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Future Projections of the Western and Central North Pacific Striped Marlin Stock

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Abstract

Stock projections were conducted to evaluate the impact of various levels of fishing intensity on future spawning stock biomass and catch based on the recent stock assessment of WCNPO striped marlin stock. The stochastic projections were implemented to incorporate variability of terminal numbers at age in the stock assessment that were propagated forward in future possibilities and uncertainty of potential future recruitment process to reflect the incompleteness of knowledge about the state of nature and ultimately, cast the results in a probabilistic analysis. Decision table reported spawning stock biomass in terminal projection year (2017) relative to 2012 indicated that the current level of exploitation (rate or level) is likely to be unsustainable if future recruitment is about 2004-2008 level. Reductions in the fishing are predicted to decrease some risk and would likely produce larger increase of yield in 2017 relative to 2012 than current level.

Introduction

In December 2011, the Billfish Working Group (BILLWG) of the International Scientific Committee completed the second full stock assessment (SA) of striped marlin found in the Western and Central area of the North Pacific (Piner *et al.* 2011 and BILLWG 2012a). The SA was conducted using Stock Synthesis (SS), an age structured and length based model of population dynamics (Methot 2005; 2011). Based on the life history of the species, the stock is assumed to be both productive (Piner and Lee 2011a; 2011b) and resilient (Brodziak 2011). Despite the productivity of the stock, the assessment results indicated that current fishing mortality (expressed as $F_{X\%}$ and defined as the average of 2007-2009) was above F_{MSY} and spawning biomass was below SB_{MSY}. Providing management bodies with alternative management options and their resulting effects on this stock are needed.

Stock assessment models simplify the causation of population dynamics into process, with the introduction of maximum complexity in those processes deemed the most important or best informed by the data. Important structural complexity in the striped marlin SA included: single sex annual model with observations and derived quantities evaluated on a quarterly timescale, natural mortality (*M*) was assumed to be age-specific, estimation of initial age structure, and fishery selectivity patterns for some fisheries were time varying. Other important structure in the SA model included: recruitment was based on the Beverton and Holt spawner recruit model and due to the long protracted spawning season and variability in juvenile growth, calculated spawning biomass used in the spawner-recruit (SR) relation and the timing of recruitment occurs in different seasons. Recruitment estimated in the model from 1975-

2008, with the 2009 and 2010 taken from the spawner-recruit relation. The first quarter began on January 1st which was consistent with how data was developed (primarily CPUE). The assessment included sensitivity analyses to various assumed parameters. Finally we note that important complexity not included in the model was: sex-specificity, explicit spatial structure and time varying life-history traits.

Forecasts of future stock response to fishing can be done with much more simplified dynamic models as we no longer need to fit to observed data. The objectives of this paper were to 1) develop a simplified projection model to describe expected trends in future spawning biomass and catch. 2) evaluate in a stochastic projection various levels of uncertainty that reflect the incompleteness of knowledge about the state of nature governing the recruitment process. This includes uncertainty in the SA estimates of terminal population size. 3) Evaluate the role of fishing intensity on future spawning stock biomass and 4) cast the results in a probabilistic analysis.

Materials and Methods

Basic dynamics

Projections were performed using software developed for the US West Coast groundfish fisheries, the basic dynamics are annual and were described by Punt (2010) for version 3.12b using an age-structured population dynamics model:

$$N_{y,a} = \begin{cases} R_y & \text{if } a = 0 \\ N_{y-1,a-1}\, e^{-Z_{y-1,a-1}} & \text{if } 0 < a < a_{max} \\ N_{y-1,a_{max}-1}\, e^{-Z_{y-1,a_{max}-1}} + N_{y-1,a_{max}}\, e^{-Z_{y-1,a_{max}}} & \text{if } a = a_{max} \end{cases}$$

where *y* is the projecting year,

$N_{y,a}$ is the number of fish at age *a* in the start of year *y*,
R_y is the recruitment during year *y*,
a_{max} is the oldest age during year *y*,
$Z_{y,a}$ is the total mortality at age *a* during year *y*:

$$Z_{y,a} = M_a + F_y \sum_f S_a^f \eta^f$$

M_a is the instantaneous rate of natural mortality at age *a*,
F_y is the fishing mortality at fully-selected (i.e. $\sum_f S_a^f \eta^f \rightarrow 1$) age during year *y*,
S_a^f is the selectivity by fishery *f* at age *a*,
η^f is the relative weighting factor by fishery *f* determined by the proportion of maximum selectivity at age for each fishery in which $\sum_f \eta^f = 1$.

