-85 tagging program based on relative tags per tonne for each release-recapture stratification. For example, the estimate of movement rate from HG to BoP is calculated as the ratio of tags per tonne of HG released tags caught in BoP to the tags per tonne of HG released tags caught in HG.

		Sub-stock of release	
		HG	EN
Sub-stock	HG	0.65	0.03
of	BoP	0.28	0.04
Recapture	EN	0.08	0.93

TABLE 5.2: Indication of movement rates from the 1993-94 tagging program based on relative tags per tonne for each release-recapture stratification. For example, the estimate of movement rate from HG to BoP is calculated as the ratio of tags per tonne of HG released tags caught in BoP to the tags per tonne of HG released tags caught in HG.

		Sub-stock of Release		
		HG	BoP	EN
Sub-Stock	HG	0.69	0.12	0.03
of	BoP	0.18	0.86	0.08
recapture	EN	0.12	0.02	0.89

Crossland (1982) suggests that movement from HG to EN occurs in Summer and movement from HG to BoP occurs during Summer and Autumn. There is very little earlier work on movement into the HG since most tagging studies only released tags in HG. During autumn there is movement into deeper water and a possible movement to other sub-stocks during winter (Paul 1967, Crossland 1976, Crossland 1982). It is possible that Movement from BoP to HG and EN to HG occurs during winter.

Relative tag return data indicates that movement is age dependent. Movement from HG to BoP appears to decrease with age and movement from BoP to HG appears to increase with age (Figure 5.1). The relatively low levels of movement associated with the EN sub-stock generate insufficient data to provide information on age dependent movement. These results indicate that the age-specific component should be incorporated into models of SNA1 that include movement between the sub-stocks.

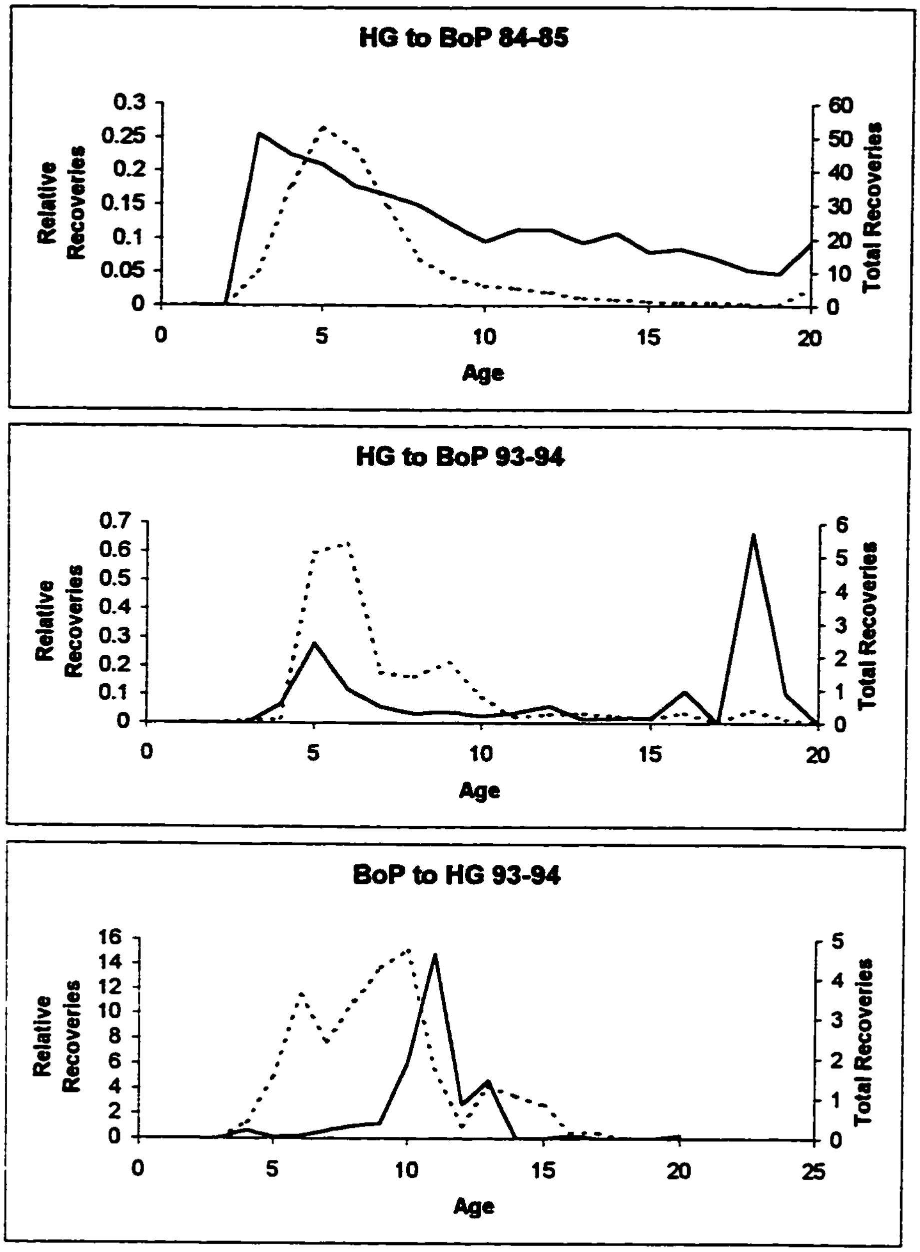

FIGURE 5.1: Ratios of recoveries to releases by age. Top panel. The solid line represents the ratio of recoveries caught in BoP to those caught in HG from releases in HG during the 1984-85 tagging program. The dashed line represents the total number of recoveries caught in BoP from releases in HG. Middle panel. The solid line represents the ratio of recoveries caught in BoP to those caught in HG from releases in HG during the 1993-94 tagging program. The dashed line represents the total number of recoveries caught in BoP from releases in HG. Bottom panel. The solid line represents the ratio of recoveries caught in HG those caught in BoP from the releases in BoP during the 1993-94 tagging program. The dashed line represents the total number of recoveries caught in HG from the releases in BoP. There is no correction of the age at recovery for the year of recovery.

Movement in the model is simplified by assuming that it occurs as a discrete event at the start of the season and there is no movement out of the SNA1 area (i.e. SNA1 is a closed population, see Chapter 2 for a description of this approach). The model assumes that there is no movement directly between BoP and EN, and all individuals moving between these two sub-stocks have to reside in HG for at least one season.

Movement is assumed to be seasonal and the distribution of movement over the four seasons is modeled using a normal distribution. This allows movement to peak in a particular season, but also occur in other seasons based on the information in the data. The normal distribution is described by three parameters; 1) total movement, 2) mean season of movement and 3) standard deviation of movement. Movement is calculated for each season and then normalized so it sums to one. These values are then multiplied by the total movement for the year. This is repeated for movement between each of the sub-stocks. The equation for seasonal movement without subscripting for area (for clarity) is given below. The maximum is taken of three normal distributions to avoid differences in how movement is calculated for the first and last seasons.

$$m_s = \max\left[\exp\left(\frac{(s-\mu)^2}{2\sigma^2}\right), \exp\left(\frac{(s-\mu-4)^2}{2\sigma^2}\right), \exp\left(\frac{(s-\mu+4)^2}{2\sigma^2}\right)\right]$$

where:

m_s is the proportion of the total annual movement that occurs in season s

s is the season. 1 = summer, 2 = autumn, 3 = winter, 4 = spring.

μ is the mean season of movement

σ is the standard deviation for the season of movement

Movement is assumed to occur only in individuals 3 years and older. Younger individuals are assumed to be resident in their sub-stock of birth. Movement from HG to BoP and from BoP to HG are assumed to follow a logistic relationship, with HG to BoP decreasing with age and BoP to HG increasing with age. Movement from EN to HG and

HG to EN is assumed to be constant with age. The logistic curves are parameterized with 2 parameters, 1) the age at 50% of full movement and 2) the age at 95% of full movement. The equation for age-specific movement without subscripting for area (for clarity) is given below.

$$m_a = m_{full}\left[1+\exp\left(-\ln(19)\frac{a-a_{50}}{a_{95}-a_{50}}\right)\right]^{-1}$$

m_a is the movement at age a
m_{full} is the full movement for the season and sub-stocks of interest
a_{50} is the age at 50% movement
a_{95} is the age at 95% movement

5.2.3 Seasonal time structure

The model is based on a four season time structure, which differs from the usual annual time step. Modeling seasons allows for the incorporation of seasonal movement, seasonal growth and seasonal fishing. Previous assessment models have been based on an annual time structure (Gilbert 1994, Gilbert and Sullivan 1994, Maunder and Starr 1998). The observation error simulation tagging model, initially developed for snapper by Ray Hilborn (pers. comm. School of Fisheries, University of Washington, Seattle, USA) and extended by a number of researches, used a monthly time structure and the current version incorporates a seasonal growth function (Gilbert et al 1996). The seasons used in the Integrated Model are summer (December-February), autumn (March-May), winter (June-August), spring (September to November), as given by Davies and Walsh (1995).

Summer is chosen as the first season as it is when spawning occurs. Spawning extends form September to March and peaks from November to January (Francis 1994). Initiation and cessation of spawning varies annually and appears to be related to water temperature

(Scott and Pankhurst 1992). Inter-annual variation in the duration of spawning is not implemented in the model.

5.2.4 Selectivity

Selectivity for the three commercial gears associated with catch-at-age data (longline, single trawl, and Danish seine) is modeled using a double normal, which allows for a domed shaped selectivity curve. The double normal includes three parameters, a common mean, variance for the left hand limb, and a variance for the right hand limb. The variance parameters for each gear are common between sub-stocks, but a separate mean is used for each sub-stock and gear combination. This parameterization allows the shape of the selectivity curve to be similar between sub-stocks for each gear, but can be shifted to the left or right in each sub-stock. All other commercial fishing gears are grouped into a single category. Selectivity for the other commercial fishing gears and the recreational fishery are fixed based on data from the 1984-85 tagging program (Gilbert and Sullivan 1994, Table 5.3).

$$v_{a,l}^{m} = \begin{cases} \exp\left\{ \dfrac{-\left(a - a_{\mathrm{full}}{}_{\mathrm{l}}^{\mathrm{m}}\right)^2}{v_L^m} \right\} & \text{for} \quad a \le a_{\mathrm{full}}{}_{\mathrm{l}}^{\mathrm{m}} \\ \exp\left\{ \dfrac{-\left(a - a_{\mathrm{full}}{}_{\mathrm{l}}^{\mathrm{m}}\right)^2}{v_R^m} \right\} & \text{for} \quad a > a_{\mathrm{full}}{}_{\mathrm{l}}^{\mathrm{m}} \end{cases}$$

$v_{a,l}^{m}$ is the age-specific selectivity for age a in location l by method m.

TABLE 5.3: Selectivity for other commercial and recreational gears.

Age	Other Commercial	Recreational	Age	Other Commercial	Recreational
1	0.000	0.000	11	0.846	0.864
2	0.000	0.000	12	0.685	0.892
3	0.010	0.000	13	0.471	0.628
4	0.408	0.577	14	0.525	0.636
5	0.979	1.141	15	0.553	0.621
6	1.058	1.108	16	0.453	0.516
7	1.126	1.107	17	0.594	0.649
8	1.000	1.000	18	0.788	0.708
9	0.752	0.910	19	0.639	0.587
10	0.781	0.871	20	0.415	0.596

5.2.5 Recruitment

Recruitment in HG, measured by a pre-recruit trawl survey in the HG, has been correlated with sea surface temperature (Francis 1993). The temperature recruitment relationship has been developed (Francis 1993) and validated (Maunder and Starr 1998) for the HG stock only. The temperatures used to generate the relationship have been recorded at Leigh in the HG, which is close to the HG-EN border. It is possible that recruitment in EN and BoP is also correlated with sea surface temperature. Catch-at-age data support a correlation between HG and BoP recruitment (Davies and Walsh 1995). There are only 4 sets of catch-at-age data for EN, which prevents the estimation of individual annual recruitment strengths in combination with selectivity and movement for this sub-stock. It is therefore assumed that the temperature-recruitment relationship also holds for BoP and EN.

The regression developed by Francis (1993) does not use all the information available for recruitment estimates. Catch-at-age data also provides information on year class strength (Maunder and Starr 1998). By estimating the parameters of the temperature recruitment relationship inside the population dynamics model while fitting to the pre-recruit trawl survey data and the catch-at-age data, all the information on annual recruitment strength can be included in the parameters of the temperature-recruitment relationship. The temperature-recruitment relationship is used to model annual recruitment fluctuations around the mean recruitment (represented by virgin recruitment R_0).

The form of the temperature recruitment-relationship follows the original regression model of Francis (1993):

$$r_y = \exp\ (\alpha + \beta T_{y-1})$$

T_y is the average Leigh SST for the period February to June in year y (Table 5.4)
r_t is the relative year class strength for fish of age one in year y

The parameter α is obtained from the constraint that the mean r_t for the years 1967-97 equals one and β is estimated in the model fitting procedure. The formulation for α defines mean recruitment equal to the average over the period 1967 to 1997, which in turn defines virgin biomass, B_0. A separate α and β is estimated for each sub-stock allowing the range of the recruitment strengths to differ between sub-stocks.

$$\alpha = \ln\left(\frac{1997 - 1967 + 1}{\sum_{1967}^{1997} \exp(\beta T_y)}\right)$$

TABLE 5.4: Average February to June sea surface temperature recorded at the Leigh Marine Station (Annala and Sullivan 1998). These sea surface temperature data are used to determine relative recruitment at age one in the following year.

Year	Temperature	Year	Temperature
1970	19.40	1984	18.30
1971	19.62	1985	18.78
1972	18.48	1986	19.02
1973	19.02	1987	17.98
1974	19.72	1988	18.54
1975	18.84	1989	19.28
1976	18.04	1990	19.04
1977	18.30	1991	18.10
1978	19.38	1992	17.32
1979	18.68	1993	17.68
1980	18.00	1994	18.30
1981	19.68	1995	19.24
1982	18.46	1996	18.78
1983	17.24	1997	18.28

5.2.6 Growth

Growth of snapper has been observed to vary between different locations around New Zealand's coastline. Catch-at-age data indicate differences in growth rates between the three sub-populations in SNA1 (Davies and Walsh 1995). Growth also shows a seasonal component, with most occurring in summer and autumn (Annala and Sullivan 1997).

The von Bertalanffy growth equation is used to describe growth with separate parameters for each sub-stock (Annala and Sullivan 1998, Table 5.5). The length weight relationship of Paul (1976) is used to calculate weight at age from the lengths determined using the von Bertalanffy equation. BoP weight-at-age is determined by taking the average weight-at-age calculated using the von Bertalanffy growth equations estimated from age-length keys in 1990, 1992 and 1996 (pers com. C. Walsh, National Institute of Water and Atmospheric Research, Auckland, New Zealand) and from the weight-at-age data given in Gilbert 1986.

$$w_{a,l} = 0.04467 L_{a,l}^{2.793}$$

$$L_{a,l} = L_{\infty,l}\left(1 - e^{-K_l(a - t_{0,l})}\right)$$

where:

$w_{a,l}$ is the weight at age a in location l

$L_{a,l}$ is the length at age a in location l

$L_{\infty,l}$, K_l and $t_{0,l}$ are the von Bertalanffy parameters for location l

Growth is assumed to occur equally in the summer and autumn seasons and cease in winter and spring. Weight-at-age from the von Bertalanffy growth equation is assumed to be average weight for the year. Weight-at-age for each season is calculated using the equations described in Table 5.6 and the values are given in Tables 5.7 to 5.9.

TABLE 5.5: von Bertalanffy parameters used to calculate weight-at-age (Gilbert and Sullivan 1994; pers com. C. Walsh, National Institute of Water and Atmospheric Research, Auckland, New Zealand).

	Linf	K	t0
HG	58.8	0.102	-1.11
BoP 1990	58.1	0.12	-1.05
BoP 1992	47.6	0.18	-0.43
BoP 1996	56.5	0.10	-1.64
EN	46.2	0.128	-1.40

TABLE 5.6: Formula used to determine seasonal weight.

Season	Weight Formula
Summer	$w_{a-1}+\frac{3}{4}\left(w_a-w_{a-1}\right)$
Autumn	$w_a+\frac{1}{4}\left(w_{a+1}-w_a\right)$
Winter	$w_a+\frac{2}{4}\left(w_{a+1}-w_a\right)$
Spring	$w_a+\frac{2}{4}\left(w_{a+1}-w_a\right)$

TABLE 5.7: Predicted weight-at-age (kg) by season for the Hauraki Gulf.

Age	Summer	Autumn	Winter	Spring
1	0.04	0.04	0.04	0.04
2	0.09	0.13	0.15	0.15
3	0.17	0.23	0.26	0.26
4	0.29	0.35	0.39	0.39
5	0.42	0.50	0.54	0.54
6	0.58	0.66	0.70	0.70
7	0.74	0.83	0.87	0.87
8	0.92	1.01	1.05	1.05
9	1.10	1.19	1.23	1.23
10	1.28	1.36	1.41	1.41
11	1.45	1.54	1.58	1.58
12	1.63	1.71	1.75	1.75
13	1.79	1.87	1.91	1.91
14	1.95	2.03	2.07	2.07
15	2.11	2.18	2.22	2.22
16	2.25	2.32	2.35	2.35
17	2.39	2.45	2.48	2.48
18	2.51	2.57	2.60	2.60
19	2.63	2.69	2.71	2.71
20	2.74	2.77	2.77	2.77

TABLE 5.8: Predicted weight-at-age (kg) by season for the Bay of Plenty.

Age	Summer	Autumn	Winter	Spring
1	0.06	0.06	0.06	0.06
2	0.13	0.18	0.22	0.22
3	0.25	0.32	0.35	0.35
4	0.39	0.47	0.50	0.50
5	0.54	0.62	0.66	0.66
6	0.70	0.78	0.82	0.82
7	0.86	0.94	0.98	0.98
8	1.02	1.10	1.14	1.14
9	1.18	1.25	1.29	1.29
10	1.33	1.40	1.43	1.43
11	1.47	1.54	1.57	1.57
12	1.60	1.67	1.70	1.70
13	1.73	1.79	1.82	1.82
14	1.85	1.90	1.93	1.93
15	1.95	2.00	2.03	2.03
16	2.05	2.10	2.12	2.12
17	2.14	2.18	2.21	2.21
18	2.23	2.27	2.28	2.28
19	2.30	2.34	2.35	2.35
20	2.37	2.39	2.39	2.39

TABLE 5.9: Predicted weight-at-age (kg) by season for East Northland.

Age	Summer	Autumn	Winter	Spring
1	0.05	0.05	0.05	0.05
2	0.09	0.13	0.15	0.15
3	0.17	0.21	0.24	0.24
4	0.26	0.31	0.34	0.34
5	0.37	0.42	0.45	0.45
6	0.48	0.53	0.56	0.56
7	0.59	0.65	0.68	0.68
8	0.70	0.76	0.79	0.79
9	0.82	0.87	0.90	0.90
10	0.92	0.97	1.00	1.00
11	1.02	1.07	1.10	1.10
12	1.12	1.16	1.19	1.19
13	1.21	1.25	1.27	1.27
14	1.29	1.33	1.35	1.35
15	1.36	1.40	1.41	1.41
16	1.43	1.46	1.48	1.48
17	1.49	1.52	1.53	1.53
18	1.55	1.57	1.59	1.59
19	1.60	1.62	1.63	1.63
20	1.64	1.65	1.65	1.65

5.3 The integrated model equations

This section gives the equations of the integrated tagging and population dynamics model that is applied to the SNA1 sock. Table 5.10 gives the description of the model parameters.

TABLE 5.10: Description of model parameters.

Parameter	Description
A	Age
s	Season
y	Year
l	Sub-stock (location)
m	Gear (method)
$amax$	Maximum age in the model which is used to group all older fish. The model assumes that fish this age and older all have the same characteristics. $amax$=20
$smax$	The number of seasons used in the model
k	Tag release group
$N_{y,s,a,l}$	Number at age a in year y, season s and location l at the start of the year
$\dot{N}_{y,s,a,l}$	Number at age a in year y, season s and location l after movement
$p_{x\to l\|s,a}$	Proportion of individuals of age a that move from location x to location l in season s
M_s	Rate of instantaneous natural mortality in season s
$C_{y,s,a,l}$	Catch in numbers of age a fish in year y, season s, and location l.
$C^m_{y,s,a,l}$	Catch in numbers by method m of age a fish in year y, season s, and location l.
$u^m_{y,s,l}$	Exploitation rate in season s of year y for gear m in location l
$v^m_{a,l}$	At age a to gear m in location l
$C^{*m}_{y,s,l}$	Catch in weight by method m for year y, season s, and location l.
$B^m_{y,s,l}$	Exploitable biomass for method m in location l at the start of season s after movement in year y
$w_{s,a,l}$	Weight at age a for location l during season s
$T^k_{y,s,a,l}$	Number fish tagged in release k alive at age a in year y, season s and location l at the start of the year
$\dot{T}^k_{y,s,a,l}$	Number fish tagged in release k alive at age a in year y, season s and location l after movement
$R^k_{y,s,a,l}$	Number of age a tag releases from release k in location l during season s of year y
$\hat{r}^{k,m}_{y,s,a,l}$	Number of predicted recoveries of age a from release group k in location l during season s of year y by method m.
$\hat{r}^k_{y,s,a,l}$	Number of predicted recoveries of age a from release group k in location l during season s of year y summed over all methods
$R_{0,l}$	Average recruitment in location l
$\varepsilon_{y,l}$	Annual recruitment scaler for year y in location l

5.3.1 Model dynamics of the total population

Movement is assumed to occur at the start of a season, before fishing, and is modeled following a deterministic Markov process where the direction of movement of an individual is only dependent on it's current sub-stock of residence (Deriso et al. 1991).

The numbers in location l after movement are equal to the sum of individuals that move into location l plus the individuals that stay in location l.

$$\dot{N}_{y,s,a,l} = \sum_{x} p_{x \to l|s,a} N_{y,s,a,x}$$

$N_{y,s,a,l}$ is the number at age a in year y. season s, and location l at the start of the year.
$\dot{N}_{y,s,a,l}$ is the number at age a in year y, season s and location l after movement.
$p_{x \to l|s,a}$ is the probability that a fish in location x moves to location l given it is of age a in season s

Fishing and natural mortality are modeled using a difference equation that assumes catch is taken in the middle of the season (*see* Maunder 1993, Maunder and Starr 1998). This approximates catch and natural mortality occurring simultaneously throughout the season (Gilbert 1986). The numbers in the next season are equal to the numbers this season times survival minus catch corrected for half a season's survival.

First Season

$$N_{y+1,1,a+1,l} = \dot{N}_{y,smax,a,l} e^{(-M_{smax})} - (C_{y,smax,a,l}) e^{(-0.5M_{smax})}$$

Plus group in the first season

$$\begin{aligned} N_{y+1,1,amax,l} = {} & \dot{N}_{y,smax,amax-1,l} e^{(-M_{smax})} - (C_{y,smax,amax-1,l}) e^{(-0.5M_{smax})} \\ & + \dot{N}_{y,smax,amax,l} e^{(-M_{smax})} - (C_{y,smax,amax,l}) e^{(-0.5M_{smax})} \end{aligned}$$

Other seasons

$$N_{y,s+1,a,l} = \dot{N}_{y,s,a,l} e^{(-M_s)} - (C_{y,s,a,l}) e^{(-0.5M_s)}$$

M_s is the instantaneous natural mortality rate in season s
amax is the maximum age used in the model, all older individuals are assumed to have the same characteristics as an individual of age *amax*.
smax is the last season of the year.

Predicted catch-at-age is calculated using the separability assumption (exploitation rate is divided into a seasonal component *u* and a age-specific component *v*) and summing over all gears

$$C_{y,s,a,l} = \sum_{m} C^{m}_{y,s,a,l}$$

$$C^{m}_{y,s,a,l} = \dot{N}_{y,s,a,l} u^{m}_{y,s,l} v^{m}_{a,l}$$

$C_{y,s,a,l}$ is the total number of fish caught in location *l* of age *a* during season *s* of year *y*

$C^{m}_{y,s,a,l}$ is the total number of fish caught in location *l* during season *s* of year *y* of age *a* by method *m*

$u^{m}_{y,s,l}$ is the annual exploitation rate in location *l* during season *s* of year *y* for method *m*

$v^{m}_{a,l}$ is the vulnerability at age to method *m* in location *l*

The exploitation rate for gear *m* in season *s* of year *y* is calculated as the catch for *m* divided by the vulnerable biomass, $B^{m}_{y,s,l}$, for method *m*. This formulation assumes that there is no error in the total catch.

$$u^{m}_{y,s,l} = \frac{C^{*m}_{y,s,l}}{B^{m}_{y,s,l}}$$

$$B^{m}_{y,s,l} = \sum_{a} \dot{N}_{y,s,a,l} v^{m}_{a,l} w_{s,a,l}$$

$C^{*m}_{y,s,l}$ is the total weight of the catch in location *l* during season s of year *y* by method *m*

$B^m_{y,s,l}$ is the exploitable biomass in location l at the start of season s in year (or after movement) y for method m

$w_{s,a,l}$ is the weight of an age a fish in location l during season s

5.3.2 Tag dynamics

The tagged population, T, is modeled assuming the same behavior as the total population. The only difference between the tagged and total populations is that recruitment to the tagged population occurs through releases, which are assumed to occur at the start of the season before movement and fishing. Each set of releases that can be uniquely identified in the recoveries is modeled as a separate population.

$$\dot{T}^k_{y,s,a,l} = \sum_x p_{x\to l|s,a}\left(T^k_{y,s,a,x} + R^k_{y,s,a,l}\right)$$

First season.

$$T^k_{y+1,1,a+1,l} = \dot{T}^k_{y,smax,a,l}e^{(-M_{smax})} - \hat{r}^k_{y,smax,a,l}e^{(-0.5M_{smax})}$$

Plus group in the first season

$$\begin{aligned} T_{y+1,1,a\max,l} &= \dot{T}^k_{y,s\max,a\max-1,l}e^{(-M_{s\max})} - \hat{r}^k_{y,s\max,a\max-1,l}e^{-0.5M_{s\max}} \\ &\quad + \dot{T}^k_{y,s\max,a\max,l}e^{(-M_{s\max})} - \hat{r}^k_{y,s\max,a\max,l}e^{-0.5M_{s\max}} \end{aligned}$$

Other seasons

$$T^k_{y,s+1,a,l} = \dot{T}^k_{y,s,a,l}e^{(-M_s)} - \hat{r}^k_{y,s,a,l}e^{(-0.5M_s)}$$

$$\hat{r}^k_{y,s,a,l} = \sum_m \hat{r}^{k,m}_{y,s,a,l}$$

$$\hat{r}^{k,m}_{y,s,a,l} = \dot{T}^k_{y,s,a,l}u^m_{y,s,l}v^m_{a,l}$$

$\hat{r}^{k,m}_{y,s,a,l}$ is the predicted number of recoveries of age a from release group k in location l during season s of year y by method m

$T^{k}_{y,s,a,l}$ is the number of age a tagged fish from release k in location l at the start of season s in year y

$\dot{T}^{k}_{y,s,a,l}$ is the number of age a tagged fish from release k in location l after movement during season s of year y after movement

$R^{k}_{y,s,a,l}$ is the number of age a tag releases from release k in location l during season s of year y

5.3.3 Recruitment

Recruitment is assumed to be independent of stock size and no stock-recruitment relationship is used. A recruitment anomaly is added to allow annual recruitment variation based on the temperature-recruitment relationship described in a previous section. Recruitment at age one is assumed to occur at the start of the first season (summer), which corresponds to the spawning season, and before movement or fishing occurs.

$$N_{y+1,1,1,l} = R_{0,l}\varepsilon_{y,l}$$

$R_{0,l}$ is the virgin recruitment in location l

$\varepsilon_{y,l}$ is the recruitment anomaly for year y in location l.

5.3.4 Initial conditions

The model is started from an exploited population in 1970. The initial age-structure and population size are calculated from a deterministic equilibrium with regard to natural mortality, initial fishing mortality and movement. An exploited population is generated by simulating each cohort over the number of years corresponding to its age in the population during 1970. Movement, initial fishing mortality and natural mortality are all included in the dynamics to determine the initial conditions. The plus group is more complex and is generated by summing up the individuals that would be alive in cohorts from the maximum age to age 200.

$$N_{1970,1,1,l} = R0_l$$

$$\dot{N}_{1970,s,a,l} = \sum_{x} p_{x \to l|s,a} N_{1970,s,a,l}$$

First Season

$$N_{1970,1,a+1,l} = \dot{N}_{1970,s\max,a,l} e^{-M_{s\max}} e^{-Finit_l}$$

Other seasons

$$N_{1970,s+1,a,l} = \dot{N}_{1970,s,a,l} e^{-M_s} e^{-Finit_l}$$

5.3.5 Virgin spawning biomass

Virgin spawning biomass is calculated from a deterministic equilibrium with regard to natural mortality and movement using the same method to calculate the initial conditions in 1970, but without fishing mortality.

5.4 The data

5.4.1 Total catch

Total catch by gear, season and sub-area from 1970 is presented in Tables A1 to A15 (in Appendix A). The separation of catch into sub-area, gear and season is based on the available data contained in the Fishery Statistics Unit (FSU) and Catch Effort Landings Returns (CLER) data bases. Total catch has been scaled to equal that used in the current SNA1 assessment (Annala and Sullivan 1998), which includes an assumed amount of under reported domestic catch and unrecorded Japanese longline catch during the 1970s. The catch has been converted from fishing year (October to September) to a year based on the four seasons used in the integrated model (December to November).

5.4.2 Catch-at-age

Catch-at age data is available for the three main commercial gears (long line, single trawl and Danish seine) for a number of different seasons and years for the three sub-stocks (Tables A16 to A23 in Appendix A). The data aggregates ages 20 an older into a plus. Catch-at-age data for spring was aged to the following January (e.g. an individual of age 3 years and 9 months in spring would be given an age of 4. It was necessary to decrement the ages in the spring data by one year and then use age 19 as a plus group. Effective sample sizes for inclusion in the likelihood were taken from the average number of fish used to generate the age length keys (800 in Davies and Walsh 1995). This number was then divided by the number of times that age-length key was used to calculate a set of catch-at-age data. It is assumed that there is no aging error in the catch-at-age data.

5.4.3 Tagging data from the 1983-84 BoP program

Data for individual tag returns are not available for the 1983-84 BoP tagging program. The published estimate of total biomass is the only piece of information from this tagging program that can be used. The current estimate is 5,833 which is adjusted for the effect of growth and 15% under reporting of tag recoveries (Annala and Sullivan 1998).

The BoP tagging estimate is used to represent the total population above 25cm in the summer of 1984. The average proportion above 25cm in the four year old cohort is assumed to be 0.5 and is used to scale the numbers of four year olds in the biomass calculation. Fish aged 5 and above are assumed to be above 25cm and fully represented in the tagging biomass estimate.

The likelihood from the BoP tagging program is arbitrarily multiplied by 100. The reason to increase the weighting on this piece of data is that it is competing with the other tagging programs which are comprised of a large amount of age-specific recovery data and will dominate over a single total biomass data point. This is an unfortunate necessity due to the unavailability of the raw data from the 1983-84 BoP tagging program. Arbitrarily increasing the weight on this piece of data makes estimates of uncertainty invalid, but it is carried out here because the main focus is point estimates and investigating the model fit to the data. The alternative is to essentially ignore the biomass from the 1983-84 BoP tagging program completely.

5.4.4 Tagging data from the 1984-85 HG-EN program

Age-specific releases were calculated by putting the release length frequency data through an age-length key (Table A24). Only one age-length key (for the HG) is available for the time of release and this is used for both HG and EN releases. Releases were corrected for initial gear-specific tagging mortality (pers com. P. Starr, New Zealand Seafood Industry Council, Wellington, New Zealand).

Age-specific recaptures for 1995 to 1997 were calculated by putting the length of release through the age-length key (Tables A25 to A48). Length at recapture was not available because the recoveries were made by fishers and there are no age-length keys corresponding to the time of recapture. Length at release is available because each tag can be used to identify individual release information. A number of recoveries (7.45%) did not have complete information and these were used to calculate a scaling factor (1.0745) to scale up the recoveries with complete information. The recoveries were also scaled up to incorporate an under reporting factor of 0.15 (Gilbert and Sullivan 1994). A tag loss rate of 0.104 per season was included in the model to reduce the number of predicted recoveries. Recoveries where made voluntarily by fishers returning tags. Effective sample size for the recoveries use in the likelihood is equal to the catch (A49 to A51).

The likelihood from the 1984-85 tagging program is arbitrarily multiplied by 0.25. This reduction in weighting is because the 1993-94 program is thought to be of higher quality (Gilbert et al. 1996), but has only a quarter of the recoveries. The down weighting is an attempt to give these two tagging programs similar weighting.

5.4.5 Tagging data from the 1993-94 program

Age-specific releases were calculated by putting the release length frequency data through an age-length key (Table A24). Each sub-stock had it's own age-length key. Releases were corrected for initial gear-specific tagging mortality (pers com. P. Starr, New Zealand Seafood Industry Council, Wellington, New Zealand).

Age-specific recaptures for 1994 and the summer of 1995 were calculated by putting the estimated length of release through the age-length key (Tables A52 to A72). Despite length at recovery been measured there were no age-length keys corresponding to the time of recovery. The age at recovery is also collected but was not available at the time of this study. Because the tags could not be uniquely associated with their length at release, the length at release was back calculated from the length of recapture using a growth curve (pers com. P. Starr, Seafood Industry Council, Wellington, New Zealand). Sampling was carried out by research staff and the sample size for use in the likelihood is smaller than the total catch (Tables A73). The number of recaptures were increased to correct for the detection rate of the sampling equipment. The detection rate was 0.851 (Gilbert et al. 1996).

5.4.6 Pre-recruit trawl surveys

Pre-recruit trawl surveys have been carried out in the HG since 1984 (Francis et al. 1995). Relative year-class strengths are estimated from these trawl surveys based on the number of 1+ snapper caught. These relative year class strengths have been shown by catch-at-age analysis to carry through to the exploitable population (Maunder and Starr 1998). The trawl survey data (Table 5.11) can be used as an estimate of relative recruitment strength in HG.

TABLE 5.11: Relative recruitment index for the HG from the pre-recruit trawl surveys (Annala and Sullivan 1998).

Year at age 1	Relative Recruitment Index
1984	1.24
1985	3.64
1986	5.08
1987	5.78
1988	2.61
1989	3.92
1990	10.4
1992	3.47
1993	1.22
1994	1.39
1997	5

5.5 The likelihood function

The observed data from the fishery (e.g. catch-at-age data and tag recoveries) are compared to predictions made by the population dynamics model under a specific set of parameter values. A search is conducted to find the best set of parameter values that result in predictions that maximize the likelihood function (or minimize the negative log-likelihood), which is a statistical measure of the closeness of the observed and predicted values. These best parameter values are called the maximum likelihood estimates. Maximum likelihood has become the standard for parameter estimation in the fisheries literature (*see* Polacheck et al 1993, Hilborn and Mangle 1997). Chapter 2 discussed the appropriate likelihoods to use for the integrated model. When tagging data is divided into different strata based on area, age, size or other factors, the multinomial likelihood function is appropriate (because the multinomial distribution models the probability of N trials with more than two types of outcomes) and commonly used (i.e. Klieber and Hampton 1994, Klieber and Fonteneau 1991, Anganuzzi et al. 1994, Deriso et al 1991). The multinomial is also appropriate for catch-at-age data because each fish sample has an outcome based on its age. The 1984 BoP biomass estimate and the pre-recruit trawl surveys are included as lognormal likelihoods.

5.5.1 Tagging

The multinomial likelihood function with each tag release as a trial, as described in Chapter 2, is used in this analysis. The likelihood is slightly complicated by the plus group. If an individual is caught in the plus group it is not possible to determine which age-class that individual was released in. Therefore, the older release age-classes have to be grouped in a way that avoids this problem. The grouping depends on the time period of the recovery data. For example, the 1984-85 tagging program was assumed to release all individuals at the start of summer 1985 and recoveries were made from summer 1985 to spring 1987. Individuals aged 18 and 19 would be recaptured in the plus group during 1987. Therefore, all releases 18 and older were grouped into one age-group. The 1993-94 tagging program was assumed to release all individuals at the start of summer 1994 and recoveries were made from summer 1994 to summer 1995. All individuals 19 years an older were grouped into one age-group for the 1993-94 tagging program. Because these age groups have very similar characteristics, grouping these ages is not thought to have a large influence on the results.

$$L(\text{parameters} \mid \text{tag\_data}) = \prod_{k} \prod_{a'} \left[\left(1 - \sum_{t,s,l,m} \hat{p}^{k,m}_{y'+t,s,a'+t,l} \right)^{\left(R^{k}_{a'} - \sum_{t,s,l,m} r^{k,m}_{y'+t,s,a'+t,l} \right)} \prod_{t,s,l,m} \hat{p}^{k,m}_{y'+t,s,a'+t,l} {}^{r^{k,m}_{y'+t,s,a'+t,l}} \right]$$

The probability of an individual being recovered in a stratum is equal to the predicted number recoveries in that stratum divided by the number of releases.

$$\hat{p}^{k,m}_{y'+t,s,a'+t} = \frac{\hat{r}^{k,m}_{y'+t,s,a'+t}}{R^{k,m}_{a'}}$$

a' is the age at release

y' is the year of release

s is the season of recovery

k is the release group

t is the time after release in years

l is the location of recapture

5.5.2 Catch-at-age

Catch-at-age data is commonly included in the likelihood function using a multinomial formula. If we assume that the catch-at-age data is independent from the tagging data then we can simply add the negative log-likelihood from the catch-at-age data to the total negative log-likelihood.

$$L(\text{parameters} \mid \text{C@A\_data}) = \prod_{m}\prod_{l}\prod_{y}\prod_{s}\prod_{a} {p'^{m}_{y,s,a,l}}^{C^{s,m}_{y,a,l}}$$

$$p'^{m}_{y,s,a,l} = \frac{\dot{N}_{y,s,a,l} v^{m}_{a,l}}{\sum_{a} \dot{N}_{y,s,a,l} v^{m}_{a,l}}$$

$C^{S,m}_{y,s,a,l}$ is the number of fish of age a in the catch at age sample from year y and season s in location l for method m

$v^{m}_{a,l}$ is the vulnerability at age in location l for method m

$\dot{N}_{y,s,a,l}$ is the number at age a in year y, season s and location l after movement.

5.5.3 1984 BoP biomass estimate

The model is fit to the pre-recruit trawl survey data by assuming lognormal observation error with known coefficients of variation.

$$L(B_{1984}^{BoP} \mid \text{parameters}) = \frac{1}{\sqrt{2\pi}\sigma_B} \exp\left(-\frac{\left(\ln(B_{1984}^{BoP}) - \ln(\hat{B}_{1984,1,BoP})\right)^2}{2(\sigma_B)^2} \right)$$

B_{1984}^{BoP} is the biomass estimate for BoP from the 1983-84 tagging program.

$\hat{B}_{1984,1,BoP}$ is the model predicted biomass in BoP at the start of summer 1984 after movement.

σ_B is approximately equal to the CV of the 1984 BoP biomass estimate.

5.5.4 Pre-recruit trawl surveys

The model is fit to the pre-recruit trawl survey data by assuming lognormal observation error with known coefficients of variation.

$$L(I_y \mid \text{parameters}) = \frac{1}{\sqrt{2\pi}\sigma_I} \exp\left(-\frac{\left(\ln(I_y) - \ln(\hat{I}_y)\right)^2}{2(\sigma_I)^2} \right)$$

$$\hat{I}_y = qN_{y,1,1,HG}$$

I_y is the observed index value in year y

σ_I is approximately equal to the CV of the pre-recruit trawl surveys

q is the survey catchability coefficient.

5.6 Estimated parameters

A total of 41 parameters are estimated for the model (Table 5.12).

5.7 Fixed values

Natural mortality is assumed to be equal for all seasons. M=0.075/4 (Annala and Sullivan 1998).

The cv for the BoP total biomass estimate is set at 0.3 (Annala and Sullivan 1998).

$\sigma_B = 0.3$

The cv for the pre-recruit trawl survey index is set at 0.3 (Annala and Sullivan 1998).

$\sigma_I = 0.3$

5.8 Priors

This section describes the priors used to constrain the parameter values. For most of the parameters uniform priors are used to represent a lack of prior information. Uniform priors are not always uninformative, but they do represent vague prior information and the shape of the uninformative prior distribution will not be important if the likelihood is dominant (Gelman et al. 1995). The analysis in this Chapter focuses on estimating the mode of the joint posterior distribution rather than a full Bayesian integration. The uniform priors will be uninformative for the mode of the joint posterior distribution.

Some of the uniform priors used in this analysis are improper distributions because they can not be integrated (Gelman et al. 1995). These are the priors that use a uniform distributions from negative to positive infinity and are used to represent lack of prior information. Because of the large amount of information for these parameters in the data the posterior distribution will be proper.

TABLE 5.12: Parameters estimated in the model fitting procedure.

Parameter	Description
$R0_{HG}$	Average recruitment at age one in HG
$R0_{BoP}$	Average recruitment at age one in BoP
$R0_{EN}$	Average recruitment at age one in EN
$HG_{to}BoP_{mean}$	Mean season for movement from HG to BoP
$HG_{to}EN_{mean}$	Mean season for movement from HG to EN
$BoP_{to}HG_{mean}$	Mean season for movement from BoP to HG
$EN_{to}HG_{mean}$	Mean season for movement from EN to HG
$HG_{to}BoP_{sd}$	Standard deviation of seasonal movement from HG to BoP
$HG_{to}EN_{sd}$	Standard deviation of seasonal movement from HG to EN
$BoP_{to}HG_{sd}$	Standard deviation of seasonal movement from BoP to HG
$EN_{to}HG_{sd}$	Standard deviation of seasonal movement from EN to HG
$HG_{to}BoP_{total}$	Total annual movement from HG to BoP
$HG_{to}EN_{tota}$	Total annual movement from HG to EN
$BoP_{to}HG_{tota}$	Total annual movement from BoP to HG
$EN_{to}HG_{tota}$	Total annual movement from EN to HG
$a50_{HGtoBoP}$	Age at 50% of full movement from HG to BoP
$a95_{HGtoBoP}$	Age at 95% of full movement from HG to BoP
$a50_{BoPtoHG}$	Age at 50% of full movement from BoP to HG
$a95_{BoPtoHG}$	Age at 95% of full movement from BoP to HG
$Finit_{HG}$	Equilibrium fishing mortality for HG in 1970
$Finit_{BoP}$	Equilibrium fishing mortality for BoP in 1970
$Finit_{EN}$	Equilibrium fishing mortality for EN in 1970
β_{HG}	Scaling parameter of the temperature-recruitment relationship in HG
β_{BoP}	Scaling parameter of the temperature-recruitment relationship in BoP
β_{EN}	Scaling parameter of the temperature-recruitment relationship in EN
q	Catchability coefficient of the pre-recruit trawl survey index.
$afull_{HG}^{LL}$	Age at full selectivity for longline in HG
$afull_{HG}^{ST}$	Age at full selectivity for single trawl in HG
$afull_{HG}^{DS}$	Age at full selectivity for Danish seine in HG
$afull_{BoP}^{LL}$	Age at full selectivity for longline in BoP
$afull_{BoP}^{ST}$	Age at full selectivity for single trawl in BoP
$afull_{BoP}^{DS}$	Age at full selectivity for Danish seine in BoP
$afull_{EN}^{LL}$	Age at full selectivity for longline in EN
$afull_{EN}^{ST}$	Age at full selectivity for single trawl in EN
$afull_{EN}^{DS}$	Age at full selectivity for Danish seine in EN
V_{L}^{LL}	Variance of the left hand limb of the selectivity curve for longline.
V_{L}^{ST}	Variance of the left hand limb of the selectivity curve for single trawl
V_{L}^{DS}	Variance of the left hand limb of the selectivity curve for Danish seine
V_{R}^{LL}	Variance of the right hand limb of the selectivity curve for longline.
V_{R}^{ST}	Variance of the right hand limb of the selectivity curve for single trawl
V_{R}^{DS}	Variance of the right hand limb of the selectivity curve for Danish seine

5.8.1 Virgin recruitment

The priors for virgin recruitment are taken from the current assessment (see Chapter 6). It is very unlikely that the estimated virgin recruitment is less than half or more than twice that estimated in the current assessment. Even Gilbert's (1994) sensitivity analysis of mean recruitment periods only covered a range of 85% to 130% of the baseline analysis. The combined HG-BoP virgin recruitment was split 0.8:0.2 based on their relative biomass values from the two tagging programs. Using the same data to generate priors and to fit the model is not totally appropriate, but restricting the virgin recruitment in this way is necessary to avoid estimates of zero virgin recruitment for some of the sub-stocks.

$R0_{HG} \sim U(5600, 22400)$
$R0_{BoP} \sim U(1400, 5600)$
$R0_{EN} \sim U(2500, 10000)$

5.8.2 Initial fishing mortality rate.

The current assessment (presented in Annala and Sullivan (1998), see Chapter 6) assumes an initial fishing mortality rate of 0.04 for EN. This value was fixed because the assessment model wants to estimate an unrealistically low value. The working group agreed that 0.04 was a minimum estimate for the equilibrium fishing mortality rate in 1970. A tagging program in the Hauraki Gulf from 1974 to 1977 estimated an annual exploitation rate of 6.3 % and a biomass of 29,000 t (Crossland 1980). These are thought to be underestimates because the catch they were based on were under estimates (Crossland 1982). This relates to an approximate minimal equilibrium fishing mortality rate in 1970 of 0.065. The BoP stock is thought to be at a similar exploitation state as the HG in 1970. Both HG and BoP are thought to be much more exploited in 1970 than EN. It is unlikely that 1970 equilibrium fishing mortality rate is greater than 0.4. The initial fishing mortality rates are entered into the model as seasonal rates and are constant for each season.

$Finit_{HG} \sim U(0.015, 0.1)$

$Finit_{BoP} \sim U(0.015, 0.1)$

$Finit_{EN} \sim U(0.01, 0.1)$

5.8.3 Movement

Priors for movement are based on the discussions presented earlier in this chapter. The prior for the mean season of movement is assumed to be normally distributed with means taken from the discussion on movement presented earlier. There is much more information on movement from HG, therefore movement from HG is given a cv=0.2 and movement into HG is given a cv=0.5. Taking in consideration that the model assumes movement occurs at the start of the season, the following priors are used.

Mean season of movement.

$HG_{to}BoP_{mean} \sim N(2, 0.4^2)$

$HG_{to}EN_{mean} \sim N(1.5, 0.3^2)$

$BoP_{to}HG_{mean} \sim N(4.5, 2.25^2)$

$EN_{to}HG_{mean} \sim N(4.5, 2.25^2)$

Standard deviation of the season of movement.

$HG_{to}BoP_{sd} \sim U(-\infty, \infty)$

$HG_{to}EN_{sd} \sim U(-\infty, \infty)$

$BoP_{to}HG_{sd} \sim U(-\infty, \infty)$

$EN_{to}HG_{sd} \sim U(-\infty, \infty)$

Total annual movement

$HG_{to}BoP_{total} \sim U(0, 0.5)$

$HG_{to}EN_{total} \sim U(0, 0.1)$

$BoP_{to}HG_{total} \sim U(0, 0.5)$

$EN_{to}HG_{total} \sim U(0, 0.1)$

Age-specific movement is quite evident in the tag recoveries (Figure 5.1). The difference in movement rates between age 3 and age 20 appear to be much greater than 50% (taking into consideration the recovery sample size by age). Using a uniform prior between 0 and 20 for a50 and a95 requires the difference in movement rates between ages 0 and 20 to be at least 50%, and it also prevents these parameters reducing the effect of the total movement parameter.

