CHAPTER 11

PACIFIC OCEAN PERCH

by

Paul D. Spencer and James N. Ianelli

Executive Summary

In 2005, BSAI rockfish have been moved to a biennial assessment schedule to coincide with the frequency of trawl surveys in the Aleutian Islands and the eastern Bering Sea slope. These surveys occur in even years, and for these years a full assessment of POP the BSAI area will be conducted. The 2004 full assessment can be found at http://www.afsc.noaa.gov/refm/docs/2004/BSAIpop.pdf. In the odd years in which the surveys are not conducted, the existing model will be updated with new catch information and extended to the current year, and an executive summary containing the biological and fishing mortality reference points and the harvest projections will be presented. It is recommended that the ABCs from the updated model be used for 2006 and 2007.

Summary of results

There is no change in the model structure from 2004, and the only change in the input data was an updated 2004 catch and adding an estimate of the 2005 catch. The 2004 catch was increased from the preliminary estimate of 11,032 t used in the 2004 assessment to the final estimate of 11,230 t, and the 2005 catch was set at 9,893 t, the observed level through Oct 8.

The estimate of 2006 total biomass is 385,240 t, an increase of 1% from the 2005 estimate of total biomass of 381,768 t obtained from the 2004 assessment. The estimate of 2006 SSB is 133,310 t, a decrease of less than 1% from the estimate of 2005 SSB of 133,351 t obtained in the 2004 assessment. The projected 2006 ABC and OFL are 14,819 t and 17,571 t, respectively; these values are also the projected ABC and OFL for 2007, assuming the 2006 ABC is taken as catch in that year. A comparison of results from the 2004 and 2005 assessments are shown below.

	2004 assessment		2005 assessment	
	Year		Year	
	2005	2006	2006	2007
M	0.05	0.05	0.05	0.05
tier	3b	3b	3b	3b
Total Biomass	381,768 t	383,766 t	385,240 t	386,820 t
SSB	133,351 t	132,624 t	133,310 t	132,811 t
$B_{100\%}$	355,654 t	355,654 t	354,243 t	354,243 t
$B_{40\%}$	142,262 t	142,262 t	141,697 t	141,697 t
$B_{35\%}$	124,479 t	124,479 t	123,985 t	123,985 t
$F_{35\%}$	0.058	0.058	0.058	0.058
F_{ofl}	0.054	0.053	0.054	0.053
$F_{40\%}$	0.048	0.048	0.048	0.048
maximum F_{abc}	0.045	0.045	0.045	0.045
recommended F_{abc}	0.045	0.045	0.045	0.045
OFL	17,330 t	17,047 t	17,571 t	17,571 t
Maximum allowable ABC	14,615 t	14,620 t	14,819 t	14,819 t
recommended ABC	14,615 t	14,620 t	14,819 t	14,819 t

Area apportionment

The apportionment of ABC by area within the BSAI is based upon survey data through 2004, and thus the percentages are identical to those used in the 2004 assessment. The following table shows the recommended apportionment for 2006.

	EBS	Eastern AI	Central AI	Western AI	Total
Area apportionment	20.0%	22.0%	21.7%	36.3%	100%
ABC (2006)	2964	3260	3213	5382	14819

Responses to the Comments of the Statistical and Scientific Committee (SSC)

From the December, 2004, minutes: "*Regarding the contribution of older females to stock productivity, the SSC requests that the SAFE authors examine the consequences for rockfish management in both the BSAI and GOA if it is true that older females have a disproportionate large contribution to stock productivity, and are also disproportionately harvested due to their* *size. We request that this type of management strategy evaluation be done for those species for which loss of older females is most prevalent or suspected. We also request that an evaluation of the actual degree of loss of older aged females be provided, including an evaluation of how to adjust for earlier fishery data where there may have been intense fishing prior to historic age collections. We encourage comparison of BSAI and GOA results"*

A manuscript examining how common fishing mortality reference points, such as F_{msy} and $F_{spr\%}$, are affected by the dependence of reproductive success upon the spawner age was presented at the 2005 Lowell Wakefield symposium on rockfish, is currently in review, and is attached as an Appendix to this SAFE chapter. Within this manuscript, GOA and BSAI POP are examined as specific applications and the results are compared to each other. For other species of Alaska rockfish, such as northern rockfish, the available stock-recruitment data are not sufficiently informative to conduct this type of analysis.

The degree of loss of older aged fish for several species is shown in Figure 1, where old fish was defined as 40% of the maximum age observed (40 for AI POP, 34 for GOA POP, and 24 for northern rockfish and dusky rockfish). There appears to be some decline in the loss of old POP in the GOA, but the proportion of old POP in the AI has been variable without trend. Similarly, the data for northern rockfish show opposite trends between the two areas. This type of analysis is confounded with recruitment trends, as an influx of recruits in recent years (as we suspect have occurred for AI northern rockfish) will necessarily result in a decline in the proportion of old fish. Thus, it would be desirable to have longer time series in order to separate variation in age structure due to recruitment patterns versus reduction in older aged fish due to fishing.

Fishery-independent data on age structure does not exist prior to the initiation of research trawl surveys in the 1980s, which was well after the intense fishing that occurred in the 1960s. Information on fishery age composition for POP from the 1960s does exist, and Chikuni (1975) does comment on the fluctuations in the age composition in the catch; we are not aware of age composition data for other Alaska rockfish species during this time period. Chikuni's (1975) analysis must be interpreted with caution for a least two reasons. First, the age composition in the POP fishery appears to be highly sensitive to changes in gear and fishing grounds, and thus does not likely provide a true picture of population changes. For example, Chikuni (1975) notes that proportion of fish aged 14 and older increased on the EBS slope due to elimination of seine trawls and paired trawl which evidently capture more of the younger fish, and exploration of new fishing grounds. Secondly, the ages for the fishery catch were not based on the 'break and burn" methodology and are this biased downward, hindering examination of the proportion of old fish. Because Chikuni (1975) defines "old" fish as greater than 15 years, the proportion of fish meeting this condition is quite sensitive to recruitment fluctuations. Given these caveats, the 1960s data on changes in age composition in the fishery were not used to infer changes in proportion of old fish in the population.

References

Chikuni, S. 1975. Biological study on the population of Pacific ocean perch in the north Pacific. Bull. Far Seas Fish. Res. Lab. (Shimizu) 12:1-119.

