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Growth, mortality, and yield estimates for rig (Mustelus lenticulatus)

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GROWTH, MORTALITY, AND YIELD ESTIMATES FOR RIG (Mustelus lenticulatus)

M.P. Francis and R.I.C.C. Francis

1. INTRODUCTION

In 1988, when the last major stock assessment was carried out for rig, very little information was available on the growth rate of the species (M. Francis 1988a). It was assumed that rig grew very slowly, like many other shark species, and that their natural mortality rate was correspondingly low. The instantaneous natural mortality rate, *M*, was set conservatively at 0.1, and this value was used in the estimation of Maximum Constant Yield (MCY) for east coast South Island (ECSI) and west coast South Island (WCSI) rig stocks (which correspond closely with management stocks SPO3 and SPO7 respectively).

In recent years, a number of techniques have been used to age sharks, usually by examining vertebral growth rings (Cailliet 1990). Attempts were made to age rig using a variety of methods for visualising vertebral rings but results were inconclusive. In the absence of an ageing technique, other methods for estimating rig growth rates have been investigated. In this paper we report growth estimates obtained from length-frequency and tagging data. A detailed analysis of the results has been prepared for publication (Francis & Francis in press). The growth rate estimates reported here are also used, in conjunction with other information, to provide revised estimates of M.

Rig have low fecundity, suggesting that recruitment may be strongly dependent on adult stock size. The effect of such a dependence on the equation used to estimate MCY for SPO3 and SPO7 is explored, and the management implications discussed.

2. GROWTH RATE ESTIMATES

2.1 Introduction

Rig growth rates have been estimated in two previous studies. Jones & Hadfield (1985) followed the growth of newly born rig in Porirua and Pauatahanui Inlets, near Wellington, over a 6 month period in 1983–84 by measuring samples caught by set net.

Holden (1974) developed a method for extrapolating elasmobranch embryonic growth rates to provide estimates of post-embryonic von Bertalanffy growth parameters. Application of this technique to rig produced estimates of the ages at maturity for east coast South Island rig of 2.3–3.9 years for males and 2.6–4.0 years for females (Francis 1981).

In this paper we analyse four data sets to provide improved estimates of rig growth rates: (1) the data set used by Jones & Hadfield (1985) is re-analysed and extended with new measurements of 0+ rig made during 1984–85; (2) length-frequency data of rig trawled in Pegasus Bay in 1983–84 are analysed; (3) length-frequency data of rig trawled in the

Hauraki Gulf in 1964–66 are analysed and the results compared with three other lengthfrequency samples collected from the Hauraki Gulf in 1980–82; and (4) growth rates are estimated for adult rig tagged around the South Island.

2.2 Data

All length measurements are total lengths to the nearest centimetre below actual length; to compensate for this, 0.5 cm was added to mean lengths.

2.2.1 Length-frequency samples of 0+ rig in Porirua and Pauatahanui Inlets, 1983–85

The methods used to collect rig in Porirua and Pauatahanui Inlets in 1983–84 were described by Jones & Hadfield (1985). Set nets of five different mesh sizes (62, 90, 118, 137, and 157 mm) were used, so despite the fact that set nets are size-selective (Kirkwood & Walker 1986), it is likely that the juvenile population was adequately sampled. In 1984–85, rig were caught as described by Jones and Hadfield (1985), except that only 62, 90, and 118 mm mesh nets were used, and only Porirua Inlet was sampled. 0+ rig were easily identified by the umbilical scar between their pectoral fins. Apart from 0+ rig, only adults greater than 75 cm long were caught.

2.2.2 Length-frequency samples of rig trawled in Pegasus Bay, 1983–84

Rig were collected from Pegasus Bay during four cruises by the research trawlers *Kaharoa* and *James Cook*. Fine mesh codends or codend liners of 15–50 mm mesh were used to retain all juvenile rig. Length data were grouped into 2 cm class intervals before analysis.

2.2.3 Length-frequency samples of rig trawled and set netted in the Hauraki Gulf, 1964-66 and 1980-82

Rig were collected from the Hauraki Gulf during eight cruises in 1964–66 by *Ikatere* using 25–32 mm mesh codend liners. Length data were grouped into 2 cm class intervals before analysis.

Three length-frequency data sets were available for comparison with the 1964–66 series. Between January 1980 and March 1981, the Auckland Regional Authority carried out a set net survey of the upper Waitemata Harbour using eight mesh sizes in the range 25–140 mm. During two of the sampling periods (January-February 1980 and March 1981) significant numbers of juvenile rig were caught and measured; those results are reported here. The third data set was obtained from catches made by *Kaharoa* in the Hauraki Gulf in May-June 1982, using 35–38 mm mesh codends.

2.2.4 Tagging data, 1982–84

During 1982–84, 1873 rig were tagged around the South Island. The objectives of that study were to examine movement patterns and exploitation rates. M. Francis (1988b, 1989) provided further details of the tagging methods.

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All rig were measured at tagging. Estimation of growth rates was not an objective, and no special effort was made to encourage fishers to measure recaptured rig, or return the whole fish for measurement by MAF Fisheries staff. However, a considerable number of recaptured rig were measured, and growth information derived from those measurements is presented here. A major disadvantage is that re-measurement methods were far from standard: some measurements were obviously estimates, many had to be converted from inches to centimetres, and they were variously made on live, freshly dead, and frozen and thawed rig. Measurements that were obviously imprecise (e.g., "three feet", "one metre") were discarded, but measurements that appeared precise were included in the analysis even if they were highly improbable (e.g., measurements that implied shrinkage of 10 - 30 cm).

2.3 Analysis

2.3.1 Length-frequency data

Von Bertalanffy growth curves were fitted to the Pegasus Bay and Hauraki Gulf lengthfrequency distributions using the MULTIFAN model, version 2 (Fournier et al. 1990). This model simultaneously analyses multiple sets of length-frequency samples using a maximum likelihood method to estimate the proportions of fish in each age class, and the von Bertalanffy parameters. 1 September was chosen as the nominal birth date.

