ISC/05/Plenary/7

Preliminary Research Concerning Biological Reference Points Associated With North Pacific Albacore Population Dynamics and Fisheries

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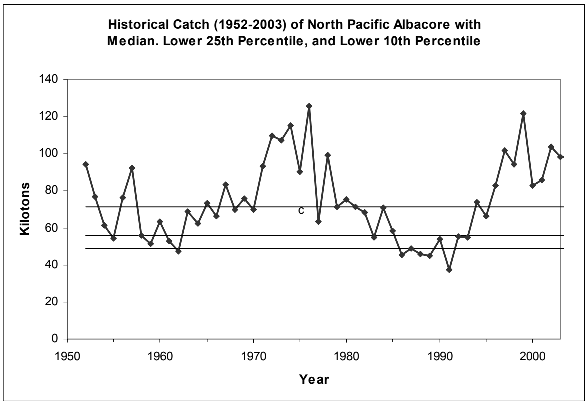
EXECUTIVE SUMMARY

The *Nineteenth North Pacific Albacore Workshop* (NPALBW19) was convened in November 2004 in Nanaimo, British Columbia, Canada. Among the workshop's recommendations is a call for additional research on biological reference points that may be appropriate for albacore management in the North Pacific.



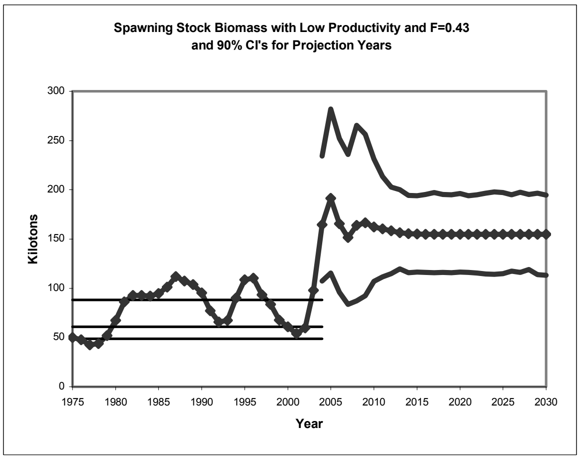
Recognizing that productive, large-scale albacore fisheries have been conducted in the North Pacific for more than 50 years, it would seem prudent to maintain the albacore spawning stock biomass (SSB) at levels that historically, have produced these catches. This paper introduces a straightforward, fishing mortality-based, reference point designed to ensure that SSB in future years remains within the range of the historically 'observed' SSB. Potential utilization of this new reference point (F_{SSB}) for albacore requires full accounting for the uncertainty in the stock assessment results and the likely uncertainty regarding future condition of the stock. Finally, the approach can be used by fishery managers to associate a probability of success to any selected F_{SSB} level – allowing full use of the precautionary principle in the face of uncertainty.

The approach is illustrated using the results of the stock assessment carried out during NPALBW19. All input parameter values and assumptions are consistent with those used in the NPALBW19 assessment. Further, the Workshop's uncertainty analyses regarding levels of stock productivity and current fishing mortality rate (F) are carried forth into the reference point analysis. More specifically, current stock conditions were projected forward for 26 years (2005-2030) with constant F under the following four scenarios:

(a) Low Productivity and Low Current F
(b) Low Productivity and High Current F
(c) High Productivity and Low Current F
(d) High Productivity and High Current F

where 'low productivity' was represented by the mean recruitment (R) for the period 1975-89 (R = 22.5 million recruits), and 'high productivity' was defined as the mean R for the period 1990-2000 (R = 31 million recruits). For 'low F', fishing mortality was taken to be 0.43 (i.e., arithmetic mean of ages 4-9+ in 2003), whereas the 'high F' hypothesis was based on an F of 0.68 (i.e., mean estimates of ages 7-9+ in 2003). The simulations were fully stochastic, incorporating uncertainty in the stock size estimates and other parameters from the assessment as well as uncertainty in recruitment in future years. The projection results (2005-2030) along with the time series of 'observed' SSB from the stock assessment (1975-2004) are shown below. As with the catch figure, above, the median 'observed' SSB over the assessment period, the lower 25th percentile, and the lower 10th percentile are also displayed.

[a]



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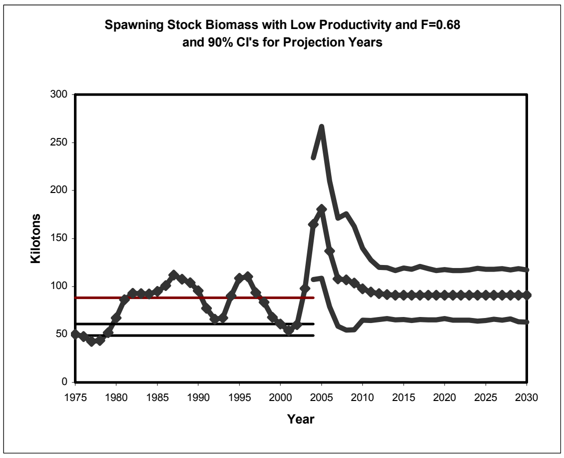

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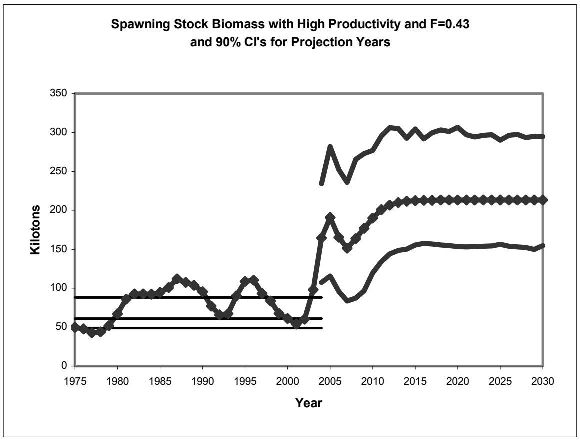

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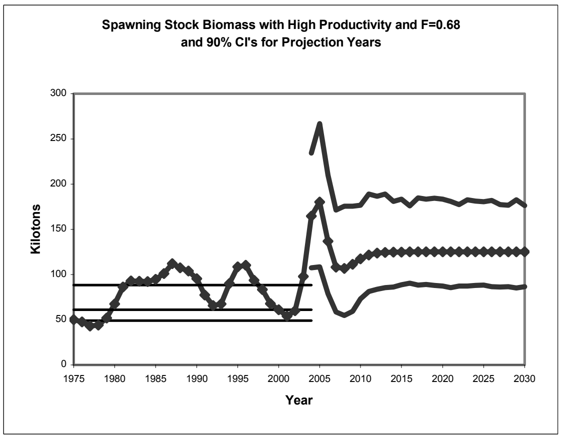
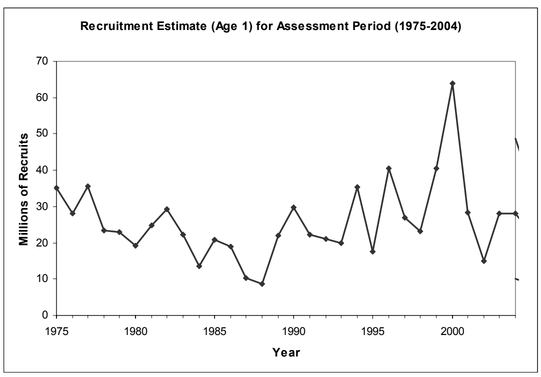


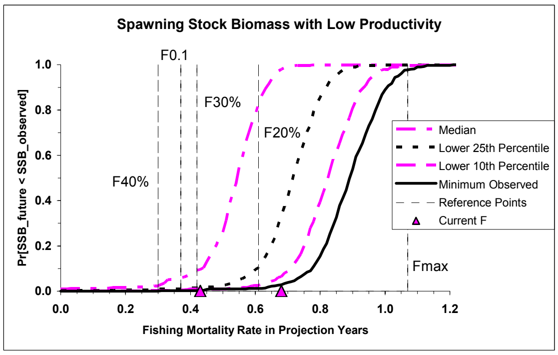
The minimum ‘observed’ SSB over the assessment period (43 kt) occurred in 1977, but SSB estimates were at a similarly low level throughout the late 1970’s. Although low SSB estimates also occurred in 1992 and again in 2001, those estimates are 54% and 26% greater than the 1977 SSB, respectively. Although formal statistical confidence intervals are not available for the early period estimates, it should be noted that the population demographics during the late 1970's are atypical in that the number of age 6+ fish is unusually small relative to younger ages. Further, it is always most troublesome (with any model) to estimate the number of older animals in the first years of the assessment period (the catch-at-age begins in 1975). It may be prudent, therefore, to consider SSB thresholds other than the minimum SSB as the basis for an F_{SSB} reference point, e.g. the lower 10th percentile of ‘observed’ SSB ($F_{SSB-10\%}$), the lower quartile ($F_{SSB-25\%}$), etc.

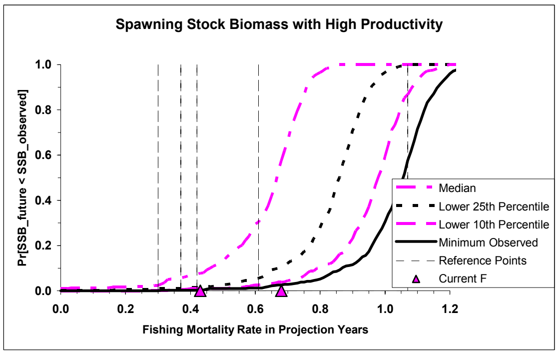


For all four scenarios, the near-term SSB forecasts are clearly dominated by an extraordinarily strong 1999 year-class (i.e. age 1 recruits in 2000), which first reached partial maturity (50%) in 2004 and then became fully mature in 2005. Retrospective analysis, carried out by the NPALBW19, indicated that the strength of the 1999 and more recent year classes may have been overestimated in the assessment. However, a retrospective (downward) correction for recent year classes was not carried out at the Workshop. This may be a useful area for future research if F_{SSB} reference points are to be considered for albacore management.

The population projections and the uncertainty about them were used to construct probability profiles. Each profile gives the probability that the SSB will fall below a specific threshold level during one or more years of the projection period. The threshold levels considered were:

(1) minimum SSB over the assessment period ($F_{SSB\text{-}Min}$);
(2) lower 10th percentile ($F_{SSB\text{-}10\%}$);
(3) lower 25th percentile ($F_{SSB\text{-}25\%}$); and
(4) 50th percentile (median) ($F_{SSB\text{-}50\%}$).





For example in the top panel (low productivity), the F that will cause SSB to fall below the minimum 'observed' SSB during one or more years of the projection period (with 50% probability) is F=0.89. For reference, the traditional reference points (from NPALBW19) are displayed as well as the 'Low F' (0.43) and 'High F' (0.68) estimates of current F.

Finally, the fishing mortality rates that will maintain the SSB above the four threshold levels (listed above) with two degrees of certainty (50% and 95%) are given the text table, below. For example, if managers desire to maintain SSB above the 25th percentile of 'observed' SSB with a 95% probability of success, then the fishing mortality rate should not exceed F=0.55 in a low productivity regime and not exceed F=0.57 in a high productivity regime. In general, a higher desired probability of success requires a more precautionary fishing mortality rate.

		Low Productivity		**High Productivity**	
		Probability Level Desired		**Probability Level Desired**	
SSB Threshold Desired		**50%**	**95%**	**50%**	**95%**
Minimum Observed SSB	$F_{SSB\text{-}Min}$	0.89	0.72	1.05	0.78
Lower 10th Percentile	$F_{SSB\text{-}10\%}$	0.82	0.66	0.98	0.71
Lower 25th Percentile	$F_{SSB\text{-}25\%}$	0.72	0.55	0.86	0.57
Median	$F_{SSB\text{-}50\%}$	0.54	0.33	0.67	0.33

Four SSB threshold levels and two probability levels are provided here but other levels may be desired by fishery managers. Expanded tables can be provided for additional threshold and probability levels.