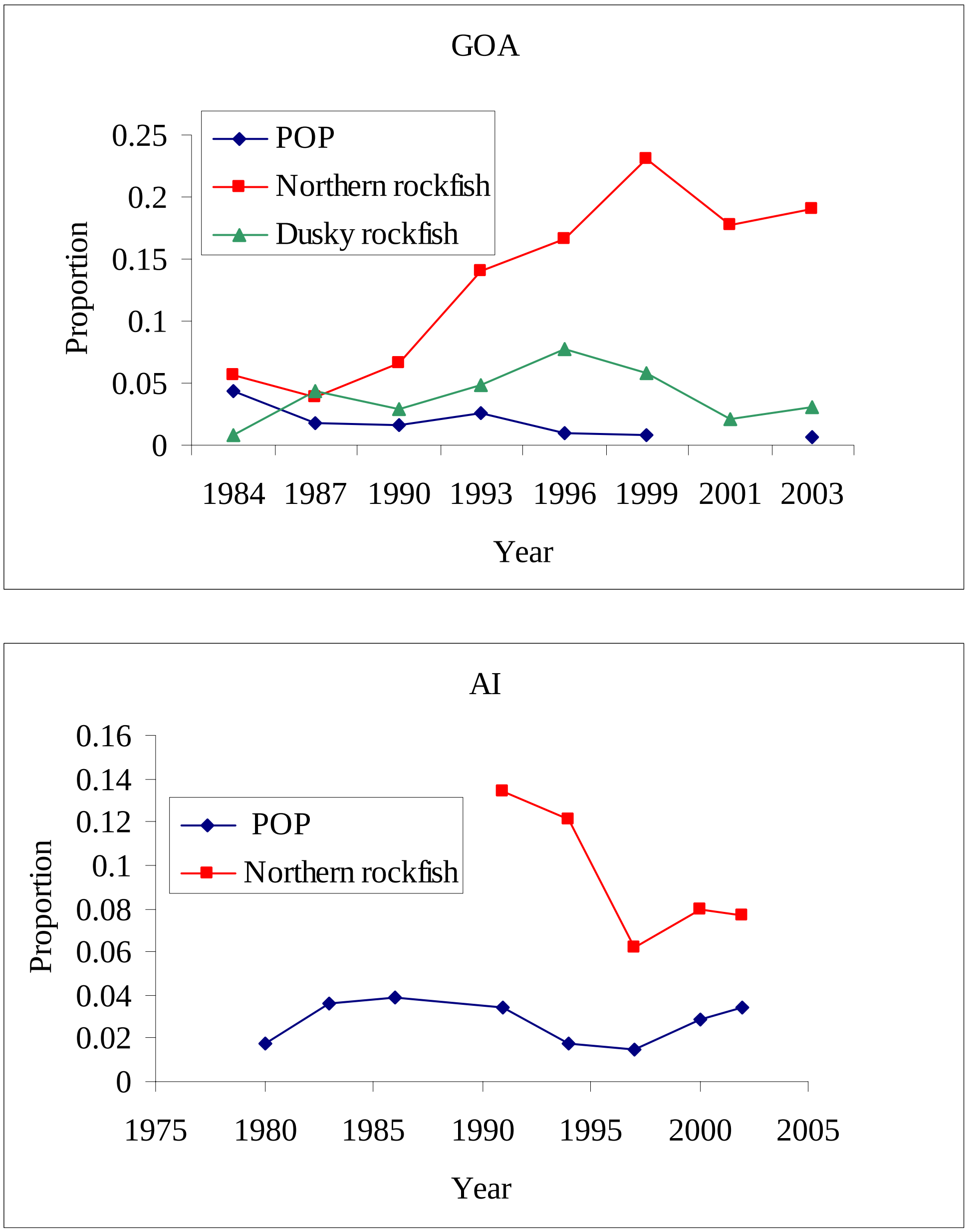

Figure 1. Proportion of old fish for selected rockfish species in the GOA and AI survey areas, based upon research trawl surveys.

Appendix 1. The effect of maternal age of spawning on estimation of F_{msy} for Alaskan Pacific ocean perch.

Paul Spencer, Dana Hanselman, and Martin Dorn

*Abstract

Recent laboratory research suggests that rockfish larval survival rates increases with the age of the spawner, thus potentially necessitating more conservative harvest policies that explicitly consider the age structure of the spawning stock biomass. In this study, we use simple deterministic population dynamic equations to examine the effect of reduced spawning effectiveness of younger spawners on commonly use fishing rate reference points such as F_{msy} and $F_{xx\%}$, the fishing rates corresponding to the maximum sustained yield and conservation of *xx%* of the reproductive output per recruit relative to an unfished population, respectively. Reduced effectiveness of younger spawners results in reduced reproductive output conserved for a given level of fishing mortality, but also increased resiliency in stock-recruitment curves due to an equivalent number of recruits being associated with a reduced measure of reproductive output. For Bering Sea/Aleutian Islands and Gulf of Alaska POP, these two effects nearly equally counteracted each other, producing stable F_{msy} estimates for three different measures of reproductive output. However, estimates of $F_{xx\%}$ rates that consider both the uncertainty in stock-recruitment parameters and the degree to which maternal age affects reproductive success are more conservative than those based on analyses using spawning stock biomass as reproductive output. These results indicate that perception of stock resiliency is not necessarily independent of the life-history parameters describing production of reproductive output. The degree of adjustment of $F_{xx\%}$ rates needed for Alaska POP is not currently known, and will depend upon further analyses with realistic environmental variability and careful consideration of the range and weight of stock-recruitment and life-history parameters evaluated.

*Introduction

Declines in rockfish off the U.S. West Coast (California, Oregon, and Washington) have occurred during the past two decades, resulting in the development of rebuilding plans for several species and the declaration of the U.S. West Coast fishery a failure by the U.S. Secretary of Commerce (Parker et al. 2000, Dorn 2002). The collapse of West Coast rockfish has drawn increased attention to rockfish fishery management policies, which are based upon the principle of setting an upper limit of fishing mortality to $F_{40\%}$, a rate that corresponds to conserving 40% of the estimated spawning stock biomass per recruit (SPR) obtained from an unfished population. This fishing mortality reference point originates from Clark (1993), who used stochastic simulations to show that $F_{40\%}$ produces a large fraction of the equilibrium maximum sustainable yield (MSY) and reduced the likelihood of low biomass for stocks described with a plausible range of stock-recruitment curves and levels of recruitment autocorrelation. Thus, a $F_{40\%}$ harvest rate is intended as proxy to F_{msy}, the harvest rate associated with MSY, in cases where MSY cannot be reasonably estimated. Attention to the $F_{40\%}$ policy have primarily occurred in two areas: 1) stock-recruitment curves typical for rockfish may be less productive than the range considered by Clark (1993), suggesting that policies that conserve more than 40% of the unfished SPR may be appropriate; and 2) harvest policies for rockfish must recognize the reduction of reproductive capacity associated with the truncated age compositions of exploited populations (Leaman 1991).

