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Very Preliminary North Pacific Swordfish Assessment[1]

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For this preliminary assessment, Japanese and Hawaiian longline data were taken from an area in the north Pacific bounded to the south by 15° N and to the east by 135 W. This central and western region of the north Pacific is also bounded by areas of relatively low swordfish CPUE (Figure 1), and is here taken to house a so called "unit stock". This assumes that there is little exchange of swordfish to the south or the east of the region. The region includes activities of Japanese and Hawaiian longline fleets, for which complete catch and effort data by monthly 5° square strata are available. Other longline fleets and other gear have also taken swordfish in the area, but data on these, particularly effort data, are not as complete.

Though total catch data are available for the Japanese and Hawaiian fleets, comprehensive catch at size or catch at age data are not. Therefore, two assessment models requiring only total catch and effort were tested. One of these is the Pella-Tomlinson model, which incorporates the concepts of net production rate in a fish stock and the carrying capacity. The other model estimates explicit inputs to and outputs from the stock in terms of recruitment and natural mortality in addition to fishing mortality.

For either of these models to be effective in assessing the status of a fish stock, there needs to be a degree of "contrast" in the data, meaning that the stock should have been subjected to a wide variety of fishing effort levels. This appears to be the case, particularly for the Japanese data, which extends from 1952 through 1996 (Figure 2), giving some hope that meaningful results could be obtained.

Pella-Tomlinson Model:

The underlying differential equation describing the population dynamics of the Pella-Tomlinson model is

(1) $$\frac{\partial N}{\partial t} = r\left[1-\left(\frac{N}{k}\right)^{m-1}\right]N - FN$$

where N is the swordfish abundance, t is time, r is the maximum rate of population increase, k is the carrying capacity, F is the fishing mortality, and m is shape parameter. Turning this into a difference equation with unit (one year) time steps gives

(2) $$N_{t+1} = N_t + rN_t - rN_{t+1}\left(\frac{N_t}{k_t}\right)^{m-1} - F_t N_{t+1}$$

where t is now a subscript for year. Note that N on the right side of the equation is sometimes subscripted with t+1. This is a strategy, called implicit time stepping, that prevents the instability that can result from the model diving into negative abundance territory. Solving for N_{t+1} and defining the starting abundance gives

(3) $$N_{t+1} = \frac{(1+r)N_t}{1+r\left(\frac{N_t}{k_t}\right)^{m-1} + F_t} \quad ; \quad N_0 = \beta k_0$$

which is now a stable difference equation where the starting abundance is estimated to be a fraction β of the carrying capacity at the start, and where F_t, the fishing mortality from both the Japanese and US fleets, is given by

(4) $$\begin{aligned} F_t &= F_t^J + F_t^U \\ F_t^J &= q_t^J E_t^J e^{\delta E_t^J} \quad ; \quad \sum \delta E_t^J = 0 \end{aligned}$$

where the superscripts, J and U, stand for Japanese and US respectively, where q is the catchability, and where the effort, E, is modified in each year by an exponential error factor constrained by the requirement that the sum of the factors is zero. Predicted catch for the two fleets is given by

$$\hat{C}_t^J = F_t^J N_t \; ; \; \hat{C}_t^U = F_t^U N_t \tag{5}$$

Note that k and q are subscripted by year, meaning that they are allowed to vary with time. They are constrained to vary in an auto-correlated time series as follows:

$$\begin{aligned} k_{t+1} &= k_t e^{\delta k_t} \quad ; \quad k_1 = k_0 \\ q_{t+1}^J &= q_t^J e^{\delta q_t^J} \quad ; \quad q_1^J = q_0^J \\ q_{t+1}^U &= q_t^U e^{\delta q_t^U} \quad ; \quad q_{39}^U = q_0^U \end{aligned} \tag{6}$$

There are 45 years of Japanese catch and effort data (1952—1996) but only 7 years of US (Hawaiian fleet) data. Therefore the catchability series for the US fleet start in year 39 of the time series. The model as it is explained to this point is basically the same one Fournier (199_) uses as an example to demonstrate the use of AD Model Builder – in his case used to fit a Pella-Tomlinson model to north Pacific halibut data. In the present case the model is modified to allow two fleets instead of just one, and catchability is given the possibility to vary with time. The procedure for fitting the model to data, that is, estimating the model parameters, makes use of AD Model Builder and is also adapted from Fournier's example. The estimated parameters of the model are:

Parameter symbol	*Parameter description*	*Count*
r	Maximum rate of population increase	1
k_0	Carrying Capacity at start	1
β	Starting abundance as fraction of k_0	1
δE_t^J	Japanese E-deviations	45
δE_t^U	US E-deviations	7
k_0	Carrying Capacity at start	1
δk_t	k-deviations	44
q_0^J	Japanese catchability at start	1
δq_t^J	Japanese q-deviations	44
q_0^U	US catchability in year 39	1
δq_t^U	US q-deviations	6
	Total	151

Parameters are estimated by minimizing an objective function that incorporates the sum of squares of deviations between logarithms of observed data and model predictions. However, with 150 parameters and only 52 data points (45 for Japan, and 7 for Hawai'i), it is necessary to put further constraints on the parameter values by adding extra terms to the objective function. The objective function, then, is given by

$$\Omega = \frac{n_T}{2}\left[\begin{aligned} &\sum\left(\log(C_t^J) - \log(\hat{C}_t^J + 10^{-20})\right)^2 + \sum\left(\log(C_t^U) - \log(\hat{C}_t^U + 10^{-20})\right)^2 \\ &+ W_E\left[\sum\left(\delta E_t^J\right)^2 + \sum\left(\delta E_t^U\right)^2\right] \\ &+ W_k \sum\left(\delta k_t\right)^2 \\ &+ W_q\left[\sum\left(\delta q_t^J\right)^2 + \sum\left(\delta q_t^U\right)^2\right] \end{aligned}\right] \tag{7}$$

where C_t^J and C_t^U are the observed Japanese and U.S. catches, where W_E, W_k, and W_q are weighting factors used to set the relative importance of the different sources of deviance, and where

(8)
$$n_T = \left[\begin{array}{c} \text{count}\left(C_t^J\right) + \text{count}\left(C_t^U\right) + \text{count}\left(\delta E_t^J\right) + \text{count}\left(\delta E_t^U\right) \\ + \text{count}\left(\delta k_t\right) + \text{count}\left(\delta q_t^J\right) + \text{count}\left(\delta q_t^U\right) \end{array} \right]$$

$$n_T = 45 + 7 + 45 + 7 + 44 + 44 + 6 = 198$$

A further modification of this model was made to accommodate catch of swordfish by fleets for which there is no information on effort, or very unreliable information (Taiwan and Korea longline and Japanese drift gillnet). During a part of the time series this "cryptic" catch amounted to a substantial portion of the harvest. To account for it without knowledge of associated effort or catchability, the model was modified to force removal of an observed cryptic catch, C_t^C, in each time step. Thus Equation 3 is changed to:

(9)
$$N_{t+1} = \frac{(1+r)N_t}{1 + r\left(\frac{N_t}{k_t}\right)^{m-1} + F_t} - C_t^C$$

Of course the model is now unstable because the abundance at the beginning of a time step (first term on the right in the above equation) might not be enough to satisfy the cryptic catch (second term above) in which case the abundance will be negative. However, I was able to force the model fitting procedure to avoid negative situations by two further modifications. At each time step instead of directly calculating N_{t+1} from equation 9, a temporary, trial abundance is calculated, i.e.