Annual fishing mortality is either specified or determined by solving the catch equation:

$$C_y^f = \sum_{a=0}^{a_{max}} \frac{w_a^f N_{y,a} S_a^f \eta^f F_y}{Z_{y,a}} (1 - e^{-Z_{y,a}});\; C_y = \sum_f C_y^f$$

where w_a^f is the weight at age *a* caught by fishery *f*.

To do the projections, the following quantities from the stock assessment were required:

1. Terminal numbers at age (2010) to start projection;
2. Selectivity at age (S_a^f) for each fishery to govern age structure of catch by fishery;
3. Weight at age (w_a^f) for each fishery to govern the weight of catch within fishery;
4. Fecundity at age (φ_a) (population weight at age *proportion mature at age) to calculate spawning biomass which is $\sum_{a=0}^{15} \varphi_a N_{y,a}$;
5. Assumptions of future recruitment process;
6. Natural mortality to govern natural deaths;
7. Maximum age (a_{max}) treated as a plus group for projection.

Data structure for projections

Forecasts of future stock response to fishing were conducted with simplified dynamic models as observed data were not fit in projections. The model structure was simplified from the base-case stock assessment (Table 1). The stock assessment calculated expected dynamics seasonally, but projections calculated dynamics (e.g. catch, spawning biomass) annually. Within the stock assessment, the first season started January 1st (January-March) which was consistent with how data was compiled. However, for projections the year began July 1st, which corresponded to the timing of recruitment in the stock assessment model (season 3). In the stock assessment model, natural mortality (*M*) was modeled as age specific, with each age-class moving to the next on January 1st and therefore subjected to the next age-classes *M*. Because our projections used a birth year, age specific *M* was a combination of the *M* from July-December and next January-June as was consistent with the stock assessment. Spawning biomass in the stock assessment model was calculated at the beginning of a protracted spawning season (season 2). In the projections, spawning biomass was calculated for July 1st. Numbers at age used to start the projection were from season 3 (July 1st) in the stock assessment model.

Compilation of fleet selectivity patterns and weights at age

The assessment model contained a total of 18 individual fisheries with 10 fisheries containing observations of the proportion of length at age. Fisheries without observations of the proportion of length at age were assumed to share a selectivity pattern with a similar fishery that was consistent with the assumptions in the stock assessment. To simplify projections the fisheries were reduced from 18 to 3 based on similarity of the selectivity patterns, defined as follows:

1. **Asymptotic fishery**: JPN_DRIFT (F5), JPN_OTHER_early (F11) and JPN_SQUID (F7) that was assumed to mirror the F5 selectivity pattern;
2. **Longline fishery**: All domed-shape selectivity patterns that did not take age 0 catch including the JPN_DWLL2 (F2), JPN_DWLL3 (F3), JPN_CLL (F4), JPN_OTHER_late (F12), TWN_LL (F13) and other fisheries that were assumed to have selectivity patterns that mirrored these fisheries;
3. **Age 0 fishery**: Domed-shaped selectivity patterns that allow age 0 catch including the JPN_DWLL1 (F1), HW_LL (F16) and WCPO_OTHER (F17).

Selectivity at age *a* by fishery *f* used in the projections was calculated using derived quantities obtained from the stock assessment model as:

$$S_a^f = \frac{C_a^f}{N_a}$$

where f is the aggregated fisheries used in the projections that have similar selectivity pattern, C_a^f is the aggregated catch (in numbers) by fishery f at age a, N_a is the number of fish at age a in the start of birth year. Selectivity was normalized (0-1) across ages for each fishery and averaged for the years 2007-2009. Similarly, weight-at-age within fishery was the average of fishery weight-at-age for the season that most of the catch was taken during 2007-2009. Weight-at-age was taken from season 3 for asymptotic fishery and from season 1 for longline and age 0 fisheries.

Uncertainty

Different sources of uncertainty have been identified when conducting the stochastic projections (Francis and Shotton 1997). Three key sources of uncertainty were considered in the stochastic projections, the predicted numbers at age in the final year of the stock assessment (i.e. 2010), which were the first year of the projection, alternative processes that govern the future recruitment, and performance measure describing the future performance of the fishery under each of the alternative management options.

Initial population size-at-age

Initial population size-at-age uncertainty for the projections was simulated from the assumed multivariate normal distributions using parametric bootstrap method, where the maximum likelihood estimates (MLE) of the initial population size at age vector from the stock assessment model and its estimated covariance matrix formed the sampling distribution. 100 uncorrelated samples were simulated from the number at age during the 2012 meeting (BILLWG 2012b). Some of the random multivariate normal samples contained small negative values, on the order of -0.0001, for one of the older age classes (age 10 above) that were converted to absolute values. This conversion had a negligible effect on the overall mean population size of the samples because the negative values were very small numbers.

