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CALCULATION OF PLAUSIBLE MAXIMUM SUSTAINABLE YIELD (MSY) FOR BLUE SHARKS (*Prionaceglauca*) IN THE NORTH PACIFIC

by

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ABSTRACT

A range of plausible values for maximum sustainable yield (MSY) and associated fishing mortality at MSY (Fmsy) was calculated from preliminary results of a stock assessment of blue sharks in the North Pacific. The assessment is a collaborative project between the National Marine Fisheries Service Honolulu Laboratory and the National Research Institute of Far Seas Fisheries in Shimizu, Japan. That project is still in progress. Its current state consists of several estimated scenarios produced by Multifan-CL, giving a history of abundance, recruitment, fishing mortality, and other parameters. The different scenarios depend on a) assumptions implicit in setting up the data for input to Multifan-CL, b) various structural assumptions involved in setting up Multifan-CL, and c) choosing and structuring a steady-state, population dynamics model for interpreting the output from Multifan-CL. These scenarios were used as a basis for MSY calculations resulting in estimates of MSY ranging from 1.8 to nearly 4 times the current catch of blue shark per year and Fmsy ranging from 2 to 15 times current fishing mortality levels.

At present no evidence has come to light to help narrow the scope of the various scenarios or of the other assumptions implicit in this analysis. In some cases, where the effect on blue shark productivity is obvious, the most conservative of a plausible range of assumptions was chosen. For example, the age at maturity for females was assumed to be the oldest of the range reported in the literature. The effect of this bias is a tendency to underestimate MSY and Fmsy. In other cases, a range of assumptions has been tested (hence the proliferation of scenarios) or is yet to be tested. Obviously, much work needs to be done to shore up and test the robustness of these calculations and other aspects of the blue shark assessment.

The indications to date of this work, and of the blue shark assessment in general, are that under the current fishing regime in the North Pacific, the blue shark population appears to be in no danger of annihilation or stock collapse. In further refinements of the assessment, it is likely that the numbers will be revised, perhaps considerably, but it is very unlikely that this central conclusion will change.

INTRODUCTION

This work was motivated by the requirement of the Sustainable Fisheries Act that a quantity which can (with at least minimal justification) be called a “maximum sustainable yield” (MSY) shall be calculated for all catch or bycatch species. In the case of blue sharks in the North Pacific, present knowledge allows only very tentative quantification of MSY. Nevertheless, a range of examples of what might be called “plausible” MSY was calculated.

The information base supporting the calculation consists of the results of a Multifan-CL analysis of North Pacific blue sharks (Kleiber et al., in prep.) and additional life-history information on blue sharks. The data on which the Multifan-CL analysis is based consist of catch, effort, and size composition data collected during the period 1971 through 1998 from fisheries in the North Pacific that catch significant numbers of blue sharks. The pelagic longline data are split into eight fleets consisting of Hawai'i based and Japanese vessels operating with either deep or shallow gear and in two geographic zones, one north of 25° N and one between the equator and 25° N. Large and small mesh drift nets operating north of 25° N add two additional fleets to the analysis.

While Multifan-CL is a very sophisticated statistical estimation tool (Fournier et al., 1998), it is not a highly sophisticated population dynamics model and does not deal in such abstractions as MSY. However, it does provide estimates of tangible population data such as abundance at age and recruitment. If such data are input into a population dynamics model that has some kind of density dependence, then estimates of MSY and associated fishing mortality at MSY (Fmsy) can be obtained. The estimates are thus contingent on the results of a Multifan-CL analysis (itself a work in progress) and on the particular population dynamics model chosen.

ANALYSIS

The output used from Multifan-CL consisted of abundance at age, recruitment (actually the abundance of the youngest age class at the start of each year), natural mortality, and fishing mortality at age. The Multifan-CL analysis at this point consists of several different scenarios depending on various structural assumptions, for example, the spatial breakdown of the North Pacific into subregions or the number of age classes to carry in the model. To date, most of the variability between scenarios has to do with a structural parameter Q_t, which sets a constraint on the ability of catchability to vary over time: the smaller the value of Q_t the lesser the constraint and the greater the variation in catchability over time. As yet little evidence has been uncovered to favor one or the other of these scenarios.

Figure 1 shows predicted abundance trends in four scenarios produced by Multifan-CL and differing by a range of values of Q_t. The qt50 scenario stands apart from the others in showing lower abundance and lesser degree of recovery following the drop during the 1980s. This is confirmed in Table 1 with the comparison of the prevailing abundance at the end of the time series with that at the start. Estimates of natural mortality, fishing mortality, and exploitation rate, also shown in Table 1, indicate that the qt50 scenario shows the greatest impact of the fishery on the blue shark population. This scenario is thus the least optimistic in assessing blue shark stock status.