(10)
$$N_{temp} = \frac{(1+r)N_t}{1 + r\left(\frac{N_t}{k_t}\right)^{m-1} + F_t} - C_t^C$$

Then N_{t+1} is taken to be

(11)
$$N_{t+1} = \frac{\left(\left|N_{temp}\right| + N_{temp}\right)}{2}$$

$$\Omega \leftarrow \Omega + \left(\left|N_{temp}\right| - N_{temp}\right)^2$$

that is, the average of N_{temp} and its absolute value. Thus, if N_{temp} is positive, N_{t+1} is set to N_{temp}, but if N_{temp} is negative, N_{t+1} is set to zero. In addition, at each time step a penalty term is added to the objective function:

so that when the fitting procedure tries to go into regions of negative abundance it receives a penalty of the square of twice the magnitude of the projected negative values. In practice, all final converged values of the objective function till now have had a penalty of zero, though there could well have been some positive penalties on the path to convergence.

Natural Mortality and Recruitment Model:

This model is similar in many ways to the model detailed above in that the input data are the same and same techniques are used for model fitting and for accommodating the cryptic catch. However the concept of carrying capacity and maximum rate of natural increase are replaced by explicit elements for recruitment and mortality. The basic differential equation for this model is:

$$\frac{\partial N}{\partial t} = R - ZN \quad ; \quad Z = F + M \tag{12}$$

Integrating over unit time steps and incorporating cryptic catch produces the following difference equation:

$$N_{t+1} = \frac{R_t}{Z_t} + \left(N_t - \frac{R_t}{Z_t}\right)e^{-Z_t} - C_t^C \quad ; \quad Z_t = F_t^J + F_t^U + M \tag{13}$$

with Japanese and Hawaiian catch given by

$$C_i^J = \frac{F_i^J}{Z_t}(R + N_t - N_{t+1}) \quad ; \quad C_i^U = \frac{F_i^U}{Z_t}(R + N_t - N_{t+1}) \tag{14}$$

Effort deviations and time varying catchability is specified as in the Pella-Tomlinson model. Recruitment is directly estimated as an auto-correlated time series similar to the carrying capacity and catchability time series in the Pella-Tomlinson model. Thus recruitment is given by

$$R_t = R_{t-1}e^{\delta R_{t-1}} \quad ; \quad R_1 = R_0 \tag{15}$$

The unfished equilibrium abundance does not appear explicitly in this model, but would be given by *R/M* from Equation 12 with F set to zero. Thus in analogy to the Pella-Tomlinson model, the starting abundance is given by

$$N_0 = \beta \frac{R_0}{M}$$

The estimated parameters for this model are:

Parameter symbol	*Parameter description*	*Count*
R_0	Recruitment at start	1
δR_t	R-deviations	44
M	Natural Mortality	1
β	Starting abundance as fraction of R_0/M	1
δE_t^J	Japanese *E*-deviations	45
δE_t^U	US *E*-deviations	7
q_0^J	Japanese catchability at start	1
δq_t^J	Japanese *q*-deviations	44
q_0^U	US catchability in year 39	1
δq_t^U	US *q*-deviations	6
	Total	151

The objective function is given by

$$\Omega = \frac{n_T}{2}\left[\begin{array}{l} \sum\left(\log(C_t^J) - \log(\hat{C}_t^J + 10^{-20})\right)^2 + \sum\left(\log(C_t^U) - \log(\hat{C}_t^U + 10^{-20})\right)^2 \\ \quad + \; W_E\left[\sum\left(\delta E_t^J\right)^2 + \sum\left(\delta E_t^U\right)^2\right] \\ \quad + \; W_R \sum\left(\delta R_t\right)^2 \\ \quad + \; W_q\left[\sum\left(\delta q_t^J\right)^2 + \sum\left(\delta q_t^U\right)^2\right] \end{array}\right] \tag{16}$$

where

$$n_T = \left[\begin{array}{c} \text{count}\left(C_t^J\right) + \text{count}\left(C_t^U\right) + \text{count}\left(\delta E_t^J\right) + \text{count}\left(\delta E_t^U\right) \\ + \text{count}\left(\delta R_t\right) + \text{count}\left(\delta q_t^J\right) + \text{count}\left(\delta q_t^U\right) \end{array}\right] \tag{17}$$

$$n_T = 45 + 7 + 45 + 7 + 44 + 44 + 6 = 198$$

Results

Some difficulty was encountered in fitting the models to the data. The parameters must be bounded to prevent the searching procedure from wandering into unreasonable territory. However, runs were rejected if one or more of the parameters converged close to or against a boundary. For at least some settings of weighting factors, there were multiple minima in the objective function. Also, for some settings and some regions of parameter space, the Hessian matrix was not positive definite, that is, the objective function was flat or curved downward in one or more dimensions. With judicious use of parameter bounds, starting search at various points in parameter space, and fitting in phases (keeping some parameters constant till convergence is achieved in other parameters) – i.e. many of the "tricks of the trade" available with AD Model Builder – some examples of convergence to reasonable parameter values were obtained.

Pella-Tomlinson Model:

The fitting procedure converged most readily when most of the residual error was ascribed to effort deviations rather than to catch deviations by setting a low value of the weighting factor for effort deviations, W_E. Figure 5 shows the results obtained with W_E set to 0.1 implying that our uncertainty in effective effort is about 10 times greater than our uncertainty about catch. The result is very small deviations in catch and large ones in effort. Note that there are stanzas lasting several years during which the effort deviations are either all positive or all negative. In this run of the model the weighting factors for catchability and carrying capacity deviations, W_q and W_k, were both set to 100, which effectively inhibits variability in those factors. Therefore the q and k lines are flat. In this, and all other runs of the model, the abundance is projected for 10 years beyond the end of the data (to year 2006) assuming no fishing effort and a constant k equal to k in the last year of the data. The estimate of r (ca. 2% per year) is low, but the fishing mortality is even lower on average, which means a low exploitation rate. The shape parameter, m, in this and all other fittings of this model is approximately 2, implying a quadratic shape to the yield versus effort curve. The abundance at the start of the time series is almost three times k. So the scenario features a population with the following characteristics: has a slow turnover rate; was somehow pushed way above its carrying capacity prior to the start of the fishery; is slowly decaying toward that carrying capacity; is largely unaffected by the mild exploitation of the fishery.

For the results given in Figure 6, W_q and W_k were set to 0.1, which gives q and k some freedom to vary in time. Much of the effort deviation of the previous run is now absorbed by variation in q with the result that the effort deviations are smaller than previously, and runs of all positive or all negative deviation are not so apparent. The estimate of r is even smaller than before, but fishing mortality is about three times larger than before and also about three times larger than r – an extraordinarily high exploitation rate. In this case k remained constant even though it had freedom to vary, and the starting abundance is greater relative to k than before. The scenario in this case is one of an even slower turnover in the population that, again, was somehow pushed above its carrying capacity. The fishery is taking advantage of this windfall by heavily exploiting the population, and if that exploitation rate were to continue, the abundance would no doubt eventually decay to much less than the carrying capacity.