State of nature (future recruitment process)

Alternative processes that govern the future recruitment were explored:

1. Recruitment (R): Re-sample estimates of recruitment (R_y) for a pre-specified set of historical years from the stock assessment that represents the likely future recruitment;
2. Recruits per Spawner (R/SB): Re-sample estimates of recruits per spawner ratio (R_y/SB_y) for a pre-specified set of historical years from the stock assessment that represents the likely future recruitment given the spawning biomass;
3. Spawner-recruit deviation (σ_R) around the spawner-recruit relation (SR): Recruitment deviations from the spawner-recruit relation estimated in the stock assessment were evaluated for temporal autocorrelation (Durbin-Watson) and that level of autocorrelation included in the analysis.

$$R_y = \frac{4hR_0SB_y}{SB_0(1-h) + SB_y(5h-1)} e^{\varepsilon_y - 0.5\sigma_R^2}$$

$$\varepsilon_y = \rho\varepsilon_{y-1} + \sqrt{1-\rho^2}\delta_y;\ \delta_y \sim N(0, \sigma_R^2)$$

where ρ is the extent of temporal auto-correlation in the residuals about the stock-recruitment relationship, ε is the error follows a first-order autoregressive process and each δ_y is normally distributed with mean 0 and variance σ_R^2.

The future stock status of striped marlin is dependent on the true state of nature of the production of future recruits. Re-sampling R/SB implies a linear relationship of spawners and recruits. Harvest strategies that reduce spawning biomass will directly reduce recruitment and quickly drive the stock to unacceptable levels. In contrast, low exploitation levels result in unrealistic optimism as re-sampling R/SB implies no density dependent reduction in recruitment at large spawning stock sizes, which is to say there is no compensation (i.e., steepness = 0.2). If the true state of nature is R, this implies the other extreme. Namely, recruitment is not strongly tied to changes in spawning biomass and may imply a more environmentally driven stock hypothesis (i.e., steepness = 1). The use of expectations of SR relationship allows some extent of compensation rather than assuming either one of two extremes (constant recruitment or constant recruits/spawner), and is also more internally consistent in the assessment model assuming a particular form of SR model.

Mean of steepness was estimated as 0.87 from the independent study (Brodziak 2011). This suggested that the hypothesis of no compensation (re-sampling R/SB) is less plausible than compensation hypothesis (re-sampling R) or hypothesis of SR relation for the WCNPO striped marlin. BILLWG could not make decision on which process will best describe future recruitment. The projections were conducted using both recruitment (R) and spawner-recruit (SR) relation hypotheses to move forward.

Harvest scenarios

Projections started in 2010 (July 1st-June 30st) and continued through 2017. The first two years of the projection (2010, 2011) were assumed to have the current exploitation level ($F_{14\%}$) or imputed catch (2,500 mt) depending on the management options and fishery allocations defined in the stock assessment as the average of the period 2007-2009. Starting on July 1st, 2012, additional projections with varying fishing intensities were conducted. Spawning stock biomass (SB) in terminal projection year (2017) relative to 2012 was used as the performance measure to describe the future performance of the fishery by percentiles (5th, 25th, median, 75th and 95th) of 4,000 simulations (40 simulations for 100 samples of population sizes).

Projections were conducted 8 years, 6 levels of harvest rates and 2 levels of constant catches.

1. Constant $F_{X\%}$ levels (6 levels):
    - average during 2001-2003: $F_{12\%}$;
    - average during 2007-2009 defined as current: $F_{14\%}$;
    - F_{MSY}: $F_{17.8\%}$;
    - $F_{20\%}$;
    - $F_{30\%}$;
    - No fishing: $F_{100\%}$;

2. Constant catch (2 levels):
    - 80% of average catches during 2007-2009: 2,500 mt;
    - 80% of highest catches during 2000-2003: 3,600 mt (CMM 2010-01).

Results and discussion

Life history and fishery parameters used in the projections are given in Table 2 and July 1st estimates of spawning biomass can be found in Appendix. The estimates of *M* at age are somewhat lower than the base case reflecting the birth year cycle. Selectivity at age and resulting weights at age for the aggregated 3 fleets are representative of the base case only.