The main assumptions of the MULTIFAN model are: (1) the lengths of the fish in each age class are normally distributed around their mean length; (2) the mean lengths at age lie on or near a von Bertalanffy growth curve; (3) the standard deviations of the actual lengths about the mean length at age are a simple function of the mean length at age (Fournier et al. 1990). Details of the fitting of the MULTIFAN model are provided by Fournier et al. (1990) and Francis & Francis (in press).

Four models, based on different growth hypotheses, were fitted to the data: (1) constant length standard deviation across all age classes; (2) variable standard deviation across age classes; (3) constant standard deviation, plus seasonal growth; and (4) variable standard deviation plus seasonal growth.

Separate MULTIFAN analyses were carried out for males, females, and both sexes combined. In the first Hauraki Gulf sample (September 1964), 0+ rig were not sexed (n = 21), and they were included in all three analyses.

2.3.2 Tagging data

Growth estimates were obtained from the tagging data using the maximum likelihood method and computer program GROTAG of R. Francis (1988a). With the initial data set (130 fish: 44 females and 86 males) the proportion of outliers estimated by GROTAG was 0.15. Though outliers have little effect on the parameter estimates, they do compromise the significance testing (R. Francis 1988a); 16 outliers (3 females and 13 males) were removed from the data.

Differences in growth rate by sex and by stock were investigated. For the latter, rig were assigned to ECSI or WCSI stocks on the basis of release locality.

2.3.3 Significance testing

For the analyses of both the length-frequency and tagging data sets, the procedure was to start by fitting a simple model, and then to gradually increase its complexity by introducing additional parameters (e.g., parameters to allow seasonal variation in growth). At each stage, new parameter estimates were made. The introduction of additional parameters will always improve the fit (or at least not make it worse). The problem is to test whether such an improvement in fit is statistically significant. Since both MULTIFAN and GROTAG use likelihood methods this test can be done as a likelihood ratio test. Specifically, we assume that, under the null hypothesis, the model without the additional parameters is correct. Twice the increase in log-likelihood is distributed as a χ^2 distribution with degrees of freedom equal to the number of additional parameters (Kendall & Stuart 1967).

Following Fournier et al. (1990) we have used a significance level of 0.10 for testing whether there is any gain in introducing an additional age class in the length-frequency analyses. All other tests (for both length-frequency and tagging data analyses) were carried out with the more usual significance level of 0.05.

2.4 Results

2.4.1 Length-frequency samples of 0+ rig in Porirua and Pauatahanui Inlets, 1983–85

Growth of Pauatahanui juveniles was almost linear between December 1983 and April 1984, after which no increase was detected (Fig. 1). At the end of May, Pauatahanui rig averaged 49 cm. Rig caught in Porirua Inlet in March 1984 had mean lengths similar to those in Pauatahanui (Fig. 1). However, by April-May, Porirua rig were slightly shorter than Pauatahanui rig, averaging about 46 cm.

Rig caught in Porirua Inlet during the 1984–85 summer were 3–4 cm longer than Porirua and Pauatahanui rig at the corresponding times in 1983–84 (Fig. 1). Otherwise growth was very similar between years.

2.4.2 Length-frequency samples of rig trawled in Pegasus Bay, 1983–84

Most of the rig caught (70% over all samples) were males. Rig from the ECSI stock had mean lengths at maturity of 87 cm (males) and 102 cm (females) (M. Francis, unpubl. data). Only two females longer than 102 cm were caught, and 96% of the 209 rig longer than 87 cm were males.

The results of the MULTIFAN models are presented in Figs 2 and 3 and Table 1. For both sexes combined, and males alone, constant standard deviation and seasonal growth with seven age classes provided the best fit. The two growth curves were practically identical, reflecting the lack of adult females in the samples (Fig. 3). For females, only five age classes were discriminated, and the best fit had variable standard deviation and seasonal growth. The female growth curve was virtually the same as for males over the age range 1.5–3 years, but showed increasing divergence towards the limits of the data

(Fig. 3). All three growth curves had strong seasonal components with maximum growth in spring and minimum growth in autumn.

If the Pegasus Bay male MULTIFAN model adequately represents ECSI male growth to maturity, their estimated age at maturity (length 87 cm) is 5.0 years. Female age at maturity (length 102 cm) cannot be estimated from the MULTIFAN curve because this would involve extrapolation well beyond the limits of the data.

2.4.3 Length-frequency samples of rig trawled and set netted in the Hauraki Gulf, 1964-66 and 1980-82

Similar numbers of large males and females were present in the Hauraki Gulf samples.

The results of the MULTIFAN models for the 1964–66 data are presented in Figs 3 and 4 and Table 2. For both sexes combined, variable standard deviation with seven age classes provided the best fit. For males, variable standard deviation and seasonal growth with eight age classes provided the best fit. For females, variable standard deviation with six age classes provided the best fit. All three growth curves were similar (Fig. 3).

Length-frequency histograms for rig netted in 1980–82 are shown in Fig. 5. Major 0+ modes occurred in the Waitemata Harbour set net samples at 34–42 cm (January-February 1980) and 38–46 cm (March 1981). The 0+ mode in the Hauraki Gulf trawl sample was at 46–52 cm (May-June 1982). It should be noted that the 0+ modes in these three histograms represent three different year classes. 0+ rig were considerably longer in May-June 1982 than at the equivalent times in 1965 (modes at 38–46 cm in May and 42–48 cm in June-July) (Figs 4, 5).

Only sparse data on length at maturity are available for Hauraki Gulf rig. Maturity status was determined for a few rig caught by *James Cook* in 1973. The smallest mature male was 69 cm and the largest immature male was 74 cm, with seven rig in the range of overlap. The smallest mature female was 80 cm and the largest immature female was 84 cm, with five rig in the range of overlap (L.J. Paul, Fisheries Research Centre, Wellington, pers. comm.). These data suggest that males mature at about 72 cm and females at about 82 cm, corresponding with approximate ages from MULTIFAN growth curves of 3.7 and 4.7 years, respectively.

2.4.4 Tagging data, 1982–84

Most recaptured rig (90%) were at liberty less than 3 years. The longest periods at liberty were 9.0 years for males and 6.8 years for females. At the time of analysis of the data, the longest periods at liberty for rig that were **re-measured on recapture** were 6.0 and 4.9 years for males and females respectively.

