Harvest policy considerations for re-evaluating the minimum size limit in the Pacific halibut commercial fishery

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Abstract

The Pacific halibut harvest strategy uses a minimum size limit of 32 inches (81.3 cm) in its commercial fishery. The stock assessment estimates increasing trends in total halibut numbers and total biomass in spite of a decade long of declining trend in exploitable biomass. The differing estimated trends have been interpreted as resulting from decreasing availability of larger halibut to the commercial gear due to a decade's long decline in size-at-age, and increased estimates of recent recruitment. The estimated coastwide accumulation of halibut below the size limit has prompted requests to consider lowering or eliminating the current minimum size limit. This report evaluates the potential effects of modifying the current minimum size limit (MSL), along with the effect of different assumptions and methods on evaluating results. Three main methods were used. First was a comparison between female maturity at age with both potential future and observed historical changes in selectivity and commercial landings. Second was a coastwide yield per recruit and spawning biomass per recruit analysis. Third was a spatially structured and migratory yield per recruit and spawning biomass per recruit analysis. A fourth analysis was conducted by gradually decreasing the MSL, using simulated changes in selectivity shapes under the assumption of gradual changes in weights at age of the resulting catch. Reducing or eliminating the MSL is expected to increase the capture of immature females, as supported by comparing expected changes in selectivity at age and cumulative distributions of observed catch at age for different historical periods with different MSL. A reduction or elimination of MSL does increase the proportion females at older ages relative to status quo, with as much as 80% improvement, however the actual proportions in the population are still quite low (12% to 22% at age 25). Eliminating the MSL and assuming that retention will be similar to that of the survey, results in decreased coastwide yield per recruit and decreased spawning biomass per recruit when accounting for smaller weights-at-age expected from changes in commercial selectivity. When assuming that elimination of the MSL results in commercial landings similar to the IPHC survey, the proportion of females in the catch and in the population only marginally changes from status quo conditions. A larger decrease in the proportion of females in the catch and increase in the proportion in the population could be achieved by a major change in commercial selectivity towards smaller sizes and younger ages. However, this would result in the capture of immature females as much as four years before they mature, would require precise control of a low harvest rate (around 0.1) and would achieve lower yield per recruit than the status quo. The migratory analysis produced similar results to the coastwide yield per recruit and spawning biomass per recruit and it had low sensitivity to different assumptions on migration. Minor reductions in the MSL along with harvest rate reductions are expected to produce at most 3% increases in yield per recruit but greater reductions in the MSL including its elimination are expected to reduce both yield per recruit and spawning biomass per recruit. The proportion of females in the population between the extremes of current MSL and a MSL of 65cm would change from 44% to 45% for ages 6 and older, and from 12% to 22% at age 25. Overall, decreasing the MSL is expected to reduce yield per recruit and spawning per recruit

under most conditions evaluated in this work. At the extreme of MSL of 65cm, the proportion of females in the catch would be still predominantly female and although the proportion of females at older ages would increase, the actual proportions in the population would still be quite low.

Introduction

Size limits are one of the available harvest tactics to implement a harvest strategy (Hilborn and Walters 1992). Pacific halibut has been commercially exploited since 1888 using a variety of fishing gear types until 1944 when nets were prohibited and longline became the main fishing gear in the directed commercial fishery (Bell 1981). The commercial fishery operated without a minimum size limit (MSL) between 1888 and 1940 when a 5 lb minimum weight was established. In 1944 a 26 inch, or 66 cm (equivalent to the 5 lb set in 1940) minimum size limit was introduced and remained in place until 1973 when it was changed to a minimum size limit of 32 inches or 81.3 cm (Myhre 1974) that still stands today. Reasons behind past changes in MSL included protection of juveniles and expected increased yield per recruit. The stock assessment has estimated increasing trends in total halibut numbers and total biomass during the last decade in spite of a decade long of declining trend in estimated exploitable biomass. The differing estimated trends have been interpreted as resulting from decreasing availability of larger halibut to the commercial gear due to a decade's long decline in size-at-age, and increased estimates of recent recruitment. The stock assessment estimated coastwide accumulation of halibut below the size limit has prompted requests to consider lowering or eliminating the current MSL.

Female halibut have a faster growth rate than males. The current size limit of 81.3 cm, combined with the sexual dimorphism in growth of halibut, results in a commercial fishery that is predominantly comprised of females. The sex ratio in the commercial catch is not known as the fish are eviscerated at sea, though survey data are used to estimate sex ratio at length (Clark 2004). The IPHC setline survey does provide direct estimates of the variability in sex ratio at length (Fig. 1). The potential higher ratio of males in the commercial catch, as evidenced by their increased preponderance in the survey catch below the current MSL, has also been part of the rationale for considering lowering the MSL.