Based on the recruitment time series (Figure 1), projections resampled recruitments from 1994-2008 due to the lower and less variation recruitment estimated than early period (1975-1993). Recruitment prior to 1994 appeared to be from a somewhat higher spawning biomass estimates and corresponds to generally higher levels of recruitment. Recent recruitment from 2004-2008 appeared to be at the lowest level and was resampled in the projections as one of states of nature. Recruitment from 2009-2010 were not re-sampled in the projections as those estimates were the expectations of the spawner-recruit (SR) relation.

The stock assessment assumed h=0.87 with σ_R=0.6 (model estimate=0.62). The same assumption was used to generate deviations from around the SR relation. A negative but insignificant temporal auto-correlation of recruitments were found from 1975-2008 (p=0.32) and insignificant correlation from 1994-2008 (p=0.46) and 2004-2008 (p=0.12). Because the autocorrelation was generally weak, no autocorrelation was assumed in the deviations for the projections.

Results of projections were summarized in the decision table for alternative $F_{X\%}$ and catches (Table 3). The decision table reported spawning stock biomass in terminal projection year (2017) relative to 2012, where alternative fishing intensities and catches were implemented. Projected trajectory of median spawning stock biomass and catch from 2012 to 2017 were shown in Table 4 and Table 5, respectively.

Constant $F_{X\%}$scenarios

When current (2007-2009) $F_{14\%}$ level is maintained, the stock is projected to have less than 25% probability of SB_{2017} < SB_{2012} under the recruitment hypotheses of $R_{y=1994-2008}$ and SR, but have greater risk of SB_{2017} < SB_{2012} (between 75% and 95%) under the recruitment hypothesis of $R_{y=2004-2008}$. If fishing increases to 2001-2003 level ($F_{12\%}$), the probability of SB_{2017} < SB_{2012} increases. Conversely, if fishing reduces to MSY level ($F_{17.8\%}$) or lower extent at $F_{20\%}$, stock would have zero chance to fall below 2012 level for $R_{y=1994-2008}$ and SR, yet still have certain risk of SB_{2017} < SB_{2012} for $R_{y=2004-2008}$. When fishing reduces to $F_{30\%}$, spawning stock biomass will certainly be above 2012 level for all recruitment hypotheses and have 50% of chance to rebuild to SB_{MSY} level by 2015 for $R_{y=1994-2008}$ and SR. If there is no fishing after 2012, spawning stock biomass will have 50% of chance to rebuild to the SB_{MSY} level by 2014 for all recruitment hypotheses.

Across all states of nature, fishing at the $\mathrm{F}_{20\%}$ level provides a safe level of harvest if one takes less than 50% of risk as a threshold. In the next few years reducing fishing from the current level to $\mathrm{F}_{20\%}$

level would likely lead to some reduction in yield; however this reduction of yield would be less through projected years. Also, fishing at $F_{20\%}$ level would likely produce larger increase of catches in 2017 relative to 2012 than current level.

Constant catch scenarios

When catch is reduced 20% from current level (average 2007-2009) which is about 2,500 mt, spawning stock biomass is projected to have zero chance to fall below 2012 level for $R_{y=1994-2008}$ and SR but have some risk of SB_{2017} < SB_{2012} (between 50% and 75%) for $R_{y=2004-2008}$. If catches increases to 3,600 mt (about 80% of highest catches during 2000-2003), the stock is projected to have zero chance to fall below 2012 level for SR, less than 25% chance of SB_{2017} < SB_{2012} for $R_{y=1994-2008}$, and greater risk of SB_{2017} < SB_{2012} (between 75% and 95%) for $R_{y=2004-2008}$.

Across all states of nature, constant catches at levels ≤2,500 mt appear sustainable if one takes 50% of risk as a threshold. However catches at 3,600 mt increase the risk in particular under assumptions of $R_{y=2004-2008}$ and is not supported by the future exploitable biomass.

It is also apparent that the uncertainty in stock trends (across states of nature and reasonable exploitation levels), as expressed by the largest % decline or increase, is quite a bit larger in the constant catch management practices than constant fishing intensity management practices. Therefore caution should be used if constant catch based management is considered.

There are additional sources of uncertainty that were not evaluated in the projections (Francis and Shotton 1997), in particular, model uncertainty and additional parameter uncertainty. This assessment included sensitivity analyses to various assumed parameters and it was noted that the assessment model was most sensitive to the assumptions about spawner-recruit steepness (*h)* and natural mortality (*M)*. Projections of this stock that integrate across different life history models could draw a more realistic conclusion of uncertainty in the percentiles describing the tails. One example of additional parameter uncertainty is the true strength of the 2009 and 2010 recruitments. The stock assessment sampled those recruitment levels from the expectations of the SR curve because of a lack of information in the model to inform those estimates. In the projections these same levels were assumed to be consistent with the stock assessment. As true recruitment is either above or below the expected, the short term forecast may be biased.