Figure 7 shows results of a run in which the weighting factors and parameter bounds were identical to those in the run shown in Figure 6, but the starting point in parameter space was different. In particular, the k-deviations started out with non-zero estimates resulting from a run with W_k set to 0.01, that is, with even greater freedom of variation. With these starting values the estimation procedure converged to a very different set of parameter estimates. In this case k varies in time, and r is much greater (ca. 20% per year) than in either of the previous runs, so much so that the exploitation rate is now low even though the fishing mortality is hardly different from the previous run. In this scenario the population is turning over rapidly and tracking with some delay the variations in the carrying capacity while the fishery, with its low exploitation rate, has little effect. The runs shown in Figures 6 and 7 are an example of multiple minima in the objective function.

Recruitment and Mortality Model:

This model had more difficulty in converging than the Pella-Tomlinson model, although it converged readily with R- and q-deviations effectively turned off (large values of W_R and W_q). The conditions of this run correspond to the Pella-Tomlinson run shown in Figure 5. The results (Figure 8) are roughly similar, but with an even lower exploitation rate and not quite as large a discrepancy between the starting abundance and the equilibrium abundance.

Figure 9 shows results with q-deviations still turned off but some freedom for the R-deviations (W_R set to 0.6). There is some fluctuation in recruitment, but other than that the results are similar to the previous run. For the results in Figure 10, W_R was diminished slightly to 0.5, and the results are dramatically different, demonstrating an extreme sensitivity to a weighting factor. In fact, the Figure 10 does not represent a true convergence because two parameters, R_0 and M, are pushed against their upper bounds (10^9 and 0.9 respectively). Raising the bounds by orders of magnitude just resulted in these parameters pushing against their bounds again. This is an example of "runaway" parameter estimates. Attempts to free up the q-deviations gave similar results in that more than a very mild amount of variation in q also produced runaway parameters.

Holding M to a fixed value (0.2 yr^{-1}) prevented R_0 from running away, and allowed a proper convergence with considerable freedom of variation in catchabilities and in R (Figure 11). In this case the catchabilities, q^J and q^U, are an order of magnitude higher than in other runs presented above, as is the fishing mortality, which is relatively close on average to M. Therefore there is a substantial exploitation rate, but not extraordinarily high as in Figure 6. As a result, the abundance is held substantially below the carrying capacity until the fisheries (in the model) close in 1997, and thereafter the abundance climbs toward its equilibrium. In contrast to Figure 7 with its overall decline in carrying capacity (and abundance), in this scenario the carrying capacity and abundance are trending upwards. However, the abundance is much lower.

Discussion

The results obtained with these models indicate a variety of contrasting possible scenarios varying from declining to rising abundance trends, from slow to fast turnover rates, and from minimal to very high exploitation rates. This, together with the difficulty that these models show in converging on reasonable parameter estimates, indicates that the fishery data may not contain enough "contrast", i.e. not enough information, to easily determine the model parameters. As a consequence, there is little power in the data now at hand to resolve the differences between the various scenarios. Multiple minima in the objective function, great sensitivity to weighting factors, and runaway parameter estimates are all indicative of lack of contrast. This is in spite of the large variation in effort. The problem is that the population must respond to the changing effort in order to produce a useful signal, but if the maximum of a variable exploitation rate is still very light, there will be little discernable response in the dynamics of the population, and the variations will be mostly related to environmental variables. From that point of view, Figure 7, the Pella-

Tomlinson results with varying k, is perhaps the most realistic scenario, but because of the sensitivity to the choice of weighting factors, it seems premature to accept those results as definitive.

The problem with low contrast is worse for the natural mortality and recruitment model than for the Pella-Tomlinson because it attempts to disassemble the parameter r, which represents net productivity, into components of gross production and mortality. This requires more information than just determining the net production. Using up some of the degrees of freedom by allowing q or R_0 to vary, makes disassembly of net production impossible. Therefore R_0 and M can vary boundlessly as long as net production stays about the same, which results in runaway parameter estimates. Fixing one of these parameters (M) to an assumed value allowed proper convergence on the other. Perhaps a Bayesian prior probability distribution applied to either or both parameters would also allow proper convergence. Another possibility, currently being tested, is to replace the variable recruitment series with a two-parameter recruitment function, which would use up many fewer degrees of freedom than the recruitment series.

In addition to the problem of contrast, a likely source of difficulty is that the structures of these models are badly inconsistent with the data, that is, the biological and other processes coded in the models could be inconsistent with the real processes that produced the data. Figure 11 is instructive in this regard. Recruitment, R_t shows a bump in early 1990s that could be accommodating the increase in fishing mortality as the Hawaiian fishery starts up. It would be interesting to see if the other variations in R_t are associated with major changes in the distribution of the Japanese fishery. Of course what really matters is the distribution of the fishery in relation to the distribution of the fish, which is also changeable. In the model, the fish "stock" is a well-defined entity, and any changes in abundance of that stock are related to processes of recruitment and mortality. But what could be really happening is that the boundaries of what might nebulously be called the "effective" stock might be changing geographically, that is, the effective definition of what constitutes the "stock" – what is in and what is out – might be changing in time. Until we come to grips with this problem, any stock assessment will always be imbued with basic questions such as: abundance of what?; fishing effort applied to what?; and so on. These questions will remain as long as our assessment models insist on treating the resource as a "unit stock" even with more sophisticated models that deal with catch at age. The way forward seems to me to involve recognizing the spatial heterogeneity in the swordfish populations and the fisheries and incorporating that heterogeneity explicitly in spatially disaggregated models as has been done for albacore and yellowfin tuna in the south Pacific. Such models will necessarily need to deal with movement of fish as well as fleets. They will also require new sources of data, particularly tagging data, which not only give greater power to estimate parameters of population dynamics in a local area, but also power to estimate movement or exchange rates of fish between local areas.