In the best GROTAG model fit, the expected annual growth increment was greater for females than males, but the difference declined with increasing length: females grew 60% faster than males at 70 cm, but only 46% faster at 100 cm. Rig that were 70 cm long at tagging would be expected to reach lengths of 93.5 cm (females) and 86.1 cm (males) after 5 years at liberty. No significant difference was found between growth rates in the

ECSI and WCSI stocks, but recapture sample sizes were small and confidence limits were large.

2.5 Discussion

There is considerable variability in the mean length of the 0+ age class at a given time of year. Porirua rig were longer in 1984–85 than both Porirua and Pauatahanui rig in 1983–84. Also, the poor fit of the von Bertalanffy growth curve to the 1+/2+ age class in the 1964–66 Hauraki Gulf combined sexes data (Fig. 4) suggests that there are inter-annual differences in the length of rig on a given date. In the Hauraki Gulf, 0+ rig were longer in the 1980–82 samples than at the corresponding times in 1965. These differences could be due to (1) variable length at birth; (2) variable date of birth; (3) variable growth before the first samples were obtained; (4) for the Hauraki Gulf data, density-dependent change in growth rate following a reduction in rig abundance between 1964–66 and 1980–82; or some combination of these.

The growth curves generated by MULTIFAN models must be used cautiously. Sample sizes were frequently small, and adult females were not represented in the Pegasus Bay samples. Samples from both Pegasus Bay and Hauraki Gulf were probably biased towards smaller rig, because large rig are able to avoid trawl nets. ECSI male rig grow to at least 119 cm (Massey & Francis 1989), and Hauraki Gulf rig grow to at least 118 cm (L.J. Paul, unpubl. data), but only one rig longer than 110 cm was caught in each set of samples.

If large adults evade capture, the mean lengths of the older age groups will be underestimated, L_{∞} will be too low and K will be too high. This bias probably affects all the MULTIFAN growth curves, particularly the Pegasus Bay female curve. Biased samples may also result from mesh selectivity, especially for set net samples (Kirkwood & Walker 1986), and the tendency of rig to segregate by size and sex (Francis & Smith 1988).

The MULTIFAN models discriminated only five to eight age classes in the lengthfrequency data. Alternative estimates of ECSI and WCSI male rig life span were obtained by estimating their age at tagging from the Pegasus Bay male MULTIFAN curve in Fig. 3, and then adding their time at liberty (Table 3). Male life span in these stocks probably exceeds 13 years. A female tagged at a length of 103 cm remained at liberty for 6.8 years, suggesting that female life span is at least as high as that of males. Our estimates of life span are likely to be minima, because rig tags are still being returned.

GROTAG models detected no difference in growth rate between ECSI and WCSI stocks. Male and female WCSI rig are shorter at maturity than ECSI rig (Francis & Mace 1980) suggesting that they mature at younger ages.

The comparison of growth rates derived from length-frequency and tagging data is not straightforward. The former type of data produces the same growth information as age-length data, i.e., estimates of the expected growth of fish of a given **age**. Growth estimates from tagging data describe the expected growth of fish of a given **length** (unless, of course, the recaptured fish have been aged). R. Francis (1988b) pointed out that these

different types of growth (age-based and length-based) are not directly comparable and suggested that the best that can be done to compare them is via a graph such as Fig. 6.

MULTIFAN and GROTAG growth rate estimates are based mainly on small and large rig respectively, with overlap only in the 70-90 cm length range (Fig. 6). Furthermore, the only data set pair not affected by temporal or geographical separation, or sex, is the Pegasus Bay male MULTIFAN estimate and the GROTAG male estimate (since the tagging programme and length-frequency data collection coincided in time, and the tagging area encompassed Pegasus Bay). Annual growth increments estimated from lengthfrequency data were 2.7 to 3.3 times greater than those estimated from tagging data (Fig. 6). Such a large difference can not be explained by the difference between age- and length-based growth, nor by poor fit of the MULTIFAN model to the data, so we regard the difference as significant. There are at least three possible explanations. First, regional differences may occur within the South Island area covered by the tagging programme. This seems unlikely given that GROTAG found no differences between the WCSI and ECSI stocks. Second, tagging may have a negative effect on growth rates. Negative, zero, and reduced growth increments of tagged sharks have been reported frequently, and only some of this is attributable to measurement error; there is clear evidence that the growth rates of several species of sharks have been reduced by tagging (Ketchen 1975, Gruber 1981, Davenport & Stevens 1988, Stevens 1990). Third, set net mesh selectivity may bias the growth estimates; e.g., large fast-growing fish of a given age class may be undersampled relative to small slow-growing fish. In a study of tagged Mustelus antarcticus. Dow & Walker (1989) found that growth rate estimates increased by 13-14% at a length of 80 cm and 33-84% at 120 cm after correcting for mesh selectivity. In our study, most of the rig were recaptured by the set net fishery. Thus tagging effects and mesh selectivity may account for the discrepancy we observed between length-frequency and tagging growth estimates.

Growth estimates derived from both MULTIFAN and GROTAG analyses appear to suffer serious biases. In the length-frequency samples, immature rig are more likely to have been sampled representatively than adults, so if the von Bertalanffy growth curve fits the data well, reliable estimates of juvenile growth are possible from the MULTIFAN analyses. This suggests that estimates of age at maturity are likely to be unbiased.

Hauraki Gulf females mature 1 year later than Gulf males, and Gulf males mature younger than Pegasus Bay males (Table 4). The estimated age at maturity of Pegasus Bay males (5.0 years) is greater than the 2.3–3.9 years estimated by Francis (1981) using Holden's (1974) embryonic growth extrapolation technique, indicating that post-embryonic growth is slower than embryonic growth.

Ageing studies on other *Mustelus* species show that females mature at about the same age or somewhat later than males (Table 4). Pegasus Bay male rig mature at a similar age to males of the closely-related Australian *M. antarcticus* (Table 4). If Pegasus Bay female rig show the same close correspondence with female *M. antarcticus*, an age at maturity of about 7 years is indicated.

