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Validating the Hauraki Gulf snapper pre-recruit trawl surveys and temperature recruitment relationship using catch at age analysis with auxiliary information

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Executive Summary

Estimates of relative recruitment by year class for snapper in the Hauraki Gulf are made using catch at age data. These estimates appear to be well correlated with published estimates of relative year class strengths which have been made using a temperature-recruitment relationship based on pre-recruit trawl surveys. Direct comparison between the pre-recruit trawl surveys with the model recruitment indices shows that the two sets of indices appear to be similar, but the correlation is not statistically significant. This lack of significance is likely to be the result of error in the estimates of both indices and the few years available for comparison. When indices estimated indirectly using temperature are included, the correlations become significant, indicating that the fluctuations in year-class strengths established early in the life history of Hauraki Gulf snapper persist into the fishery.

Sensitivity analyses show that the relative year class strengths appear to be mainly insensitive to most of the assumptions investigated.

The catch at age data show that the recruitment of a cohort into the snapper fishery does not follow the same ogive for all year classes. This implies that a model using the pre-recruit estimators to predict recruitment and a fixed selectivity ogive will overestimate the current yield for years characterised by slow growth of the recruiting year class.

Introduction

An age-structured model with gear specific selectivity at age is used to model the Hauraki Gulf snapper (*Pagrus auratus*) stock (a substock of SNA 1). The model begins with the biomass estimate of stock size and age structure from the 1984–85 tagging experiment (Sullivan *et al.* 1988). This biomass estimate is assumed to represent a biomass at the beginning of the fishing year. Annual recruitment is estimated by maximising the likelihood of biomass indices based on longline CPUE data and proportional catch at age data from the longline fishery.

Previous assessments (e.g., Gilbert & Sullivan 1994) have used external estimates of yearly recruitment strengths which are based on either a) pre-recruit trawl surveys in the Hauraki Gulf; or b) when these were not available, a relationship developed between sea surface temperatures and the trawl survey estimates of pre-recruits (Francis 1993). In contrast, this assessment uses proportional catch at age data derived from sampling the commercial catch (Davies & Walsh 1995) to estimate the relative annual recruitment. This approach is similar to that used in the assessment made for the west coast North Island snapper (N. Davies, NIWA, pers. comm.). The estimates of relative recruitment strengths derived from this analysis are independent of the recruitment strength estimates based on the trawl surveys or on the temperature/recruitment relationship. These sets of relative recruitment strengths can be then compared for similarity in those years which have been independently estimated.

Model Description

Initial Biomass: The model begins with the estimates of initial stock size in numbers for fish of age 5 and older at the start of the 1984–85 fishing year. These estimates are derived from the results of a tagging experiment which covered the Hauraki Gulf and east Northland (Sullivan *et al.* 1988). The numbers at age were calculated based on a total biomass estimate for the Hauraki Gulf of 28 087 t; this estimate assumes a 15% under-reporting of tags. This model also assumes that there is no ambiguity when applying fishing year catches which begin in October to annual cohorts which begin in the following January.

The age 4 cohort was not included in the initial input biomass because it does not appear to be completely recruited to the fishery. This conclusion is based on the following comparison: Table 1 shows that the 1981 year class (age 4 in 1985) was three times larger than average as estimated from the temperature-recruitment relationship (Francis 1993); however, Table 3.2 of Appendix 3 shows that the tagging estimate shows a relatively low proportion of age 4s in the biomass. If this estimate for age 4 biomass is used in the model, the model estimates that the recruitment strength for the 1981 year class was lower than average. Therefore, it was concluded that a significant fraction of this cohort had not reached the minimum 25 cm size required for tagging.

Model Procedure: The numbers at age were calculated in each successive fishing year by subtracting catch and natural mortality and incrementing the age of each cohort (Appendix 1 provides all equations). This method is similar to stock reduction analysis (Francis 1992, Maunder 1993). All fish were assumed to die after reaching the maximum age class in the model ($a_{max} = 50$). It should be noted that the vulnerability of each age class is assumed to differ, depending on the gear type. These selectivities (Table 3.5) were estimated from the 1984 tagging experiment (Sullivan *et al.* 1988), but the methodologies and the results of this analysis have not been formally published (K.J. Sullivan, formerly NIWA now Ministry of Fisheries, pers. comm.).

Because the catch at age data contain no information for the cohorts which recruit after the 1993–94 fishing year, recruitment was assumed to follow the temperature-recruitment relationship after the 1989 cohort (see Table 1).

Parameters Estimated: The parameters estimated by the model are the recruitments at age 1 into the population over the period being considered (fishing years 1985–94; year classes 1981–89). These were estimated by maximising the likelihood of biomass indices based on longline CPUE data and the proportional catch at age data, using the procedures described in Appendix 2. These were the estimated year classes because only fish aged 5 to 10 were used in the proportion of catch at age likelihood calculations. This was because the age 4s do not appear to be completely vulnerable to the fishery (see above) and the catch at age data do not appear to be as reliable for the older age classes. Observed coefficients of variation (*c.v.*s) from the sampling programme were used to weight the variance in the likelihood calculations. These *c.v.*s were modified as described in Appendix 2 so that the error for the catch at age data would be scaled appropriately relative to the CPUE likelihood.

Fitting Procedure: The model was fitted to proportion at age in the catch rather than using the catch at age data as an exact input as is done in Virtual Population Analysis (Punt 1994). Those years with available catch at age data for the longline fishery in the Hauraki Gulf were used (Table 3.6). These data were collected only for either the summer or the spring-summer fishing seasons, but it was assumed that they were a reliable estimate of the annual proportion at age caught by the longline fishery throughout the entire fishing year. This is because most of the catch (usually about 75%) is taken in this period.

Input Data: A longline CPUE abundance index (Table 3.4) was used to indicate the relative mid-year abundance by weight of the population which was vulnerable to the longline fishery. This index was estimated for the entire SNA 1 Fishstock and may introduce some bias as the remainder of the data used apply specifically to the Hauraki Gulf.

The initial biomass data, the catch data, the proportion catch at age data, the selectivity estimates, and the biological parameters used are described in Appendix 3. Recreational catch is calculated as 20% of the commercial catch (Gilbert & Sullivan 1994).

Although the only parameters estimated by this model are the recruitments into the fishery during the 1985–94 period, this value can be used to estimate the virgin biomass if it is assumed that this is a reasonable estimate of the average recruitment. This can be done because no stock-recruitment relationship is used in this model (steepness = 1.0; Gilbert & Sullivan 1994); it is also assumed that recruitment variation is entirely driven by temperature (Francis 1993). Under these assumptions, the virgin biomass can be easily calculated from the mean virgin recruitment (Appendix 1).

Sensitivity Analyses: The baseline model described above was modified as follows for sensitivity analyses which were carried out to determine the effect of different assumptions on the recruitment estimates.

1. Sensitivity to the inclusion of the CPUE abundance index was investigated by a) increasing the weight given to the CPUE abundance index by doubling the catch at age variance scaler and b) by omitting the CPUE abundance index from the fitting procedure.