Introduction

This paper generally addresses the topic of biological reference points important to the management of albacore fisheries of the North Pacific Ocean. Specifically, this research reflects preliminary, simulation analysis that focuses on determination of future fishing mortality (*F*) rates that result in levels of stock biomass (B) and spawning stock biomass (*SSB*) observed historically (1975-04). It is important to note that this analysis is strictly an initial, first-step research effort to better understand North Pacific albacore population dynamics associated with candidate *F*-based maximum sustainable yield (MSY) proxies, such as ($F_{20\%}$, $F_{40\%}$, $F_{0.1}$, and F_{Max}), i.e., tentative plans are underway to convene an Intersessional Meeting of the North Pacific Albacore Workshop (NPALBW) in 2005 that will address this topic to a much greater extent than presented in this analysis. In this context, readers should consult Stocker (in press, 2005) for conclusions concerning the status of the albacore stock generated from the most recent assessment conducted by the NPALBW in 2004, including biological reference point and projected abundance statistics, which generally represent the basis of this analysis

Methods

Input Data and Assumptions

This simulation analysis was based on similar input data as were used in 'Model Scenario 1' (i.e., final, NPALBW-consensus model) of the most recent VPA-based assessment conducted in November-December 2004 (namely, the *Nineteenth North Pacific Albacore Workshop*, see Stocker in press, 2005). That is, the initial conditions and vital biology-related rates used to determine candidate biological reference points and projection-related estimates associated with Model Scenario 1 were also incorporated in this analysis. Specifically, this analysis used terminal year (2004) stock numbers-at-age (N_a) and fishing mortality rate (F_{2003}) as estimated in Model Scenario 1. Age-specific estimates of weight, maturity, and natural mortality, as well as the partial recruitment (*PR*) schedule (i.e., selectivity ogive) are presented in Figure 1.

Further, the uncertainty analysis that was used to conduct the assessment above was also used in this analysis. That is, inherent uncertainty surrounding current levels of both stock 'productivity' (i.e., recruitment) and fishing pressure (i.e., *F*) was evaluated via the following table:

'Low productivity'/'Low *F*'
'Low productivity'/'High *F*'
'High productivity'/'Low *F*'
'High productivity'/'High *F*'

‘Low productivity’ represented the mean recruitment for the period 1975-89 (R = 22.5 million recruits), whereas ‘high productivity’ was defined as the mean R for the period 1990-00 (R = 31 million recruits). For ‘low F’, fishing mortality was assumed to be 0.43 (i.e., arithmetic mean of ages 4-9+ in 2003), whereas the ‘high F’ hypothesis was based on an F of 0.68 (i.e., mean estimates of ages 7-9+ in 2003). Finally, the simulation analysis was carried out 26 years, (2005-2030), with all assumed rates described above being held constant over this time period.

Annual estimates (1975-04) of important management-related stock parameters (spawning stock biomass, total biomass, and recruitment) generated from Model Scenario 1 are presented in frequency-histogram format in Figure 2, as well as the spawning stock biomass/recruitment relationship in Figure 3. Finally, the suite of F-based biological reference points – discussed in recent reports of the *North Pacific Albacore Workshop* – is illustrated in Figure 4 and provided in detail in Table 1.

Simulation and Probability Analyses

The equations and pseudo code for the simulation and probability analyses are provided in the appendix to this paper. In brief, the analyses were structured to determine the level of fishing mortality that would maintain the stock above the minimum spawning stock biomass that had been ‘observed’ over the assessment period (1975-2004). In addition to spawning stock biomass, total stock biomass and annual catch were examined in a parallel fashion. Finally, biomass threshold levels other than minimum ‘observed’ biomass were also explored.

The simulations used the best estimates of stock status from the recently completed *Nineteenth North Pacific Albacore Workshop* for its initial conditions. This included the point estimates from the population analysis as well as the full range of uncertainty about the estimates. For years in the projection period (2005-2030), recruitment variability was modeled via a Monte Carlo process using observed recruitment from the assessment period.

Results and Discussion

The results of the simulations are summarized graphically for each of the productivity/fishing mortality scenarios, i.e.

‘Low Productivity / Low F’ (Figure 5)
‘Low Productivity / High F’ (Figure 6)
‘High Productivity / Low F’ (Figure 7)
‘High Productivity / High F’ (Figure 8)

These population projections and the uncertainty about them were used to construct probability profiles for stock biomass (Figure 9), spawning stock biomass (Figure 10), and catch (Figure 11). Each profile gives the probability that stock biomass, spawning stock biomass, or catch will fall below a specific threshold level during one or more years of the projection period.

The threshold levels considered were:

- minimum biomass or catch over the assessment period;
- lower 10^{th} percentile over the assessment period;
- lower 25^{th} percentile over the assessment period; and
- 50^{th} percentile (median) over the assessment period.

For example in the top panel of Figure 9, the fishing mortality rate that will cause stock biomass to fall below the minimum 'observed' biomass during one or more years of the projection period (with 50% probability) is F=0.65. For reference, the F-based biological reference points (cf. Table 1) are displayed as well as the 'Low F' (0.43) and 'High F' (0.68) estimates of current F.

Finally, Table 2 provides the fishing mortality rates that will maintain the spawning stock biomass (SSB) above the four threshold levels (listed above) with two degrees of certainty (50% and 95%). For example, if managers desire to maintain the SSB above the 25^{th} percentile of observed SSB with a 95% probability of success, then the fishing mortality rate should not exceed F=0.55 in a low productivity regime and not exceed F=0.57 in a high productivity regime. In general, a higher desired probability of success requires a more precautionary fishing mortality rate.

Four SSB threshold levels and two probability levels are provided but other levels may be desired by fishery managers. Similar tables can also be provided for additional threshold and probability levels. Further, similar analysis can be provided for total stock biomass and catch, if desired.

References

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Ueyanagi, S. 1957. Spawning of the albacore in the Western Pacific. Rep. Nankai Reg. Fish. Res. Lab. 6:113-124.

Table 1. Rates of fishing mortality (F), annual catch (C), stock biomass (ages ≥1, B), and spawning stock biomass (SSB) for a range of F_{MSY} and F_{Limit} proxy biological reference points from uncertainty analysis associated with NPALBW19 Model Scenario 1 (Stocker *in press*). Generated statistics are based on assumptions regarding current levels of productivity (recruitment) and F: (a) high productivity/low F; (b) high productivity/high F; (c) low productivity/low F; (d) low productivity/high F. Recent estimates of fishing mortality (F_{2003}), catch (C_{2004}), stock biomass on January 1 (B_{2004}), and spawning stock biomass at the beginning of the spawning season (SSB_{2004}) are highlighted in bold. Similarly, the corresponding projected estimates in 2010 are also shown in bold. This table was adapted from the draft report of NPALBW19.

A HiPro/LoF

		F **(per yr)**		***C*** **(1,000 mt per yr)**		***B*** **(1,000 mt)**	**Percent of unfished**		***SSB*** **at mid-yr (1,000 mt)**	**Percent of unfished**
No Fishing		0.00	C_0 =	0	B_0 =	1,153	100	SSB_0 =	724	100
Potential F_{MSY} Proxy Reference Points	**F_{2003} =**	**0.43**	**C_{2004} =**	**98**	**B_{2004} =**	**438**	38%	**SSB_{2004} =**	**165**	23%
	$F_{40\%}$ =	0.30	C_{MSY} =	91	B_{MSY} =	656	57%	SSB_{MSY} =	291	40%
	$F_{30\%}$ =	0.42	C_{MSY} =	100	B_{MSY} =	562	49%	SSB_{MSY} =	216	30%
	$F_{0.1}$ =	0.37	C_{MSY} =	97	B_{MSY} =	600	52%	SSB_{MSY} =	246	34%
Potential F_{Limit} Reference Points	$F_{20\%}$ =	0.61	C_{Limit} =	107	B_{Limit} =	464	40%	SSB_{Limit} =	144	20%
	F_{Max} =	1.07	C_{Limit} =	110	B_{Limit} =	334	29%	SSB_{Limit} =	61	8%
			C_{2010} =	**92**	**B_{2010} =**	**534**		**SSB_{2010} =**	**190**	

B HiPro/HiF

		F **(per yr)**		***C*** **(1,000 mt per yr)**		***B*** **(1,000 mt)**	**Percent of unfished**		***SSB*** **at mid-yr (1,000 mt)**	**Percent of unfished**
No Fishing		0.00	C_0 =	0	B_0 =	1,153	100	SSB_0 =	724	100
Potential F_{MSY} Proxy Reference Points	**F_{2003} =**	**0.68**	**C_{2004} =**	**98**	**B_{2004} =**	**438**	38%	**SSB_{2004} =**	**165**	23%
	$F_{40\%}$ =	0.30	C_{MSY} =	91	B_{MSY} =	656	57%	SSB_{MSY} =	291	40%
	$F_{30\%}$ =	0.42	C_{MSY} =	100	B_{MSY} =	562	49%	SSB_{MSY} =	216	30%
	$F_{0.1}$ =	0.37	C_{MSY} =	97	B_{MSY} =	600	52%	SSB_{MSY} =	246	34%
Potential F_{Limit} Reference Points	$F_{20\%}$ =	0.61	C_{Limit} =	107	B_{Limit} =	464	40%	SSB_{Limit} =	144	20%
	F_{Max} =	1.07	C_{Limit} =	110	B_{Limit} =	334	29%	SSB_{Limit} =	61	8%
			C_{2010} =	**104**	**B_{2010} =**	**432**		**SSB_{2010} =**	**117**	

Table 1. Continued.

C LoPro/LoF

		F (per yr)		C (1,000 mt per yr)		B (1,000 mt)	Percent of unfished		SSB at mid-yr (1,000 mt)	Percent of unfished
	No Fishing	0.00	C_0 =	0	B_0 =	837	100	SSB_0 =	525	100
Potential F_{MSY} Proxy Reference Points	**F_{2003} =**	**0.43**	**C_{2004} =**	**98**	**B_{2004} =**	**438**	52%	**SSB_{2004} =**	**165**	31%
	$F_{40\%}$ =	0.30	C_{MSY} =	66	B_{MSY} =	476	57%	SSB_{MSY} =	211	40%
	$F_{30\%}$ =	0.42	C_{MSY} =	73	B_{MSY} =	408	49%	SSB_{MSY} =	157	30%
	$F_{0.1}$ =	0.37	C_{MSY} =	70	B_{MSY} =	435	52%	SSB_{MSY} =	178	34%
Potential F_{Limit} Reference Points	$F_{20\%}$ =	0.61	C_{Limit} =	78	B_{Limit} =	337	40%	SSB_{Limit} =	104	20%
	F_{Max} =	1.07	C_{Limit} =	80	B_{Limit} =	243	29%	SSB_{Limit} =	44	8%
			C_{2010} =	**76**	**B_{2010} =**	**419**		**SSB_{2010} =**	**162**	

D LoPro/HiF

		F (per yr)		C (1,000 mt per yr)		B (1,000 mt)	Percent of unfished		SSB at mid-yr (1,000 mt)	Percent of unfished
	No Fishing	0.00	C_0 =	0	B_0 =	837	100	SSB_0 =	525	100
Potential F_{MSY} Proxy Reference Points	**F_{2003} =**	**0.68**	**C_{2004} =**	**98**	**B_{2004} =**	**438**	52%	**SSB_{2004} =**	**165**	31%
	$F_{40\%}$ =	0.30	C_{MSY} =	66	B_{MSY} =	476	57%	SSB_{MSY} =	211	40%
	$F_{30\%}$ =	0.42	C_{MSY} =	73	B_{MSY} =	408	49%	SSB_{MSY} =	157	30%
	$F_{0.1}$ =	0.37	C_{MSY} =	70	B_{MSY} =	435	52%	SSB_{MSY} =	178	34%
Potential F_{Limit} Reference Points	$F_{20\%}$ =	0.61	C_{Limit} =	78	B_{Limit} =	337	40%	SSB_{Limit} =	104	20%
	F_{Max} =	1.07	C_{Limit} =	80	B_{Limit} =	243	29%	SSB_{Limit} =	44	8%
			C_{2010} =	**83**	**B_{2010} =**	**332**		**SSB_{2010} =**	**98**	

Table 2. Fishing mortality rates that will maintain the spawning stock biomass (SSB) above the respective threshold level with the given probability. Four distinct SSB threshold levels and two probability levels are provided but other levels may be desired by fishery managers. For example, if managers desire to maintain the SSB above the 25th percentile of observed SSB with a 95% probability of success, then the fishing mortality rate should not exceed F=0.55 in a low productivity regime and not exceed F=0.57 in a high productivity regime. In general, a higher desired probability of success requires a more precautionary fishing mortality rate.