To seek density dependence for a population dynamics model that could allow determination of MSY, the relationship between parental stock and subsequent recruitment was investigated. Figure 2 shows recruitment trends estimated by Multifan-CL, and Figure 3 shows the corresponding trends in parental stock, which is the abundance of all ages from onset of maturity. Age at maturity in this case was assumed to be 7 years, the maximum of a reported range of 5 to 7 years (Cailliet and Bedford, 1983; Nakano, 1994). At this stage of the investigation we are making precautionary assumptions when possible. Erring on the side of greater age at maturity means erring on the side

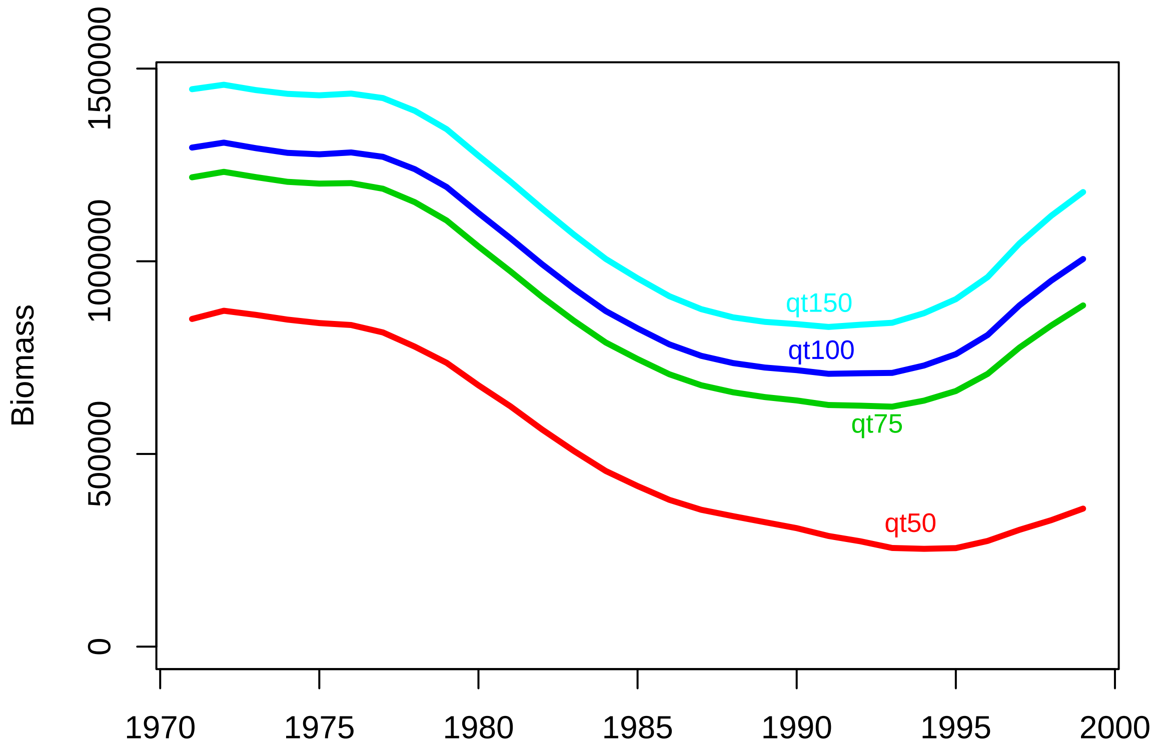

Figure 1. Relative blue shark biomass trajectories in four Multifan-CL scenarios.

Table 1. Some results from Multifan-CL in four scenarios. N_{end} – average abundance at the end; N_{start} average abundance at the start; M – natural mortality; F_{end} – fishing mortality at the end; E_{end} – exploitation rate at the end. The "end" in this case refers to the average since 1992, and "start" refers to the average prior to 1957.

	qt50	qt75	qt100	qt150
N_{end}	23×10^6	50×10^6	57×10^6	67×10^6
$\frac{N_{\text{end}}}{N_{\text{start}}}$	0.53	0.75	0.79	0.83
M	0.22	0.27	0.27	0.27
F_{end}	0.19	0.07	0.06	0.05
E_{end}	0.47	0.20	0.17	0.15

of lower productivity of the stock, which in turn means erring on greater impact of harvest by the fishery.