2. Sensitivity to the initial biomass estimate was investigated by using two additional estimates of the initial biomass: a) 32 300 t (this assumes no under-reporting bias) and b) 37 145 t (15% higher than (a)).

3. The sensitivity to the selectivity of age 4 fish was investigated by assuming a selectivity of 0 at age 4 for all methods.

4. The sensitivity to the age specific relative selectivities was investigated by dropping these selectivities and assuming that all ages were equally vulnerable to all gears.

5. The effect of increasing the scope of the model was investigated by using the combined Hauraki Gulf and Bay of Plenty catch and biomass data. This was done by combining the two initial biomass estimates (34 435 t, assuming a 15% under-reporting bias) and by using the combined catches for these two areas (Table 3.4).

Results

Base Model

The time series of recruitments estimated by the base model shows a good relationship to the recruitment indices estimated by both the pre-recruit trawl surveys and to the indices estimated using the temperature-recruitment relationship (Figure 1, Table 1). The relationship with the temperature indices appears to be stronger (see Table 1) as the time series is slightly longer.

Correlation coefficients between the two sets of independent recruitment indices are not significant when all the available data are included (Table 2). However, if the 1989 year class is dropped (as this year class appears to be very poorly represented in the fishery), the correlation coefficient improves considerably for both series, although only the correlation with the temperature-recruitment relationship is statistically significant. The lack of a statistically significant fit with the pre-recruit trawl survey may be the result of the small number of overlapping observations (only six) and possibly the error in both estimates. However, the persistence of the year class strengths estimated by the temperature-recruitment relationship (and by inference the pre-recruit trawl surveys) indicate that variation in year class strength established early in the life history appears to be maintained subsequently in the relative age class strengths seen in the longline catch at age data.

The catch at age proportions estimated by the model fit well in most years to the catch at age proportions estimated by the catch sampling (Figure 2). In most years, the age 4 catch proportions estimated by the model appear to be positively biased relative to the catch sampling data. This appears to be a result of a possible overestimate of the age 4 longline selectivity and may represent a bias in the tagging programme. The tagging experiment marked only fish larger than 25 cm, but this represents only the upper length classes for 4 year olds, especially in years of slow growth.

Some age classes in some years appear to fit the catch at age data poorly. This may be due to sampling error, to differential growth between year classes, or to some cohorts being incompletely recruited to the fishery. The 1989 year class fits the catch at age data very poorly because it is estimated only from one data set (the 1993–94 fishing year) and it appears to be incompletely recruited to the fishery. The model estimates this year class to be quite small while the independent pre-recruit estimators indicate that this year class should be well above average (*see* Table 1). This difference is probably the result of slow growth which has caused this year class to be incompletely recruited even at age 5. In support of this conclusion, age sampling (Table 3) indicated that 20–30% of this age class had not reached the minimum legal size of 25 cm in the 1993–94 fishing year (age 5 for this cohort). This contrasts with the usual modelling assumptions for SNA 1 that all age 4 fish are fully recruited to the fishery.

The base model likelihood is calculated by giving approximately equal weight to the two sources of biomass information: the CPUE abundance index and the catch at age data. The predicted abundance indices (q) under this assumption appear to fit the observed CPUE abundance indices well (Figure 3). The variance scaler for the catch at age data ($\hat{\sigma}_{CA}$) is estimated at 3.37 (Equation 2.9). This increases the *c.v.* for the catch at age data beyond the simple sampling *c.v.*s and gives effectively more weight to the CPUE abundance indices (otherwise the catch at age data would overwhelm the CPUE data).

Sensitivity Analyses

1. Effect of the different likelihood data sets: There is little difference between the recruitment indices estimated by either of the data sets used to condition this model (CPUE abundance indices or the catch at age data; *see* Figure 1). However, the absolute estimate of the average recruitment is highly dependent on the weight given to the CPUE abundance indices (Table 4). For example, the average recruitment of age 1 fish is estimated to be 5.8 million when both sets of data are used, but this value increases to 9.5 million age 1 recruits if the catch at age data are used alone. A similar sensitivity is seen in the estimates for S_{cur} (current spawning biomass) and S_0 (virgin spawning biomass). S_{cur}/S_0 seems to be less sensitive to the weight given to the CPUE abundance indices. The predicted fit to the observed CPUE abundance indices remains similar to the base model when the relative weight of the CPUE abundance indices is increased (Figure 4). However, when the CPUE abundance indices are excluded from the likelihood calculations, the biomass trajectory estimated by the model appears to increase while the observed CPUE abundance indices decrease (compare Figures 3 and 5), indicating that if there is any information on biomass in the catch at age data, it contradicts the CPUE abundance series.

2. Size of initial biomass: The estimated relative recruitment indices and the estimates of average recruitment appear to be insensitive to the size of the initial 1985 biomass (Figure 6, Tables 4 and 5). S_{cur} and S_{cur}/S_0 increase as the size of the initial 1985 biomass increases, while S_0 remains the same as it is linked directly to R_0 (*see* Table 4).

3. Removing age 4s from the fishery: Setting the selectivity of age 4 to 0 appears to change the estimated relative recruitment indices and causes somewhat larger deviations from the average than for the other sensitivity analyses (Figure 7, *see* Table 5). It also appears to decrease the estimated average absolute recruitment relative to the base case (*see* Table 4). The estimate for S_0 also decreases relative to the base case, while the estimates for S_{cur} and S_{cur}/S_0 are insensitive.

4. Removing the relative selectivities at age: Removing these selectivities by assuming constant selectivity appears to have little effect on all the estimated values relative to the base model run (*see* Tables 4 and 5, Figure 7).

5. Increasing the scope of the model: Combining the Bay of Plenty with the Hauraki Gulf data appears to have had a small effect on the estimated relative recruitment indices (Table 5, Figure 8). The estimated average recruitment, S_{cur}, and S_0 all increase as expected, while S_{cur}/S_0 declines slightly relative to the base case (*see* Table 4).

Conclusions

Estimates of relative recruitment by year class for snapper in the Hauraki Gulf have been made using catch at age data from the longline fishery in the same area. These estimates appear to be well correlated with published estimates of relative year class strengths which have been made using a temperature-recruitment relationship based on pre-recruit trawl surveys (Francis 1993).

Direct comparison between the pre-recruit trawl surveys with the model recruitment indices show that the two sets of indices appear to be similar but that the correlation is not statistically significant. This lack of significance is likely to be the result of error in the estimates of both indices and the few years available for comparison. When indices estimated indirectly using temperature are included, the correlations become significant, indicating that the fluctuations in year-class strengths established early in the life history of Hauraki Gulf snapper persist into the fishery.

The correlations between apparent year class strength in the fishery and the predicted age 1 cohort based on the temperature relationship appear to be strong given the current data sets. However, predictive correlations based on external information such as temperature do not necessarily imply causation and may not maintain the same high level of correlation in the future.