Selectivity is one of the main components of models of populations under exploitation and relates to the fishing process. Changes in selectivity, along with the assumptions regarding how to model selectivity, are expected to have profound effects on the performance of stock assessments and harvest policies. Since the beginning of the commercial fishery for Pacific halibut in 1888, selectivity has been determined by the operational characteristics of the longline gear (hook size and spacing), behavior of the fishermen (e.g. historical expansion of the fishery towards deeper and northern waters and fishing grounds selection) and varying MSL. Changes in MSL are expected to result in changes in fishery selectivity. The selectivity of fish to the commercial fishing gear is affected by availability and vulnerability. Typically, selectivity describes the vulnerability of fish of a particular characteristic (say its age, size, sex) to the fishing gear as well as the availability of fish to the gear. The availability may be related to spatial differences in size or age of fish, for example different areas may have different age structure as fish migrate from nursery to adult areas. Selectivity can be a function of length, age, or both. Selectivity may also may differ between sexes, or change over time and/or space. Different assumptions on the processes that selectivity describes can have a large influence on the stock assessment results and management advice (Parma 2002). In the case of Pacific halibut, the modeling of selectivity has changed over time. In the past it was modeled as a sole function of the age of the fish, however changes in size at age over time created issues that were partially resolved by including size in the modeling of selectivity. This attempted to capture the changes in size at age, but also described part of the mechanics of the fishing gear: halibut of different sizes had different probabilities of being caught by the gear used, fish too small to be taken by the gear characteristics (say their mouth size too small for a typical hook size) were less likely to be caught than halibut large enough to be taken by the fishing gear. However, halibut size did not seem to be the only characteristic affecting its selectivity and age seemed to have an effect, probably affecting the availability of fish of different ages as they migrated through different areas. During that time (early 1990s to 2006), different selectivities were used for different areas on their closed-area models. The recent renewed understanding that halibut continue migrating after the age/size at which they enter the fishery (Webster and Clark 2007, Valero and Webster 2012, Webster et al. in prep.) resulted in the adoption of a coastwide model with a single common coastwide selectivity schedule modeled as a function of halibut size.

The objective of this report is to illustrate the effect of alternative assumptions, methods and criteria on the evaluation of potential pros and cons of changing the current MSL in the Pacific halibut commercial fishery.

Materials and Methods

1. Selectivity and maturity at age

Changes in fishery selectivity following management changes such as changes in MSL are difficult to predict (Clark and Parma 1995, Allen and Pine 2000). For this part of the analysis, we assumed that a reduction in the MSL would result in either:

1) The commercial fishery selectivity changes to the selectivity currently estimated for the IPHC survey (Fig. 2).
2) Although hook size and spacing are standardized in the IPHC survey, there are no regulations regarding hook size and spacing in the commercial gear, so reductions or elimination of the MSL could result in departures beyond those expected when assuming the commercial fishery selectivity would only change to that of the IPHC survey. In this scenario, the commercial fishery selectivity shape is unaltered but it is centered 20 cm towards smaller sizes as currently estimated (Fig. 2). A similar approach, with a larger selectivity shift towards smaller sizes was used by Parma (1998) in order to illustrate tradeoffs between yield gains and spawning biomass reductions if a reduction or elimination in MSL results in commercial selectivity to change towards smaller sizes than those of the IPHC survey. This scenario could be expected if potential reductions of elimination of the MSL results in major changes in commercial fishing gear, for example smaller hooks and shorter spacing. Intermediate commercial selectivity values are calculated in a subsequent section of this report. The goal of this part of the analysis was to capture the overall impact rather than try to predict gradual changes.

For each potential change in selectivity at size, resultant selectivity at age and sex was computed using coastwide lengths-at-age averaged (only average lengths and the mean predicted age at length are presented for the conversion) between 2008 and 2010 (Fig. 2, bottom). Potential reductions in MSL are expected to change not only the fishery selectivity but also the weight-at-age of the catch. Under the current MSL, the commercial fishery cannot legally retain halibut smaller than 32 inches, therefore the minimum weight of legally landed halibut is (on average) somewhat larger than the weight of fish in the population associated with the MSL. Modeling work for Pacific halibut at the IPHC typically assumes that the weight-at-age of halibut caught in the survey is a good approximation of the weight-at-age of the population, at least for halibut older than age 6. We assumed that an elimination of the MSL would result in the weight-at-age of the commercial catch to be that of the survey. The rationale for this assumption is straightforward for the assumed selectivity changes (commercial selectivity changes to that of the survey): if the selectivity is assumed to be that of the survey, the weights-at-age should be expected to be the ones of the survey. In the second case of the shifted commercial selectivity towards smaller sizes, departures from the weight-at-age of the survey could be expected if average weight-at-age of younger (but now selected at smaller sizes) ages were smaller under the lower MSL. However, that does not appear to be the case as average weights associated with MSLs of 65 cm and 60 cm are lower than those of the younger ages in both the survey and commercial catches (Fig. 3).