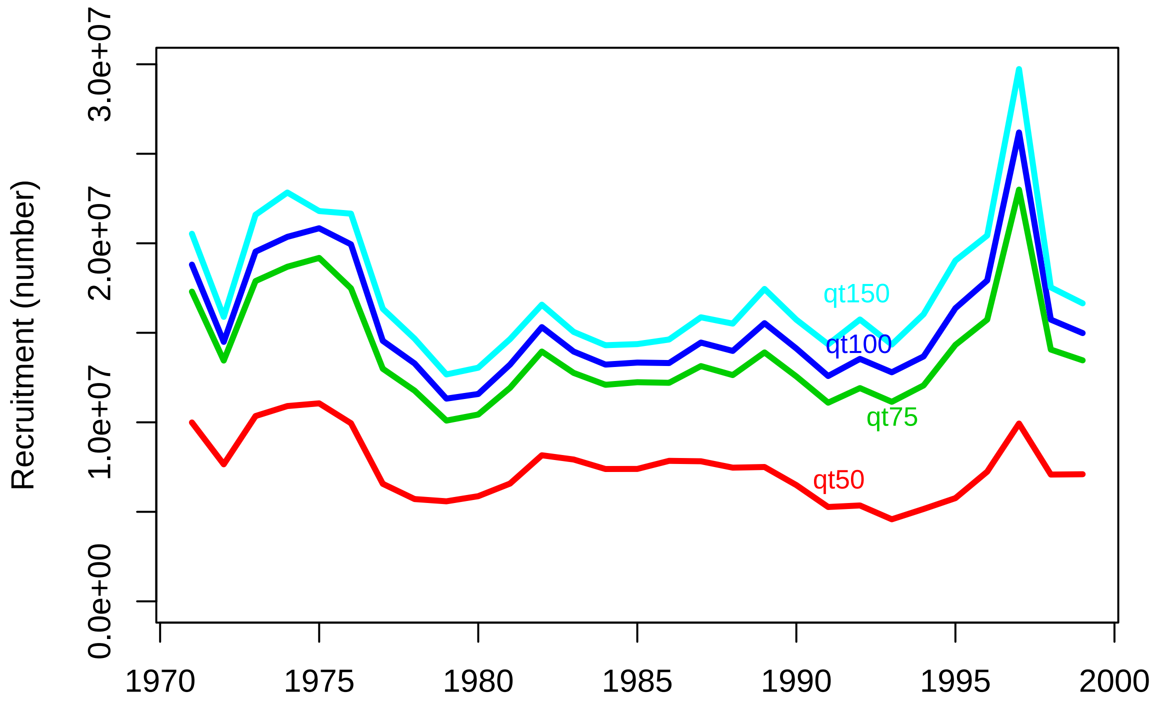

Figure 2. Recruitment trajectories for four Multifan-CL scenarios assuming recruitment at age 1. Q_t values indicate degree of constraint on catchability variation.

To examine the stock-recruitment relationship, recruitment in the various scenarios was plotted against parental stock with a one year lag (Fig. 4). A Beverton-Holt model was chosen to represent the stock-recruitment relationship. A parameterization of that model is

$$R = \frac{\alpha \beta P}{\alpha + \beta P} \tag{1}$$

where R is recruitment, P is the parental abundance, α is the asymptotic maximum recruitment level for large parental abundance, and β is the limiting slope of the curve as parental abundance approaches zero. The latter parameter could be called the recruitment potential; that is, the maximum number of recruits per parent per year. This recruitment relationship provides density dependence in a simple population dynamics model detailed below.

The solid lines in Figure 4 are Beverton-Holt recruitment curves that were fitted to the points by virtue of an AD Model Builder (Anon., 1996) template. The resulting parameter estimates are given in Table 2. The confidence bounds on the fitted curve are based on approximate standard errors of estimates of $\log(R)$. The confidence bounds of α and β are likewise obtained from estimates of the log of the parameters from the inverse Hessian matrix.

To put the estimates of β into perspective, a range of possible values was calculated for recruitment potential based in part on life-history information. For a litter size ℓ, a female blue shark would be expected to contribute $\ell \exp(-M_1)$ recruits to age-1 on a particular year in which she is pregnant, where M_1 is the natural mortality of pups in their first year. For a breeding interval B years,