The sensitivity analyses show that the relative strengths of the recruitment of each year class estimated by the model appear to be insensitive to most of the assumptions in the model (*see* Table 5), with the possible exception of setting the selectivity at age 4 to 0. However, the magnitude of the average recruitment (in numbers of fish) is sensitive to the inclusion of the CPUE abundance indices and to the use of a selectivity at age 4 (*see* Table 4). The ratio S_{cur}/S_0 is sensitive to the size of the initial biomass estimate and to the inclusion of the CPUE abundance indices.

The catch at age data show that the recruitment of a cohort into the snapper fishery does not follow the same ogive for all year classes. For instance, there is evidence that the large 1989 year class is growing more slowly than average because of cold water conditions or density-dependent effects. This implies that a model using the pre-recruit estimators to predict recruitment and a selectivity ogive will overestimate the current yield for those years which are characterised by slow growth of the recruiting year class. This is also important when considering what proportion of the stock is represented in an absolute biomass estimate.

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Table 1: Comparison of relative recruitment indices estimated by the model using the catch at age data with relative recruitment indices estimated by the pre-recruit trawl survey and by the temperature-recruitment relationship (Annala 1995). (N/A, years with no pre-recruit trawl survey; –, not estimated)

Year class (age 0+)	Catch at age base model	Pre-recruit trawl survey	Temperature -recruitment relationship
1981	2.32	N/A	3.02
1982	0.66	N/A	0.90
1983	0.33	0.28	0.27
1984	1.46	0.83	0.76
1985	1.52	1.15	1.23
1986	1.12	1.31	1.56
1987	0.47	0.59	0.55
1988	0.79	0.89	0.97
1989	0.33	2.27	2.03
1990	–	N/A	1.60
1991	–	0.79	0.63
1992	–	0.28	0.29
1993	–	0.32	0.41
1994	–	N/A	0.76

Table 2: Correlation of recruitment indices calculated using the catch at age data with independently estimated recruitment indices (Table 1). The year classes correlated with the pre-recruit indices begin in 1983 and the with the temperature-based indices begin in 1981

	Pre-recruit trawl survey		Temperature-recruitment relationship	
Years included in correlation	Correlation coefficient	Level of significance (number of observations)	Correlation coefficient	Level of significance (number of observations)
All years	-0.02	0.96 (7)	0.62	0.07 (9)
Omit 1989 year class	0.76	0.07 (6)	0.86	0.01 (8)

Table 3: Data from age length key for Hauraki Gulf snapper for the 5 year old cohort in 1993–94 (1989 year class; modified from Davies & Walsh 1995). These calculations assume that sampling for age was random, which is probably violated

Length (cm)	Proportion of 5 year olds sampled
20	0.00
21	0.00
22	0.05
23	0.15
24	0.08
25	0.20
26	0.17
27	0.14
28	0.08
29	0.08
30	0.02

Table 4: Average recruitment (R_{avg}) in numbers (1 year olds), current (start of the 1994–95 fishing year) spawning biomass (S_{cur}) in tonnes, virgin spawning biomass (S_0) in tonnes, and the ratio of current biomass to virgin spawning biomass (S_{cur}/S_0) for the base model and the sensitivity analyses. Spawning biomass (S) is defined as all fish at age 4 years and older

Parameter	Base model	Increased weight for CPUE	No CPUE	B_{85} = 32 300 t	B_{85} = 37 145 t	Zero selectivity at age 4	Constant selectivity	+ BoP catch and 1985 biomass
R_{avg} (millions)	5.8	5.6	9.5	5.6	5.8	4.9	5.6	7.9
S_{cur} (1000 t)	23.9	22.7	49.4	28.1	35.9	21.1	23.8	29.0
S_0 (1000 t)	157.9	154.1	259.2	152.5	158.4	135.1	152.9	216.3
S_{cur}/S_0 (%)	15.1	14.7	19.1	18.5	22.6	15.6	15.5	13.4

Table 5: Comparison of relative recruitment indices estimated by the base model to those estimated by the models used in the sensitivity analyses (note: +BoP = includes Bay of Plenty catch and biomass estimates)

Year class (age 0+)	Base model	Increased weight for CPUE	No CPUE	B_{85} = 32 300t	B_{85} = 37 145t	Zero selectivity for age 4	Constant selectivity	+ BoP
1981	2.32	2.25	2.31	2.15	2.01	2.69	2.37	2.47
1982	0.66	0.64	0.63	0.64	0.62	0.70	0.68	0.67
1983	0.33	0.32	0.31	0.32	0.32	0.37	0.33	0.32
1984	1.46	1.47	1.37	1.47	1.46	1.40	1.47	1.42
1985	1.52	1.50	1.48	1.56	1.58	1.39	1.51	1.48
1986	1.12	1.09	1.15	1.18	1.22	1.04	1.10	1.09
1987	0.47	0.49	0.51	0.49	0.51	0.42	0.46	0.46
1988	0.79	0.88	0.86	0.83	0.88	0.73	0.75	0.75
1989	0.33	0.36	0.38	0.36	0.40	0.26	0.33	0.32

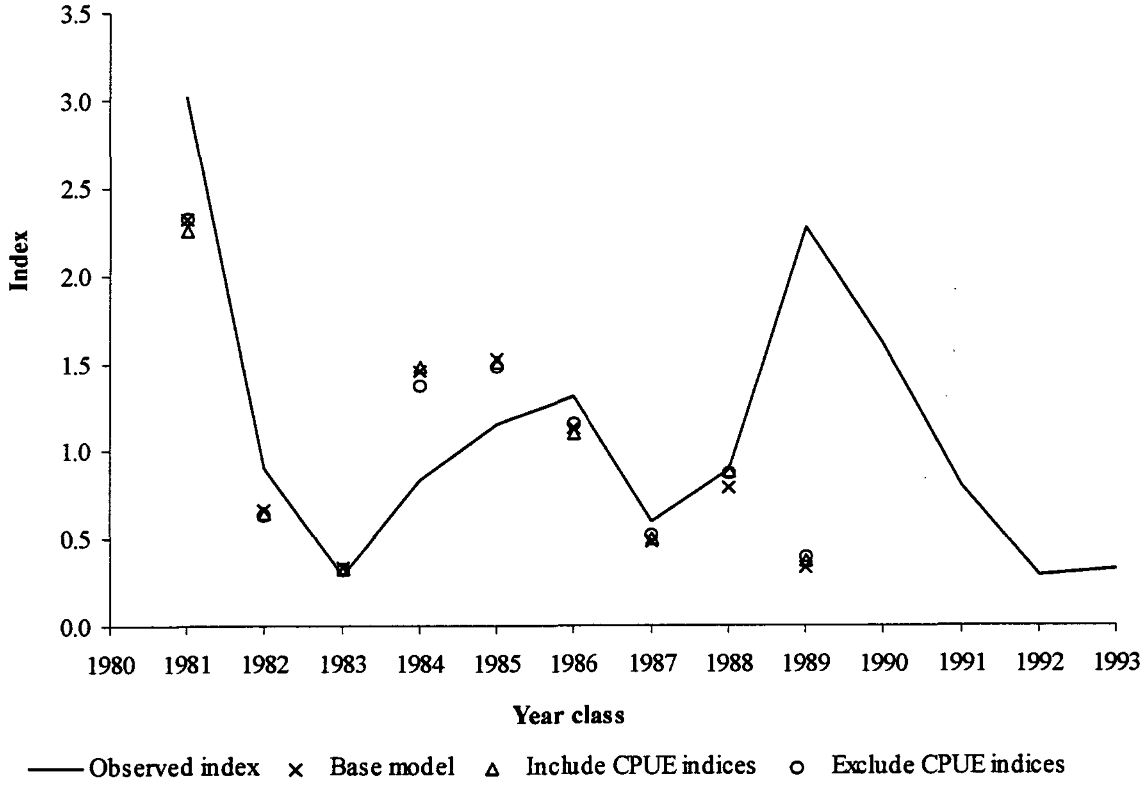

Figure 1: Comparison of model estimated relative recruitment with relative recruitment from the observed recruitment index. The base model is compared with increased weight (in the likelihood calculations) for the CPUE index and with excluding the CPUE index in the likelihood calculation.