This stock assessment changed the fundamental productivity of the stock by increasing stock turnover (*M*) and resilience (*h*) based on the best available estimates (Brodziak 2011; Piner and Lee 2011a; 2011b). These changes have made the stock resistant to significant levels of fishing. Despite these optimistic changes in life history, the current stock biomass is low and increases in the exploitation level above that observed recently has a real probability of driving spawning biomass lower.

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Table 1. Comparison of model structure of stock assessment model with projection model.

Model structure	Stock assessment	Projection
Dynamics calculated	Quarterly	Annually
Year	January-December	July-June
Spawning biomass calculated	April	July
Recruitment	July	July
Selectivity patterns (number of fisheries, age- or length- based assumption)	18, length	3, age
Age-based natural mortality changes	January 1st	July 1st

Table 2. Age-specific model parameters used in the projection.

Age	Fecundity-at-age (season 3)	Natural mortality-at-age	Fishery 1 (young domed-shape)		Fishery 2 (domed-shape)		Fishery 3 (asymptotic-shape)	
			Weight-at-age	Selectivity-at-age	Weight-at-age	Selectivity-at-age	Weight-at-age	Selectivity-at-age
0	0.00	0.505	18.14	0.08	22.92	0.00	3.51	0.00
1	1.16	0.450	30.13	0.54	33.95	0.31	35.40	0.14
2	5.52	0.415	40.76	0.86	41.90	0.73	46.31	0.46
3	14.63	0.39	49.97	1.00	49.28	0.99	55.56	0.72
4	27.00	0.38	57.55	0.91	56.13	1.00	64.25	0.85
5	40.15	0.38	63.67	0.72	62.25	0.90	72.43	0.92
6	52.36	0.38	68.58	0.55	67.55	0.79	79.91	0.95
7	62.9	0.38	72.52	0.43	72.02	0.70	86.50	0.97
8	71.65	0.38	75.69	0.34	75.73	0.63	92.14	0.98
9	78.76	0.38	78.22	0.28	78.76	0.58	96.86	0.99
10	84.47	0.38	80.24	0.24	81.23	0.55	100.76	0.99
11	89.01	0.38	81.86	0.22	83.22	0.52	103.94	1.00
12	92.62	0.38	83.14	0.20	84.81	0.51	106.50	1.00
13	95.47	0.38	84.15	0.19	86.09	0.49	108.55	1.00
14	97.71	0.38	85.72	0.18	88.06	0.48	110.19	1.00
15	101.165	0.38	85.72	0.17	88.06	0.47	112.77	1.00

Table 3. Decision table of projected percentiles of relative spawning stock biomass in 2017 relative to 2012 (SB_{2017}/SB_{2012}) for alternative states of nature (columns) and harvest scenarios (rows). Fishing intensity ($F_{X\%}$) alternatives are based on 12% (average 2001-2003), 14% (average 2007-2009 defined as current), 17.8% (MSY level), 20%, 30%, and 100% (no fishing). Catch alternatives are based on the 80% of average catches during 2007-2009 (2,500 mt) and 80% of average catches during 2000-2003 (3,600 mt). Red blocks indicate the declining trend of SB in 2017 from 2012 where SB_{2017}/SB_{2012} is less than one.

Run	Harvest scenario	Recent recruitment ($R_{y=2004-2008}$)					1994-2008 recruitment ($R_{y=1994-2008}$)					Beverton-Holt spawner-recruit relation (SR)				
		5th	25th	50th	75th	95th	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
1	$F_{2001-2003} = F_{12\%}$	0.45	0.51	0.61	0.75	0.87	0.72	0.87	0.98	1.06	1.18	0.66	0.88	1.06	1.25	1.52
2	$F_{2007-2009} = F_{14\%}$	0.53	0.61	0.72	0.86	1.00	0.85	1.03	1.14	1.23	1.36	0.83	1.09	1.29	1.51	1.82
3	$F_{MSY} = F_{17.8\%}$	0.69	0.79	0.92	1.09	1.25	1.12	1.32	1.45	1.55	1.69	1.14	1.47	1.72	1.98	2.34
4	$F_{20\%}$	0.78	0.89	1.05	1.21	1.39	1.26	1.48	1.62	1.72	1.88	1.32	1.68	1.95	2.24	2.62
5	$F_{30\%}$	1.19	1.34	1.58	1.76	1.97	1.90	2.18	2.35	2.48	2.68	2.08	2.56	2.91	3.28	3.79
6	No fishing = $F_{100\%}$	3.37	3.65	4.21	4.53	4.96	4.93	5.49	5.82	6.06	6.47	5.43	6.33	7.07	7.81	8.72
7	Catch = 2,500 mt	0.61	0.71	0.95	1.27	1.80	1.41	1.97	2.33	2.67	3.10	1.63	2.49	3.23	4.03	5.28
8	Catch = 3,600 mt	0.60	0.65	0.75	0.88	1.12	0.98	1.18	1.48	1.80	2.25	1.05	1.51	2.20	3.01	4.37