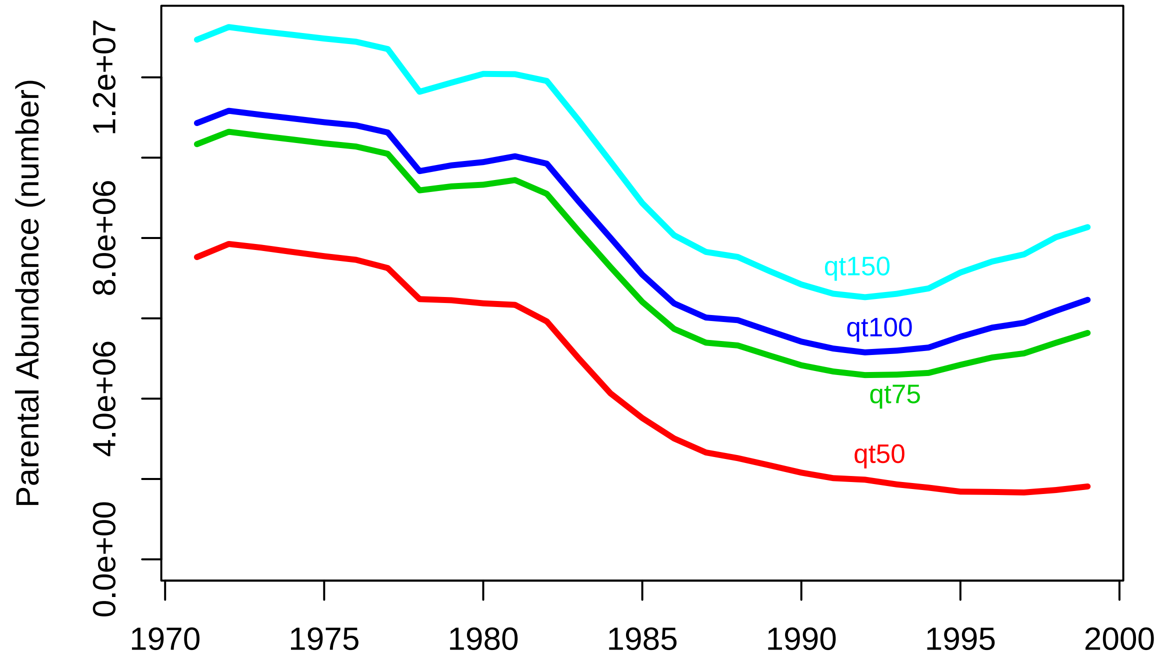

Figure 3. Parental stock trajectories for four Multifan-CL scenarios assuming maturity at age 7. Q_t values indicate degree of constraint on catchability variation.

the expected contribution from this female's second pregnancy would be $\ell \exp(-M_1)\exp(-BM)$, where M is natural mortality of mature sharks and $\exp(-BM)$ is thus the probability this female survives through the breeding interval. Summing this female's contribution over her possible lifetime as a parent we get the following convergent infinite series:

$$\text{expected recruits per female} = \sum_{i=0}^{\infty} \ell e^{-M_1} e^{-iBM} = \frac{\ell e^{-M_1}}{1 - e^{-BM}}$$

With a natural mortality of M, the average lifetime as a parent is $1/M$, and assuming a sex ratio of 1:1, the recruitment potential is given by

$$\text{expected recruits per parent per year} = \frac{1}{2}\frac{M\ell e^{-M_1}}{(1 - e^{-BM})} \tag{2}$$

Considering parameter values for the above equation, the natural mortality estimate, M, is taken from each Multifan-CL scenario (Table 1). Natural mortality during the first year, M_1, is likely to be higher than M, but it has not been measured. For the moment, it is assumed to be approximately twice the parental natural mortality. Pups per litter, ℓ, is reported to average 26 for blue sharks in the North Pacific with a maximum of 62 (Nakano, 1994). Litter sizes as high as 135 have been observed in other regions (Gubanov and Grigor'yev, 1975). Stevens (1984) points out that actual litter sizes are probably larger than observed because pups are often aborted during