The benefits of delaying the capture of fish after maturity have being pointed out early and frequently in the history of fisheries science (Holt 1895, Hilborn and Walters 1992, Smith 1994, Myers and Mertz 1998). Selectivities in the commercial fishery for Pacific halibut and IPHC survey are currently modeled as a sole function of fish size, although the potential joint effect of fish age was noted when this formulation was adopted. Female halibut grow faster than males and this result in sex specific selectivities. Female maturity is determined by age (Hare 2010). Although coastwide fishery and survey selectivities at size are currently used in halibut stock assessment work, different sizes-at-age among IPHC regulatory areas results in different selectivities at age among areas. Sex and area specific selectivities at age were computed based on average 2008-2010 sizes-at-age. Female maturity was compared with selectivities at age for the commercial fishery, the IPHC survey, and a commercial fishery selectivity shifted 20 cm towards smaller sizes (Fig. 2). Area-specific cumulative distributions of female halibut captured by the commercial fishery and IPHC survey during 2009 were also plotted against female maturity. Changes in the relationship between commercially landed halibut and female maturity for historical periods with different MLS were also compared by plotting female maturity at age and cumulative catch at age. The sex composition of the commercial catch for years after 1996 is estimated based on the sex ratio of survey catches at length (Clark and Hare 2006). For earlier years, the sex composition of the commercial catches is not available so cumulative distributions of age for sexes combined was used instead for the following periods: 1935-1939 (No MSL), 1945-1973 (MSL: 65 cm) and 1974-1990 (MSL: 81.3 cm).

2. Yield per recruit and biomass per recruit

A standard age-based (ages 6 to 55) two-sex model was used to calculate yield per recruit and female spawning biomass per recruit. Size and weight-at-age were averaged for the 2008-2010 years. The basic equations are:

(i) $$N_{a=6,s} = 0.5$$

(ii) $$N_{a+1,s,} = N_{a,s} e^{-(M+S^{f}_{a,s}F)}$$

(iii) $$C_{a,s} = \frac{F \cdot S^f_{a,s} N_{a,s}}{M + S^f_{a,s} F}\left[1 - e^{-(M + S^f_{a,s} F)}\right]$$

(iv) $$Y = \sum_{a=6}^{55} C_{a,s} w^f_{a,s}$$

(v) $$EB = \sum_{a=6}^{55} N_{a,s} S^f_{a,s} w^f_{a,s}$$

(vi) $$HR = \frac{Y}{EB}$$

(vii) $$SB = \sum_{a=6}^{55} N_{a,s=1} w^s_{a,s=1} Mat_a$$

where $N_{a,s}$ is numbers of fish at age *a* and sex *s*, *M* is natural mortality (fixed at 0.15yr^{-1}, the value used in the assessments); $S^f_{a,s}$ is the selectivity of the commercial fishery for age *a* and sex *s*, $S^s_{a,s}$ is the selectivity of the IPHC survey for age *a* and sex *s*, *F* is the instantaneous rate of fishing mortality, *C* is catch in numbers, *Y* is yield in weight, *EB* is exploitable biomass, *SB* is spawning biomass, *HR* is harvest rate and *Mat* is female maturity.

Yield per recruit and female spawning biomass per recruit were calculated for the following scenarios:

(1) Status quo: MSL: 81.3, commercial selectivity as estimated for 2008-2010 and harvest rate of 0.215. Weight-at-age of the commercial catch is set at the 2008-2010 average commercial weight-at-age.

(2) Commercial selectivity set to the 2008-2010 IPHC survey selectivity, harvest rate of 0.215, weight-at-age of the commercial catch from the 2008-2010 average weight-at-age in the IPHC survey.

(3) The commercial fishery selectivity shape is unaltered but it is centered 20 cm towards smaller sizes as currently estimated (Fig. 2), harvest rate of 0.215. Weight-at-age of the commercial catch is set at the 2008-2010 average weight-at-age in the IPHC survey. This approach will tend to overestimate population weight at age; it is presented here to allow for comparisons with recent per-recruit analysis (e. g., Hare 2011)

(4) Same as scenario 2 but with HR at a level that reduces spawning biomass per recruit at a level equivalent to that of the status quo.

(5) Same as scenario 3 but with HR at a level that reduces spawning biomass per recruit at a level equivalent to that of the status quo.

(6 to 9) Same as scenarios 2 to 5 but with weight-at-age of the commercial catch set at the 2008-2010 average commercial weight-at-age. This approach will tend to overestimate population weight at age; it is presented here to allow for comparisons with recent per-recruit analysis (e. g., Hare 2011)

In addition to calculating yield per recruit and spawning biomass per recruit, female proportion at age in the population and in the commercial catch was calculated for scenarios 1 to 3.