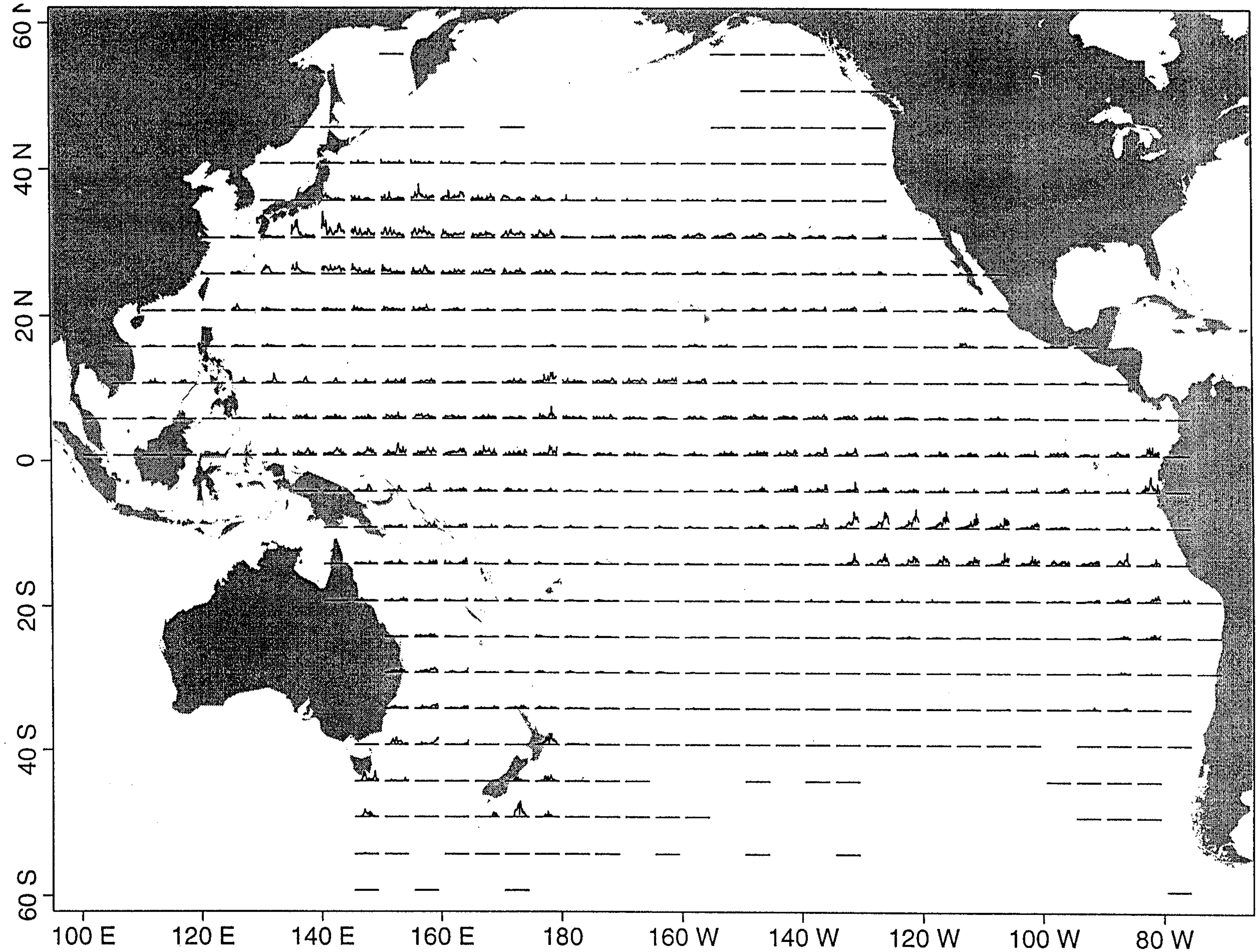

Figure 1. Catch, effort and CPUE for the Japanese longline fleet throughout the Pacific Ocean.

See Correction

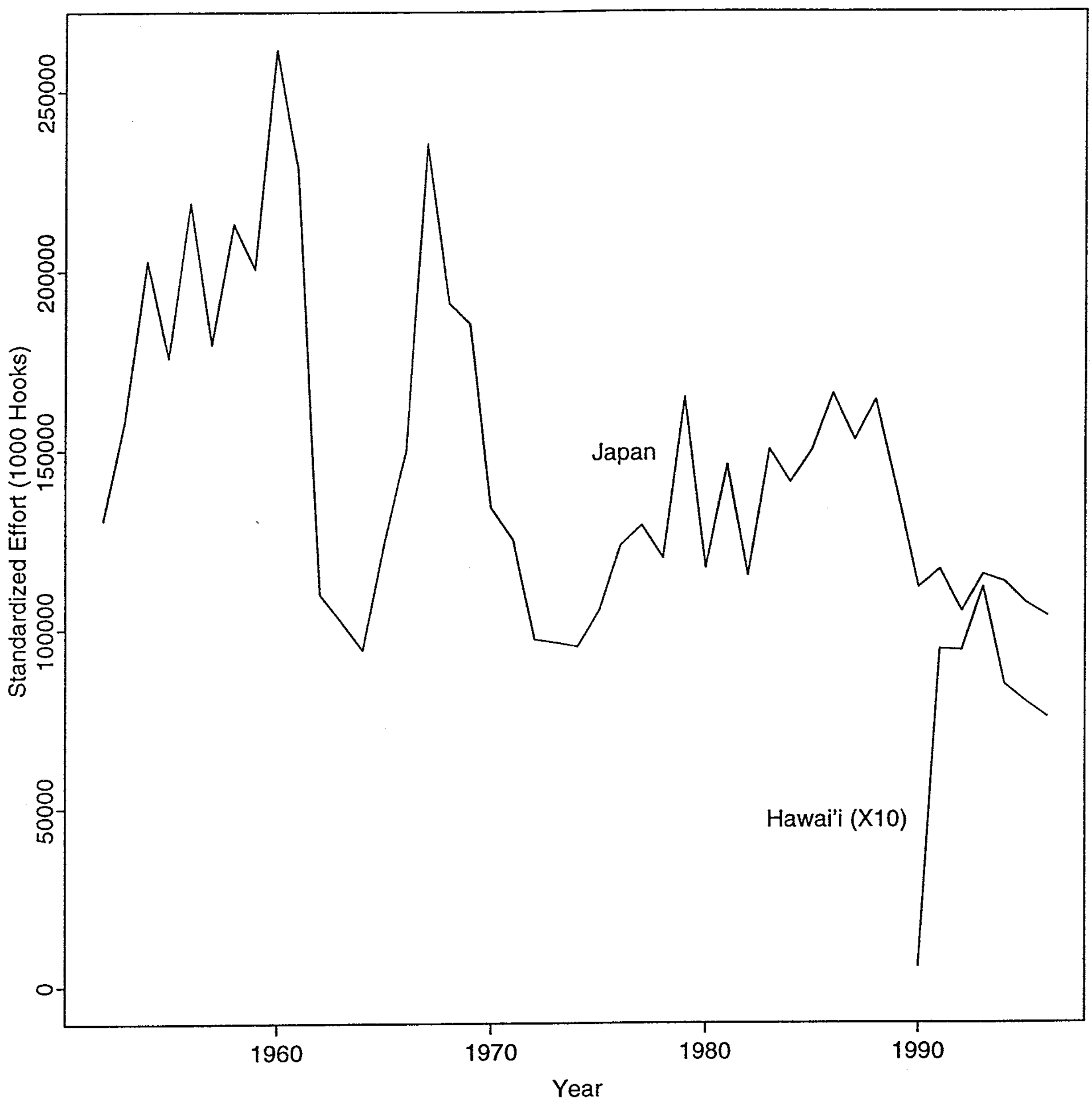

Figure 2. Effective swordfish effort for Japanese and Hawaiian longline fleets. Effective effort is the catch aggregated by year divided by the average CPUE in each year (CPUE averaged over 5 degree squares). For the Hawaiian data, the CPUE was determined only from trips identified as swordfish (---or mixed?---) trips.