For West Coast rockfish, analyses of stock-recruitment data suggests that fishing mortality rates more conservative than $F_{40\%}$ are appropriate. Dorn (2002) conducted a Bayesian meta-analysis of rockfish stock-recruitment data and found estimated stock recruitment relationships for West Coast rockfish to be generally less productive than the range considered by Clark (1993), and suggested that a risk neutral harvest rate policy of $F_{50\%}$ is appropriate for these stocks (Dorn 2002). Additionally, Clark (2002) recommended that for stocks with low resiliency, SPR rates of $F_{50\%}$ or $F_{60\%}$ may be required to maintain an adequate balance of maximizing yield while preserving stock size.

Research on the reproductive biology of rockfish suggests that the reproductive capacity of the stock may be a function of the age structure, in particular the proportion of old fish in the population. Leaman (1987, 1991) noted that rockfish are long-lived with deterministic growth, and older fish allocate a large proportion of available energy to reproduction. The removal of older females by thus disproportionately reduces spawning output such that reproductive value (the expected lifetime number of offspring from a female of a particular age in a stable age distribution) is highly sensitive to increases in fishing mortality. Additionally, Berkeley et al. (2004a) found in laboratory studies that older black rockfish (*Sebastes melanops*) produced larvae with increased survival rates; thus, exploitation can be expected to disproportionately remove the most effective spawners. The implication from these studies is that simply conserving spawning biomass is not sufficient, and managers should aim to preserve spawning biomass with a desirable age structure.

Given the collapse of several West Coast rockfish species, considerable interest exists in determining whether management policies for Alaska rockfish are sufficiently conservative. In 2002, a panel charged with evaluating the $F_{40\%}$ policy for Alaska groundfish (Goodman et al. 2002) suggested that the currently used $F_{40\%}$ policy may not provide sufficient conservation for Alaska rockfish. Dorn's (2002) meta-analysis is the only study that simultaneously considered the productivity of both West Coast and Alaska rockfish, evaluating eight West Coast stocks, one British Columbia Pacific Ocean perch (POP) stock, and three Alaska POP stocks (at that time, Bering Sea and Aleutian Islands POP were assessed as separate stocks). The Alaska POP stocks show greater resiliency than the West Coast stocks, with MSY occurring at SPR rates of approximately $F_{30\%}$. The finding of observed greater productivity in the Bering Sea/Aleutian Islands POP and Gulf of Alaska POP has been repeated in recent stock-recruitment analysis, which have found that estimated the F_{msy} reference points are greater than the proxies of $F_{40\%}$ (Spencer and Dorn 2003, Hanselman et al. 2004). However, these studies have not considered how changes in age structure may affect estimates of stock productivity and estimation of harvest reference points such as F_{msy}. For example, the analyses of Clark (1991,1993) evaluate the correspondence of F_{msy} and $F_{spr\%}$ rates when spawning stock biomass is used as a measure of stock reproductive output. How would expressing reproductive output in units that reflect differential spawning effectiveness between age groups change the results of Clark's (1991,1993) analyses, and what would be the effect upon the estimate of F_{msy} for a particular stock?

The purpose of this study is to consider the effect of the maternal age of spawning on F_{msy} and proxies to F_{msy}. The analysis consists of converting reproductive output from units of spawning stock biomass to "viable larvae", the per unit production of which is a function of spawner age. First, we consider under what conditions this conversion of units can be expected to affect estimates of fishing reference points. Second, we use deterministic population dynamics equations to illustrate the effect upon estimation of F_{msy}, assuming that stock-recruitment parameters are well estimated. Third, we estimate F_{msy} for BSAI and GOA POP using a variety of measures of reproductive capacity, and compare these estimates to currently used fishing mortality reference points. Finally, we illustrate how common fishing rate proxies to F_{msy} that aim to conserve a specified proportion of the reproductive output per recruit are affected by maternal effects on larval viability.

*Methods

Standard population dynamics equations were used to estimate yield per recruit and spawning biomass per recruit as a function of fishing mortality for a population with life history characteristics equivalent to those estimated for Bering Sea/Aleutian Islands POP. These life history parameters describe a stock with relatively low natural mortality (M = 0.05), moderate von Bertalanffy K parameter (K = 0.17), and age at 50% selection in the fishery less than age at 50% maturity (Figure 1), and are viewed as broadly representing common life-history characteristics of exploited rockfish in the north Pacific.

Viable larvae are introduced as a measure of reproductive output that discounts the output from younger spawners via a larval survival curve. Viable larvae were estimated as

$$\text{Viable larvae } = \sum_a s_a f_a p_a N \qquad (1)$$

where N is total number of fish, p_a is the proportion at age , f_a is fecundity at age, and s_a is proportion of larvae surviving to two weeks.

Two separate larval survival curves were considered: 1) a proxy curve adapted from the black rockfish laboratory data of Berkeley et al. (2004a); and 2) a knife-edged curve in which no larvae produced from a spawner younger than 20 years would survive. Berkeley et al. (2004a) develop an asymptotically increasing relationship between maternal age and the time required for 50% mortality of black rockfish larvae, and this relationship was modified to model larval mortality rate for POP (Figure 2a). Relative to black rockfish, POP have both an older generation time and age at maturity. The curve describing time to 50% larval mortality for POP thus had a higher x-intercept and lower slope to reflect these considerations and was used to calculate the proportion of larvae surviving two weeks (Figure 2a), a period arbitrarily chosen to provide some contrast in the larval survival rates by age. The knife-edged survival curve provides a scenario of extreme maternal effects on reproductive output, thus creating contrast between measures of reproductive output that consider intermediate and no effects on larval survival, represented by the larvae produced with the proxy curve and SSB, respectively.