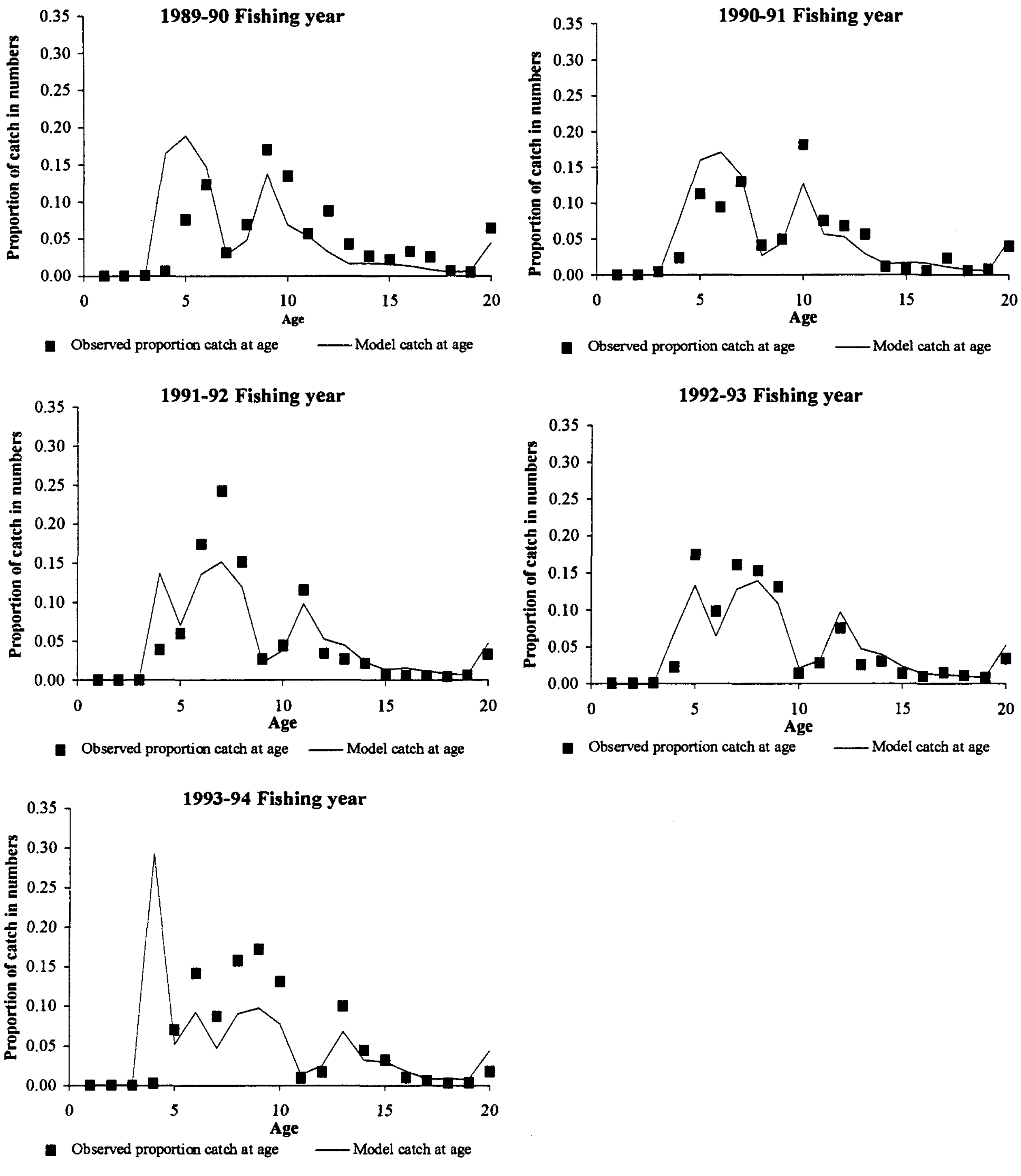

Figure 2: Fit of the proportion of catch at age by fishing year predicted from the base model to the observed Hauraki Gulf longline proportional catch at age data.

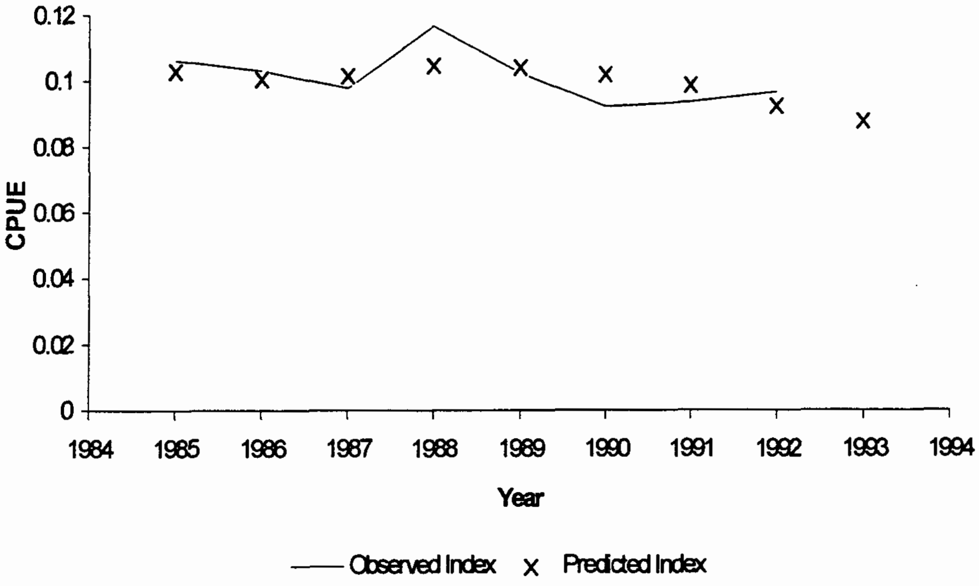

Figure 3: Fit of the observed longline CPUE abundance index to the predicted abundance index using the base model assumptions (equal weight to CPUE indices and proportional catch at age data).