$a50_{HGtoBoP} \sim U(0,20)$
$a95_{HGtoBoP} \sim U(0,20)$
$a50_{BoPtoHG} \sim U(0,20)$
$a95_{BoPtoHG} \sim U(0,20)$

5.8.4 Selectivity

It is well documented that the age 4 cohort is often contains a proportion of individuals less than the 25cm legal minimal size (Maunder and Starr 1998). The age at full selectivity must be at least age 5 and no greater than the maximum age. There is no additional reliable information for selectivity other than that used to fit the model.

$afull \sim U(5, 20)$ for all gears and areas

$varL \sim U(-\infty, \infty)$ for all gears

$varR \sim U(-\infty, \infty)$ for all gears

5.8.5 Recruitment

Recruitment is very restricted by the temperature-recruitment relationship and there is abundant information in the recruitment index and the catch-at-age data.

$\beta \sim U(-\infty, \infty)$

$\ln(q) \sim U(-\infty, \infty)$

5.9 Objective function

The parameters of the model are estimated using an iterative minimization routine to minimize the total negative log-posterior probability given in the equation below. The total negative log-likelihood for the model fit is the sum of the negative log-likelihood of the proportion of catch-at-age data, the negative log-likelihood of the tag data, and the negative log-likelihood of the pre-recruit trawl survey data. Thus observations are assumed to be independent between the two processes. The tagging data likelihoods are weighted as discussed above. The non-uniform priors (mean season of movement) are combined with the total negative log-likelihood and the total negative log-posterior is minimized to give the estimates of the parameters. The auto differentiation version of an iterative modified Newton-Raphson method supplied with AD Model Builder (© Otter Research) is used. The bounds for uniform priors are implemented internally in AD Model Builder. The details of the different components of the likelihood function are described below.

Total negative log-posterior probability =

$$
\begin{aligned}
&-0.25\ln L(\text{parameters}\mid \text{tag\_data}_{85}) - \ln L(\text{parameters}\mid \text{tag\_data}_{94})\\
&-\ln L(\text{parameters}\mid \text{C@A\_data}) - 100\ln L(\text{parameters}\mid B_{1984}^{BoP}) - \ln L(\text{parameters}\mid \bar{I})\\
&-\ln \text{Prior}(HG_{to}BoP_{mean}) - \ln \text{Prior}(HG_{to}EN_{mean}) - \ln \text{Prior}(BoP_{to}HG_{mean})\\
&-\ln \text{Prior}(EN_{to}HG_{mean})
\end{aligned}
$$

$$
L(\text{parameters}\mid \text{tag\_data}) = \prod_{k}\prod_{a'}\left[\left(1-\sum_{t,s,l,m}\hat{p}_{y'+t,s,a'+t,l}^{k,m}\right)^{\left(R_{a'}^{k}-\sum_{t,s,l,m} r_{y'+t,s,a'+t,l}^{k,m}\right)}\prod_{t,s,l,m}\hat{p}_{y'+t,s,a'+t,l}^{k,m}{}^{r_{y'+t,s,a'+t,l}^{k,m}}\right]
$$

$$
L(\text{parameters}\mid \text{C@A\_data}) = \prod_{m}\prod_{l}\prod_{y}\prod_{s}\prod_{a} p_{y,s,a,l}^{\prime m}{}^{C_{y,a,l}^{S,m}}
$$

$$
L(\text{parameters}\mid B_{1984}^{BoP}) = \frac{1}{\sqrt{2\pi}\sigma_{B}}\exp\left(-\frac{\left(\ln(B_{1984}^{BoP}) - \ln(\hat{B}_{1984,1,BoP})\right)^{2}}{2(\sigma_{B})^{2}}\right)
$$

$$
L(\text{parameters}\mid \bar{I}) = \prod_{y}\frac{1}{\sqrt{2\pi}\sigma_{I}}\exp\left(-\frac{\left(\ln(I_{y}) - \ln(\hat{I}_{y})\right)^{2}}{2(\sigma_{I})^{2}}\right)
$$

$$
-\ln \text{Prior}(HG_{to}BoP_{mean}) \propto \frac{(2 - HG_{to}BoP_{mean})^{2}}{2(0.4)^{2}}
$$

$$
-\ln \text{Prior}(HG_{to}EN_{mean}) \propto \frac{(1.5 - HG_{to}EN_{mean})^{2}}{2(0.3)^{2}}
$$

$$
-\ln \text{Prior}(BoP_{to}HG_{mean}) \propto \frac{(4.5 - BoP_{to}HG_{mean})^{2}}{2(2.25)^{2}}
$$

$$
-\ln \text{Prior}(EN_{to}HG_{mean}) \propto \frac{(4.5 - EN_{to}HG_{mean})^{2}}{2(2.25)^{2}}
$$

where:

$$
\hat{p}_{y'+t,s,a'+t,l}^{k,m} = \frac{\hat{r}_{y'+t,s,a'+t,l}^{k,m}}{R_{a'}^{k}}
$$

R_{a}^{k} is the number released in release group k of age a

$r_{y,s,a,l}^{k,m}$ is the observed number of recoveries from release group k in year y, season s and location l of age a caught by method m.

$\hat{r}^{k,m}_{y,s,a,l}$ is the model predicted number of recoveries from release group k in year y, season s and location l of age a caught by method m.

a' is the age at release

y' is the year of release

s is the season

k is the release group

t is the time after release in years

l is the location

m is the method

$$p'^{m}_{y,s,a,l} = \frac{\dot{N}_{y,s,a,l} v^{m}_{a,l}}{\sum_{a} \dot{N}_{y,s,a,l} v^{m}_{a,l}}$$

$C^{S,m}_{y,s,a,l}$ is the number of fish of age a in the catch at age sample from year y and season s in location l for method m

$v^{m}_{a,l}$ is the vulnerability at age in location l for method m

$\dot{N}_{y,s,a,l}$ is the number at age a in year y, season s and location l after movement.

B^{BoP}_{1984} is the biomass estimate for BoP from the 1983-84 tagging program.

$\hat{B}_{1984,1,BoP}$ is the model predicted biomass in BoP at the start of summer 1984 after movement.

σ_B is approximately equal to the CV of the 1984 BoP biomass estimate(Annala and Sullivan 1998).

$\hat{I}_y = qN_{y,1,1,HG}$

q is the survey catchability coefficient.

I_y is the observed index value in year y

σ_I is approximately equal to the CV of the pre-recruit trawl surveys (Annala and Sullivan 1998).

$\mathrm{HG_{to}BoP_{mean}}$ is the mean season of movement from HG to BoP and the notation follows the same style for the other mean season of movement parameters.

5.10 Sensitivity analysis

Sensitivity analysis is used to determine the influence of model assumptions on the results. The assumptions that are usually tested are model structure, parameter values, and the factors used to weight different data sources. The 11 sensitivity tests listed below are used to investigate some of the assumptions made in the application of the Integrated Model to the SNA1 assessment.

1) No constraints on the parameter values. This analysis is used to investigate the effect of the priors on the analysis. As can be seen in the results section, some of the key parameters are estimated at the bounds of their priors making the priors very informative. Removing the priors from the analysis is used to investigate the effect of the priors.
2) Fixed the initial fishing mortality rate parameters at their minimum values. The initial fishing mortality rate is an important parameter in the model and the model has difficulty estimating reasonable values for this parameter. This analysis and analyses (3) and (4) are used to determine the effect of the initial exploitation rates on the results.
3) Fixed initial Fs at the half the minimum values.
4) Fixed initial Fs at two times the minimum values.
5) Down weight the catch-at-age data by dividing the sample size by 10. This is used to investigate the influence of the catch-at-age data on the results.
6) Use the full weight of the 1984-85 tagging program likelihood. This is used to investigate the effect of down weighting the 1984-85 tagging program likelihood.
7) Remove the factor that increases the weight on the likelihood from the 1983-84 BoP tagging program biomass estimate. This is used to determine the effect of increasing the weight on the likelihood from the 1983-84 BoP tagging program biomass estimate, which was used to compensate for the lack of raw tagging data.
8) Remove the 20% under-reported catch from the recovery sample size used for the 1984-85 tagging program. It is unknown whether fishers returned tags from the unreported catch and the effect this will have on the analysis needs to be investigated.

9) Fitting the model to estimates of total biomass rather than age-specific recoveries and assuming no movement between the sub-stocks. This analysis is similar to the current assessment (Annala and Sullivan 1998, see chapter 6), except it separates HG and BoP. Biomass estimates are given in Table 5.13. This analysis is used in conjunction with 9 to 11 to investigate the effect of movement and the integration of tagging data with the population dynamics model.
10) Fitting the model to estimates of total biomass rather than age-specific recoveries and using movement estimates from the base case. This analysis is used to determine the effect of movement.
11) The same as (8), except the likelihood for the biomass estimates is multiplied by 100 to down weight the effect of the catch-at-age data.
12) The same as (9), except the likelihood for the biomass estimates is multiplied by 100 to down weight the effect of the catch-at-age data.

TABLE 5.13: Biomass estimates (t) used in the sensitivity analyses 8-11 (Annala and Sullivan 1998, N. Davies pers com., National Institute of Water and Atmospheric Research, Auckland, New Zealand). The 1994 estimates are based on all gears and the split between HG and BoP is assumed to be 75:25.

	HG	BoP	EN
1984		5833	
1985	23447		15638
1994	21225	7075	13700

5.11 Results

5.11.1 Results for the base case

The estimation procedure could not estimate all the parameters from the data used. Despite priors on the mean season of movement, these parameters had to be fixed at their prior means to allow the estimation procedure to converge on a solution. All the results discussed below have the mean season of movement fixed.

The HG sub-stock is estimated to have about three times as much recruitment as the other two sub-stocks that have similar size recruitment (Table 5.14). Due to the differences in initial fishing mortality, the biomass levels in 1970 do not reflect the recruitment for each sub-stock (Figure 5.2). Both HG and EN have estimates of initial fishing mortality on their lower bounds (Table 5.14). The estimate of initial fishing mortality for BoP is much higher than the other two sub-stocks. All three sub-stocks decline from their 1970 initial starting biomass (Figure 5.2). The HG biomass levels off in the late 1980s, but the BoP and EN stocks keep declining to their current biomass levels. The current depletion level is quite well estimated with minimum width 95% confidence bounds of 0.175-0.212, 0.163-0.177 and 0.153-0.213 for HG, BoP and EN respectively (Figure 5.3). The narrow confidence intervals for BoP are probably a result of the high weighting factor applied to the 1984 biomass estimate for BoP. The BoP sub-stock shows much higher annual fluctuations in biomass than the other two sub-stocks. All three sub-stocks are projected to rebuild in the future under deterministic recruitment and current removals. HG shows the fastest rebuilding rate.

Variation in annual recruitment is estimated to be slightly smaller for HG than the other two sub-stocks (Figure 5.4). In addition, the fit of the estimated annual relative recruitment for HG to the pre-recruit trawl surveys is poor, underestimating the amount of variation in recruitment shown by the pre-recruit trawl survey (Figure 5.5).

The rate of movement is much higher from BoP to HG than in any other direction (Figure 5.6). This movement rate is estimated at its upper bound of 0.5. Full movement from BoP to HG does not occur until age 6, with no movement for age 4 and only half full movement for age 5. Movement from BoP to HG is equally divided between all seasons (Figure 5.6). Movement from HG to BoP declines with age and although it is much smaller than movement from BoP to HG, it will have a large effect due to the larger HG biomass. The movement from HG to BoP is spread out over all seasons, with spring having the least movement. Movement from HG to EN and from EN to HG is at about the same rate as movement from HG to BoP, with movement from HG to EN only occurring in Summer and Autumn and movement from EN to HG occurring in Spring and Summer.

Selectivity estimates for all three gears have very steep left hand limbs. Single trawl has a lower age at full selectivity for all sub-stocks than longline and Danish seine (Figure 5.7). The right hand limb for long line is much flatter than for the other two gears. The single trawl and Danish seine right hand limbs are similar to those of other commercial gears and recreational which have been fixed in the analysis.

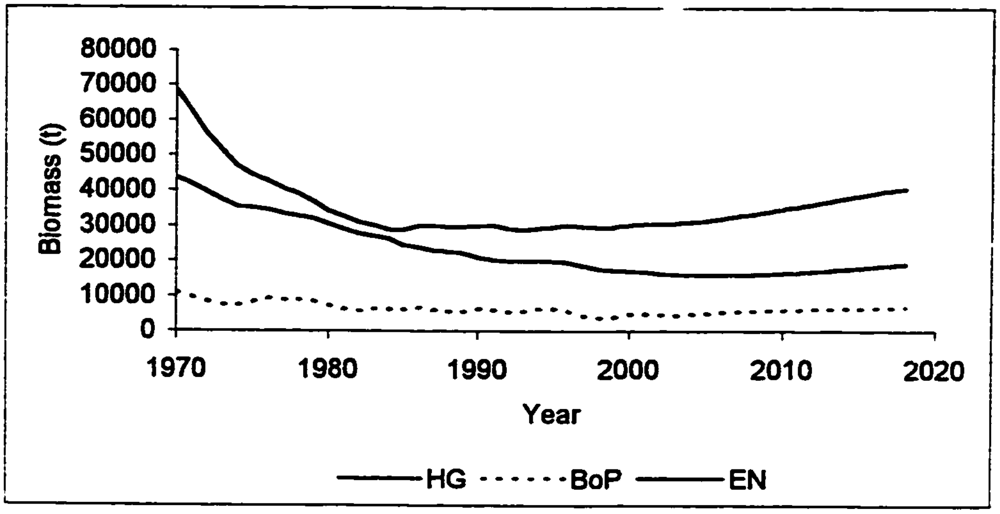

FIGURE 5.2: Biomass trajectories of the three sub-stocks for the base case analysis.

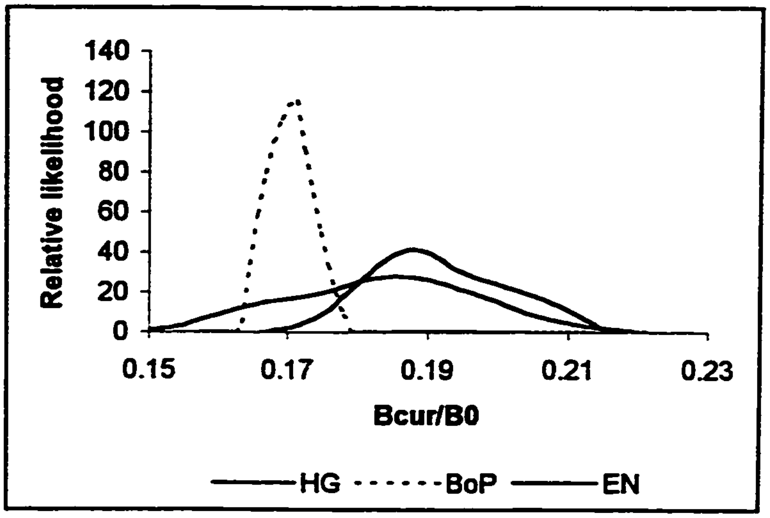

FIGURE 5.3: Likelihood profiles of the current depletion level (B_{cur}/B_0) for the three sub-stocks.

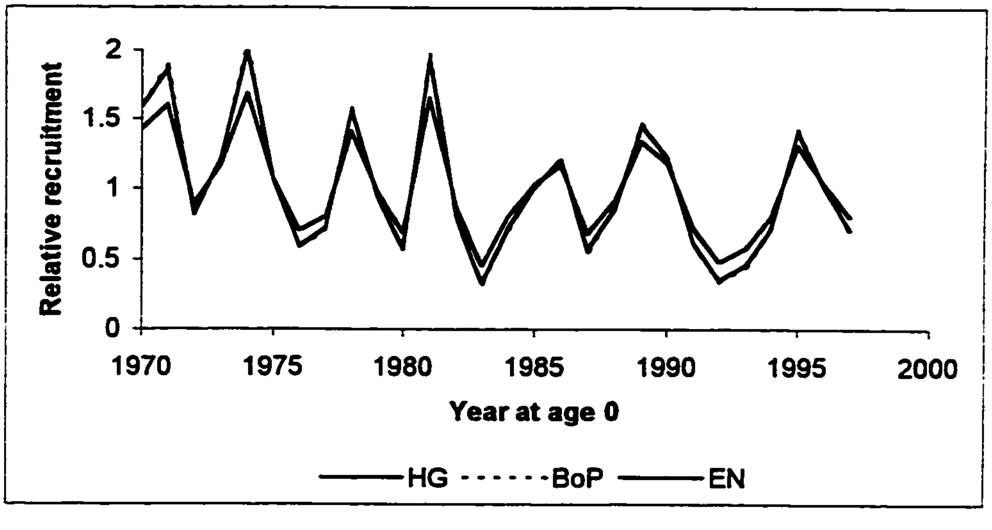

FIGURE 5.4: Annual recruitment residuals for each sub-stock

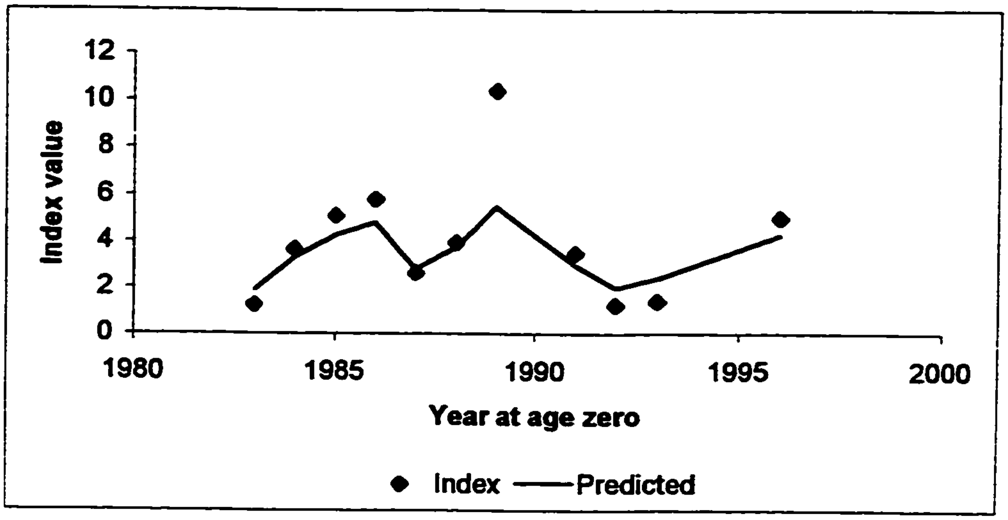

FIGURE 5.5: Fit of the HG annual recruitment residuals to the pre-recruit trawl survey index.

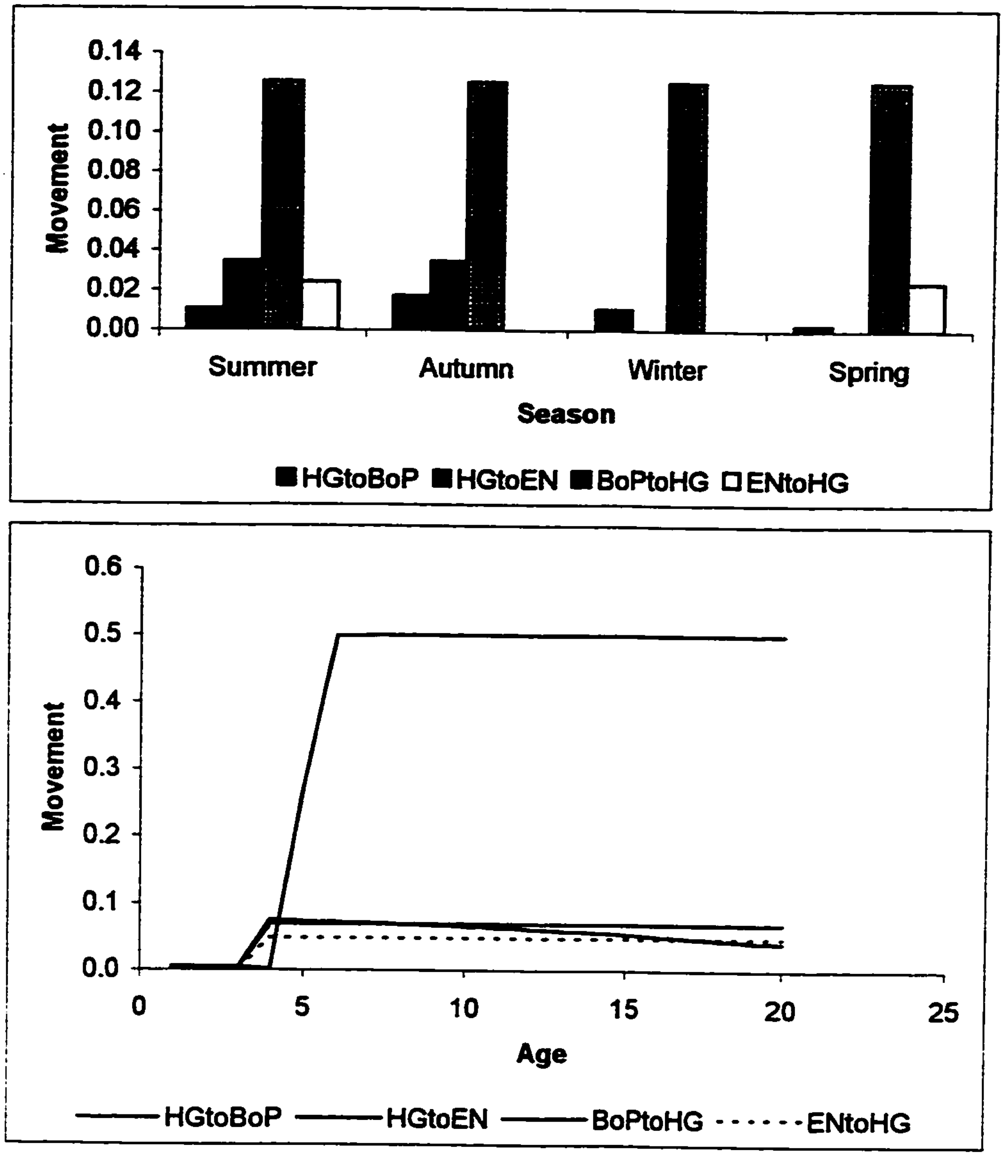

FIGURE 5.6: Age and season specific movement (proportion per season) between the sub-stocks.

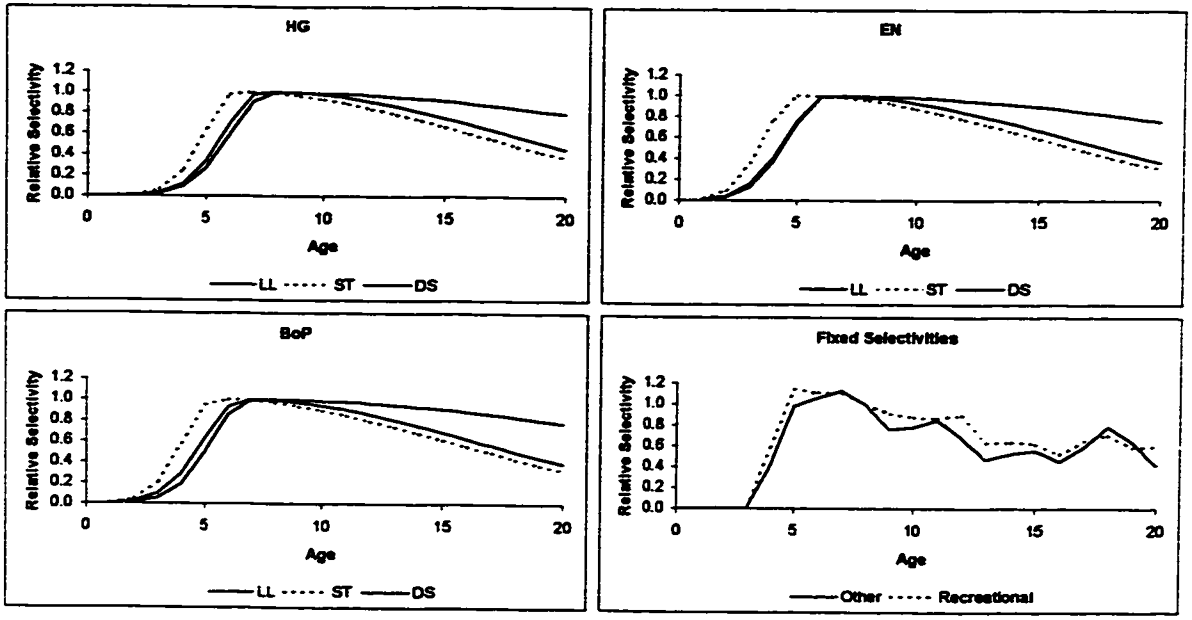

FIGURE 5.7: Estimated selectivity for longline (LL), single trawl (ST) and Danish seine (DS) for the three sub-stocks, and fixed selectivities for other commercial gears (Other) and recreational catch (Recreational).

TABLE 5.14: Results from the base case compared to results from the sensitivity analyses for no constraints on parameters and fixed initial fishing mortalities.

		Base	No Constraints	Fixed F	Fx0.5	Fx2
Negative log Likelihood		45315	45247	45316	45322	45371
R0	HG	11415	3055	11882	11955	10699
	BoP	4015	11131	3837	3647	4607
	EN	4007	5848	3372	2500	6487
	Total	19436	20034	19091	18102	21793
InitialF	HG	0.0150	0.0000	0.0150	0.0075	0.0300
	BoP	0.0313	0.3366	0.0150	0.0075	0.0300
	EN	0.0100	0.0000	0.0100	0.0050	0.0200
B1998/B0	HG	0.188	0.169	0.193	0.211	0.185
	BoP	0.175	0.255	0.174	0.169	0.192
	EN	0.186	0.201	0.178	0.182	0.229
B2018/B0	HG	0.260	0.253	0.254	0.234	0.314
	BoP	0.323	0.503	0.311	0.275	0.393
	EN	0.201	0.223	0.178	0.122	0.320

TABLE 5.15: Negative log-likelihood values from the sensitivity analyses for the different data components. Total negative log-likelihood and the negative log-likelihood for catch-at-age data should not be compared against the base case for the down weighted catch-at-age sensitivity analysis. Total negative log-likelihood and the negative log-likelihood for the 1984-85 tagging program should not be compared against the base case for the full weighted 1984-85 tagging program sensitivity analysis.

	Base	No Constraints	Fixed F	Fx0.5	Fx2	C@A	Full85	BoP84	N020%
C@A	35911	35832	35915	35923	35933	3615	35940	35894	35909
Tag85	4735	4726	4737	4738	4734	4708	18805	4728	4729
Tag94	4661	4675	4655	4651	4696	4631	4699	4654	4656
BoP biomass	1	4	1	3	0	0	1	2	1
Recruitment	7	9	7	7	6	4	7	8	7
Total	45315	45247	45316	45322	45371	12958	59453	45286	45303

C@A – catch-at-age likelihood
Tag85 – 1984-85 tagging program likelihood
Tag94 – 1993-94 tagging program likelihood
BoP biomass – 1983 BoP tagging biomass estimate likelihood
Recruitment – pre-recruit trawl survey likelihood

TABLE 5.16: Results from the sensitivity analyses for down weighted catch-at-age data, full weight on the 1984-85 tagging program, and excluding the 20% under reporting from the 1984-85 tagging program sample size. Negative log-likelihood include weighting factors.

		Base	Down Weight C@A	Full 85 Weight	Normal BoP 84 weight	No 20%
Negative log Likelihood		45315	12958	59453	45286	45303
R0	HG	11415	12648	11850	9351	10736
	BoP	4015	2738	3640	5600	4215
	EN	4007	3567	5559	4144	4625
	Total	19436	18953	21049	19095	19576
InitialF	HG	0.0150	0.0150	0.0150	0.0150	0.0150
	BoP	0.0313	0.0151	0.0585	0.0150	0.0607
	EN	0.0100	0.0100	0.0100	0.0100	0.0100
B1998/B0	HG	0.188	0.171	0.208	0.189	0.171
	BoP	0.175	0.173	0.193	0.247	0.172
	EN	0.186	0.169	0.250	0.186	0.179
B2018/B0	HG	0.260	0.212	0.305	0.248	0.253
	BoP	0.323	0.275	0.353	0.390	0.329
	EN	0.201	0.156	0.297	0.189	0.208

TABLE 5.17: Results from the sensitivity analyses that fit to total biomass estimates.

		Base	Total No Movement	Total with Movement	Total No Movement x 100	Total with Movement x 100
Negative log Likelihood		45315	35979	35890	36014	35891
R0	HG	11415	9833	10887	9753	10532
	BoP	4015	3885	5600	3874	5600
	EN	4007	6021	2500	5464	2500
	Total	19436	19738	18987	19091	18632
InitialF	HG	0.0150	0.0150	0.0150	0.0150	0.0150
	BoP	0.0313	0.0519	0.0152	0.0518	0.0168
	EN	0.0100	0.0101	0.0100	0.0100	0.0100
B1998/B0	HG	0.188	0.196	0.217	0.190	0.202
	BoP	0.175	0.061	0.243	0.059	0.231
	EN	0.186	0.299	0.149	0.195	0.134
B2018/B0	HG	0.260	0.407	0.281	0.401	0.261
	BoP	0.323	0.000	0.402	0.000	0.389
	EN	0.201	0.243	0.154	0.002	0.129

The negative log-likelihood for the base case is a very large number (Table 5.14). The fit to the catch-at-age data contributes 80% of the negative log-likelihood (Table 5.15), the 1984-85 and 1993-94 tagging programs contribute about the same amount (10% each), and the BoP biomass estimate and the pre-recruit trawl survey index contribute essentially nothing.

5.11.2 Fit to Catch-at-age data

There appears to be no obvious trend in the overall residuals from the catch-at-age data for any of the gear sub-area combinations (Figure 5.8). There is possibly a slight underestimation of the plus group for long line in BoP and EN and for the 1970s HG Danish seine data. There is a possible underestimation of Danish seine 5 to 9 year olds in HG. The low cohort size that appears in the BoP catch-at-age data as age 5 in summer 1995 is overestimated across all gear types. The EN catch-at-age data is highly variable from year to year and it is difficult to determine cohorts that are consistently over or under predicted.

5.11.3 Fit to the 1984-85 tagging program data

HG releases. The model generally underestimates young ages and overestimates older ages for HG recoveries (Figures 5.9 to 5.13). The exception is other commercial gears, which is underestimated for all ages. Recoveries in BoP are underestimated for young ages and overestimated for old ages with longline, underestimated for all ages with single trawl and Danish seine, and only underestimated for young ages with other commercial gears. Recoveries in EN are slightly underestimated for young ages and greatly overestimated for old ages with longline and other commercial gears, and underestimated for all ages with single trawl and Danish seine.

EN releases. The model generally underestimates young ages and overestimates older ages for EN recoveries (Figures 5.9 to 5.13). The exception is other commercial gears, which is greatly overestimated for all ages. Recaptures in HG are also generally underestimated for young ages and overestimates for older ages. Recaptures in EN are generally underestimated for all ages.

5.11.4 Fit to the 1993-94 tagging program data

HG releases. The Model fit to the HG releases caught in HG are reasonably good, except for a large underestimation for all ages with Danish seine (Figures 5.14 to 5.17). There is also a slight underestimation of 6 year olds and over estimation of 7, 8 and 9 year olds for longline. HG releases caught in BoP are greatly underestimated for ages 5 and 6. Unlike recoveries in HG, the Danish seine recoveries in BoP are not underestimated for ages other then the 5 and 6 year olds. The HG releases recaptured in EN are underestimated for ages 5 to 8.

BoP releases. The Model fit to the BoP releases caught in BoP are reasonably good, except for a large underestimation of 6 year olds with Danish seine and a large over estimation of 5 year olds for longline (Figures 5.14 to 5.17). The model consistently underestimates the number 8 to 15 year olds recovered in HG. The number of recoveries in EN is underestimated, but the observed recoveries are so small that this difference does not accurately describe the model performance.

EN releases. The model greatly underestimates the EN releases recovered in EN for all ages (Figures 5.14 to 5.17). Recoveries are also underestimated in HG and BoP.

5.11.5 Results for the Sensitivity analysis

Constraints (1)

The base case estimates the initial exploitation rates for HG and EN at their lower bounds (Table 5.14). Removing all the constraints (priors) on the parameters results in HG and EN being estimated to be at unexploited population sizes in 1970 (Finit=0, Table 5.14). Conversely, the initial mortality rate for BoP is ten times larger than in the base case. The majority of recruitment has been transferred from HG in the base case to BoP when there are no constraints on the parameters. There is also an increase in recruitment in EN. The negative log-likelihood is 68 units lower than the base case, which indicates a much better fit to the data (considering a change of two units per parameter is significant using AIC). Most of the reduction in the total negative log-likelihood is due to a better fit to the catch-at-age data (Table 5.15). The fit to the 1984-85 tagging program is also better but the fit to the 1993-94 tagging program is worse.

Fortunately, despite the large difference in initial fishing mortality rates and sub-stock recruitment estimates, the biomass trajectories are very similar to the base case (Figure 5.18). The biggest difference is in BoP which starts out much lower in 1970 and ends up higher for most of the other years. EN biomass starts out larger than in the base case. The total biomass trajectory for SNA1 is very similar to the base case.

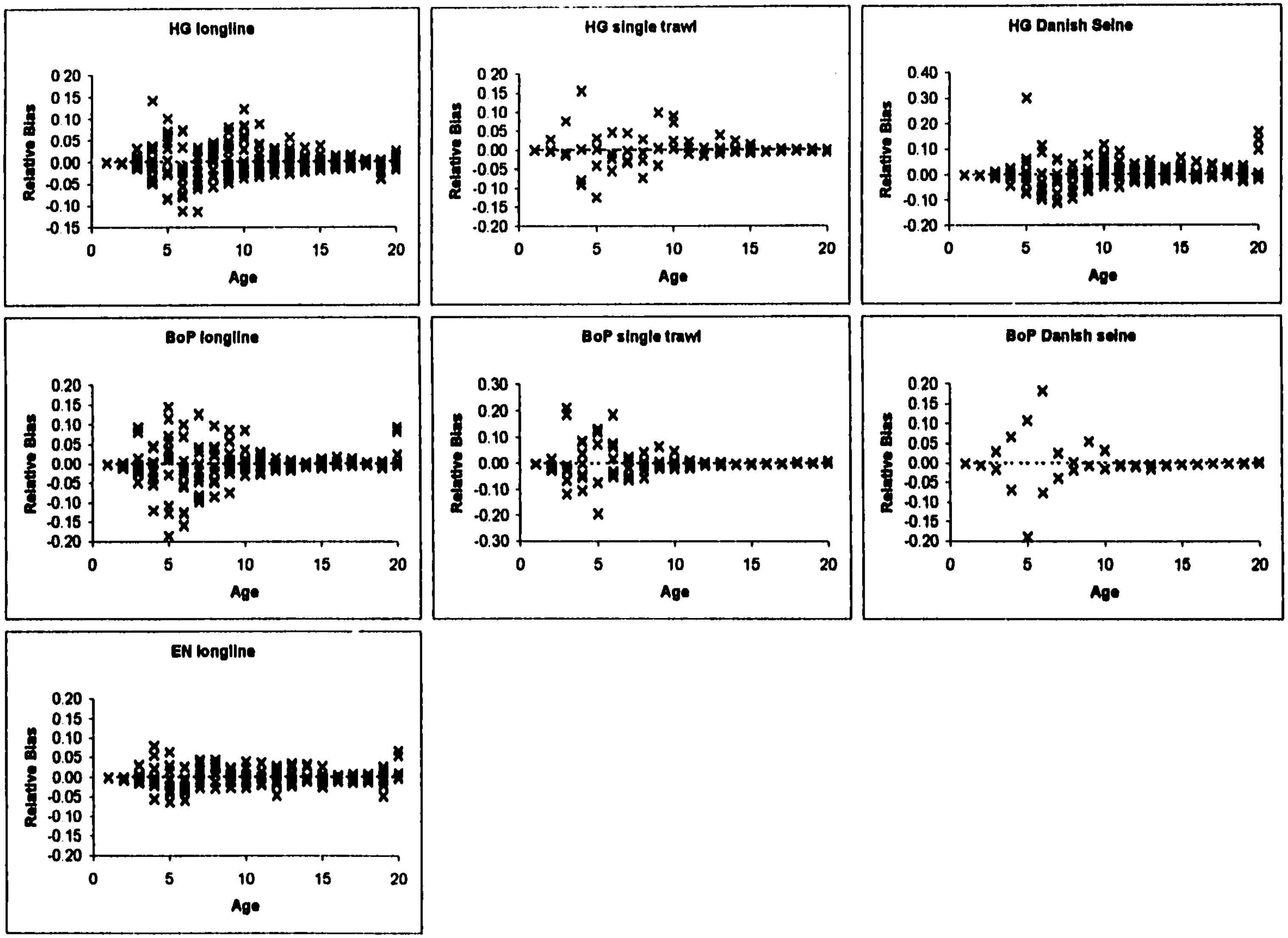

Figure 5.8. Catch-at-age residuals for all gears and sub-stocks.

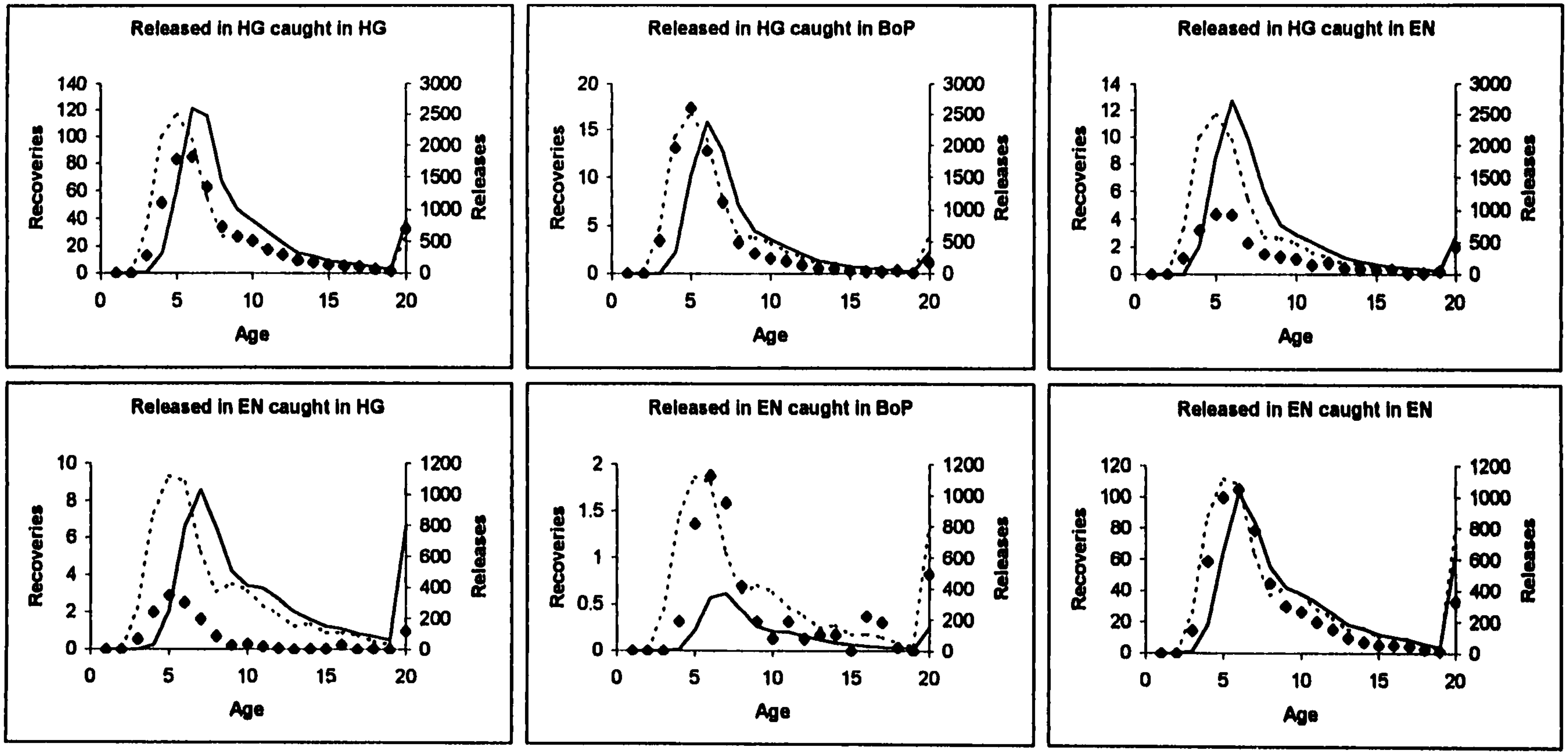

Figure 5.9. Longline recoveries from the 1984-85 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

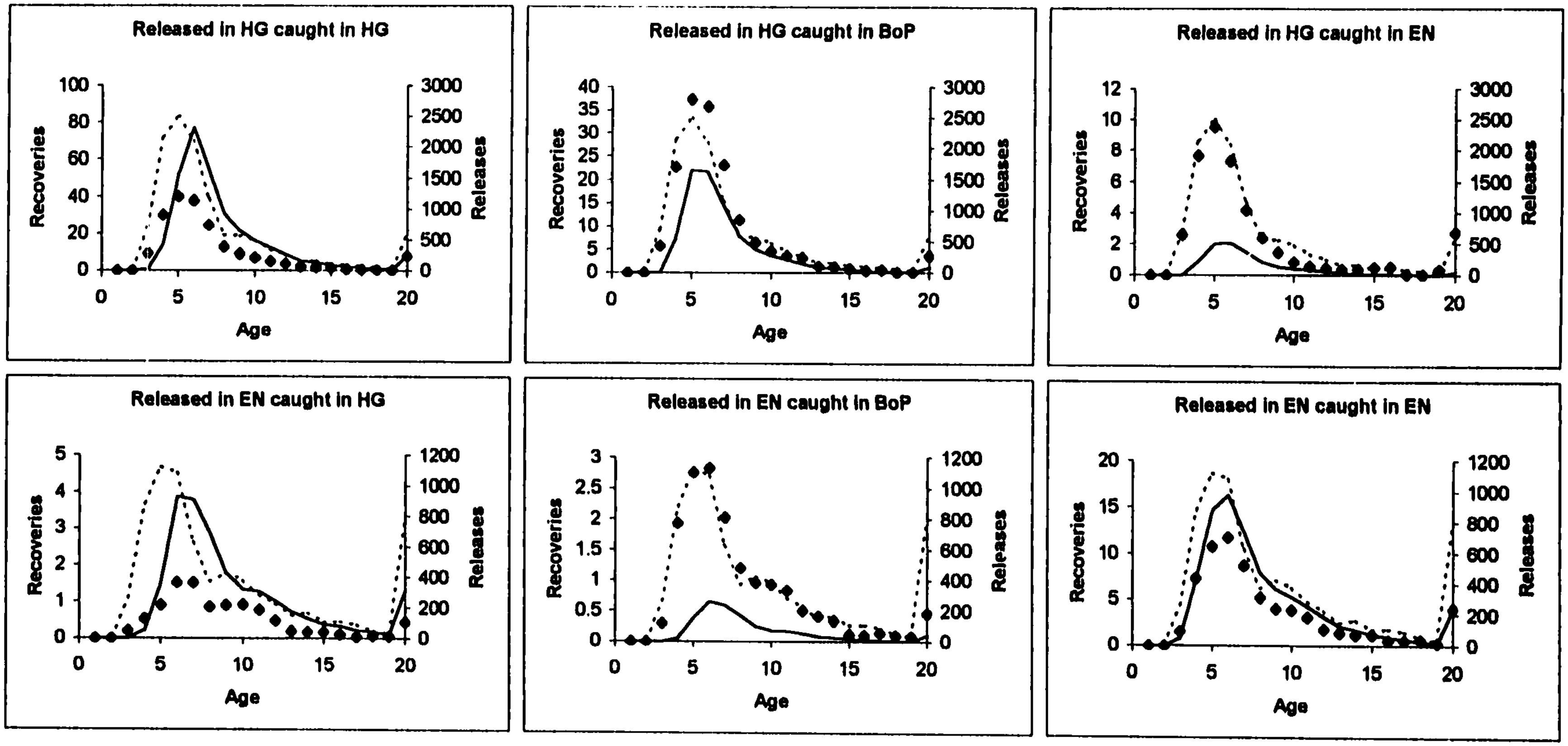

Figure 5.10. Single trawl recoveries from the 1984-85 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

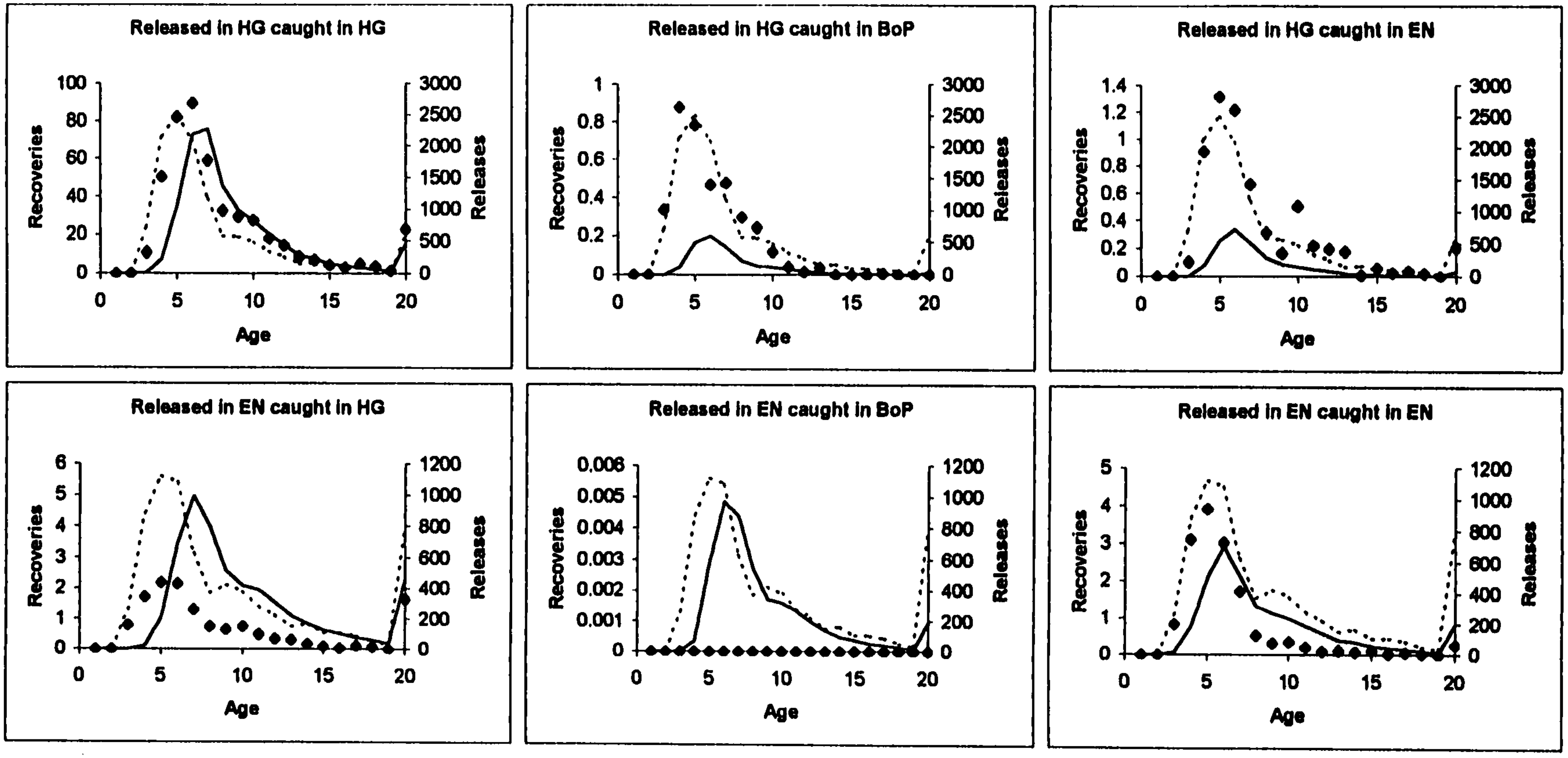

Figure 5.11. Danish seine recoveries from the 1984-85 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