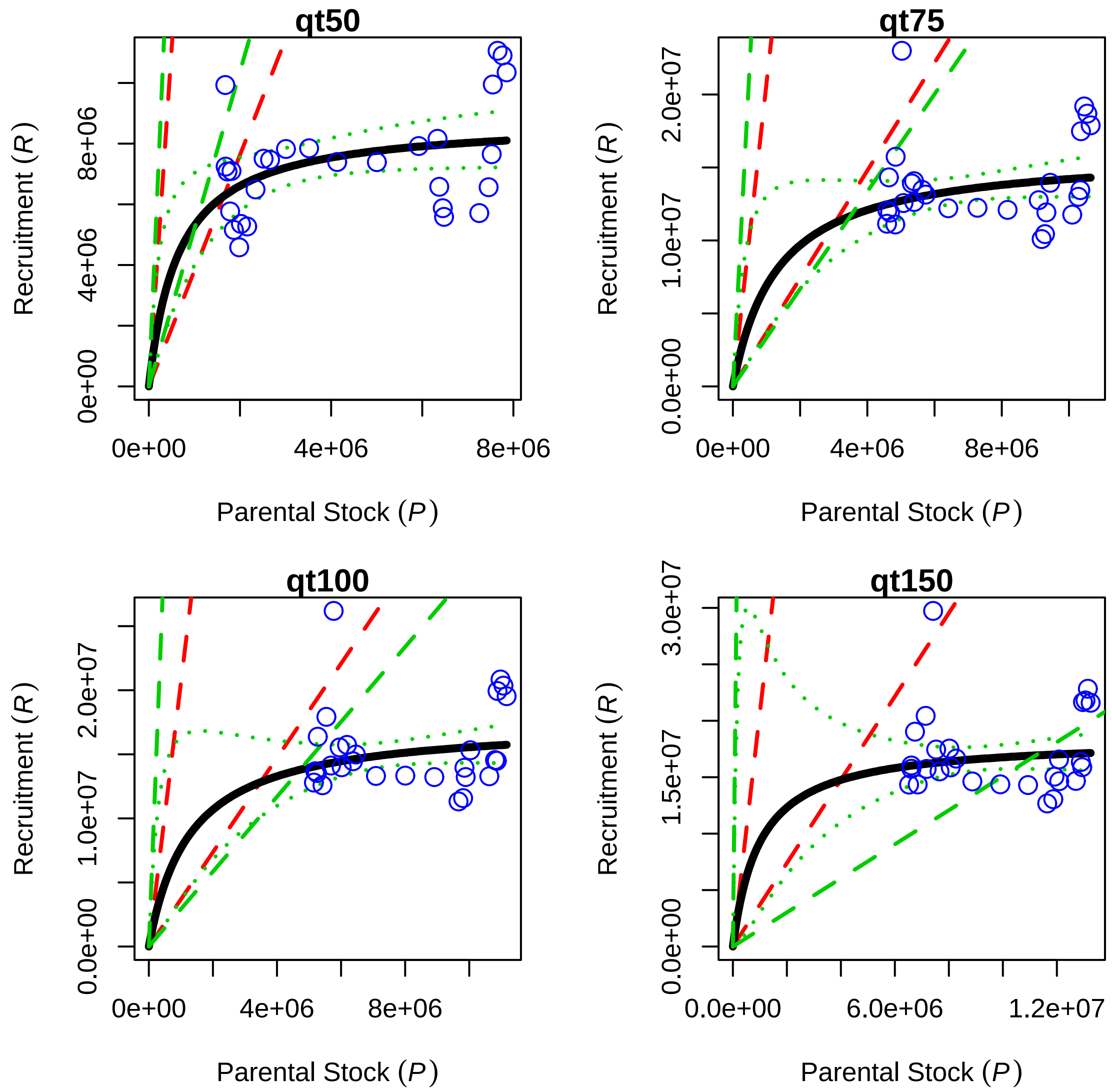

Figure 4. Stock-recruitment relationships for North Pacific blue shark from four Multifan-CL scenarios. **Circles:** recruitment to age-1 plotted against parental abundance 1 year earlier. Onset of maturity assumed at age-7. **Solid line:** Fit of Beverton-Holt curve to circular points. **Dotted lines:** Approximate upper and lower 95% confidence bounds. **Dashed lines:** Slopes show ranges of β: darker (red) lines indicating range based on life-history considerations and lighter (green) lines indicating approximate 95% confidence bounds from the curve fit.

the capture of pregnant females. The breeding interval, B, is not well known but is surely not less than 1 year. John Stevens (pers. comm.) guesses it to be in the range of 1 to 3 years. For long breeding intervals, the denominator in Equation 2 above approaches 2, which would be the case if each female bred only once.

To get a sense of the possible range in recruitment potential, we could assume for the high end a litter size of 62 and a breeding interval of 1 year and for the low end a litter size of 26 and a breeding interval of 3 years. This leads to the theoretical ranges for β in Table 2 and the slopes of the darker (red) dashed lines in Figure 4. The 95% confidence ranges from the curve fits, and

Table 2. Parameter estimates and approximate 95% confidence bounds of Beverton-Holt stock-recruitment curves for four Multifan-CL scenarios. In addition, "β range" is a theoretical range of β based on blue shark life-history information.

	qt50	qt75	qt100	qt150
α	8.8×10^6	16×10^6	18×10^6	18×10^6
c.b.(α)	[7.3–11]×10^6	[13–21]×10^6	[13–23]×10^6	[14–24]×10^6
β	13	13	14	19
c.b.(β)	5.2–34	3.3–44	2.9–64	1.5–227
β range	3.8–22	3.7–21	3.7–21	3.7–21

the theoretical ranges for β are roughly comparable for the smaller values of Q_t; but confidence ranges become much larger for higher values of Q_t. This reflects the wide uncertainty (dotted lines in Fig. 4) in what recruitment would be at low levels of parental stock in scenarios that have not experienced low levels of parental stock. An important implication of the theoretical ranges of β is that the Beverton-Holt curves are not implausible, including the steep parts at low parental abundance.

With a Beverton-Holt curve available, it is possible to calculate yields as a function of fishing mortality with a steady-state model defined as follows:

$$\text{population abundance by age class} = N_a, a = 1 \ldots n$$

where age class n contains animals of age n and older.

$$\begin{aligned} \text{recruitment to age class } 1 &= R \\ \text{fishing mortality at age} &= F_a \\ \text{natural mortality (constant)} &= M \\ \text{total mortality at age} &= Z_a = F_a + M \end{aligned}$$

Assuming steady-state, abundances are given by

$$\begin{aligned} N_1 &= R \\ N_a &= N_{a-1} e^{-Z_{a-1}}, \quad a = 2 \ldots n-1 \\ N_n &= \frac{N_{n-1} e^{-Z_{n-1}}}{1 - e^{-Z_n}} \end{aligned} \tag{3}$$