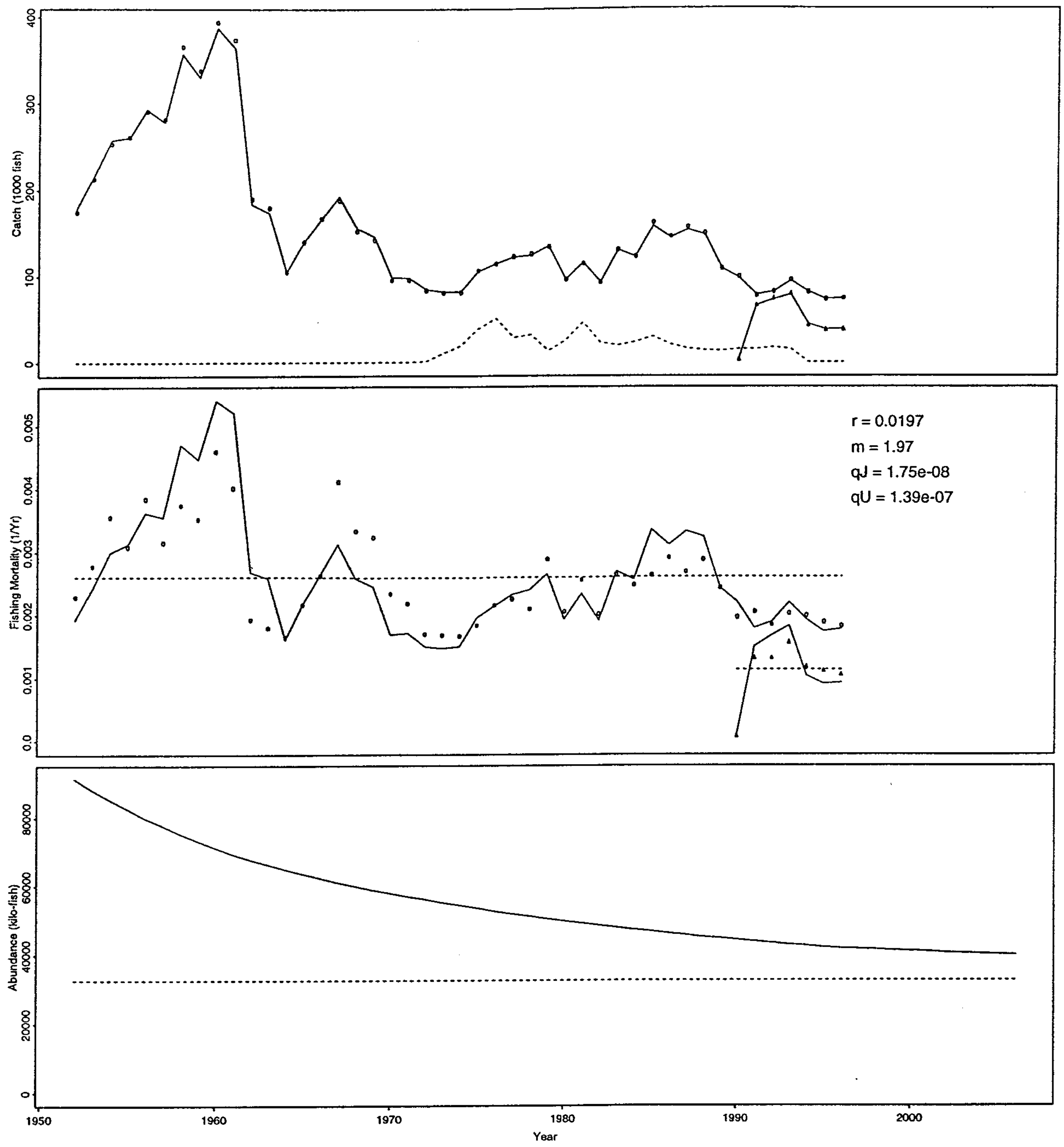

Figure 5. Results of fitting Pella-Tomlinson model (W_E= 0.1, W_q= 100, W_k= 100).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for *r*, *m*, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated carrying capacity (k_t).

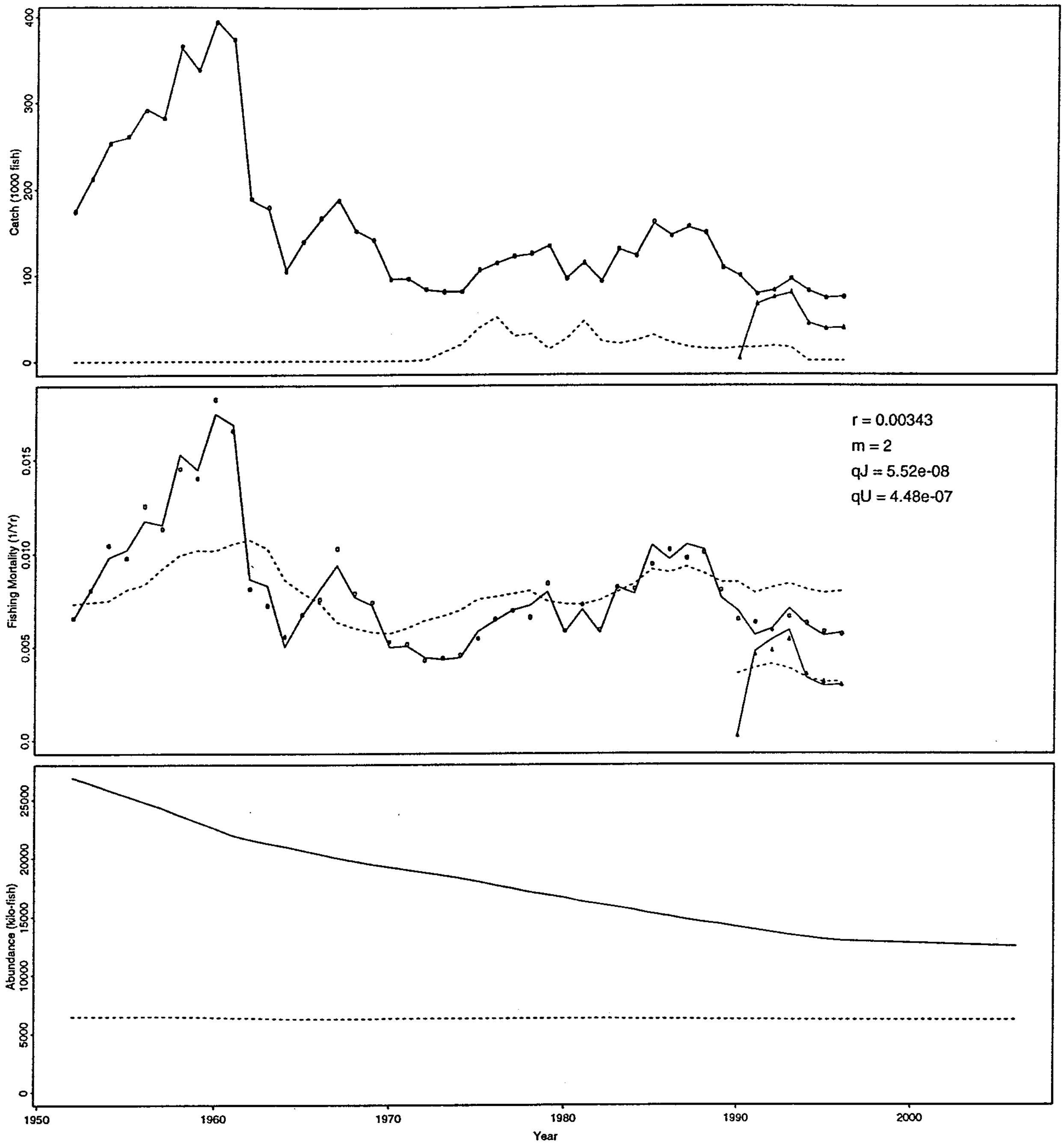

Figure 6. Results of fitting Pella-Tomlinson model ($W_E = 0.1$, $W_q = 0.1$, $W_k = 0.1$ – first try).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated carrying capacity (k_t).