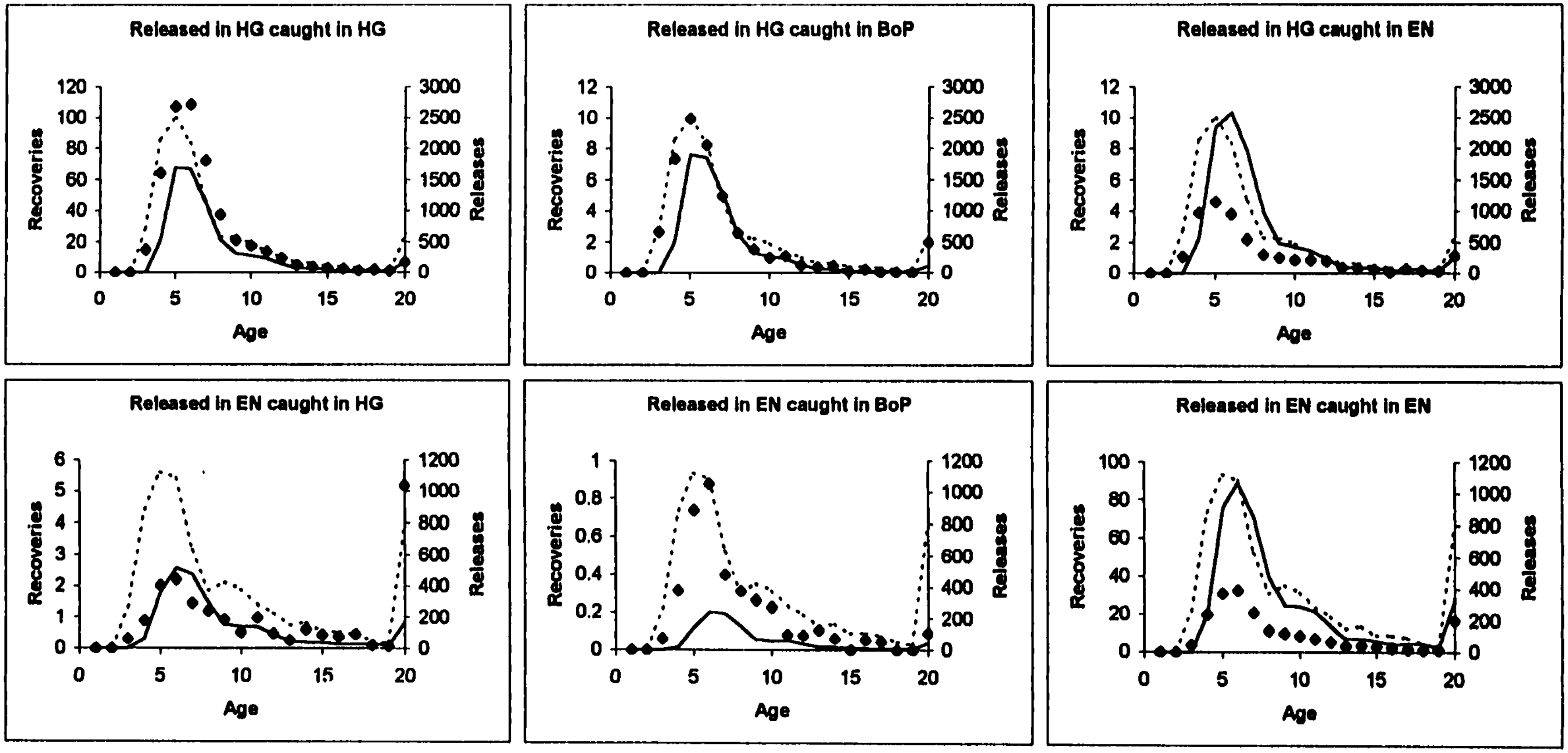

Figure 5.12. Other commercial gear recoveries from the 1984-85 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

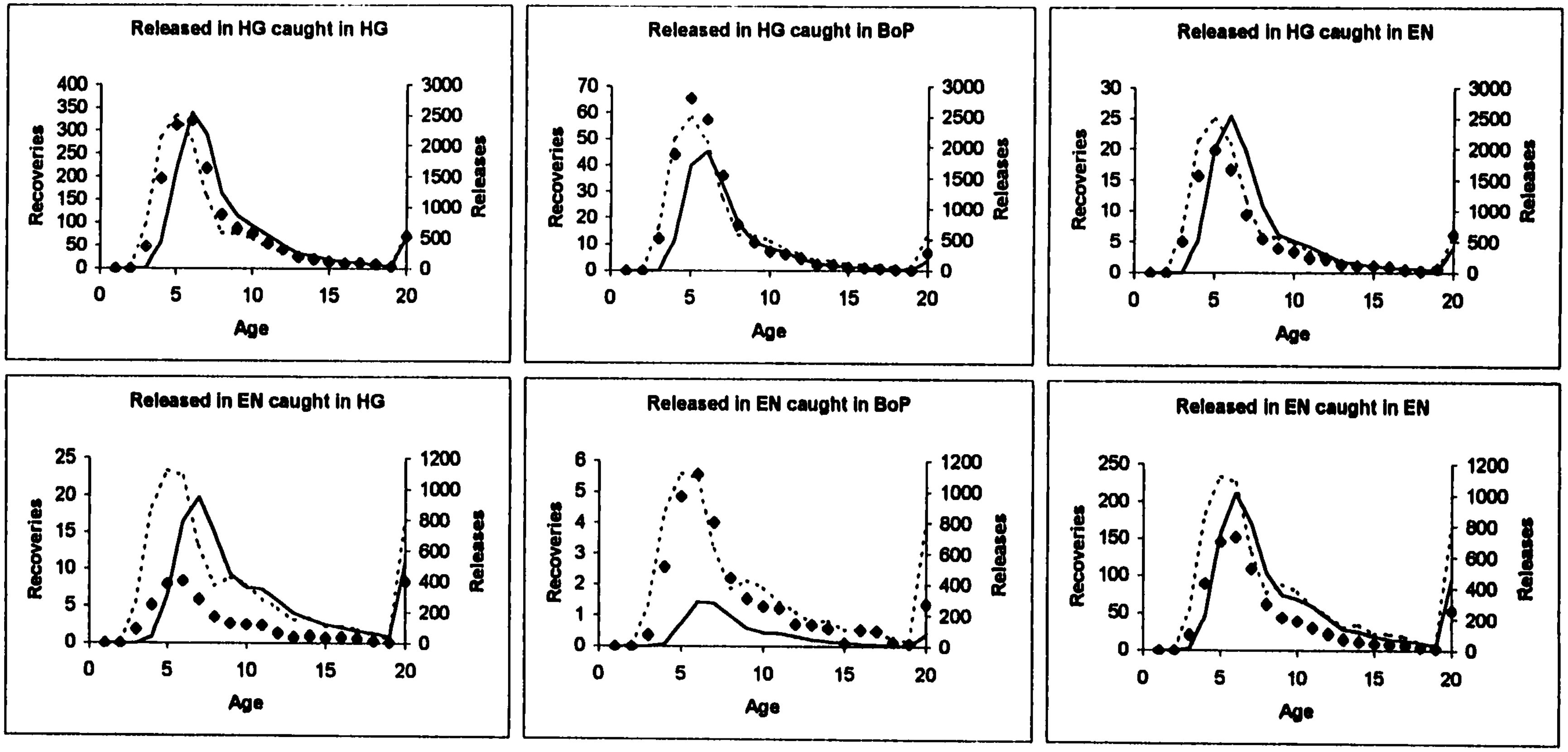

Figure 5.13. Total recoveries from the 1984-85 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

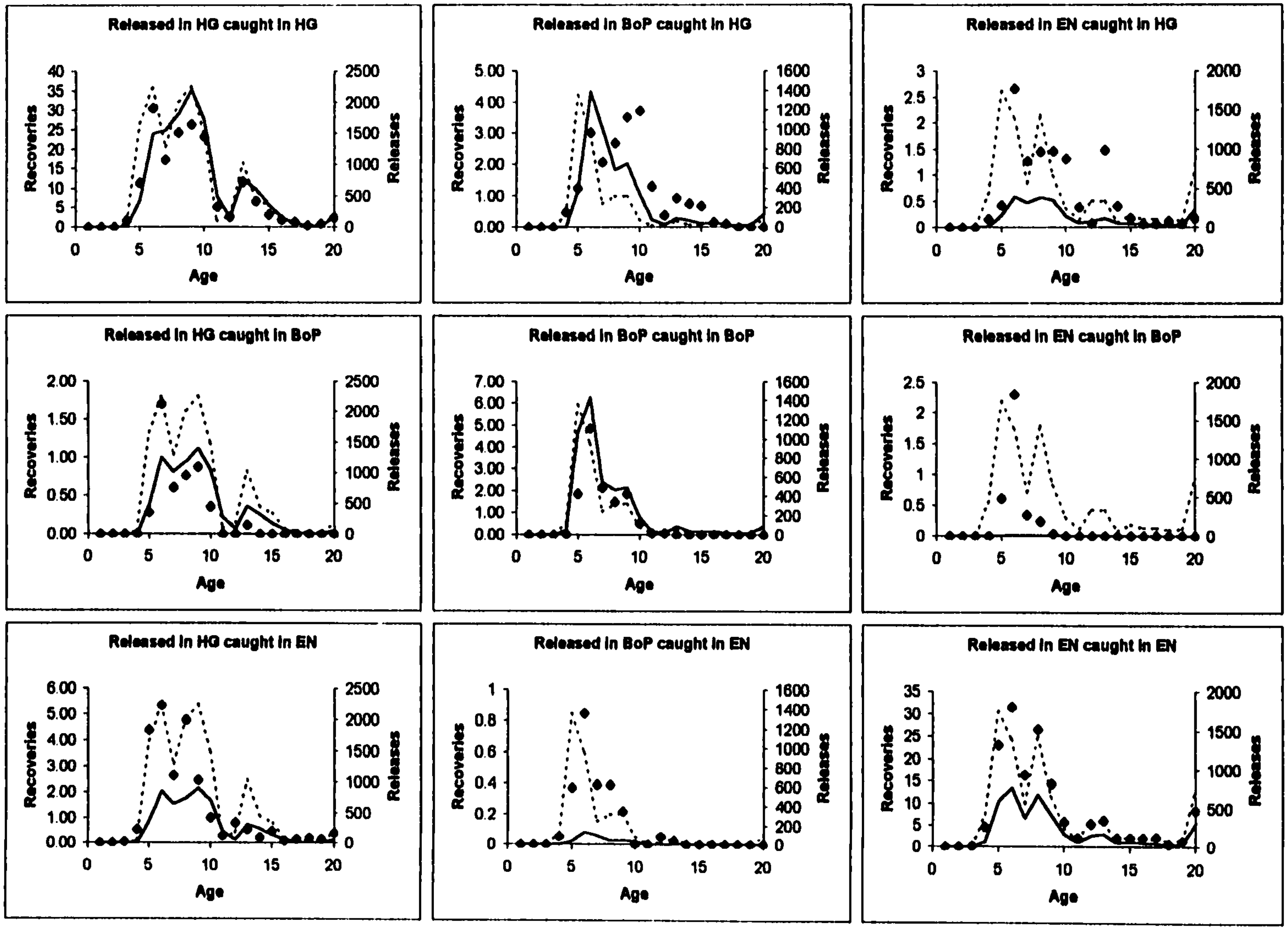

Figure 5.14. Long line recaptures from the 1993-94 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

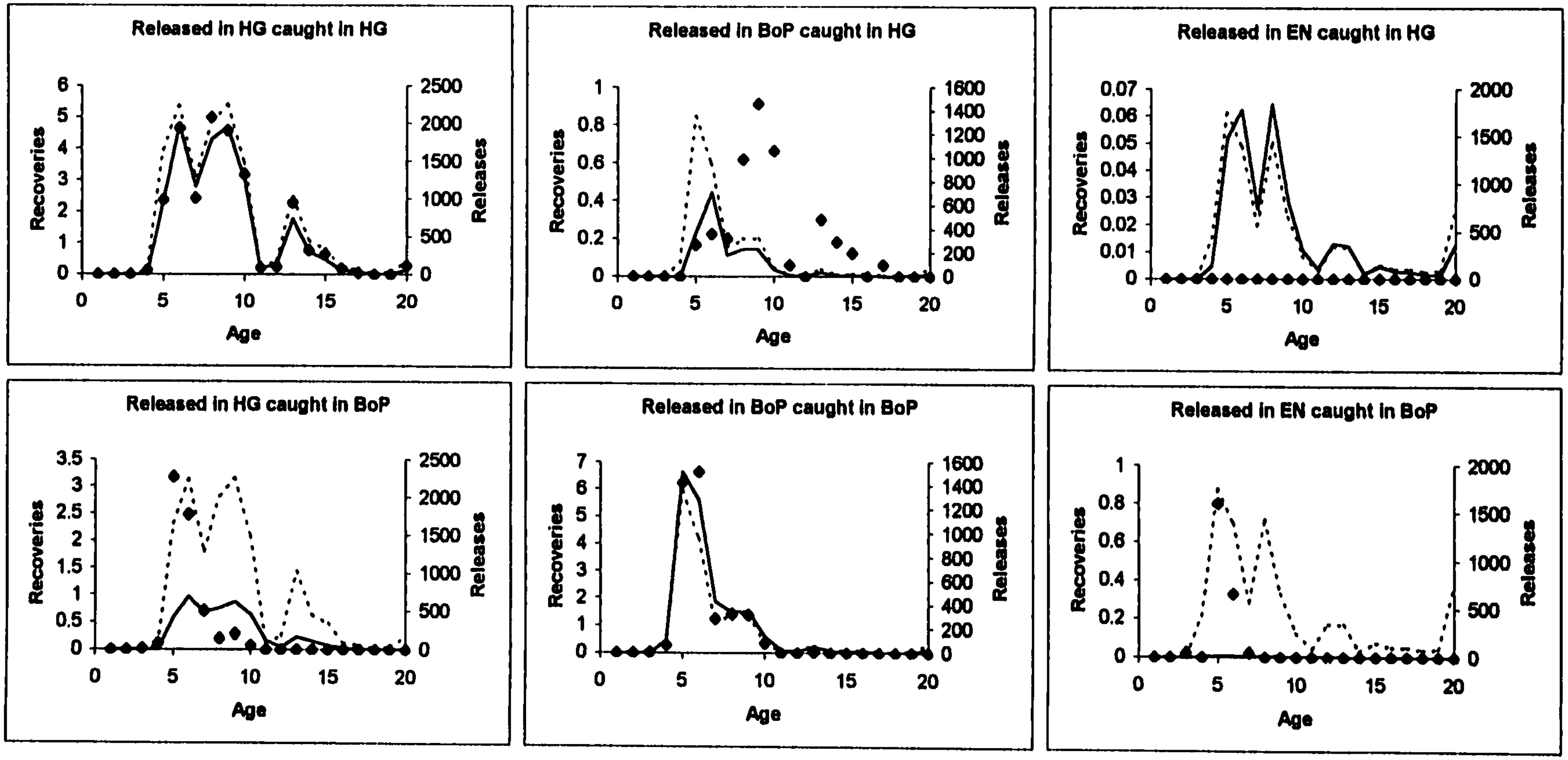

Figure 5.15. Single trawl recoveries from the 1993-94 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

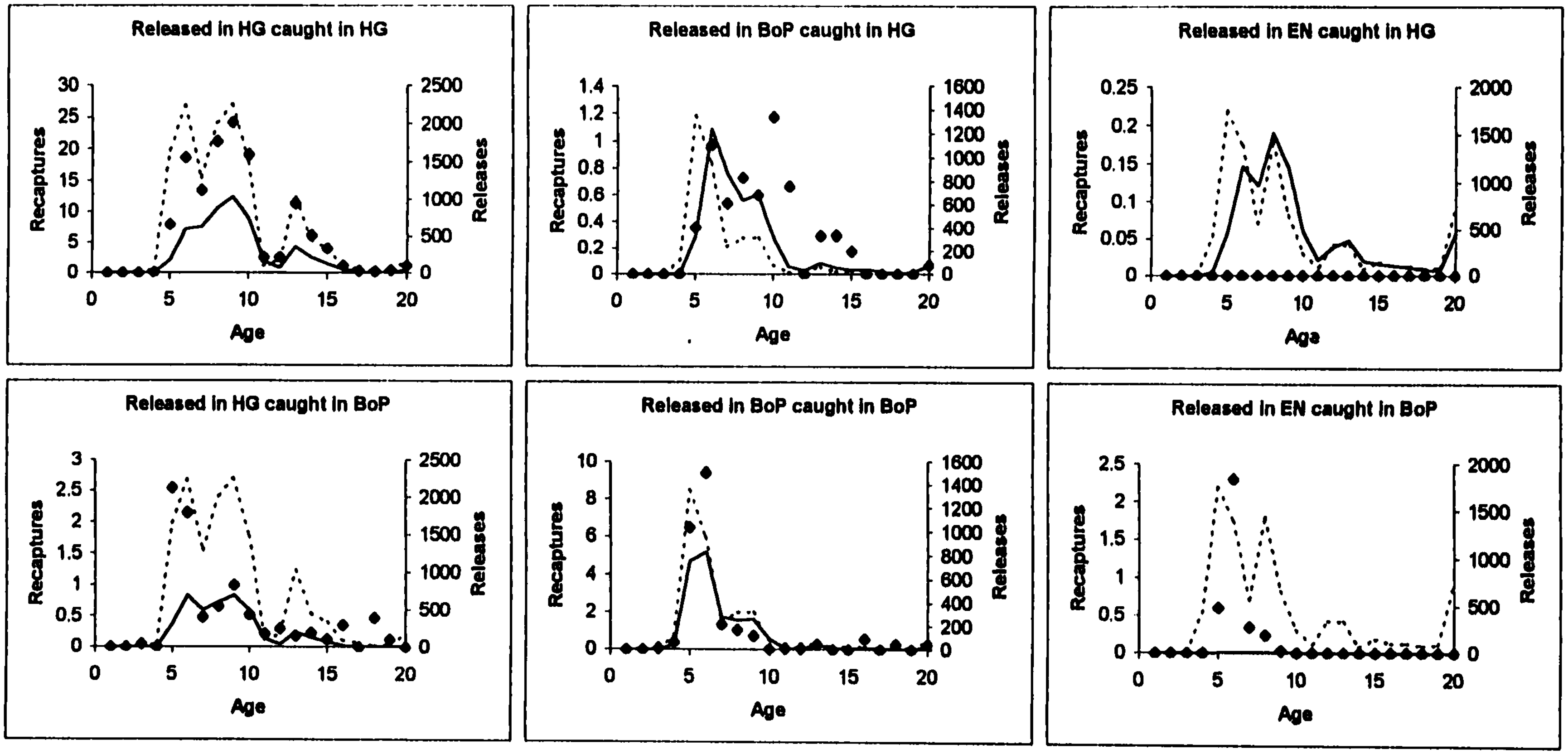

Figure 5.16. Danish seine recoveries from the 1993-94 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

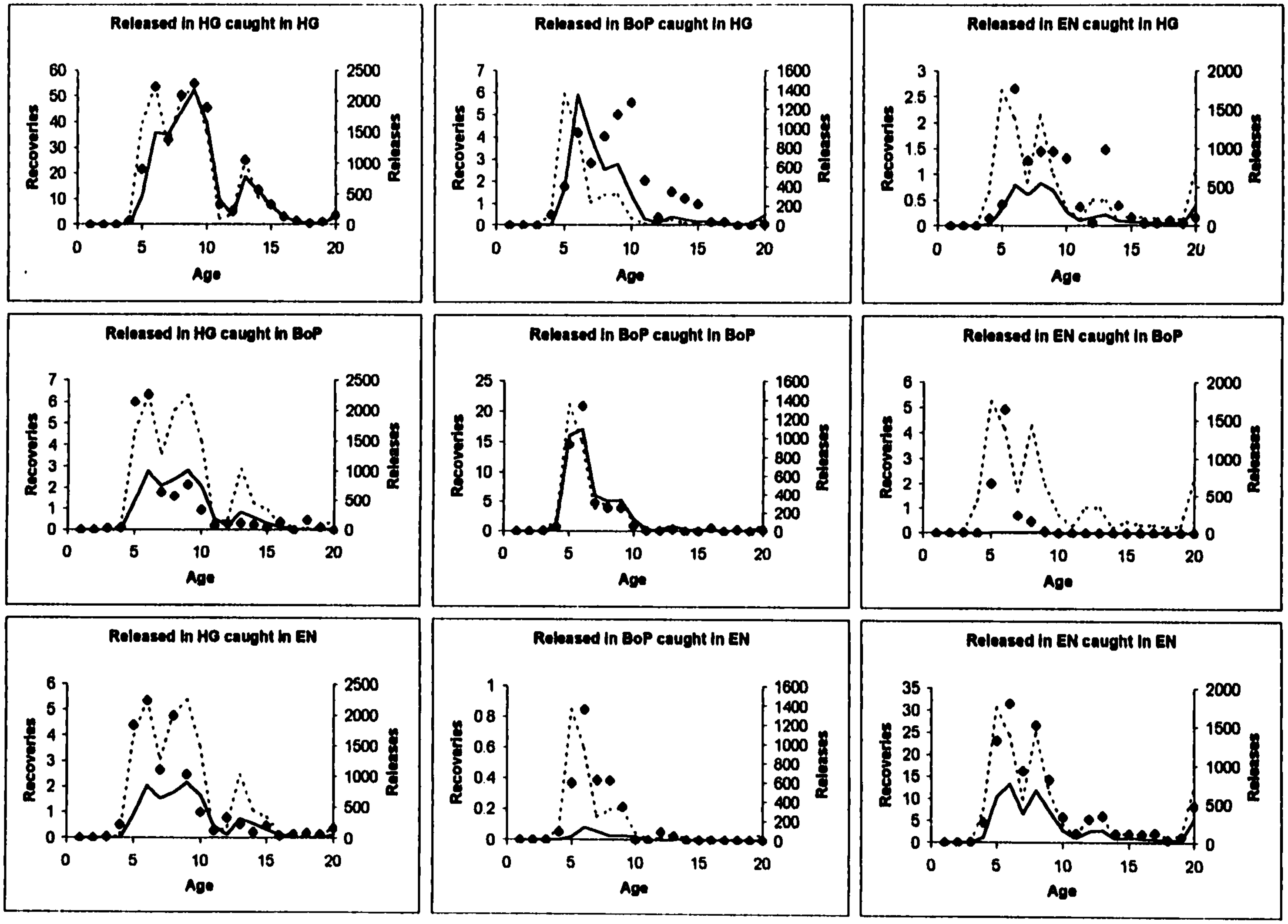

Figure 5.17. Total recoveries from the 1993-94 tagging program. Solid line is predicted recoveries, diamonds are observed recoveries and the dashed line is releases.

Initial F (2, 3 and 4)

Fixing the initial fishing mortalities at their lower bounds essentially only reduces the initial fishing mortality for BoP (Table 5.14). The BoP fishing mortality is reduced by half, but has very little effect on the results, except reducing recruitment into EN. The likelihood is only one unit larger than the base case indicating that there may not be much information in the data to determine the initial exploitation rate for BoP. This lack of information is shown in the likelihood profile on the initial fishing mortality for BoP (Figure 5.19) with 95% minimum width confidence intervals of 0.0158-0.0673 season^{-1}. Conversely, their appears to be very strong information for low estimates of initial fishing mortality for HG and EN. The minimum width confidence bounds for these two sub-stocks are 0.0150-0.0161 and 0.0100-0.0107 season $^{-1}$, respectively. When constraints are removed from the parameters the relative information content about the initial fishing mortality rates stays the same. The minimum width confidence bounds are 0.0000-0.0003, 0.1256-0.5907 and 0.0000-0.0002 season^{-1} for HG, BoP and EN respectively.

All the biomass trajectories show a similar trend (Figure 5.20), the higher the initial fishing mortality rate the lower the biomass in 1970 and the faster the stock rebuilds.

Catch-at-age weighting (5)

Down weighting the catch at age data reduces the amount of recruitment in BoP (Table 5.16). It also reduces the BoP estimate of initial fishing mortality by two thirds to the lower bound. In all sub-stocks, rebuilding is not as fast as the base case (Figure 5.21) indicating that the catch-at-age data is driving the upward trend in biomass. The negative log-likelihood is reduced for all data compared to the base case (Table 5.15). Note that the likelihood for the catch-at-age component in Table 5.15 is reduced because of the reduction in the catch-at-age sample size and the total negative log-likelihood should not be compared to the base case.

Weighting of the 1984-85 tagging program (6)

Putting full weight on the 1984-85 tagging program makes the biomass levels much higher (Table 5.16, Figure 5.21). Most of this effect is in EN and very little in BoP. The small effect in BoP is probably due to the fact that there were no releases in BoP for the 1984-85 tagging program. The negative log-likelihood is increased for the catch-at-age data and the 1993-94 tagging program.

Normal weighting on the 1983-84 BoP tagging biomass estimate (7)

Using the unweighted likelihood for the 1984 BoP biomass estimate doubles the biomass in BoP (Figure 5.22) and the BoP biomass in 1998 is a much higher fraction of the virgin biomass than in the base case (Table 5.16). BoP recruitment is estimated at its upper bound and all three initial fishing mortalities are estimated at their lower bounds. Using the unweighted likelihood for the 1984 BoP biomass has very little effect on the other two sub-stocks.

1984-85 tagging program recovery sample size (8)

Excluding the 20% under reported catch from the sample size used in the 1984-85 tagging program has very little effect on the biomass trajectories (Figure 5.21), but doubles the initial fishing mortality rate for BoP and changes the recruitment distribution between stocks (Table 5.16). The small effect on the biomass trajectories is possibly due to the down weighting applied to the data from this tagging program. The total negative log-likelihood is 12 units lower than the base case indicating that the 20% under reporting should not be included in the sample size for the 1984-85 tagging program (using the likelihood ratio test and assuming under reporting is a parameter). Surprisingly, the reduction in negative log-likelihood occurs for the catch-at-age data and the two tagging programs (Table 5.15).

Movement (9, 10, 11 and 12)

The effect of movement was investigated by fitting the model to total biomass estimates, rather than raw tag data, with and without movement. Despite no additional parameters being estimated and no detailed tagging data used in the likelihood function, the negative log-likelihood for the movement case is 89 units smaller than the non-movement case

(Table 5.17). The reduction in the negative log-likelihood is due to a better fit to the catch-at-age data indicating that there is information in the catch-at-age data on movement between the sub-stocks.

By assuming movement only occurs at age 3 and above reduce the negative log-likelihood by around 70 units. Including a logistic increase in movement with age for BoP to HG movement drops the negative log-likelihood by around another 80 units. Including a logistic decrease in movement with age for HG to BoP movement only drops the negative log-likelihood by around another 15 units.

When movement is included, BoP recruitment is estimated at it's upper bound and EN recruitment at it's lower bound, which reverses the magnitude of the recruitment for these two sub-stocks compared to when there is no movement. The initial exploitation rate in BoP is much lower when movement occurs.

There is a large difference between movement and no movement for both HG and BoP, the assessment is much more optimistic for HG and much more pessimistic for BoP when there is no movement. Without movement the BoP population would go extinct within the 20 year projection timeframe and HG rebuilds much quicker (Figure 5.23).

When there is no movement, the catch-at-age data has a big influence on the EN stock. Reduced weighting on the catch-at-age data reduces the EN virgin recruitment and cause the population to go from about B_{MSY} (approximately 24%B0) under the base case to being almost extinct for the down weighted catch-at-age sensitivity after the 20 year projection timeframe. This sensitivity to catch-at-age data is not seen when movement is modeled.

The movement cases are very similar to the integrated model base case for HG and total SNA1 biomass trajectories, but higher than the base case for BoP and lower than the base case for EN.

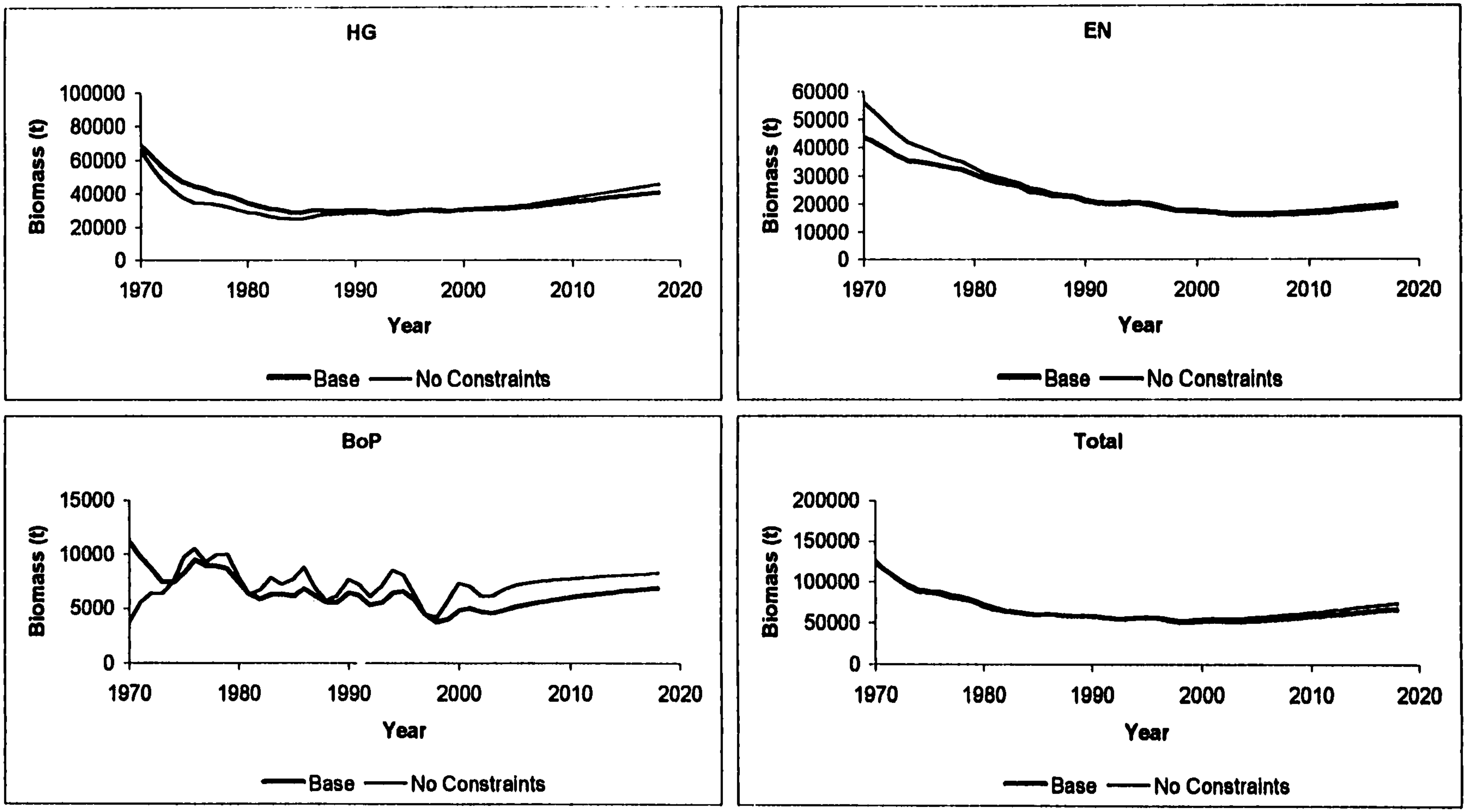

Figure 5.18. Biomass trajectories from the sensitivity analysis with no constraints on the parameters.

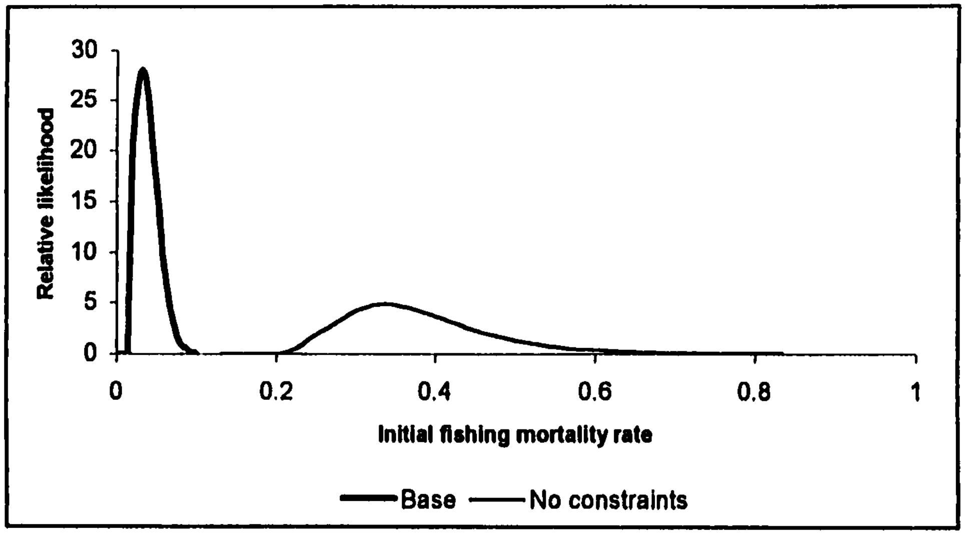

Figure 5.19. Likelihood profiles for the initial exploitation rate in BoP from the base case and the unconstrained sensitivity. Profiles for HG and EN are not plotted because they are estimated at their bounds and essentially have no uncertainty.

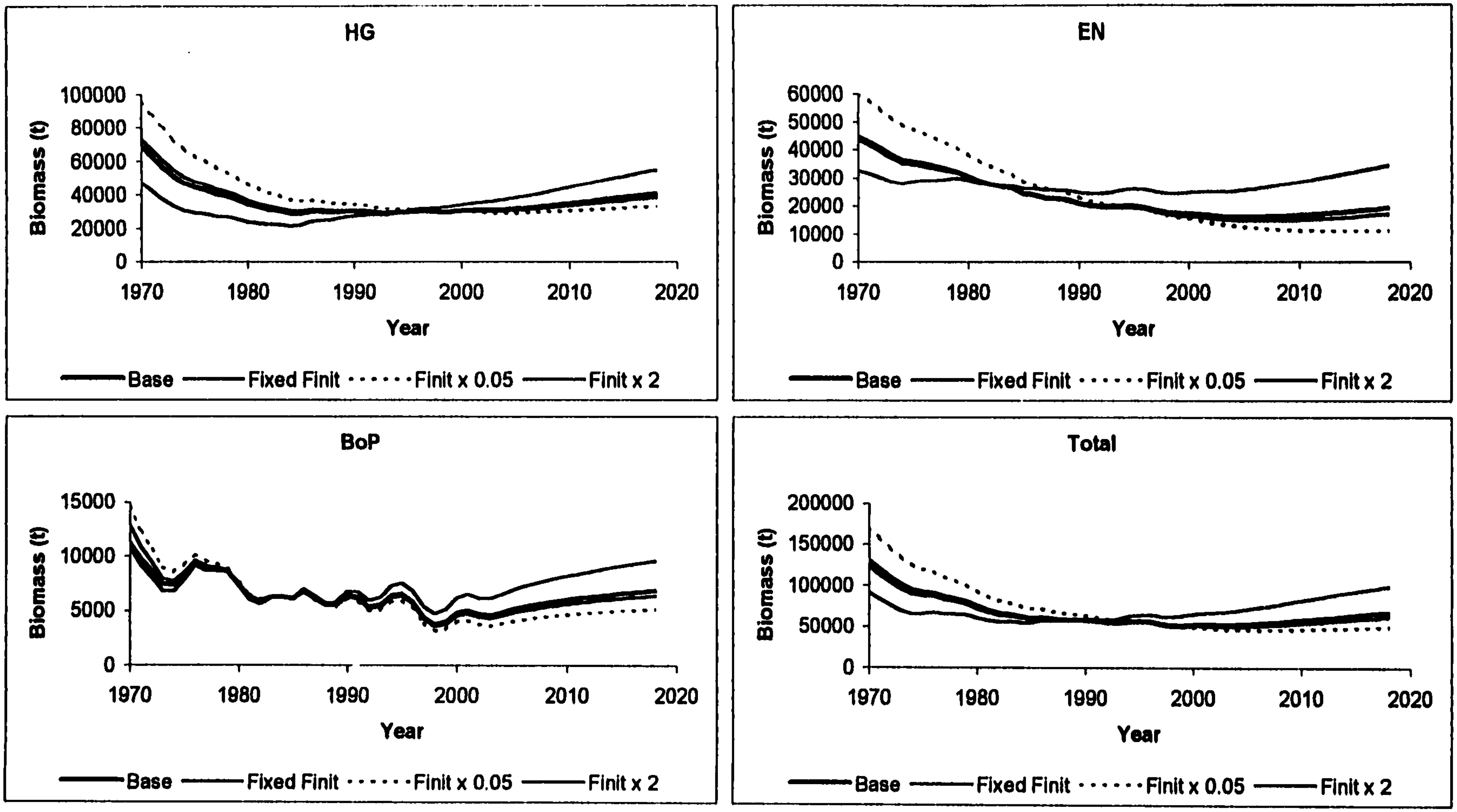

Figure 5.20. Biomass trajectories from the sensitivity analyses with initial fishing mortality rate fixed.

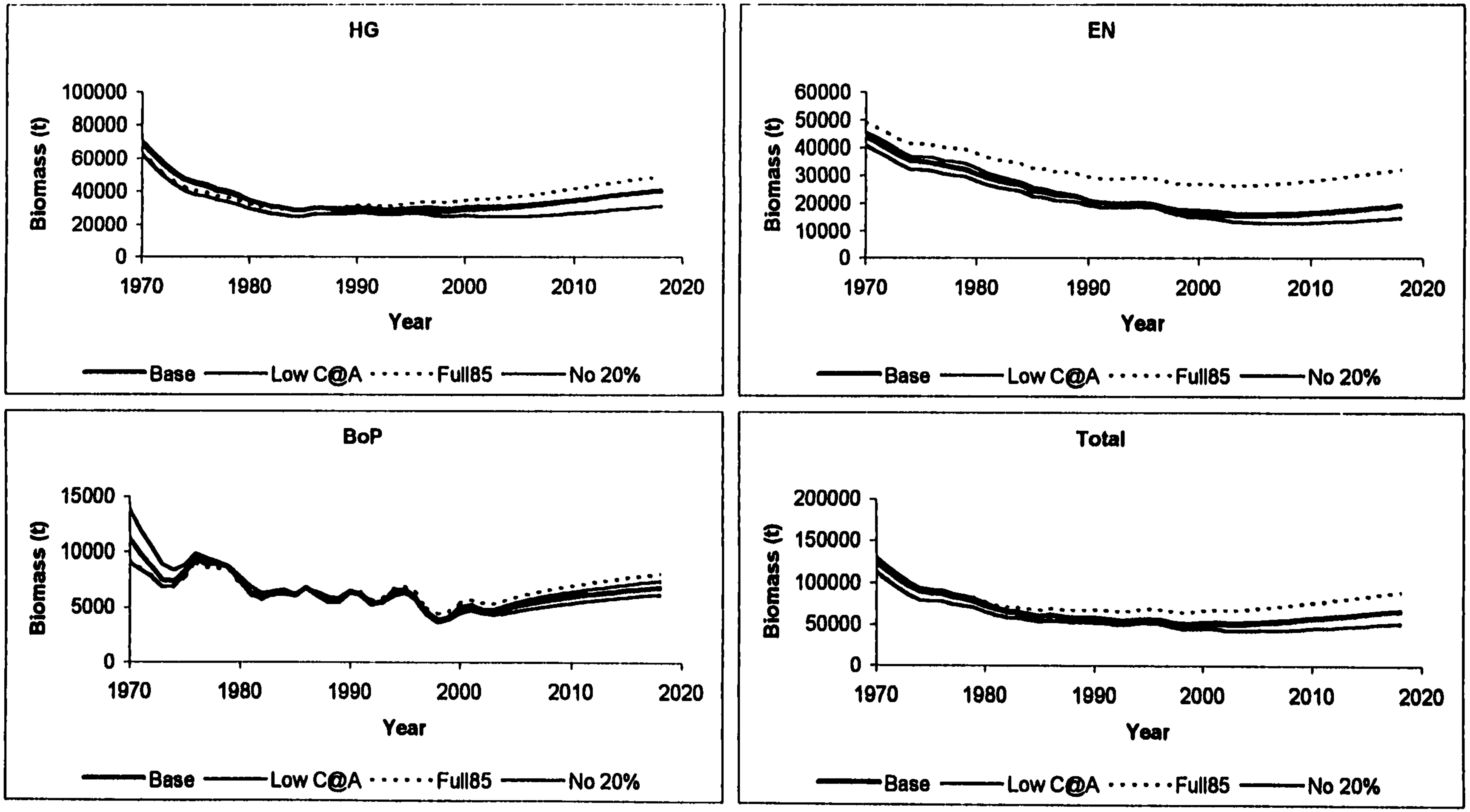

Figure 5.21. Biomass trajectories from the sensitivity analyses with reduced weight in the likelihood function for catch-at-age data (Low C@A), full weight in the likelihood function for the 1984-85 tagging program (Full85) and not incorporating the 20% unreported catch in the recovery sample size for the 1984-85 tagging program (No 20%).

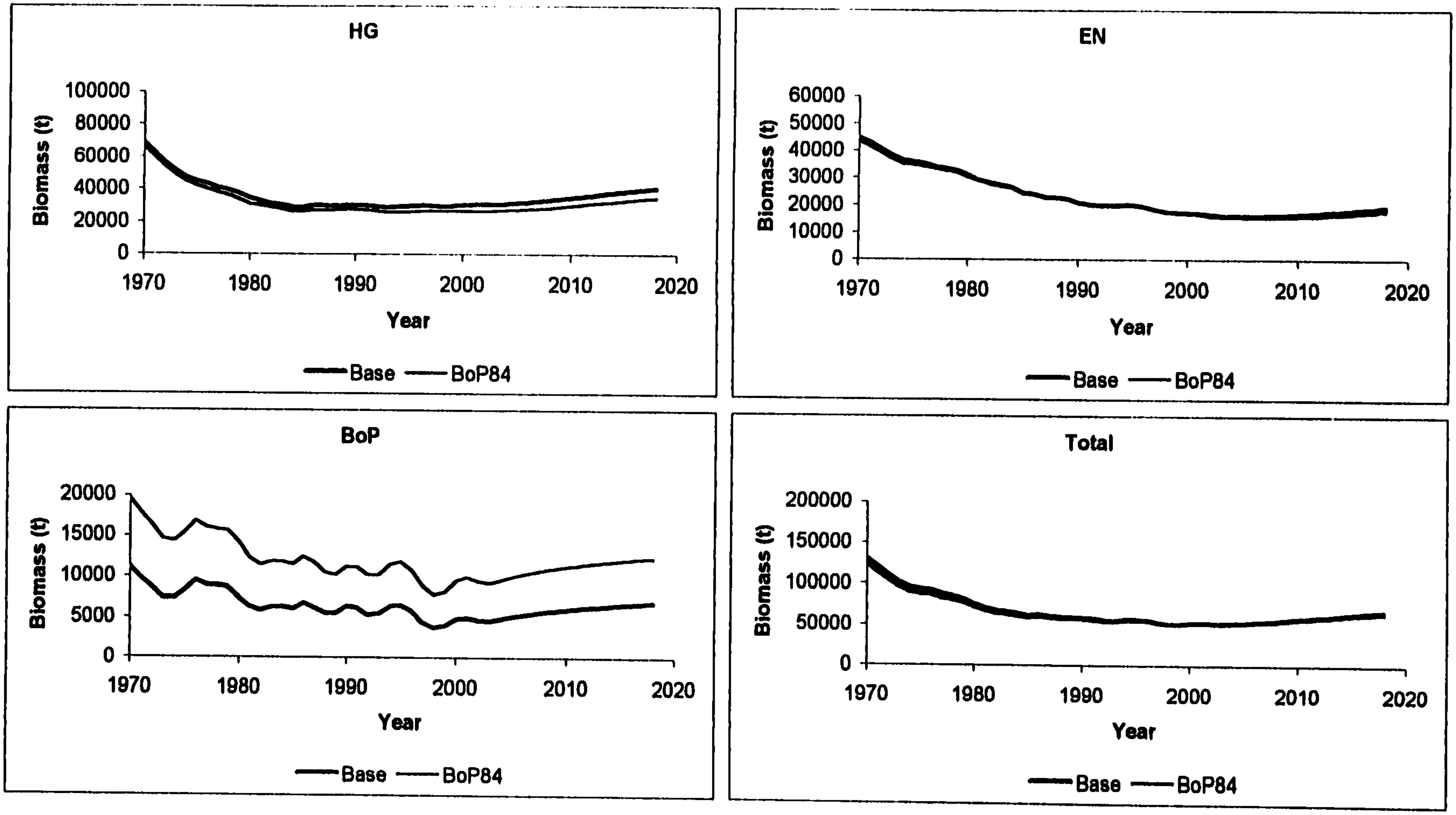

Figure 5.22. Biomass trajectories from the base case and the sensitivity analysis using an unweighted likelihood function for the 1983-84 BoP tagging biomass estimate.