3. Migratory yield per recruit and biomass per recruit

In addition to the coastwide per recruit modeling described in the previous section, area-specific yield per recruit and biomass per recruit were calculated for a spatially structured model with migration similar to the one used in Valero and Hare (2010a, 2011). The model includes ages 1 to 50, which is an accumulating age or plusgroup. Sex-specific size at age, maturity at age, and selectivity (survey and commercial) at size are the same as described in the previous section. The model used here includes six areas: Area 4 (a combination of IPHC regulatory Areas 4A, 4B, and 4CDE) and regulatory Areas 3B, 3A, 2C, 2B, and 2A (Fig. 4). The basic equation describing population dynamics and migration is the following:

$$\text{(viii)} \qquad N_{a+1,s,i} = e^{-(M+S^f_{a,s}F)} \sum_{k=1}^{K} \Theta_{a,i}(k \to i) N_{a,s,k}$$

where Θ is a matrix of annual migration rates among areas and $(k \to i)$ denotes the matrix element containing the migration rate between area *k* and area *i*. Migration is assumed to occur instantaneously at the beginning of the year, before any source of mortality occurs. Analysis of traditional (Hoag et al. 1983, Quinn et al. 1985) and PIT tag (Webster and Clark 2007, Webster et al. in prep.) recoveries suggest that the fraction of fish migrating is a function of fish size/age, with smaller/younger fish more likely to migrate than larger/older fish. Two migration scenarios were used. In the first scenario (“1M”) fish of all sizes migrate following a single migration matrix based on results of the PIT tag model (Webster 2009). In the second scenario (“2M”), migration of halibut smaller than 65 cm is based on tagging results of juveniles (Hilborn et al. 1995, Valero and Webster 2012) whereas migration of halibut larger than 65 cm is based on PIT tag model results (Webster 2009, Webster et al. in prep.). Other equations are area specific versions of equations iii to vii listed in the previous section (For more details see Valero and Hare 2010a). The distribution of age 1 halibut was based on the relative distribution of age one halibut based on IPHC juvenile trawl surveys (Best 1977, see Fig. 2 in Valero and Hare 2010b). Yield per recruit and spawning biomass per recruit were calculated for each area under different migration scenarios for scenarios 1 to 5 described in the previous section. Per recruit calculations were based on age six halibut.

4. Gradual changes in MSL and gradual changes in selectivity

To analyze the potential effects of gradual changes in the size limit upon fishery yield and female spawning biomass, we used a deterministic per-recruit model very similar to that used by Hare (2011) to quantify the effect of differentially accounting for the catch of U32 halibut. The model is age- and sex-specific as follows:

$$N_{6,s} = 0.5$$

$$EBio = \sum_{a,s} N_{a,s} * comm.w_{a,s} * comm.sel_{a,s}$$

$$FSBio = \sum_{a=8,y}^{50} N_{a,s=f} * surv.w_{a,s=f} * Mat_a$$

$$Mat_a = \frac{1}{1+e^{(-0.563*(a-11.59))}} \qquad \text{for } a \geq 8$$

$$CN_{a,s} = HR * N_{a,s} * comm.sel_{a,s}$$

$$CW_{a,s} = CN_{a,s} * comm.w_{a,s}$$

$$DN_{a,s} = HR * N_{a,s} * disc.sel_{a,s}$$

$$DW_{a,s} = DN_{a,s} * comm.w_{a,s}$$

$$N_{a+1,s} = \left(N_{a,s} * e^{-M/2} - CN_{a,s} - DN_{a,s}\right) * e^{-M/2}$$

Where, *a* is age, *s* is sex, *M* is natural mortality (set at 0.15yr^{-1}), maximum age is 50, *Mat* is female maturity, *HR* is harvest rate, *N* is numbers in the population, *CN* and *CW* are commercial numbers and weight, respectively, in the catch, *DN* and *DW* are discard numbers and weight, respectively, killed but not retained in the catch, *EBio* is exploitable biomass, *FSBio* is female spawning biomass, *surv.w* is survey weight, *comm.w* is commercial weight which varies as a linear function of the MSL as described below, *comm.sel* is commercial selectivity, and *disc.sel* is discard selectivity.

The length-based selectivities used in this part of the analysis are illustrated in Figure 13. Two different sets of selectivities, termed Pattern A and Pattern B are derived, both on the basis of modifying the current commercial selectivity curve estimated from the halibut stock assessment. For Pattern A, we assume that relative selectivity for halibut over 90 cm would not be affected by a reduced size limit, but that selectivities below 90 cm would increase. Such a pattern might arise if less "shaking" of fish visually judged to be near the size limit occurs as the size limit decreases. Selectivity at length in the current halibut assessment is estimated as a piecewise linear function at every 10 cm interval, with intermediate values interpolated. Selectivity is assumed to be 1.0 at a length of 120 cm and other sizes are computed relative to that size. Selectivities are 0.27, 0.06, and 0.004 at 90, 80, and 70 cm respectively (note that despite the size limit of 81.3 cm, halibut below that size are still landed thus resulting in selectivities greater than 0 down to 70 cm). To model how selectivity would change with a reduced size limit, we incrementally shifted the relative selectivities at 80 and 70 cm. Thus, for a size limit reduced by 2 cm, the 0.06 selectivity at 80 cm was shifted to 78 cm and the 0.004 selectivity at 70 cm was shifted to 68 cm, with intermediate values linearly interpolated.