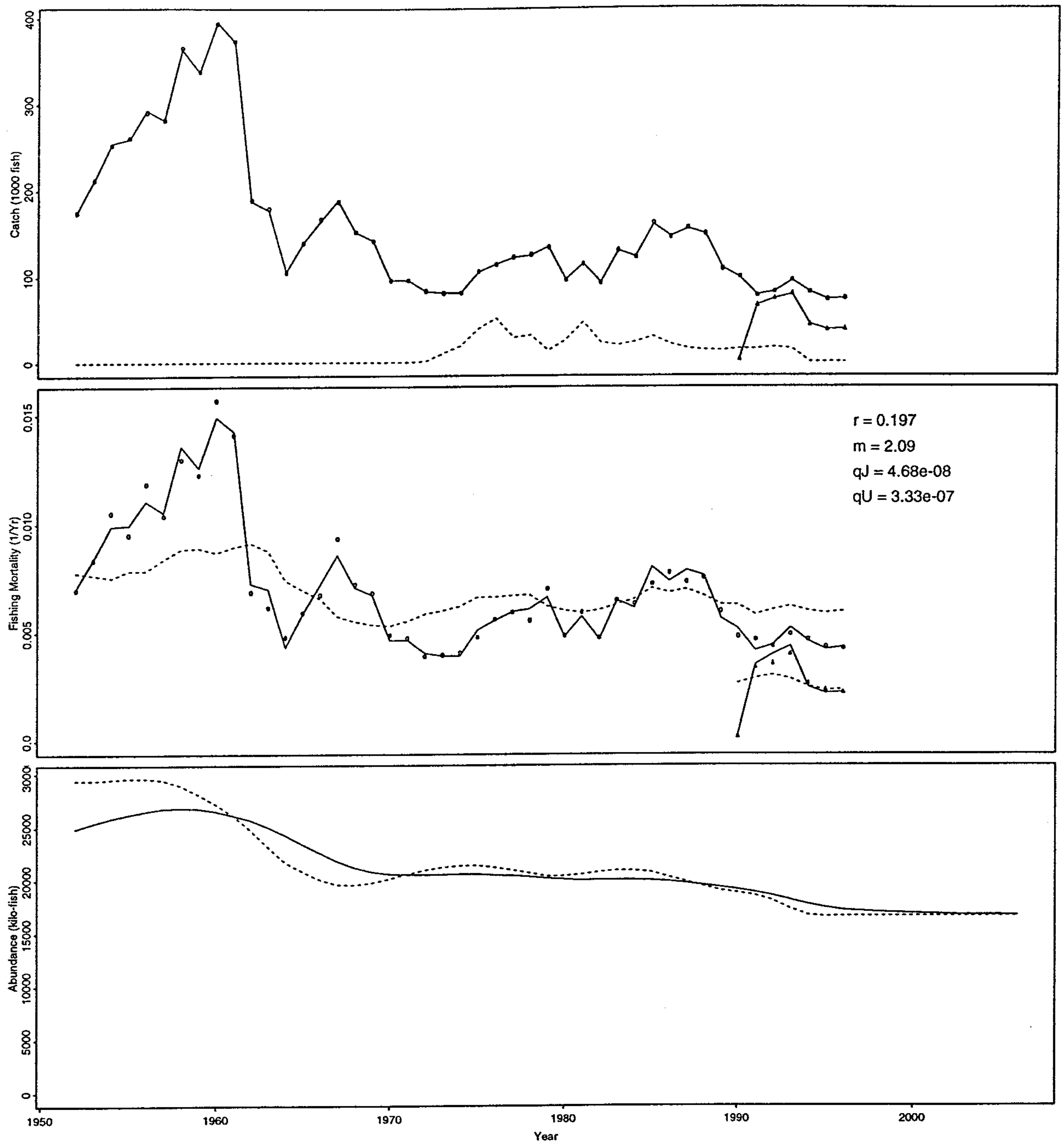

Figure 7. Results of fitting Pella-Tomlinson model ($W_E = 0.1$, $W_q = 0.1$, $W_k = 0.1$ – second try, different starting values).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated carrying capacity (k_t).