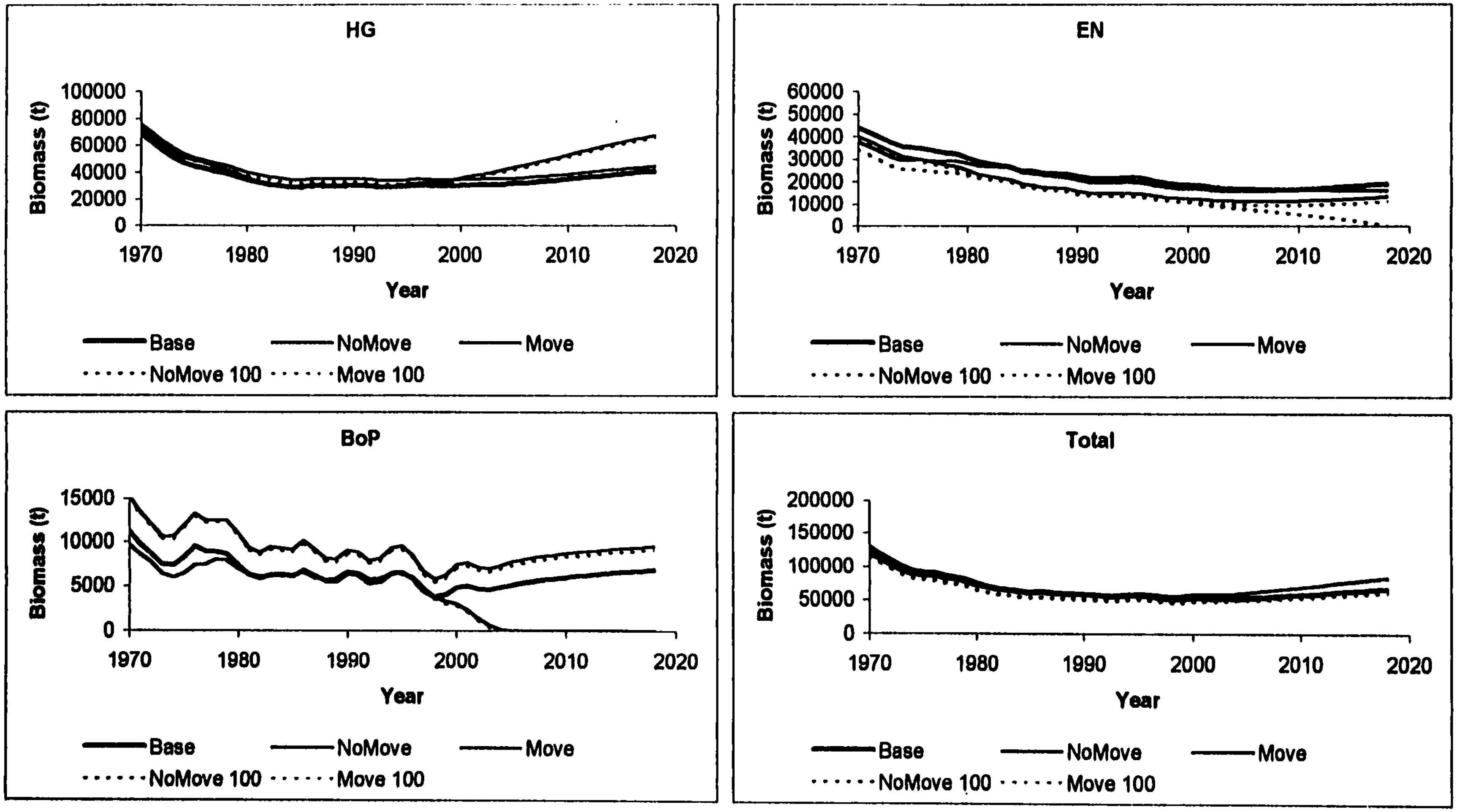

Figure 5.23. Biomass trajectories from the sensitivity analyses which fits to estimates of total biomass.

5.12 Conclusions

An Integrated Tagging and Catch-at-Age Analysis (ITCAAN) is applied to the SNA1 snapper fishery. Movement between the three sub-stocks is a major dynamic included in the model and has a large influence on the results. Unrealistic estimates of initial fishing mortality indicate that the model is misspecified, but the sensitivity analyses suggest that the overall results are quite robust to a number of assumptions and that the population should rebuild. Incorporation of movement into the assessment model appears to have the greatest effect on the results for the individual sub-stocks. The stock assessment of the total SNA1 stock is most sensitive to the initial fishing mortality rates, to the weighting of catch-at-age data and to the weighting of the 1984-85 tagging program.

5.12.1 General status of the stocks

All three sub-stocks are most likely to have current biomass levels that are below the levels that support Maximum Sustainable Yield (assuming the biomass that supports MSY is approximately 24% of the virgin biomass, Annala and Sullivan 1997), but will rebuild under current removals. EN is the only sub-stock that is unlikely to rebuild to a biomass that would support MSY within the 20 year projection timeframe. The results overall are fairly consistent across all the sensitivities investigated, except when movement between HG and BoP is ignored. The exchange of individuals between the three sub-stocks, particularly between HG and BoP, is large and the decision to ignore movement in the assessments can be the difference between a predicted rebuild and a predicted collapse.

There is a need for the investigation of management systems for interacting sub-populations. The research presented in this chapter focuses on assessment methods and only presents a simple management evaluation of a deterministic forward projection under current removals. Research that investigates management strategies for systems with interacting sub-populations needs to be applied to the SNA1 stock. In the comparisons presented above, MSY is assumed to be the same as estimated in previous assessments (around 24%, Annala and Sullivan 1997). It is unknown what effect interactions between the sub-populations will have on estimates of MSY and the biomass level that will support MSY (B_{MSY}). Factors including estimated selectivity and the differences in growth rates between the sub-populations will influence MSY calculations. It is possibly that the total biomass of SNA1 is equal to B_{MSY}, but the distribution of biomass between the sub-stocks does not produce MSY or the catch distribution between the sub-stocks is not optimal.

5.12.2 Starting in 1970

The initial fishing mortality rates in 1970 are critical parameters in the model. The higher the initial fishing mortality rate the faster the stock rebuilds (Figure 5.20). This faster rebuild occurs because catch from 1970 to 1985 comes from recruitment rather than from accumulated biomass, increasing the estimates of recruitment and reducing the 1970 biomass. Higher recruitment indicates that the stock is more productive and causes the population to rebuild much faster under the current catch levels. The assessment has difficulty estimating values for the initial fishing mortality rates; estimates of initial fishing mortality rates for HG and EN are at their lower bounds and the estimate for BoP has large confidence intervals. Removing the constraints on the initial fishing mortality rates causes HG and EN to be estimated as unexploited in 1970; this is despite of it being well documented that there has been significant catch from both sub-stocks prior to 1970 (Gilbert 1994). In addition to the unrealistic initial fishing mortality rates, the majority of recruitment is transferred from HG in the base case to BoP when the parameters are unconstrained. This result is contrary to the evidence from trawl surveys which show that most of the juvenile abundance is in the HG (Langley 1993). These unrealistic values are precisely estimated indicating that the model is misspecified. The misspecification could be in a fixed parameter value (e.g. natural mortality), a main structural part of the model (e.g. stock recruitment relationship), a minor structural part of the model (e.g. selectivity slowly changing over time) or part of the fitting procedure that describes how the predicted values relate to the observed values (e.g. process error in selectivity).

It is unknown what causes the estimates of initial fishing mortality rates to be low for HG and EN. After a large number of sensitivity tests (not reported here), the only analysis that obtained estimates of initial fishing mortality rates above the lower bounds was a model with no movement and fixed constant selectivity over age that was fit to total biomass estimates, catch-at-age data and the pre-recruit trawl survey index. It appears from the results presented in this chapter that the data prefer a decline from 1970 to the 1980s due to fishing of accumulated biomass rather than due to fishing of recruitment, indicating the there is a large difference between the biomass levels in 1970 and in the 1980s and 90s. Below I have listed a number of possible model misspecifications that may be the cause of the unrealistic initial fishing mortality rates.

- *Increasing the age of the plus group.* The average size of a snapper is still increasing at age 20, which is the age used for the plus group in the current assessment (Annala and Sullivan 1998) and the analyses presented in this dissertation. Therefore, the average weight of a fish in the plus group is underestimated, and the model may need to reduce the initial fishing mortality rate to make up for the lost biomass. Increasing the average weight of an individual in the plus group by 25% (not reported here) did not aid in the estimation of the initial fishing mortality rates. It is possible that there is a more complex model behavior involved in the age of the plus group and the only way to tests this is to restructure the model to have a larger plus group. Most data is only available up until age 20; therefore, increasing the age of the plus group will require modification of the likelihood calculations. Increasing the age of the plus group would also greatly increase the time required to estimate the parameters.
- *Stock-recruitment relationship.* The current assessment does not use a stock-recruitment relationship, but bases recruitment on a temperature-recruitment relationship. The data used to derive the temperature-recruitment relationship is only available over a short period where the stock size has remained fairly constant. Despite of the well documented relationship between recruitment and temperature for snapper (Francis 1993) there is no data to rule out an underlying stock-recruitment relationship. A stock recruitment relationship will allow more recruitment in 1970 when the population size is high compared to the 1980s and 90s when the population

size is low. The higher recruitment in 1970 relative to the 1980s and 90s may allow for higher initial fishing mortality rates in 1970 which will be offset by higher virgin recruitment levels to give similar biomass levels in 1970 to a situation with no stock recruitment relationship. The stock recruitment relationship will reduce recruitment in the 1980s and 90s allowing the biomass levels to fit the tagging data despite the increase in virgin recruitment.

- *Lower natural mortality rate*. Sensitivity analyses (not reported here) show that low levels of natural mortality correspond to more realistic (higher) initial fishing mortality rates in 1970. When the natural mortality rate for the integrated model application to the SNA1 stock was reduced the unconstrained initial exploitation rate for HG increased (0.025 and 0.040 for M=0.06 and 0.04 respectively), but the initial exploitation rate for EN stayed at zero. The natural mortality has recently been increased from 0.06 to 0.075 based on data from the west coast snapper fishery. This data needs to be re-evaluated to determine the possibility of lower natural mortality rates. It would be possible to use the Integrated Modeling approach to integrate this data into the analysis and allow for the estimation of natural mortality simultaneously with the other parameters.
- *Age-structured natural mortality*. Higher rates of natural mortality for younger fish may help to explain the low estimates of initial fishing mortality rates. Higher rates of natural mortality for younger fish will increase the 1970 population size where exploitation rates are low relative to the population size in the 1980s and 90s where exploitation rates are high. The data from the west coast snapper fishery indicate that natural mortality may be higher for younger individuals. As mentioned above this data could be integrated into the analysis, but care has to be taken because any estimates of age-specific natural mortality will be confounded with selectivity.
- *Temporal changes in selectivity*. The results in this chapter and those of Maunder and Starr (1998) have indicated temporal changes in selective for young ages due to annual variations in growth rates or other factors. It is possible that these temporal changes in selectivity may explain the low initial fishing mortality rate estimates.

Modeling of temporal changes in selectivity for the SNA1 assessment will be limited by the short timeframe of the catch-at-age data available for this fishery.

The estimates of low initial fishing mortality rates cause great concern because they are important parameters in the model and especially considering that they are precisely estimated and significantly different from expectations based on prior information. The only reassuring factor is that the unconstrained sensitivity analysis gives very similar results to the base case. To obtain a good assessment and understanding of the SNA1 stock it is important to determine the initial fishing mortality rates in 1970. Research needs to be directed to developing methods that can estimate the initial fishing mortality rates (e.g. the suggestions listed above).

5.12.3 Movement

Movement between the three SNA1 sub-stocks influences the results of the stock assessment. Without including movement in the assessment the BoP sub-stock goes extinct under current removals, the HG stock has a much faster rebuild rate, and the EN sub-stock assessment is much more sensitive to the weighting given to catch-at-age data. The results suggest that modeling the HG and BoP sub-stocks independently would cause biased estimates, which supports the combining of the HG and BoP sub-stocks in the current assessment. The analysis presented in this chapter have shown that explicitly modeling of the interaction between the sub-stocks is possible and should be carried out in future assessments.

Age-specific movement appears to be important for the dynamics of the SNA1 stock. Young fish move from HG to BoP and older fish move from BoP to HG. This age-structured movement explains the higher proportion of young fish in BoP. HG releases caught in BoP are greatly underestimated for ages 5 and 6 indicating that most of the movement from HG to BoP is young fish of ages around 5 and 6. The underestimation of HG releases recovered in EN for young ages also suggests movement of young fish from HG to EN. The model also consistently underestimates the number of BoP releases recovered at ages 8 to 15 years in HG giving more evidence to age-specific movement from BoP to HG. The fit to the catch-at-age data is greatly increased when movement is included in the model. The negative log-likelihood for the catch-at-age data drops by 88 units indicating that the catch-at-age data provides information on movement and probably age-specific movement.

Seasonal movement is very strong in the SNA1 stock (Crossland 1982). Unfortunately, there is not enough information in the data to estimate all the movement parameters for each season independently. The lack of information is due to the releases being all from a single season. The number of parameters in the model was reduced by modeling the seasonal distribution of movement with a normal distribution. Even with this modification, the mean season of movement has to be fixed to obtain convergence. The inability to estimate seasonal movement is most likely due to the tags being released in only one season. If the mean season of movement was fixed at the incorrect season, the variance parameter would be increased to allow movement in the other seasons. Movement from BoP to HG is equally divided between all seasons (Figure 5.6) indicating that either the mean season for this movement was fixed at wrong level or movement occurs in all seasons. It may be possible to define a seasonal movement sub-model that performs better than the one used in this study, but it is likely that releases in all seasons are needed to estimate seasonal movement.

5.12.4 Estimation of recruitment

The model had difficulty estimating recruitment for the sub-stocks. Even with priors constraining the variation in recruitment, the model could not estimate recruitment as individual year-class strengths for BoP and EN. If convergence was obtained, recruitment in 1971 was many times greater than the average recruitment. The high recruitment in 1971 increased the biomass level in 1970s compared to virgin biomass and this estimate is likely to be driven by the same problems associated with the low estimates of initial fishing mortality rates. Also, there is very little data (possibly some information from the 1984-85 tagging program) on the relative strength of the 1971 cohort. For these reasons, recruitment in BoP and EN was assumed to follow the temperature recruitment relationship. There is some evidence in BoP that the temperature recruitment relationship does not hold for all years; for example the BoP 1990 year class is always over estimated by the model. The EN catch-at-age data is too variable to determine if recruitment does not follow the temperature recruitment relationship.

For future assessments of the SNA1 stock I recommend that the temperature recruitment relationship is used to describe the underlying annual recruitment fluctuations of each sub-stock, but the annual fluctuations are allowed to vary around this relationship. Therefore, annual recruitment strengths would be allowed to differ from the relationship if there was supporting information in the data. This would be particularly useful for the BoP and EN sub-stocks, where there is evidence that recruitment strengths for some years differ from the temperature-recruitment relationship. Implementation would involve the estimation of area-specific annual deviations that are constrained using a prior distribution.

$$r_{y,l} = \exp\left(\alpha + \beta T + \varepsilon_{y,l}\right)$$

where $\varepsilon_{y,l}$ has a normal distribution with mean 0 and specified standard deviation.

The BoP biomass trajectory shows much greater annual fluctuations than the other two sub-stocks. These fluctuations are due to BoP's small population size and high proportion of young fish making it much more sensitive to recruitment fluctuations. BoP biomass shows a very strong correlation with BoP relative recruitment five years earlier (Figure 5.24).

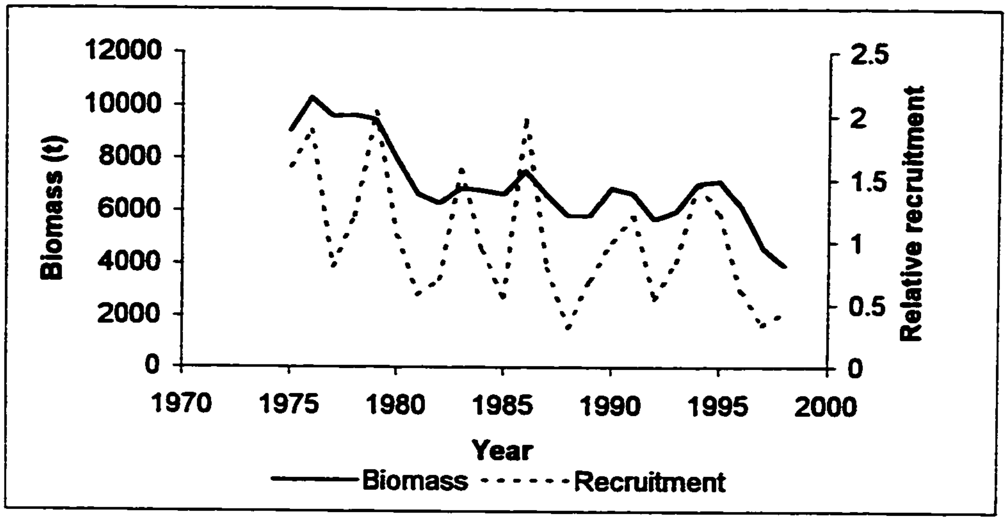

FIGURE 5.24: Comparison of BoP biomass with relative recruitment in BoP five years earlier

5.12.5 Estimation of selectivity

Reasonable selectivity estimates were obtained for the three main gear types (longline, single trawl and Danish seine). Because of the lack of catch-at-age data the model could not estimate selectivity for the other commercial gear group. There is no catch-at-age data for the other commercial gear group and the only information for it's selectivity is from the 1984-85 tagging program. Previous SNA1 assessments have been unable to estimate selectivity and recruitment simultaneously (Annala and Sullivan 1997). The integrated model estimated the recruitment and selectivity parameters simultaneously, but a number of restrictions were applied to both selectivity and recruitment. The number of selectivity parameters was reduced by assuming that the shape of the selectivity curve for each gear did not change between sub-stocks. Only the age at full selectivity changed between sub-stocks. Recruitment was simplified for BoP and EN by assuming that it also followed a temperature recruitment relationship. The ability to estimate selectivity and recruitment simultaneously was not a result of integrating the tagging data with the population dynamics model. The model fit to total biomass estimates was also able to estimate selectivity and recruitment simultaneously.

There is evidence that gear selectivity has changed between the 1984-85 tagging program and the 1993-94 tagging program. The recoveries of younger individuals are under estimated in the 1984-85 tagging program. The under estimation is due to the estimated selectivity for young individuals (Figure 5.25); this difference could mean that selectivity is different in 1985 than in the 90s when most of the catch-at-age data was collected. If selectivity is assumed to be constant over age there is an improvement in the fit to the 1984-85 tagging program data, but the fit to the catch-at-age data for young individuals is poor (Figure 5.26). It is possible that the introduction of the Quota Management System (QMS) in 1986 caused a change in selectivity. The QMS may have changed fishers behavior by allowing them to target areas with larger fish that may be more profitable without having to reduce their overall catch and total profits. This difference could also be due to a number of other factors. One problem with determining selectivity-at-age is the influence of selectivity-at-length on the release phase. Selectivity-at-length will positively bias the average lengths of releases for the young age-classes. Therefore, there will be a difference in the selectivity of tagged fish and the selectivity of the total population for the young age-classes. The 1984-85 tagging program tagged more of the younger age-classes than the 1993-94 tagging program, but it is unknown if this difference has any effect on the results. There is a large variation in the growth rates of young age-classes, and this can greatly effect selectivity estimates (Maunder and Starr 1998). The 1985 four and five year olds were estimated to be 36% and 91% recruited respectively, and the 1994 four and five year olds were estimated to be 3% and 68% recruited respectively. These differences could also have an influence on the estimates of selectivity.

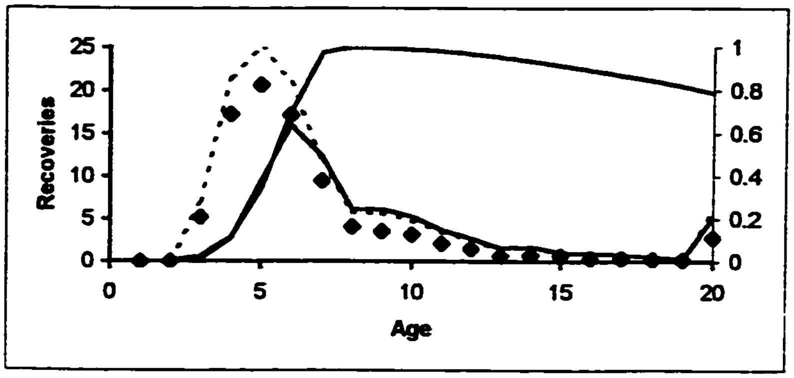

FIGURE 5.25: The effect of selectivity on the longline recaptures in HG during Autumn 1985 of HG releases. The Diamonds represent the observed recoveries. The black solid line represents the predicted recoveries. The dashed line are the number releases scaled to a maximum of one. The solid gray line is the estimated selectivity curve for longline in HG.

5.12.6 Discrepancies in return rates

Previous assessments have identified a number of discrepancies in the tag return rates. The length stratified Danish seine relative recovery rates from the 1993-94 tagging program decline over time, and the rates are much higher than for other gears (Gilbert et al 1996). The higher recovery rates for Danish seine are only clearly evident in the HG releases caught in HG. The integrated model does not explain the reduction in return rates over time. By summer 1995 the model return rates are at the same level as the observed return rates (Figure 5.27). The higher return rates for Danish seine are not observed in the overall results of the 1984-85 tagging program (Figure 5.11), but can be seen by observing seasonal recoveries. Recaptures by Danish seine are under estimated by the model in the first year but overestimated in the second year (Figure 5.28). Explicit modeling of tag clumping and preferable fishing grounds for the different gears may be needed to determine the discrepancy in return rates for Danish seine.

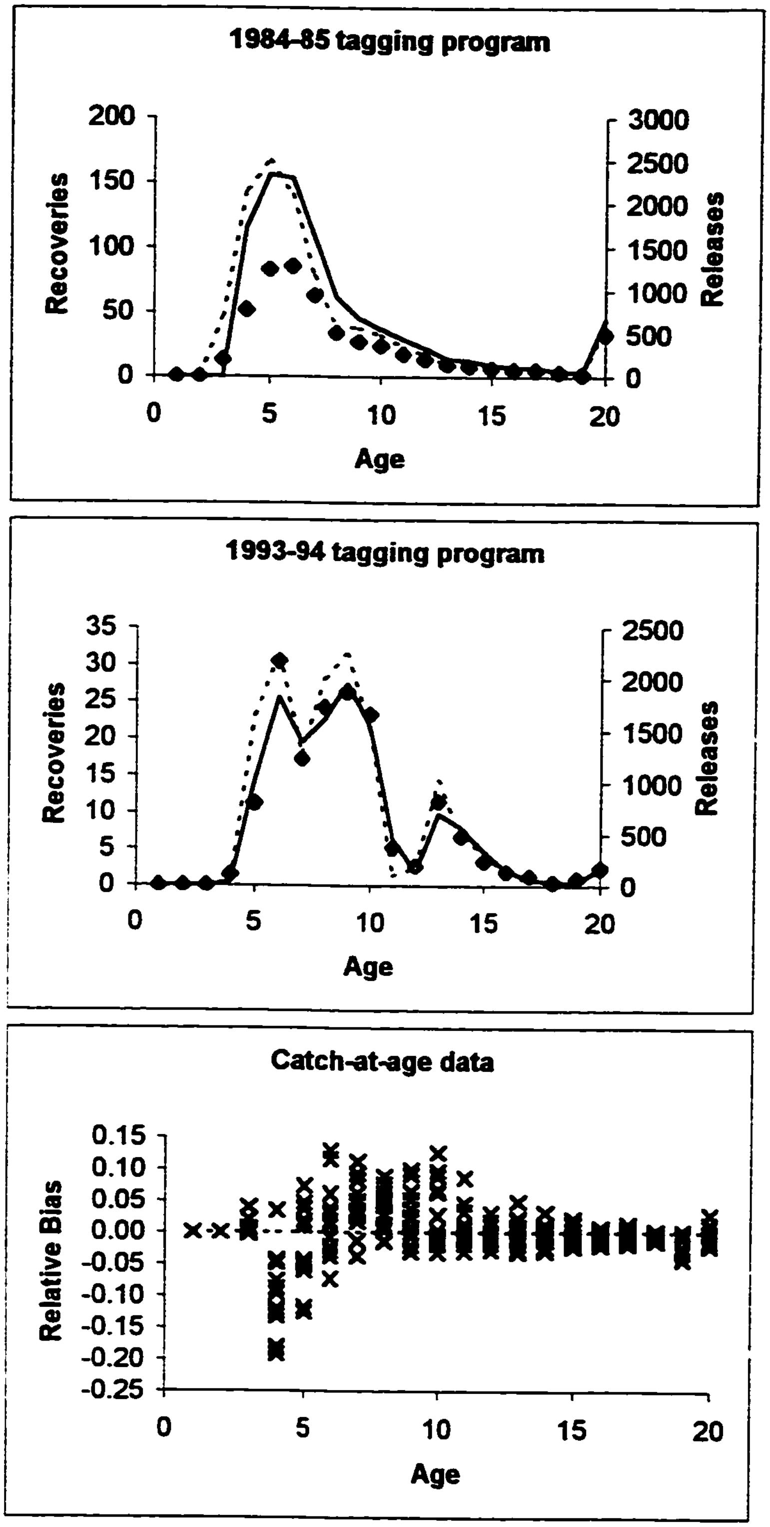

FIGURE 5.26: Fit to the 1984-85 (top) and 1993-94 (middle) tagging program HG releases recovered in HG by longline and the residuals from the fit to long line catch-at-age data (bottom) when selectivity is constant over age.

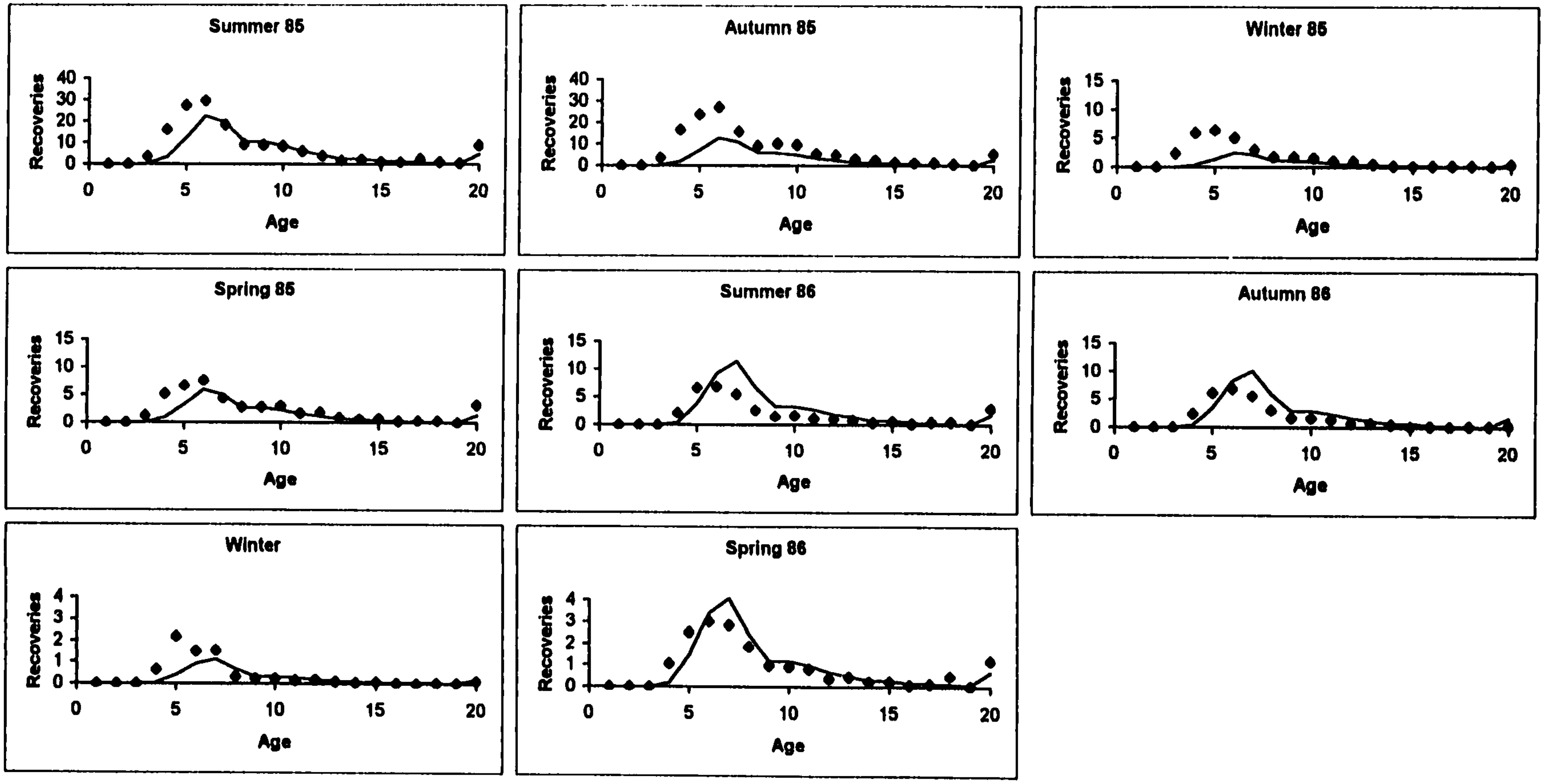

Figure 5.27. Recoveries of 1984-85 HG releases caught by Danish seine in the HG.

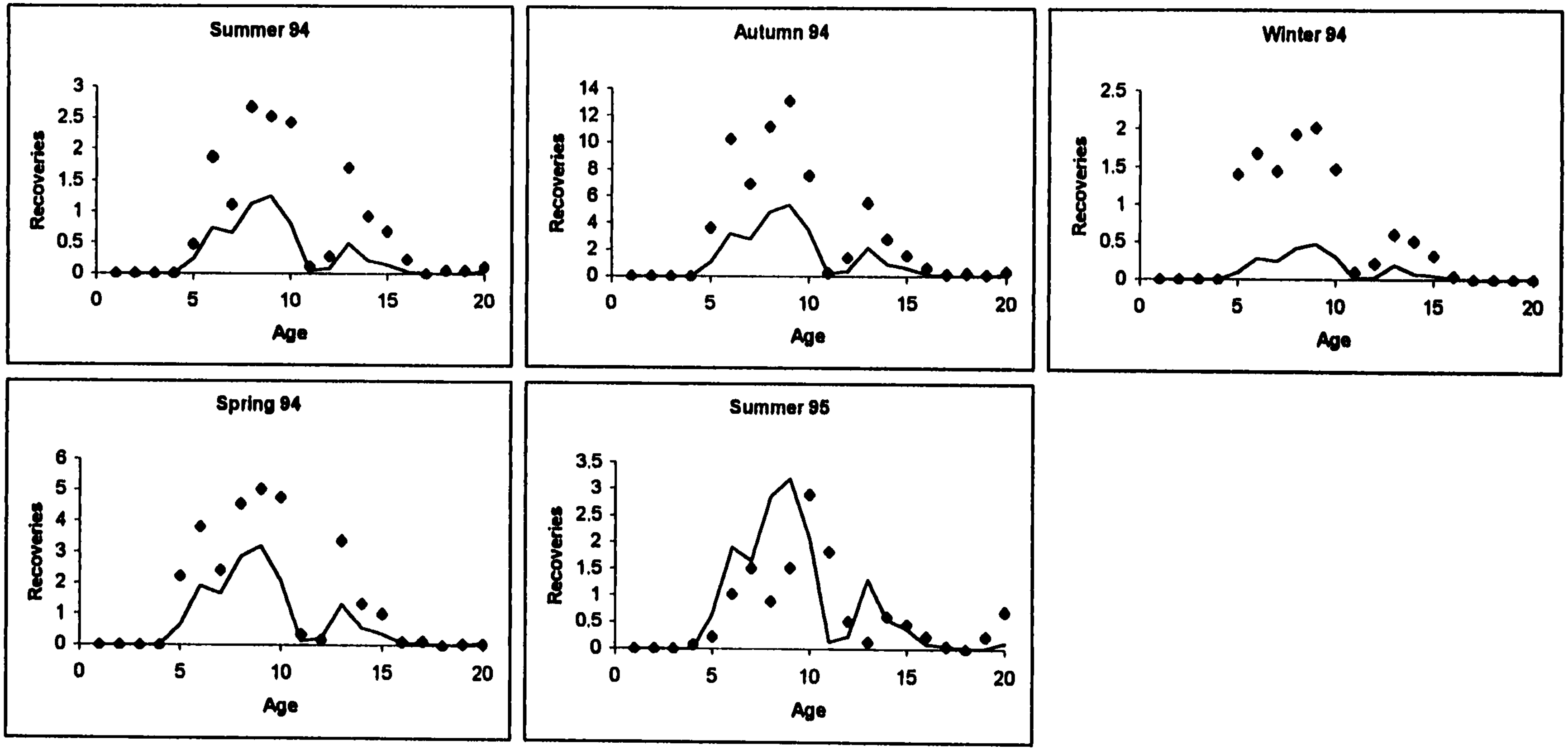

Figure 5.28. Recoveries of 1993-94 HG releases caught by Danish seine in the HG.

The 1984-85 tagging program showed seasonal differences in recovery rates (Gilbert et al. 1996). The Integrated Model overestimates HG releases that were recovered in HG during Spring and Summer by longline and possibly single trawl. The model consistently under estimates recoveries in Spring and Summer for the other commercial gear group. Because recoveries were reported by fishers, it is unknown whether there is a bias in the season that was reported or if there is a real difference in seasonal recovery rates. Extending the number of years of the 1993-94 tagging program may have helped detect seasonal return rates and they would be unaffected by fisher reporting bias.

There may be a problem of either reporting rates or designation of catch from other commercial gear group because the difference between predicted and observed recoveries is quite different from the long line, single trawl and Danish seine gears. Selectivity is not estimated for this gear, but estimation of selectivity is not likely to modify these results because they are consistent for all ages.

The model overestimated longline, single trawl and Danish seine recoveries for all seasons in 1987. This indicates that the observed return rate for 1987 may be poor because fishers underreported recoveries or there was an increase in tag loss. The 1987 data should either be dropped from the analysis or an additional tag loss parameter estimated.

Longline catch has higher recoveries for trawl released tags compared to longline released tags. The computer program size and memory requirements of the integrated model made it impractical to implement different release gear types, and this discrepancy could not be investigated. With the current developments in computing power, it is likely that a more detailed model that differentiates between release gear types could be possible in the future. This model could then be used to investigate this discrepancy.

The model underestimates the recovery of 1993-94 EN releases in all areas, but overestimates recoveries of EN releases caught in HG and EN for the 1984-85 tagging program. The sensitivity that gives full weight to the 1984-85 tagging program increases the biomass in all sub-stocks especially EN reducing the number of recoveries. This indicates a discrepancy between the two tagging programs, and there could possibly be an error in the estimates of tagging mortality for the EN releases in 1993-94.

5.12.7 Overall conclusions

This study has shown that the Integrated Model is a useful tool to investigate the assessment of the SNA1 snapper stock. One of the main recommendations that can be taken from this study is that movement between the sub-stocks should be incorporated into the assessment, if there is a management desire to know the status of each of the sub-stocks. Another major area of concern highlighted in this study is the need to obtain good estimates of the initial fishing mortality rates in 1970. The model misspecification that causes very low estimates of the initial mortality rates needs to be found and corrected.

The following is a list of recommended changes for the next assessment of the SNA1 stock.

- Model the SNA1 stock as three interacting sub-stocks.
- Include a stock recruitment relationship in the population dynamics model.
- Increase the age of the plus group.
- Re-evaluate the rate of natural mortality and the possibility of age-specific natural mortality.
- Estimate independent annual selectivity parameters for ages 4 and 5.
- Estimate two sets of selectivity parameters, one for before the Quota Management System was introduced and one for after.
- Allow for variation around the temperature-recruitment relationship.

Chapter 6: Current Assessment

6.1 Introduction

This chapter describes the current assessment of the SNA1 snapper stock (reported in Annala and Sullivan 1998). The results from this analysis can be compared with the results of the Integrated Model.

The assessment of the SNA1 snapper (*Pagrus auratus*) fishery off the north east coast of the North Island, New Zealand is the responsibility of the Snapper Fishery Assessment Working Group (FAWG) administered by the Ministry of Fisheries. This assessment has been evolving at a dramatic rate since the early 1990s. This rate of change has been accelerated by the involvement of fishery scientists employed by the Fishing Industry who provide alternative assessments (Maunder and Starr 1998, Maunder 1998) and the consequent cooperation between industry and Government scientists (Gilbert et al. 1996; see Starr et al. 1998 for a discussion about cooperation between industry and government in fishery assessment).

Assessments of the SNA1 stock in the early 1990s used an age-structured model and the total catch history to project the population forward from an unexploited stock size in 1850 (Gilbert 1994). The results from this assessment were highly dependent on assumptions about decadal scale recruitment levels that were derived from a temperature-recruitment relationship (Gilbert 1994). Concerns with the uncertain catch history and the high sensitivity to assumptions about recruitment promoted the development of a short-term model (Gilbert and Sullivan 1994). Catch-at-age data were added to the short-term model to avoid the use of the temperature-recruitment relationship (Maunder and Starr 1998). The short-term model was abandoned because of the high uncertainty in the quantities of interest (maximum sustainable yield and current status, Gilbert et al. 1996, Maunder 1998) and finally a total catch history catch-at-age model was developed (reported in Annala and Sullivan 1997).

Despite the complex catch-at-age analysis used, there are still many problems with the SNA1 assessment (Maunder 1998). A major concern is the use of a fixed temperature-recruitment relationship to determine recruitment for temperatures beyond the range of observed data and for years well before the establishment of the relationship. The assumptions contained in the temperature recruitment relationship determine both the current status of the population and the future productivity of the population (Maunder 1998). Maunder (1998) suggests that a mid-term model would be more appropriate because it reduces the reliance of the model on historical recruitment and catch, but will also produce results that have less uncertainty than the short-term model. The starting year suggested was after the period of Japanese catch that was of unknown size. This will require starting from an exploited population size and the estimation of at least one additional parameter, the initial population size.

Estimates of uncertainty are important in the management of the SNA1 fishery. Bayesian analysis has become an accepted method to determine uncertainty in an assessment (Punt and Hilborn 1997). The Bayesian method has an advantage over traditional methods because it allows for uncertainty in parameters that are usually given fixed values. Uncertainty is incorporated by including prior distributions for these parameters. Bayesian analysis also allows for the calculation of probabilities by integrating across all parameter values. Bayesain analysis has been previously used to assess the SNA1 stock (Maunder 1998), but before this analysis, has never been presented to decision makers (reported in Annala and Sullivan 1998).

The SNA1 stock is divided into 3 sub-stocks; Hauraki Gulf (HG), Bay of Plenty (BoP) and East Northland (EN). For assessment purposes HG and BoP are combined into a single stock and EN is assessed separately. For each stock, there has been two tagging programs estimating biomass for the 1984-85 fishing year (1983-84 for BoP, but it is used as an estimate for 1984-85 to be consistent with the HG estimate) and 1992-93 fishing year. These two tagging programs refer to years 1985 and 1993 in the text following the convention to label fishing years by the highest calendar year they cover. Catch-at-age data has been collected for different gears and areas since 1989 (Davies and

Walsh 1995). A time series of one year old abundance from a pre-recruit trawl survey, starting in 1983, is available for most years (Francis 1993).

The Sapper Working Group agreed on a number of management reference points and performance indicators to assess the status of the SNA1 population (Annala and Sullivan 1998). These reference points and performance indicators are the main focus of this assessment.

1) The point estimate of current stock status, B_{1998}/B_{MSY}
2) the point estimate of stock status in 20 years under status quo TACC (Total Allowable Commercial Catch) and deterministic recruitment, B_{2018}/B_{MSY}
3) the probability of stock increase in 20 years under status quo TACC and stochastic recruitment, $P(B_{2018}>B_{1998})$
4) the probability of a stock rebuild in 20 years under status quo TACC and stochastic recruitment, $P(B_{2018}>B_{MSY})$
5) the expected stock status in 20 years under status quo TACC and stochastic recruitment, $E(B_{2018}/B_{MSY})$.

A mid-term catch-at-age model starting in 1970 is used to assess the status of the HG-BoP and EN sub-stocks and Bayesian analysis is used to calculate probability statements. The model design and its assumptions are a joint effort between the authors of this paper and the Snapper Working Group. Results suggest that the current removals are sustainable and the stocks should rebuild to (HG-BoP) or remain above (EN) levels that will support MSY.

6.2 Model Description

An age-structured model (Maunder and Starr 1998) with gear specific selectivity at age is used to model the SNA1 snapper stock. The Hauraki Gulf and Bay of Plenty sub-stocks are combined into one assessment (HG-BoP) and the east northland (EN) sub-stock is assessed separately. The modeling begins from an exploited stock size and age-structure in 1970 and the numbers at age in each successive fishing year are calculated by subtracting catch and natural mortality, and incrementing the age of each cohort. The model is fit to two tagging biomass estimates (1985 and 1994), catch-at-age data and a pre-recruit trawl survey index.

6.2.1 Model Structure

The age-structured model approximates continuous fishing and natural mortality by removing catch from the middle of the year (Maunder 1993, Maunder and Starr 1998). Fishing mortality is separated into annual and age-specific components. Each gear has its own age-specific selectivity pattern. The maximum age class in the model ($a_{max} = 20$) is used as a plus group to accumulate all older fish. Natural mortality is assumed to be constant over age and time. The von Bertalanffy growth equation and a length-weight relationship are used to describe growth. The model equations are described below and the biological parameters used are described in Table 6.1.

TABLE 6.1: Biological parameters used in the model (Annala and Sullivan 1998).

Parameter	Symbol	EN	HG-BoP
Natural mortality	M	0.075	0.075
length-weight scalar	A	0.04467	0.04467
length-weight exponent	B	2.793	2.793
Von Bertalanffy L-infinity	L_{inf}	46.2	58.8
Von Bertalanffy K	K	0.128	0.102
Von Bertalanffy t_0	t_0	-1.40	-1.11

$$N_{y+1,a\max 1} = \left(N_{y,a\max} + N_{y,a\max-1}\right)e^{(-M)} - (C_{y,a\max} + C_{y,a\max-1})e^{(-0.5M)} \qquad \text{if } a = a_{max}$$

$$N_{y+1,a+1} = N_{y,a}e^{(-M)} - (C_{y,a})e^{(-0.5M)} \qquad \text{otherwise}$$

$$N_{y+1,1} = R_0 r_y$$

$$C_{y,a} = \sum_{m=1}^{m_{max}} u_y^m N_{y,a} v_a^m s_a \qquad \text{if } a = 4 \text{ or } a = 5$$

$$C_{y,a} = \sum_{m=1}^{m_{max}} u_y^m N_{y,a} v_a^m \qquad \text{otherwise}$$

$$u_y^r = \frac{C_y^{*r}}{B_y^r}$$

$$C_y^{*r} = p_y^r C_y^{*c}$$

$$u_y^m = \frac{C_y^{*c} p_y^m}{B_y^m}$$

$$B_y^m = \sum_{a=k}^{a_{max}} N_{y,a} v_a^m w_a s_a \qquad \text{if } a = 4 \text{ or } a = 5$$

$$B_y^m = \sum_{a=k}^{a_{max}} N_{y,a} v_a^m w_a \qquad \text{otherwise}$$

$$w_a = b_i \left(L_\infty \left(1 - \exp\left(-k\left(a - t_0\right)\right)\right)\right)^{b_u}$$

where:

$N_{y,a}$ is the number of fish of age a in year y
M is the instantaneous natural mortality rate
R_0 is the virgin or average recruitment
a_{max} is the age of the plus group
r_y is the annual recruitment multiplier for year y

$C_{y,a}$ is the total number of fish caught of age a in year y

u_y^r is the recreational annual fishing rate for year y

u_y^m is the commercial annual fishing rate for year y for method m

p_y^m is the proportion of the commercial catch in weight taken by method m

p_y^r is the recreational catch in weight as a proportion of the commercial catch

v_a^m is the vulnerability of fish age a to method m

s_a is the annual vulnerability and age specific modifier for age 4 and 5 fish

C_y^{*c} is the commercial catch in weight for year y

C_y^{*r} is the recreational catch in weight for year y

w_a is the weight of a fish age a

B_y^m is the commercially exploitable biomass in year y for method m

b_i is the length weight scale parameter

b_{ii} is the length weight exponent parameter

L_∞, k and t_0 are the von Bertalanffy growth parameters

The modifications for the change in recreational minimum legal size are not shown in the above equations.

6.2.2 Recruitment

For the HG-BoP sub-stock a relationship between sea surface temperature (SST) and recruitment is used to determine annual recruitment. In previous assessments the parameters of this relationship have been pre-specified externally to the model (Gilbert et al. 1996). These parameter estimates were derived from a regression of relative abundance of one year olds in the pre-recruit trawl survey and SST recorded at the Leigh marine laboratory (Francis 1993). This regression does not use all the information available for recruitment estimates. Catch-at-age data also provide information on year class strength (Maunder and Starr 1998). By estimating the parameters of the temperature recruitment relationship inside the population dynamics model while fitting to the pre-recruit trawl survey data and the catch-at-age data, all the information on annual recruitment strength can be included in the parameters of the temperature-recruitment relationship. The temperature-recruitment relationship is used to model the annual fluctuations around the average recruitment (represented by virgin recruitment R_0).

The form of the temperature recruitment-relationship follows the original regression model of Francis (1993):

$$r_y = \exp\left(\alpha + \beta T_{y-1}\right)$$

$$\alpha = \ln\left(\frac{1997 - 1967 + 1}{\sum_{1967}^{1997} \exp(\beta T_y)}\right)$$

T is the average Leigh SST for the period February to June in year y (Table 6.2)
r_t is the relative year class strength for fish of age one in year y

The parameter α is obtained from the constraint that the mean r_t for the years 1967-97 equals one and β is estimated in the model fitting procedure. This formulation defines mean recruitment equal to the average over the period 1967 to 1997, which intern defines virgin biomass, B_0.

The SSTs used in the HG-BoP model may not be appropriate to use for the EN stock. The SSTs were recorded within the HG sub-stock and there is evidence of different recruitment patterns from the catch-at-age data between the EN and HG-BoP sub-stocks. For this reason, the SST data were not used in the EN assessment and annual recruitment residuals around the mean recruitment for the EN stock are estimated as free parameters. The log deviations are scaled so they average zero over the period estimated. Average recruitment was used for years in which recruitment was not estimated. For the EN sub-stock a log-normal prior, mean = 1 and CV = 0.6 is used to constrain annual recruitment variation. The inclusion of a distribution to constrain the annual recruitment residuals is part of Bayesian analysis, but is often not recognised as such. The mode of the joint posterior distribution is used in the same manner as maximum likelihood estimates (i.e. the posterior probability is maximised to estimate the parameters). This is similar to the method of support described by Edwards (1992).

TABLE 6.2: Average February to June sea surface temperature recorded at the Leigh Marine Station (Annala and Sullivan 1998). These data are used to determine relative recruitment at age one in the following year.

Year	Temperature	Year	Temperature	Year	Temperature
1951	18.16	1967	18.24	1983	17.24
1952	18.38	1968	18.40	1984	18.30
1953	18.26	1969	17.54	1985	18.78
1954	18.58	1970	19.40	1986	19.02
1955	19.20	1971	19.62	1987	17.98
1956	19.00	1972	18.48	1988	18.54
1957	18.86	1973	19.02	1989	19.28
1958	18.56	1974	19.72	1990	19.04
1959	18.00	1975	18.84	1991	18.10
1960	18.22	1976	18.04	1992	17.32
1961	18.16	1977	18.30	1993	17.68
1962	18.86	1978	19.38	1994	18.30
1963	18.30	1979	18.68	1995	19.24
1964	18.18	1980	18.00	1996	18.78
1965	17.88	1981	19.68	1997	18.28
1966	18.58	1982	18.46		

A selectivity ogive is used to adjust the proportion of 4 and 5 year olds entering the fishery in any given year (Table 6.3). This ogive allows for annual variable growth rates which produce differences in the proportion of an age-class greater than the 25 cm commercial size limit in each cohort (Maunder and Starr 1998). The ogive is obtained directly from length-at-age data collected from otolith samples. For years where no samples are available, the mean of the annual values is used.