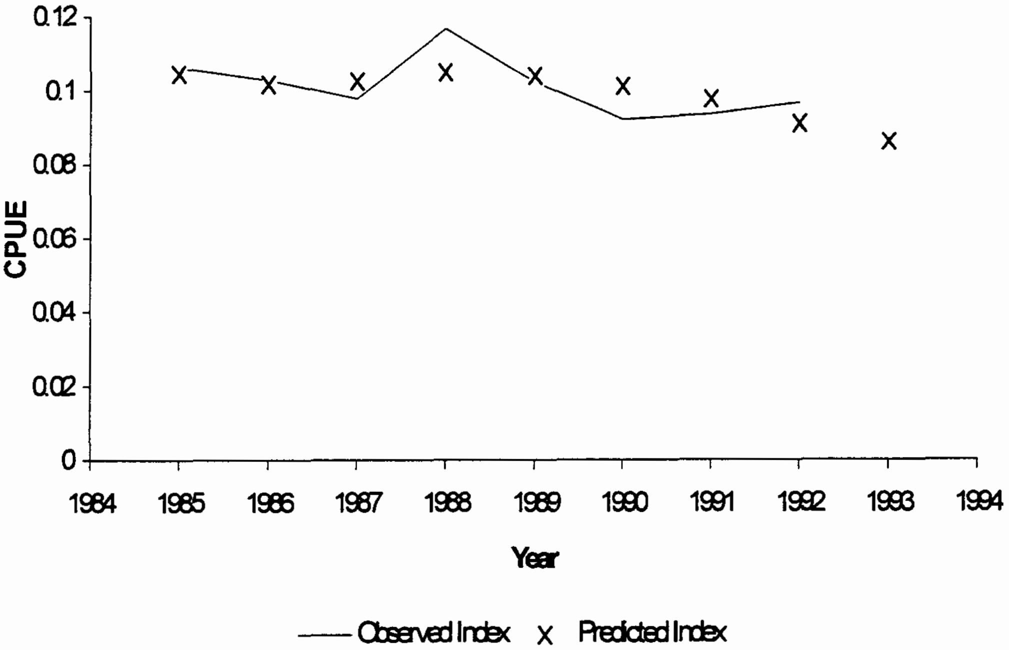

Figure 4: Fit of the observed longline CPUE abundance index to the predicted abundance index with increased weight for CPUE abundance indices.

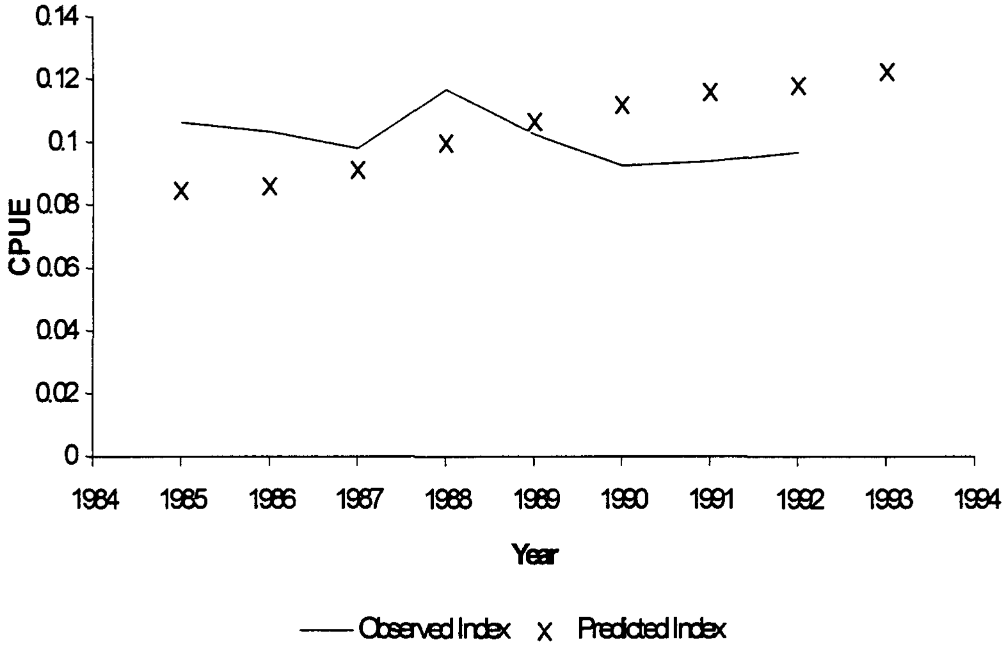

Figure 5: Fit of the observed longline CPUE index to the predicted abundance index when the CPUE abundance index has been excluded from the analysis.

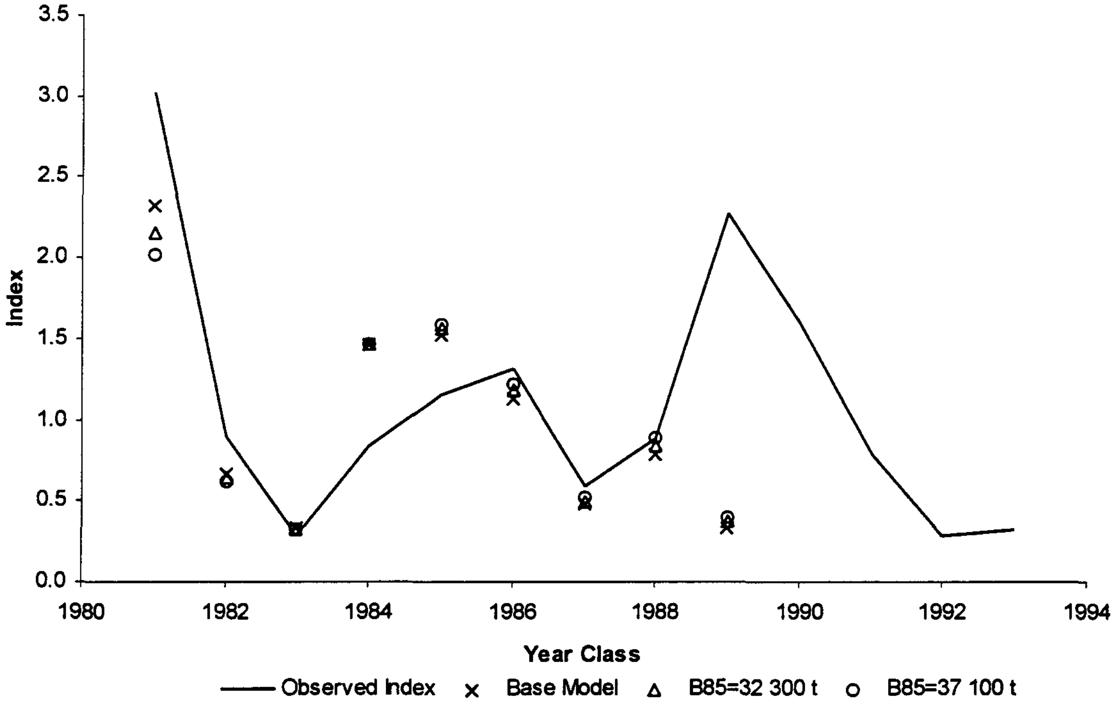

Figure 6: Comparison of model estimated relative recruitment with relative recruitment from the observed recruitment index. These recruitment indices are compared with recruitment indices calculated when using alternative estimates of initial biomass.