Little information is available regarding fecundity of Alaskan POP, although studies in other areas indicate that larger females attain fecundities of 305,000 (Hart 1973) and 350,000 (Leaman 1991). Phillips (1964) presents the fecundity-length relationships for 10 species of rockfish off the U.S. West Coast, and the species most closely matching the observations of Leaman (1991) and Hart (1973) were splitnose rockfish. A fecundity at length relationship for Alaskan POP was developed by increasing the original splitnose rockfish length measurements by 30 mm to adjust for the larger size of POP (Figure 2b).

A Beverton-Holt recruitment curve was used for computation of equilibrium yield, and was re-parameterized using R_0, the expected recruitment consistent with the reproductive capacity of an unfished stock S_0, and a parameter that measures the resiliency of the stock, h, defined as the proportion of R_0 that recruits when the reproductive capacity of the stock is reduced to 20% of S_0 (i.e., the steepness parameter of Mace and Doonan (1988)). The reparameterized Beverton-Holt curve is given by

$$R = \frac{0.8\, R_0\, h\ S}{0.2\, \varphi_0\ R_0 (1 - h) + (h - 0.2) S}, \qquad (2)$$

where $S_0 = \varphi_0 R_0$, and φ_0 is either SSB or viable larvae per recruit (defined as SPR and LPR, respectively) for an unfished stock. Steepness ranges between 0.2 (recruits related linearly to viable larvae) to 1.0 (recruits independent of larvae). Equilibrium recruitment and yield were obtained for a sequence of harvest rates where LPR and SPR is reduced to a fraction *p* of unfished LPR or SPR (*p* = 1.00,0.99, . . . ,0.01), and F_{MSY} was estimated as the instantaneous fishing mortality rate associated with the level of *p* at which equilibrium yield is maximized.

**Application to Alaska POP

Estimates of F_{msy} for GOA and BSAI POP using larvae (produced with either the proxy or knife-edged survival curve) and SSB as measures of reproductive output were made with a Bayesian estimation procedure. A brief description is given here, and more details can be found in Spencer et al. 2004. Time series of numbers at age, including recruits, for each stock were obtained from age-structured stock assessments (Spencer et al. 2004, Hanselman et al. 2003), and estimates of viable larvae were made from Eq. 1 using the appropriate life-history parameters from each region. There are three parameters for which priors need to be developed, R_0, h , and σ^2, the variance of expected recruitment. The prior for steepness was modeled by assuming that β, the logit of h, was normally distributed (after rescaling h into the interval (0,1), $(h - 0.2) / 0.8$, and simplifying). For h in the interval (0.2,1.0) the logit β ranges from -∞ to +∞, allowing straightforward specification of a mean and variance. A normal prior was used for R_0, and a locally uniform prior for σ on a log scale was used. The log joint posterior distribution is the sum of the log-likelihood and the log prior, and the mode of the joint posterior distribution was obtained using the AD Model Builder nonlinear optimization software (Otter Research 1996).

The prior for β was based upon levels of reproductive success (*R/S* at the origin relative to an unfished stock, R_0/S_0) considered plausible for rockfish. Dorn et al. (2003) generated a prior distribution from these considerations by using a potential increase in reproductive success of 8 (β = 0.34) as the midpoint of the distribution (corresponding to the middle of the range of stock-recruitment curves considered by Clark (1991)), and set the prior variance so that factors 4 and 16 were located at the 10th and 90th percentiles of the distribution. For Alaska POP, the same variance was used but the midpoint of the distribution was lowered to reflect a potential increase in reproductive success of 4 (β = -0.51), thus reflecting the perceived lower productivity of rockfish relative to the values considered by Clark (1991). The midpoint of this distribution corresponds to a steepness of 0.50, closer to the value of 0.39 found for five rockfish stocks in a meta-analysis by Myers et al. (1999). Prior estimates of R_0 were derived from estimates of recruits consistent with the stock size in the first year of the age-structured stock assessment model, and a relatively large coefficient of variation of 0.22 was used.

**Estimation of fishing rate proxies to F_{msy}

The yield curves above require knowledge of the stock-recruitment parameters h and R_0, and for cases where these parameters are unknown Clark (1991,1993) proposed application of fishing mortality rates likely to preserve at large portion of the MSY across a range of stock-recruitment relationships. Clark (1991) considered yield curves produced from a series of stock-recruitment relationships in which the level of reproductive success ranged from 4 to 16. The "maximin" criteria, defined as the maximum of the minimum yield for each level of fishing mortality, was used to identify the optimal fishing rate. In this study, the same methodology is applied to examine how the unit of reproductive output may affect the harvest rate proxies. Consistent with Clark (1991,1993), yield curves corresponding to the reproductive success of 4 and 16 times an unfished stock were produced (intermediate levels of reproductive success were seen not to affect the maximin fishing mortality rate) for each of the three measures of reproductive output, and the optimal fishing rate proxy was then identified explicitly considering uncertainty not only in stock-recruitment relationships, but also the degree to which spawner age affects larval viability.

*Results

Spawning stock biomass is commonly used as a proxy for reproductive output (i.e., eggs produced) in stock-recruitment analyses, and under the assumption of a linear (density-independent) relationship this substitution does not affect the stock-recruitment analyses (Rothschild and Fogarty 1989). Similarly, recasting reproductive output from SSB to viable larvae will not change the stock-recruitment analysis unless there is a non-linear relationship between these measures, and this can be evaluated by examining whether the ratio of viable larvae to SSB changes with stock size. Spawning stock biomass can be expressed as the sum, over all ages, of the product of numbers at age, weight at age, and maturity at age, and the ratio of viable larvae (Eq. 1) to SSB is

$$\frac{\sum_a f_a s_a p_a}{\sum_a m_a w_a p_a} \tag{3}$$

where m_a and w_a are the proportion mature at age and weight at age, respectively. Although density-dependent changes in fecundity, proportion mature at age, and growth may occur for rockfish (Leaman 1991), attention upon the production of viable larvae has largely focused upon the reduction of the age structure associated with exploited populations (Berkeley et al. 2004b). Thus, the major factor expected to affect the per unit production of viable larvae in the presence of age-dependent maternal effects is p_a, and Eq. 3 provides a framework for assessing how several factors may affect the ratio of viable larvae to SSB.

The relationships between SSB, viable larvae (produced with the proxy curve) and mean age for an equilibrium population with constant recruitment are shown in Figure 3a. As fishing mortality increases the mean age decreases, resulting in the production of viable larvae decreasing at a greater rate than SSB due to the dependence of larval survival on spawner age. Thus, the proportion of viable larvae per recruit conserved, relative to an unfished stock, at any given fishing mortality rate is lower than the proportion of SSB conserved. For example, a fishing rate of 0.048 would conserve 40% of the SSB but only 35% of the viable larvae per recruit when estimated with the proxy mortality curve, and 27% of the viable larvae per recruit when estimated with knife-edged curve (Figure 3b).