	Low Productivity		High Productivity	
	Probability Level Desired		Probability Level Desired	
SSB Threshold Desired	**50%**	**95%**	**50%**	**95%**
Minimum Observed SSB	0.89	0.72	1.05	0.78
10th Percentile	0.82	0.66	0.98	0.71
25th Percentile	0.72	0.55	0.86	0.57
Median	0.54	0.33	0.67	0.33

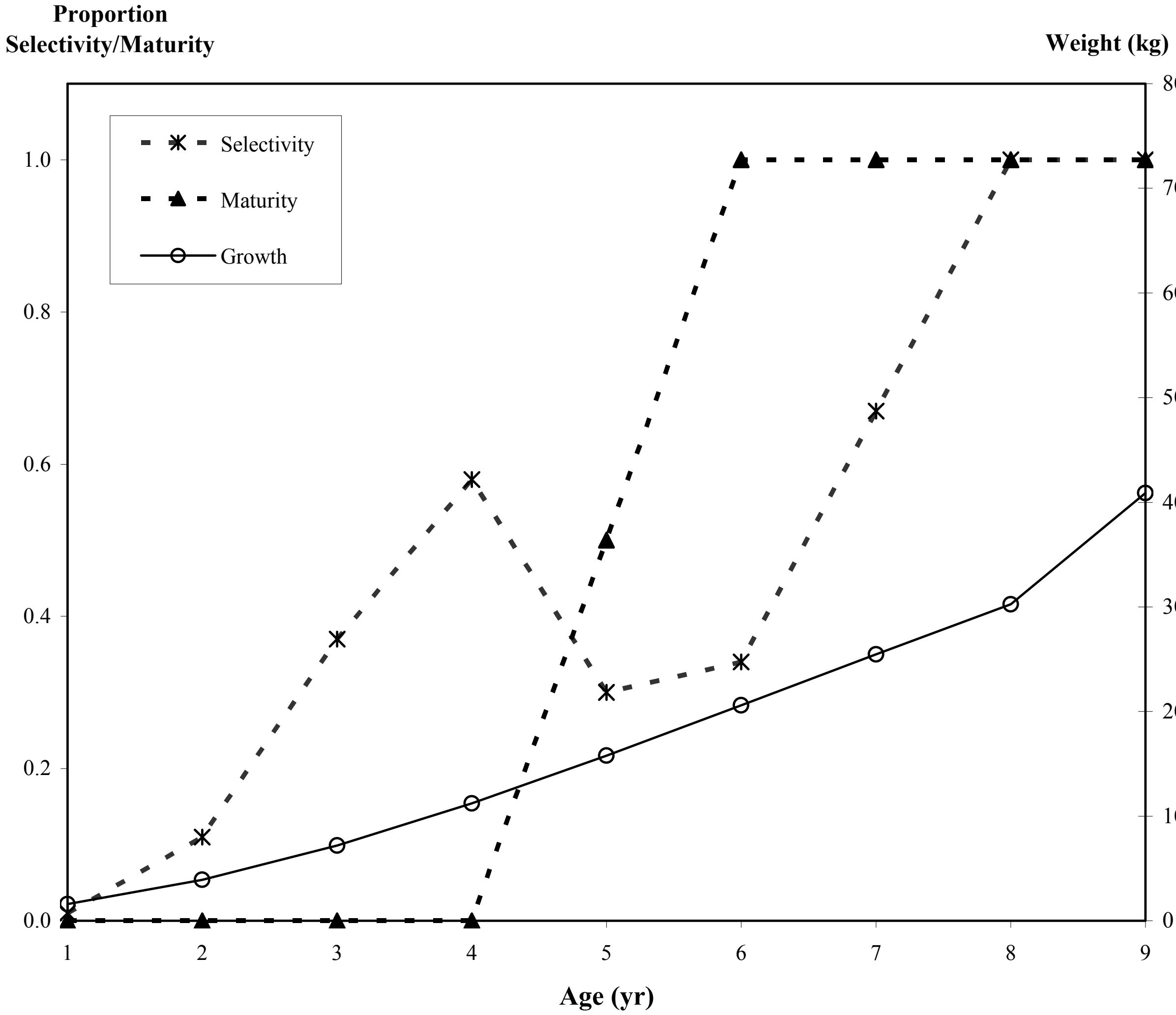


Figure 1. Maturity and growth (in weight, kg) schedules used along with estimates of numbers-at-age to calculate stock biomass (B) and spawning stock biomass for both the assessment period (1975-2004) and for the projection period (2005-2030). Maturity ogive is from Ueyangi (1957). Weight-at-age time series reflects mid-year estimates and is based on Suda (1966) and Suda and Warashina (1961). Age-9 reflects a 'plus group' (>9 years of age) and its mean weight was calculated as the average weight of ages 9.5-12.5. The partial recruitment vector (selectivity) was used for all projection years. Following the draft report of NPALBW19, it reflects average partial recruitment over the period 1995-2003. Natural mortality (*M=0.3*) was time and age invariant.

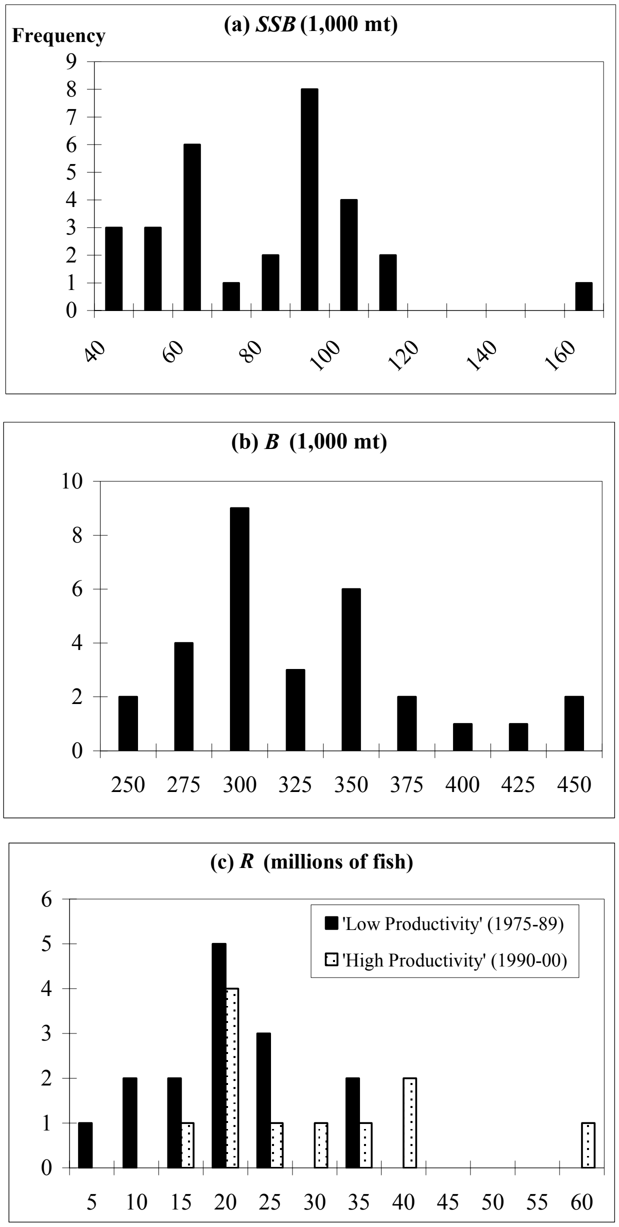


Figure 2. Frequency histograms for annual estimates of stock parameters generated from Model Scenario 1 (*Nineteenth North Pacific Albacore Workshop*): (a) spawning stock biomass (*SSB* : 1975-04); (b) biomass (*B* : 1975-04); and (c) recruitment (*R* : low productivity from 1975-89 and high productivity from 1990-00). Bins reflect low end of range, e.g., for *SSB* , 3 years had estimates of 40,000 to 49,999 mt.

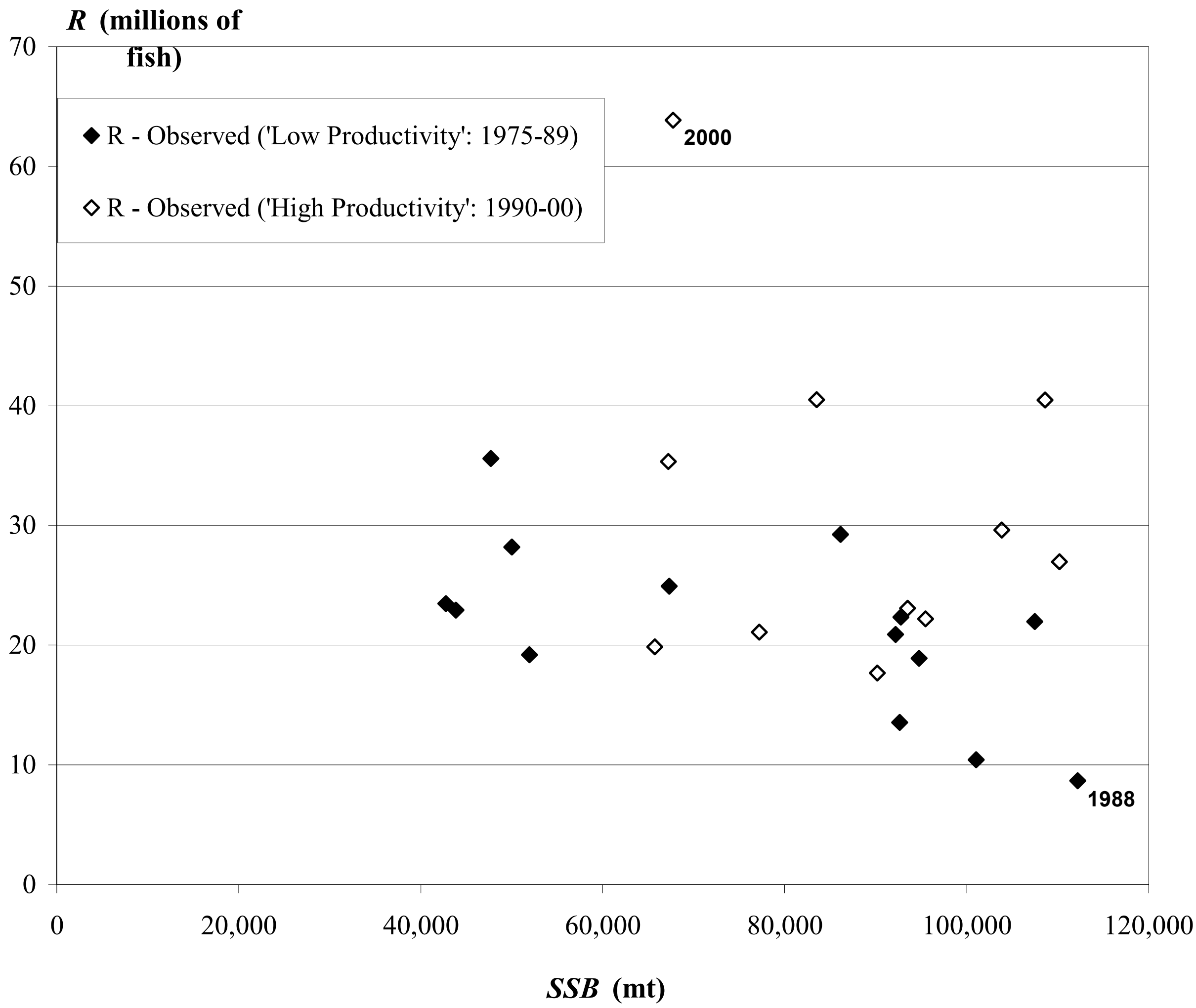


Figure 3. Estimates of spawning stock biomass (SSB) and subsequent recruitment at age 1 (R) for North Pacific albacore based on Model Scenario 1 associated with the *Nineteenth North Pacific Albacore Workshop*. Estimates of recruitment in 2000 (largest R in 'high productivity' period 1990-00) and 1988 (smallest R in 'low productivity' period 1975-89) are noted.