Growth curves for rig derived from MULTIFAN models fall within the range of curves for other species of *Mustelus* (Fig. 7). Moulton et al. (1991) presented estimates of the

mean lengths of *M. antarcticus* at ages 3, 7, and 11 years for South Australia and Bass Strait over two time periods. Length-at-age estimates were at the upper end of the range shown in Fig. 7, and straddled the growth curve for female *M. californicus* (curve 5). The male-female pairs of growth curves for *Mustelus* species other than rig show that the two sexes grow at nearly identical rates for the first 2–4 years of life, after which females grow faster than males. In most, if not all, species of *Mustelus*, females also grow larger and live longer than males (Francis 1981, Table 4, references in Table 4).

3. MORTALITY RATE

3.1 Introduction

The instantaneous natural mortality rate, M, is one of the hardest biological parameters to estimate. We have no information which will allow us to determine M precisely. However, a number of techniques exist which may indicate the likely magnitude of M. Four such techniques are applied to rig in this section, and results are summarised in Table 5.

3.2 Mortality rate estimates based on rig life span

Hoenig (1983) compared published estimates of mortality rate and life span for fishes, cetaceans, and molluscs. He found a significant negative relationship between the two variables that explained (for fishes) 68% of the variability in *M*. Minimum life span for **male** rig is 13 years. Because tagged rig are still being returned, and females probably live longer than males, life span in this stock is likely to exceed 15 years. Life span in other *Mustelus* species is not known to exceed 16 years (Table 4). However, many of the estimates in Table 4 were based on small samples from fished populations, suggesting that they too underestimate actual life span. The likely life span of rig is 15–20 years.

Using Hoenig's (1983) fish regression¹, and life spans of 15–20 years, M is estimated to be in the range 0.21–0.28. Recent rig stock assessments have used M = 0.1. Rig would have to live to 40 years to produce a value of M as low as 0.1.

M is frequently estimated using the "rule of thumb" equation $M = \log_e 100/(\text{life span})$ (Annala 1992). This rule is based on Hoenig's suggestion that life span be taken as the age reached by 1% of the population. Using this rule, life spans of 15–20 years produce *M* values in the range 0.23–0.31.

3.3 Mortality rate estimates based on growth parameters and water temperature.

Pauly (1980) examined the relationship between reported values of M, the von Bertalanffy growth parameters K and L_{∞} , and the "mean annual temperature at the position where the

¹ $\log_e M = 1.46 - 1.01 \log_e(t_{max})$

fish were caught". He obtained a multiple regression relationship² that explained 72% of the variability in M.

Rig occur all round New Zealand, and therefore experience a wide range of mean temperatures. However, growth parameters are known only for Pegasus Bay and Hauraki Gulf rig. Mean annual temperatures of 13 and 18 °C were used for Pegasus Bay and Hauraki Gulf respectively, based on Lyttelton and Auckland recordings (Greig et al. 1988).

Using Pauly's (1980) regression and the growth parameters in Tables 1 and 2, M was estimated to be 0.19 and 0.51 for Pegasus Bay males and females, and 0.30 and 0.61 for Hauraki Gulf males and females, respectively.

These estimates are based on biased growth parameters, because of the escapement of large rig from the trawl samples. In both Pegasus Bay and the Hauraki Gulf, MULTIFAN discriminated fewer age classes of females than males, and L_{∞} for females was much lower than for males (Tables 1, 2). Females grow longer and probably older than males, so the female growth curves are almost certainly less reliable than those for males. Consequently the *M* estimates for females (0.51 and 0.61) are considered to be too high.

3.4 Mortality rate estimate based on population replacement rate

Holden (1974) suggested a method for estimating the average mortality rate of sharks **over their whole life span**. The basic premise of the method is that female sharks must produce enough female young during their reproductive years to replace themselves. If the average total production of female young per adult female is known, the mortality rate required to balance female numbers between generations can be calculated. Additional data required for the calculation are female age at maturity and maximum age.

None of the required input data are known for rig, so some assumptions and approximations are necessary. If we assume that the population age structure is stationary over time, the mean number of young produced per female in a given year will be the same as the mean number produced by a female over its whole lifetime. The age structure of a population will only be stationary if mortality and recruitment are constant through time.

Francis & Mace (1980) obtained rig samples from set nets at Kaikoura and Nelson in 1977–79 and 1978–80 respectively. At these times, intensive set net fisheries for rig had been operating for about 2 years (Francis & Smith 1988), suggesting that the age structure may have been altered to some extent by an increase in fishing mortality. Also, the samples were probably not representative of the populations because of the size selectivity of set nets. Both small and large females would have been under-represented. Recruitment variability is probably low because of the low fecundity of rig.

² $\log_{10}M = -0.0066 - 0.279 \log_{10}L_{\infty} + 0.6543 \log_{10}K + 0.4634 \log_{10}T$

The mean numbers of ovulated eggs or embryos per female were 10.7 at both Kaikoura and Nelson. Since not all eggs develop into embryos, mean production was rounded down to 10 young, of which five are females (since embryos have a 1:1 sex ratio).

If the age at 50% maturity of Pegasus Bay females is assumed to be 7 years, and maximum age 15–20 years, Z is estimated from Holden's equation³ to be 0.37. (At this level of Z, uncertainty in the maximum age has a negligible effect on the estimate.) Because high fishing mortality had operated on the fishery for only about 2 years, Z is comprised mostly of natural mortality, M.

This estimate refers to the whole life of rig (Holden 1974), and because juvenile mortality is likely to be higher than adult mortality (through higher predation) the estimate of M provides an upper limit to the likely natural mortality of the exploited portion of the population.

3.5 Mortality rate estimates for *Mustelus antarcticus*

In southern Australia there is a substantial fishery for *Mustelus antarcticus*. This species is very closely related to New Zealand rig, differing mainly in the size of its fins and vertebral numbers. Unlike rig, the Australian species has been aged using vertebral ring counts, and has a similar life span to rig (Table 4). Estimates of *M* for *M. antarcticus* have been made using a Paloheimo model applied to cohort analysis (which requires age-frequency data from the commercial catch), and recaptures from a tagging programme. Estimates were 0.20 and 0.28 (Dow 1986a, b) respectively.