Pattern B was derived by modeling selectivity as a logistic function. A logistic function was first fitted to the 10 cm interval values of the assessment commercial selectivity. This fit, which is very similar to the piecewise linear model, provides two parameters: k (slope) and L50 (length at 50% selectivity). The estimated values for the logistic fit were: 0.1677 (k) and 97.132 (L50). We then shifted the logistic curve to the left to mimic the commercial fishery response to a decreasing size limit. This was accomplished by keeping the same value of the k parameter and decreasing L50 by 1 cm for each cm the size limit was reduced. This type of pattern might result if more fishers shift to smaller gear, or lower their discard rates on smaller fish. The effective selectivities of sequentially shifting both selectivity patterns are illustrated as dashed red lines in Figure 13.

The capture, release, and subsequent mortality of halibut is termed discard (or release) mortality. On the basis of previous work, discard mortality is estimated to be 16% of discarded catch if careful release procedures are followed. The precise level of discard catch and mortality, absent cameras or onboard observers, cannot be precisely known. For the halibut assessment, commercial discard is estimated from the relative numbers of commercially legal (over 32 inches, or O32) to commercially sublegal (under 32 inches, or U32) halibut in the top 33% of the IPHC survey stations and applied to the total commercial catch. For the purposes of this analysis, however, we need an estimate of discard selectivity at length. In theory, a reduction in the size limit should result in a reduction in discard mortality and an increase in yield. To estimate discard mortality, we proceeded as follows. We assumed that the actual capture selectivities by the commercial fishery are described by the selectivity estimated for the IPHC setline survey (blue line in Fig. 13). Discard probability (or selectivity) was set equal to the difference between survey selectivity at length and the appropriate (for the reduced size limit) commercial size limit. As the size limit is increasingly lowered, the commercial selectivity curve begins to reach, or exceed, the survey selectivity curve. For lengths where the commercial curve exceeds the survey curve, discard selectivities were set to zero. Discard mortality was then computed as 16% of the discard selectivity. The parameters of the female maturity curve were taken from Hare and Clark (2005). Survey weights at age were taken from the halibut stock assessment dataset and averaged across the years 2008 through 2010.

Commercial weight-at-age, which is a key factor in estimating YPR, was linearly interpolated between the survey weight-at-age and the 2008-2010 mean commercial weight-at-age as the MSL was changed in the simulations. The form of the interpolation was as follows: Survey weights-at-age were used for a MSL of 65 cm and commercial weights at age for MSLs of 81-85 cm. A linear interpolation was used to set weights-at-age for each cm change in the MSL, thus adding 1/16 of the difference in mean weight-at-age between the survey and commercial weights-at-age to the survey weight-at-age, for each cm the MSL was greater than 65 cm (up to 81 cm). The effect of this interpolation can be visualized from Figure 3 which illustrates the smaller survey and larger commercial observed weights-at-age. While more sophisticated approaches are possible, involving growth modeling and integration across variability in size-at-age, this method provides an approximation of the effect of capturing smaller halibut in the commercial catch as a result of a decreased size limit, and is more realistic than using a static commercial weight-at-age for all MSLs. The reduced commercial weights-at-age were interpolated similarly for both selectivity patterns, even though Selectivity Pattern A assumed no change in selectivity above 90 cm.

Summary statistics were computed as follows:

$$YPR = \sum_{a,s} CW$$

$$SPR_{ratio} = \frac{FSBio_{fished}}{FSBio_{unfished}}$$

$$AAFS = \frac{\sum_{a=8}^{50} N_{a,s=f} * Mat_a * age}{\sum_{a=8}^{50} N_{a,s=f} * Mat_a}$$

$$AWC = \frac{YPR}{NIC}$$

$$RNIC = \frac{\sum_{a,s} CN}{CN_{statusquo}} \times 100$$

$$DPR = \sum_{a,s} DW$$

Where YPR is yield per recruit, SPR_{ratio} is ratio of FSBio per recruit to unfished FSBio per recruit, AAFS is average age of female spawners in the population, AWC is average weight in the catch, NIC is numbers in the catch, RNIC is NIC relative to NIC at status quo (i.e., MSL of 81.3 cm, HR of 0.215), and DPR is discard weight per recruit.