Table 4. Projected trajectory of median spawning stock biomass (*SB* in mt) for alternative states of nature (columns) and harvest scenarios (rows). Fishing intensity ($F_{X\%}$) alternatives are based on 12% (average 2001-2003), 14% (average 2007-2009 defined as current), 17.8% (MSY level), 20%, 30%, and 100% (no fishing). Catch alternatives are based on the 80% of average catches during 2007-2009 (2,500 mt) and 80% of average catches during 2000-2003 (3,600 mt). Green blocks indicate the projected *SB* is greater than MSY level (SB_{MSY}=2,713 mt).

Run	Harvest scenario	Recent recruitment ($R_{y=2004-2008}$)						1994-2008 recruitment ($R_{y=1994-2008}$)						Beverton-Holt spawner-recruit relation (SR)					
		2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017
1	$F_{2001-2003} = F_{12\%}$	1229	995	838	769	746	744	1333	1320	1311	1309	1309	1306	1317	1314	1342	1362	1383	1394
2	$F_{2007-2009} = F_{14\%}$	1229	1102	963	898	884	879	1333	1439	1495	1510	1522	1525	1317	1431	1529	1610	1667	1703
3	$F_{MSY} = F_{17.8\%}$	1229	1260	1176	1169	1140	1135	1333	1615	1790	1870	1916	1929	1317	1601	1838	2024	2160	2261
4	$F_{20\%}$	1229	1331	1287	1318	1291	1287	1333	1692	1936	2064	2133	2162	1317	1679	1985	2238	2423	2572
5	$F_{30\%}$	1229	1558	1698	1859	1935	1943	1333	1942	2447	2792	3015	3135	1317	1923	2509	3033	3483	3830
6	No fishing = $F_{100\%}$	1229	2069	2928	3750	4585	5170	1333	2491	3890	5340	6639	7755	1317	2468	3957	5692	7524	9320
7	Catch = 2,500 mt	1537	1670	1553	1486	1548	1461	1640	2145	2641	3109	3499	3825	1625	2141	2787	3546	4386	5243
8	Catch = 3,600 mt	1537	1455	1276	1239	1168	1158	1640	1845	2023	2188	2313	2419	1625	1854	2171	2584	3056	3568

Table 5. Projected trajectory of catch (mt) for alternative states of nature (columns) and harvest scenarios (rows). Fishing intensity ($F_{X\%}$) alternatives are based on 12% (average 2001-2003), 14% (average 2007-2009 defined as current), 17.8% (MSY level), 20%, 30%, and 100% (no fishing). Catch alternatives are based on the 80% of average catches during 2007-2009 (2,500 mt) and 80% of average catches during 2000-2003 (3,600 mt).

Run	Harvest scenario	Recent recruitment ($R_{y=2004-2008}$)						1994-2008 recruitment ($R_{y=1994-2008}$)						Beverton-Holt spawner-recruit relation (SR)					
		2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017	2012	2013	2014	2015	2016	2017
1	$F_{2001-2003} = F_{12\%}$	3700	2794	2536	2427	2412	2408	4471	4403	4378	4402	4399	4376	4373	4431	4520	4586	4588	4648
2	$F_{2007-2009} = F_{14\%}$	3303	2677	2537	2412	2379	2383	3974	4113	4201	4240	4246	4224	3884	4154	4374	4543	4652	4745
3	F_{MSY} $=F_{17.8\%}$	2732	2442	2372	2328	2281	2285	3267	3649	3868	3948	3971	3962	3195	3685	4066	4374	4583	4740
4	$F_{20\%}$	2476	2311	2275	2275	2234	2239	2955	3412	3663	3782	3818	3819	2890	3441	3878	4232	4491	4680
5	$F_{30\%}$	1690	1786	1863	1923	1915	1919	2001	2559	2912	3108	3187	3220	1957	2574	3103	3533	3881	4139
6	No fishing = $F_{100\%}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Catch = 2,500 mt	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
8	Catch = 3,600 mt	3218	2657	2453	2394	2342	2346	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600