3.6 Discussion

Estimates of M for rig ranged from 0.19 to 0.61 (Table 5). However, if the high values based on biased growth parameters are omitted the range becomes 0.19 to less than 0.37. Considering the *ad hoc* methods used, and the necessary assumptions and approximations, the results of the three methods are surprisingly consistent. A range of 0.2–0.3 appears most likely for M. It seems highly unlikely that M is as low as the value of 0.1 used previously to estimate MCY for the WCSI and ECSI stocks.

The fact that M estimates for the closely related M. antarcticus fall within the same range as those for rig provides additional support for the latter.

4. **YIELD ESTIMATES**

4.1 Introduction

The growth and mortality rate estimates enable us to carry out yield per recruit analyses, and re-assess previous MCY estimates for SPO3 and SPO7. Growth and mortality

³ $Z = Y \exp(-Z t_m) \{1 - \exp[-Z(t_{max} - t_m)]\}$ where Y is the average number of female young produced, t_{max} is the maximum age, and t_m is the age at 50% maturity.

parameters used in this section are summarised in Table 6. In compiling this table we have assumed that (1) the von Bertalanffy growth curves derived for Hauraki Gulf and Pegasus Bay rig apply generally to the SPO1 and SPO3 rig stocks respectively; (2) rig recruit at age 5 in both stocks; and (3) male and female weight-length relationships for SPO3 rig apply also to SPO1 rig. Note that the bias in the von Bertalanffy parameters discussed in section 2.5 will lead to bias in estimates of MCY and F given below.

4.2 Yield per recruit

Estimates of $F_{0,I}$ for both sexes combined for SPO1 and SPO3 were derived from yield per recruit analyses using M values of 0.2 and 0.3. Results are given in Table 7.

4.3 Estimation of Maximum Constant Yield (MCY) for SPO3

MCY for SPO3 was estimated using the Monte Carlo simulation method of Francis (1992). This involved simulating fishing for long periods of time with constant catch, and repeating the process for a range of target catch levels (expressed as percentages of B_0 , the mean recruited biomass of the virgin stock). MCY is defined as the lesser of two target catch levels: the target catch that produces the maximum mean catch, and the maximum safe target catch (i.e., that which maintains the spawning stock biomass above 20% of its mean virgin level at least 90% of the time).

Two stock-recruit parameters are required for this analysis: the steepness of the stock-recruit relationship (defined as the fraction of the mean virgin recruitment that is, on the average, produced when the spawning stock is reduced to 20% of its mean virgin level), and $\sigma_{\rm R}$, the standard deviation of the natural logarithm of recruitment.

We have no stock-recruitment data for rig, and we are not aware of any published stockrecruitment relationships for any other elasmobranch. Nevertheless, some inferences can be made from their reproductive biology. Elasmobranchs produce few large young, and their recruitment probably depends strongly on adult stock size at small to moderate stock sizes (Anderson 1990, Hoenig & Gruber 1990). In female rig, fecundity increases exponentially with length (Francis & Mace 1980) and perhaps linearly with age. This indicates that recruitment may also be affected by the age-structure of the population, which in turn is affected by the size of the stock. For example, a heavily fished population will tend to have a high proportion of young females which have a low reproductive output.

For these reasons we have used steepness values of 0.35 and 0.50, on the basis that the steepness for rig is likely to be at the bottom end, or lower, of the range of values considered by Francis (1992) to be plausible for teleosts (0.50 to 0.95). Similarly, $\sigma_R = 0.4$ was chosen, being the lowest value used by Francis (1992). (Since MCY depends much more strongly on steepness than on σ_R , it was not felt necessary to use more than one value of the latter parameter.)

The ability of a population to withstand harvesting depends on the strength of a number of compensatory mechanisms. For example, under exploitation individuals may grow faster, mature earlier, show increased fecundity, or suffer reduced natural mortality at some stages of life. However, in the simple population model used in these simulations,

compensation appears in only one parameter - steepness. Thus the low steepness values used here may be thought of as representing weak compensation in general. They are consistent with the principle that elasmobranchs in general have weak compensatory mechanisms (Anderson 1990, Hoenig & Gruber 1990).

Age at maturity was assumed equal to age at recruitment, both being set to 5 years.

Results of the MCY simulations are shown in Fig. 8 and Table 8. Note that the maximum safe target catch is usually close to the target catch that maximises the mean catch (Fig. 8). These results show that the rules:

$$MCY = 0.25 * F_{o,l} * B_o \text{ and } MCY = 0.25 * M * B_o$$
(1)

for calculating MCY are not safe for use with SPO3. For example, with M = 0.2, these rules would imply MCY = 5.5% B_0 or 5.0% B_0 respectively, levels of harvesting that are unsustainable for this stock (Fig. 8). Similarly, with M = 0.3, equations (1) lead to MCY = 9.25% B_0 or 7.5% B_0 respectively, which are also unsustainable (Fig. 8). This conclusion depends mostly on the low steepness values used (Francis 1992). Thus we assume that equations (1) are unsafe for any rig stock, and probably for any elasmobranch.

Because we have no estimate of B_0 for any rig stock, the results of Table 8 do not allow us to provide absolute estimates of MCY. Further, these results invalidate previous estimates of MCY for SPO3 and SPO7 because they were based on the equations

$$MCY = 0.5*F_{0,l}*B_{av} \text{ and } MCY = 0.5*M*B_{av}$$
(2)

which derive from equations (1) (together with the assumption that, over the period that B_{av} is calculated, the biomass is likely to have been at about half the virgin level). Because equations (1) are unsafe for rig, it must be assumed that equations (2) are also unsafe.

4.4 Estimation of F_{CAY} for SPO3

The lack of current biomass estimates makes it impossible to estimate Current Annual Yield (CAY) for any rig stocks. However, it is of interest to estimate, for one stock (SPO3), the fishing mortality, F_{CAY} , that should be used to calculate CAY. This was done using the same simulation method as above except that fishing was simulated with constant F, rather than with constant catch. F_{CAY} is defined in a way analogous to the definition of MCY in section 4.3: F_{CAY} is the lesser of two fishing mortalities, that which produces the maximum mean catch, and the maximum safe fishing mortality.

For all combinations of M and steepness, the F that produces the maximum mean catch is between two-thirds and three-quarters of the maximum safe F (Fig. 9). For this stock (and, by extension, for other rig stocks) M and $F_{0.1}$ are almost always unsafe harvesting levels (Fig. 9), and are always greater than F_{CAY} (Table 8).