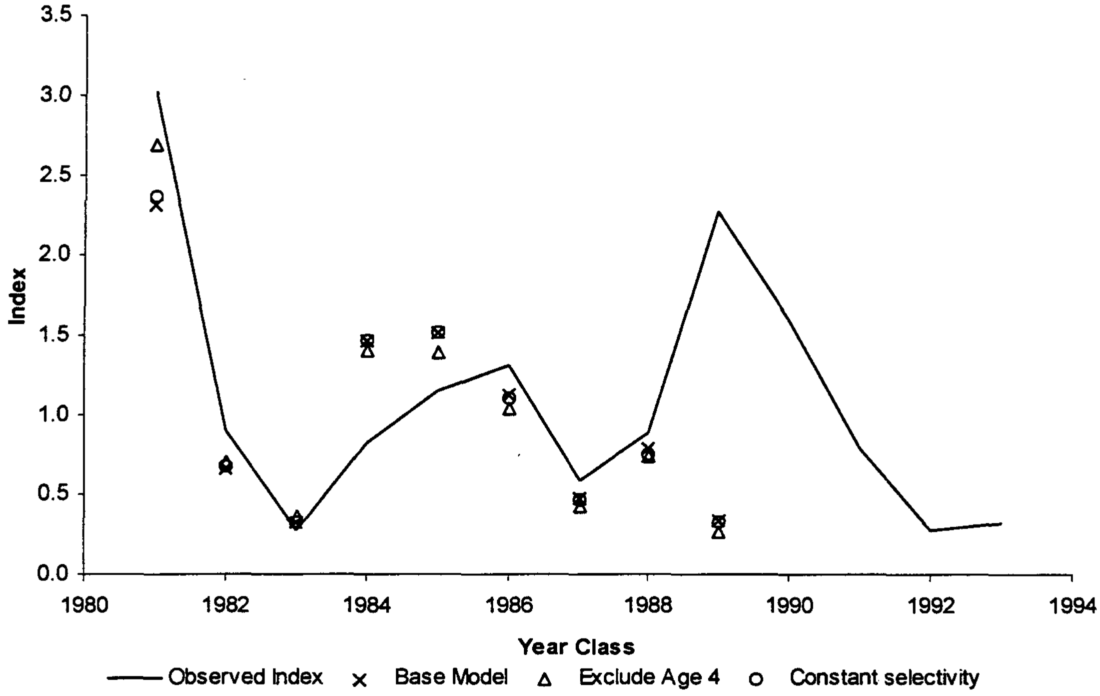

Figure 7: Comparison of model estimated relative recruitment with relative recruitment from the observed recruitment index. These recruitment indices are compared with recruitment indices calculated when using 0 selectivity at age 4 or when using no variation in the selectivity at age.

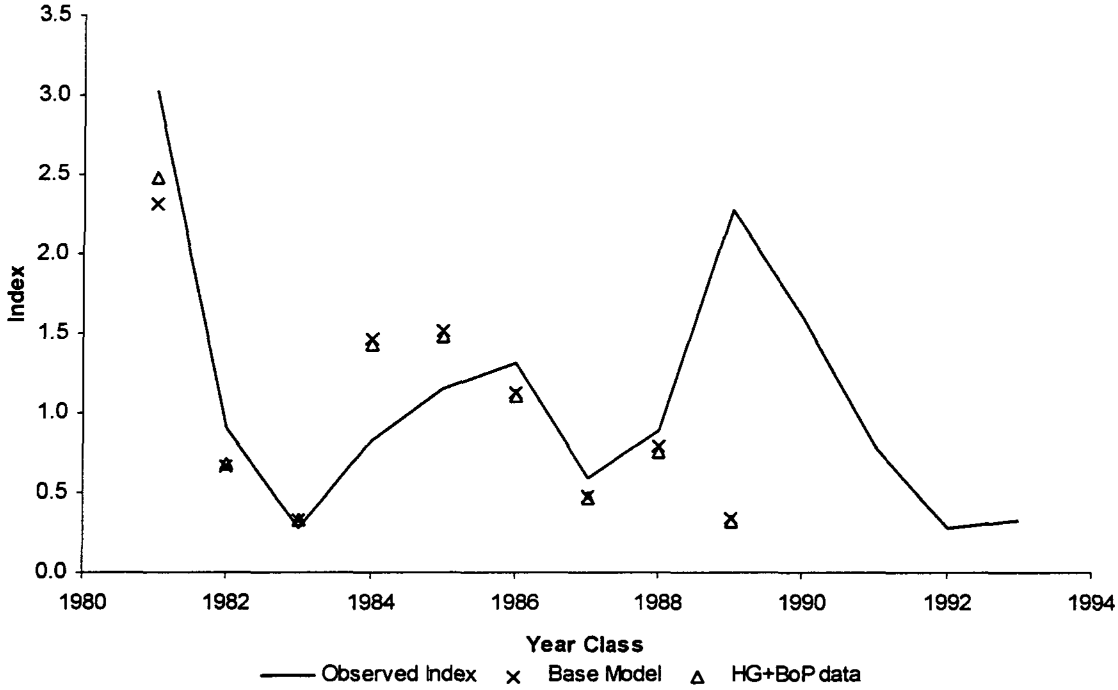

Figure 8: Comparison of model estimated relative recruitment with relative recruitment from the observed recruitment index. These recruitment indices are compared with recruitment indices calculated with a similar model which combines the Hauraki Gulf and Bay of Plenty data.

Appendix 1

Model Equations

A difference equation model (eq. 1.1) that assumes catch is taken in the middle of the year is used (*see* Maunder 1993). This approximates catch and natural mortality occurring simultaneously throughout the year (Gilbert 1986). The model uses method specific selectivities, including recreational catch, and method specific annual harvest rates.

$$N_{y+1,a+1} = N_{y,a}e^{-M} - C_{y,a}\,e^{-0.5M} \qquad \textbf{(1.1)}$$

$$C_{y,a} = \sum_{m=1}^{m_{num}} u_y^m N_{y,a} v_a^m \qquad \textbf{(1.2)}$$

$$u_y^r = \frac{C_y^{*r}}{B_y^r} \qquad \textbf{(1.3)}$$

$$C_y^{*r} = p_y^r C_y^{*c} \qquad \textbf{(1.4)}$$

$$u_y^m = \frac{C_y^{*c} p_y^m}{B_y^m} \qquad \textbf{(1.5)}$$

$$B_y^m = \sum_{a=k}^{a_{max}} N_{y,a} v_a^m w_a \qquad \textbf{(1.6)}$$

$$S_y = \sum_{a=k}^{a_{max}} N_{y,a}\, w_a \qquad \textbf{(1.7)}$$

$$N_{y,1} = R_y \qquad \textbf{(1.8)}$$

where:

$N_{y,a}$ is the number of fish of age a in year y
M is the instantaneous natural mortality rate
$C_{y,a}$ 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
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
S_y is the spawning biomass in year y
R_y is the recruitment at age 1 in numbers in year y
k is the age at recruitment to the fishery and reproduction (= 4 years)
a_{max} is the maximum age in the model (= 50 years)
m_{num} is the number of methods of commercial fishing in the model

Initial Conditions

Initial conditions for ages 5 to 50 were calculated as follows:

$$N_{85,a} = \frac{B_{1985}}{\sum_{a=1}^{a_{\max}} p_a w_a} p_a \tag{1.9}$$

B_{1985} is the total biomass from the 1985 tagging programme in weight
p_a is the proportion at age in numbers from the 1985 tagging programme
(these estimates are used without error)

Parameters Estimated

The parameters estimated are:

$N_{85,2\text{-}4}$ the number of age 1 recruits for the 1981–1983 year classes in numbers scaled by the appropriate level of natural mortality (to complete the initial population in 1985 as it was deemed that the tagging estimate was not reliable for ages less than 5)

$N_{85\text{-}90,1}$ recruitment at age 1 for the 1984 to 1989 year classes

The average recruitment at age 1 for the period was calculated as follows:

$$R_{avg} = \frac{\sum_{y=1981}^{1989} R_y}{(1989 - 1981 + 1)} \tag{1.10}$$

For the purposes of this analysis, this estimate of R_{avg} was used as an estimate of R_0. The virgin biomass (S_0) can then be calculated from R_0 using the procedure given by Francis (1992).

$N_{91\text{-}94,1}$ these recruitments were calculated directly from the temperature-recruitment relationship (Francis 1993) and from R_{avg}

Appendix 2

Fitting Likelihoods

CPUE ABUNDANCE INDICES

The mid year biomass series created by the model is assumed to be linearly related to the longline CPUE abundance indices by a constant of proportionality, q, the catchability coefficient (eq. 2.1).

$$I_y^p = q\frac{1}{2}(B_y^{ll} + B_{y+1}^{ll}) \qquad \textbf{(2.1)}$$

I_y^p is the model predicted CPUE abundance index for year y
q is the catchability coefficient
B_y^{ll} is the start of year biomass vulnerable to longline in year y

The likelihood function used to fit to the time series of longline CPUE abundance indices assumes lognormal observation error:

$$I_y^o = I_y^p \, e^{\varepsilon_y}$$
$$\text{where} \quad \varepsilon_y \sim N(0, \sigma_{CPUE}^2) \qquad \textbf{(2.2)}$$

I_y^o is the observed CPUE abundance index for year y
σ_{CPUE} is the *c.v.* of the CPUE abundance indices

$$L(I_y^o | parameters) = \frac{1}{\sqrt{2\pi}\,\sigma_{CPUE}} \exp\left(-\frac{(\ln(I_y^o) - \ln(I_y^p))^2}{2\sigma_{CPUE}^2}\right) \qquad \textbf{(2.3)}$$

The negative log likelihood is defined as:

$$-\ln(L(\mathbf{I}^o | parameters)) = -\sum_{y=1}^{n_{CPUE}} \ln(L(I_y^o | parameters)) \qquad \textbf{(2.4)}$$

n_{CPUE} is the number of CPUE observations

The estimate of $_{CPUE}$ which maximises the likelihood can be found by setting the derivative of eq. 2.3, with respect to $_{CPUE}$, to equal zero and solving for $_{CPUE}$:

$$\hat{\sigma}_{CPUE} = \sqrt{\frac{\sum_{y=1}^{n_{CPUE}} (\ln(I_y^o) - \ln(I_y^p))^2}{n_{CPUE}}} \tag{2.5}$$

Similarly the value of q which maximises the likelihood can be found:

$$\hat{q} = \exp\left(\frac{\sum_{y=1}^{n_{CPUE}} \ln\left(\frac{I_y^o}{\frac{1}{2}(B_y^{ll} + B_{y+1}^{ll})} \right)}{n_{CPUE}} \right) \tag{2.6}$$

PROPORTION OF CATCH AT AGE

The likelihood function used to fit to the longline proportion of catch at age data assumes lognormal observation error weighted by the coefficients of variation (eq. 2.7 and 2.8).

$$L(P_{y,a}^o \mid parameters) = \frac{1}{\sqrt{2\pi}\sigma_{CA} cv_{y,a}} \exp\left(-\frac{(\ln(P_{y,a}^o) - \ln(P_{y,a}^p))^2}{2(\sigma_{CA} cv_{y,a})^2} \right) \tag{2.7}$$

$$P_{y,a}^p = \frac{C_{y,a}^{ll}}{\sum_{a=1}^{a_{\max}} C_{y,a}^{ll}} \tag{2.8}$$

$C_{y,a}^{ll}$ is the longline commercial catch from the model in numbers of age a individuals in year y.

$cv_{y,a}$ is the coefficient of variation on the catch at age data for age a in year y.

$_{CA}$ is the variance scalar for the catch at age data

$_{CA}$ is estimated as its maximum likelihood estimate (eq. 2.9) only when fitting to catch at age data. This gives a minimum value for $_{CA}$ which incorporates sampling, observation, and process error. This value is then fixed when fitting to both CPUE and catch at age data. This step was required because the *c.v.*s provided for the catch at age data represented only the sampling error, which accounts for only part of the error for these data. These catch at age *c.v.*s are small and caused the catch at age data to be heavily weighted when combined with the CPUE likelihood. Therefore, the above procedure was adopted to estimate the extent of the error of this component in the context of the full model. In effect, this scaled the catch at age data relative to the CPUE data.

$$\hat{\sigma}_{CA} = \sqrt{\frac{\sum_{y=1}^{n_{cay}} \sum_{a=1}^{n_{caa}} \frac{(\ln(P^{o}_{y,a}) - \ln(P^{p}_{y,a}))^2}{cv^2_{y,a}}}{n_{cay} n_{caa}}} \quad , \quad (2.9)$$

n_{cay} is the number of years with catch at age data
n_{caa} is the number of age classes within each year with catch at age data

The negative log likelihood is defined as:

$$-\ln(L(\boldsymbol{P}^{o} | parameters)) = -\sum_{y=1}^{n_{cay}} \sum_{a=1}^{n_{caa}} \ln(L(P^{o}_{y,a} | parameters)) \qquad \textbf{(2.10)}$$

TOTAL LIKELIHOOD

The total negative log likelihood is the sum of the negative log likelihood of the CPUE index and the negative log likelihood of the proportion of catch at age data. The total negative log likelihood is minimised to give the best estimates of the parameters.