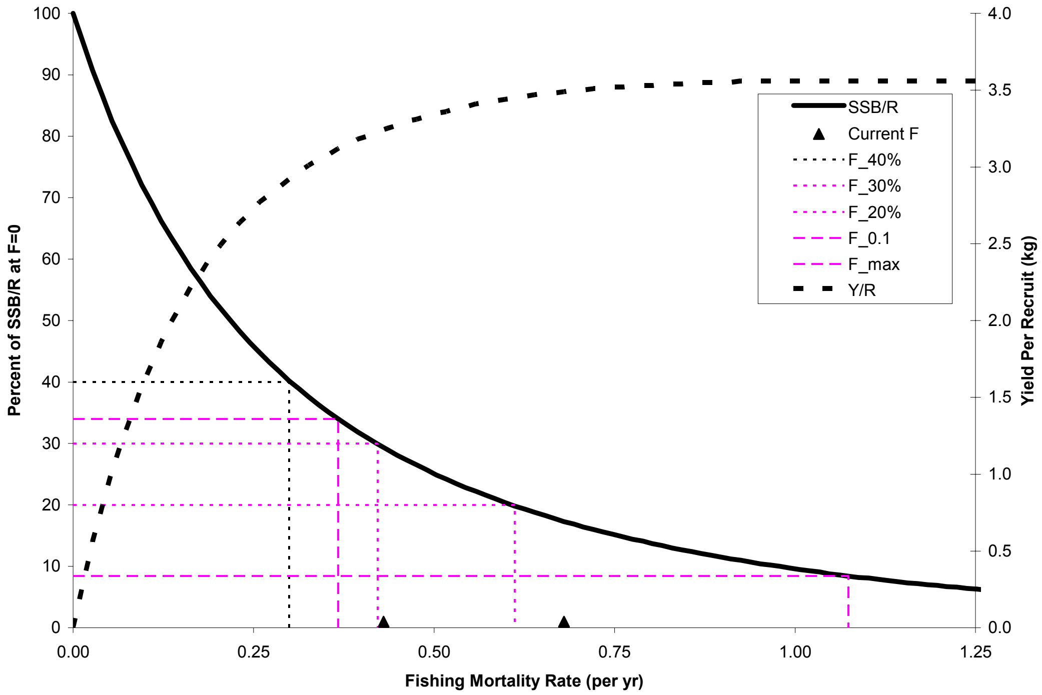
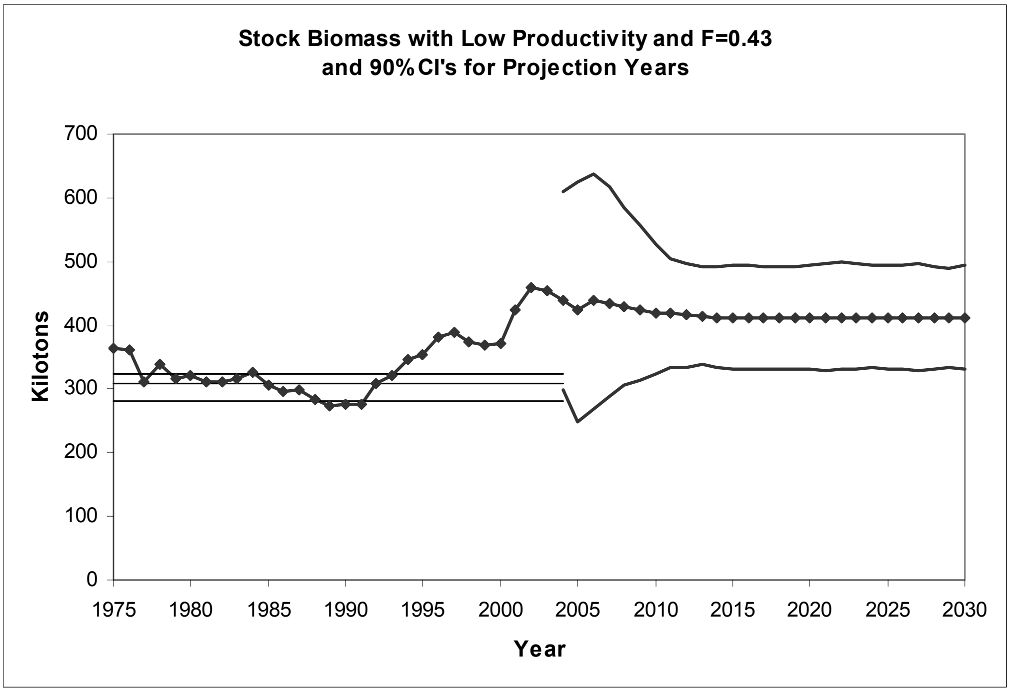


Figure 4. Equilibrium yield-per-recruit (Y/R in kg) and spawning stock biomass per recruit (% of SSB/R at F=0) as a function of fishing mortality rate (F) for North Pacific albacore associated with Model Scenario 1. A suite of F-based biological reference points are also displayed. The current F (2003) reflects a 'range' based on a 'low' (0.43) and 'high' (0.68) assumption involved in Workshop's uncertainty analysis (Stocker *in press*).



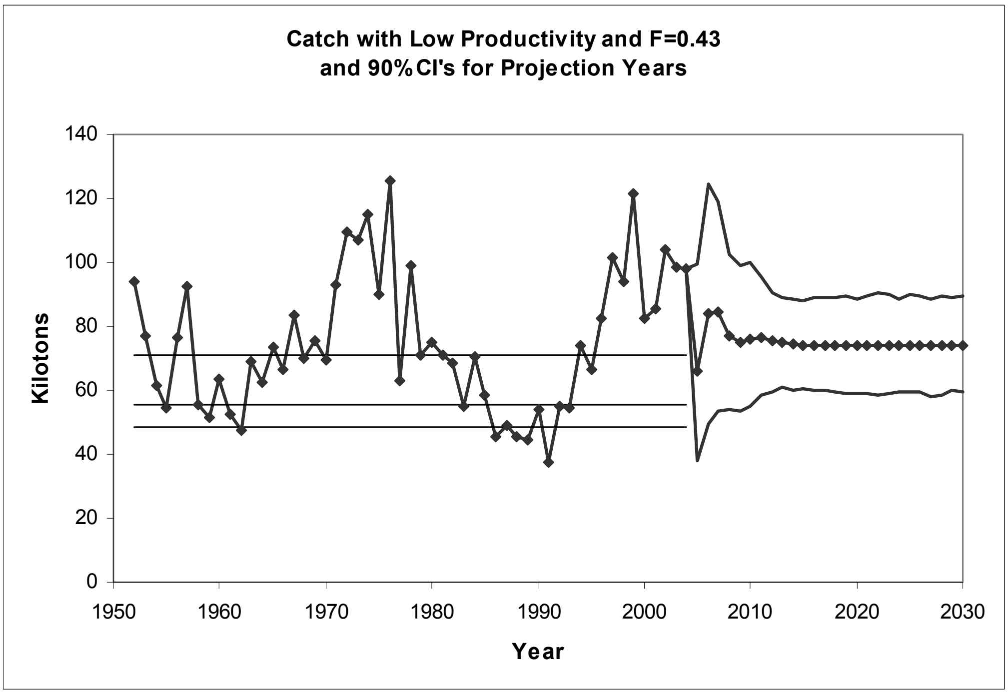
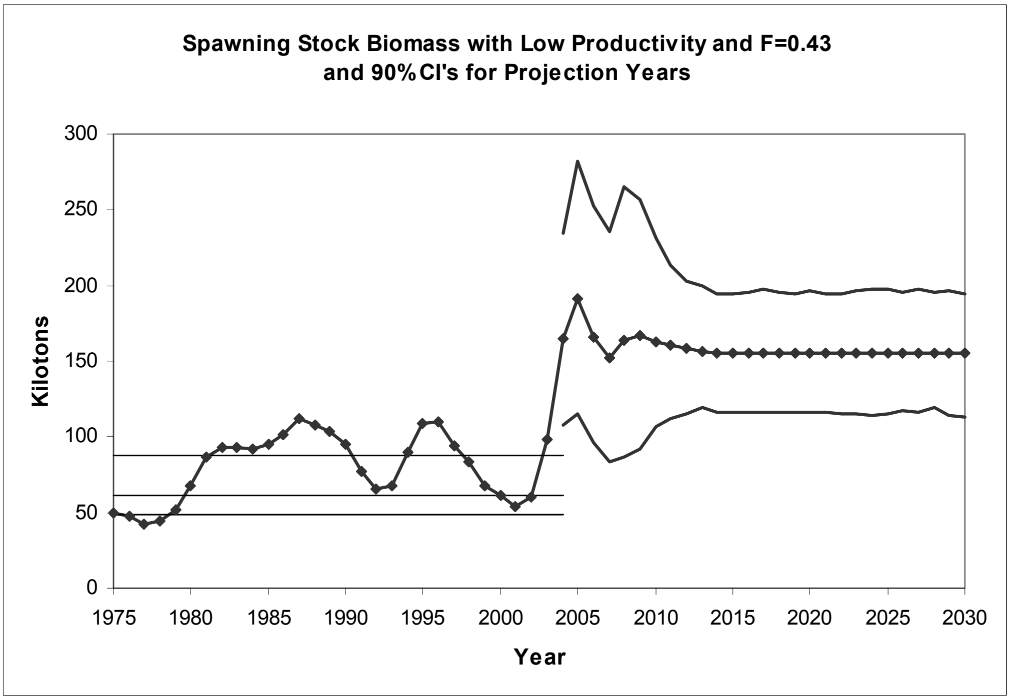


Figure 5. Stock biomass, spawning stock biomass, and recruitment (1975-2030) and catch 1952-2030. The catch period is 1952-2004, stock assessment period is 1975-2004 and projection years are 2005-2030. Confidence intervals (90%) are given for all estimates during the projection years. The three horizontal lines (from top to bottom) represent the median value over the assessment or catch period, the 25th percentile, and the 10th percentile, respectively. The stock projections were done under the 'Low Productivity / Low F' scenario.