4.5 Sensitivity of MCY and F_{CAY} to growth parameters

The estimates of MCY and F_{CAY} for SPO3 were insensitive to changes in the growth parameters. For M = 0.2 and steepness = 0.5, the calculations of sections 4.3 and 4.4 were repeated with two alternative sets of growth parameters obtained by: (1) increasing L_{∞} and decreasing K by one standard error; and (2) decreasing L_{∞} and increasing K by one standard error (using parameter values and standard errors from Table 1). (L_{∞} and K were changed in opposite directions because their estimates are always highly negatively correlated.) The resulting changes in MCY and F_{CAY} were always less than 3%.

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6. **REFERENCES**

- Anderson, E.D. 1990: Fisheries models as applied to elasmobranch fisheries. NOAA Technical Report NMFS 90: 473-484.
- Annala, J.H. (Comp.) 1992: Report from the Fishery Assessment Plenary, May 1992: stock assessments and yield estimates. 222 p. (Unpublished report held in MAF Fisheries Greta Point library, Wellington.)
- Cailliet, G.M. 1990: Elasmobranch age determination and verification: an updated review. NOAA Technical Report NMFS 90: 157-165.
- Compagno, L.J.V. 1984: FAO species catalogue. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. Part 2. Carcharhiniformes. FAO Fisheries Synopsis 125, vol. 4: 251-655.
- Davenport, S. & Stevens, J.D. 1988: Age and growth of two commercially important sharks (*Carcharhinus tilstoni* and *C. sorrah*) from northern Australia. *Australian Journal of Marine and Freshwater Research* 39: 417-433.
- Dow, N.G. 1986a: Application of an extended Paloheimo model to cohort analysis for gummy shark, Mustelus antarcticus Günther, from the southern Australian shark fishery during 1971-83. Background paper, Third Southern Shark Assessment Workshop, Department of Conservation, Forests and Lands, Melbourne.
- Dow, N.G. 1986b: Application of two tag-recapture models to gummy shark, *Mustelus* antarcticus Günther, and school shark, *Galeorhinus galeus* (Linnaeus), from the southern Australian shark fishery. *Background paper*, *Third Southern Shark Assessment* Workshop, Department of Conservation, Forests and Lands, Melbourne.
- Dow, N.G. & Walker, T.I. 1989: Growth parameter estimation from tagging and ageing data in a length-selective fishery. In: Southern shark assessment project final FIRTA report: March 1989. Part A. Victoria Department of Conservation, Forests and Lands, Fisheries Division Internal Report 175a.
- Fournier, D.A., Sibert, J.R., Majkowski, J., & Hampton, J. 1990: MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Canadian Journal of Fisheries and Aquatic Science 47: 301-317.
- Francis, M.P. 1979: A biological basis for the management of New Zealand moki (*Latridopsis ciliaris*) and smoothhound (*Mustelus lenticulatus*) fisheries. Unpublished M.Sc. thesis, University of Canterbury.
- Francis, M.P. 1981: Von Bertalanffy growth rates in species of *Mustelus* (Elasmobranchii: Triakidae). *Copeia 1981*: 189-192.

Francis, M.P. 1988a: Rig. N. Z. Fisheries Assessment Research Document 88/24.

- Francis, M.P. 1988b: Movement patterns of rig (*Mustelus lenticulatus*) tagged in southern New Zealand. N. Z. Journal of Marine and Freshwater Research 22: 259-272.
- Francis, M.P. 1989: Exploitation rates of rig (Mustelus lenticulatus) around the South Island of New Zealand. N. Z. Journal of Marine and Freshwater Research 23: 239-245.
- Francis, M.P. & Francis, R.I.C.C. in press: Growth rate estimates for New Zealand rig (Mustelus lenticulatus). Australian Journal of Marine and Freshwater Research.
- Francis, M.P. & Mace, J.T. 1980: Reproductive biology of *Mustelus lenticulatus* from Kaikoura and Nelson. N. Z. Journal of Marine and Freshwater Research 14: 303-311.
- Francis, M.P. & Smith, D.W. 1988: The New Zealand rig fishery: catch statistics and composition, 1974-85. N. Z. Fisheries Technical Report No. 7. 30 p.
- Francis, R.I.C.C. 1988a: Maximum likelihood estimation of growth and growth variability from tagging data. N. Z. Journal of Marine and Freshwater Research 22: 42-51.
- Francis, R.I.C.C. 1988b: Are growth parameters estimated from tagging and age-length data comparable? *Canadian Journal of Fisheries and Aquatic Science* 45: 936-942.
- Francis, R.I.C.C. 1992: Recommendations concerning the calculation of maximum constant yield (MCY) and current annual yield (CAY). Draft N. Z. Fisheries Assessment Research Document.
- Greig, M.J., Ridgway, N.M., & Shakespeare, B.S. 1988: Sea surface temperature variations at coastal sites around New Zealand. N. Z. Journal of Marine and Freshwater Research 22: 391-400.
- Gruber, S.H. 1981: Lemon sharks: supply-side economists of the sea. Oceanus 24(4): 56-64.
- Hoenig, J.M. 1983: Empirical use of longevity data to estimate mortality rates. *Fishery* Bulletin 82: 898–903.
- Hoenig, J.M. & Gruber, S.H. 1990: Life-history patterns in the elasmobranchs: implications for fisheries management. NOAA Technical Report NMFS 90: 1-16.
- Holden, M.J. 1974: Problems in the rational exploitation of elasmobranch populations and some suggested solutions. *In*: Harden Jones, F.R. (Ed.), Sea fisheries research, pp. 117-137. Elek (Scientific Books), London.
- Jones, J.B. & Hadfield, J.D. 1985: Fishes from Porirua and Pauatahanui Inlets: occurrence in gill nets. N. Z. Journal of Marine and Freshwater Research 19: 477-484.