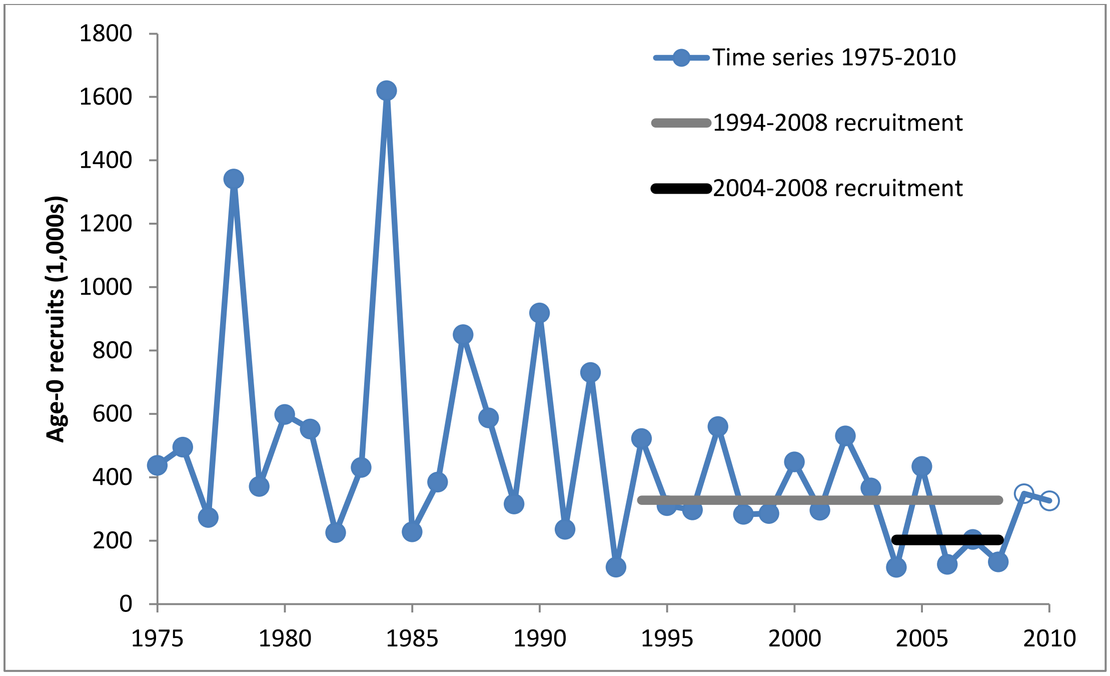

Figure 1. Historical trends in recruitment of WCNPO striped marlin (age-0) estimated by the SS3 base-case model and the assumed periods of median (1994-2008) and low (2004-2008) recruitments used for future projection scenarios.