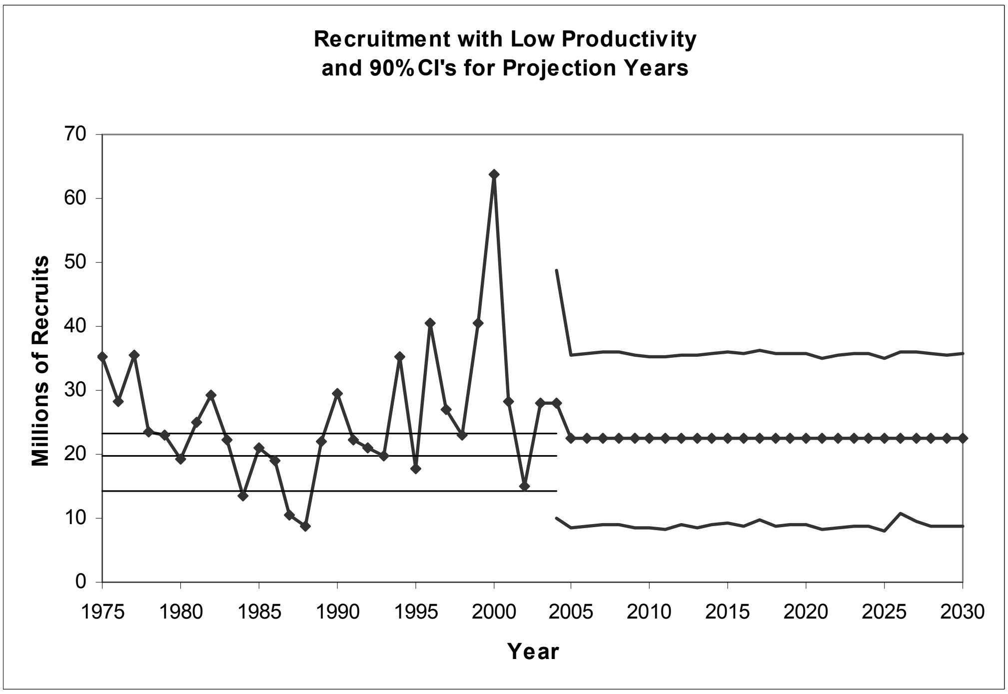
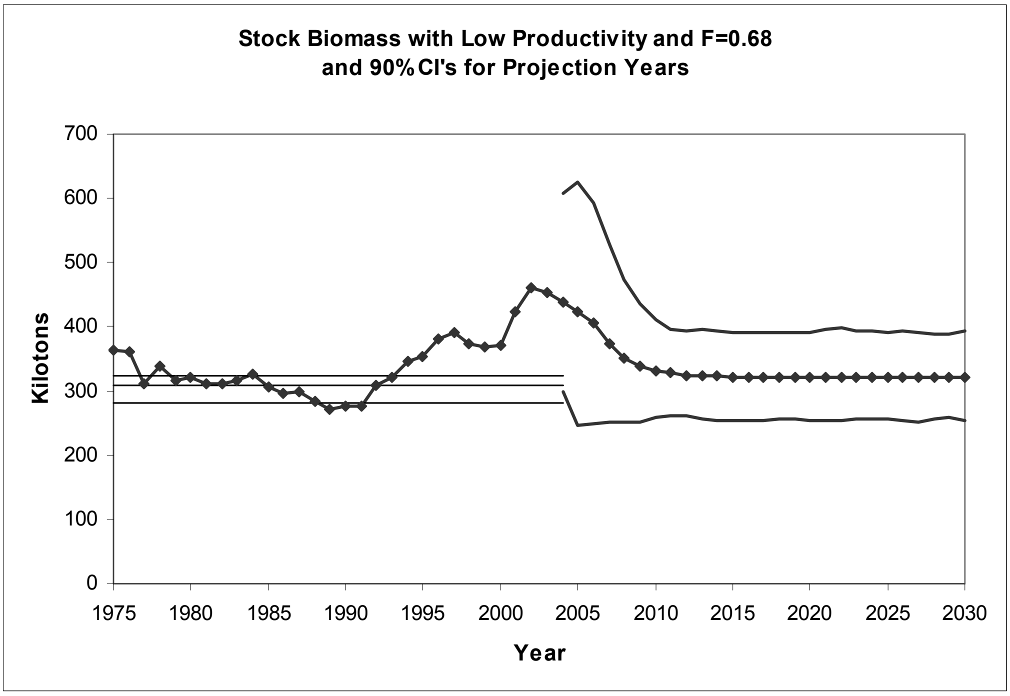


Figure 5. Continued



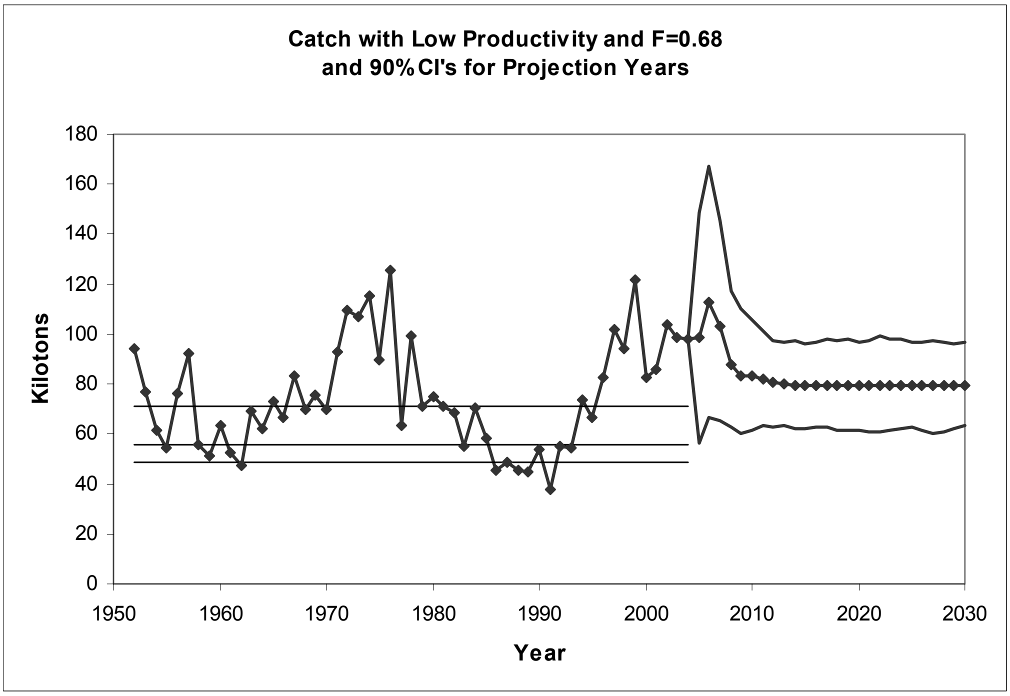


Figure 6. Stock biomass, spawning stock biomass, and recruitment (1975-2030) and catch 1952-2030. The catch period is 1952-2004, stock assessment period is 1975-2004 and projection years are 2005-2030. Confidence intervals (90%) are given for all estimates during the projection years. The three horizontal lines (from top to bottom) represent the median value over the assessment or catch period, the 25th percentile, and the 10th percentile, respectively. The stock projections were done under the 'Low Productivity / High F' scenario.

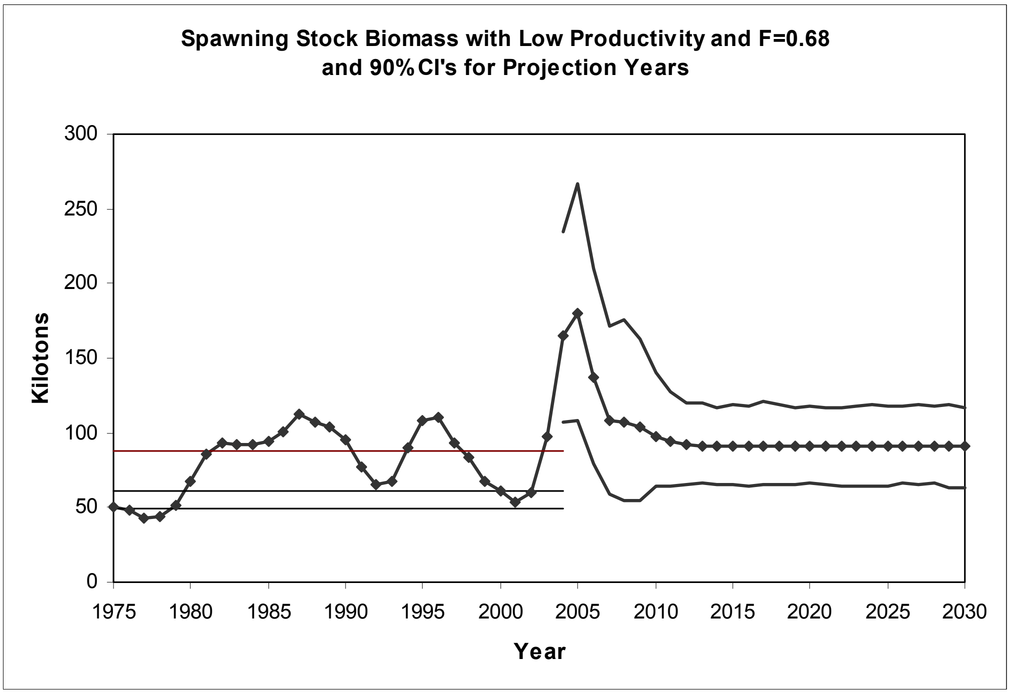
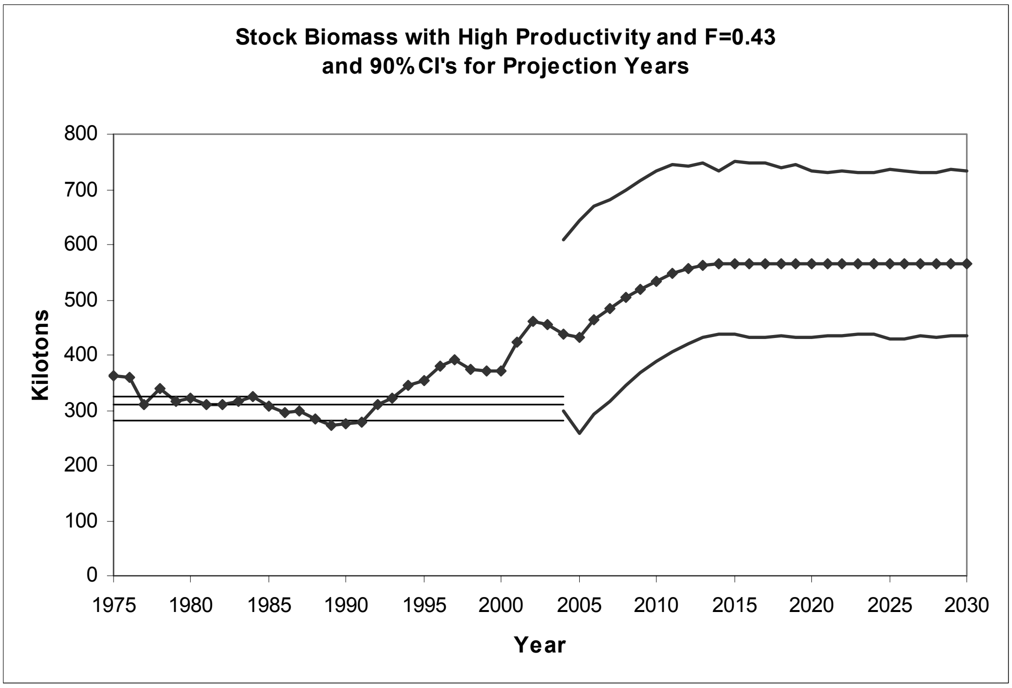


Figure 6. Continued



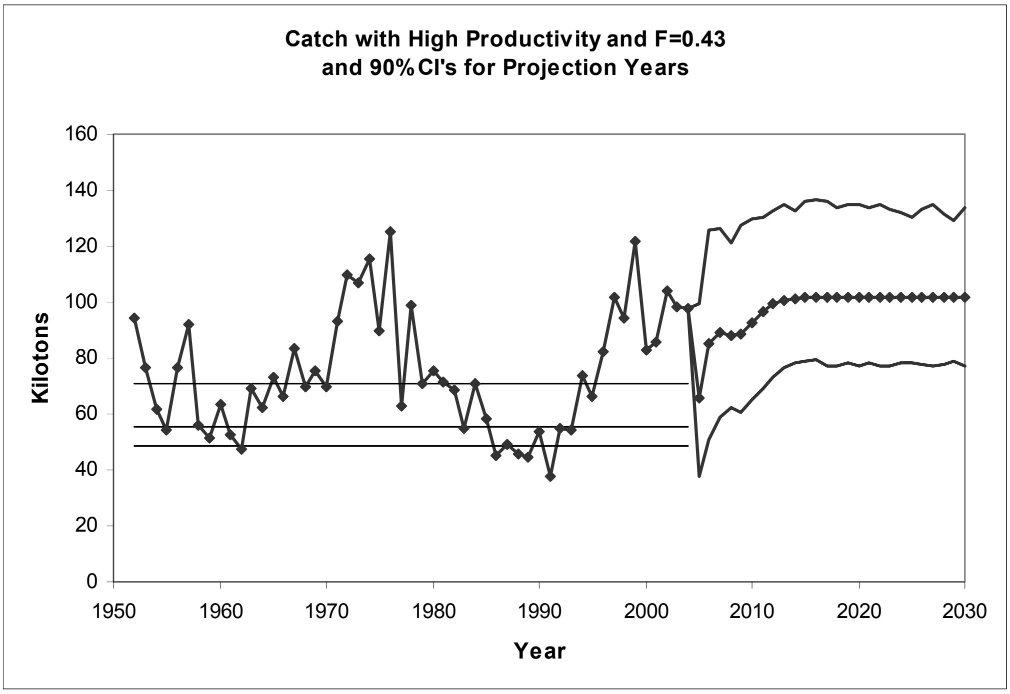


Figure 7. Stock biomass, spawning stock biomass, and recruitment (1975-2030) and catch 1952-2030. The catch period is 1952-2004, stock assessment period is 1975-2004 and projection years are 2005-2030. Confidence intervals (90%) are given for all estimates during the projection years. The three horizontal lines (from top to bottom) represent the median value over the assessment or catch period, the 25th percentile, and the 10th percentile, respectively. The stock projections were done under the 'High Productivity / Low F' scenario.