TABLE 6.3: Age four and five annual selectivity scalers.

	HG-BoP		EN	
Year	4	5	4	5
1970	0.394	1.00	0.22	1.00
1971	0.394	1.00	0.22	1.00
1972	0.394	1.00	0.22	1.00
1973	0.394	1.00	0.22	1.00
1974	0.394	1.00	0.22	1.00
1975	0.394	1.00	0.22	1.00
1976	0.394	1.00	0.22	1.00
1977	0.394	1.00	0.22	1.00
1978	0.394	1.00	0.22	1.00
1979	0.394	1.00	0.22	1.00
1980	0.394	1.00	0.22	1.00
1981	0.394	1.00	0.22	1.00
1982	0.394	1.00	0.22	1.00
1983	0.394	1.00	0.22	1.00
1984	0.394	1.00	0.22	1.00
1985	0.360	0.91	0.22	1.00
1986	0.500	0.93	0.22	1.00
1987	0.600	0.93	0.22	1.00
1988	0.394	1.00	0.22	1.00
1989	0.394	1.00	0.22	1.00
1990	0.250	0.85	0.22	1.00
1991	0.700	0.97	0.43	0.83
1992	0.394	1.00	0.22	1.00
1993	0.160	0.91	0.23	0.91
1994	0.030	0.68	0.01	0.68
1995	0.140	0.55	0.22	1.00
1996	0.394	1.00	0.22	1.00
1997	0.394	1.00	0.22	1.00
1998	0.394	1.00	0.22	1.00

6.2.3 Initial Conditions

Both the HG-BoP and EN sub-stocks are modeled from an exploited state in 1970. It is assumed that the population is in a state of equilibrium fishing mortality in 1970. For the HG-BoP sub-stock recruitment associated with each age-class in the initial population is calculated using the temperature recruitment relationship. For EN average recruitment is assumed to determine the initial age-structure. SST is not used to calculate the numbers in the HG-BoP plus group, instead a scale parameter relative to the equilibrium fishing mortality rate for the younger fish, *f*, is estimated for the plus group.

$$\dot{N}_{1970,1} = R_0 \exp(M(a-1)) \qquad \text{if } a \le 4$$

$$\dot{N}_{1970,a+1} = \dot{N}_{1970,a} \exp(Fs_a + M) \qquad \text{if } a = 4 \text{ or } a = 5$$

$$\dot{N}_{1970,a+1} = \dot{N}_{1970,a} \exp(F + M) \qquad \text{if } 5 < a < a_{max}$$

$$N_{1970,a\,max} = \frac{\dot{N}_{1970,a\,max-1} \exp(F + M)}{1 - \exp(F + M)} f \qquad \text{if } a = a_{max}$$

$$N_{1970,a} = \dot{N}_{1970,a} r_{1970-a+1} \qquad \text{if } a < a_{max}$$

where:

F is the initial equilibrium fishing mortality rate in 1970

f is the plus group scaler

6.3 Catch

Catch is divided into 5 different gear types for each sub-stock; long line, single trawl, Danish seine, other commercial and recreational for HG-BoP (Table 6.4), and long line, single trawl, pair trawl, other commercial and recreational for EN (Table 6.5). The separability assumption is used to divide fishing mortality into year and age-specific components. Age specific selectivity is determined by combining estimates from the two tagging programs (Tables 6.6 and 6.7). An additional level of unreported domestic catch is added to the commercial catch. The level of under-reporting for commercial catch is 20% pre-1987 and decreases to 10% beginning in 1987. Unreported Japanese catch in the period 1960-77 is set at 15 000 t in EN and 15 000 t in HG-BoP and added to the commercial long line catch. Japanese catch is divided between the years by assuming catches increase linearly to a peak in 1968 then decline linearly (Annala and Sullivan 1997).

Recreational catch estimates are available for three years 1985 1994 and 1996 and are 370, 723, and 711 t for EN and 1230, 2071 and 1611 t for BoP, respectively (Annala and Sullivan 1998). Recreational catch in other years is set to the mean level after modifying the 1996 catch estimate to account for the 1994 size limit change and the 1995 bag limit reduction to 1706 t and 631 t per year for HG-BoP and EN, respectively.

The effect of the size limit increase from 25cm to 27 cm in 1994 was included by assuming that all 4 year old fish were returned to the water. An 80% survival rate was assumed for the 4 year olds returned to the water.

6.4 Parameters Estimated

The parameters estimated differ between the models used for the HG-BoP and EN sub-stocks. The HG-BoP model estimates five parameters: mean recruitment (R_0), the pre-1970 instantaneous fishing mortality rate (F), the plus group scaler (f), the slope of the SST recruitment relationship (β), and the trawl survey catchability coefficient (q).

The EN analysis estimates: mean recruitment (R), the pre-1970 instantaneous fishing mortality rate (F), and 16 annual recruitment parameters from 1976 to 1991 (r_y). The plus scaler is fixed at 1 and the pre-recruit trawl survey indices are not used. Year class strengths are set to average for the years 1967 to 1975 and 1992 to 1997.

6.4: Catch by gear type for Hauraki Gulf and Bay of Plenty combined (*pers. com.* K. Sullivan, Ministry of Fisheries, Wellington, New Zealand). Catch includes under reporting and Japanese long line catch.

Year	Long Line	Single Trawl	Danish seine	Other	Recreational
1970	5397.2	2479.2	2082.0	991.2	1706
1971	5677.0	2676.0	2247.6	1070.4	1706
1972	4958.2	2305.2	1936.8	922.8	1706
1973	4642.8	2163.6	1818.0	865.2	1706
1974	4353.8	2038.8	1712.4	814.8	1706
1975	3323.2	1490.4	1251.6	596.4	1706
1976	3887.2	1848.0	1552.8	739.2	1706
1977	3935.4	1914.0	1608.0	765.6	1706
1978	4401.6	2500.8	2101.2	1000.8	1706
1979	4400.4	2500.8	2100.0	1000.8	1706
1980	2919.6	1659.6	1393.2	663.6	1706
1981	3265.2	1855.2	1557.6	741.6	1706
1982	3008.4	1708.8	1435.2	684.0	1706
1983	2509.2	1425.6	1197.6	570.0	1706
1984	2900.4	1647.6	1384.8	658.8	1706
1985	2348.4	1764.0	1558.8	889.2	1230
1986	2491.2	1416.0	1112.4	621.6	1706
1987	1442.1	1157.2	561.0	324.5	1706
1988	1943.7	1096.7	774.4	581.9	1706
1989	2026.2	1780.9	611.6	520.3	1706
1990	1784.2	1670.9	783.2	496.1	1706
1991	1820.5	1361.8	1023.0	570.9	1706
1992	2270.4	1448.7	1400.3	541.2	1706
1993	2219.8	1161.6	1025.2	367.4	1706
1994	2053.7	814.0	987.8	411.4	2071
1995	1945.9	641.3	1019.7	328.9	1569
1996	1701.7	1100.0	605.0	393.8	1611
1997	1501.5	1094.5	869.0	338.8	1611

TABLE 6.5: Catch by gear type for East Northland (*pers. com.* K. Sullivan, Ministry of Fisheries, Wellington, New Zealand). Catch includes under reporting and Japanese long line catch.

Year	Long Line	Single Trawl	Pair Trawl	Other	Recreational
1970	2154.8	241.2	280.8	190.8	630
1971	2300.2	286.8	333.6	228.0	630
1972	2287.0	297.6	346.8	236.4	630
1973	2172.0	288.0	334.8	228.0	630
1974	1383.8	132.0	154.8	105.6	630
1975	1379.2	146.4	170.4	116.4	630
1976	1410.4	166.8	194.4	133.2	630
1977	1398.6	178.8	207.6	141.6	630
1978	1315.2	282.0	328.8	224.4	630
1979	1558.8	334.8	390.0	266.4	630
1980	1350.0	290.4	337.2	230.4	630
1981	1239.6	266.4	309.6	211.2	630
1982	1134.0	243.6	283.2	193.2	630
1983	1102.8	236.4	276.0	188.4	630
1984	1209.6	260.4	302.4	206.4	630
1985	786.0	102.0	577.2	103.2	370
1986	865.2	103.2	332.4	108.0	630
1987	642.4	75.9	138.6	75.9	630
1988	789.8	84.7	201.3	94.6	630
1989	790.9	302.5	72.6	266.2	630
1990	893.2	160.6	361.9	257.4	620
1991	731.5	163.9	161.7	215.6	620
1992	763.4	251.9	107.8	143.0	620
1993	784.3	231.0	211.2	93.5	620
1994	847.0	224.4	200.2	115.5	723
1995	925.1	158.4	188.1	140.8	562
1996	1102.2	284.9	118.8	128.7	711
1997	1025.2	243.1	111.1	148.5	711

TABLE 6.6: Age specific selectivity by gear type for HG-BoP (*pers. com.* K. Sullivan, Ministry of Fisheries, Wellington, New Zealand).

Age	Long Line	Single Trawl	Danish seine	Other	Recreational
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0.520	0.995	0.650	0.816	1.154
5	0.348	0.599	0.790	0.979	1.141
6	0.610	0.793	0.910	1.058	1.108
7	0.692	0.851	0.950	1.126	1.107
8	1.000	1.000	1.000	1.000	1.000
9	1.010	1.027	1.000	0.752	0.910
10	1.037	0.978	1.000	0.781	0.871
11	0.944	0.942	1.000	0.846	0.864
12	1.023	1.019	1.000	0.685	0.892
13	1.019	0.933	1.000	0.471	0.628
14	0.975	0.947	1.000	0.525	0.636
15	1.022	0.897	1.000	0.553	0.621
16	1.110	0.857	1.000	0.453	0.516
17	0.931	0.863	1.000	0.594	0.649
18	0.881	0.918	1.000	0.788	0.708
19	0.930	0.829	1.000	0.639	0.587
20	0.978	0.828	1.000	0.415	0.596

TABLE 6.7: Age specific selectivity by gear type for EN (*pers. com.* K. Sullivan, Ministry of Fisheries, Wellington, New Zealand).

Age	Long Line	Single Trawl	Pair Trawl	Other	Recreational
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0.867	1.202	0.843	0.816	1.154
5	0.924	1.163	0.887	0.979	1.141
6	0.927	1.086	1.006	1.058	1.108
7	0.975	1.058	1.028	1.126	1.107
8	1.000	1.000	1.000	1.000	1.000
9	1.010	1.027	1.000	0.752	0.910
10	1.037	0.978	1.000	0.781	0.871
11	0.944	0.942	1.000	0.846	0.864
12	1.023	1.019	1.000	0.685	0.892
13	1.019	0.933	1.000	0.471	0.628
14	0.975	0.947	1.000	0.525	0.636
15	1.022	0.897	1.000	0.553	0.621
16	1.110	0.857	1.000	0.453	0.516
17	0.931	0.863	1.000	0.594	0.649
18	0.881	0.918	1.000	0.788	0.708
19	0.930	0.829	1.000	0.639	0.587
20	0.978	0.828	1.000	0.415	0.596

6.5 Data and Likelihoods

The model is fit to two tagging biomass estimates (1985 and 1994) and catch-at-age data (Tables 6.8 to 6.11). The HG-BoP model is also fit to the pre-recruit trawl survey data (Table 6.12). An extensive catch-at-age sampling program has been running since 1990 (Davies and Walsh 1995). Catch-at-age data are available for a number of years, areas and gears. While these data were only collected for either the summer or the spring-summer fishing seasons, it is assumed that these data are a reasonable estimate of the annual proportion-at-age caught in these fisheries throughout the entire fishing year. This assumption is made because a majority (usually about 75%) of the catch is taken during this period. HG catch-at-age data is used to represent the total HG-BoP catch-at-age. Only fish aged 5 to 20 were used for the catch-at-age likelihood because there are insufficient data for the younger age classes. Additional historic Danish seine catch-at-age data for the HG-BoP sub-stock are available for 1970-73.

Likelihood functions are used to fit the model to the data (see below). Lognormal error was assumed for the trawl survey recruitment indices, tagging biomass observations and catch-at-age data. The CV assumed for each data set determines its relative weighting in the likelihood function. The assumed CVs are:

a) pre-recruit trawl survey, σ_R=0.3,
b) tagging biomass estimates, σ_B=0.3 for 1985 and 0.2 for 1994,
c) catch-at-age, $\sigma_{C@A}=5c\sqrt{n}$ (where *c* and *n* are defined in the text below)

In some years the catch-at-age data for several methods were based on the same age length key. These data sets are therefore not statistically independent, so the CV for each proportion at age is scaled by the square root of the number of methods with catch-at-age data for that year (*n*). The 1970 to 1973 catch-at-age data are from single landings rather than from the 30-50 landings sampled to produce the 1990s catch-at-age estimates. Therefore, for the 1970s Danish seine catch-at-age data, *n* is arbitrarily set to 16 to allow for the smaller sample size. The number 5 in the formula was arbitrarily chosen to reduce the weighting of the catch-at-age data and to compensate for random year to year variation around the mean selectivity curve. The variable *c* is the sampling CV corresponding to the estimated proportion-at-age. The sampling CV for a given age, year and method is:

$$c^{m}_{y,a} = a^{m}\left(p^{m}_{y,a}\right)^{b^{m}}$$

where:

$p^{m}_{y,a}$ is the observed proportion at age *a* in year *y* caught by method *m*

a^{m} and b^{m} are gear specific parameters given in Table 6.13.

6.5.1 Catch at Age

The model is fit to the proportional catch-at-age by assuming lognormal observation error with known coefficients of variation (Maunder & Starr 1998).

$$L(\text{parameters} \mid P^m_{y,a}) = \frac{1}{\sqrt{2\pi}\,5c^m_{y,a}\sqrt{n}}\exp\left(-\frac{\left(\ln(P^m_{y,a}) - \ln(\hat{P}^m_{y,a})\right)^2}{2(5c^m_{y,a}\sqrt{n})^2}\right)$$

$$\hat{P}^m_{y,a} = \frac{C^m_{y,a}}{\sum_{a=1}^{a_{max}} C^m_{y,a}}$$

$$c^m_{y,a} = a^m\left(P^m_{y,a}\right)^{b^m}$$

$C^m_{y,a}$ is the model commercial catch in numbers of age a individuals in year y for method m.

$P^m_{y,a}$ is the observed proportion at age a in year y caught by method m

n is the square root of the number of methods with catch-at-age data for year y
For the 1970s data, n is arbitrarily set to 16 to allow for the smaller sample size.

The negative log likelihood from the catch-at-age data is:

$$-\ln(L(\text{parameters} \mid \overline{P})) = -\sum_m \sum_y \sum_{a=5}^{20+} \ln(L(\text{parameters} \mid P^m_{y,a}))$$

6.5.2 Tagging

The model is fit to the two tagging biomass estimates by assuming lognormal observation error with known coefficients of variation.

$$L(\text{parameters} \mid B_y) = \frac{1}{\sqrt{2\pi}\sigma_B} \exp\left(-\frac{\left(\ln(B_y) - \ln(\hat{B}_y)\right)^2}{2(\sigma_B)^2} \right)$$

B_y is the tagging biomass estimate in year y.

$$\hat{B}_y = \sum_{a=4}^{5} N_{y,a} w_a s_{y,a} + \sum_{a=6}^{a\max} N_{y,a} w_a$$

σ_B is approximately equal to the CV of the biomass estimate. $\sigma_B = 0.3$ for 1985 and 0.2 for 1994

The negative log likelihood from the tagging data is:

$$-\ln(L(\text{parameters} \mid \overline{B})) = -\sum_{y} \ln(L(\text{parameters} \mid B_y))$$

6.5.3 Pre-recruit trawl survey

The model is fit to the pre-recruit trawl survey data by assuming lognormal observation error with known coefficients of variation.

$$L(\text{parameters} \mid I_y) = \frac{1}{\sqrt{2\pi}\sigma_I} \exp\left(-\frac{\left(\ln(I_y) - \ln(\hat{I}_y)\right)^2}{2(\sigma_I)^2} \right)$$

$$\hat{I}_y = qN_{y,1}$$

q is the survey catchability coefficient.

σ_I is approximately equal to the CV of the pre-recruit trawl surveys

The negative log likelihood from the pre-recruit trawl survey data is:

$$-\ln(L(\text{parameters} \mid \bar{I})) = -\sum_{y} \ln(L(\text{parameters} \mid I_y))$$

6.5.4 Annual Recruitment residuals

A log-normal prior with CV approximately equal to 0.6 is assumed for the annual recruitment residuals in the EN model.

$$\text{Prior}(r_y) = \frac{1}{\sqrt{2\pi}\sigma_r} \exp\left(-\frac{\ln(r_y)^2}{2(\sigma_r)^2}\right)$$

r_y is the relative year class strength for fish of age one in year y

σ_r is the standard deviation of the natural logarithm of the annual recruitment anomalies

6.5.5 Total negative log-likelihood

The total negative log-likelihood is the sum of the negative log-likelihood of the tagging biomass estimates, the proportion of catch at age data, and in the case of HG-BoP the pre-recruit trawl survey. The negative log of the prior for annual recruitment residuals is added to the total negative log-likelihood for the EN model. The total negative log-posterior probability is minimized to give the best estimates of the parameters. The bounds for uniform priors are implemented internally in AD Model Builder. The details of the different components of the likelihood function are described below.

The total negative log-posterior probability for the combined HG-BoP stock is:

$$= -\sum_{m}\sum_{y}\sum_{a=5}^{20+} \ln(L(\text{parameters} \mid P_{y,a}^{m})) - \sum_{y} \ln(L(\text{parameters} \mid B_y)) - \sum_{y} \ln(L(\text{parameters} \mid I_y))$$

The total negative log-posterior probability for the EN stock is:

$$= -\sum_{m}\sum_{y}\sum_{a=5}^{20+} \ln(L(\text{parameters} \mid P_{y,a}^{m})) - \sum_{y} \ln(L(\text{parameters} \mid B_y)) - \sum_{y} \ln(\text{Prior}(r_y))$$

$$L(\text{parameters} \mid P_{y,a}^{m}) = \frac{1}{\sqrt{2\pi}5c_{y,a}^{m}\sqrt{n}} \exp\left(-\frac{\left(\ln(P_{y,a}^{m}) - \ln(\hat{P}_{y,a}^{m})\right)^2}{2(5c_{y,a}^{m}\sqrt{n})^2} \right)$$

$$L(\text{parameters} \mid B_y) = \frac{1}{\sqrt{2\pi}\sigma_B} \exp\left(-\frac{\left(\ln(B_y) - \ln(\hat{B}_y)\right)^2}{2(\sigma_B)^2} \right)$$

$$L(\text{parameters} \mid I_y) = \frac{1}{\sqrt{2\pi}\sigma_I} \exp\left(-\frac{\left(\ln(I_y) - \ln(\hat{I}_y)\right)^2}{2(\sigma_I)^2} \right)$$

$$\text{Prior}(r_y) = \frac{1}{\sqrt{2\pi}\sigma_r} \exp\left(-\frac{\ln(r_y)^2}{2(\sigma_r)^2} \right)$$

where:

$$\hat{P}_{y,a}^{m} = \frac{C_{y,a}^{m}}{\sum_{a=1}^{a_{\max}} C_{y,a}^{m}}$$

$$c_{y,a}^{m} = a^{m}\left(P_{y,a}^{m}\right)^{b^{m}}$$

$C_{y,a}^{m}$ is the model predicted commercial catch in numbers of age a individuals in year y for method m.

a^{m} and b^{m} are the parameters of the relationship between CV and proportion for the catch-at-age data.

$P^m_{y,a}$ is the observed proportion at age a in year y caught by method m

n is the square root of the number of methods with catch-at-age data for year y

B_y is the tagging biomass estimate in year y.

$\hat{B}_y$ is the model predicted biomass in year y.

σ_B is approximately equal to the CV of the biomass estimate (Annala and Sullivan 1998).

I_y is the observed value for the pre-recruit trawl survey index for year y

$\hat{I}_y = qN_{y,1}$

q is the survey catchability coefficient.

σ_I is approximately equal to the CV of the pre-recruit trawl surveys (Annala and Sullivan 1998).

r_y is the relative year class strength for fish of age one in year y

σ_r is the standard deviation of the natural logarithm of the annual recruitment anomalies

TABLE 6.8: Observed HG long line raw proportion of catch at age (Davies & Walsh 1995). Data are normalized to sum to one when used in the model.

Age	1990	1991	1992	1993	1994	1995	1996	1997
5	0.0758	0.1125	0.0598	0.1740	0.0699	0.0372	0.0550	0.0242
6	0.1230	0.0943	0.1741	0.0979	0.1413	0.1700	0.0902	0.1509
7	0.0318	0.1301	0.2425	0.1606	0.0869	0.1348	0.2911	0.1222
8	0.0695	0.0413	0.1513	0.1527	0.1572	0.0921	0.1450	0.2609
9	0.1703	0.0494	0.0266	0.1311	0.1717	0.1197	0.0866	0.1369
10	0.1341	0.1812	0.0441	0.0135	0.1308	0.1823	0.1049	0.0501
11	0.0569	0.0750	0.1155	0.0278	0.0093	0.1197	0.0656	0.0795
12	0.0873	0.0676	0.0338	0.0748	0.0164	0.0160	0.0491	0.0468
13	0.0424	0.0561	0.0269	0.0252	0.0996	0.0089	0.0064	0.0494
14	0.0267	0.0113	0.0213	0.0295	0.0444	0.0372	0.0023	0.0060
15	0.0220	0.0084	0.0076	0.0131	0.0314	0.0223	0.0596	0.0024
16	0.0329	0.0058	0.0062	0.0096	0.0096	0.0113	0.0056	0.0264
17	0.0258	0.0234	0.0059	0.0146	0.0056	0.0045	0.0023	0.0053
18	0.0068	0.0057	0.0044	0.0108	0.0025	0.0011	0.0050	0.0032
19	0.0050	0.0081	0.0061	0.0085	0.0032	0.0018	0.0023	0.0054
20	0.0638	0.0395	0.0332	0.0334	0.0170	0.0171	0.0259	0.0243

TABLE 6.9: Observed HG trawl raw proportion of catch at age (Davies & Walsh 1995). Data are normalized to sum to one when used in the model.

Age	1990	1991	1994
5	0.1745	0.2325	0.0937
6	0.2109	0.1447	0.1682
7	0.0445	0.1583	0.1000
8	0.0815	0.0416	0.1588
9	0.1637	0.0342	0.1788
10	0.1317	0.1243	0.1171
11	0.0479	0.0465	0.0072
12	0.0485	0.0343	0.0128
13	0.0186	0.0288	0.0768
14	0.0094	0.0059	0.0342
15	0.0114	0.0031	0.0246
16	0.0100	0.0021	0.0069
17	0.0072	0.0100	0.0037
18	0.0026	0.0021	0.0016
19	0.0008	0.0036	0.0019
20	0.0143	0.0190	0.0107

TABLE 6.10: Observed HG Danish seine raw proportion of catch at age (Davies & Walsh 1995). Data are normalized to sum to one when used in the model.

Age	1970	1971	1972	1973	1992	1994	1995	1996
5	0.0155	0.0497	0.0645	0.3511	0.0459	0.0555	0.0310	0.0505
6	0.0001	0.0172	0.0473	0.0674	0.1608	0.1499	0.1605	0.0957
7	0.0309	0.0459	0.0290	0.0366	0.2573	0.0931	0.1431	0.3236
8	0.1289	0.0459	0.0462	0.0248	0.1565	0.1723	0.0966	0.1436
9	0.0670	0.0669	0.0366	0.0284	0.0280	0.1876	0.1276	0.0890
10	0.1134	0.1052	0.0806	0.0307	0.0457	0.1375	0.1898	0.1064
11	0.0258	0.0956	0.0839	0.0745	0.1226	0.0088	0.1285	0.0616
12	0.0361	0.0249	0.0860	0.0307	0.0358	0.0153	0.0169	0.0492
13	0.0619	0.0096	0.0462	0.0922	0.0290	0.0874	0.0086	0.0051
14	0.0515	0.0287	0.0312	0.0118	0.0219	0.0401	0.0340	0.0014
15	0.0928	0.0478	0.0280	0.0426	0.0070	0.0289	0.0216	0.0509
16	0.0206	0.0574	0.0280	0.0059	0.0070	0.0073	0.0086	0.0052
17	0.0515	0.0191	0.0538	0.0189	0.0070	0.0034	0.0035	0.0015
18	0.0258	0.0268	0.0269	0.0366	0.0042	0.0015	0.0011	0.0031
19	0.0206	0.0096	0.0237	0.0426	0.0057	0.0019	0.0012	0.0007
20	0.2268	0.1300	0.1849	0.0556	0.0323	0.0079	0.0092	0.0130

TABLE 6.11: Observed EN long line raw proportion of catch at age (Davies & Walsh 1995). Data are normalized to sum to one when used in the model.

Age	1994	1995	1996	1997
5	0.1291	0.1089	0.0620	0.0216
6	0.1311	0.1701	0.1020	0.0893
7	0.0695	0.1377	0.1445	0.1380
8	0.1703	0.0906	0.1030	0.1994
9	0.0892	0.0882	0.0773	0.1139
10	0.0416	0.0875	0.0786	0.0571
11	0.0160	0.0260	0.1025	0.0714
12	0.0582	0.0080	0.0210	0.0903
13	0.0550	0.0602	0.0258	0.0176
14	0.0105	0.0534	0.0586	0.0115
15	0.0258	0.0128	0.0529	0.0549
16	0.0177	0.0162	0.0150	0.0263
17	0.0160	0.0227	0.0113	0.0042
18	0.0128	0.0126	0.0109	0.0085
19	0.0153	0.0056	0.0051	0.0072
20	0.1156	0.0608	0.1114	0.0803

TABLE 6.12: Relative recruitment indices from the pre-recruit trawl surveys (Annala and Sullivan 1998).

Year at age 1	Relative Recruitment Index
1984	1.24
1985	3.64
1986	5.08
1987	5.78
1988	2.61
1989	3.92
1990	10.4
1992	3.47
1993	1.22
1994	1.39
1997	5

TABLE 6.13: Gear specific parameters to determine sampling CV for catch-at-age data (*pers com.* N. Davies, NIWA, Auckland, New Zealand).

		HG		EN
	long line	trawl	Danish seine	long line
a	0.0403	0.0533	0.0430	0.0370
b	-0.4626	-0.3952	-0.4171	-0.5154

6.6 Estimation

Parameters of the model are estimated using the automatic differentiation minimizer supplied with ADModel Builder (© Otter Research). MSY and the associated derived parameters of management interest are generated by simulating the model to equilibrium, given the model parameter estimates.

6.7 Projections

A deterministic projection is made with the population dynamics model to the year 2018 using the maximum likelihood parameter estimates. Commercial catch is assumed to be at the SNA1 TACC level of 4500 t (plus a 10% overrun), with a catch split of 0.25:0.75 between EN and HG-BoP. Projected catches are apportioned between commercial methods according to the proportions in the 1996-97 fishing year. Recreational catch in each sub-stock is assumed to follow the estimated 1996 exploitation rates and are capped under the assumption that future management measures would constrain total SNA1 recreational catch to 2600 t. This total catch is split into 1800 t and 800 t split for HG-BoP and EN, respectively, corresponding to proportions of the 1996 recreational estimates. The annual year class strengths predicted from SST-recruitment relationships for the years 1992 to 1997 are used to calculate the absolute recruitment to 2001 for the HG-BoP model. Constant recruitment equal to the estimated mean absolute recruitment was assumed for other years up to 2018 for the HG-BoP model and for all years in the EN model.

6.8 Bayesian Analysis

A Bayesian framework (Punt and Hilborn 1997) is used to derive estimates of uncertainty in the derived parameters of management interest and for the calculation of performance indicators based on probability.

The Bayesian procedure is conducted in three steps:

a) Samples of the joint posterior distribution of parameters are generated using the Markov Chain Monte Carlo procedure (MCMC) supplied with ADModel Builder (© Otter Research).
b) A marginal posterior distribution is found for each quantity of interest by integrating the product of the likelihood and the priors over all model parameters; and the mean and 95% confidence intervals of the parameters of interest can be estimated;
c) For each sample of the posterior, 20 year projections are generated assuming catch as defined above in the projections section. Future annual recruitment is randomly sampled from a log-normal distribution with mean and variance taken from the estimates of historical recruitment. This step is used to calculate the fishery performance indicators.

The priors used in the Bayesian analysis are all chosen to be non-informative except the prior for natural mortality. Uniform priors are not always uninformative, but they are vague and the shape of the prior is not important if the likelihood is dominant (Gelman et al. 1995). A constrained range of possible values for the natural mortality parameter was agreed to by the snapper working group (Annala and Sullivan 1998). The range for the other parameters where chosen so the bounds would not influence the results. The priors for the catchability coefficient (q) and the plus scaler (f) were made to be uniform on a log scale because they are scaling parameters. The priors used are given in Table 6.14.

TABLE 6.14: Priors on model parameters used in the Bayesian analysis.

Parameter	HG-BoP	EN
R_0	U(0,300000)	U(0,300000)
M	0.075 or U(0.06,0.09)	0.075 or U(0.06,0.09)
F	U(0.0,0.3)	0.04 or U(0.0,0.3)
f	log-U(-5,5)	N/A (set to 1)
β	U(0,100)	N/A
Q	log-U(-15,0)	N/A
R_y	N/A	log-N(1,0.6^2)

6.9 Model Runs

For the EN sub-stock, the working group decided on a base case that fixed the initial instantaneous fishing mortality rate at 0.04 yr^{-1} and fixed natural mortality at 0.075. This base case was chosen because maximum likelihood estimates of the initial fishing mortality were much lower than considered possible (estimated at nearly zero, which is unlikely given that estimated average annual catch in the 1960s is similar to that for the 1980s and 90s). In addition to the base case, two sensitivities were also carried out; 1) No constraint on the initial fishing mortality rate (and a fixed natural mortality at 0.075) and 2) no constraint on the initial fishing mortality rate and a uniform prior on natural mortality from 0.06 to 0.09 yr^{-1}.

For the HG-BoP sub-stock, the working group decided on a base case that had no constraint on the initial fishing mortality rate and fixed natural mortality at 0.075. One sensitivity was carried out that included a uniform prior on natural mortality from 0.06 to 0.09 yr^{-1}.

When a uniform prior was put on the natural mortality, this constrained the maximum likelihood estimate (MLE) of natural mortality to be within the specified range. As mentioned above, the mode of the joint posterior is used in the same manner as the MLE.

6.10 Results

6.10.1 EN

In the base case assessment the EN sub-stock is assessed to be above B_{MSY} and is expected to remain above B_{MSY} over the projection period under current removals (Table 6.15). Confidence bounds on the biomass trajectory from the Bayesian analysis are large and the MLE biomass trajectory lies slightly below the mean of the posterior for each annual biomass (Figure 6.1).

Two sensitivity tests to the base case were performed, one where no constraint was placed on the initial pre-1970 F value and the other assumed a uniform prior on natural mortality (from 0.06 to 0.09) along with no constraint on initial F. The maximum likelihood estimates for both sensitivities were less optimistic than the base case assessment with each sensitivity estimating that the biomass would decline over the projection period (Table 6.15). However, the deterministic estimate for B_{2018} remained above B_{MSY} for both sensitivities. A projected decline would be an unlikely scenario as the estimated level of pre-1970 fishing mortality was implausibly low for both sensitivity tests, given the high level of removals which preceded the beginning year of the model.

TABLE 6.15: EN maximum likelihood estimates of biomass and yield . Virgin biomass (B_0), biomass in 1998 (B_{1998}), Maximum Sustainable Yield (MSY) including overruns. All biomass estimates are for the beginning of season (t)

	B_0	B_{MSY}	B_{1998}	B_{1998}/B_{MSY}	MSY	B_{1970}/B_0	B_{2018}/B_{MSY}
Base case	66 900	13 900	19 100	1.37	2200	0.58	1.46
Estimate F	58 000	12 050	16 500	1.37	1790	0.91	1.17
Estimate F & M is U[0.06, 0.09]	70 600	14 800	17 400	1.18	1850	0.63	1.1

TABLE 6.16: Performance indicators for the EN sub-stock.

	$P(B_{2018} > B_{1998})$	$P(B_{2018} > B_{MSY})$	$E(B_{2018} / B_{MSY})$
Base case	0.67	0.94	1.65
Estimate F	0.63	0.89	1.62
Estimate F & M is U[0.06, 0.09]	0.62	0.87	1.61

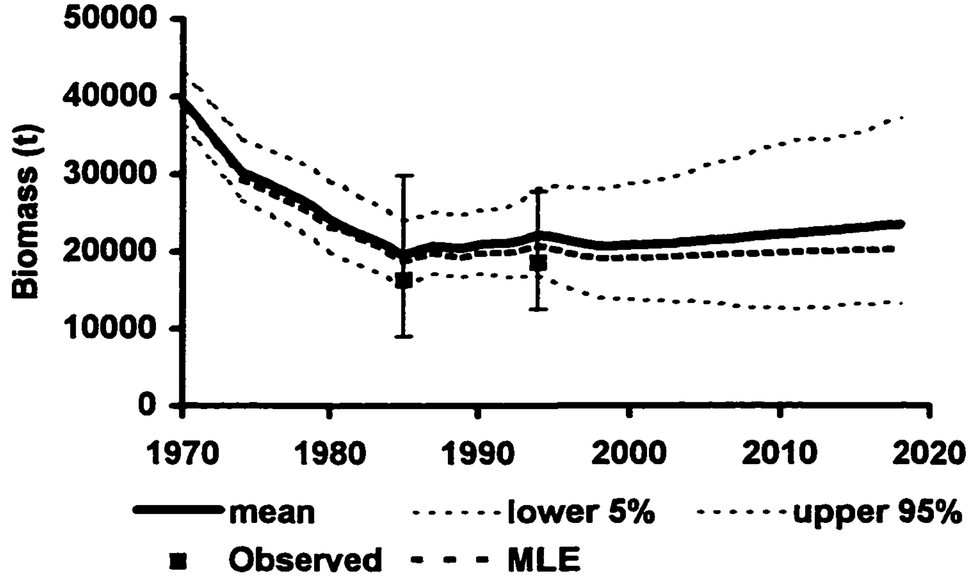

FIGURE 6.1: EN biomass trajectories of the mean, lower 5% and upper 95% of the posterior of each annual biomass estimate from the base case assessment. Also plotted are the observed biomass estimates from the 1985 and 1994 tagging programmes (including +/- 2SE using lognormal model CV's) and the maximum likelihood biomass trajectory (MLE).

Performance indicators using the Bayesian procedure for the base case and the two sensitivity analyses are presented in Table 6.16. In all cases, the probability of the sub-stock remaining above B_{MSY} at the end of the 20 year period is high (from 87% to 94%). The high probability of remaining above B_{MSY} for these three model runs is due to the relatively flat posteriors for M (Figure 6.2) and F (Figure 6.3), indicating that the likelihoods remain high over the range of plausible values for these two parameters.

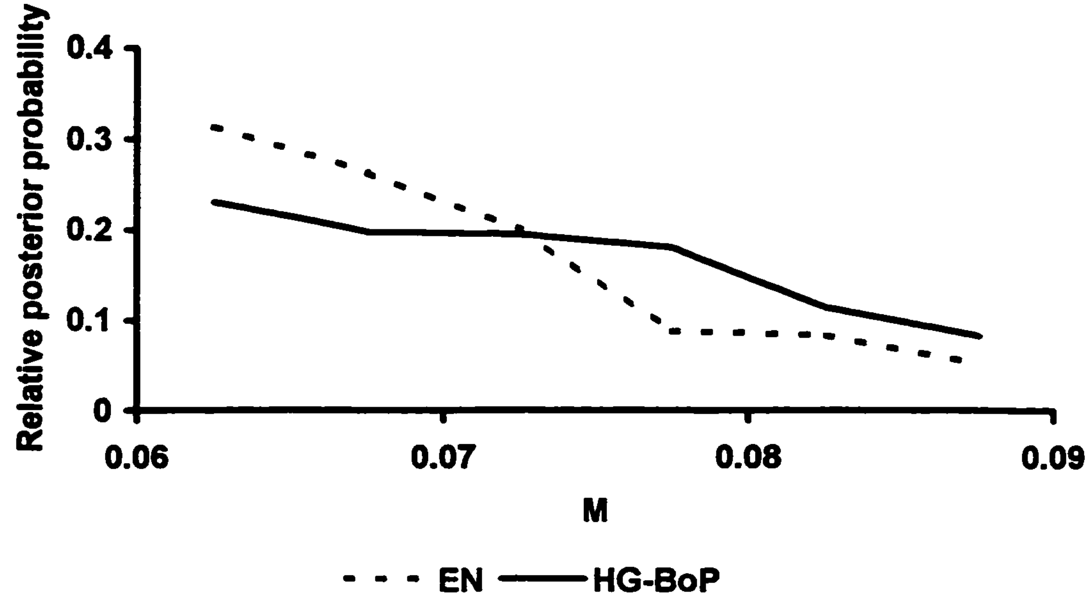

FIGURE 6.2: Posterior probability distributions for natural mortality (*M*) for the EN and HG-BoP sub-stocks.

6.10.2 HG-BoP

In the base case assessment, the HG-BoP sub-stock is assessed to be below B_{MSY} but is expected to rise above B_{MSY} over the projection period (Table 6.17). Confidence bounds on the biomass trajectory are tighter than for the EN sub-stock (reflecting the larger amount of catch-at-age data, the trawl survey data, and the reduced number of parameters due to the temperature-recruitment relationship) and the MLE biomass trajectory lies largely on the mean of the posterior for each annual biomass (Figure 6.4).

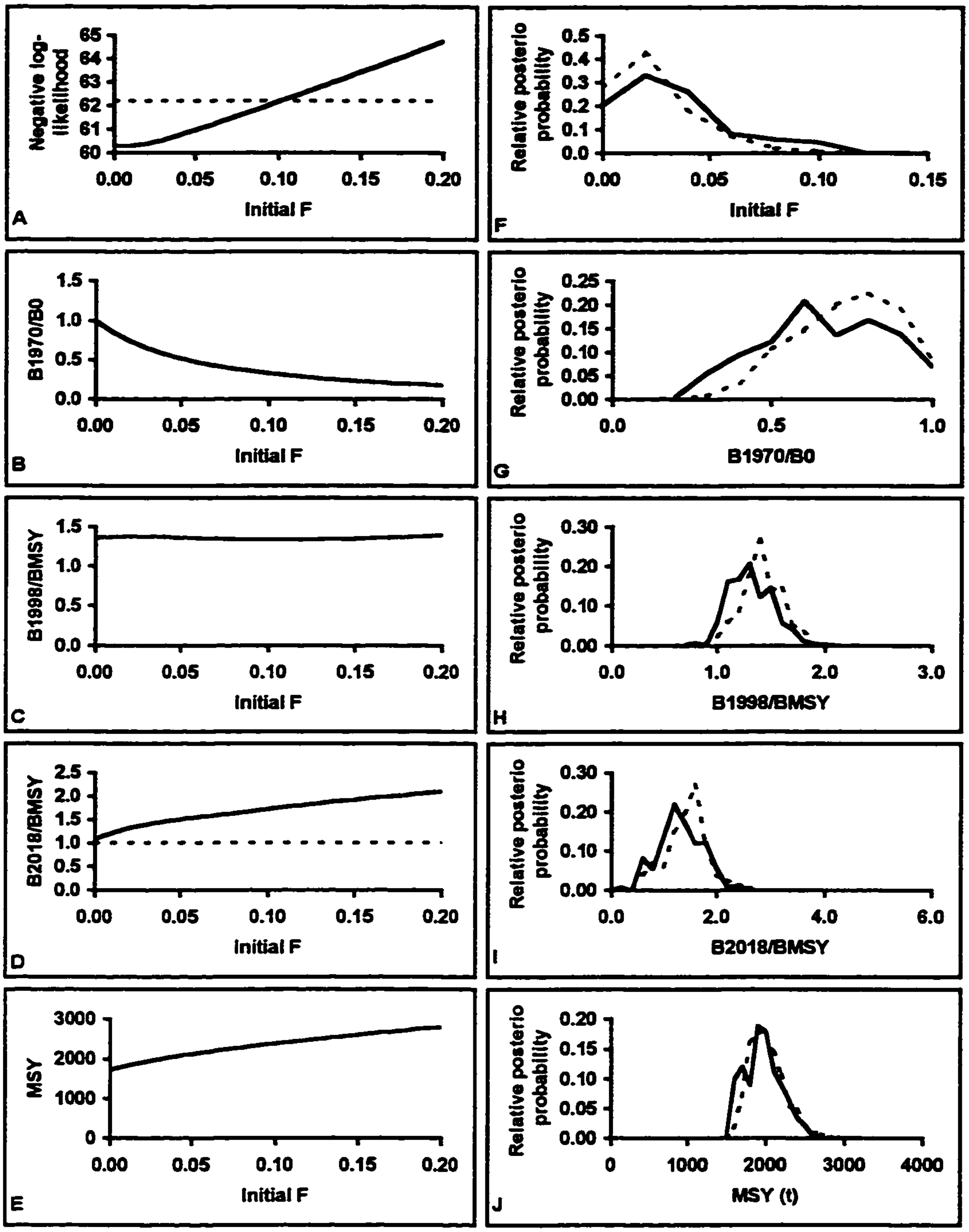

FIGURE 6.3: Results from the EN analysis. a) negative log-likelihood profile for the initial fishing mortality rate (*F*), the dashed line intersects at the 95% confidence intervals. b-e) values for the different management parameters under different initial fishing mortality rates, the dashed line in d represents Bmsy. f-j) posterior distributions from the sensitivity analyses, solid lines represent posteriors from the analysis with a prior on *M* and *F*, dashed lines represent posteriors from the analysis with a prior on *F*.

One sensitivity test was performed by placing a uniform prior on natural mortality (from 0.06 to 0.09). In this run, B_0 was estimated to be larger than in the base case and the present stock status was estimated to be lower (Table 6.17). However, this scenario also projects deterministically that B_{2018} will exceed B_{MSY}. The maximum likelihood estimate of M was .061, but the posterior was quite flat, indicating that there is little information in these data to estimate this parameter.

TABLE 6.17: HG-BoP maximum likelihood estimates of biomass and yield . Virgin biomass (B_0), biomass in 1998 (B_{1998}), Maximum Sustainable Yield (MSY) including overruns. All biomass estimates are beginning of season (t)

	B_0	B_{MSY}	B_{1998}	B_{1998}/B_{MSY}	MSY	B_{1970}/B_0	B_{2018}/B_{MSY}
BASE CASE	259 000	61 000	44 000	0.72	7240	0.35	1.39
M is U[0.06, 0.09]	320 500	75 200	44 000	0.58	7670	0.26	1.27

TABLE 6.18: Performance indicators for the HG-BoP sub-stock.

	$P(B_{2018} > B_{1998})$	$P(B_{2018} > B_{MSY})$	$E(B_{2018} / B_{MSY})$
Base case	1.00	0.90	1.41
M is U[0.06, 0.09]	1.00	0.91	1.42

Performance indicators using the Bayesian procedure for the base case and the single sensitivity analysis are presented in Table 6.18. In each case, the probability of exceeding B_{MSY} at the end of the 20 year period is high (about 90%). The similar probability for exceeding B_{MSY} for the M sensitivity analysis is due to the relatively flat posterior for this parameter (Figure 6.2), indicating that the likelihoods are high over the range of the prior, and the fact that in the base case M is set at the mid-point of the range of the uniform prior for M.

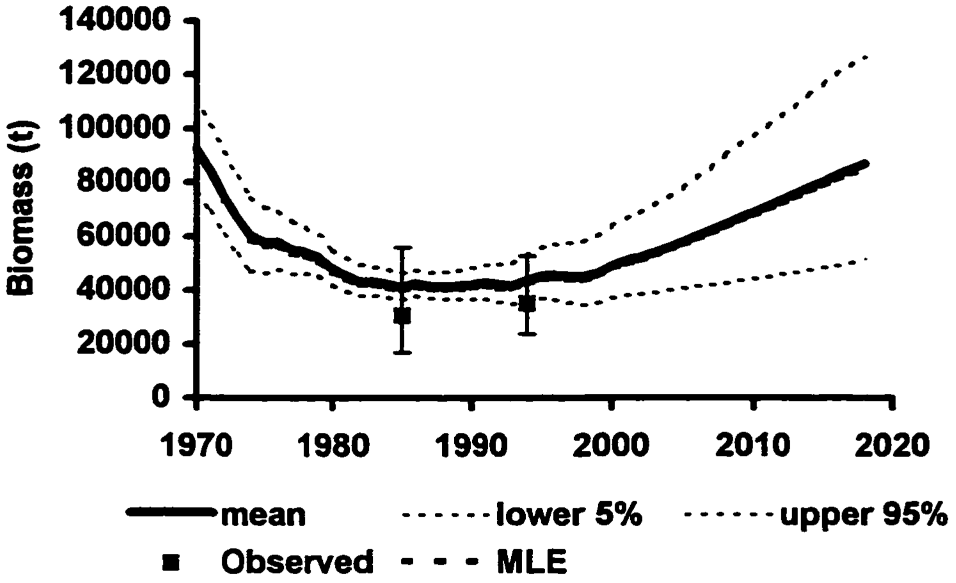

FIGURE 6.4: HG-BoP biomass trajectories of the mean, lower 5% and upper 95% of the posterior of each annual biomass estimate from the base case assessment. Also plotted are the observed biomass estimates from the 1985 and 1994 tagging programmes (including +/- 2SE using lognormal model CV's) and the maximum likelihood biomass trajectory (MLE).

6.10.3 General Results

Results for each of the sub-stocks (EN and HG-BoP) are highly dependent on the initial fishing mortality rate (Figures 6.3 and 6.5). The initial fishing mortality rate determines the size of the biomass in 1970 at the start of the modeling period as a ratio of the virgin biomass (Figures 6.3b and 6.5b). The 1970 biomass level as a ratio of the virgin biomass determines what proportion of catch is from recruitment and what is from fishing down biomass. The higher the exploitation rate in 1970, the more productive the stock has to be to sustain the catch from 1970 to 1994 and to fit the biomass estimates. For low initial fishing mortality rates the current status in relation to B_{MSY} (Figures 6.3c and 6.5c), the projected status compared to B_{MSY} (Figures 6.3d and 6.5d) and the MSY (Figures 6.3e and 6.5e) are all lower than for high initial fishing mortality rates. The exception is the current status for EN (Figure 6.3c),which is the same independent of initial exploitation rate.

The profile of the negative log-likelihood against initial fishing mortality shows that the data for EN are very uninformative about the initial fishing mortality rate (Figure 6.3a). The maximum likelihood estimates of initial fishing mortality is near zero and an initial fishing mortality rate of 0.10 yr^{-1} is on the border of being significantly different from the maximum likelihood estimate. The deterministic projected biomass in 2018 remains above B_{MSY} even when the initial fishing mortality rate is zero (Figure 6.3d).

The data for HG-BoP are much more informative about the initial fishing mortality rate (Figure 6.5a). The 95% confidence interval for the initial fishing mortality rate for this sub-stock ranges from 0.04 to 0.10. The deterministic projected biomass in 2018 is above B_{MSY} even at the lower bound of 0.04 yr^{-1} (Figure 6.5d). All the catch-at-age data show similar information supporting an initial fishing mortality rate between 0.04 and 0.10 yr^{-1} (Figure 6.6). The addition of the 1970s Danish seine catch-at-age data was included in this analysis to provide additional information for determining the initial fishing mortality rate. However, based on the profiles of the negative log-likelihood, these 1970s data apear to be the least infromative for the initial fishing mortality rate (Figure 6.6e).