- Kendall, M.G. & Stuart, A. 1967: The advanced theory of statistics. Vol. 2. Inference and relationship. Charles Griffin, London.
- Ketchen, K.S. 1975: Age and growth of dogfish Squalus acanthias in British Columbia waters. Journal of the Fisheries Research Board of Canada 32: 43-59.
- Kirkwood, G.P. & Walker, T.I. 1986: Gill net mesh selectivities for gummy shark, Mustelus antarcticus Günther, taken in south-eastern Australian waters. Australian Journal of Marine and Freshwater Research 37: 689-697.
- Massey, B.R. & Francis, M.P. 1989: Commercial catch composition and reproductive biology of rig (*Mustelus lenticulatus*) from Pegasus Bay, Canterbury, New Zealand. N. Z. Journal of Marine and Freshwater Research 23: 113-120.
- Moulton, P.L., Walker, T.I., & Saddlier, S.R. 1991: Age and growth studies of gummy shark, *Mustelus antarcticus* Günther, and school shark, *Galeorhinus galeus* (Linnaeus) from southern Australian waters. *In*: Southern shark database project: final FIRDTA report, April 1991. Victoria Department of Conservation and Environment, Fisheries Division Internal Report 189.
- Pauly, D. 1980: On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *Journal du Conseil, Conseil Permanent International l'Exploration de la Mer 39*: 175–192.
- Stevens, J.D. 1990: Further results from a tagging study of pelagic sharks in the north-east Atlantic. Journal of the Marine Biological Association of U. K. 70: 707-720.
- Tanaka, S. & Mizue, K. 1979: Studies on sharks XV. Age and growth of Japanese dogfish Mustelus manazo Bleeker in the East China Sea. Bulletin of the Japanese Society of Scientific Fisheries 45: 43-50.
- Taniuchi, T., Kuroda, N., & Nose, Y. 1983: Age, growth, reproduction, and food habits of the star-spotted dogfish *Mustelus manazo* collected from Choshi. *Bulletin of the Japanese Society of Scientific Fisheries* 49: 1325-1334.
- Walker, T.I. 1983: Investigations of the gummy shark, *Mustelus antarcticus* Günther, from south-eastern Australian waters. Unpublished report to the Australian Fishing Industry Research Committee.
- Walker, T.I. 1989: Fishery situation report southern shark. In: Southern shark assessment project final FIRTA report: March 1989. Part B. Victoria Department of Conservation, Forests and Lands, Fisheries Division internal report 175a.
- Wang, T.-M. & Chen, C.-T. 1981: Reproduction of smooth dogfish, *Mustelus griseus* in northwestern Taiwan waters. *Journal of the Fisheries Society of Taiwan* 8: 23-36.

- Wang, T.-M. & Chen, C.-T. 1982: Age and growth of smooth dogfish, *Mustelus griseus* in northwestern Taiwan waters. *Journal of the Fisheries Society of Taiwan* 9: 1-12.
- Yudin, K.G. & Cailliet, G.M. 1990: Age and growth of the gray smoothhound, *Mustelus californicus*, and the brown smoothhound, *M. henlei*, sharks from central California. *Copeia 1990*: 191-204.

	Both sexes	Males	Females	
SD	С	C	V	
Age classes	7	7	5	
\tilde{K} (/yr)	0.10 (0.01)	0.11 (0.01)	0.40 (0.02)	
L_{∞} (cm)	176.9 (7.3)	161.1 (7.5)	87.0 (0.9)	
t_0 (yr)	-2.12 (0.05)	-1.91 (0.04)	-0.68 (0.01)	
Amplitude ϕ_1	0.95 (0.01)	0.95 (0.01)	0.87 (0.26)	
Phase ϕ_2 (yr)	0.31 (0.02)	0.28 (0.02)	0.33 (0.04)	
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Table 1: Von Bertalanffy growth parameter estimates (with standard errors) for 1983–84 Pegasus Bay best-fit MULTIFAN models. Amplitude and phase parameters describe seasonal growth. SD = standard deviation, C = constant, V = variable.

Table 2: Von Bertalanffy growth parameter estimates (with standard errors) for 1964–66 Hauraki Gulf best-fit MULTIFAN models. Amplitude and phase parameters describe seasonal growth. SD = standard deviation, V = variable.

	Both sexes Males		Females	
SD	V	V	v	
Age classes	7	8	6	
<i>K</i> (/yr)	0.36 (0.00)	0.16 (0.01)	0.42 (0.01)	
L_{∞} (cm)	95.5 (0.3)	118.7 (2.4)	90.7 (0.6)	
t_0 (yr)	-0.90 (0.00)	-2.02 (0.02)	-0.77 (0.00)	
Amplitude ϕ_1	_	0.51 (0.11)	_	
Phase ϕ_2 (yr)	_	-0.04 (0.04)	· <u> </u>	

Stock	Length at tagging (cm)	Estimated age at tagging (years)	Time at liberty (years)	Estimated age at recapture (years)
ECSI	84	4.6	6.3	10.9
	99	6.5	6.0	12.5
	72	3.3	6.0	9.3
	95	5.9	5.9	11.8
	93	5.6	5.0	10.6
	79	4.1	5.0	9.1
	95	5.9	5.0	10.9
WCSI	82	4.3	9.0	13.3
	78	4.0	8.9	12.9
	92	5.4	7.7	13.1
	82	4.3	5.7	10.0

Table 3: Life span estimates for tagged male ECSI and WCSI rig at liberty for 5 or more years.

Species	Location	Sex	Length at maturity (cm)	Age at 1 maturity (years)	Maximum age (years)	Sources
M. antarcticus	Australia (Bass Strait)	M F	95 114	4.7	13	Walker (1983), Moulton et al. (1991)
M. antarcticus	Australia (South Aust.)	M F	-	-	12 15	Moulton et al. (1991)
M. californicus	California	M F	57 - 65 70	1.3 - 1.9 2.1	6 9	Compagno (1984), Yudin & Cailliet (1990)
M. griseus	Taiwan	M F	68 - 72 70 - 74	5.5 - 6.5 5.3 - 6.0	9 9	Wang & Chen (1981, 1982)
M. henlei	California	M F	52 - 66 51 - 63	2.2 - 4.0 1.9 - 3.2	7 13	Compagno (1984), Yudin & Cailliet (1990)
M. lenticulatus	New Zealand (Pegasus Bay)	M F	87 102	5.0	>13	This paper, M. Francis (unpubl. data)
M. lenticulatus	New Zealand (Hauraki Gulf)	M F	72 82	3.7 4.7	-	This paper, L.J. Paul (pers. comm.)
M. manazo	Japan (Choshi)	M F	64 - 66 64 - 68	3.0 - 3.3 3.4 - 4.0	9 9	Taniuchi et al. (1983)
M. manazo	Japan (East China Sea)	M F	60 62 - 66	1.9 2.0 - 2.5	8 10	Tanaka & Mizue (1979)

Table 4: Length and age at 50% maturity, and life span estimates for *Mustelus* species. Age estimates for species other than *M. lenticulatus* are based on vertebral ring counts.