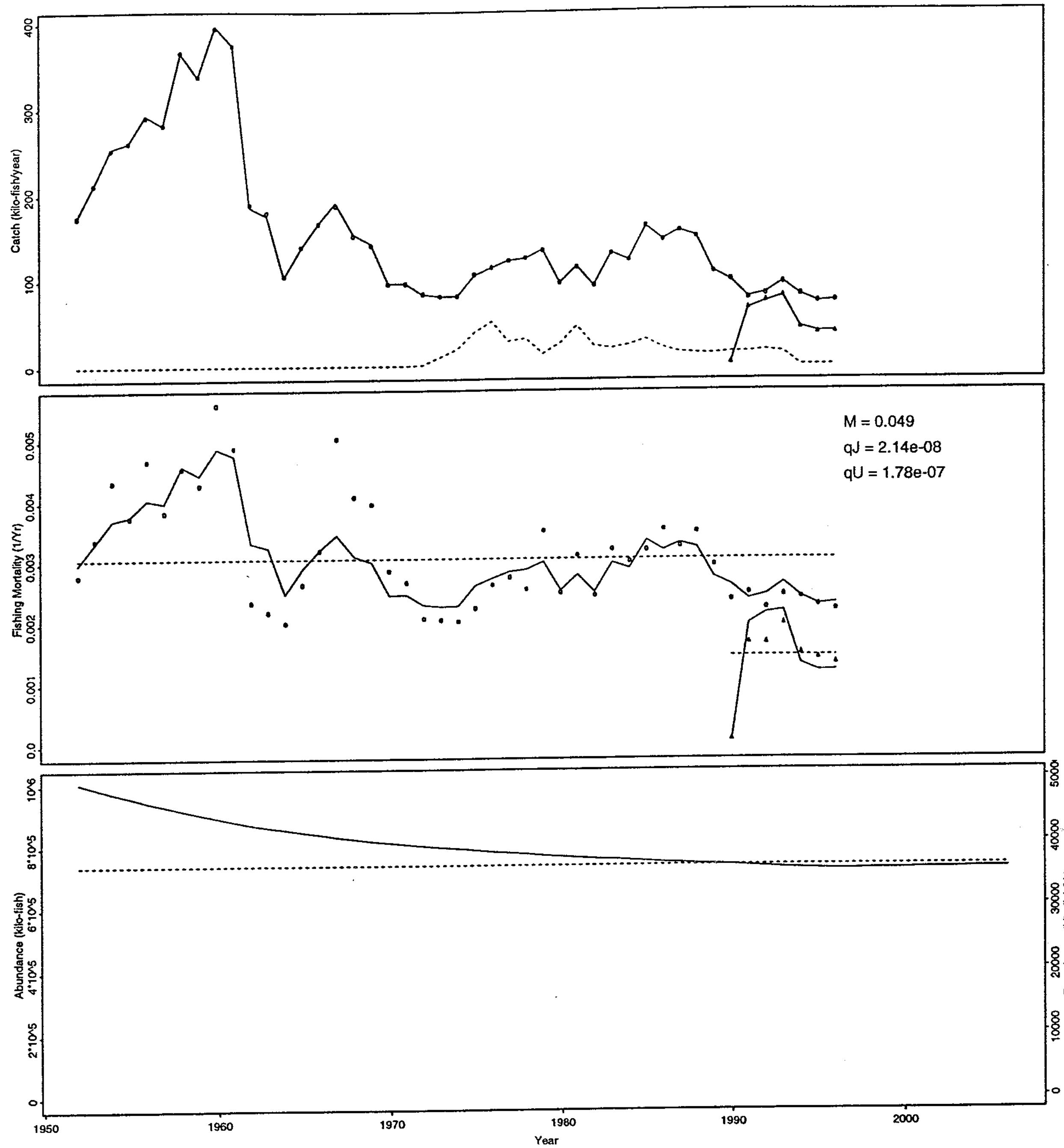

Figure 8. Results of fitting directly estimated recruitment model ($W_E = 0.1$, $W_q = 100$, $W_R = 100$).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated recruitment, R_t (right hand scale) or equilibrium abundance, R_t/M (left hand scale).

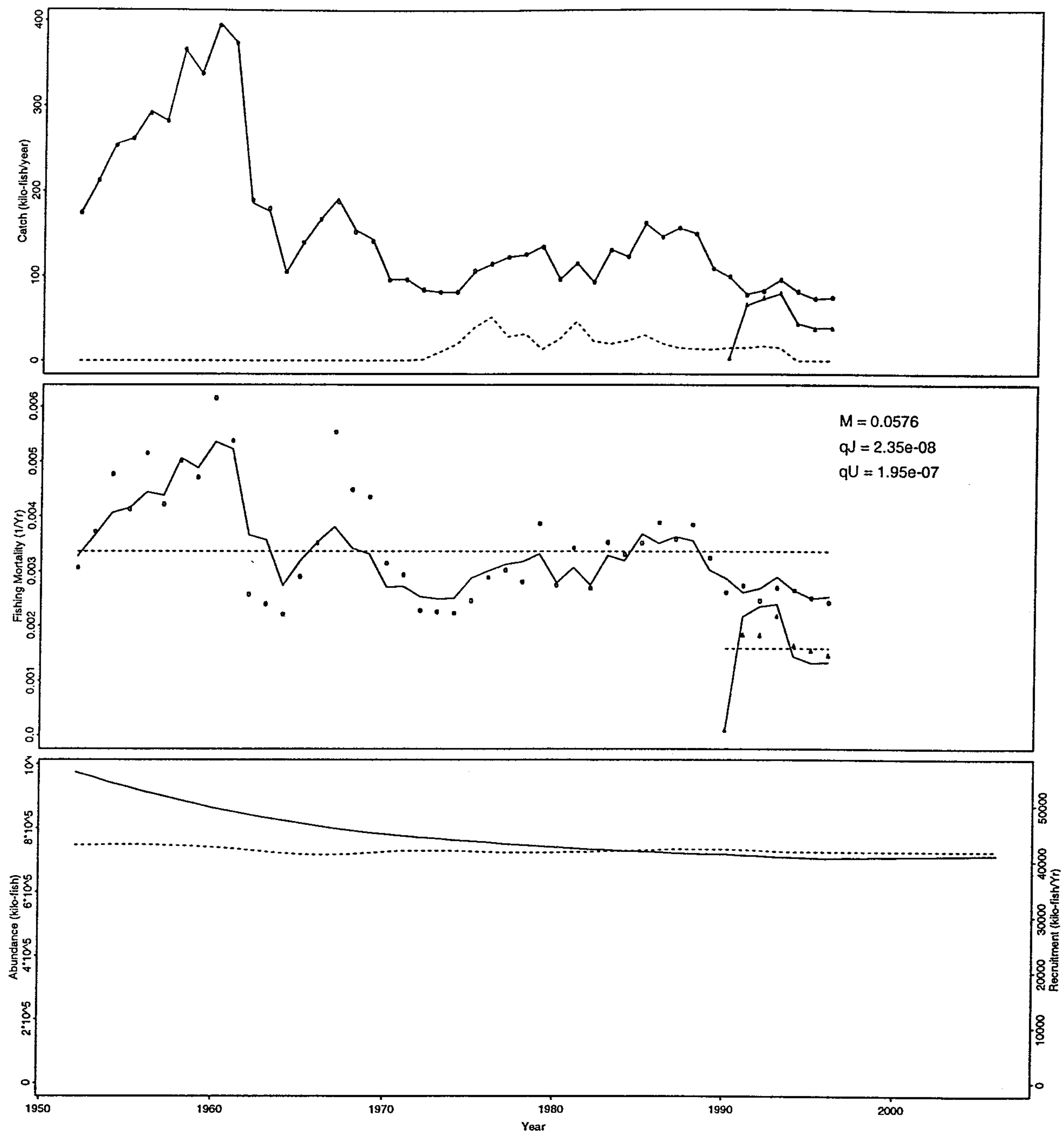

Figure 9. Results of fitting directly estimated recruitment model ($W_E = 0.1$, $W_q = 100$, $W_R = 0.6$).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated recruitment, R_t (right hand scale) or equilibrium abundance, R_t/M (left hand scale).