The posterior distributions for B_{1970}/B_0, B_{1988}/B_{MSY}, B_{2018}/B_{MSY} and MSY are similar to that expected from the likelihood profile on the initial fishing mortality rate (Figures 6.3 and 6.5). One main difference is the larger range of values for B_{1998}/B_{MSY} for the EN posterior (Figure 6.3h). The addition of uncertainty in natural mortality had very little effect on the posteriors. The posteriors for M were relatively flat showing that there is little information in the data to estimate M (Figure 6.2). Both EN and HG-BoP have similar posteriors for M with more probability associated with lower values for M.

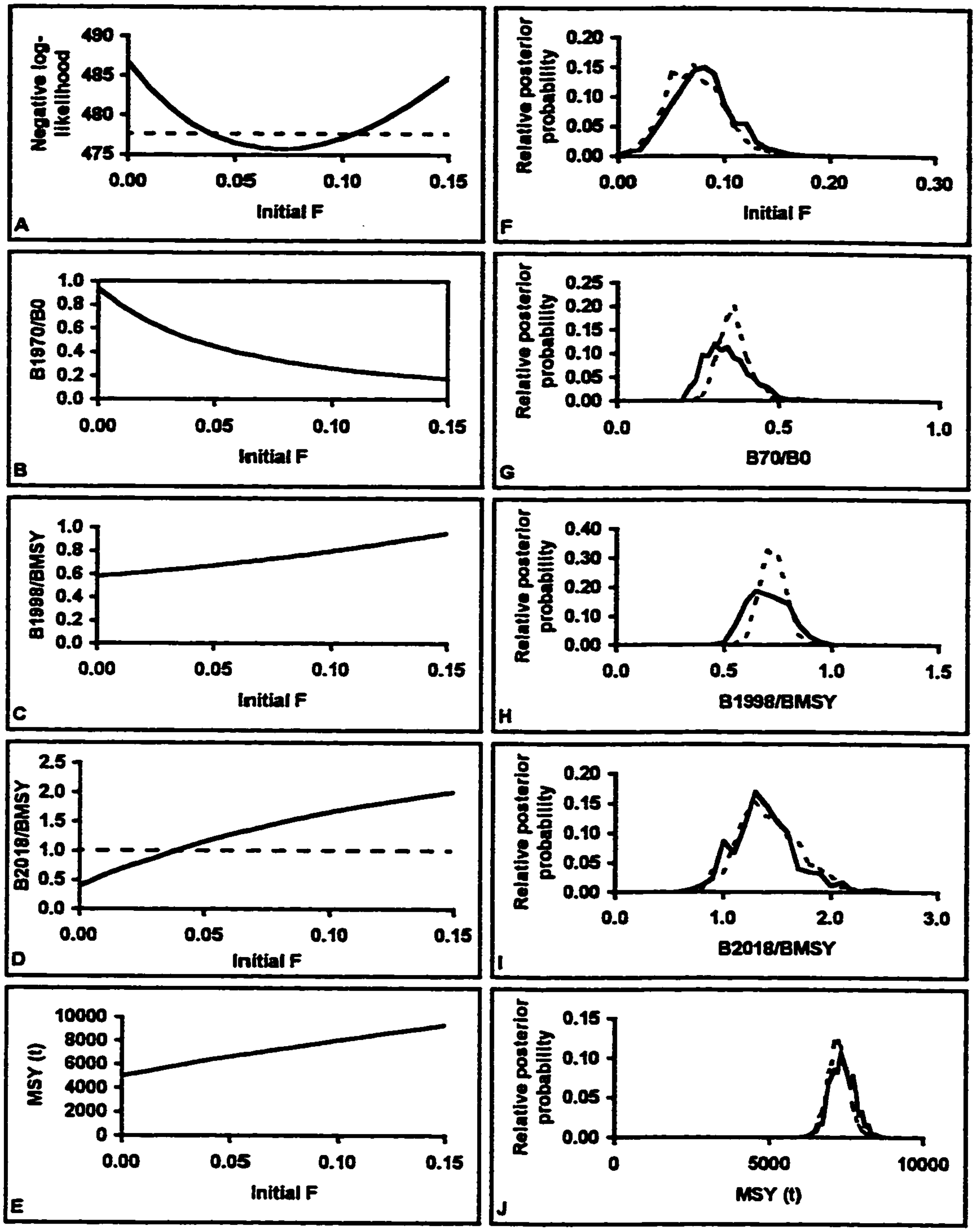

FIGURE 6.5: Results from the HG-BoP analysis. a) negative log-likelihood profile for the initial fishing mortality rate (*F*), the dashed line intersects at the 95% confidence intervals. b-e) values for the different management parameters under different initial fishing mortality rates, the dashed line in d represents Bmsy. f-j) posterior distributions from the sensitivity analyses, solid lines represent posteriors with from the analysis with a prior on *M* and *F*, dashed lines represent posteriors from the analysis with a prior on *F*. Analyses for Figures a-e fix the plus group scaler (*f*) to one.

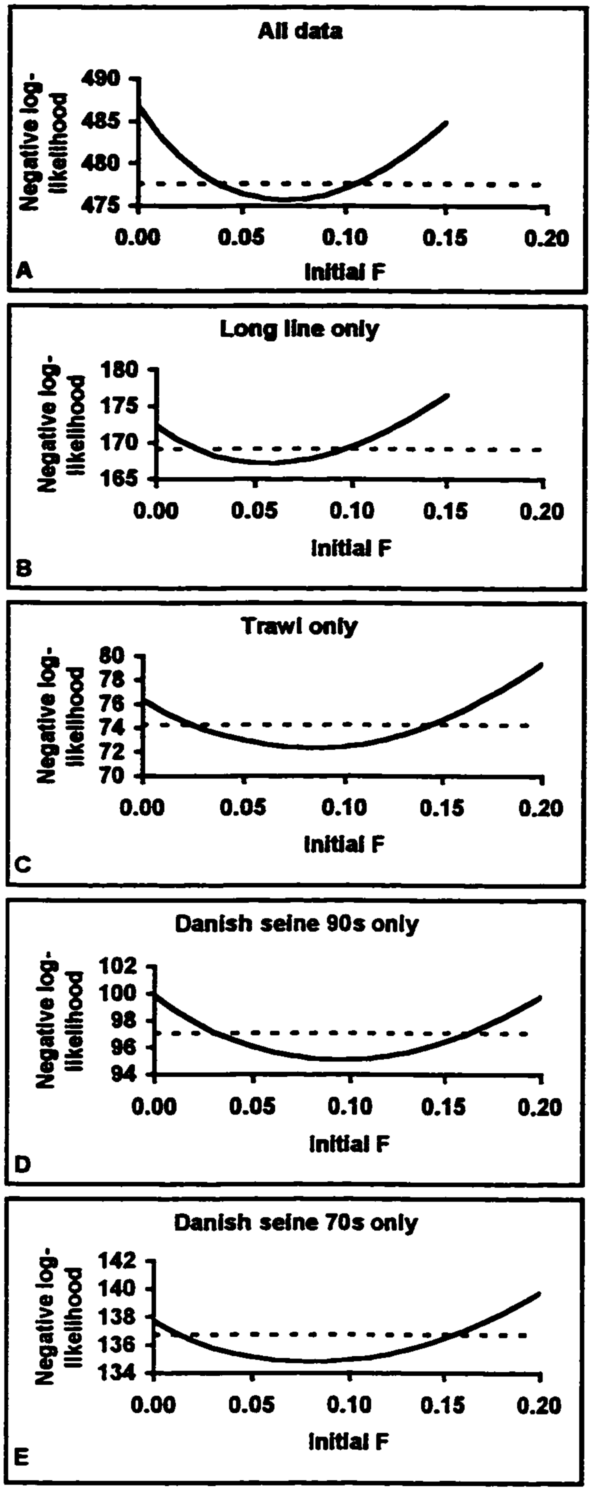

FIGURE 6.6: Negative log-likelihood profiles for different sets of catch-at-age data for the HG-BoP sub-stock. The horizontal dashed line indicates 95% confidence intervals. The plus group scaler (*f*) is fixed at one for these analyses.

6.11 Conclusions and Discussion

Assessment results suggest that the current removals (TACC = 4500 t) are sustainable and the SNA1 stock should rebuild to levels that will support MSY within the 20 year management timeframe. The HG-BoP sub-stock is currently below the level that will support MSY, but will rebuild to above this level within the 20 year management timeframe under the current estimated removals. The EN sub-stock is currently above the level that will support MSY and will remain above this level within the 20 year management timeframe under the current estimated removals. We believe that this assessment of the SNA1 stock is the best that is available and is a big improvement of recent years.

This assessment greatly improves over previous assessments of the SNA1 stock. Firstly, it has incorporated the suggestion of Maunder (1998) to abandon both the long and short term models and uses a mid term model. The long-term model of Gilbert (1994) was very dependent on the assumptions made in the modeling process, particularly with regard to the recruitment processes. By allowing for uncertainty in the 1970 biomass through the mid-term model and the introduction of an initial fishing mortality rate parameter, the analysis gives more realistic estimates of uncertainty.

The second major improvement is that it uses Bayesian analysis to give estimates of uncertainty that can be used in the decision making process. A previous assessment (Annala and Sullivan 1996) used an adhoc method of giving equal weight to a large number of sensitivity analysis and randomly selecting from these for stochastic forward projections. There was no forward projections or risk analysis done in 1997 (Annala and Sullivan 1997) but scientists employed by the fishing industry introduced results from a simple Bayesian analysis to the working group meetings. Bootstrap analysis has been used to calculate uncertainty in recent assessments with limited success (Annala and Sullivan 1998). Other assessments have used ranges for parameter values and different models as sensitivity tests (Gilbert 1994, Annala 1995, Gilbert et al. 1996). Sensitivity tests are only useful if they give similar results or if they can be associated with relative probabilities. We feel that the Bayesian method (Punt and Hilborn 1997) is a much more formal methodology for incorporating uncertainty into the analysis.

Both the EN and HG-BoP analyses indicate that natural mortality is lower that the 0.075 assumed in the base case. The value 0.075 yr^{-1} was recently increased from 0.06 yr^{-1} based on an analysis of early catch-at-age data from the SNA8 stock (Annala and Sullivan 1997). It is unlikely that the overall natural mortality rate is much lower than 0.06 yr^{-1}, but it is possible that there is age or size specific natural mortality rates that greatly differ from the assumed 0.075 yr^{-1}. An analysis using a uniform prior on M from 0.06 to 0.09 yr^{-1} showed that there was very little effect of including this uncertainty into the assessment, probably because the data give similar probability throughout the range of M value{ used. Other results have shown that a level of natural mortality ranging from 0.06 to 0.09 yr^{-1} will not change the results that the EN and HG-BoP stocks will be above B_{MSY} in 20 years under current removals (Annala and Sullivan 1998).

The 1970s Danish seine catch-at-age data was introduced into the analysis to provide information on the initial fishing mortality rate used to generate the age-structure and population size in 1970. It was thought that this early data would be very informative, but it turned out to be the most uninformative data among all the HG-BoP catch-at-age data. This was unfortunate because the initial fishing mortality rate is probably the most important parameter in terms of model sensitivity. The lack of information in the 1970s data is most likely due to inconsistency in the data between years, which may be a consequence of the small sample sizes and the number of trips sampled.

There is no 1970s catch-at-age data for the EN sub-stock and there are only four years of catch-at-age data available in the 1990s. This lack of catch-at-age data and lack of a temperature-recruitment relationship reduces the information available for the EN assessment as can be seen in the flat likelihood profile for the initial fishing mortality rate. It is a concern that the posterior of initial fishing mortality for EN has higher probability for very low values. Prior belief of the working group gives these low values nil probability. This indicates that the model is misspecified. The misspecification could be in the structure of the population dynamics model, in the fixed parameter values, or in the models used to describe how the observed data relates to the population dynamics. There is little concern at present, because even under a zero initial fishing mortality rate, the population is projected to be above B_{MSY}. Future research needs to be directed at discovering methods to determine the initial fishing mortality rate.

The initial fishing mortality is highly confounded with the plus scaler parameter. When fixing the initial fishing mortality and estimating all the other parameters, the plus scaler parameter would be estimated to give a B1970/B0 ratio that is similar to when all parameter are estimated. Therefore, the plus scaler was fixed at one when determining the effect of the initial fishing mortality rates in Figures 6.3, 6.5 and 6.6. The confounding between the initial fishing mortality rate and the plus scaler indicates that the most important component of the model is the depletion level in 1970.

The estimate of initial fishing mortality rate is consistent from all sources of catch-at-age data for the HG-BoP analysis. One concern is that information contained in the catch-at-age data is highly dependent of selectivity parameters. Previous assessments of the SNA1 stock have found difficulty in estimating recruitment and selectivity parameters simultaneously (Annala and Sullivan 1997). Estimation of selectivity parameters was attempted in this assessment of the SNA1 stock, but due to confounding with other parameters, the minimization routine would produce different answers depending on the starting point. Other methods need to be investigated to estimate selectivity parameters. Bayesian analysis could be used to overcome this confounding, but it would require a large amount of computer power to provide sufficient posterior distributions to be useful. It is also desirable to understand the basic model before leaping into a full Bayesian analysis and believing the results.

The Bayesian analysis gives an estimate of uncertainty and allows for the calculation of probability statements for the parameters of interest. The posterior distributions are not totally smooth, but comparison of consecutive sets of values indicates that there is convergence to the general shape of the posterior for the quantities of interest. Inclusion of uncertainty in the initial fishing mortality rate appears to account for a large amount of the uncertainty in the analysis. This is a great improvement over the total catch-history model, which produces much tighter confidence intervals.

Chapter 7: Overall conclusions

7.1 Performance of the Integrated Model

Hilborn et al.'s (1995) suggestion that an integrated tagging and population dynamics model would be a useful tool in fisheries stock assessment has been given additional support from the results presented in this dissertation. The advantages of the Integrated Model (Table 7.1) stem from combining all data into a single analysis. The Integrated Model allows for the best use of all the information contained in the data, prevents inconsistencies between analyses, automatically allows for the correlation between parameters that is often ignored in prior distributions, and also allows detailed investigation of the model fit.

TABLE 7.1: Advantages of the integrated modeling approach.

Advantages
Includes all information from the data
Standardizes dynamics and parameters for all analyses
Automatically incorporates correlation between parameters
Allows detailed investigation of the model fit
Allows the incorporation of any dynamics (e.g. movement)

Despite the advantages of the integrated model, there are a number of problems associated with the complex models required for the integrated analysis and with the influential power of the detailed raw data that is integrated into the fitting procedure (Table 7.2).

TABLE 7.2: Disadvantages of the integrated modeling approach.

Disadvantages
Complex models needed to incorporate the raw data can cause over parameterization or parameter confounding
Model misspecification becomes a problem due to the complex models and detailed data used for the integrated model
Requires large amounts of computer resources

7.1.1 Model misspecification

Model misspecification and large amounts of detailed data may interact to create apparently precise estimates that are in error. Model misspecification occurs when an influential process (including error structure) is left out of the model, a process is incorporated into the model incorrectly, or an incorrect value for a fixed parameter is used. When raw data is integrated into the model, it contains a large amount of information and the model parameters are estimated to explain this data. If the model is misspecified, the model parameters will be estimated in a way that compensates for the model misspecification and may be inconsistent with prior information. The large amount of detailed data used in the Integrated Model may cause small confidence intervals for these parameters; the result is the dilemma of precise estimates that we know are wrong.

Model misspecification appears to be a common problem when complex models are used with large amounts of detailed data. Hampton (1991b) found that estimates of area-specific natural mortality differed by implausibly large amounts when using an unconstrained tagging model. Using a two-area model for bluefin tuna that integrated summarized tagging data with a virtual population analysis, Punt and Butterworth (1995) estimated reporting rates for the two areas that differed by unrealistic amounts.

A common problem in models that include migration is the occurrence of negative biomass estimates indicating inconsistency in data sources or model misspecification (Quinn et al 1990). The application of the Integrated Model to the SNA1 stock indicates some form of model misspecification: the initial 1970 fishing mortality rates for HG and EN are precisely estimated at unrealistically low levels that contradict prior information about significant levels of catch occurring before 1970 (According to Gilbert 1994 the average annual commercial catch in the 1960s was higher than the average for the 1980s and 90s).

Sensitivity analysis is often used to investigate the effect of model misspecification, but it is of little use to management unless probabilities can be assigned to the different sets of parameters or model structures. Sensitivity analysis involves estimating the model parameters under different values for fixed parameters or different model structures. It can be used to determine what parameters or model structures are most influential on the results. Although sensitivity analysis is very useful in directing research, it is less useful for advice to management. As the number of sensitivity analyses increases, the result from the most pessimistic sensitivity test gets more pessimistic. Management may choose a conservative strategy to ensure that the population is safe, if the true situation turns out to be the most pessimistic case. In the situation where all sensitivity tests support a particular management action, sensitivity analysis can actually help management by increasing the confidence in that management action. This is the situation for the SNA1 stock where nearly all of the sensitivities predict a rebuild under current removals. In reality, management needs to make informed decisions based on the probability of different outcomes. The only way to provide this advice is to assign probability statements to each of the sensitivity tests.

The problem of model misspecification in complex models with large amounts of detailed data needs to be addressed in future research. As discussed below, the application of Bayesian analysis, which is one possible approach to the problem of misspecification, will be of little help when there are large amounts of detailed data. A recent development in fisheries stock assessment that involves adding a large number of constrained process errors to the model in an attempt to avoid model misspecification may be a promising area of research (National Research Council 1998). This method takes a general approach at addressing model misspecification. The most common use of this method is to apply a constrained random walk to parameters that may change over time. For example, this method was used for selectivity and catchability parameters in a recent study carried out by the National Research Council (1998).

7.1.2 Confounding of parameters

Confounding of parameters becomes a common problem as models become more complex. Confounding occurs when two parameters are highly correlated, and there is insufficient information in the data to distinguish the effects of each parameter. Often only a combination of the parameters can be estimated and not the individual parameters themselves. For example, the total combined recruitment may be well determined in the simulation tests, but the individual sub-stock recruitments may not be. Confounding between parameters can also produce unrealistic parameter estimates, but this confounding differs from model misspecification (mentioned above) by the fact that confidence intervals for confounded parameters should be large. Covariance estimates, joint confidence intervals, or joint posteriors can be used to identify which parameters are confounded.

The simulation tests presented in Chapter 3 indicate that the Integrated Model can reduce confounding between movement and sub-stock recruitment by the addition of catch-at-age data in the analysis. Sub-stock recruitment and movement are often confounded because any situation between the following two extremes can explain the data: 1) Recruitment can occur in another sub-stock and movement can move those recruits into the sub-stock of interest or 2) recruitment can occur in the sub-stock of interest and no movement occurs. Although one would expect tagging data to be informative about the movement rates, the large variance in estimates of sub-stock recruitment from the simulation tests (Chapter 3) indicates that small random errors in recovery data can cause widely varying results. From the reduced variation in the estimates of sub-stock recruitment from the simulation tests we can conclude that the integrated modeling approach reduces the confounding of movement and sub-stock recruitment due to the inclusion of catch-at-age data.

The Integrated Model does not overcome all the problems with estimating parameters that are confounded in the SNA1 application. The confounding of movement with other parameters in the SNA1 application is large enough that the mean season of movement cannot be estimated in the model. Quinn et al. (1985) also had difficulties obtaining convergence when using an observation error implementation of their migratory model. Anganuzzi (1995) suggests that in most cases the parameter estimation of a complex tagging model will be complicated by the absence of enough contrast in the data or by confounding between parameters. Compare this to the r-K confounding that occurs when fitting a Schaefer model to catch and effort data from a one-way trip (Hilborn and Walters 1992). The inability to estimate movement is supported by Porch's (1995) simulation analysis, which showed that true mixing rates are indistinguishable from a wide range of possibilities.

Despite the estimation problems in models containing movement parameters, there have been a number of cases of success in estimating the parameters. Hilborn et al. (1995) were able to estimate movement, size-specific natural mortality, tagging mortality and size selectivity with low confounding. The ability to estimate movement and the amount of detail depends on the amount of data available. For example, Anganuzzi et al. (1994) were able to estimate movement and selectivity simultaneously, but they were unable to determine if movement occurred as a single event immediately after tagging or annually. Hilborn (1990) suggests that movement and fishing mortality rates are estimable when fish are marked and released in all sub-stocks, and that time-specific natural mortality rates are only estimable when assumptions are made relating fishing effort to mortality. The estimation of seasonal movement in the SNA1 application probably requires releases in all seasons.

Recruitment and selectivity are two sets of parameters that have been found to be confounded in the SNA1 assessments (Annala and Sullivan 1997). The application of the Integrated Model to the SNA1 stock enables the estimation of both recruitment and selectivity. The ability to estimate these parameters is not due to the integration of tagging data with the population dynamics model, but rather to restricting recruitment to follow the temperature recruitment relationship and to sharing some selectivity parameters between the sub-stocks.

In the application of the Integrated Model to the SNA1 fishery there are 16 pairs of parameters that have correlation coefficients with absolute values greater than 0.5. The maximum absolute correlation coefficient is 0.90, which is between the variance of the left-hand limb of the Danish seine selectivity curve and the age at full selectivity for Danish seine in the HG. As expected from the large amount of movement between HG and BoP, there is a large negative correlation between the estimates of average recruitment for HG and BoP (Table 7.3). Surprisingly, there is an even larger negative correlation between average recruitment for HG and EN.

TABLE 7.3: Correlation matrix of average recruitments from the three sub-stocks.

	HGR0	BoPR0	ENR0
HGR0	1.00		
BoPR0	-0.78	1.00	
ENR0	-0.80	0.44	1.00

Parameter confounding may not be as important as suggested by the amount of uncertainty in the parameter estimates. Often the management quantities of interest are not affected by the confounding of two model parameters. For example, if r and K are inversely confounded in a Schaefer model, the effect of confounding on estimates of MSY will not be as large as the effect on r and K, because MSY is calculated as the product of r and K (MSY = rK/4). The relationship is not as clear with the complex models used for the integrated analysis, and likelihood profiles or Bayes posteriors are needed to determine the effect of parameter confounding on management quantities like MSY.

The high complexity of the models and the large number of parameters used in the Integrated Model requires much more information than is usually directly available from the fishery of interest. In effect the model is over parameterized. Bayesian analysis (as discussed below) has become commonly used to add prior information that can be used to remove confounding between parameters.

7.1.3 Use of priors to remove confounding, over parameterization and model misspecification

As mentioned above, information is often included through the use of priors in a Bayesian context in order to avoid confounding between parameters and to prevent over parameterization in complex models. The additional information included in the prior is expected to help define the parameter's value. A problem arises when the model is misspecified. The large amount of catch-at-age and age-structured tagging data used for estimation produces a very large negative log-likelihood. A prior for a single parameter has essentially no impact on the total negative log-likelihood. As was discovered in the SNA1 application, the data can drive parameters to unrealistic values when the model is misspecified and priors have no influence on the result. Priors will only be useful for parameters that are confounded. The exception is that bounds on the priors greatly restrict the parameter estimates and can have a large influence on the results.

The inclusion of lognormal priors on recruitment residuals and normal priors for the mean season of movement in the SNA1 application does not improve the ability to estimate these parameters. The problem with estimating recruitment residuals is related to the model misspecification that causes unrealistic estimates of the initial fishing mortality rates. When a recruitment residual is estimated for 1971, the prior has no influence on the residual and it is estimated to be very large. This increases the biomass in the 1970s relative to the virgin biomass. It is unknown why the model could not estimate the mean season of movement when a prior was included for this parameter. It is possible that a different model structure for seasonal movement may perform better.

7.1.4 Incorporation of Movement

A major area of improvement in fisheries stock assessment indicated by the Integrated Model presented in this dissertation is the incorporation of movement into the population dynamics model. Incorporation of movement in stock assessment has been touted as a forefront of fisheries research (Quinn et al 1990). When there is a need to manage individual sub-stocks, the movement between sub-stocks should be included in the analysis to prevent large biases in the estimation of sub-stock status. While the Integrated Model is not required to incorporate movement into the stock assessment, still it provides a clear framework that makes incorporation and estimation of movement, or any other dynamic, straightforward. Other methods like migratory catch-at-age analysis (Quinn et al. 1990) use fixed movement parameters that are estimated externally from the population dynamics model.

Ignoring movement can cause large biases in the estimation of individual sub-stock current status and recruitment, as seen in both the simulation tests and the SNA1 application. Punt and Butterworth (1995) also found large differences in results between models that included and ignored movement for bluefin tuna. Without including movement in the assessment of the SNA1 stock, the assessment is much more optimistic for HG and much more pessimistic for BoP. These results are similar to those of Mullen (1994) who found that catch of yellowfin tuna from the coastal fishery in the eastern Pacific Ocean prior to the late 1960s was sustained by immigration from a larger offshore refuge. Incorporation of movement is not always as influential as in the SNA1 assessment. Quinn et al. (1990) found very little change in biomass trajectories when migration was incorporated into a model to assess halibut; they found that model error structure is much more important. Porch et al. (1996) found that a two-stock Virtual Population Analysis (VPA) with mixing does not produce significantly better estimates than a non-mixing VPA when tested against artificial data sets that include mixing. The results presented in this dissertation suggest that total combined productivity and combined current status of the sub-stocks are not seriously biased by movement between the sub-stocks, but it is important that movement is included in analysis if management at the sub-stock level is being considered.

7.1.5 Investigating the fit

A main advantage of the Integrated Model is that integrating the tagging data with the population dynamics model allows for the investigation of the model in more detail. Inspection of how the model fits to the data promotes the generation of new hypotheses or increases support for current hypotheses. The application of the Integrated Model to the SNA1 stock has identified the following: the importance of movement to the assessments of the three sub-stocks, the significance of age and seasonal-structure of movement, and the difference in selectivity between the 1984-85 tagging program and selectivity in the 1990s.

7.1.6 Aging error

The integrated tagging and population dynamics model described in this dissertation relies on knowing the age of tagged and recaptured fish. Therefore, problems with age determination can cause difficulties in applying the Integrated Model and may introduce bias into the results. Age can usually only be determined after a fish is killed; therefore, only the recoveries can be directly aged by otolith reading or other methods. Age at release is usually determined by putting the length at release through an age-length key that was collected at the time of release. In addition, the age information that is taken from recaptured fish is often unreliable. Depending on the design of the tagging study, age or even length measurements may not be available for recoveries. These problems may prevent the use of the Integrated Model or increase the error in the age-specific tagging data. Error in age determination will directly affect the results of the Integrated Model; this is one area of research that would be useful in evaluating the Integrated Model. Methods that are used to determine the influence of aging error in catch-at-age analysis can be used to investigate the influence of aging error in the integrated tagging and population dynamics model. The Integrated Modeling approach can also be used in a length based modeling framework and the error in length determination will be much smaller than for age determination. Length-based Integrated Models would be another area of useful research.

7.1.7 Computational Requirements

The Integrated Model is very computer intensive. For the SNA1 application each tag release stratum (area and time) is modeled as a separate set of three sub-populations. The total population is also modeled as a set of three sub-populations. All these populations are modeled over four seasons, creating 72 times more population dynamics calculations for the SNA1 Integrated Model than for the current assessment model. There also are many more likelihood calculations because the model is fit to age-structured tagging data over a number of seasons. These additional calculations add up to a large amount of CPU time. It takes about two days to find the maximum likelihood estimate (MLE) for the SNA1 application (programmed in AD Model Builder © Otter Research) on a Pentium 90 with 32 MB of RAM. The program is too large for the available memory and requires continuous disk access. The estimation time is reduced to under an hour when a Pentium 200 with 64 MB of RAM is used. Running a program over the weekend to get a final assessment is not a major problem, but if the program takes that long to run then the development phase will be very long.

It is very time-consuming to develop models that take long periods of time to estimate their parameters, because a program usually needs to be run a number of times to check for any programming errors. I usually check all my programs by repeating the calculations in Microsoft Excel. Excel is ideal for this use because it is conceptually different from a procedural programming language and prevents the same errors being made in both versions of the model. The SNA1 Integrated Model is so large that only parts of the model can be programmed in a single Excel Workbook without having to wait forever for all the cells to calculate, and even then it is not practical to run solver to estimate the parameters.

It may be possible to reduce the estimation time by modifying the computer program. The program models the tagged populations from the start of the assessment time period

(1970), but tag releases first occur in 1985, resulting in a large number of wasted calculations. The computer program could be modified to model the tagged populations only from the time of release to the time of the last recapture sample. The number of likelihood calculations could be reduced in the Integrated Model by grouping older age groups that have similar characteristics; for example, when selectivity is asymptotic. Modeling the three sub-populations as a single large population would reduce the number of calculations and could still be carried out using the integrated modeling approach. Using only a single population could be further reduce calculations because it is not necessary to model the tagged individuals as a separate population. The number of age a tagged individuals alive in time t is equal to the number of releases in time t' that are of age a' (where $a'=a-(t-t')$) multiplied by the ratio of the numbers in the total population aged a at time t to the numbers in the total population aged a' at time t'. This simplification cannot be used when there is movement between sub-populations, because it is not possible to determine the sub-population of origin and this is important for estimating movement.

The large computational requirements of the Integrated Model make a full Bayesian integration impractical. A fully integrated Bayesian analysis (Punt and Hilborn 1997) would be useful in an Integrated Model framework to allow the description of uncertainty and confounding in parameter estimates. Because of the intense computational requirements of the Integrated Model, it takes five days to do one million Markov Chain Monte Carlo simulations. The posterior distribution does not converge within these one million simulations, making Bayesian integration impractical for the application of the Integrated Model to the SNA1 stock. It is possible that the restructuring of the computer program mentioned above or a more powerful computer may make Bayesian integration of the Integrated Model attainable in a reasonable time frame.

7.2 Comparisons with the current assessment

The main differences between the current SNA1 assessment (described in Chapter 6) and the application of the Integrated Model to the SNA1 stock (described in Chapter 5) are:

1) Integration of the tagging data with the population dynamics assessment model
2) Modeling interactions (movement) between the three sub-stocks
3) A seasonal time structure.

Of these differences, modeling of movement has the greatest influence on the assessments of the individual sub-stocks. Movement does not have a large influence on the overall assessment of the SNA1 stock. These results are also supported by the simulation tests presented in Chapter 3. Fixing the initial fishing mortality rates has the biggest influence on the overall assessment of the SNA1 stock. The integration of tagging data with the population dynamics model appears to have little influence on the assessment of HG or the overall SNA1 stock, but produces a significantly lower biomass trajectory for BoP and a higher biomass trajectory for EN. The effect of including the seasonal time structure in the SNA1 assessment is unknown.

7.2.1 East Northland sub-stock

EN is the only sub-stock for which comparisons can be made directly between the current assessment and the results of the Integrated Model. The current assessment estimates that the EN biomass is currently well above the level that will support Maximum Sustainable Yield (B_{MSY}) and projects that the EN biomass will slightly increase under current removals. In spite of starting at a similar biomass level in 1970, the Integrated Model estimates the current EN biomass to be lower than B_{MSY} (assuming the B_{MSY}/B_0 ratio is the same as in the current assessment), but also projects the EN biomass to slightly increase under current removals. The sensitivity analysis that most closely resembles the current assessment for EN (fitting to total biomass estimates and no movement) estimates the current biomass to be about the same as in the current assessment, but the biomass is projected to decrease under current removals. The difference in results could be due to the estimation of selectivity or the assumed temperature-recruitment relationship in the Integrated Model. The results for EN when fitting to total biomass are also very sensitive to the relative weighting applied to the biomass estimates. The relative weighting given to each data set often has a large influence on the results when there are conflicting trends in the data. For example, Quinn et al. (1990) found their age-structured migration model is sensitive to the weighting of catch-at-age data compared to effort.

The results for EN are sensitive to the inclusion of movement in the model. By including movement, the status of EN goes from a population that is above B_{MSY} and declining under current removals to a population that is below B_{MSY} and slightly increasing under current removals. The sensitivity to movement is about the same as sensitivity to other considerations, such as the weighting assigned to the catch-at-age data.

7.2.2 The Hauraki Gulf and BoP sub-stocks

The HG and BoP sub-stocks are combined into a single stock in current assessments (Annala and Sullivan 1998; see Chapter 6), and the results of the Integrated Model analysis suggest that this is preferable to analyzing HG and BoP as separate non-interacting stocks. When the estimates of HG and BoP from the Integrated Model are combined, they give a very similar level of depletion in 1998 compared to the current assessment, but the absolute biomass is much smaller. When using the Integrated Model, the initial biomass in 1970 is much smaller and the projected rebuild is much slower compared to the current assessment. The sensitivity analysis that fits to total biomass estimates and excludes movement is much closer to the results of the current assessment for combined HG and BoP. This suggests that the difference between the Integrated Model and the current assessment is due to the incorporation of age-specific tagging data and movement.

The overall results from the Integrated Model differ between the HG and BoP sub-stocks, providing evidence that management decisions may need to differ between the two sub-stocks. BoP is estimated to be much more exploited in 1970 than HG and has a much faster projected rebuild. HG and BoP have very similar levels of depletion in 1998. The results suggest that despite the differences between HG and BoP, combining HG and BoP for assessment purposes, as done in the current assessment, is preferable to analyzing HG and BoP as separate non-interacting stocks. It would be valuable to have the data from the 1984 BoP tagging program that would provide more information on movement from

BoP to HG and possibly increase the estimability of the model parameters. The loss of this data highlights how important it is that efforts are made to preserve data that may become valuable as new assessment techniques are developed.

7.3 Problems in the SNA1 assessment

Chapter 4 introduced a number of problems associated with the previous assessments of the SNA1 stock. Unfortunately, the Integrated Model was unable to overcome all of these problems and also identified some additional problems. The major remaining problems are the discrepancies in tag return rates, the estimation of the initial fishing mortality rate in 1970, and the possible temporal change in selectivity.

7.3.1 Discrepancies in tag return rates

The Integrated Model could not overcome the discrepancies in tag return rates from the two tagging programs. The higher return rates by Danish seine are probably due to clumping of tags. The Danish seine method targets schools of snapper, so if the tagged fish happen to be schooling snapper then Danish seine would have higher return rates. It will require a more complex model to determine the influence of this dynamic on the assessment models. It may be possible to develop a model that tracks the preferred fishing grounds of the different gear types and how the release of tags is distributed. There is also speculation by fishers that there are two types of snapper, resident and transient. It is possible that a higher proportion of either of these types of fish are tagged and that the Danish seine gear targets these fish.

The resident-transient behavior has an influence on how movement should be incorporated into the model. The seasonal differences in recovery rates from the 1984-85 tagging program support the hypothesis of resident and transient fish. If tag releases occurred when transient fish were out of the fishing area, recovery rates will decrease when the transient fish return. Porch (1995) and Powers and Cramer (1996) presented a model that incorporated transient behavior (non-Markovian movement) of fish between two sub-stocks. This is a promising area of research that may provide insight into the dynamics and assessment of the SNA1 stock. Transient behavior and fidelity can be difficult to estimate from standard fisheries tagging data (Schwarz and Arnason 1990).

Due to the computational intensity of the Integrated Model, it is not practical to investigate the effect of release method on recovery rates. It is likely that a similar model to that suggested to investigate the Danish seine recoveries is also needed to investigate the effects of release method.

7.3.2 Starting in 1970

Changing from a total catch history model that starts in 1850 to a mid-term model that starts in 1970 has removed assumptions about historic catch and recruitment, but has resulted in a different set of problems related to the estimation of the initial fishing mortality rate. Estimates of the initial fishing mortality rate are either imprecise or if they are precise, the estimates are unrealistic. Imprecise estimates indicate that the information contained in the data is insufficient, and more data or additional assumptions are needed. Parameters that are precisely estimated at unrealistic values indicate that the model is misspecified and requires investigation of the model stucture and assumptions used. Fortunately for the SNA1 stock, the sensitivity analysis suggests that under the current removals the range of plausible fishing mortality rates in 1970 will allow the SNA1 population to rebuild. In the future, the estimation of the initial fishing mortality will become more important as the stock is rebuilt and assessment moves towards optimizing the benefits from the stock.

One major area of research for the SNA1 fishery is the development of techniques that will help overcome the problems in estimating the depletion level in 1970 or the corresponding fishing mortality rate. It appears from the results presented in this dissertation that the data indicate a decline in biomass from 1970 to the 1980s due to fishing of accumulated biomass rather than the catch coming from recruitment. This indicates that there is a large difference between the biomass levels in 1970 and the biomass levels in the 1980s and 90s. The results indicate a number of areas that may help in understanding the unrealistically low estimates of initial fishing mortality in 1970.

- *Increasing the age of the plus group.* The average size of a snapper is still increasing at age 20, which is the age used for the plus group in the current assessment and the analyses presented in this dissertation. Increasing the age of the plus group will increase the biomass size of the lightly exploited 1970 population in comparison to the heavily exploited population in the 1980s and 90s. This increased biomass will reduce the amount of recruitment needed to support the total catch while still having similar biomass levels in the 1980s and 90s. An alternative to the reduction in recruitment is an increase in the initial fishing mortality rate in 1970, which will reduce the biomass in 1970.
- *Including a stock-recruitment relationship.* The current assessment does not use a stock-recruitment relationship, but bases recruitment on a temperature-recruitment relationship. A stock-recruitment relationship will allow more recruitment in 1970 when the population size is high compared to the 1980s and 90s when the population size is low. The higher recruitment in 1970 relative to the 1980s and 90s may allow for higher initial fishing mortality rates in 1970, which are offset by higher virgin recruitment levels. This will give similar biomass levels in 1970 compared to a situation with no stock-recruitment relationship. The stock-recruitment relationship will reduce recruitment in the 1980s and 90s, allowing the biomass levels to be similar despite the increase in virgin recruitment.
- *Re-evaluation of the natural mortality rate.* Sensitivity analyses show that low levels of natural mortality correspond to more realistic (higher) initial fishing mortality rates in 1970. The natural mortality rate has recently been increased from 0.06 to 0.075 based on data from the west coast snapper fishery. This data needs to be re-evaluated to determine the possibility of lower natural mortality rates. It is also possible that life history theory or relationships with other biological characteristics may be useful in determining natural mortality (Gunderson 1996).
- *Investigating age-structured natural mortality.* Higher rates of natural mortality for younger fish may help to explain the low estimates of initial fishing mortality rates. Higher rates of natural mortality for younger fish would increase the 1970 population

size where exploitation rates are low relative to the population size in the 1980s and 90s where exploitation rates are high. The data from the west coast snapper fishery indicate that natural mortality may be higher for younger individuals, but any estimates will be confounded with selectivity.

- *Incorporating changes in selectivity.* It is possible that the changes in selectivity that are observed in the Integrated Model application may explain the low initial fishing mortality rate estimates.

7.3.3 Changes in selectivity

Recent research in fisheries stock assessment has focussed on temporal changes in selectivity (National Research Council 1998) and this may be an important factor in the SNA1 assessment. Maunder and Starr (1998) highlighted the annual changes in selectivity due to variable growth for the youngest cohorts in the Hauraki Gulf snapper fishery. The results of the Integrated Model suggest a difference in selectivity for the youngest ages between the 1984-85 tagging program and the 1990s. This difference could be due to a number of factors.

- Annual changes in growth rates of the youngest age-classes cause changes in selectivity (Maunder and Starr 1998).
- Selectivity at length will positively bias the length of tagged individuals in the youngest age-classes, causing the selectivity of tagged and untagged fish to be different for these age-classes.
- The introduction of the Quota Management System caused behavioral changes in fishers, causing a change in selectivity.
- Technological changes in fishing gear or equipment caused a change in selectivity.

7.3.4 Estimating recruitment

It was difficult to estimate annual recruitment strength for the three sub-populations without using the temperature-recruitment relationship for the BoP and EN sub-stocks. I recommend that in future assessments of the SNA1 stock the temperature-recruitment relationship be used to describe the underlying annual recruitment fluctuations of each sub-stock, but the annual fluctuations be allowed to vary around this relationship. In this way the annual recruitment strengths would be allowed to differ from the temperature-recruitment relationship if there is supporting information in the data. This would be particularly useful for the BoP and EN sub-stocks, where there is evidence that recruitment strengths for some years differ from the temperature-recruitment relationship. Implementation would involve the estimation of area-specific annual deviations ($\varepsilon_{y,l}$) that are constrained using a prior distribution.

$$r_{y,l} = \exp\left(\alpha + \beta T + \varepsilon_{y,l}\right)$$

where $\varepsilon_{y,l}$ has a normal distribution with mean 0 and specified standard deviation.

Total recruitment is equal to:

$$R_{y,l} = f(S_{y,l})r_{y,l}$$

where $f(S_{y,l})$ is the stock recruitment-relationship.

7.4 Optimal tagging design for the Integrated Model

To be most effective, the Integrated Model needs a specific tagging study design. It is very important to consider the method that will be used to analyze the data when designing a tagging program. The tagging studies in SNA1 were not designed with the application of an Integrated Model in mind, but it is important that any further tagging programs in SNA1 are. Tagging programs require the following attributes to improve the applicability of the Integrated Model:

1) The length, sub-stock and time of release for every tagged fish needs to be recorded. Combined with an age length key, this will allow the determination of ages for the released fish.
2) An age-length key needs to be collected for each sub-stock at the time of release.
3) It must be possible to determine the release details from any recovered fish by using uniquely coded tags. This will allow the release stratum to be determined for any recaptured tagged fish.
4) The age at recovery needs to be determined, preferably by directly aging recovered fish rather than using an age-length key.
5) Fish sampled for tags should also be sampled for age-structure (this is not required for the Integrated Model presented in this dissertation but may be useful for further development of the Integrated Model).
6) Fish should be released and sampled in all sub-stocks and in all seasons. This will allow the estimation of seasonal movement between all the sub-stocks.
7) Tag loss should be minimized and recoveries should occur over a number of years. This will increase the amount of data from a release group and may be beneficial, if there is temporal variation in the population's dynamics.

There are a number of differences between the 1993-94 tagging program and the 1984-85 tagging program for SNA1. Both programs have advantages and disadvantages, and these should be considered when designing a new tagging program (Tables 7.4 and 7.5).

TABLE 7.4: Advantages and disadvantages of the 1984-85 tagging program.

Advantages	Disadvantages
Large number of recoveries	Large tag loss rate
Long time span of recoveries	Unknown underreporting rate
Known length at release from recovery data	Uncertain recovery sample size
Recoveries include all gears	Did not release in BoP

TABLE 7.5: Advantages and disadvantages of the 1993-94 tagging program.

Advantages	Disadvantages
Known recovery sample size	Only sampled the three main gears
Known underdetection rate	Expensive recovery phase
No fisher reporting bias	Problems with access to fish for sampling
Covered all sub-stocks	Only approximately half the release lengths available from recapture data

7.5 Management strategies for interacting sub-stocks

Movement has been shown to be an important factor in assessing a fishery. Research should to be carried out to determine the influence of movement on management strategies. The analyses presented in this dissertation investigate an assessment procedure and do not consider management strategies. Movement between stocks is especially a concern to international fishery management agencies. The main management problems associated with movement occur in stocks that move through international boundaries. New Zealand is isolated and has very few stocks that it shares with other countries. The introduction of Individual Transferable Quotas (ITQs) has created problems in New Zealand's fisheries management system similar to those seen in internationally managed fisheries. The resources owned in one Quota Management Area (QMA) will be affected by the actions of fishers operating in a neighboring QMA when there is significant movement of fish between the two areas. One advantage in New Zealand over international management is that fishers can own rights to the resources in many areas. It is common for the large players to own resources in all of the interacting QMAs, making it easier to come to agreement over management actions. Interactions between QMAs is not a problem with the SNA1 stock because it is contained in one QMA, but it may be a problem for other New Zealand stocks.

Investigation of management strategies for interacting sub-stocks would be useful in conjunction with the application of the Integrated Model to the SNA1 stock. It is unknown whether estimates of Maximum Sustainable Yield (MSY) and the biomass at MSY (B_{MSY}) for SNA1 will be the same under movement assumptions. There are also yield-per-recruit considerations when there is age-specific movement (Deriso et al. 1991). Loss in yield-per-recruit occurs when the full individual growth potential of the fish, adjusted for natural mortality, is not captured by the selectivity of the gear and the exploitation rate. When movement is age-specific, one sub-stock is often exploited at ages where the potential gain from individual growth is still high. To maximize yield-per-recruit, the fishery should be closed for this sub-stock. Closing a fishery to benefit another fishery is politically very difficult to do, particularly when the participants differ between the fisheries.

The inability to precisely estimate sub-stock recruitment may force management to act conservatively on all sub-stocks. The Integrated Model has difficulties estimating individual sub-stock average recruitment. This implies that it is important to conserve all sub-stocks to protect the resource, since it is uncertain where recruitment is coming from. Understanding the biology and ecology of the species is needed to determine how important recruitment from each sub-stock is to the conservation of the total stock. Possibly pre-recruit trawl surveys might be used to estimate the relative distribution of recruitment between the different sub-stocks.

7.6 Overall Conclusions

The Integrated Model provides a powerful approach that will be a key part of the future of fisheries stock assessment. As computer power increases, the Integrated Model will become more available to quantitative fisheries scientists and develop into an invaluable research tool. The integration of raw data into the population dynamics model provides the base for more detailed investigation of data, therefore allowing testing or development of new hypotheses. The flexible framework allows for the incorporation of complex dynamics; as more detailed data is collected the Integrated Model framework will become more useful.

The tagging data available for the SNA1 stock is limited and SNA1 may not be the most appropriate application to demonstrate the benefits of the integrated modeling approach. The application of the Integrated Model to other species that have a larger temporal range of data may help in understanding the importance of the integrated modeling approach to fisheries stock assessment. An ideal application for the Integrated Model is the stock of sablefish off the West Coast of Canada, which has a large tagging data base with many years of release and recovery data. It would be straight forward to combine the two sablefish models presented in Haist et al. (1997) in the integrated modeling framework.

Development of other types of integrated models will benefit areas other than tagging analysis. A number of suggested Integrated Models are listed below.

- *Integration of standardized CPUE analysis.* The integration of standardized Catch Per Unit Effort (CPUE) analysis and surplus production models (e.g. Xiao 1998), as outlined in Chapter 1, is a simple application of an Integrated Model that can be routinely used in fisheries stock assessment. Integration of standardized CPUE can easily be incorporated into any population dynamics models, including age-structured models. It may be possible to estimate parameters of more complex relationships between CPUE and abundance, such as density dependent effects on CPUE or non-linear relationships, if the raw data is integrated into the population dynamics model.
- *Integration of trawl survey data.* Trawl survey data can be integrated into the population dynamics model in the same way as described for CPUE data.
- *Integration of environmental variables.* The integration of the temperature-recruitment relationship into the population dynamics model for the SNA1 assessment is another example of the integrated modeling approach. Instead of using the relationship generated by regressing abundance estimates from pre-recruit trawl survey data against sea surface temperature (Francis 1993), the temperature and pre-recruit trawl survey data were included in the population dynamics model. Thus, the relationship was determined while fitting to all the other data. Other environmental variables can be integrated in the same way.
- *Integration of growth estimation in size-based models.* The estimation of growth from tagging data can be integrated with a size-based population dynamics model. Both tagging data (e.g. Punt et al. 1997) and length frequencies (e.g. Fournier et al. 1990)

have been used to estimate growth parameters, but recent analyses have ignored the growth information in the length frequency data. Tagging data is first used to estimate a growth transition matrix (Punt et al. 1997), and this transition matrix is then used in a sized-based model that is fit to length frequency data (Punt and Kennedy 1997). Integration of the type of tagging data used for growth estimation into a sized-based model is a much simpler task than the models presented in this dissertation. With the performance of AD Model Builder it should become the standard method of assessment. A similar method could also be used in age-structured models, especially if the distribution of size-at-age is being modeled.