For age at maturity, m, the parental abundance will be

$$P = \sum_{a=m}^{n} N_a \tag{4}$$

Note that P is a function of R because it depends on the N_as (Equation 4) which are in turn dependent on R (Equation 3). The parental abundance per recruit, $P(1)$, is the result of substituting 1 for R in Equation 3. Therefore

$$P = P(R) = RP(1) \tag{5}$$

and R can be calculated by substituting the right side of Equation 5 for P in the Beverton-Holt relation (Equation 1) and solving for R:

$$R = \frac{\alpha\beta P(1) - \alpha}{\beta P(1)} \tag{6}$$

The N_as at steady-state are then obtained inserting the calculated value of R in Equation 3, and the corresponding yield is estimated from

$$Y = \sum_{a=1}^{n} \frac{F_a}{Z_a} N_a (1 - e^{-Z_a})$$

This yield model was used to calculate a base-case yield for each Multifan-CL scenario with the following input values:

- Age of maturity m of 7 years—the maximum of a reported range of 5 to 7 years (Cailliet and Bedford, 1983; Nakano, 1994).
- The estimated parameters, $\hat{\alpha}$ and $\hat{\beta}$, from the Beverton-Holt curves (Table 2).
- Natural mortality estimate $\hat{M}$ from the corresponding Multifan-CL scenarios (Table 1).
- Recent average vector of fishing mortality at age, $\hat{F}_a$, from the same scenarios (Table 1).

With these values the yield model should produce a steady-state estimate of yield from the North Pacific fishery operating with constant fishing mortality and selectivity as it was on average in the time series after 1992. Figure 5 compares the abundance at age in each Multifan-CL scenario with that in the corresponding yield model. The qt50 scenario does not fit as closely as the other scenarios, indicating that the population in this case is not as close to equilibrium as it is in the other scenarios. The slight rise in abundance at age-15 in the latter scenarios results from the fact that age class 15 includes all older ages as well. The lower total mortality (natural plus fishing, Table 1) allows enough survival to ages older than 15 years to cause the rise.

With the benefit of a yield model, it is possible to calculate values of steady-state yield with different fishing mortality regimes. Keeping the age selectivities the same as in the base cases, different fishing mortalities were input to the yield model for each scenario by way of a multiplier, F_{mult}, on the base case fishing mortalities; that is

$$F_a = \hat{F}_a F_{mult}$$

The results for a range of F_{mult} (Fig. 6) show a range of MSY from approximately 1.7 to 3 times current catches with Fmsy ranging from approximately 2 to 8 times current levels of fishing mortality. The lowest Q_t values result in the lowest value of MSY and Fmsy. The calculations were repeated for a number of additional scenarios covering an extended range of Q_t, and the results for Q_t values less than 50 are almost identical to those for qt50 (Fig. 7). For values of Q_t larger than 200, MSY reaches a plateau at almost 4 times current blue shark catches with Fmsy ranging between 12 and 15 times current fishing mortality levels. For Q_t very large, Multifan-CL approaches the more traditional stock assessment analyses in which catchability is forced to be constant in time. Therefore, traditional assessment procedures could very well produce MSY and Fmsy estimates at or exceeding the upper end of the ranges shown here.