Conversely, a reduction in mean age combined with measuring reproductive output in viable larvae results in more productive stock-recruitment curves than would occur if reproductive output was measured in SSB. This occurs because although reproductive output is reduced, the definition of recruits has not been altered. Thus, an identical level of recruits would result from a stock with diminished reproductive output, resulting in an interpretation of increased steepness h and resiliency. Consider a case where the number of recruits is defined as a function of viable larvae (as measured from the proxy survival curve), via the Beverton-Holt curve with a steepness parameter h of 0.5. Relating the number of recruits derived from this curve to viable larvae (as produced from the knife-edged survival curve) results in an estimated steepness of 0.62, whereas relating the same number of recruits to SSB results in an estimated steepness of 0.43 (Figure 4).

The effect of converting reproductive capacity to viable larvae on F_{msy} will involve a tradeoff between the greater conservatism implied by the reduced reproductive output per recruit and the greater resiliency implied by an increased steepness in the stock-recruitment curve. Examples of this tradeoff can be seen in the application to BSAI and GOA POP, where the estimates of F_{msy} obtained from each of the three measures of reproductive output were very similar to each other. For the BSAI POP, the estimates of steepness ranged from 0.86 (SSB) to 0.95 (larvae with knife-edged mortality curve), whereas the estimates of $F_{40\%}$ decreased from 0.049 to (SSB) to 0.032 (larvae with knife-edged mortality curve) (Table 1, Figure 5). Estimated F_{msy} was relatively stable, decreasing from 0.088 (SSB) to 0.083 (larvae with knife-edged mortality curve) (Table 1, Figure 6). A similar pattern was seen for the GOA POP, where steepness increased across the three measures of reproductive output from 0.82 to 0.93, $F_{40\%}$ decreased from 0.058 to 0.036, and F_{msy} decreased slightly from 0.10 to 0.087.

Incorporation of uncertainty in the degree to which spawner age affects larval survival resulted in estimated proxy fishing mortality reference points being more conservative than those attained from consideration of stock-recruitment uncertainty alone. The yield curves for each of the three measures of reproductive output are shown in Figure 7(a-c), and correspond to stock recruitment curves with reproductive success either 4 or 16, spanning the range considered by Clark (1991). With reproductive output measured in SSB, the proxy fishing mortality rate resulting from the maximin criterion occurs at an F_{spr} rate of $F_{43\%}$, identical to the results of Clark (2002) for Beverton-Holt curves. With reproductive output defined as larvae (either from the proxy of knife-edged survival curves), the proxy fishing reference points would conserve a similar amount of the reproductive output, but the fishing mortality would decrease from 0.044 (SSB) to 0.031 (larvae with the knife-edged curve). An analysis which incorporates uncertainty in the degree of maternal effects upon larval survival in addition to uncertainty in stock-recruitment parameters precludes presenting yield curves in terms of relative reproductive output per recruit, and the yield curves for all three measures of reproductive output are plotted against F in Figure 7d. Here, the identified proxy fishing mortality is $F = 0.035$, more conservative than the value of 0.044 that only considers reproductive output as SSB.

*Discussion

Effective reproductive output of rockfish may be expected to decline at a faster rate than SSB with increased fishing, due to a reduced mean age and age-dependent spawner effectiveness (Berkeley et al. 2004a). However, in order to incorporate this observation in operational management advice it becomes necessary to examine its effect upon commonly used reference points such as F_{msy}. It is important to note that although the reproductive output may be diminished, relative to SSB, the measure of recruits has not been altered. Ideally, one would obtain recruitment estimates from juvenile surveys, although in practice they are typically obtained from stock assessment models utilizing age-composition data from fisheries and surveys; in either case, recruits are simply defined as the number of young fish entering the population. Thus, relating an identical number of recruits with a diminished measure of reproductive output implies greater resilience and stock productivity. The effect upon F_{msy} can thus be seen as the interaction between a reduction in the reproductive output per recruit conserved at a given fishing level (implying more conservative management) with the increased productivity obtained from the stock-recruitment curve (implying that the stock can support increased fishing mortality rates). For Alaska POP, these two opposing processes nearly equally compensated for each other and produced F_{msy} estimates that were fairly robust across a series of measures of reproductive output. However, this would not be expected to be a universal result, and for any given stock the incorporation of age-dependent maternal effects on spawning effectiveness may either increase or decrease F_{msy} depending, in part, on how the shape of the stock-recruitment curve is affected. Additionally, these results indicate that the perception of population resiliency obtained from the stock-recruitment parameters is not independent of the life-history parameters governing reproductive output.

Consideration of uncertainty in stock-recruitment relationships led to the development of $F_{40\%}$ as a proxy for F_{msy}, and additional uncertainty regarding the extent to which spawner age structure affects reproductive output would produce more conservative proxy reference points. Similar to the results found by Clark (2002) for Beverton-Holt recruitment curves, the results presented here indicate that conserving approximately 40% of the reproductive output per recruit is desirable even if the definition of reproductive output changes from SSB to larvae (produced with either the proxy or knife-edged mortality curves). However, the level of fishing mortality associated with these reference points decreases as reproductive output changes from SSB to viable larvae (produced with the knife-edged curve). Although the work of Clark (1991) evaluated a variety of combinations of life-history parameters, for any given stock it is assumed that the relevant life-history parameters would be known, thus allowing *SPR* rates to be mapped into a particular *F* rate. In practice, it is unlikely that the extent to which of maternal age affects reproductive output will be known with reasonable certainty, thus creating uncertainty in the life-history parameters in addition to the stock-recruitment parameters. Because expressing reproductive output as SSB represents one bound where these maternal effects are assumed to not occur, any consideration of the maternal effects on reproductive output would produce relatively more conservative harvest rate proxies (Figure 7). Additionally, the yield curves were obtained from the standard assumption where the stock-recruitment parameters are not a function of age-structure, although the analysis could be modified to reflect that stocks with truncated age structure may be described by less productive stock-recruitment curves (Longhurst 2002). In future studies, careful consideration should be given to the range and weights given to the stock recruitment curves and life-history parameters, as this will largely determine the harvest rate proxies obtained from this type of analysis.