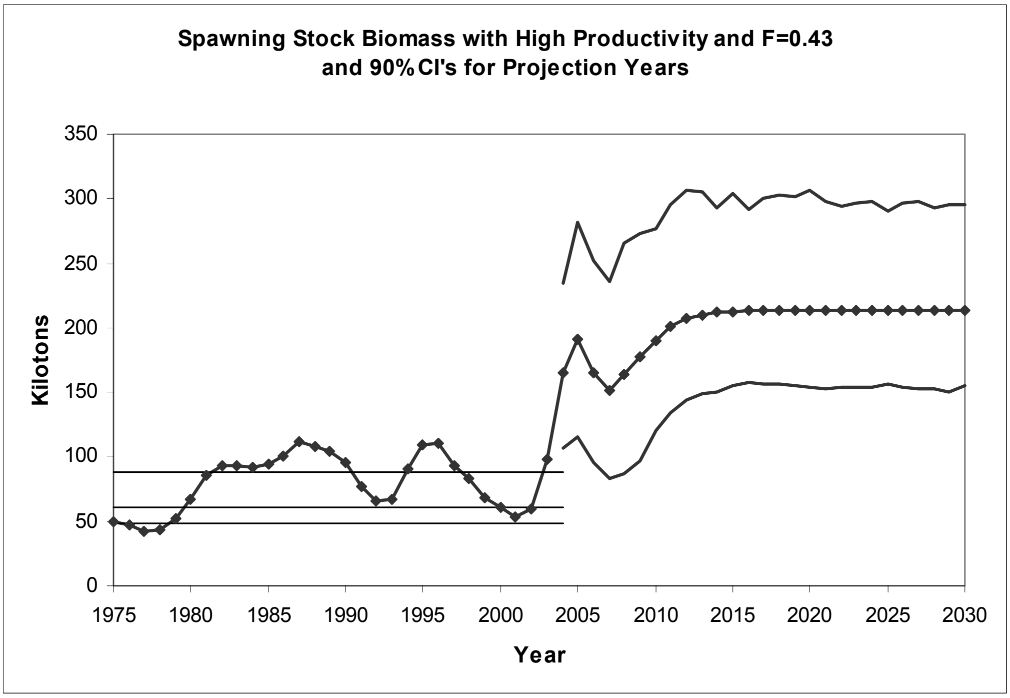
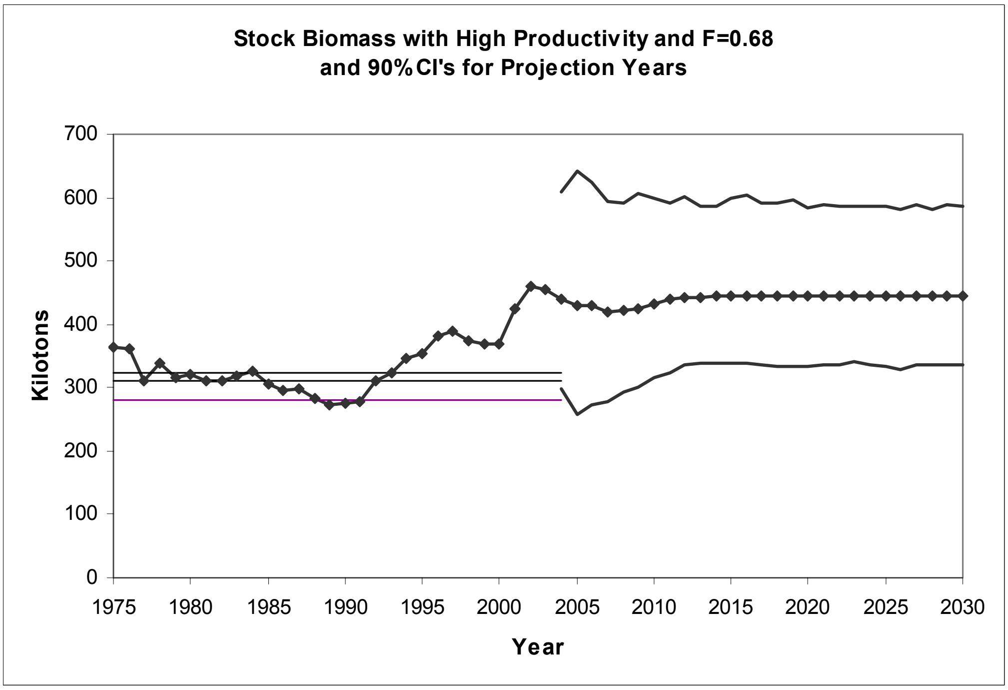


Figure 7. Continued



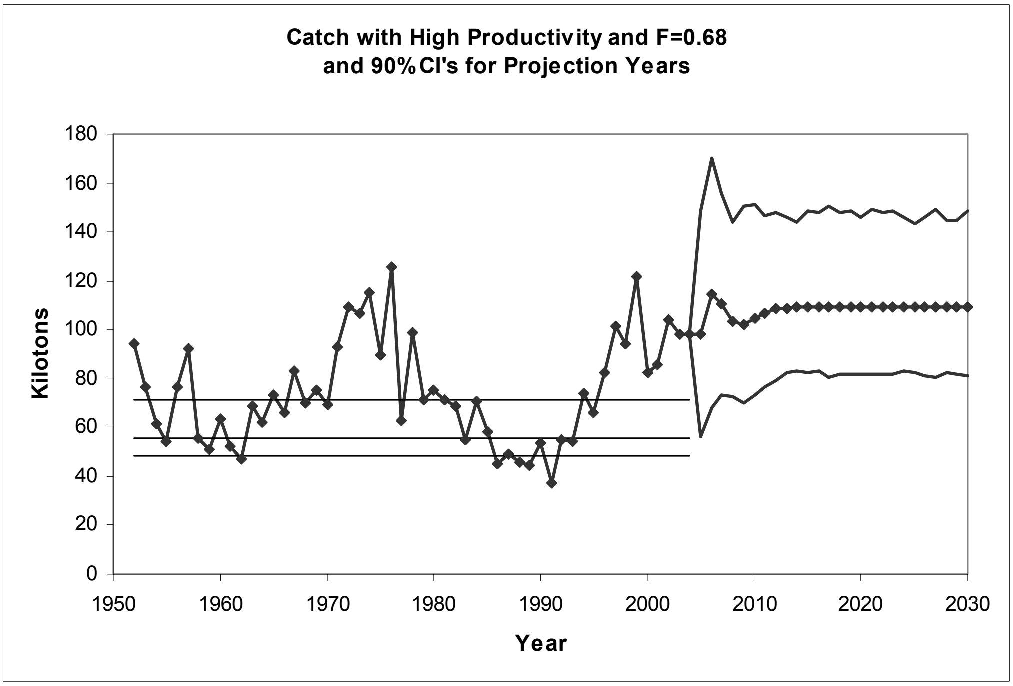


Figure 8. Stock biomass, spawning stock biomass, and recruitment (1975-2030) and catch 1952-2030. The catch period is 1952-2004, stock assessment period is 1975-2004 and projection years are 2005-2030. Confidence intervals (90%) are given for all estimates during the projection years. The three horizontal lines (from top to bottom) represent the median value over the assessment or catch period, the 25th percentile, and the 10th percentile, respectively. The stock projections were done under the 'High Productivity / High F' scenario.

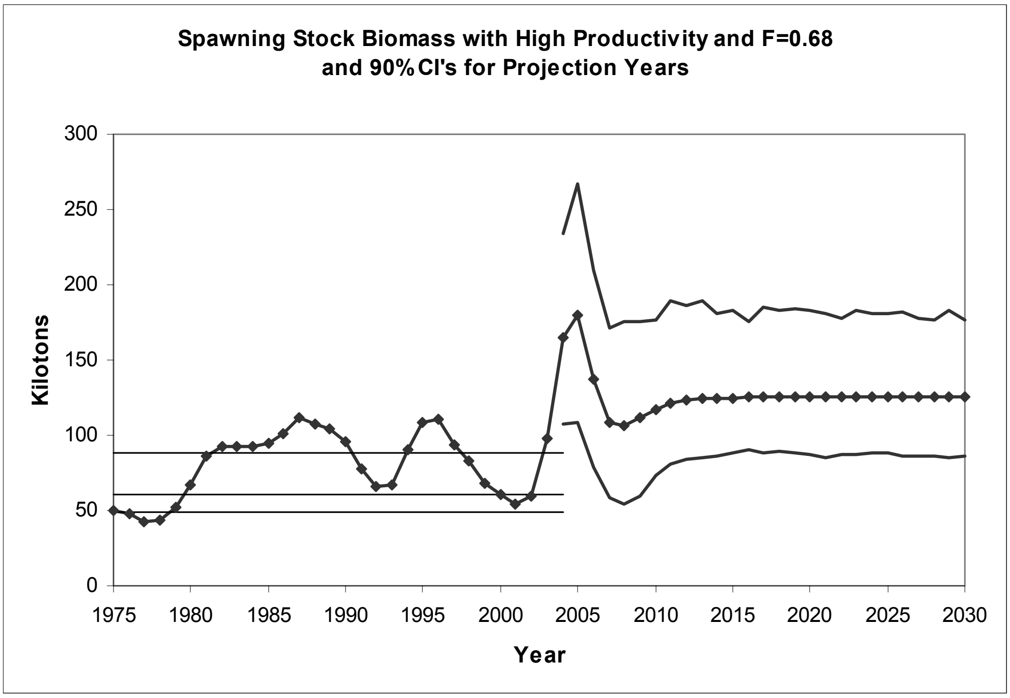
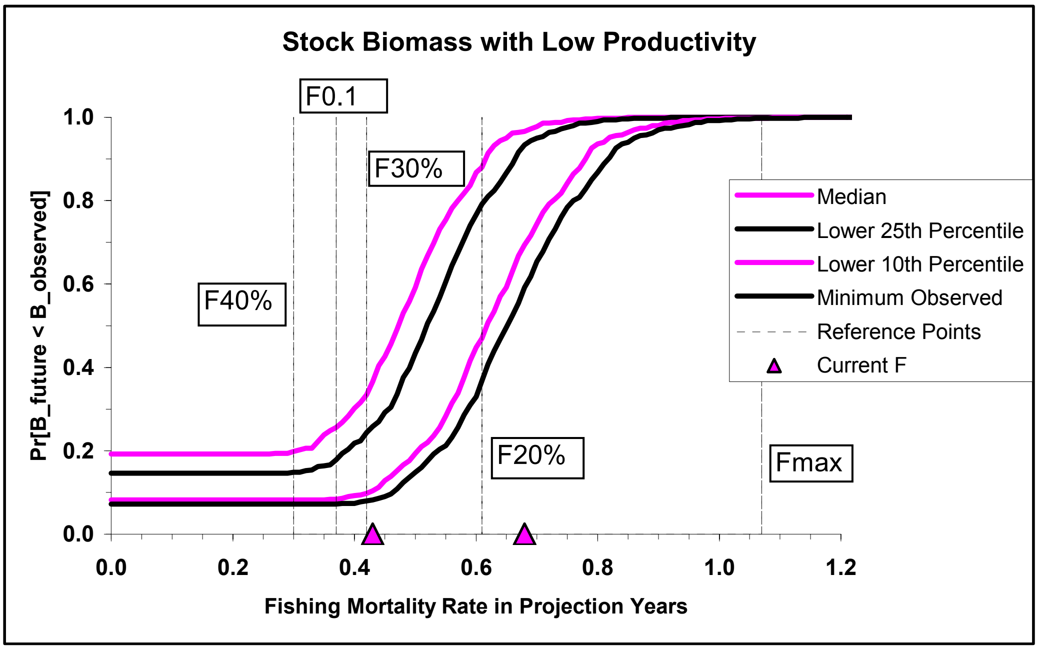