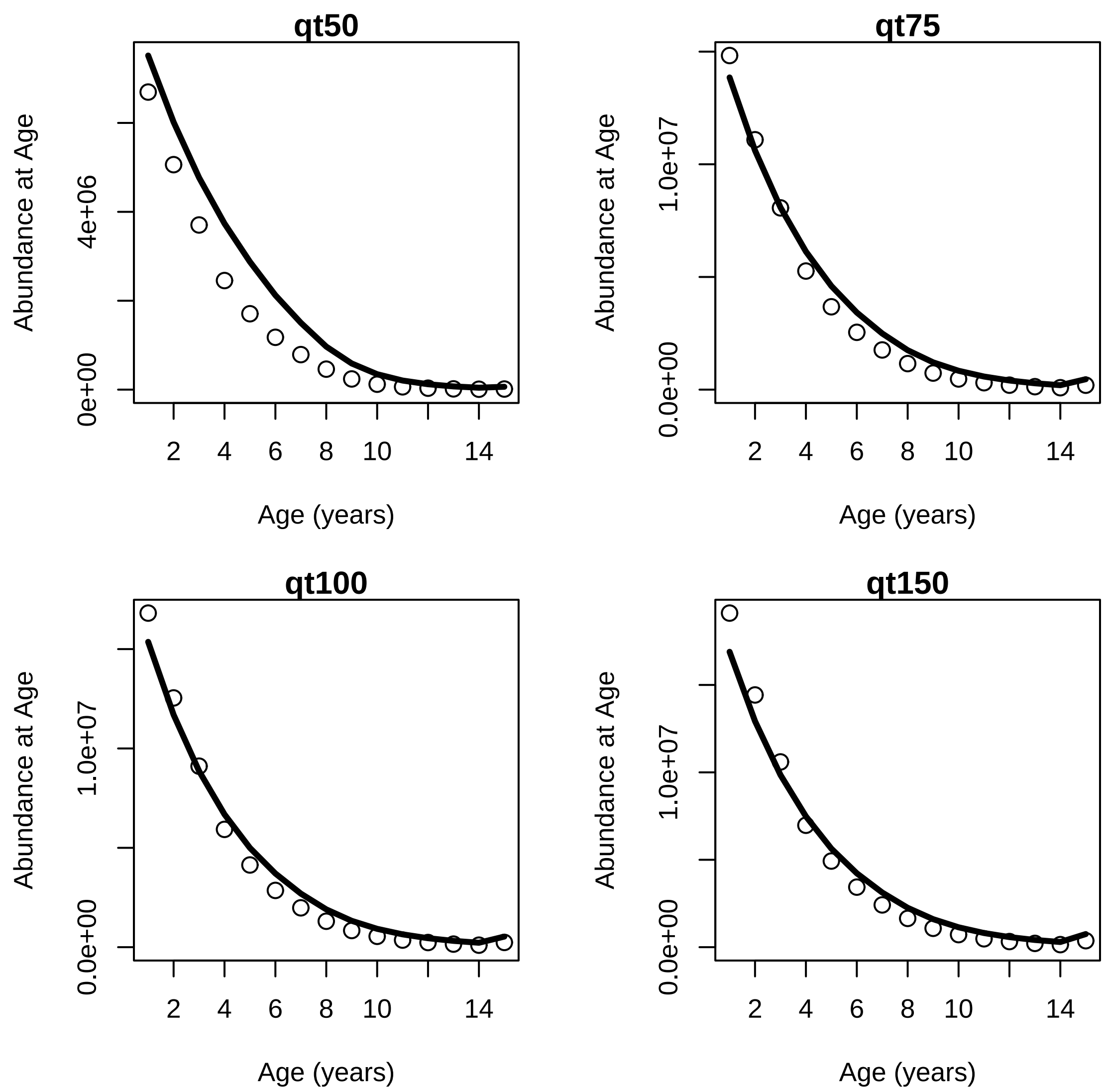

Figure 5. Abundance at age in the base case of the yield model (line) compared with that of the Multifan-CL scenario averaged over years 1993–98 (points).

DISCUSSION AND CONCLUSION

The values for MSY and Fmsy calculated in this study are contingent on several scenarios resulting from Multifan-CL analyses and on one of a number of possible yield models. The Multifan-CL analyses are in turn based on a number of structural assumptions as well as assumptions involved in processing data for input to Multifan-CL. The yield model likewise is based on assumptions, such as the form of the stock-recruitment function and the age at maturity. In driving up exploitation in the yield model by way of a fishing mortality multiplier, the distribution of effort among various fleets was implicitly assumed to be constant regardless of the total effort. However, some other regimes for changing fishing effort could easily result in different values for MSY and Fmsy.

For one structural assumption in Multifan-CL, the setting of Q_t, a wide range of values was tested resulting in a range of results. Other structural assumptions remain to be tested, but where

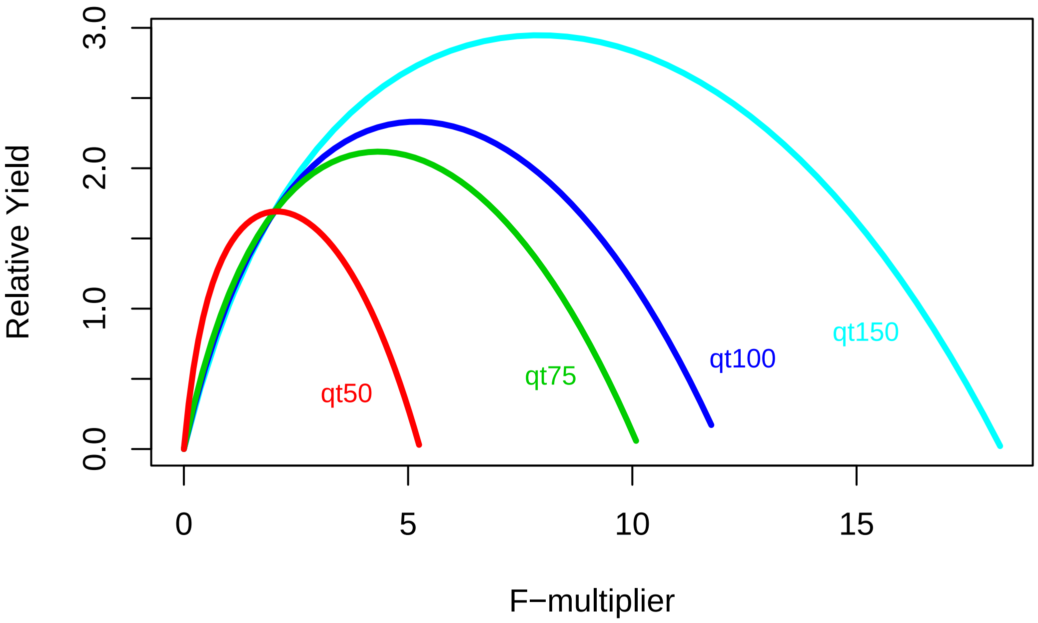

Figure 6. Results from yield model for a range of fishing mortality multipliers applied to four Multifan-CL scenarios. Yield is expressed relative to 1.1 million, the average annual blue shark catch, 1993–98.