Given the uncertainty in stock-recruitment relationships for Alaska POP, perhaps the best use of

F_{msy} estimates is as a qualitative indicator to assess the need for any directional changes in the currently used harvest rate proxies. The currently used $F_{40\%}$ estimates for Alaska POP are more conservative than estimates of F_{msy} based upon any of the three measures of reproductive output, indicating that the current harvest policy is not inconsistent with the available data on stock productivity. As with much stock-recruitment data, it can be difficult to parse out how much of the recruitment signal is attributable to spawner output and how much is attributable to environmental conditions. The estimates of high resiliency for Alaska POP derive from a few strong recruitments during favorable environmental conditions in the 1980s, and these results may not be repeated in different environmental conditions. Similarly, much of what we perceive as the low productivity of rockfish recruitment derives from West Coast data collected during a period of unproductive environmental conditions (McGowen et al. 1998), and this confounding, in part, prompted Dorn (2002) to advise cautious interpretation of his meta-analysis results. What is desired is knowledge of how species with rockfish life-history characteristics respond to a variety of environmental regimes, and development of robust management strategies appropriate for this range of environmental variation. Management Strategy Evaluation (MSE, Stokes et al. 1999) appears to be one promising approach for addressing these questions and will be pursued in future research. Additionally, the development of the $F_{40\%}$ concept was derived with reference to constant harvest rate policies, although in practice a more conservative control rule is applied to Alaska groundfish stocks in which the harvest rate decreases as the stock is reduced below $B_{40\%}$. Thus, the current harvest policy corresponds to conserving more than 40% of the SSB per recruit for a significant range of stock sizes, and mapping the relationship between the current control rule and a constant harvest rate policy remains an interesting application for MSE analyses.

Given the unique aspects of rockfish biology such as high longevity, late ages at maturity, ovivivparity, high recruitment variability, and potentially complex spatial and temporal formation of spawning aggregations, the concept of applying F_{spr} harvest rates over broad spatial areas has been questioned (Berkeley et al. 2004b). However, it is important to distinguish between those aspects of rockfish biology that can be addressed within an F_{spr} framework and those that pertain to the appropriate spatial scale of the unit stock for management purposes. Many of the aspects of rockfish life-history such as unusually low natural mortality rates, late ages at maturity, and recruitment curves with low resiliency are addressed within an F_{spr} framework. For example, previous work by Clark (2002) demonstrates that for stocks with reduced resiliency the optimal fishing rates may conserve up to 50% or 60% of the SSB per recruit, and this study illustrates how the basic framework can be modified to consider the effects of maternal age on reproductive output. Definition of the appropriate spatial scale upon which to base management actions, however, is a prerequisite for applying any type of management policy, including those based upon either fishing rate reference points or spatial closed areas. In other words, one potential response to information suggesting localized spawning aggregations would be application of the fishing mortality reference points to finer spatial scales so as to prevent localized depletion.

In summary, deterministic analysis were used in this paper to evaluate how fishing mortality reference points may be affected by maternal effects upon reproductive output, with the finding that although the F_{msy} for any given stock may either increase or decrease, the harvest rate proxies intended to conserve a certain portion of the reproductive output per recruit would be expected to be reduced. However, the extent to which these proxy mortality rates for rockfish would decrease is not currently known, and MSE simulations with realistic environmental variability will be used in future research to address this issue. In this study, an unusually wide range of potential maternal effects upon reproductive output was used illustrate general trends, and the range of productivity levels in the stock-recruitment curves paralleled those used by Clark (1991) to allow comparability. However, in order to produce meaningful management advice it will become important to appropriately weight the life-history and stock recruitment parameters in the analysis, and additionally consider more complex recruitment processes where the expected productivity may be a function of the age structure of the population.

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Figure captions

Figure 1. Selectivity, maturity, and weight at age for BSAI POP, all shown on a relative scale.

Figure 2. (a) Days to 50% survival for black rockfish larvae (dashed line) from Berkeley (2004a) as a function of spawner age, and modified curve used for POP (solid line); the estimated proportion of POP surviving to two weeks (shown for ages 3-25+) is shown in the dotted line. (b) fecundity at length for splitnose rockfish (data points and dashed line) from Phillips (1964) and adapted for POP (solid line); the resulting fecundity at age is shown in (c).

Figure 3. (a) Relationship of SSB (solid line) and mean age (dashed line) to viable larvae per recuit, each shown relative to their maxima; the declines in all three relate to increases in fishing mortality from an unfished condition. The dotted line indicates a 1:1 slope. (b) The proportion of SSB per recruit (solid line), and larvae per recruit produced with the proxy (dashed line) and knife-edged (dotted line) survival curves, relative to an unfished stock.

Figure 4. Stock-recruitment curves for three measures of reproductive output, plotted on relative scales: SSB (solid line), larvae from proxy survival curve (dashed line), and larvae from knife-edged survival curve (dotted line).

Figure 5. Stock recruitment data (a-b) and estimated stock-recruitment curves (c-d) for BSAI POP and GOA POP with scaled reproductive output measured as SSB (circles, solid lines), larvae from proxy survival curve (triangles, dashed lines), and larvae from knife-edged survival curve (crosses, dotted lines).

Figure 6. Relative yield as a function of fishing mortality for BSAI POP (a) and GOA POP (b) with reproductive output defined as SSB (solid lines), larvae (proxy survival curve; dashed lines), and larvae (knife-edged survival curve; dotted line).

Figure 7. (a-c) Relative yield as a function of either relative spawner pre recruit or larvae per recruit for three measures of reproductive output with reproductive success of 4 (dashed line) and 16 (solid line); the maximin F_{spr} or F_{lpr} are denoted by the vertical lines. (d) Relative yield for all three measures of reproductive output and two levels of reproductive success plotted against F.

Figure 1.