- *Meta analysis*. Populations that share characteristics (e.g. natural mortality may be assumed equal for all populations of a certain species) can have their analyses integrated. Then, information from each population can be used to estimate the shared parameters. A simple example would be to model each population using a Schaefer model sharing the same intrinsic rate of increase, but with each having different carrying capacity parameters.
- *Multispecies analysis.* With multispecies analysis, researches have already been using an integrated approach to assess populations (Magnusson 1995). Although many of the parameters used in the multispecies analysis are estimated outside the model or deterministically inside the model, recently integrated approaches are being developed to estimate these parameters statistically within the population dynamics model (pers comm. Jesus Jurado-Molina, School of Fisheries, University of Washington).
- *Ecosystem analysis.* With ecosystem analysis, researches have already been using an integrated approach to assess populations. Many of the parameters used in the ecosystem analysis are estimated outside the model and an integrated approach could be used to estimate these parameters simultaneously with the other parameters of the model.

The results of this study have provided some useful insights into the assessment of the SNA1 stock. Based on these results the following changes are recommended for the next assessment of the SNA1 stock.

1) Model the SNA1 stock as three interacting sub-stocks.
2) Include a stock recruitment relationship in the population dynamics model.
3) Increase the age of the plus group.
4) Re-evaluate the rate of natural mortality and the possibility of age-specific natural mortality.
5) Estimate independent annual selectivity parameters for ages 4 and 5.
6) Estimate two sets of selectivity parameters, one for before the Quota Management System was introduced and one for after.
7) Allow for variation around the temperature-recruitment relationship.

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Appendix A: Data for the SNA1 application

Table A1. Long line catch (tonnes) in the Hauraki Gulf by year and season.

Year	Summer	Autumn	Winter	Spring
1970	1251.81	942.11	646.12	1630.20
1971	1383.59	1027.58	687.33	1359.69
1972	1096.65	824.96	565.30	1310.42
1973	1096.58	819.68	555.05	1245.96
1974	1030.99	769.32	519.25	1040.94
1975	841.93	633.99	435.25	1131.91
1976	959.69	709.89	471.15	1157.13
1977	959.14	704.29	460.72	1338.14
1978	1004.63	691.40	392.04	1247.71
1979	1020.62	702.40	398.27	896.68
1980	680.27	468.17	265.46	924.07
1981	767.24	528.02	299.40	859.68
1982	689.84	474.76	269.20	772.51
1983	619.82	426.57	241.87	877.84
1984	515.33	310.42	158.45	675.72
1985	420.03	333.01	188.32	643.34
1986	506.78	315.81	123.68	432.87
1987	265.43	233.70	168.14	782.09
1988	420.88	328.08	179.29	613.61
1989	452.00	362.86	146.91	442.97
1990	428.88	294.83	171.10	513.57
1991	421.02	274.90	194.37	659.51
1992	594.73	370.50	244.02	636.30
1993	589.83	435.80	251.47	600.28
1994	524.73	317.34	198.29	513.58
1995	475.52	319.94	169.99	350.32
1996	394.30	323.16	170.17	378.46
1997	369.74	303.03	159.57	354.88

Table A2. Single trawl catch (tonnes) in the Hauraki Gulf by year and season.

Year	Summer	Autumn	Winter	Spring
1970	862.65	548.31	72.66	432.49
1971	991.54	630.24	83.52	344.40
1972	756.73	480.99	63.74	340.01
1973	771.04	490.09	64.95	323.91
1974	729.11	463.44	61.42	262.30
1975	579.15	368.12	48.78	302.30
1976	695.61	442.14	58.59	312.99
1977	709.88	451.21	59.80	378.41
1978	872.40	554.51	73.49	391.04
1979	886.52	563.49	74.68	273.81
1980	591.02	375.66	49.78	291.11
1981	666.27	423.49	56.12	267.47
1982	598.89	380.66	50.45	240.39
1983	538.23	342.11	45.34	277.12
1984	287.62	295.31	44.35	151.20
1985	221.10	205.77	57.63	165.52
1986	190.50	175.93	34.16	84.61
1987	442.58	157.91	13.55	95.85
1988	436.25	203.39	18.56	38.12
1989	434.98	445.81	18.92	220.26
1990	489.92	213.85	56.85	225.94
1991	371.93	285.27	23.67	232.52
1992	557.49	259.55	8.13	131.71
1993	385.51	183.02	24.03	179.12
1994	205.57	141.96	16.70	119.52
1995	226.69	194.89	22.16	57.50
1996	248.49	152.94	43.57	120.81
1997	233.01	143.41	40.86	113.28

Table A3. Danish seine catch (tonnes) in the Hauraki Gulf by year and season.

Year	Summer	Autumn	Winter	Spring
1970	582.26	471.72	97.18	470.22
1971	669.36	542.28	111.71	376.13
1972	511.01	414.00	85.29	370.23
1973	520.73	421.87	86.91	352.82
1974	492.20	398.75	82.15	286.21
1975	390.90	316.69	65.24	328.66
1976	469.78	380.59	78.41	340.76
1977	479.34	388.34	80.00	411.34
1978	589.14	477.29	98.33	425.56
1979	598.34	484.74	99.86	299.31
1980	398.77	323.07	66.55	316.43
1981	449.61	364.25	75.04	291.47
1982	404.28	327.53	67.47	262.02
1983	363.41	294.42	60.65	301.42
1984	403.19	407.03	44.63	407.28
1985	391.10	273.58	61.96	172.44
1986	296.76	322.96	43.03	178.77
1987	134.48	201.21	27.17	372.07
1988	177.39	160.96	45.28	121.60
1989	286.07	116.77	0.26	82.90
1990	117.17	161.42	90.95	240.67
1991	372.73	169.48	46.25	201.54
1992	463.99	273.13	99.84	172.67
1993	280.35	284.74	53.75	119.49
1994	294.55	231.27	26.26	156.50
1995	218.21	196.25	45.33	60.38
1996	114.18	133.95	14.16	77.71
1997	107.07	125.61	13.28	72.87

Table A4. Other commercial catch (tonnes) in the Hauraki Gulf by year and season.

Year	Summer	Autumn	Winter	Spring
1970	205.27	233.02	92.22	240.92
1971	236.05	267.97	106.05	200.35
1972	180.29	204.67	81.00	191.56
1973	183.51	208.32	82.44	183.74
1974	173.42	196.87	77.91	151.80
1975	137.93	156.58	61.97	167.76
1976	165.60	187.99	74.40	176.33
1977	169.00	191.85	75.92	209.66
1978	207.79	235.89	93.35	220.49
1979	211.15	239.70	94.86	161.87
1980	140.65	159.67	63.19	162.36
1981	158.52	179.95	71.21	152.72
1982	142.68	161.97	64.10	137.17
1983	128.08	145.40	57.54	153.93
1984	173.47	256.67	37.71	234.27
1985	230.86	193.52	50.93	170.37
1986	164.68	109.98	50.06	75.00
1987	37.40	72.80	48.92	96.94
1988	108.54	100.33	56.50	55.76
1989	93.74	169.34	45.09	107.50
1990	62.82	86.34	55.11	151.76
1991	108.93	144.05	52.63	54.41
1992	69.10	84.05	55.01	63.10
1993	35.66	50.88	43.22	33.61
1994	21.73	41.68	45.37	54.80
1995	24.22	32.57	20.37	23.01
1996	58.38	61.25	24.45	47.64
1997	54.74	57.43	22.93	44.67

Table A5. Recreational catch in (tonnes) the Hauraki Gulf by year and season.

Year	Summer	Autumn	Winter	Spring
1970	528.76	419.44	49.16	109.15
1971	528.76	419.44	49.16	109.15
1972	528.76	419.44	49.16	109.15
1973	528.76	419.44	49.16	109.15
1974	528.76	419.44	49.16	109.15
1975	528.76	419.44	49.16	109.15
1976	528.76	419.44	49.16	109.15
1977	528.76	419.44	49.16	109.15
1978	528.76	419.44	49.16	109.15
1979	528.76	419.44	49.16	109.15
1980	528.76	419.44	49.16	109.15
1981	528.76	419.44	49.16	109.15
1982	528.76	419.44	49.16	109.15
1983	528.76	419.44	49.16	109.15
1984	528.76	419.44	49.16	109.15
1985	381.23	302.41	35.44	78.70
1986	528.76	419.44	49.16	109.15
1987	528.76	419.44	49.16	109.15
1988	528.76	419.44	49.16	109.15
1989	528.76	419.44	49.16	109.15
1990	528.76	419.44	49.16	109.15
1991	528.76	419.44	49.16	109.15
1992	528.76	419.44	49.16	109.15
1993	528.76	419.44	49.16	109.15
1994	641.89	509.18	59.68	132.51
1995	486.46	385.88	45.23	100.42
1996	499.32	396.08	46.42	103.08
1997	499.32	396.08	46.42	103.08

Table A6. Long line catch (tonnes) in the Bay of Plenty by year and season.

Year	Summer	Autumn	Winter	Spring
1970	193.39	303.36	334.09	230.20
1971	167.65	262.99	289.63	251.37
1972	210.70	330.51	363.99	230.01
1973	156.43	245.38	270.23	194.10
1974	145.58	228.36	251.50	132.75
1975	75.07	117.75	129.68	123.70
1976	108.40	170.04	187.27	149.21
1977	119.43	187.35	206.33	213.53
1978	193.57	303.64	334.40	243.18
1979	183.91	288.49	317.72	187.80
1980	120.19	188.53	207.63	164.00
1981	130.61	204.87	225.63	169.09
1982	130.41	204.57	225.29	131.02
1983	82.51	129.43	142.54	109.10
1984	98.48	122.69	131.15	114.81
1985	83.98	95.21	138.52	130.24
1986	123.78	174.87	157.22	102.02
1987	31.40	73.65	130.57	55.75
1988	52.41	51.20	55.26	39.99
1989	28.79	51.85	37.66	8.29
1990	9.13	72.04	101.41	115.09
1991	76.78	79.83	100.47	119.86
1992	97.37	79.31	64.33	66.91
1993	55.62	119.89	102.59	67.55
1994	49.63	116.40	123.56	64.43
1995	49.64	94.70	165.62	72.86
1996	58.55	167.36	148.12	106.10
1997	54.90	156.93	138.89	99.49

Table A7. Single trawl catch (tonnes) in the Bay of Plenty by year and season.

Year	Summer	Autumn	Winter	Spring
1970	188.77	178.66	128.22	109.50
1971	163.63	154.87	111.14	118.64
1972	205.65	194.63	139.68	109.77
1973	152.64	144.47	103.68	92.20
1974	142.15	134.54	96.55	63.88
1975	73.27	69.34	49.76	58.22
1976	105.78	100.12	71.85	70.61
1977	116.58	110.34	79.19	100.29
1978	188.93	178.81	128.32	115.46
1979	179.55	169.93	121.95	89.92
1980	117.36	111.07	79.71	77.65
1981	127.48	120.65	86.59	80.17
1982	127.25	120.43	86.43	62.74
1983	80.53	76.22	54.70	51.69
1984	267.42	198.37	158.05	133.23
1985	290.80	309.39	155.71	121.63
1986	266.88	241.35	85.73	108.16
1987	192.20	120.41	59.27	55.35
1988	98.78	69.02	96.73	110.18
1989	93.37	150.58	113.80	56.68
1990	92.23	130.22	284.35	157.95
1991	109.38	104.30	112.09	139.92
1992	101.29	79.66	89.62	109.35
1993	153.10	110.29	75.74	55.16
1994	46.98	103.15	101.72	87.49
1995	63.73	44.88	60.04	60.10
1996	196.86	205.97	101.37	125.56
1997	184.60	193.14	95.06	117.74

Table A8. Danish Seine catch (tonnes) in the Bay of Plenty by year and season.

Year	Summer	Autumn	Winter	Spring
1970	76.84	141.47	151.66	137.43
1971	66.62	122.65	131.48	141.13
1972	83.75	154.19	165.30	140.96
1973	62.17	114.46	122.71	114.55
1974	57.87	106.55	114.22	86.30
1975	29.82	54.91	58.86	67.91
1976	43.08	79.32	85.03	85.62
1977	47.47	87.40	93.70	115.17
1978	76.94	141.66	151.86	143.00
1979	73.08	134.55	144.24	117.51
1980	47.75	87.92	94.26	94.27
1981	51.88	95.51	102.39	98.56
1982	51.80	95.37	102.25	82.40
1983	32.79	60.37	64.72	63.27
1984	4.89	0.57	9.90	7.49
1985	1.07	0.12	5.20	0.00
1986	4.26	0.99	0.00	2.25
1987	0.00	0.00	0.84	0.00
1988	0.00	0.00	0.00	0.00
1989	0.00	0.00	0.00	0.00
1990	0.00	63.91	101.63	110.11
1991	29.35	141.58	95.11	122.35
1992	112.27	136.69	46.93	69.51
1993	36.90	58.64	61.89	55.59
1994	38.06	47.34	80.53	49.57
1995	49.81	108.08	103.30	98.66
1996	9.76	59.34	99.44	129.58
1997	9.15	55.64	93.25	121.51

Table A9. Other commercial catch (tonnes) in the Bay of Plenty by year and season.

Year	Summer	Autumn	Winter	Spring
1970	75.59	71.86	13.32	76.11
1971	65.56	62.32	11.55	88.44
1972	82.45	78.39	14.53	73.93
1973	61.14	58.12	10.77	64.96
1974	56.90	54.09	10.03	39.78
1975	29.37	27.92	5.18	44.39
1976	42.38	40.29	7.47	51.39
1977	46.71	44.40	8.23	77.89
1978	75.73	71.99	13.35	81.76
1979	71.97	68.42	12.68	58.95
1980	47.00	44.68	8.28	56.33
1981	51.04	48.52	8.99	57.31
1982	51.02	48.50	8.99	40.85
1983	32.25	30.66	5.68	37.16
1984	77.63	82.06	33.35	41.69
1985	87.80	111.97	33.45	67.38
1986	91.81	65.78	13.46	24.23
1987	35.50	49.57	10.37	19.91
1988	150.68	9.17	2.37	138.76
1989	9.06	9.62	3.34	0.00
1990	76.48	32.99	9.73	47.90
1991	50.65	60.77	8.92	218.24
1992	23.55	74.36	9.89	100.85
1993	92.91	11.14	11.51	135.37
1994	5.65	100.96	5.39	105.89
1995	63.98	84.48	3.31	42.72
1996	89.63	117.24	11.93	23.39
1997	84.05	109.94	11.19	21.93

Table A10. Recreational catch (tonnes) in the Bay of Plenty by year and season.

Year	Summer	Autumn	Winter	Spring
1970	261.75	226.38	48.77	62.59
1971	261.75	226.38	48.77	62.59
1972	261.75	226.38	48.77	62.59
1973	261.75	226.38	48.77	62.59
1974	261.75	226.38	48.77	62.59
1975	261.75	226.38	48.77	62.59
1976	261.75	226.38	48.77	62.59
1977	261.75	226.38	48.77	62.59
1978	261.75	226.38	48.77	62.59
1979	261.75	226.38	48.77	62.59
1980	261.75	226.38	48.77	62.59
1981	261.75	226.38	48.77	62.59
1982	261.75	226.38	48.77	62.59
1983	261.75	226.38	48.77	62.59
1984	261.75	226.38	48.77	62.59
1985	188.72	163.22	35.16	45.12
1986	261.75	226.38	48.77	62.59
1987	261.75	226.38	48.77	62.59
1988	261.75	226.38	48.77	62.59
1989	261.75	226.38	48.77	62.59
1990	261.75	226.38	48.77	62.59
1991	261.75	226.38	48.77	62.59
1992	261.75	226.38	48.77	62.59
1993	261.75	226.38	48.77	62.59
1994	317.75	274.81	59.21	75.98
1995	240.81	208.27	44.87	57.58
1996	247.17	213.77	46.06	59.10
1997	247.17	213.77	46.06	59.10

Table A11. Long line catch (tonnes) in East Northland by year and season.

Year	Summer	Autumn	Winter	Spring
1970	596.27	487.91	492.63	623.19
1971	643.53	514.64	520.25	633.02
1972	642.94	508.95	514.78	610.12
1973	611.73	482.37	488.00	436.41
1974	377.63	318.00	320.60	380.85
1975	379.69	314.02	316.88	389.29
1976	392.48	317.42	320.69	391.56
1977	392.37	311.97	315.47	481.72
1978	396.36	269.21	274.74	426.74
1979	469.77	319.07	325.62	399.90
1980	406.84	276.33	282.01	361.32
1981	373.57	253.73	258.95	330.88
1982	341.75	232.12	236.89	316.61
1983	332.35	225.73	230.37	79.65
1984	500.61	260.39	280.76	455.67
1985	320.31	202.35	243.54	323.45
1986	337.90	234.61	228.29	284.55
1987	162.39	108.62	137.01	206.25
1988	330.79	140.02	134.45	339.57
1989	403.76	268.52	129.34	146.71
1990	294.89	219.13	153.77	253.90
1991	250.14	157.57	138.28	242.91
1992	288.98	161.81	145.52	192.03
1993	252.86	170.04	186.49	239.67
1994	234.63	185.15	281.14	217.85
1995	253.13	236.47	221.03	240.95
1996	270.76	275.41	288.60	291.03
1997	253.89	258.25	270.62	272.90

Table A12. Single trawl catch (tonnes) in East Northland by year and season.

Year	Summer	Autumn	Winter	Spring
1970	50.20	68.25	58.30	72.64
1971	59.69	81.16	69.32	78.57
1972	61.94	84.21	71.93	77.79
1973	59.94	81.50	69.61	48.90
1974	27.47	37.35	31.90	37.86
1975	30.47	41.43	35.39	42.78
1976	34.72	47.20	40.32	46.72
1977	37.21	50.60	43.22	66.33
1978	58.69	79.80	68.16	84.84
1979	69.68	94.74	80.92	81.47
1980	60.44	82.18	70.19	73.28
1981	55.45	75.39	64.39	67.08
1982	50.70	68.93	58.88	63.79
1983	49.20	66.90	57.14	20.66
1984	32.37	63.94	71.72	68.77
1985	9.49	47.09	74.31	41.22
1986	31.78	41.00	25.07	16.57
1987	2.92	33.97	17.97	9.20
1988	13.62	24.18	30.95	17.76
1989	19.94	132.26	58.13	70.55
1990	97.87	51.83	79.19	72.27
1991	23.25	44.74	37.56	67.69
1992	97.64	66.98	26.82	69.25
1993	26.37	67.35	71.45	86.04
1994	40.14	60.71	47.27	55.67
1995	44.40	39.49	24.89	47.01
1996	56.93	68.13	93.08	72.02
1997	53.38	63.89	87.28	67.53

Table A13. Danish seine catch (tonnes) in East Northland by year and season.

Year	Summer	Autumn	Winter	Spring
1970	166.72	32.11	20.14	71.58
1971	198.07	38.15	23.93	75.89
1972	205.90	39.66	24.88	74.15
1973	198.78	38.29	24.01	40.49
1974	91.91	17.70	11.10	36.97
1975	101.17	19.49	12.22	41.95
1976	115.42	22.23	13.94	45.24
1977	123.26	23.74	14.89	68.09
1978	195.22	37.60	23.58	83.70
1979	231.55	44.60	27.97	76.13
1980	200.20	38.56	24.19	69.15
1981	183.82	35.40	22.21	63.30
1982	168.14	32.39	20.31	61.03
1983	163.87	31.56	19.80	9.82
1984	5.42	14.88	7.31	2.19
1985	9.53	7.04	5.95	13.44
1986	7.35	8.52	0.02	0.05
1987	0.00	1.83	7.01	0.00
1988	1.20	0.00	0.00	0.23
1989	978.69	0.00	0.00	75.00
1990	83.42	34.28	10.08	86.62
1991	47.53	16.31	2.40	11.78
1992	16.41	9.19	3.79	6.31
1993	2.65	3.77	7.32	8.59
1994	8.65	9.07	5.72	3.42
1995	1.86	3.93	5.11	13.65
1996	1.86	13.07	23.11	16.61
1997	1.74	12.26	21.67	15.58

Table A14. Other commercial catch (tonnes) in East Northland by year and season.

Year	Summer	Autumn	Winter	Spring
1970	66.91	44.50	19.64	68.76
1971	79.95	53.18	23.47	73.44
1972	82.90	55.14	24.33	72.00
1973	79.95	53.18	23.47	41.75
1974	37.03	24.63	10.87	35.69
1975	40.82	27.15	11.98	40.52
1976	46.71	31.07	13.71	43.75
1977	49.65	33.03	14.57	64.40
1978	78.69	52.34	23.10	80.45
1979	93.42	62.14	27.42	74.71
1980	80.79	53.74	23.71	67.50
1981	74.06	49.26	21.74	61.78
1982	67.75	45.06	19.89	59.34
1983	66.07	43.94	19.39	13.36
1984	333.52	223.11	122.73	425.82
1985	316.78	188.08	137.32	244.63
1986	249.21	204.25	48.46	73.27
1987	41.40	59.67	19.02	92.33
1988	139.36	62.23	14.15	27.92
1989	15.98	71.72	15.14	37.99
1990	167.67	57.38	52.97	185.87
1991	52.22	47.52	45.24	64.40
1992	49.70	91.24	18.70	105.77
1993	148.55	23.10	15.58	156.55
1994	34.44	57.13	15.14	34.20
1995	139.16	84.21	14.27	43.24
1996	102.79	46.68	22.71	29.28
1997	96.39	43.77	21.30	27.46

Table A15. Recreational catch (tonnes) in East Northland by year and season.

Year	Summer	Autumn	Winter	Spring
1970	301.54	227.79	57.31	43.37
1971	301.54	227.79	57.31	43.37
1972	301.54	227.79	57.31	43.37
1973	301.54	227.79	57.31	43.37
1974	301.54	227.79	57.31	43.37
1975	301.54	227.79	57.31	43.37
1976	301.54	227.79	57.31	43.37
1977	301.54	227.79	57.31	43.37
1978	301.54	227.79	57.31	43.37
1979	301.54	227.79	57.31	43.37
1980	301.54	227.79	57.31	43.37
1981	301.54	227.79	57.31	43.37
1982	301.54	227.79	57.31	43.37
1983	301.54	227.79	57.31	43.37
1984	301.54	227.79	57.31	43.37
1985	177.09	133.78	33.66	25.47
1986	301.54	227.79	57.31	43.37
1987	301.54	227.79	57.31	43.37
1988	301.54	227.79	57.31	43.37
1989	301.54	227.79	57.31	43.37
1990	296.75	224.17	56.40	42.68
1991	296.75	224.17	56.40	42.68
1992	296.75	224.17	56.40	42.68
1993	296.75	224.17	56.40	42.68
1994	346.05	261.41	65.77	49.77
1995	268.99	203.20	51.12	38.68
1996	340.31	257.08	64.68	48.94
1997	340.31	257.08	64.68	48.94

Table A16. Long line proportional catch-at-age data for HG.

Year	1990	1991	1991	1992	1992	1993	1993	1994	1994	1995	1995	1996	1996	1997
Season	Summer	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Sample size	400	267	200	200	400	400	200	200	200	200	200	200	400	400
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0002	0.0000	0.0004	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0005	0.0039	0.0422	0.0001	0.0231	0.0003	0.0028	0.0000	0.0220	0.0000	0.0015	0.0000	0.0081	0.0000
4	0.0062	0.0237	0.0650	0.0272	0.1809	0.0212	0.0862	0.0012	0.0415	0.0170	0.0635	0.0009	0.0237	0.0070
5	0.0758	0.1125	0.1835	0.0414	0.1011	0.1625	0.1538	0.0543	0.1864	0.0302	0.0985	0.0444	0.1695	0.0199
6	0.1230	0.0943	0.2510	0.1403	0.1651	0.0926	0.0930	0.1293	0.1414	0.1429	0.3024	0.0798	0.1206	0.1509
7	0.0318	0.1301	0.1541	0.2119	0.1568	0.1532	0.1558	0.0811	0.0953	0.1239	0.1479	0.2768	0.2517	0.1112
8	0.0695	0.0413	0.0261	0.1415	0.1342	0.1460	0.1738	0.1585	0.1204	0.0869	0.0849	0.1413	0.1316	0.2425
9	0.1703	0.0494	0.0420	0.0281	0.0136	0.1260	0.1244	0.1698	0.1762	0.1186	0.1010	0.0886	0.0512	0.1314
10	0.1341	0.1812	0.1091	0.0515	0.0278	0.0132	0.0083	0.1371	0.1154	0.1922	0.0611	0.1099	0.0699	0.0491
11	0.0569	0.0750	0.0307	0.1384	0.0739	0.0276	0.0150	0.0101	0.0145	0.1268	0.0455	0.0713	0.0456	0.0706
12	0.0873	0.0676	0.0230	0.0452	0.0226	0.0763	0.0883	0.0177	0.0073	0.0184	0.0054	0.0535	0.0458	0.0493
13	0.0424	0.0561	0.0183	0.0406	0.0273	0.0295	0.0404	0.1106	0.0302	0.0114	0.0019	0.0078	0.0094	0.0534
14	0.0267	0.0113	0.0068	0.0321	0.0110	0.0332	0.0279	0.0484	0.0187	0.0487	0.0533	0.0027	0.0034	0.0098
15	0.0220	0.0084	0.0055	0.0107	0.0090	0.0166	0.0079	0.0348	0.0087	0.0280	0.0049	0.0675	0.0281	0.0039
16	0.0329	0.0058	0.0048	0.0089	0.0137	0.0106	0.0047	0.0112	0.0035	0.0155	0.0020	0.0065	0.0065	0.0399
17	0.0258	0.0234	0.0036	0.0097	0.0091	0.0162	0.0020	0.0064	0.0008	0.0061	0.0043	0.0028	0.0037	0.0077
18	0.0068	0.0057	0.0050	0.0071	0.0065	0.0136	0.0028	0.0030	0.0013	0.0016	0.0019	0.0058	0.0051	0.0048
19	0.0050	0.0081	0.0272	0.0101	0.0238	0.0118	0.0119	0.0037	0.0115	0.0025	0.0205	0.0026	0.0214	0.0078
20	0.0638	0.0395		0.0547		0.0494		0.0219		0.0263		0.0326		0.0321

Table A17. Single trawl proportional catch-at-age data for HG.

Year	1990	1990	1991	1994
Season	Summer	Spring	Summer	Summer
Sample size	400	267	267	200
1	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0306	0.0000	0.0000
3	0.0011	0.0909	0.0111	0.0000
4	0.0162	0.2456	0.0549	0.0023
5	0.1745	0.1341	0.2206	0.0937
6	0.2109	0.1429	0.1542	0.1682
7	0.0445	0.0383	0.1722	0.1000
8	0.0815	0.0320	0.0446	0.1588
9	0.1637	0.1128	0.0362	0.1788
10	0.1317	0.0436	0.1346	0.1171
11	0.0479	0.0337	0.0492	0.0072
12	0.0485	0.0273	0.0347	0.0128
13	0.0186	0.0055	0.0300	0.0768
14	0.0094	0.0034	0.0062	0.0342
15	0.0114	0.0021	0.0029	0.0246
16	0.0100	0.0106	0.0021	0.0069
17	0.0072	0.0020	0.0095	0.0037
18	0.0026	0.0036	0.0022	0.0016
19	0.0008	0.0211	0.0037	0.0019
20	0.0143		0.0170	0.0107

Table A18. Danish seine 1990s proportional catch-at-age data for HG.

Year	1991	1992	1994	1994	1995	1995	1996
Season	Spring	Summer	Summer	Spring	Summer	Spring	Summer
Sample size	200	200	200	200	200	200	200
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0192	0.0002	0.0001	0.0168	0.0000	0.0009	0.0000
4	0.0459	0.0369	0.0013	0.0342	0.0143	0.0482	0.0010
5	0.1695	0.0460	0.0555	0.1744	0.0285	0.0975	0.0526
6	0.2576	0.1534	0.1499	0.1510	0.1497	0.3358	0.0941
7	0.1518	0.2570	0.0931	0.1006	0.1369	0.1415	0.3122
8	0.0271	0.1605	0.1723	0.1301	0.0935	0.0899	0.1456
9	0.0453	0.0288	0.1876	0.1852	0.1257	0.1068	0.0882
10	0.1210	0.0461	0.1375	0.1249	0.1934	0.0605	0.1059
11	0.0360	0.1240	0.0088	0.0152	0.1314	0.0496	0.0627
12	0.0309	0.0357	0.0153	0.0065	0.0182	0.0040	0.0488
13	0.0243	0.0274	0.0874	0.0264	0.0103	0.0011	0.0061
14	0.0080	0.0200	0.0401	0.0185	0.0400	0.0481	0.0017
15	0.0074	0.0061	0.0289	0.0055	0.0241	0.0048	0.0535
16	0.0075	0.0066	0.0073	0.0026	0.0110	0.0014	0.0057
17	0.0044	0.0066	0.0034	0.0008	0.0042	0.0024	0.0017
18	0.0056	0.0039	0.0015	0.0008	0.0014	0.0006	0.0037
19	0.0371	0.0059	0.0019	0.0049	0.0016	0.0095	0.0009
20		0.0284	0.0079		0.0126		0.0163

Table A19. Long line proportional catch-at-age data for BoP.

Year	1989	1990	1990	1991	1993	1994	1994	1995	1995	1996	1996	1997
Season	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Sample size	200	200	267	267	400	400	133	133	400	400	400	400
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0039	0.0000	0.0022	0.0000	0.0009	0.0000	0.0000	0.0000	0.0018	0.0000	0.0085	0.0000
3	0.1384	0.0047	0.1024	0.0010	0.0037	0.0017	0.0178	0.0000	0.0108	0.0022	0.0345	0.0076
4	0.3804	0.1210	0.4263	0.0646	0.1670	0.0079	0.1525	0.0090	0.1319	0.0179	0.1045	0.0256
5	0.2058	0.2943	0.2782	0.2964	0.3534	0.2265	0.4357	0.0900	0.1543	0.1987	0.2392	0.0885
6	0.0298	0.1799	0.0368	0.2226	0.1142	0.2673	0.1126	0.3017	0.3814	0.1626	0.1511	0.2120
7	0.0347	0.0281	0.0143	0.0342	0.1466	0.0817	0.0402	0.0979	0.1432	0.3471	0.2468	0.1392
8	0.0870	0.0384	0.0307	0.0162	0.1215	0.1231	0.1070	0.0383	0.0398	0.1193	0.1005	0.2468
9	0.0396	0.1145	0.0341	0.0358	0.0285	0.1313	0.0741	0.1344	0.0614	0.0324	0.0133	0.1173
10	0.0114	0.0586	0.0129	0.0573	0.0035	0.0361	0.0163	0.1140	0.0291	0.0509	0.0475	0.0183
11	0.0141	0.0179	0.0056	0.0317	0.0038	0.0043	0.0000	0.0394	0.0195	0.0235	0.0255	0.0652
12	0.0047	0.0252	0.0112	0.0198	0.0172	0.0068	0.0066	0.0000	0.0011	0.0143	0.0097	0.0368
13	0.0020	0.0104	0.0025	0.0277	0.0037	0.0271	0.0054	0.0161	0.0008	0.0009	0.0007	0.0135
14	0.0056	0.0052	0.0044	0.0072	0.0055	0.0078	0.0029	0.0173	0.0086	0.0007	0.0013	0.0012
15	0.0007	0.0126	0.0048	0.0172	0.0070	0.0100	0.0024	0.0067	0.0066	0.0095	0.0080	0.0024
16	0.0031	0.0020	0.0032	0.0228	0.0017	0.0109	0.0030	0.0048	0.0047	0.0067	0.0008	0.0120
17	0.0000	0.0026	0.0012	0.0189	0.0022	0.0031	0.0010	0.0098	0.0000	0.0037	0.0010	0.0020
18	0.0049	0.0000	0.0014	0.0035	0.0040	0.0046	0.0008	0.0016	0.0000	0.0009	0.0019	0.0022
19	0.0074	0.0084	0.0165	0.0057	0.0150	0.0080	0.0176	0.0038	0.0034	0.0000	0.0037	0.0029
20		0.0141		0.1017		0.0340		0.0900		0.0036		0.0060

Table A20. Single trawl proportional catch-at-age data for BoP.

Year	1989	1990	1991	1991	1992	1994	1995
Season	Spring	Summer	Summer	Spring	Summer	Spring	Summer
Sample size	200	200	267	400	400	133	133
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0300	0.0000	0.0000	0.0139	0.0000	0.0000	0.0000
3	0.2999	0.0210	0.0022	0.2931	0.0091	0.0444	0.0000
4	0.3639	0.2857	0.1171	0.1061	0.2724	0.2479	0.0229
5	0.1488	0.3884	0.4874	0.2738	0.1140	0.4892	0.1748
6	0.0194	0.1674	0.2606	0.1074	0.3030	0.0798	0.4486
7	0.0183	0.0220	0.0265	0.0903	0.1100	0.0247	0.1037
8	0.0449	0.0236	0.0112	0.0126	0.0839	0.0522	0.0364
9	0.0187	0.0481	0.0245	0.0206	0.0104	0.0325	0.0985
10	0.0054	0.0225	0.0212	0.0474	0.0167	0.0068	0.0658
11	0.0050	0.0056	0.0077	0.0107	0.0385	0.0000	0.0149
12	0.0016	0.0060	0.0041	0.0127	0.0110	0.0022	0.0000
13	0.0009	0.0010	0.0075	0.0011	0.0110	0.0020	0.0052
14	0.0035	0.0009	0.0014	0.0000	0.0015	0.0006	0.0061
15	0.0003	0.0009	0.0021	0.0000	0.0000	0.0005	0.0014
16	0.0000	0.0006	0.0035	0.0000	0.0000	0.0005	0.0017
17	0.0000	0.0001	0.0022	0.0000	0.0012	0.0004	0.0019
18	0.0065	0.0000	0.0005	0.0000	0.0000	0.0000	0.0009
19	0.0064	0.0008	0.0009	0.0022	0.0000	0.0065	0.0007
20		0.0017	0.0112		0.0015		0.0120

Table A21. Danish seine proportional catch-at-age data for BoP.

Year	1994	1995
Season	Spring	Summer
Sample size	133	133
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0651	0.0000
4	0.2791	0.0141
5	0.4450	0.1203
6	0.0764	0.4970
7	0.0237	0.1294
8	0.0506	0.0419
9	0.0328	0.1000
10	0.0052	0.0586
11	0.0000	0.0101
12	0.0023	0.0000
13	0.0016	0.0040
14	0.0008	0.0044
15	0.0011	0.0009
16	0.0007	0.0011
17	0.0003	0.0016
18	0.0000	0.0006
19	0.0032	0.0007
20		0.0077

Table A22. Long line proportional catch-at-age data for EN.

Year	1993	1994	1994	1995	1995	1996	1996	1997
Season	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Sample size	400	400	400	400	400	400	400	400
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0018	0.0000	0.0006	0.0000	0.0000	0.0000	0.0008	0.0000
3	0.0302	0.0006	0.0426	0.0003	0.0085	0.0000	0.0094	0.0009
4	0.1678	0.0142	0.1281	0.0261	0.0600	0.0093	0.0226	0.0080
5	0.1609	0.0930	0.1852	0.0898	0.0985	0.0648	0.0885	0.0224
6	0.0756	0.1034	0.1391	0.1551	0.1463	0.1068	0.1376	0.0892
7	0.1824	0.0638	0.0886	0.1364	0.1058	0.1421	0.1850	0.1384
8	0.0874	0.1591	0.0860	0.0925	0.0812	0.0990	0.0969	0.1957
9	0.0354	0.0909	0.0830	0.0904	0.0829	0.0720	0.0447	0.1032
10	0.0130	0.0474	0.0240	0.0921	0.1076	0.0728	0.0723	0.0541
11	0.0478	0.0189	0.0073	0.0280	0.0226	0.0955	0.0731	0.0740
12	0.0427	0.0678	0.0548	0.0088	0.0268	0.0188	0.0203	0.0730
13	0.0075	0.0665	0.0490	0.0656	0.0578	0.0245	0.0133	0.0186
14	0.0198	0.0133	0.0115	0.0578	0.0563	0.0599	0.0550	0.0114
15	0.0127	0.0314	0.0147	0.0141	0.0122	0.0483	0.0339	0.0503
16	0.0116	0.0223	0.0201	0.0178	0.0111	0.0188	0.0051	0.0318
17	0.0089	0.0202	0.0110	0.0253	0.0113	0.0116	0.0132	0.0047
18	0.0117	0.0164	0.0045	0.0141	0.0049	0.0104	0.0084	0.0111
19	0.0794	0.0186	0.0462	0.0068	0.0999	0.0055	0.1077	0.0073
20	0.0000	0.1493	0.0000	0.0753	0.0000	0.1273	0.0000	0.0827

Table A23. 1970s Danish seine proportional catch-at-age data for HG.

Year	1970	1971	1972	1973
Season	Summer	Summer	Summer	Summer
Sample size	50	50	50	50
1	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000
5	0.0155	0.0497	0.0645	0.3511
6	0.0001	0.0172	0.0473	0.0674
7	0.0309	0.0459	0.0290	0.0366
8	0.1289	0.0459	0.0462	0.0248
9	0.0670	0.0669	0.0366	0.0284
10	0.1134	0.1052	0.0806	0.0307
11	0.0258	0.0956	0.0839	0.0745
12	0.0361	0.0249	0.0860	0.0307
13	0.0619	0.0096	0.0462	0.0922
14	0.0515	0.0287	0.0312	0.0118
15	0.0928	0.0478	0.0280	0.0426
16	0.0206	0.0574	0.0280	0.0059
17	0.0515	0.0191	0.0538	0.0189
18	0.0258	0.0268	0.0269	0.0366
19	0.0206	0.0096	0.0237	0.0426
20	0.2268	0.1300	0.1849	0.0556

Table A24. Tag releases.

Age	HG Summer 1985	EN Summer 1985	HG Summer 1994	BoP Summer 1994	EN Summer 1994
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	701.92	259.85	0.00	0.00	0.00
4	2159.03	880.82	46.24	118.21	427.69
5	2500.75	1123.09	1651.10	1355.48	1753.32
6	2097.87	1084.28	2238.95	956.19	1396.71
7	1167.45	629.02	1288.64	240.66	566.37
8	576.17	367.62	2011.92	316.43	1435.21
9	566.36	425.13	2249.64	318.28	656.63
10	488.16	380.50	1490.60	84.68	252.84
11	348.17	283.90	94.47	11.64	92.07
12	257.45	227.63	177.84	17.24	338.52
13	151.52	148.45	1027.89	63.90	334.16
14	167.09	166.40	457.25	18.41	62.93
15	104.22	105.10	334.06	20.95	152.65
16	96.73	107.99	94.10	26.54	102.20
17	80.91	88.90	55.20	5.88	102.16
18	54.17	52.37	21.00	10.73	75.10
19	28.97	33.00	32.82	15.65	87.91
20	580.43	793.06	170.34	67.93	722.29

Table A25. Age-specific long line recoveries caught in HG and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.31	4.26	2.25	2.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	5.18	13.96	7.28	7.36	2.02	1.92	1.88	2.24	0.00	0.00	0.00	0.00
5	7.31	16.73	8.55	8.39	7.26	6.22	5.42	5.69	0.53	0.28	0.38	0.32
6	7.36	13.94	7.13	7.56	7.93	8.01	5.88	5.91	2.01	0.83	0.84	1.48
7	4.51	7.66	4.62	4.55	6.91	6.84	4.89	4.53	2.67	0.96	0.98	1.83
8	2.87	3.29	2.22	2.73	3.47	3.87	2.37	2.28	2.09	0.46	0.67	1.23
9	4.21	2.85	2.84	3.09	1.89	1.98	1.45	1.36	0.94	0.26	0.30	0.71
10	3.29	2.60	2.80	2.80	1.88	2.14	1.27	1.82	0.41	0.11	0.18	0.17
11	2.42	1.70	1.64	2.01	1.54	1.72	0.87	1.50	0.41	0.05	0.20	0.08
12	2.07	1.20	1.27	1.86	1.09	1.28	1.11	0.85	0.28	0.01	0.10	0.07
13	1.46	0.55	0.71	1.24	0.91	0.88	0.74	0.92	0.21	0.03	0.14	0.02
14	1.73	0.60	0.52	1.10	0.66	0.84	0.28	0.55	0.15	0.00	0.04	0.03
15	0.86	0.53	0.47	0.69	0.90	0.70	0.48	0.48	0.04	0.00	0.03	0.00
16	1.03	0.28	0.35	0.66	0.70	0.38	0.19	0.44	0.06	0.00	0.05	0.02
17	1.13	0.32	0.45	0.47	1.06	0.38	0.10	0.16	0.02	0.01	0.02	0.01
18	0.64	0.18	0.33	0.33	0.25	0.24	0.16	0.56	0.01	0.00	0.00	0.00
19	0.16	0.10	0.19	0.13	0.28	0.20	0.18	0.14	0.03	0.00	0.03	0.00
20	5.49	2.27	2.39	5.24	5.25	2.42	0.72	2.57	0.14	0.00	0.04	0.01

Table A26. Age-specific single trawl recoveries caught in HG and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.94	3.83	0.59	1.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	6.04	9.39	2.87	3.61	0.58	1.35	0.34	0.19	0.00	0.00	0.00	0.00
5	7.37	9.05	3.61	3.98	3.24	3.45	1.12	0.52	0.11	0.03	0.00	0.00
6	6.87	6.98	2.68	3.00	5.01	3.84	0.78	0.64	0.82	0.06	0.00	0.00
7	3.78	3.82	1.56	1.70	4.36	2.65	0.55	0.41	0.83	0.23	0.00	0.00
8	1.99	1.68	0.73	0.66	2.64	1.61	0.11	0.13	0.76	0.30	0.00	0.00
9	2.08	1.87	0.54	0.54	1.31	0.53	0.06	0.03	0.32	0.14	0.00	0.00
10	1.83	1.49	0.41	0.50	0.85	0.45	0.02	0.04	0.07	0.10	0.00	0.00
11	1.30	0.96	0.25	0.28	0.79	0.43	0.00	0.01	0.02	0.05	0.00	0.00
12	1.09	0.86	0.18	0.15	0.51	0.15	0.02	0.01	0.03	0.01	0.00	0.00
13	0.57	0.41	0.12	0.03	0.56	0.13	0.00	0.01	0.02	0.04	0.00	0.00
14	0.45	0.43	0.16	0.13	0.27	0.10	0.00	0.00	0.01	0.03	0.00	0.00
15	0.47	0.36	0.01	0.09	0.16	0.08	0.00	0.00	0.00	0.01	0.00	0.00
16	0.21	0.39	0.04	0.01	0.11	0.02	0.00	0.01	0.00	0.00	0.00	0.00
17	0.21	0.15	0.05	0.03	0.07	0.08	0.00	0.00	0.01	0.00	0.00	0.00
18	0.14	0.15	0.02	0.05	0.08	0.04	0.00	0.00	0.00	0.01	0.00	0.00
19	0.03	0.11	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	3.61	2.09	0.18	0.09	0.43	0.09	0.00	0.00	0.00	0.00	0.00	0.00

Table A27. Age-specific Danish seine recoveries caught in HG and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	2.86	2.88	1.96	1.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	13.02	13.54	4.80	4.23	1.75	1.95	0.53	0.86	0.00	0.00	0.00	0.00
5	22.14	19.34	5.17	5.44	5.42	4.98	1.78	2.03	0.03	0.01	0.01	0.14
6	23.93	22.07	4.15	6.19	5.61	5.54	1.23	2.44	0.06	0.18	0.18	0.64
7	14.75	12.84	2.41	3.50	4.49	4.53	1.25	2.31	0.23	0.33	0.33	0.67
8	7.38	7.40	1.44	2.27	2.09	2.50	0.25	1.50	0.30	0.29	0.29	0.50
9	7.17	8.37	1.46	2.30	1.25	1.40	0.19	0.81	0.14	0.11	0.11	0.28
10	6.70	7.80	1.23	2.49	1.32	1.33	0.18	0.75	0.10	0.03	0.03	0.17
11	4.88	4.45	0.85	1.35	0.94	1.11	0.13	0.66	0.05	0.02	0.02	0.17
12	3.15	4.07	0.83	1.55	0.88	0.63	0.15	0.31	0.01	0.01	0.01	0.11
13	1.44	2.47	0.43	0.78	0.67	0.61	0.08	0.37	0.04	0.01	0.01	0.11
14	1.74	1.98	0.19	0.58	0.40	0.40	0.04	0.20	0.03	0.01	0.01	0.04
15	0.86	1.14	0.14	0.64	0.52	0.11	0.06	0.20	0.01	0.00	0.00	0.03
16	0.79	0.98	0.15	0.25	0.15	0.14	0.01	0.06	0.00	0.00	0.00	0.06
17	1.91	1.14	0.17	0.33	0.47	0.13	0.00	0.10	0.00	0.01	0.01	0.01
18	0.83	0.71	0.19	0.33	0.48	0.19	0.02	0.41	0.01	0.00	0.00	0.00
19	0.40	0.26	0.08	0.06	0.14	0.17	0.02	0.02	0.00	0.00	0.00	0.03
20	7.06	4.59	0.38	2.67	2.42	0.28	0.09	0.99	0.00	0.00	0.00	0.04

Table A28. Age-specific other commercial recoveries caught in HG and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	5.14	3.37	0.82	2.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	20.62	12.26	3.13	7.83	3.77	1.90	0.72	1.73	0.00	0.00	0.00	0.00
5	27.45	16.29	4.36	9.86	14.68	6.75	1.70	4.37	0.73	0.16	0.09	0.27
6	24.38	15.27	4.39	8.83	18.04	6.97	1.38	4.46	2.14	1.16	0.38	0.72
7	14.19	8.45	2.57	4.89	15.80	4.98	0.80	3.13	1.92	1.08	0.23	0.54
8	6.21	4.03	1.21	2.58	9.25	2.22	0.21	1.78	1.31	0.92	0.22	0.34
9	4.71	3.44	0.88	1.73	3.83	0.90	0.07	0.64	0.48	0.51	0.04	0.06
10	3.91	3.04	0.95	1.47	3.07	0.87	0.07	0.63	0.19	0.14	0.02	0.02
11	2.79	2.11	0.63	1.36	2.85	0.70	0.02	0.53	0.08	0.21	0.01	0.03
12	2.09	1.50	0.28	0.92	2.16	0.40	0.02	0.23	0.02	0.22	0.00	0.00
13	0.82	0.55	0.12	0.33	1.37	0.41	0.01	0.15	0.06	0.10	0.01	0.01
14	0.67	0.59	0.38	0.51	0.54	0.23	0.00	0.01	0.03	0.13	0.00	0.00
15	0.47	0.44	0.28	0.45	0.79	0.08	0.00	0.07	0.01	0.00	0.00	0.00
16	0.57	0.42	0.05	0.23	0.62	0.08	0.01	0.09	0.00	0.04	0.00	0.00
17	0.35	0.34	0.08	0.14	0.28	0.07	0.00	0.03	0.01	0.04	0.00	0.00
18	0.30	0.31	0.29	0.24	0.35	0.10	0.00	0.01	0.01	0.06	0.00	0.00
19	0.11	0.22	0.04	0.15	0.37	0.10	0.00	0.04	0.00	0.03	0.00	0.00
20	1.22	1.37	0.53	0.81	1.23	0.22	0.00	0.10	0.00	0.21	0.00	0.00