Figure 8. Continued



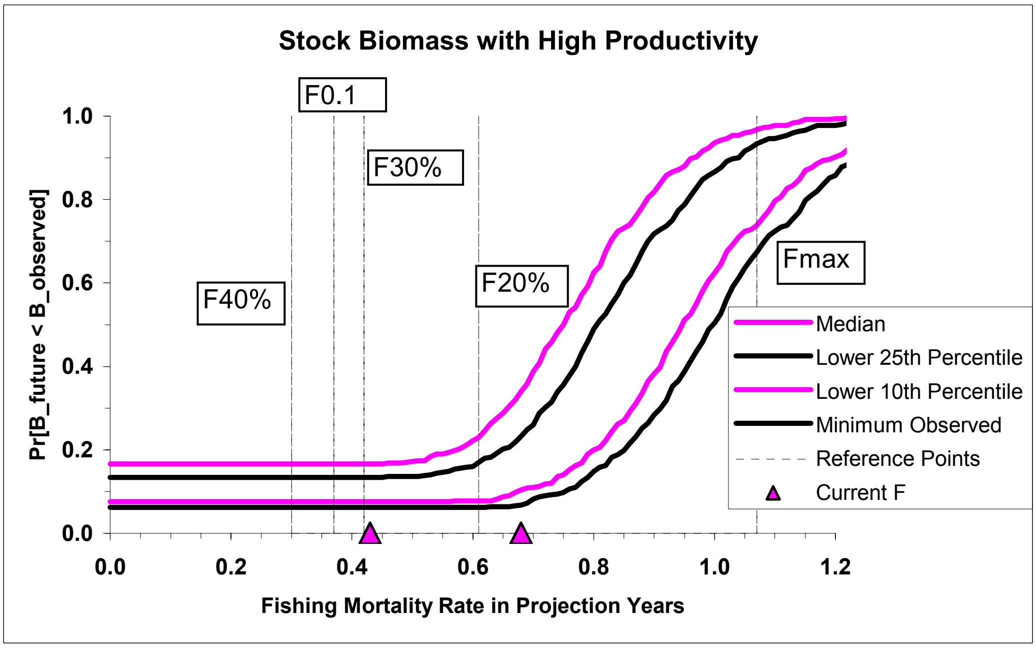
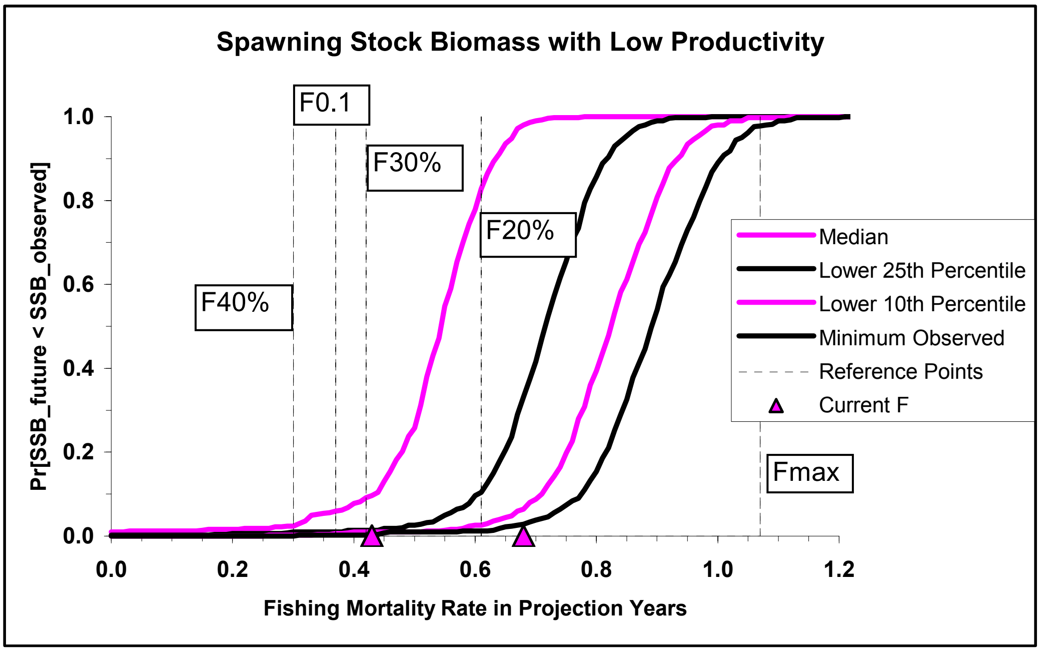


Figure 9. Probability profiles (solid lines) for the 'Low Productivity' (top panel) and 'High Productivity' (bottom panel) scenarios. Each profile gives the probability that stock biomass will fall below a specific threshold level during one or more years of the projection period. For the bottom-most profile, the threshold is the minimum 'observed' stock biomass over the assessment period. The other three profiles (from bottom to top) have as their threshold the lower 10th percentile, the lower 25th percentile, and the median 'observed' stock biomass over the assessment period, respectively. For example in the top panel, the fishing mortality rate that will cause stock biomass to fall below the minimum 'observed' biomass (with 50% probability) is F=0.65. For reference, the F-based biological reference points (cf. Table 1) are displayed with vertical dashed lines; and the 'Low F' (0.43) and 'High F' (0.68) estimates of current F are indicated with triangular markers.



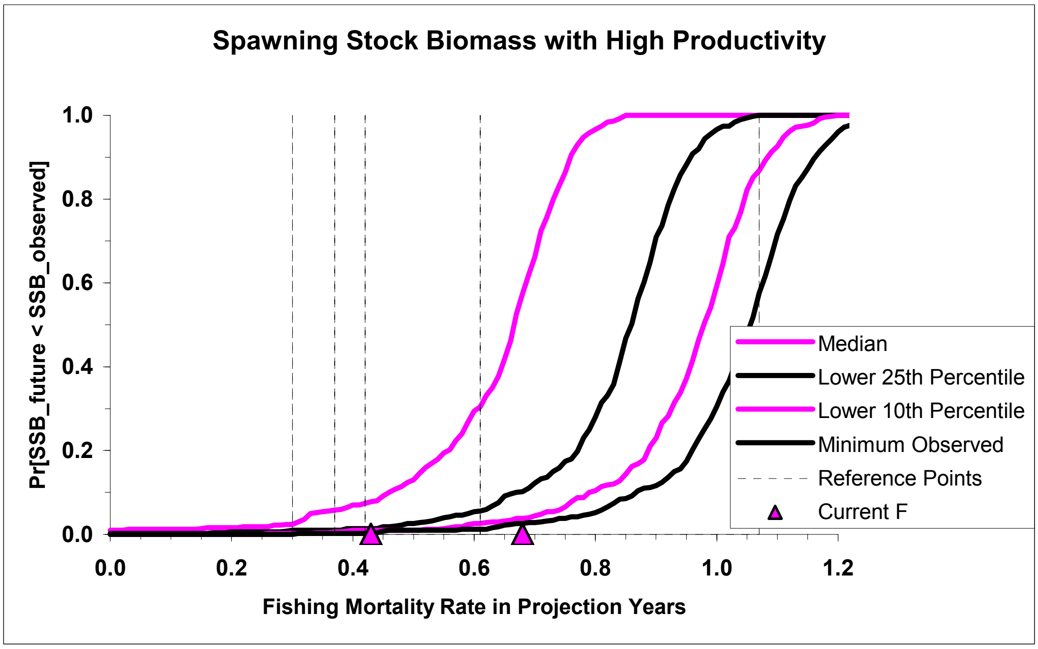
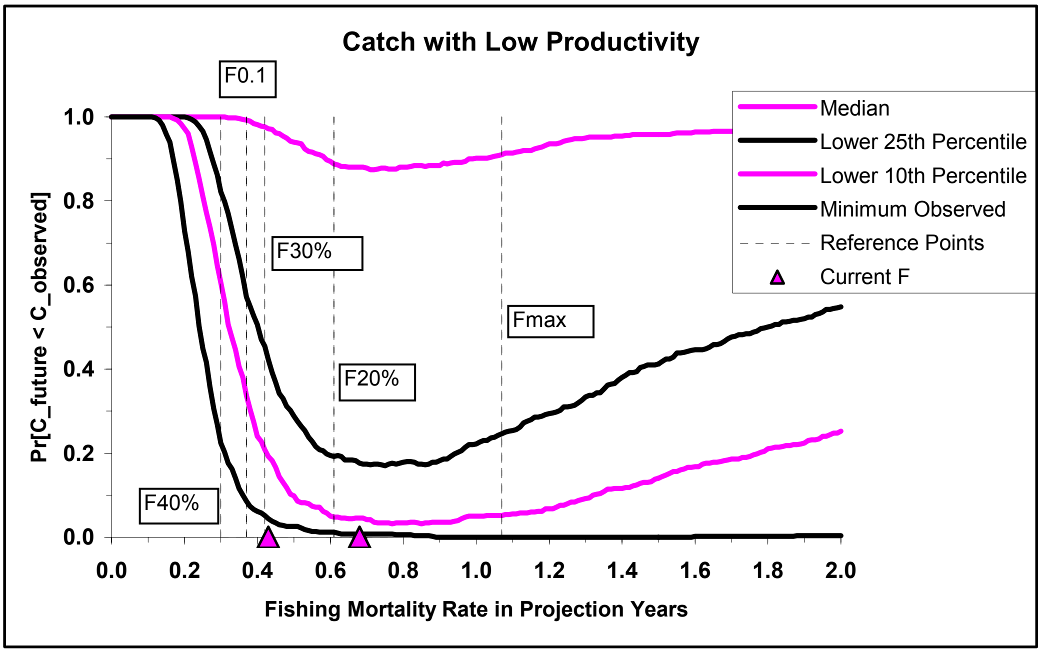


Figure 10. Probability profiles (solid lines) for the 'Low Productivity' (top panel) and 'High Productivity' (bottom panel) scenarios. Each profile gives the probability that spawning stock biomass will fall below a specific threshold level during one or more years of the projection period. For the bottom-most profile, the threshold is the minimum 'observed' spawning stock biomass over the assessment period. The other three profiles (from bottom to top) have as their threshold the lower 10^{th} percentile, the lower 25^{th} percentile, and the median 'observed' spawning stock biomass over the assessment period, respectively. For example in the top panel, the fishing mortality rate that will cause spawning stock biomass to fall below the minimum 'observed' biomass (with 50% probability) is F=0.89. For reference, the F-based biological reference points (cf. Table 1) are displayed with vertical dashed lines; and the 'Low F' (0.43) and 'High F' (0.68) estimates of current F are indicated with triangular markers.