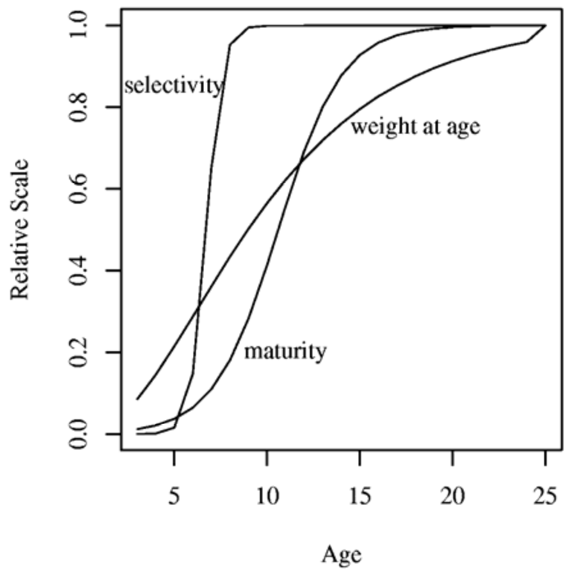
selectivity
weight at age
maturity
Relative Scale
0.0
0.2
0.4
0.6
0.8
1.0
5
10
15
20
25
Age

Figure 2

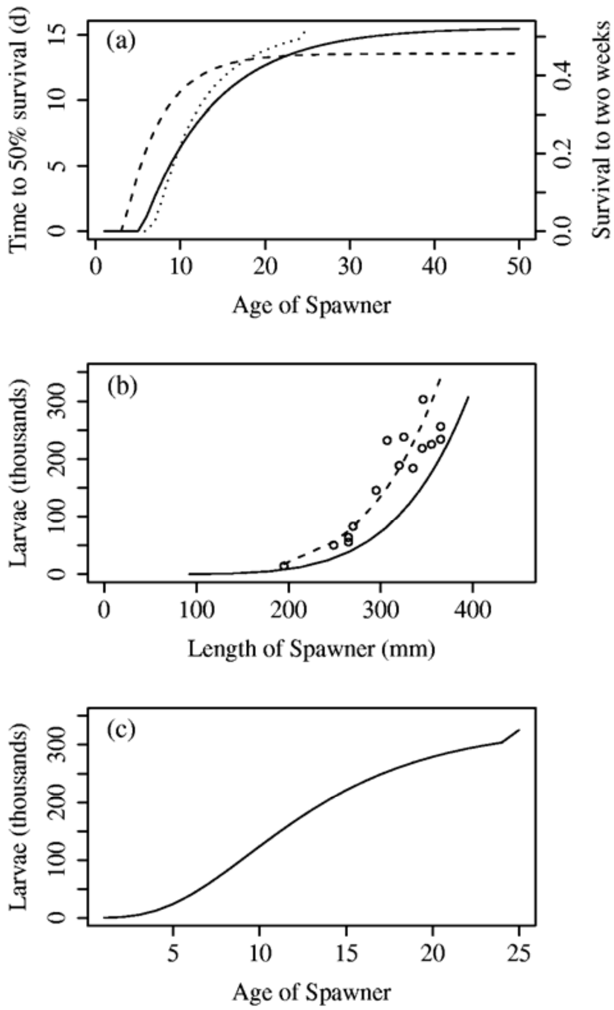
(a)
Time to 50% survival (d)
Survival to two weeks
Age of Spawner
(b)
Larvae (thousands)
Length of Spawner (mm)
(c)
Larvae (thousands)
Age of Spawner

Figure 3

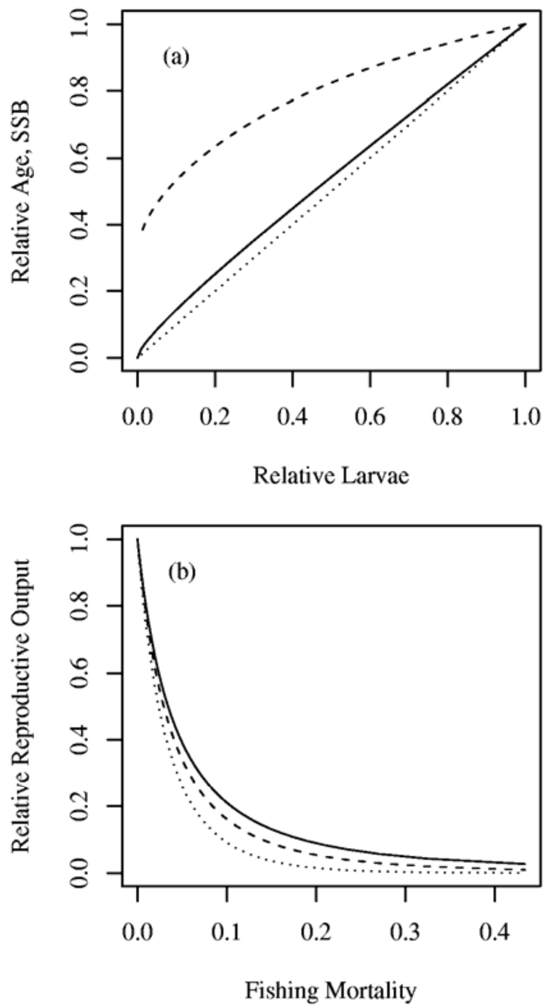
(a)
Relative Age, SSB
0.0
0.2
0.4
0.6
0.8
1.0
Relative Larvae
(b)
Relative Reproductive Output
0.1
0.3
Fishing Mortality

Figure 4.

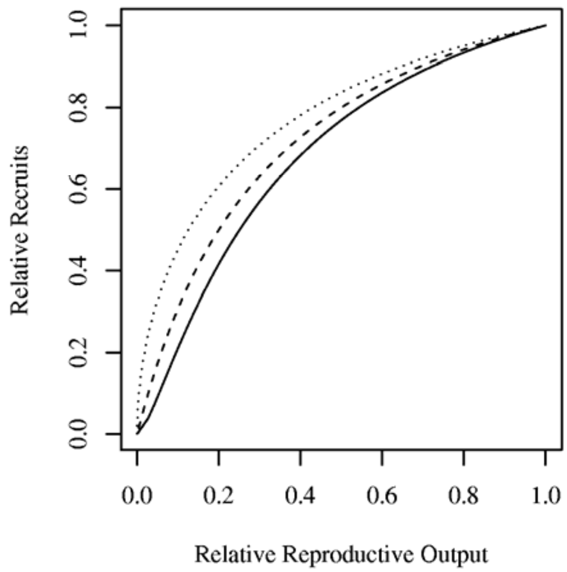
Relative Recruits
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Relative Reproductive Output

Figure 5.