These six sets of summary statistics were used to characterize changes in both the at-sea population as well as in the commercial catch as the size limit was varied. Computations were conducted across two control variables: MSL and harvest rate (HR). The HR was defined as the fraction of the EBio taken as commercial catch. Because the EBio was defined on the basis of the commercial selectivity curve, EBio increased with decreasing size limit. Thus, for example, at a given HR of 0.2, more yield would be taken at a size limit of 75 cm than at a size limit of 81 cm. However, the increased yield would also result in a greater reduction in SPR_{ratio}. In order to maintain the same level of SPR_{ratio}, the HR needs to be decreased in concert with the lowered size limit. This is a fundamental and necessary aspect of the precautionary IPHC harvest policy and critical to an understanding of how selectivities and HRs are tied to the definitions of EBio and Constant Exploitation Yield (CEY). The combinations of MSL and HR that maintain the same reduction in SPR_{ratio} as the status quo values of 81.3 cm and 0.215 HR are hereafter termed "status quo equivalents". The per-recruit calculations were made for a MSL ranging from a high of 85 cm down to a low of 65 cm, in 1-cm intervals. Harvest rate was varied across the range of 0 (i.e., no fishing) to 0.30. This structure allowed for two dimensional plotting of the summary statistics. All summary plots illustrate both the performance of the status quo (MSL of 81.3 cm, HR of 0.215) as a black dot and the status quo equivalents as blue "x's".

The interpretation, and utility, of the six summary statistics are as follows:

SPR_{ratio} – Spawning biomass per recruit ratio. Recruitment is defined as halibut entering the fishable population at age six. Thus, the calculations are based on initiating the population with a proportion of 0.5 males and 0.5 females. The population is then fished until the age six recruits reach age 50. Summing the mature females across ages gives the equilibrium FSBio. The ratio of FSBio to the unfished FSBio is the SPR_{ratio}. Note that there is no feedback loop between spawning biomass and recruitment, thus the ratio of FSBio is the same as the ratio of SPR.

YPR – Yield per recruit. This is the cumulative commercial catch per age-six recruit. For halibut, YPR tends to monotonically increase with increased HR and lowered MSL.

AAFS – Average age of female spawners. This provides a measure of how the age of female spawners in the population varies with HR and MSL.

AWC – Average weight in the catch. This is total number of halibut in the catch divided by total weight of the catch.

RNIC – Relative numbers in the catch, expressed as percentage. This is how many fish comprise the catch and is displayed relative to the numbers in the catch given the status quo values of the control parameters (i.e., MSL of 81.3 cm and a HR of 0.215).

DPR – Discard mortality per recruit. This is the cumulative loss of halibut due to capture and release. This decreases with MSL but increases with HR.

An additional set of summary statistics are provided next to better characterize the relative sex contributions to YPR, numbers in the catch, and numbers in the ocean across the range of MSLs and HRs. These output statistics are restricted to the "status quo equivalent" values and are reported in Table 6. These additional statistics are the percent female and male contribution to YPR, numbers in the catch (NIC) and numbers in the ocean (NIO).

Results

1. Selectivity and maturity at age

Coastwide, status quo conditions result in female maturity to be to the left of female commercial selectivity by around one year (Fig. 2, Bottom). That is, the rate at which females mature by age outpaces the rate at which they are captured by around a year. If the commercial selectivity of females were to match that of the IPHC survey the maturity and selectivity would be very close until about the age of 50% maturity, afterwards the maturity outpaces the selectivity (Fig. 2, Bottom). A shift in the commercial selectivity towards smaller sizes (20 cm smaller) would result in the female commercial selectivity outpacing female maturity by about four years (Fig. 2, Bottom). Results by IPHC regulatory area are similar to the coastwide results, with selectivities of Areas 2A, 2B, 2C, and 4 having greater proportions of immature females than the other areas (Fig. 5). Cumulative distributions of females at age in the commercial catch observed in 2009 show greater proportion of immature females in the commercial catch of Areas 2B, 2A, 3B (and to a lesser degree 4A) than in other areas (Fig. 6, Top). The proportion of immature females in the catch is larger for the IPHC survey selectivity and shifted towards younger females (2 to 3 years younger than 50% maturity) than in the commercial catch (less than 2 years younger than the 50% maturity) depending on the area (Fig. 6, Bottom). The proportion of immature females in survey catches is smallest for areas 3A and 4B (Fig. 6, Bottom). Several caveats for the comparisons of maturity at age and observed cumulative age distributions of the commercial catch during historical periods with different MSL should be noted. Since the sex composition of the commercial catch is unknown before 1996, the distributions include both sexes. In addition, the female maturity at age used corresponds to recent estimates in the absence of historically cotemporaneous estimates of maturity at age. Observed cumulative combined-sex age distributions of the available historical years with no MSL (1935-1939) show female maturity at age being to the right of the cumulative catch for all available areas (Area 4 was not fished at the time). That is, the capture of fish outpaced the maturity at age by up to 3 to 4 years depending on the area. Areas 2A, 2B and 2C showed the greatest proportion of immature fish in the catch (Fig. 7, Top). In a similar way, observed cumulative combined-sex age distributions of historical years with MSL: 65 cm (1945-1973) show female maturity at age being to the right of the cumulative catch for all available areas (Area 4 was not fished at the time), although the age of fish captured was larger than was the case with no MSL (Fig. 7, Center). The period 1974 to 1990 (MSL: 81.3) shows an increase in the age of capture, although except for Area 4, maturity at age still is to the right of the cumulative age distribution on the catch (Fig. 7, Bottom).