Table A29. Age-specific long line recoveries caught in HG and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.04	1.29	0.06	0.00	0.05	0.18	0.00	0.00	0.00	0.00	0.00	0.00
5	0.13	1.16	0.27	0.00	0.27	0.34	0.00	0.00	0.17	0.00	0.00	0.00
6	0.24	0.51	0.30	0.00	0.31	0.31	0.00	0.00	0.35	0.00	0.00	0.00
7	0.20	0.31	0.20	0.00	0.17	0.12	0.00	0.00	0.32	0.00	0.00	0.00
8	0.11	0.17	0.05	0.00	0.13	0.02	0.00	0.00	0.11	0.00	0.00	0.00
9	0.04	0.04	0.04	0.00	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.00
10	0.13	0.02	0.03	0.00	0.02	0.02	0.00	0.00	0.01	0.00	0.00	0.00
11	0.05	0.03	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00
12	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.01	0.00	0.01	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A30. Age-specific single trawl recoveries caught in HG and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.01	0.06	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.08	0.29	0.00	0.32	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
6	0.48	0.46	0.00	0.11	0.04	0.13	0.00	0.00	0.00	0.00	0.00	0.00
7	0.18	0.37	0.00	0.03	0.40	0.24	0.00	0.00	0.00	0.00	0.00	0.00
8	0.17	0.12	0.00	0.01	0.19	0.20	0.00	0.00	0.00	0.00	0.00	0.00
9	0.27	0.20	0.00	0.01	0.14	0.11	0.00	0.00	0.00	0.00	0.00	0.00
10	0.22	0.19	0.00	0.00	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00
11	0.17	0.06	0.00	0.00	0.27	0.13	0.00	0.00	0.00	0.00	0.00	0.00
12	0.13	0.06	0.00	0.00	0.16	0.05	0.00	0.00	0.00	0.00	0.00	0.00
13	0.04	0.00	0.00	0.00	0.11	0.02	0.00	0.00	0.00	0.00	0.00	0.00
14	0.06	0.05	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.05	0.00	0.00	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00
16	0.01	0.01	0.00	0.00	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00
17	0.03	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.03	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00
20	0.11	0.08	0.00	0.00	0.16	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Table A31. Age-specific Danish seine recoveries caught in HG and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.18	0.18	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.34	0.38	0.44	0.00	0.04	0.20	0.00	0.00	0.00	0.00	0.00	0.00
5	0.31	0.59	0.18	0.00	0.26	0.41	0.00	0.00	0.00	0.00	0.00	0.00
6	0.12	0.71	0.06	0.00	0.29	0.55	0.00	0.00	0.00	0.00	0.00	0.00
7	0.02	0.29	0.01	0.00	0.35	0.41	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.19	0.01	0.00	0.23	0.17	0.00	0.00	0.00	0.00	0.00	0.00
9	0.02	0.23	0.02	0.00	0.15	0.11	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.37	0.01	0.00	0.17	0.05	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.22	0.00	0.00	0.17	0.01	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.22	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.18	0.00	0.00	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.06	0.00	0.00	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.03	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.05	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.02	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.25	0.00	1.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A32. Age-specific other commercial recoveries caught in HG and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.07	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.29	0.00	0.00	0.34	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.91	0.00	0.00	0.31	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	1.06	0.00	0.00	0.12	0.56	0.00	0.00	0.00	0.00	0.00	0.04	0.00
7	0.69	0.00	0.00	0.02	0.33	0.00	0.00	0.00	0.00	0.00	0.13	0.00
8	0.45	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.24	0.00
9	0.31	0.00	0.00	0.02	0.13	0.09	0.00	0.00	0.00	0.00	0.20	0.00
10	0.23	0.00	0.00	0.00	0.05	0.04	0.00	0.00	0.00	0.00	0.11	0.00
11	0.65	0.00	0.00	0.00	0.07	0.04	0.00	0.00	0.00	0.00	0.04	0.00
12	0.15	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.13	0.00
13	0.10	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.00	0.05	0.00
14	0.20	0.00	0.00	0.00	0.19	0.09	0.00	0.00	0.00	0.00	0.02	0.00
15	0.10	0.00	0.00	0.00	0.18	0.09	0.00	0.00	0.00	0.00	0.00	0.00
16	0.05	0.00	0.00	0.00	0.12	0.13	0.00	0.00	0.00	0.00	0.01	0.00
17	0.15	0.00	0.00	0.00	0.08	0.13	0.00	0.00	0.00	0.00	0.02	0.00
18	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	2.41	1.00	0.00	0.00	0.41	0.35	0.00	0.00	0.00	0.00	0.02	0.00

Table A33. Age-specific long line recoveries caught in BoP and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.38	1.49	0.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.83	4.81	3.01	0.17	0.00	1.34	0.44	0.00	0.00	0.00	0.00
5	0.00	1.23	4.74	3.19	0.35	0.00	3.46	1.08	0.02	0.00	0.00	0.00
6	0.02	0.98	2.59	2.31	0.35	0.00	2.97	0.86	0.25	0.00	0.00	0.00
7	0.06	0.61	1.47	1.13	0.24	0.00	1.79	0.45	0.27	0.02	0.00	0.00
8	0.08	0.30	0.41	0.50	0.07	0.00	0.76	0.09	0.25	0.16	0.00	0.00
9	0.19	0.16	0.20	0.42	0.04	0.00	0.33	0.03	0.17	0.17	0.00	0.00
10	0.19	0.21	0.13	0.35	0.04	0.00	0.26	0.03	0.02	0.07	0.00	0.00
11	0.06	0.14	0.06	0.35	0.19	0.00	0.11	0.00	0.00	0.16	0.00	0.00
12	0.13	0.06	0.04	0.09	0.06	0.00	0.18	0.01	0.02	0.16	0.00	0.00
13	0.08	0.03	0.00	0.04	0.13	0.00	0.12	0.00	0.00	0.05	0.00	0.00
14	0.00	0.01	0.04	0.14	0.13	0.00	0.05	0.00	0.01	0.03	0.00	0.00
15	0.02	0.02	0.02	0.11	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00
16	0.02	0.03	0.00	0.05	0.03	0.00	0.01	0.00	0.00	0.03	0.00	0.00
17	0.04	0.00	0.00	0.09	0.00	0.00	0.01	0.00	0.01	0.05	0.00	0.00
18	0.04	0.02	0.00	0.10	0.03	0.00	0.08	0.00	0.00	0.01	0.00	0.00
19	0.02	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.04	0.01	0.01	0.18	0.16	0.00	0.44	0.00	0.00	0.08	0.00	0.00

Table A34. Age-specific single trawl recoveries caught in BoP and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.07	0.79	1.14	1.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	5.67	2.98	3.98	4.62	0.25	0.28	0.24	0.40	0.00	0.00	0.00	0.00
5	7.95	4.80	5.23	5.24	1.75	2.38	1.49	1.22	0.00	0.18	0.01	0.00
6	6.24	4.54	4.54	4.35	2.57	3.22	1.61	1.38	0.00	0.34	0.18	0.00
7	3.64	2.49	2.51	2.40	2.06	2.70	1.28	0.98	0.00	0.31	0.33	0.00
8	1.50	1.31	0.95	1.10	1.20	1.43	0.72	0.53	0.00	0.12	0.29	0.00
9	1.34	0.90	0.51	1.11	0.45	0.45	0.25	0.19	0.00	0.02	0.11	0.00
10	0.87	0.93	0.34	0.99	0.19	0.15	0.09	0.13	0.00	0.00	0.03	0.00
11	0.86	0.73	0.35	0.47	0.22	0.11	0.17	0.06	0.00	0.02	0.02	0.00
12	0.87	0.46	0.21	0.61	0.15	0.24	0.07	0.05	0.00	0.00	0.01	0.00
13	0.33	0.24	0.08	0.32	0.05	0.07	0.03	0.03	0.00	0.00	0.01	0.00
14	0.51	0.14	0.04	0.22	0.00	0.12	0.00	0.01	0.00	0.00	0.01	0.00
15	0.17	0.11	0.03	0.09	0.03	0.22	0.02	0.02	0.00	0.00	0.00	0.00
16	0.10	0.03	0.07	0.12	0.04	0.05	0.03	0.01	0.00	0.00	0.00	0.00
17	0.24	0.08	0.00	0.13	0.00	0.06	0.00	0.01	0.00	0.00	0.01	0.00
18	0.02	0.08	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.08	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00
20	1.52	0.38	0.01	0.53	0.02	0.50	0.01	0.00	0.00	0.00	0.00	0.00

Table A35. Age-specific Danish seine recoveries caught in BoP and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.44	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.18	0.00	0.00	0.44	0.00	0.00	0.01	0.00	0.00
6	0.00	0.00	0.00	0.06	0.00	0.00	0.18	0.00	0.00	0.13	0.00	0.00
7	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.00	0.00	0.32	0.00	0.00
8	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.22	0.00	0.00
9	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.17	0.00	0.00
10	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.07	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A36. Age-specific other commercial recoveries caught in BoP and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.53	0.54	0.95	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	1.37	1.29	2.16	0.75	0.19	0.11	0.08	0.01	0.00	0.00	0.00	0.00
5	1.96	1.29	2.33	0.91	0.65	0.42	0.36	0.13	0.00	0.00	0.00	0.00
6	1.52	1.03	1.27	0.92	0.72	0.56	0.33	0.32	0.00	0.00	0.00	0.00
7	1.11	0.46	0.63	0.51	0.60	0.41	0.11	0.22	0.00	0.00	0.00	0.00
8	0.49	0.20	0.30	0.25	0.40	0.21	0.07	0.17	0.00	0.00	0.00	0.00
9	0.25	0.31	0.16	0.12	0.13	0.15	0.05	0.07	0.00	0.00	0.00	0.00
10	0.31	0.18	0.04	0.15	0.05	0.05	0.00	0.03	0.00	0.00	0.00	0.00
11	0.21	0.08	0.25	0.21	0.15	0.01	0.00	0.01	0.00	0.00	0.00	0.00
12	0.07	0.13	0.03	0.04	0.05	0.04	0.00	0.03	0.00	0.00	0.00	0.00
13	0.04	0.07	0.01	0.12	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00
14	0.02	0.09	0.00	0.24	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
15	0.02	0.02	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.05	0.04	0.01	0.06	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00
17	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
18	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.01	0.24	0.86	0.51	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A37. Age-specific long line recoveries caught in BoP and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.06	0.00	0.00	0.19	0.01	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.27	0.00	0.00	0.60	0.18	0.00	0.00	0.00	0.05
6	0.00	0.00	0.00	0.30	0.00	0.03	0.59	0.33	0.00	0.00	0.00	0.27
7	0.00	0.00	0.00	0.20	0.00	0.13	0.36	0.29	0.00	0.00	0.00	0.31
8	0.00	0.00	0.00	0.05	0.00	0.03	0.20	0.11	0.00	0.00	0.00	0.17
9	0.00	0.00	0.00	0.04	0.00	0.03	0.02	0.03	0.00	0.00	0.00	0.13
10	0.00	0.00	0.00	0.03	0.00	0.03	0.01	0.02	0.00	0.00	0.00	0.02
11	0.00	0.00	0.00	0.01	0.00	0.19	0.02	0.01	0.00	0.00	0.00	0.02
12	0.00	0.00	0.00	0.02	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.02
13	0.00	0.00	0.00	0.00	0.00	0.13	0.01	0.01	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.01	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.25	0.00	0.00	0.00	0.03	0.01	0.01	0.00	0.00	0.00	0.01
17	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.50	0.00	0.01	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00

Table A38. Age-specific single trawl recoveries caught in BoP and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.13	0.03	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.65	0.18	0.36	0.00	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00
5	0.57	0.57	0.33	0.00	0.00	0.76	0.00	0.00	0.00	0.00	0.00	0.00
6	0.41	0.66	0.11	0.00	0.00	1.09	0.00	0.02	0.00	0.00	0.00	0.00
7	0.17	0.47	0.07	0.00	0.00	0.70	0.00	0.24	0.00	0.00	0.00	0.00
8	0.11	0.26	0.05	0.00	0.00	0.53	0.00	0.02	0.00	0.00	0.00	0.00
9	0.23	0.22	0.00	0.00	0.00	0.25	0.00	0.07	0.00	0.00	0.00	0.00
10	0.13	0.17	0.00	0.00	0.00	0.32	0.00	0.13	0.00	0.00	0.00	0.00
11	0.06	0.18	0.00	0.00	0.00	0.33	0.00	0.11	0.00	0.00	0.00	0.00
12	0.09	0.05	0.00	0.00	0.00	0.15	0.00	0.11	0.00	0.00	0.00	0.00
13	0.07	0.04	0.00	0.00	0.00	0.16	0.00	0.07	0.00	0.00	0.00	0.00
14	0.07	0.05	0.00	0.00	0.00	0.11	0.00	0.04	0.00	0.00	0.00	0.00
15	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
16	0.04	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
17	0.02	0.03	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.03	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00
19	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00
20	0.22	0.00	0.00	0.00	0.00	0.06	0.00	0.09	0.00	0.00	0.00	0.00

Table A39. Age-specific Danish seine recoveries caught in BoP and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A40. Age-specific other commercial recoveries caught in BoP and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.07	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.26	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.40	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.20	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.23	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.16	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A41. Age-specific long line recoveries caught in EN and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.18	0.57	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.34	1.48	0.34	0.01	0.17	0.09	0.17	0.00	0.00	0.00	0.00
5	0.00	0.31	1.63	0.34	0.01	0.35	0.38	0.35	0.00	0.00	0.17	0.00
6	0.00	0.12	1.57	0.14	0.03	0.32	0.23	0.32	0.00	0.00	0.77	0.00
7	0.00	0.02	0.68	0.02	0.22	0.11	0.24	0.11	0.00	0.00	0.46	0.00
8	0.00	0.00	0.46	0.07	0.08	0.03	0.10	0.03	0.00	0.00	0.44	0.00
9	0.00	0.02	0.51	0.22	0.11	0.01	0.11	0.01	0.00	0.00	0.07	0.00
10	0.00	0.00	0.38	0.11	0.14	0.01	0.19	0.01	0.00	0.00	0.05	0.00
11	0.00	0.00	0.21	0.04	0.09	0.00	0.19	0.00	0.00	0.00	0.01	0.00
12	0.00	0.00	0.27	0.09	0.11	0.00	0.07	0.14	0.00	0.00	0.00	0.00
13	0.00	0.00	0.10	0.07	0.04	0.00	0.13	0.00	0.00	0.00	0.02	0.00
14	0.00	0.00	0.13	0.07	0.03	0.00	0.08	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.17	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.21	0.04	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.04	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.01	0.00	0.03	0.00	0.04	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.12	0.00	0.03	0.00	0.04	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.47	0.22	0.01	0.00	0.06	0.86	0.00	0.00	0.00	0.00

Table A42. Age-specific single trawl recoveries caught in EN and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.67	1.23	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.01	1.70	3.50	0.72	0.10	0.00	0.00	0.18	0.00	0.00	0.00	0.00
5	0.03	1.84	3.29	1.25	0.72	0.06	0.00	0.34	0.01	0.00	0.17	0.00
6	0.22	0.87	1.79	0.96	0.96	0.27	0.00	0.31	0.18	0.00	0.35	0.00
7	0.08	0.49	0.63	0.50	0.62	0.30	0.00	0.12	0.33	0.00	0.32	0.00
8	0.19	0.23	0.31	0.22	0.38	0.20	0.00	0.02	0.29	0.00	0.11	0.00
9	0.19	0.32	0.12	0.30	0.08	0.05	0.00	0.00	0.11	0.00	0.03	0.00
10	0.14	0.20	0.02	0.16	0.06	0.04	0.00	0.02	0.03	0.00	0.01	0.00
11	0.11	0.09	0.07	0.10	0.04	0.03	0.00	0.00	0.02	0.00	0.01	0.00
12	0.08	0.10	0.03	0.12	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00
13	0.11	0.08	0.01	0.07	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.00
14	0.14	0.07	0.00	0.08	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
15	0.14	0.02	0.01	0.03	0.18	0.01	0.00	0.00	0.00	0.00	0.00	0.00
16	0.13	0.07	0.01	0.04	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.03	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
18	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.10	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.26	0.22	0.00	0.23	1.50	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Table A43. Age-specific Danish seine recoveries caught in EN and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.38	0.08	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.23	0.39	0.00	0.00	0.44	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.22	0.58	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.04	0.44	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.02	0.22	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.01	0.12	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.39	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.01	0.16	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table A44. Age-specific other commercial recoveries caught in EN and released in HG from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.06	0.73	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.13	0.40	2.03	0.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.32	0.63	2.03	0.26	0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.32	0.39	1.29	0.46	0.63	0.00	0.02	0.00	0.00	0.00	0.00	0.00
7	0.30	0.30	0.51	0.18	0.34	0.00	0.16	0.00	0.00	0.00	0.00	0.00
8	0.16	0.09	0.18	0.21	0.19	0.00	0.17	0.00	0.00	0.00	0.00	0.00
9	0.23	0.05	0.10	0.34	0.07	0.00	0.07	0.00	0.00	0.00	0.00	0.00
10	0.08	0.03	0.04	0.28	0.05	0.08	0.16	0.00	0.00	0.00	0.00	0.00
11	0.25	0.03	0.05	0.18	0.01	0.04	0.16	0.00	0.00	0.00	0.00	0.00
12	0.27	0.00	0.01	0.16	0.03	0.13	0.05	0.00	0.00	0.00	0.00	0.00
13	0.07	0.00	0.00	0.11	0.00	0.08	0.03	0.00	0.00	0.00	0.00	0.00
14	0.14	0.01	0.00	0.05	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
15	0.04	0.01	0.02	0.03	0.00	0.08	0.03	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.02	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00
17	0.08	0.00	0.00	0.07	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.07	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
19	0.04	0.00	0.00	0.03	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00
20	0.56	0.00	0.00	0.04	0.00	0.29	0.07	0.00	0.00	0.00	0.00	0.00

Table A45. Age-specific long line recoveries caught in EN and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.63	3.60	3.75	2.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	5.18	11.47	13.94	9.90	1.70	2.14	1.97	1.35	0.00	0.00	0.00	0.00
5	7.16	12.78	19.80	13.80	6.57	8.74	5.57	5.62	0.47	0.05	0.38	0.00
6	6.15	11.11	17.35	11.79	9.65	12.22	6.03	7.55	1.52	0.50	1.13	0.00
7	3.91	6.06	10.77	7.03	10.10	10.48	5.14	6.15	1.82	0.87	1.23	0.00
8	2.15	3.28	5.10	3.87	6.13	6.22	2.45	3.47	1.64	1.09	0.77	0.00
9	2.21	2.95	4.72	3.71	3.37	2.81	1.18	1.52	0.73	0.78	0.34	0.04
10	2.02	2.81	4.36	3.30	3.86	2.25	1.09	1.16	0.35	0.33	0.06	0.09
11	1.22	1.85	3.08	1.95	3.30	2.05	0.76	1.01	0.45	0.38	0.04	0.12
12	1.19	1.60	2.25	1.46	2.10	1.51	0.91	0.74	0.21	0.43	0.03	0.08
13	0.79	0.92	0.90	0.93	2.07	1.02	0.36	0.45	0.36	0.16	0.01	0.26
14	0.52	0.85	1.16	0.79	1.01	0.60	0.22	0.22	0.34	0.11	0.01	0.12
15	0.38	0.49	0.59	0.41	0.96	0.71	0.37	0.14	0.10	0.00	0.00	0.13
16	0.70	0.63	0.72	0.56	0.66	0.54	0.13	0.11	0.21	0.05	0.00	0.17
17	0.71	0.60	0.80	0.49	0.43	0.34	0.10	0.11	0.06	0.07	0.01	0.13
18	0.18	0.21	0.31	0.29	0.53	0.23	0.16	0.10	0.00	0.02	0.00	0.13
19	0.02	0.10	0.16	0.10	0.31	0.14	0.16	0.11	0.11	0.01	0.00	0.08
20	5.87	2.69	4.23	4.71	3.25	1.99	0.40	1.20	0.64	0.14	0.00	1.64

Table A46. Age-specific single trawl recoveries caught in EN and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.28	0.18	0.49	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.84	0.34	2.32	2.09	0.11	0.11	0.03	0.05	0.00	0.00	0.00	0.00
5	1.06	0.31	2.71	2.85	0.41	1.06	0.10	0.02	0.10	0.00	0.08	0.00
6	1.26	0.14	2.23	2.31	0.49	1.55	0.46	0.07	0.64	0.00	0.36	0.00
7	0.68	0.08	1.15	1.52	0.45	1.58	0.52	0.21	0.50	0.00	0.33	0.00
8	0.53	0.08	0.57	0.57	0.32	1.07	0.36	0.12	0.47	0.00	0.11	0.00
9	0.63	0.21	0.51	0.42	0.28	0.41	0.18	0.33	0.20	0.00	0.07	0.00
10	0.58	0.19	0.46	0.62	0.21	0.36	0.09	0.54	0.04	0.00	0.05	0.00
11	0.43	0.06	0.46	0.25	0.29	0.50	0.08	0.42	0.01	0.00	0.00	0.00
12	0.32	0.13	0.16	0.32	0.07	0.28	0.09	0.09	0.02	0.00	0.00	0.00
13	0.35	0.08	0.07	0.23	0.05	0.17	0.04	0.16	0.01	0.00	0.00	0.00
14	0.40	0.00	0.20	0.03	0.07	0.04	0.03	0.21	0.01	0.00	0.00	0.00
15	0.20	0.02	0.30	0.10	0.06	0.13	0.00	0.16	0.00	0.00	0.00	0.00
16	0.25	0.02	0.05	0.03	0.02	0.10	0.00	0.02	0.00	0.00	0.00	0.00
17	0.06	0.04	0.10	0.07	0.04	0.01	0.03	0.12	0.01	0.00	0.00	0.00
18	0.07	0.04	0.12	0.06	0.04	0.08	0.00	0.09	0.00	0.00	0.00	0.00
19	0.11	0.02	0.04	0.02	0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00
20	0.96	0.04	1.07	0.21	0.08	0.53	0.00	0.37	0.00	0.00	0.00	0.00

Table A47. Age-specific Danish seine recoveries caught in EN and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.20	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.13	0.59	1.62	0.00	0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00
5	0.32	0.58	1.35	0.00	0.55	0.38	0.00	0.00	0.00	0.00	0.00	0.00
6	0.22	0.37	0.93	0.00	0.66	0.25	0.00	0.00	0.00	0.00	0.00	0.00
7	0.17	0.19	0.40	0.00	0.40	0.24	0.00	0.00	0.00	0.00	0.00	0.00
8	0.07	0.02	0.13	0.00	0.18	0.04	0.00	0.00	0.00	0.00	0.00	0.00
9	0.03	0.02	0.04	0.00	0.08	0.09	0.00	0.00	0.00	0.00	0.00	0.00
10	0.01	0.02	0.03	0.00	0.02	0.21	0.00	0.00	0.00	0.00	0.00	0.00
11	0.03	0.00	0.02	0.00	0.01	0.11	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.01	0.01	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.01	0.09	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
15	0.01	0.01	0.01	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00

Table A48. Age-specific other commercial recoveries caught in EN and released in EN from the 1984-85 program.

	1985				1986				1987			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.71	0.68	1.56	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	3.86	2.92	7.48	0.47	0.11	0.81	0.40	0.00	0.00	0.00	0.00	0.00
5	6.45	3.81	9.37	1.32	0.58	2.09	1.13	0.00	0.11	0.17	0.00	0.00
6	7.85	3.38	8.55	1.88	0.59	2.22	0.92	0.00	0.64	0.35	0.00	0.00
7	4.91	1.82	4.71	1.25	0.62	1.44	0.83	0.00	1.03	0.32	0.00	0.00
8	3.17	0.78	1.88	0.89	0.31	0.93	0.35	0.00	0.80	0.11	0.00	0.00
9	3.21	0.61	1.71	1.16	0.27	0.40	0.15	0.00	0.57	0.03	0.00	0.00
10	3.05	0.65	1.28	0.86	0.54	0.31	0.07	0.00	0.28	0.01	0.00	0.00
11	2.80	0.54	0.95	0.47	0.44	0.34	0.03	0.00	0.19	0.01	0.00	0.00
12	1.99	0.26	0.80	0.66	0.35	0.14	0.05	0.00	0.14	0.00	0.00	0.00
13	1.36	0.04	0.23	0.38	0.33	0.07	0.03	0.00	0.12	0.00	0.00	0.00
14	1.35	0.29	0.36	0.42	0.28	0.00	0.01	0.00	0.05	0.00	0.00	0.00
15	1.14	0.27	0.18	0.41	0.21	0.06	0.00	0.00	0.00	0.00	0.00	0.00
16	1.13	0.07	0.11	0.35	0.03	0.07	0.01	0.00	0.00	0.00	0.00	0.00
17	0.57	0.06	0.13	0.10	0.14	0.21	0.01	0.00	0.01	0.00	0.00	0.00
18	0.45	0.23	0.12	0.09	0.24	0.00	0.00	0.00	0.01	0.00	0.00	0.00
19	0.46	0.04	0.03	0.21	0.08	0.03	0.00	0.00	0.01	0.00	0.00	0.00
20	6.54	1.56	0.56	2.05	0.87	1.88	0.00	0.00	0.03	0.00	0.00	0.00

Table A49. Recovery sample size (tonnes) in HG for the 1984-85 tagging program.

	Long Line	Single Trawl	Danish Seine	Other Commercial
1985 Summer	420.03	221.10	391.10	230.86
Autumn	333.01	205.77	273.58	193.52
Winter	188.32	57.63	61.96	50.93
Spring	643.34	165.52	172.44	170.37
1986 Summer	506.78	190.50	296.76	164.68
Autumn	315.81	175.93	322.96	109.98
Winter	123.68	34.16	43.03	50.06
Spring	432.87	84.61	178.77	75.00
1987 Summer	265.43	442.58	134.48	37.40
Autumn	233.70	157.91	201.21	72.80
Winter	168.14	13.55	27.17	48.92
Spring	782.09	95.85	372.07	96.94

Table A50. Recovery sample size (tonnes) in BoP for the 1984-85 tagging program.

		Long Line	Single Trawl	Danish Seine	Other Commercial
1985	Summer	83.98	290.80	1.07	87.80
	Autumn	95.21	309.39	0.12	111.97
	Winter	138.52	155.71	5.20	33.45
	Spring	130.24	121.63	0.00	67.38
1986	Summer	123.78	266.88	4.26	91.81
	Autumn	174.87	241.35	0.99	65.78
	Winter	157.22	85.73	0.00	13.46
	Spring	102.02	108.16	2.25	24.23
1987	Summer	31.40	192.20	0.00	35.50
	Autumn	73.65	120.41	0.00	49.57
	Winter	130.57	59.27	0.84	10.37
	Spring	55.75	55.35	0.00	19.91

Table A51. Recovery sample size (tonnes) in EN for the 1984-85 tagging program.

		Long Line	Single Trawl	Danish Seine	Other Commercial
1985	Summer	320.31	9.49	9.53	316.78
	Autumn	202.35	47.09	7.04	188.08
	Winter	243.54	74.31	5.95	137.32
	Spring	323.45	41.22	13.44	244.63
1986	Summer	337.90	31.78	7.35	249.21
	Autumn	234.61	41.00	8.52	204.25
	Winter	228.29	25.07	0.02	48.46
	Spring	284.55	16.57	0.05	73.27
1987	Summer	162.39	2.92	0.00	41.40
	Autumn	108.62	33.97	1.83	59.67
	Winter	137.01	17.97	7.01	19.02
	Spring	206.25	9.20	0.00	92.33

Table A52. Seasonal numbers-at-age of HG releases recaptured by long line in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.17	1.12
5	0.38	1.72	0.19	5.50	1.77
6	1.37	4.14	2.25	11.51	6.64
7	0.76	3.01	1.24	5.89	3.78
8	1.61	5.61	2.79	7.95	2.58
9	1.37	5.09	3.05	8.62	4.22
10	1.36	3.66	2.35	5.62	6.75
11	0.13	0.47	0.13	0.27	3.39
12	0.04	0.67	0.14	0.62	0.83
13	1.14	1.47	1.77	4.55	0.88
14	0.39	1.24	0.56	1.11	2.42
15	0.24	0.58	0.32	0.91	0.74
16	0.09	0.21	0.09	0.50	0.73
17	0.00	0.06	0.00	0.31	0.73
18	0.00	0.00	0.00	0.10	0.25
19	0.05	0.00	0.05	0.16	0.50
20	0.05	0.06	0.05	1.22	0.67

Table A53. Seasonal numbers-at-age of HG releases recaptured by single trawl in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.06	0.06	0.00	0.00	0.00
5	1.12	0.89	0.00	0.00	0.00
6	2.09	1.87	0.00	0.00	0.00
7	0.91	1.15	0.00	0.00	0.00
8	1.42	2.83	0.00	0.00	0.00
9	1.38	2.51	0.00	0.00	0.00
10	1.17	1.54	0.00	0.00	0.00
11	0.05	0.13	0.00	0.00	0.00
12	0.04	0.17	0.00	0.00	0.00
13	0.38	1.56	0.00	0.00	0.00
14	0.21	0.44	0.00	0.00	0.00
15	0.12	0.44	0.00	0.00	0.00
16	0.00	0.17	0.00	0.00	0.00
17	0.05	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.25	0.00	0.00	0.00

Table A54. Seasonal numbers-at-age of HG releases recaptured by Danish seine in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.07
5	0.40	3.09	1.19	1.89	0.19
6	1.60	8.74	1.43	3.24	0.87
7	0.94	5.92	1.23	2.06	1.29
8	2.28	9.51	1.64	3.88	0.75
9	2.15	11.14	1.72	4.27	1.30
10	2.06	6.44	1.26	4.05	2.46
11	0.10	0.22	0.08	0.29	1.55
12	0.24	1.20	0.18	0.14	0.44
13	1.46	4.70	0.51	2.87	0.11
14	0.79	2.39	0.44	1.13	0.52
15	0.58	1.34	0.27	0.87	0.40
16	0.20	0.54	0.04	0.09	0.20
17	0.00	0.17	0.00	0.11	0.05
18	0.05	0.20	0.00	0.00	0.00
19	0.05	0.10	0.00	0.05	0.20
20	0.10	0.31	0.00	0.05	0.60

Table A55. Seasonal numbers-at-age of BoP releases recaptured by long line in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.41
5	0.13	0.14	0.00	0.40	0.40
6	0.28	0.14	0.00	0.90	1.25
7	0.15	0.17	0.00	0.43	1.02
8	0.15	0.17	0.00	1.32	0.65
9	0.23	0.37	0.00	1.40	1.00
10	0.05	0.00	0.00	1.51	1.61
11	0.00	0.00	0.00	0.19	0.94
12	0.00	0.00	0.00	0.18	0.15
13	0.03	0.00	0.00	0.75	0.03
14	0.00	0.00	0.00	0.39	0.26
15	0.00	0.00	0.00	0.39	0.19
16	0.00	0.00	0.00	0.14	0.00
17	0.00	0.00	0.00	0.00	0.09
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A56. Seasonal numbers-at-age of BoP releases recaptured by single trawl in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.14	0.00	0.00	0.00	0.00
6	0.14	0.05	0.00	0.00	0.00
7	0.17	0.00	0.00	0.00	0.00
8	0.17	0.36	0.00	0.00	0.00
9	0.37	0.41	0.00	0.00	0.00
10	0.00	0.57	0.00	0.00	0.00
11	0.00	0.05	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.26	0.00	0.00	0.00
14	0.00	0.16	0.00	0.00	0.00
15	0.00	0.11	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.05	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A57. Seasonal numbers-at-age of BoP releases recaptured by Danish seine in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.28	0.00	0.00	0.03	0.00
6	0.38	0.00	0.00	0.28	0.17
7	0.14	0.00	0.00	0.15	0.17
8	0.24	0.00	0.00	0.23	0.15
9	0.17	0.00	0.00	0.15	0.19
10	0.35	0.00	0.00	0.13	0.52
11	0.00	0.00	0.00	0.00	0.57
12	0.00	0.00	0.00	0.00	0.00
13	0.25	0.00	0.00	0.00	0.00
14	0.05	0.00	0.00	0.03	0.18
15	0.15	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.06

Table A58. Seasonal numbers-at-age of EN releases recaptured by long line in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.13
5	0.00	0.00	0.00	0.03	0.33
6	0.00	0.00	0.33	0.41	1.52
7	0.00	0.00	0.12	0.25	0.71
8	0.00	0.00	0.12	0.55	0.56
9	0.00	0.00	0.21	0.35	0.68
10	0.00	0.00	0.15	0.30	0.67
11	0.00	0.00	0.00	0.00	0.33
12	0.00	0.00	0.00	0.03	0.03
13	0.00	0.00	0.66	0.60	0.00
14	0.00	0.00	0.10	0.22	0.03
15	0.00	0.00	0.10	0.05	0.00
16	0.00	0.00	0.00	0.05	0.00
17	0.00	0.00	0.00	0.05	0.00
18	0.00	0.00	0.10	0.00	0.00
19	0.00	0.00	0.00	0.05	0.00
20	0.00	0.00	0.10	0.05	0.00

Table A59. Seasonal numbers-at-age of EN releases recaptured by single trawl in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A60. Seasonal numbers-at-age of EN releases recaptured by Danish seine in HG.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A61. Seasonal numbers-at-age of HG releases recaptured by long line in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.09	0.00	0.15
6	0.00	0.00	0.65	0.00	0.80
7	0.00	0.00	0.31	0.15	0.06
8	0.00	0.00	0.50	0.15	0.00
9	0.00	0.00	0.35	0.40	0.00
10	0.00	0.00	0.11	0.20	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.10	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A62. Seasonal numbers-at-age of HG releases recaptured by single trawl in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.02	0.00	0.00
4	0.00	0.00	0.09	0.00	0.00
5	0.00	0.00	2.37	0.28	0.06
6	0.00	0.00	0.48	0.62	1.01
7	0.00	0.00	0.02	0.09	0.49
8	0.00	0.00	0.00	0.02	0.15
9	0.00	0.00	0.02	0.00	0.22
10	0.00	0.00	0.00	0.00	0.06
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A63. Seasonal numbers-at-age of HG releases recaptured by Danish seine in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.02	0.00	0.02	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.68	0.53	0.96	0.00
6	0.00	0.28	0.65	0.90	0.00
7	0.00	0.02	0.11	0.11	0.18
8	0.00	0.00	0.42	0.02	0.12
9	0.00	0.00	0.55	0.00	0.29
10	0.00	0.00	0.21	0.00	0.24
11	0.00	0.00	0.00	0.00	0.18
12	0.00	0.00	0.25	0.00	0.00
13	0.00	0.00	0.16	0.00	0.00
14	0.00	0.00	0.20	0.00	0.00
15	0.00	0.00	0.11	0.00	0.00
16	0.00	0.00	0.31	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.40	0.00	0.00
19	0.00	0.00	0.11	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A64. Seasonal numbers-at-age of BoP releases recaptured by long line in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.02	0.00	0.00	0.00
5	0.09	1.18	0.31	0.00	0.00
6	0.55	1.45	1.36	0.39	0.40
7	0.15	0.64	0.64	0.11	0.29
8	0.24	0.40	0.40	0.17	0.07
9	0.62	0.23	0.21	0.33	0.20
10	0.24	0.08	0.08	0.00	0.04
11	0.06	0.00	0.00	0.00	0.00
12	0.06	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A65. Seasonal numbers-at-age of BoP releases recaptured by single trawl in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.02	0.00	0.00	0.00
4	0.00	0.00	0.14	0.03	0.08
5	0.00	0.77	3.15	0.19	1.18
6	0.00	1.21	2.22	0.56	1.67
7	0.00	0.28	0.46	0.14	0.17
8	0.00	0.35	0.66	0.08	0.11
9	0.00	0.36	0.37	0.00	0.43
10	0.00	0.00	0.00	0.00	0.30
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.04
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A66. Seasonal numbers-at-age of BoP releases recaptured by Danish seine in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.04	0.02	0.00
4	0.30	0.00	0.00	0.00	0.04
5	0.55	0.80	2.10	1.44	0.62
6	0.15	1.45	2.88	1.34	2.18
7	0.00	0.36	0.51	0.13	0.15
8	0.12	0.32	0.41	0.07	0.00
9	0.53	0.04	0.06	0.00	0.00
10	0.00	0.04	0.00	0.00	0.00
11	0.06	0.00	0.00	0.00	0.00
12	0.06	0.00	0.00	0.00	0.00
13	0.24	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.50	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.25	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.25	0.00	0.00	0.00	0.00

Table A67. Seasonal numbers-at-age of EN releases recaptured by long line in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.09	0.28	0.00	0.00	0.15
6	0.55	0.62	0.00	0.00	0.80
7	0.15	0.09	0.00	0.00	0.06
8	0.18	0.02	0.00	0.00	0.00
9	0.03	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A68. Seasonal numbers-at-age of EN releases recaptured by single trawl in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.02	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.68	0.00	0.00
6	0.00	0.00	0.28	0.00	0.00
7	0.00	0.00	0.02	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A69. Seasonal numbers-at-age of EN releases recaptured by Danish seine in BoP.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.09	0.28	0.00	0.00	0.15
6	0.55	0.62	0.00	0.00	0.80
7	0.15	0.09	0.00	0.00	0.06
8	0.18	0.02	0.00	0.00	0.00
9	0.03	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A70. Seasonal numbers-at-age of HG releases recaptured by long line in EN.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.05	0.00	0.00
4	0.00	0.08	0.20	0.15	0.04
5	0.00	0.80	1.39	1.28	0.29
6	0.00	1.24	1.54	1.43	0.36
7	0.00	0.85	0.64	0.59	0.18
8	0.00	1.22	1.81	0.92	0.11
9	0.00	0.67	0.87	0.41	0.15
10	0.00	0.14	0.50	0.03	0.19
11	0.00	0.00	0.17	0.00	0.08
12	0.00	0.37	0.19	0.12	0.00
13	0.00	0.13	0.23	0.02	0.08
14	0.00	0.04	0.00	0.00	0.15
15	0.00	0.13	0.08	0.05	0.15
16	0.00	0.04	0.04	0.00	0.00
17	0.00	0.07	0.08	0.00	0.00
18	0.00	0.04	0.06	0.00	0.08
19	0.00	0.09	0.04	0.00	0.00
20	0.00	0.09	0.10	0.00	0.15

Table A71. Seasonal numbers-at-age of BoP releases recaptured by long line in EN.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.05	0.00	0.00	0.00
5	0.00	0.32	0.00	0.00	0.00
6	0.00	0.72	0.00	0.00	0.00
7	0.00	0.33	0.00	0.00	0.00
8	0.00	0.33	0.00	0.00	0.00
9	0.00	0.18	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00
12	0.00	0.05	0.00	0.00	0.00
13	0.00	0.02	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00

Table A72. Seasonal numbers-at-age of EN releases recaptured by long line in EN.

Age	Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.05	0.00	0.05	0.00
4	0.03	0.80	0.91	1.37	0.81
5	0.36	5.39	5.32	5.68	2.91
6	0.66	6.54	7.16	7.48	5.04
7	0.57	3.26	3.16	2.83	4.02
8	1.16	5.51	6.41	7.09	2.50
9	0.54	2.66	2.91	3.59	2.48
10	0.17	0.88	0.69	1.20	2.02
11	0.05	0.37	0.24	0.53	0.62
12	0.19	0.86	0.96	2.57	0.00
13	0.10	1.14	0.92	1.67	1.40
14	0.00	0.16	0.12	0.43	1.11
15	0.05	0.37	0.39	0.78	0.21
16	0.03	0.24	0.30	0.90	0.32
17	0.05	0.14	0.08	1.00	0.69
18	0.00	0.11	0.09	0.35	0.07
19	0.05	0.07	0.13	0.89	0.00
20	0.03	0.45	1.21	4.60	0.81

Table A73. Sample size (tonnes) for the 1993-94 tagging program.

		Summer 94	Autumn 94	Winter 94	Spring 94	Summer 95
HG	Long Line	25.74	77.54	48.14	177.10	170.78
	Single Trawl	15.07	40.51	0.00	0.00	0.00
	Danish Seine	11.84	56.44	5.24	36.81	33.71
BoP	Long Line	3.26	12.45	14.19	12.81	15.30
	Single Trawl	0.00	9.35	19.47	15.89	16.94
	Danish Seine	4.23	6.71	15.16	10.67	10.53
EN	Long Line	8.34	48.93	76.81	87.16	68.48

VITA

Mark Nicholas Maunder
University of Washington
1998

Academic Backgroud
Master of Science in Zoology with first class honors, University of Auckland, New Zealand, 1991-1993. Thesis: "Optimising harvest strategies for the west coast snapper (*Pagrus auratus*) fishery."

Bachelor of Science with a double major in Zoology and Computer Science, University of Auckland, New Zealand, 1988-1990.

Professional Background
Quantitative Fisheries Scientist (Data Management and Population Assessment). New Zealand Fishing Industry Board (NZFIB), March 1993-September 1995.

Senior Scientist. Inter-American Tropical Tuna Commission, December 1998-Present.

Peer Reviewed Papers

Maunder, M. N. and Starr, P. J. (1995) Sensitivity of management reference points to the ratio of B_{msy}/B_0 determined by the Pella-Tomlinson shape parameter fitted to New Zealand rock lobster data. New Zealand Fisheries Assessment Research Document 95/10 p22.

Maunder, M. N. and Starr, P. J. (1995) Rock lobster standardised CPUE analysis. New Zealand Fisheries Assessment Research Document 95/11 28p.

Maunder, M.N. (1997) Investigation of density dependence in salmon spawner-egg relationships using queueing theory. Ecological modelling 104: 189-197.

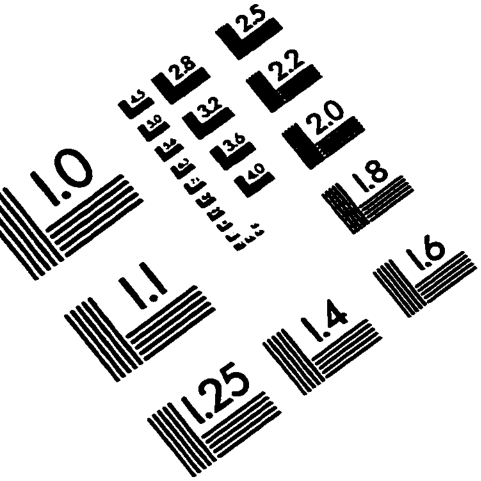
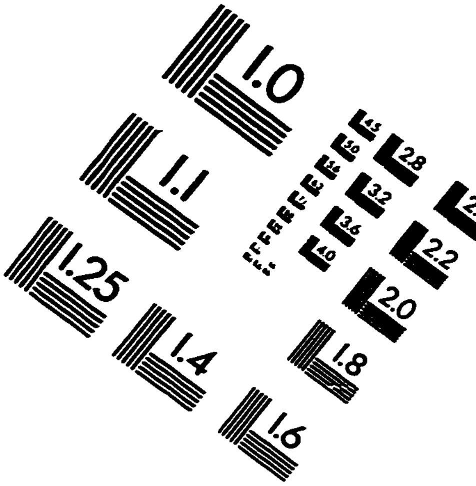
Maunder, M.N. and Starr, P.J. (1998) Validating the Hauraki Gulf snapper pre-recruit trawl surveys and temperature recruitment relationship using catch at age analysis with auxiliary information. New Zealand Fisheries Assessment Research Document 98/15 23p.

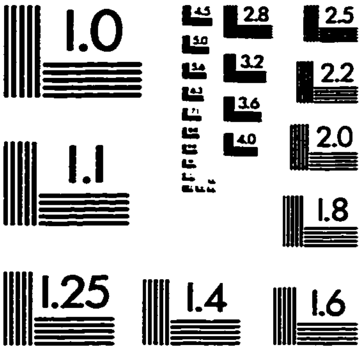
Maunder, M.N. (in press) Problems with using an environmental based recruitment index: examples from a New Zealand snapper (*Pagrus auratus*) assessment. Proceedings of the 15th Lowell Wakefield Fisheries Symposium. Fishery stock

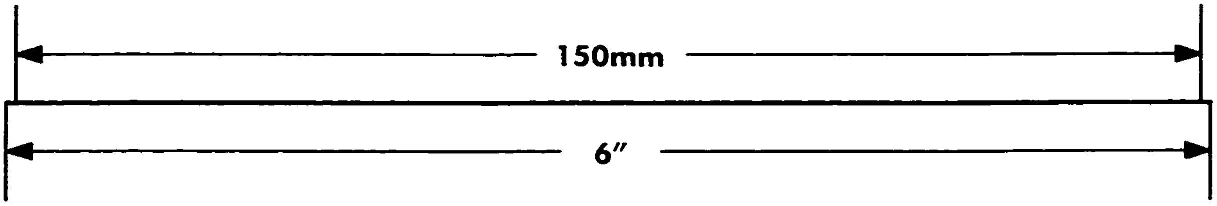
assessment models for the 21st century: combining multiple information sources. October 8-11, 1997, Anchorage, Alaska, USA.

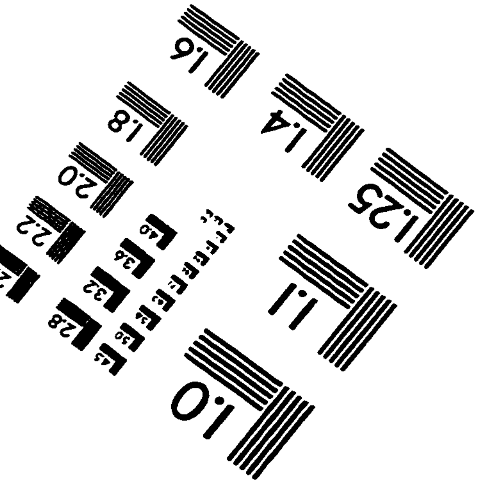
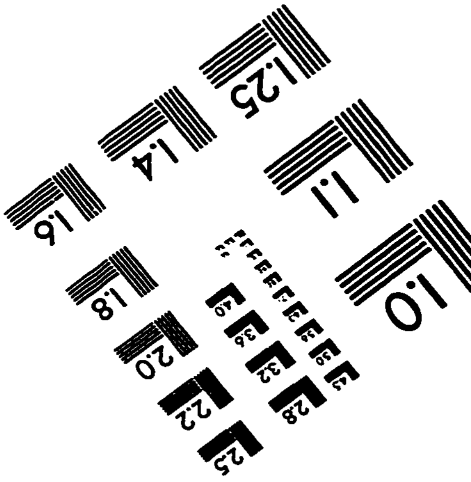
Maunder, M.N., Starr, P.J. and Hilborn, R. (accepted after modification) A Bayesian analysis to estimate loss in squid catch due to the implementation of a sea lion Population Management Plan. Marine Mammal Science.

IMAGE EVALUATION
TEST TARGET (QA-3)





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