possible, the assumptions were selected to be conservative, or pessimistic, within a range of plausible assumptions. Therefore, with different assumptions the range of values of MSY and Fmsy would likely have been shifted upward. As it is, even the most pessimistic scenarios show current catches and fishing mortalities to be comfortably below MSY and Fmsy. Obviously, much work is left to be done to shore up and test the robustness of these results, not just in the calculation of MSY, but in all phases of the blue shark assessment.

The indications to date of this work and of the blue shark assessment in general are that under the current fishing regime in the North Pacific, the blue shark population appears to be in no danger of annihilation or stock collapse. In further refinements of the assessment, it is likely that the numbers will be revised, perhaps considerably, but it is very unlikely that this central conclusion will change.

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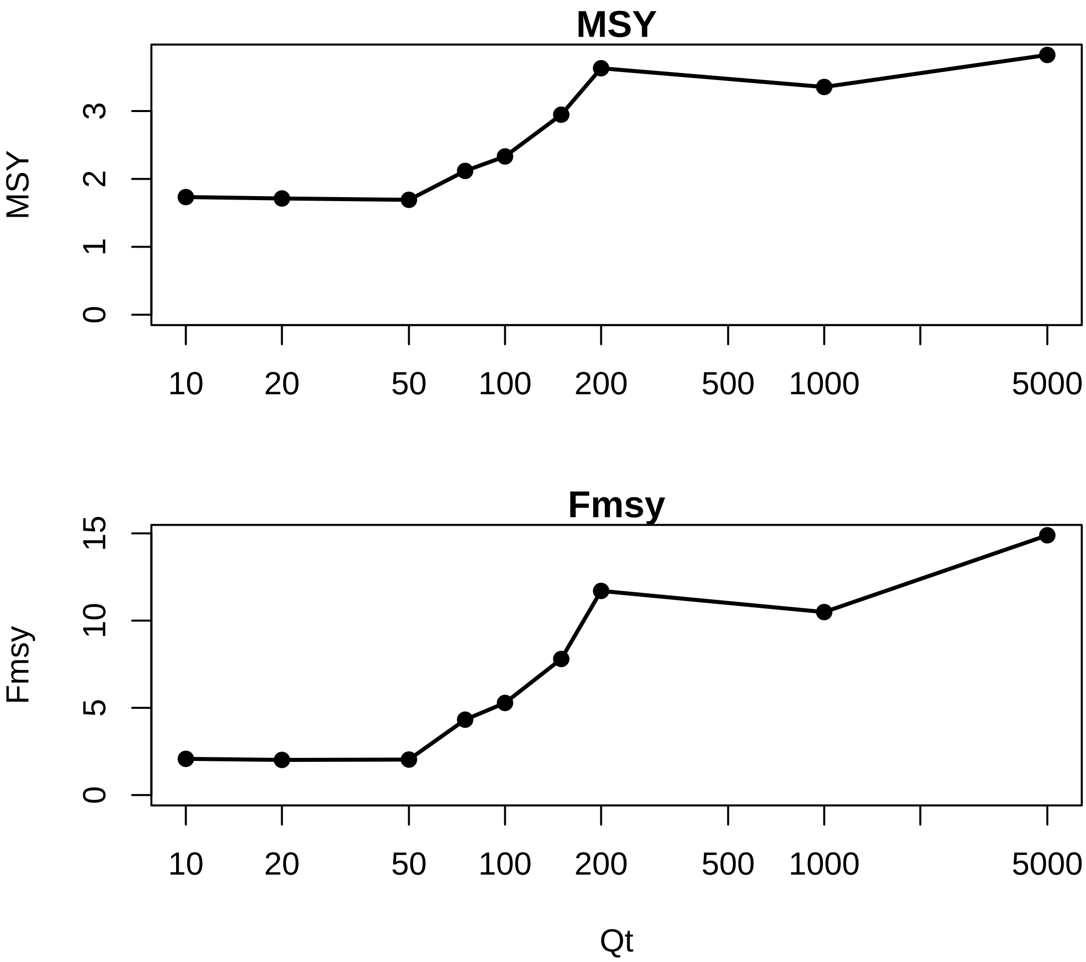

Figure 7. MSY and Fmsy results for an extended range of Q_t. MSY and Fmsy are expressed as multiples of current levels (average 1992–98) of catch and fishing mortality, respectively.

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