Appendix 3

Data

Table 3.1: Biological parameters used in the model (Gilbert & Sullivan 1994)

Natural mortality	M	0.06
Length-weight scalar	a	0.04467
Length-weight exponent	b	2.793
Von Bertalanffy L-infinity	L_{inf}	58.8
Von Bertalanffy K	K	0.102
Von Bertalanffy t_0	t_0	-1.11

Table 3.2: Initial proportion at age in numbers (K.J. Sullivan, *pers. com.*). The original data had 2.5% of the number of fish in a plus-group including all fish of age 30 and older. These have been evenly distributed to the age classes 30–50 in this model

Age	Proportion	Age	Proportion	Age	Proportion	Age	Proportion
≤4	0.218	16	0.011	28	0.007	40	0.001
5	0.190	17	0.009	29	0.004	41	0.001
6	0.162	18	0.005	30	0.001	42	0.001
7	0.089	19	0.003	31	0.001	43	0.001
8	0.046	20	0.003	32	0.001	44	0.001
9	0.049	21	0.004	33	0.001	45	0.001
10	0.043	22	0.007	34	0.001	46	0.001
11	0.032	23	0.005	35	0.001	47	0.001
12	0.024	24	0.006	36	0.001	48	0.001
13	0.016	25	0.005	37	0.001	49	0.001
14	0.019	26	0.004	38	0.001	50	0.001
15	0.011	27	0.001	39	0.001		

Table 3.3: Proportion of commercial catch by gear type for the Hauraki Gulf (K.J. Sullivan, *pers. comm.*)

Year	Longline	Single trawl	Pair trawl	Danish seine	Set net
1984–85	0.398	0.156	0.028	0.316	0.102
1985–86	0.462	0.158	0.007	0.275	0.098
1986–87	0.439	0.267	0.005	0.215	0.074
1987–88	0.486	0.209	0.015	0.213	0.076
1988–89	0.487	0.288	0.000	0.148	0.077
1989–90	0.443	0.298	0.021	0.158	0.081
1990–91	0.402	0.252	0.042	0.234	0.070
1991–92	0.446	0.246	0.000	0.246	0.062
1992–93	0.525	0.207	0.000	0.221	0.047
1993–94	0.525	0.207	0.000	0.221	0.047

Table 3.4: Total catches for the Hauraki Gulf and for the combined Hauraki Gulf Bay of Plenty (K.J. Sullivan, *pers. comm.*) and longline CPUE for SNA 1 (P.J. Starr, unpublished results)

Year	Hauraki Gulf Catch (kg)	Combined Hauraki Gulf & Bay of Plenty Catch (kg)	CPUE
1984–85	3 443 330	4 797 525	0.1061
1985–86	2 985 008	4 312 984	0.1030
1986–87	2 333 296	3 168 624	0.0978
1987–88	3 269 406	3 998 190	0.1166
1988–89	3 580 074	4 489 575	0.1022
1989–90	3 128 562	4 305 414	0.0922
1990–91	3 279 355	4 342 355	0.0936
1991–92	3 931 285	5 150 912	0.0965
1992–93	3 244 748	4 340 800	
1993–94	2 906 000	3 887 000	

Table 3.5: Age specific selectivity by gear type (K.J. Sullivan, *pers. comm.*)

Age	Longline	Single trawl	Pair trawl	Danish seine	Set net	Recreational
4	0.867	1.202	0.843	0.647	0.816	1.154
5	0.924	1.163	0.887	0.746	0.979	1.141
6	0.927	1.086	1.006	0.908	1.058	1.108
7	0.975	1.058	1.028	0.945	1.126	1.107
8	1.000	1.000	1.000	1.000	1.000	1.000
9	1.010	1.027	1.047	0.995	0.752	0.910
10	1.037	0.978	1.022	1.090	0.781	0.871
11	0.944	0.942	1.211	0.936	0.846	0.864
12	1.023	1.019	1.229	1.055	0.685	0.892
13	1.019	0.933	1.177	0.922	0.471	0.628
14	0.975	0.947	1.271	0.698	0.525	0.636
15	1.022	0.897	1.307	0.728	0.553	0.621
16	1.110	0.857	1.181	0.656	0.453	0.516
17	0.931	0.863	1.283	0.830	0.594	0.649
18	0.881	0.918	1.270	0.952	0.788	0.708
19	0.930	0.829	1.455	0.715	0.639	0.587
20	0.978	0.828	1.345	0.630	0.415	0.596
21	0.967	0.784	1.451	0.497	0.322	0.369
22	0.954	0.889	1.318	0.660	0.636	0.665
23	1.053	1.083	1.290	0.634	0.456	0.559
24	0.989	0.921	1.365	0.635	0.433	0.517
25	1.087	0.875	1.477	0.576	0.275	0.451
26	1.087	0.993	1.346	0.740	0.262	0.585
27	1.227	0.743	1.305	0.438	0.327	0.441
28	1.076	0.877	1.488	0.460	0.231	0.377
29	0.967	1.167	1.306	0.689	0.309	0.671
30+	1.047	0.888	1.402	0.533	0.332	0.415

Table 3.6: Observed Hauraki Gulf spring and summer combined long line proportion of catch at age (Davies & Walsh 1995)

Age	1989–90[1]	1990–91[1]	1991–92	1992–93	1993–94
4	0.0062	0.0237	0.0390	0.0224	0.0020
5	0.0758	0.1125	0.0598	0.1740	0.0699
6	0.1230	0.0943	0.1741	0.0979	0.1413
7	0.0318	0.1301	0.2425	0.1606	0.0869
8	0.0695	0.0413	0.1513	0.1527	0.1572
9	0.1703	0.0494	0.0266	0.1311	0.1717
10	0.1341	0.1812	0.0441	0.0135	0.1308
11	0.0569	0.0750	0.1155	0.0278	0.0093
12	0.0873	0.0676	0.0338	0.0748	0.0164
13	0.0424	0.0561	0.0269	0.0252	0.0996
14	0.0267	0.0113	0.0213	0.0295	0.0444
15	0.0220	0.0084	0.0076	0.0131	0.0314
16	0.0329	0.0058	0.0062	0.0096	0.0096
17	0.0258	0.0234	0.0059	0.0146	0.0056
18	0.0068	0.0057	0.0044	0.0108	0.0025
19	0.0050	0.0081	0.0061	0.0085	0.0032
20	0.0638	0.0395	0.0332	0.0334	0.0170

[1] summer only.

Table 3.7: Coefficients of variation for observed proportion of catch at age (Davies & Walsh 1995)

Age	1989–90	1990–91	1991–92	1992–93	1993–94
4	0.36	0.22	0.14	0.27	0.56
5	0.13	0.09	0.13	0.10	0.13
6	0.11	0.11	0.07	0.17	0.11
7	0.25	0.10	0.06	0.12	0.15
8	0.16	0.19	0.08	0.12	0.10
9	0.10	0.18	0.20	0.12	0.10
10	0.12	0.09	0.14	0.37	0.11
11	0.18	0.15	0.08	0.27	0.42
12	0.16	0.19	0.15	0.11	0.31
13	0.19	0.21	0.16	0.17	0.10
14	0.42	0.45	0.17	0.16	0.18
15	0.32	0.62	0.31	0.21	0.20
16	0.23	0.77	0.33	0.27	0.33
17	0.45	0.32	0.34	0.24	0.38
18	0.58	0.73	0.38	0.20	0.45
19	0.75	1.01	0.34	0.21	0.38
20	0.15	0.30	0.13	0.09	0.14