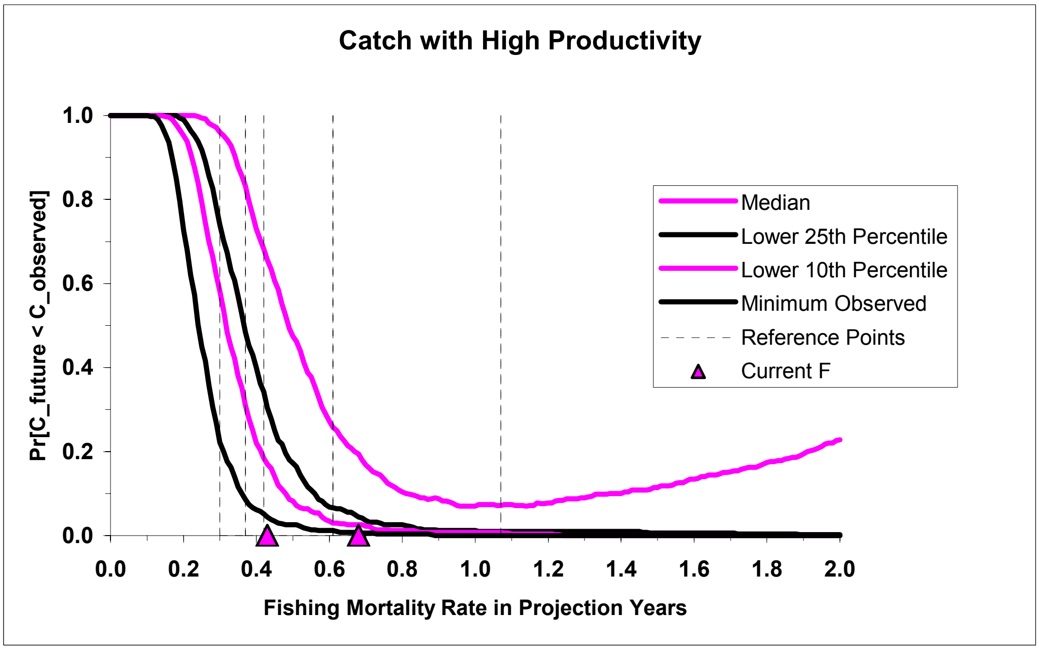


Figure 11. Probability profiles (solid lines) for the 'Low Productivity' (top panel) and 'High Productivity' (bottom panel) scenarios. Each profile gives the probability that catch will fall below a specific threshold level during one or more years of the projection period. For the bottom-most profile, the threshold is the minimum observed catch over the assessment period. The other three profiles (from bottom to top) have as their threshold the lower 10^{th} percentile, the lower 25^{th} percentile, and the median catch over the assessment period, respectively. For example in the top panel, the fishing mortality rate that has the smallest probability of causing the catch to fall below the 25^{th} percentile of observed catch is F=0.71. For reference, the F-based biological reference points (cf. Table 1) are displayed with vertical dashed lines; and the 'Low F' (0.43) and 'High F' (0.68) estimates of current F are indicated with triangular markers.

APPENDIX
Equations and Pseudo Code for Simulation and Probability Analyses

Take the stock numbers at age from the VPA-2BOX 'Model Scenario 1' results (i.e., final, NPALBW-consensus model) of the *Nineteenth North Pacific Albacore Workshop* -- Run B1k (see definition of terms at the end of this appendix):

$N_{a,y}^{k} \quad for\ a = 1,\ldots,9+;\ y = 1975,\ldots,2003;\ k = 0,\ldots,500$

Use the projection algorithm[1] below to project stock numbers in future years:

$N_{a,y}^{k} \quad for\ a = 1,\ldots,9+;\ y = 2004,\ldots,2031;\ k = 0,\ldots,500$

Pseudo Code for Projection Algorithm

$For\ k = 0,1,2,\ldots,499,500$

$$N_{1,2003}^{k} = N_{1,2004}^{k} = \frac{1}{8}\sum_{y=1992}^{1999} N_{1,y}^{k}$$

$$N_{2,2004}^{k} = N_{1,2003}^{k}\exp\left(-Z_{1,2003}^{k}\right)$$

$$Set\ N_{1,y}^{k}\ to\ random\ draw\ from \left\{N_{1,1990}^{k}, N_{1,1991}^{k},\ldots,N_{1,2000}^{k}\right\} for\ y = 2005, 2006,\ldots,2031$$

$$\overline{S}_{a}^{k} = \frac{1}{9}\sum_{y=1995}^{2003} S_{a,y}^{k} \Big/ Max_{a}\left\{\frac{1}{9}\sum_{y=1995}^{2003} S_{a,y}^{k}\right\}$$

$$Solve\ iteratively\ for\ the\ F_{2004}^{k}\ that\ gives\ C_{2004}^{k} = 98{,}000\ mt$$

$$N_{a,2005}^{k} = \begin{cases} N_{a-1,2004}^{k}\exp\left[-\left(F_{2004}^{k}\cdot\overline{S}_{a-1}^{k} + M_{a-1}\right)\right] & for\ a = 2,\ldots,8 \\ N_{a-1,2004}^{k}\exp\left[-\left(F_{2004}^{k}\cdot\overline{S}_{a-1}^{k} + M_{a-1}\right)\right] + N_{a,2004}^{k}\exp\left[-\left(F_{2004}^{k}\cdot\overline{S}_{a}^{k} + M_{a}\right)\right] & for\ a = 9+ \end{cases}$$

$For\ F = 0, 0.01, 0.02,\ldots,1.99, 2.00$

$For\ y = 2006, 2007,\ldots,2031$

$$N_{a,y,F}^{k} = \begin{cases} N_{a-1,y-1,F}^{k}\exp\left[-\left(F\cdot\overline{S}_{a-1}^{k} + M_{a-1}\right)\right] & for\ a = 2,\ldots,8 \\ N_{a-1,y-1,F}^{k}\exp\left[-\left(F\cdot\overline{S}_{a-1}^{k} + M_{a-1}\right)\right] + N_{a,y-1,F}^{k}\exp\left[-\left(F\cdot\overline{S}_{a}^{k} + M_{a}\right)\right] & for\ a = 9+ \end{cases}$$

end for

end for

end for

[1] As shown, the algorithm depicts the "high productivity" scenario in that it uses recruitment over the period 1990-2000. For the "low productivity" scenario, the algorithm remains identical except that Line 4 is modified to reflect recruitment over the period 1975-89.

Post-Projection Calculations

Calculate stock biomass (B) and spawning stock biomass at mid-year (SSB) for the VPA-2BOX time series:

$$B_y^k = \sum_{a=1}^{9+} W_a N_{a,y}^k \quad for\ y = 1975,\ldots,2004;\ \ k = 0,\ldots,500$$

$$SSB_y^k = \sum_{a=1}^{9+} Q_a W_a^S N_{a,y}^k \exp\left(-0.5 \cdot Z_{a,y}^k\right) \quad for\ y = 1975,\ldots,2004;\ \ k = 0,\ldots,500$$

For the projection years, calculate B, SSB (at mid-year), and catch (C) conditioned on F:

$$B_{y,F}^k = \sum_{a=1}^{9+} W_a N_{a,y,F}^k \quad for\ y = 2005,\ldots,2031;\ \ k = 0,\ldots,500;\ \ F = 0,0.01,...,2.00$$

$$SSB_{y,F}^k = \sum_{a=1}^{9+} Q_a W_a^S N_{a,y,F}^k \exp\left(-0.5 \cdot Z_{a,F}^k\right) \quad for\ y = 2005,\ldots,2030;\ \ k = 0,\ldots,500;\ \ F = 0,0.01,...,2.00$$

$$C_{y,F}^k = \sum_{a=1}^{9+} \frac{F \cdot \overline{S}_a^k}{Z_{a,F}^k} W_a^m N_{a,y,F}^k \left[1 - \exp\left(-Z_{a,F}^k\right)\right] \quad for\ y = 2005,\ldots,2030;\ \ k = 0,\ldots,500;\ F = 0,0.01,...,2.00$$

Probability of Reducing Biomass Below Observed Threshold Levels

Using the base case results (k=0) without bootstrap bias correction and the bootstrap replications (k=1,…,500) as estimates of the variability about the base case results, calculate for each F (0,0.01,…,2.00) the probability that at some point during 2005-2030, the SSB will fall below the minimum observed SSB over 1975-2004:

$$\Pr\left[SSB_{Future} < SSB_{Observed} \middle| F\right] = \frac{1}{500}\sum_{k=1}^{500} \left[\!\left[Min\left\{SSB_{2005,F}^k,...,SSB_{2030,F}^k\right\} < Min\left\{SSB_{1975}^k,...,SSB_{2004}^k\right\} \right]\!\right]$$

where the double bracket $[\![\ \ ]\!]$ indicates a logical test with outcome 0 (if false) or 1 (if true).

Biomass threshold levels – other than the minimum observed biomass – can also be used. For example, to use the median observed biomass as the threshold level:

$$\Pr\left[SSB_{Future} < SSB_{Observed} \middle| F\right] = \frac{1}{500}\sum_{k=1}^{500} \left[\!\left[Median\left\{SSB_{2005,F}^k,...,SSB_{2030,F}^k\right\} < Median\left\{SSB_{1975}^k,...,SSB_{2004}^k\right\} \right]\!\right]$$

Percentile levels of the observed biomass – other than the median – may also be of interest, e.g. the lower 10th or 25th percentile.

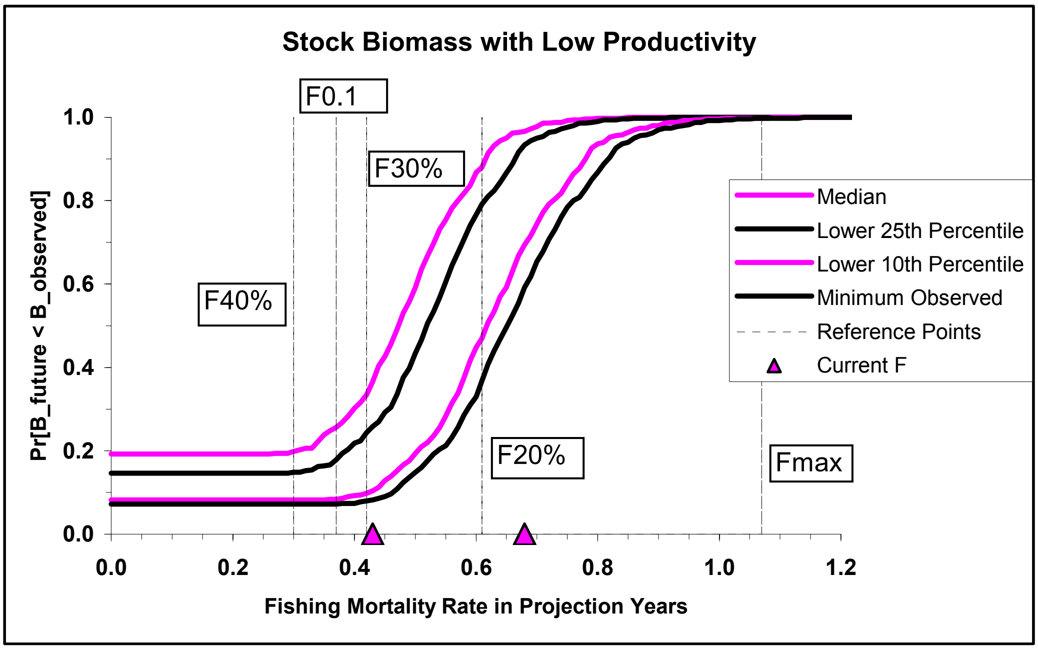
Stock biomass and catch can be treated in a similar fashion:

$$\Pr\left[B_{Future} < B_{Observed} \left| F\right.\right] = \frac{1}{500}\sum_{k=1}^{500}\left[\!\left[Min\left\{B_{2005,F}^{k},\ldots,B_{2031,F}^{k}\right\} < Min\left\{B_{1975}^{k},\ldots,B_{2004}^{k}\right\}\right]\!\right]$$

$$\Pr\left[C_{Future} < C_{Observed} \left| F\right.\right] = \frac{1}{500}\sum_{k=1}^{500}\left[\!\left[Min\left\{C_{2005,F}^{k},\ldots,C_{2030,F}^{k}\right\} < Min\left\{C_{1952},\ldots,C_{2004}\right\}\right]\!\right]$$

Presentation of Results

Results are most easily presented graphically showing probability profiles vs. F. For example:



Definition of Terms

a	age index; a=1,2,…,8,9+
y	year index; y=1975, 1976,…,2030,2031
k	index for bootstrap replication number; k=0,1,…,499,500[2]
N	population numbers at the beginning of the year
M	instantaneous rate of natural mortality (yr^{-1})
F	instantaneous rate of fishing mortality (yr^{-1})
Z	instantaneous rate of total mortality (yr^{-1})
S	selectivity (also called partial recruitment)
C	catch in weight
W	weight of an individual at the beginning of the year
W^m	weight of an individual at the middle of the year
W^S	weight of an individual at the beginning of the spawning season
Q	maturity ogive
B	stock biomass at the beginning of the year
SSB	spawning stock biomass at the beginning of the spawning season

[2]k=0 represents the agreed base case VPA-2BOX run (Run B1k); and k=1,2,…,500 represent the 500 bootstrap replications about the base case run