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Species	Estimation method	M estimates	
Rig	Life span (Hoenig 1983)	0.21–0.28	
Rig	Life span (log _e 100/life span)	0.23-0.31	
Rig	Growth parameters, temperature	0.19, 0.30, 0.51, 0.61	
Rig	Population replacement	< 0.37	
M. antarcticus	Paloheimo cohort analysis	0.20	
M. antarcticus	Tag-recapture	0.28	

Table 5: Estimates of the instantaneous natural mortality rate, M. See section 3 for details.

Table 6: Mortality estimates and growth equations used in section 4. Seasonal growth parameters were omitted from the von Bertalanffy growth equations.

Fishstock	Mortality estimates and growth equations		
A11	M = 0.2, 0.3		
SPO1&3 males ¹	Weight = $1.46*10^{-6}*Length^{3.22}$		
SPO1&3 females ¹	Weight = $3.67*10^{-7}*Length^{3.54}$		
SPO1 males	$L_t = 118.7*(1 - e^{-0.16(t + 2.02)})$		
SPO1 females	$L_t = 90.7*(1 - e^{-0.42(t + 0.77)})$		
SPO3 males	$L_t = 161.1*(1 - e^{-0.11(t + 1.91)})$		
SPO3 females	$L_t = 87.0*(1 - e^{-0.40(t + 0.68)})$		

¹ Source: Francis (1979)

Stock	М	F _{0.1}		
SPO1	0.2	0.28		
SPO1	0.3	0.45		
SPO3	0.2	0.22		
SPO3	0.3	0.37		

Table 7: Estimates of $F_{0,1}$ obtained from yield per recruit analyses for SPO1 and SPO3 rig stocks for both sexes combined using two values of natural mortality, M.

Table 8: MCY and F_{CAY} estimates for SPO3 with four combinations of natural mortality, M, and stock-recruit steepness. MCY is defined as the lesser of two target catch levels: the target catch that produces the maximum mean catch, and the maximum safe target catch. MCY and F_{CAY} were obtained from Figs 8 and 9 respectively. $F_{0.1}$ and $0.25*M*B_0$ are also shown for comparison.

М	Steepness	MCY (% <i>B</i> ₀)	0.25*M*B ₀ (%B ₀)	F _{CAY}	<i>F</i> _{0.1}
0.2	0.50	4.2	5.0	0.14	0.22
0.2	0.35	2.9	5.0	0.07	0.22
0.3	0.50	6.7	7.5	0.22	0.37
0.3	0.35	4.5	7.5	0.11	0.37



Fig. 1: Mean length (± 1 s.e.) of the 0+ rig cohort sampled with set nets in Porirua (Po) and Pauatahanui (Pa) Inlets during summer-autumn of 1983-84 and 1984-85. Numbers indicate sample sizes.



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Fig. 2: Length-frequency histograms of Pegasus Bay rig for 1983-84 (both sexes combined) showing the best fit MULTIFAN model. Curves are shown for each age class separately (normal curves) and the sum of all age classes (uppermost curve). N = sample size.



Fig. 3: MULTIFAN growth curves for Pegasus Bay 1983-84 (upper graph) and Hauraki Gulf
1964-66 (lower graph) rig. The origin on the X-axis is set at 1 September (the nominal birth date). Also superimposed are the 1983-84 Pauatahanui Inlet (Pa) growth curve from Fig. 1 (upper graph), and the mean lengths of the 0+ rig age classes from the 1980-82 Hauraki Gulf samples (lower graph).



showing the best fit MULTIFAN model. Curves are shown for each age class separately Fig. 4: Length-frequency histograms of Hauraki Gulf rig for 1964-66 (both sexes combined) (normal curves) and the sum of all age classes (uppermost curve). N = sample size.

Frequency



Fig. 5: Length-frequency histograms of Hauraki Gulf rig (both sexes combined) sampled by set net and trawl in 1980-82. N = sample size.



Fig. 6: Expected annual growth for rig. The lines for the tagged rig represent expected growth for fish of the given length; for the length-frequency data (Hauraki Gulf and Pegasus Bay) the lines represent the expected growth for a cohort whose mean length is the given length. (For example, mean lengths of male fish from Pegasus Bay at ages 3 and 4 are 67.6 and 77.6 cm respectively, so the expected annual growth at mean length 67.6 is 10.0 cm.) No line is given for Pegasus Bay females because there were too few data.



Fig. 7: Von Bertalanffy growth curves for New Zealand rig (M. lenticulatus), based on best-fit MULTIFAN models, and other Mustelus species. 1 = Pegasus Bay male M. lenticulatus;
2,3 = Hauraki Gulf male and female M. lenticulatus; 4,5 = male and female M. californicus; 6 = female M. henlei; 7,8 = male and female M. griseus; 9,10 = East China Sea male and female M. manazo. Data sources are given in Table 4. Several of the curves were truncated at the right hand end where sample sizes dropped below 5.



Fig. 8: Results of simulations to calculate MCY for rig stock SPO3 with four combinations of values for stock-recruit steepness and natural mortality, M. On each graph the solid line spawning stock biomass (S) will fall below 20% of its mean virgin value (S0). The shows the mean catch achieved, and the broken line shows the probability that the horizontal dotted line shows the maximum safe value for the latter.

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Fig. 9: Results of simulations to calculate F_{CAY} for rig stock SPO3 with four combinations of values for stock-recruit steepness and natural mortality, M. On each graph the solid line shows the mean catch achieved, and the broken line shows the probability that the spawning stock biomass (S) will fall below 20% of its mean virgin value (S0). The horizontal dotted line shows the maximum safe value for the latter.