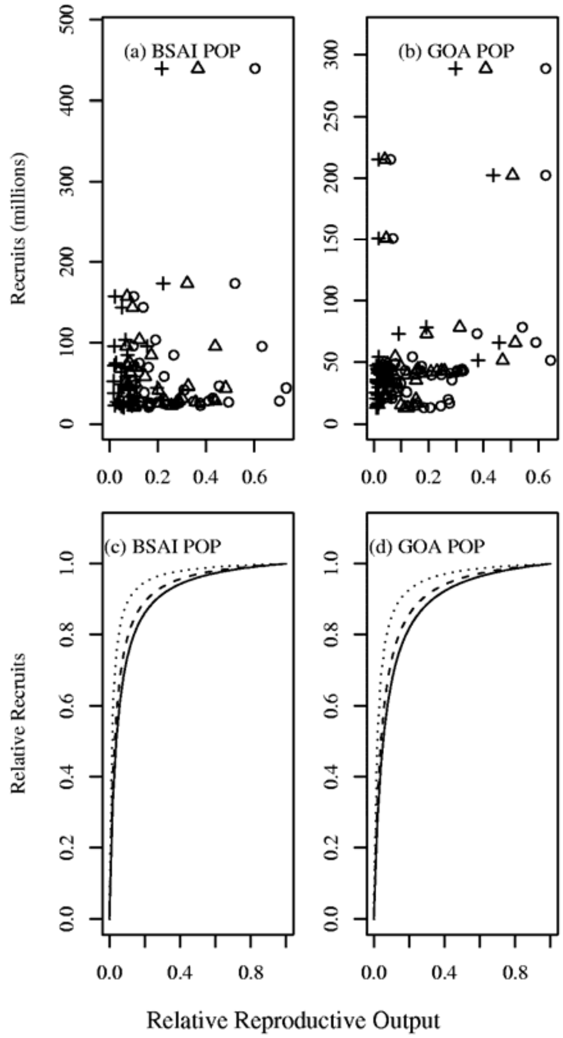
(a) BSAI POP
(b) GOA POP
(c) BSAI POP
(d) GOA POP
Recruits (millions)
Relative Recruits
Relative Reproductive Output
0
100
200
300
400
500
0
50
100
150
200
250
300
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.0
0.2
0.4
0.6
0.0
0.4
0.8
0.0
0.4
0.8
0.0
0.2
0.4
0.6
0.8
1.0

Figure 6.

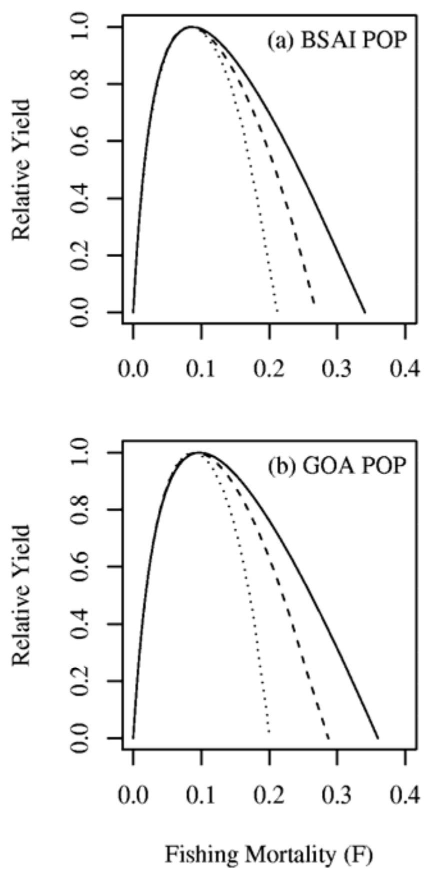
(a) BSAI POP
Relative Yield
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
(b) GOA POP
Relative Yield
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
Fishing Mortality (F)

Figure 7.

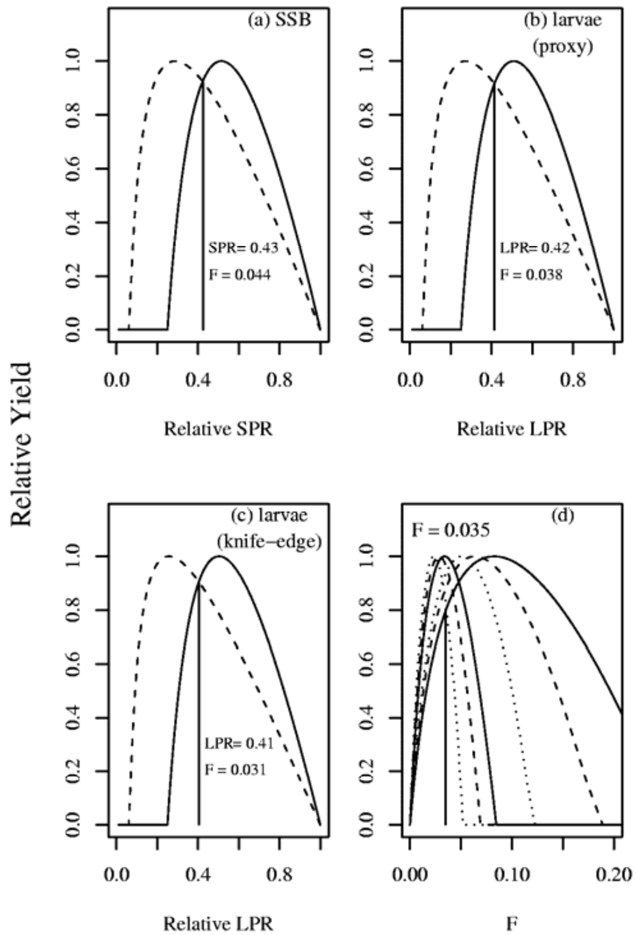
(a) SSB
SPR= 0.43
F = 0.044
Relative SPR
(b) larvae (proxy)
LPR= 0.42
F = 0.038
Relative LPR
(c) larvae (knife−edge)
LPR= 0.41
F = 0.031
Relative LPR
(d)
F = 0.035
F
Relative Yield

Table 1. Estimates of steepness, $F_{40\%}$, F_{msy}, and percent unfished SSB or larvae at F_{msy} for BSAI POP and GOA POP with three units of reproductive output.

Stock	Units of reproductive output	Steepness	$F_{40\%}$	Percent unfished SSB or larvae at F_{msy}	F_{msy}
BSAI POP	SSB	0.86	0.049	0.24	0.088
	larvae (proxy mortality)	0.89	0.041	0.2	0.084
	larvae (knife-edged mortality)	0.95	0.032	0.13	0.083
GOA POP	SSB	0.82	0.059	0.26	0.1
	larvae (proxy mortality)	0.86	0.049	0.22	0.093
	larvae (knife-edged mortality)	0.93	0.036	0.14	0.087

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