2. Yield per recruit and biomass per recruit

Coastwide yield per recruit and spawning biomass per recruit decrease when maintaining a harvest rate of 0.215 for the scenario with commercial selectivity changing to that of the IPHC survey (Table 1). A further shift of commercial selectivity towards smaller sizes results in an increase in yield per recruit but a drop in spawning biomass per recruit of 0.17 of the unfished level, compared to the status quo of 0.37. Using harvest rates that result in reductions in spawning biomass per recruit equivalent to the status quo reduces available yield per recruit and harvest rates of 0.165 with survey selectivity and 0.101 with shifted commercial selectivity (Table 2). Results are sensitive to the assumed weight at age of the commercial catch under changing selectivities. If weight at age of the commercial catch is assumed fixed (even if changing selectivity) then estimates of yield per recruit increase (Tables 3 and 4) under comparable spawning biomass per recruit reductions as the previous cases with changing weight at age of the commercial catch (Tables 1 and 2).

A reduction or elimination of MSL does increase the proportion females at older ages relative to status quo, with as much as 80% improvement, however the actual proportions in the population are still quite low (12% to 22% at age 25) (Fig. 8). A larger decrease in the proportion of females in the catch and increase in the proportion in the population would be expected in the scenario with a shift in commercial selectivity towards smaller sizes and younger ages (Fig. 8), although that will require a reduction of target HR to 0.101 (Fig. 8).

3. Migratory yield per recruit and biomass per recruit

Coastwide estimates of yield per recruit and spawning biomass per recruit reductions from the migratory model were similar (Figs. 9 to 12) to that of the single area coastwide analysis presented in the previous section. The distribution of yield per coastwide recruit varies depending on the migration scenario (Figs. 9 and 10, Top panels) but the total is similar. Under both scenarios considered here, spawning biomass per recruit reductions are greater in Areas 2 than in Areas 3 and 4 (Figs. 9 and 10, Bottom panels). Yield per recruit is lower than that of the status quo when using harvest rates that result in equivalent spawning biomass per recruit reductions as the status quo (Figs. 11 to 12, Top panels). The difference among areas in the reduction of spawning biomass per recruit is smaller when using equivalent harvest rates (Figs. 11 and 12, Bottom panels).

4. Gradual changes in MSL and gradual changes in selectivity

The purpose of this exercise is to estimate impacts on commercial yield and FSBio as the size limit is incrementally reduced, as requested by the Commission. Given the lack of a feedback loop between FSBio and recruitment, the effect of increasing selectivities at smaller sizes will be to increase the definition of EBio and generate higher yields per recruit. However, increased yield comes at the expense of reduced FSBio. To maintain the current level of FSBio conservation, decreases in the commercial MSL must be accompanied by a decrease in the HR. Given the parameter values and model structure described in the Methods section, the present MSL of 81.3 cm, together with the present commercial and discard selectivity schedules, the SPR_{ratio} is approximately 37.0%. While we will present results across the full spectrum of MSLs (65 to 85 cm) and HRs (0 to 0.30), we will focus attention on the combinations that result in the same equilibrium SPR_{ratio} as the status quo, i.e., the status quo equivalents.

There are two sets of results, corresponding to selectivity Patterns A and B, and they are illustrated in Figures 14 and 15, respectively, and discussed below. In general, the results of lowering the size limit are qualitatively similar between the two selectivity patterns. However, while qualitatively similar, there are some important differences, thus we now compare and contrast the six sets of summary statistics for the two selectivity patterns. Table 5 contains summary statistics of interest for the status quo equivalents and provides the most compact depiction of expected equilibrium impacts of reducing the size limit while maintaining the current level of FSBio conservation.

A second set of summary statistics, focusing on the sex composition of YPR, numbers in the catch (NIC) and numbers in the ocean (NIO) are listed in Table 6. This table similarly is restricted to the status quo equivalents of MSL and HR.

4.1 Impact on SPR_{ratio} (Panel a)

SPR_{ratio} is a monotonically decreasing function of fishing mortality. The rate at which it declines varies, for a given HR, between the two selectivity patterns, with a steeper decline for Pattern B. The status quo value of 37.5% is indicated by a large black dot on the plots. The HR that maintains SPR_{ratio} at (or slightly above) 37.5%, for any given MSL, can be found by drawing a horizontal line from the blue "x's" to the HR axis. These are the HR values listed in Table 5. For Pattern A, the HR that maintains SPR_{ratio} at status quo declines by approximately .01 for every 5 cm the size limit is lowered; for Pattern B, the HR declines by just under .01 for every 1 cm drop in the size limit.