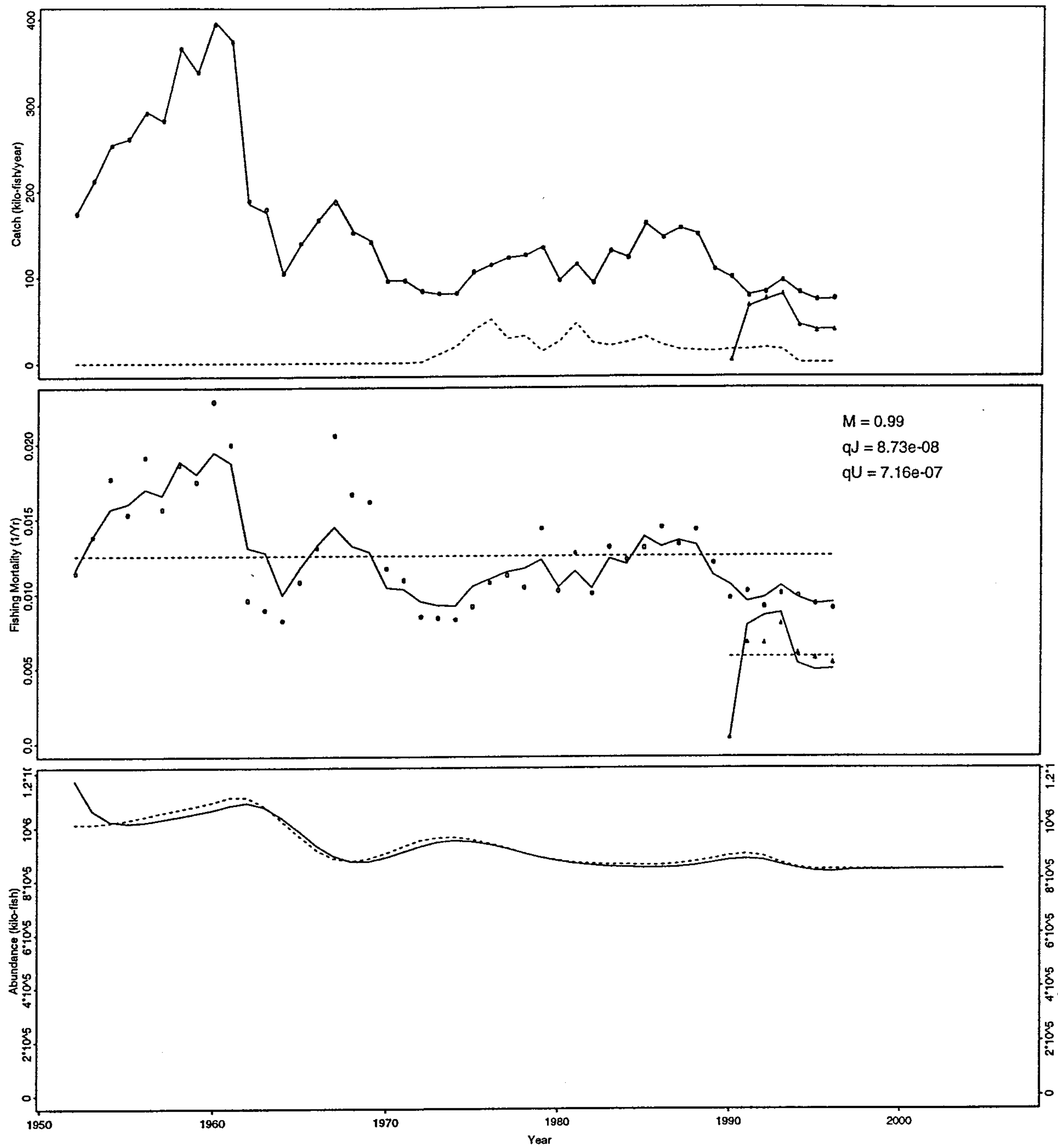

Figure 10. Results of fitting directly estimated recruitment model ($W_E = 0.1$, $W_q = 100$, $W_R = 0.5$).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated recruitment, R_t (right hand scale) or equilibrium abundance, R_t/M (left hand scale).

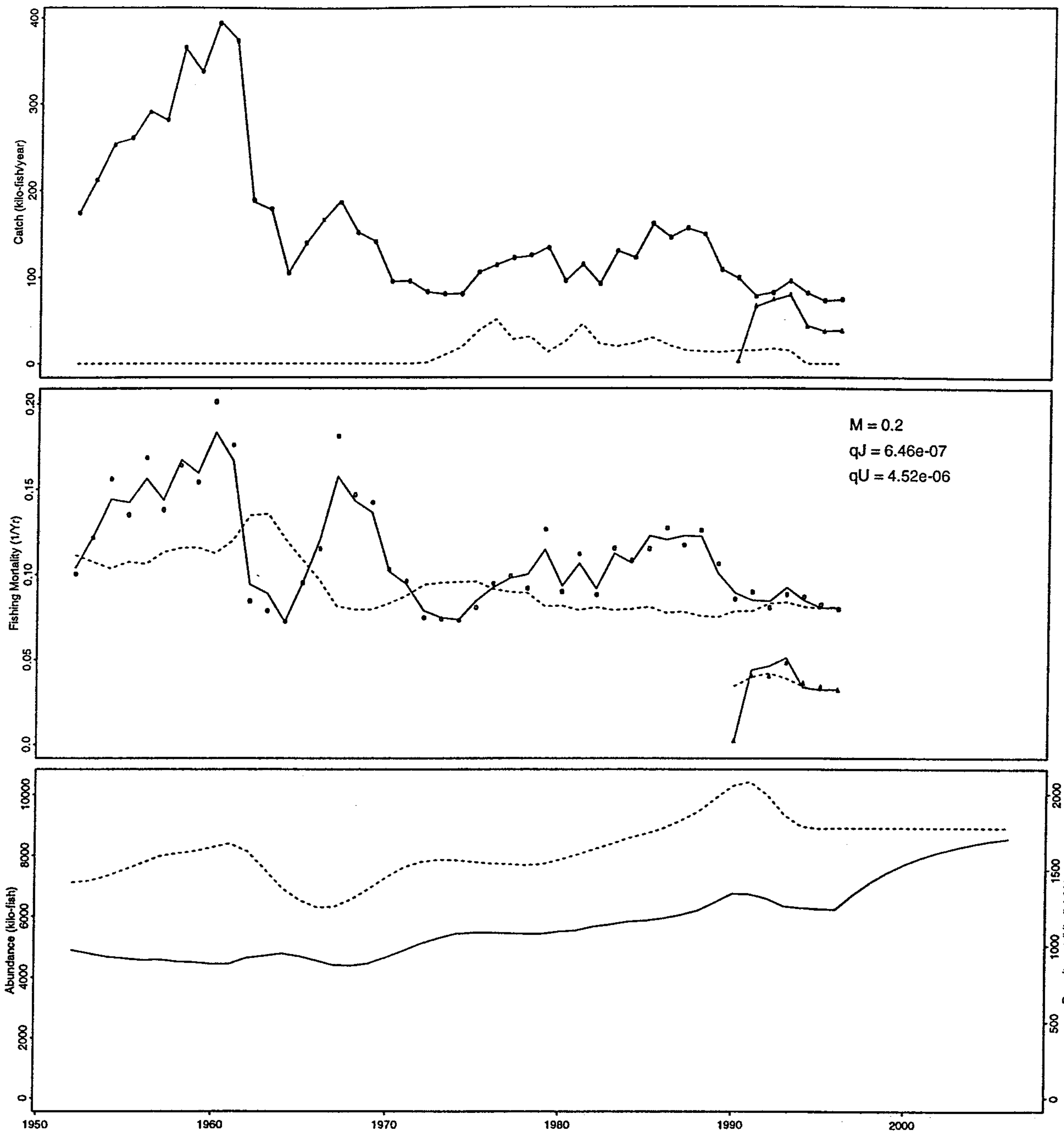

Figure 11. Results of fitting directly estimated recruitment model ($W_E = 0.1$, $W_q = 0.1$, $W_R = 0.05$, M fixed at 0.2).

Top: Solid lines – Japanese and Hawaiian longline swordfish catch predicted from model ($\hat{C}_t^J$ and $\hat{C}_t^U$). Points – observed catch (C_t^J and C_t^U). Dashed line – "cryptic" catch (C_t^C – see text).

Middle: Solid lines – swordfish fishing mortality exerted by Japanese and Hawaiian fleets (F_t^J and F_t^U). Points – fishing mortality before adjusting by effort deviations ($q_t^J E_t^J$ and $q_t^U E_t^U$ – see Equation 4). Dashed lines – catchability series multiplied by mean efforts ($q_t^J \overline{E}^J$ and $q_t^U \overline{E}^U$) to show catchability on the same scale. Estimated values for r, m, and averages over time of q_t^J and q_t^U in legend.

Bottom: Solid line – Estimated abundance (N_t). Dashed line – estimated recruitment, R_t (right hand scale) or equilibrium abundance, R_t/M (left hand scale).