Appendix

Input file (REBUILD.DAT) for Rebuilder version 3.12b. Exampled model was based on re-sampling recruitment for 1994-2008 using current (2007-2009) harvest rate (constant $F_{14\%}$).

```
#Title
SM 2011
# Number of sexes
1
# Age range to consider
0 15
# Number of fleets
3
# First year of projection (Yinit)
2010
# First year the oY could have been zero
2010
# Number of simulations
4000
# Maximum number of years
200
# Conduct projections with multiple starting values (0=No;else yes)
1
# Number of parameter vectors
100
# Is the maximum age a plus-group (1=Yes;2=No)
1
# Generate future recruitments using historical recruitments (1) historical recruits/spawner (2)
or a stock-recruitment (3)
1
# Constant fishing mortality (1) or constant Catch (2)
1
# Fishing mortality based on SPR (1) or F (2)
1
# Pre-specify the year of recovery (or -1) to ignore
-1
# Fecundity-at-age
# 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 1.16 5.52 14.63 27 40.15 52.36 62.9 71.65 78.76 84.47 89.01 92.62 95.47 97.71 101.165
# Age specific information (females then males) weight / selectivity
# wt and selex for "gender, fleet:" 1 1
18.138 30.132 40.759 49.969 57.554 63.668 68.579 72.523 75.687 78.221 80.244 81.855 83.135 84.151
85.716 85.716
0.082 0.539 0.864 1.000 0.908 0.724 0.552 0.425 0.339 0.282 0.245 0.220 0.203 0.191 0.182 0.171
# wt and selex for "gender, fleet:" 1 2
22.916 33.952 41.905 49.277 56.128 62.255 67.551 72.019 75.726 78.764 81.230 83.218 84.812 86.085
88.063 88.063
0.000 0.311 0.730 0.987 1.000 0.902 0.790 0.699 0.631 0.582 0.548 0.523 0.505 0.492 0.482 0.468
# wt and selex for "gender, fleet:" 1 3
3.508 35.398 46.314 55.562 64.246 72.434 79.908 86.496 92.137 96.864 100.761 103.935 106.497
108.552 110.191 112.774
0.000 0.143 0.464 0.718 0.855 0.921 0.955 0.972 0.983 0.989 0.993 0.995 0.997 0.998 0.999 1.000
# M and current age-structure
#
0.505 0.45 0.415 0.39 0.38 0.38 0.38 0.38 0.38 0.38 0.38 0.38 0.38 0.38 0.38 0.38
325.741 195.288 33.3391 17.0388 3.20836 3.7906 0.388353 0.514413 0.315897 0.0688192 0.0348344
0.00581874 0.00123893 0.000539158 7.09607E-05 4.26994E-05
# Age-structure at the start of year Yinit
325.741 195.288 33.3391 17.0388 3.20836 3.7906 0.388353 0.514413 0.315897 0.0688192 0.0348344
0.00581874 0.00123893 0.000539158 7.09607E-05 4.26994E-05
# Year Ynit^0
2010
# recruitment and biomass
# Number of historical assessment years
37
# Historical data
# year recruitment spawner in B0 in R project in R/S project
1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
```

```
553.587 437.619 495.212 273.226 1341.2 371.167 598.323 552.392 225.432 431.128 1620.01 227.933
384.917 850.16 587.473 315.874 918.588 235.848 730.792 116.484 522.354 310.626 297.155 560.111
283.161 285.668 448.599 296.043 530.666 366.455 115.912 434.196 125.377 203.907 133.143 348.68
325.741
18480.35551 5261.380563 4128.805075 3686.649436 2722.718081 2043.020893 3004.158281 3538.663066
3437.225006 3474.213756 2809.672595 2887.839776 3676.045136 3726.565643 3079.070088 2937.42805
2972.531297 3040.115075 3178.396067 3079.507117 2750.813391 2158.828683 1437.121074 1204.071824
1146.902924 1134.50934 960.7501858 985.0652582 1169.504248 1418.171721 1886.872212 2064.654692
2037.92472 1870.837326 1579.37126 1088.321873 983.0446912
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# Number of years with pre-specified catches

# catches for years with pre-specified catches

# Number of future recruitments to override
0
# Process for overiding (-1 for average otherwise index in data list)
# Which probability to product detailed results for (1=0.5; 2=0.6; etc.)
8
# Steepness sigma-R, and auto-correlation
0.87 0.62 0
# Target SPR rate (FMSY Proxy)
0.178
# Discount rate (for cumulative catch)
0.1
# Truncate the series when 0.4B0 is reached (1=Yes)
0
# Set F to FMSY once 0.4B0 is reached (1=Yes)
0
# Maximum possible F for projection (-1 to set to FMSY)
-1
# Definition of recovery (1=now only;2=now or before)
1
# Projection type (1, 2, 3, 4, 5, 11 or 12)
11
"# Definition of the ""40-10"" rule"
.01 .02
# Calculate coefficients of variation (1=Yes)
0
# Number of replicates to use
10
# Random number seed
-99004
# File with multiple parameter vectors
Marlin.dat
# User-specific projection (1=Yes); Output replaced (1->9)
1 8
# Catches and Fs (Year; 1/2 (F or C); value); Final row is -1
2010 1 1.0718
2011 1 1.0718
2012 3 0.14
2013 3 0.14
2014 3 0.14
-1 -1 -1
# Fixed catch project (1=Yes); Output replaced (1->9); Approach (-1=Read in else 1-9)
0 2 -1
# Split of Fs
2010 0.13 0.48 0.39
2011 0.13 0.48 0.39
2012 0.13 0.48 0.39
-1 -1 -1 -1
# Five pre-specified inputs
.12 .14 .2 .25 .3
# Years for which a probability of recovery is needed
2013 2014 2015 2016 2017 2018 2019 2020
# Time varying weight-at-age (1=Yes;0=No)
0
# File with time series of weight-at-age data
none
```

```
# Use bisection (0) or linear interpolation (1)
0
# Target Depletion
0.147
# CV of implementation error
0
```