4.2 Impact on YPR (Panel b)

Across the range of HRs and MSLs considered in this analysis, YPR tends to increase with increasing harvest rate for any given MSL, but shows a more complex response, yet relatively flat, to MSL for a given harvest rate. Restricting acceptable outcomes to the MSL/HR status quo equivalents (indicated by blue x's in Figures 14 and 15 and listed in Table 5), YPR remains equal to, or just slightly greater (3% higher at most) than, current YPR (MSL=81.3 cm, HR = 0.215) for a decreased MSL of up to 3 cm (Selectivity Pattern A) or 12 cm (Selectivity Pattern B), after which YPR decreases below the status quo. The projected increased YPR is at most 3% larger than the status quo. Beyond a MSL of about 77 cm (Selectivity Pattern A) or about 68 cm (Selectivity Pattern B), there is a steady decrease in YPR. The harvest rate required to maintain SBR at status quo also drops steadily under both patterns, though at a much greater rate for Selectivity Pattern B.

4.3 Impact on AAFS (Panel c)

Similar to SBR_{ratio}, AAFS decreases monotonically across the range of MSLs and HRs, although the effect of lowering MSL for a given harvest rate is minimal with selectivity pattern A. In the absence of fishing, the average age of female spawners in the ocean is 17; the average age would decline by at least five years at the highest HRs and would decline more rapidly under Selectivity Pattern B. The status quo AAFS is just over 13 years of age, and this would actually increase slightly (around 1% to 4%) under any of the status quo equivalent MSL (less than 81 cm)/HR combinations. This occurs because a larger fraction of the yield is expected to be composed of males, thereby reducing harvest on larger, older females. The increase in AAFS is between 0.01 (Selectivity Pattern A) and 0.03 (Selectivity Pattern B) years per cm decrease in the MSL

4.4 Impact on AWC (Panel d)

One of the biggest changes that would occur with a lowered MSL would be the average weight of halibut comprising the commercial catch. The increased selectivity at smaller sizes steadily decreases the overall average weight of fish in the catch. Under status quo, average weight is around 25 pounds; this average would be around 16 to 17 pounds at the MSL/HR extreme combination. For the status quo equivalent combinations, AWC declines between .2 and .3 pounds per cm decrease in MSL.

4.5 Impact on RNIC (Panel e)

This summary statistic provides a more straightforward indicator of how much more fish would be handled with a reduced size limit than can be easily ascertained from AWC. If we once again restrict ourselves to the status quo equivalent MSL/HR combinations, there is potential for an increase of as much as a 30% (Selectivity Pattern A) to 50% (Selectivity Pattern B) increase in RNIC at the extreme MSL of 65 cm. As the MSL is decreased from 81 cm, the RNIC increases at a rate of between 2 and 3% per cm.

4.6 Impact on DPR (Panel f)

Under status quo, DPR is approximately 0.25 pounds, or about 6.5% of YPR. For any given MSL, DPR increases with harvest rate. For any given HR, DPR decreases with MSL. Across the status quo MSL/HR combinations, DPR decreases steadily and, in the case of Selectivity Pattern B, is reduced to zero at the smallest MSLs. The decrease in DPR is around 0.015 (Selectivity Pattern A) and 0.030 (Selectivity Pattern B) per cm decrease in the MSL.

4.7 Impact on sex composition of YPR, NIC and NIO (Table 6)

The forgoing summaries aggregated sex-specific information regarding YPR and RNIC. It is of interest to more closely examine how the sex composition of certain variables, specifically YPR, numbers in the catch (NIC) and numbers in the ocean respond to a change in MSL. Under status quo, females comprise approximately 82% of the YPR, 73% of the catch (in numbers) and 44% of the age-eight and older fish remaining in the ocean (in numbers). Each of these variables changes smoothly with decreasing MSL, with rates of change slightly greater under Selectivity Pattern B. As the MSL decreases, the share of YPR derived from females declines by about 0.5% per cm decrease. The percentage female NIC drops approximately 0.8% per cm decrease while the female NIO slowly increases, though by less than 0.1% per cm decrease. At the extreme MSL of 65 cm, values for female YPR, NIC, and NIO would be between 72-74%, 61-63%, and 45.4-45.5%, respectively under the two selectivity patterns.

Discussion

An effective harvest strategy should provide a framework and tools to achieve the objectives of the fishery for which it was developed. A harvest strategy often involves a number of tradeoffs (such as between conservation and exploitation) and major decisions such as the treatment of uncertainty in biological processes, observation/estimation capabilities, and implementation of management actions. Tools to implement a harvest strategy are often called harvest tactics or control rules, with size limits being one of the most widely used. Different size limits have been used throughout the history of the Pacific halibut fishery with a progression towards increasingly larger MSL and subsequently older age composition, and a greater proportion of females, in the commercial catch. On a coastwide scale, fewer immature female halibut are currently caught in the commercial fishery than could be inferred from past distributions of commercial catch at age with no MSL or lower MSL than at present. However, regulatory areas such as Areas 2A, 2B, 2C, and Area 3B are characterized by a larger proportion of immature females in the commercial catch. Decreasing the MSL to 65 cm, the overall percentage of females in the catch is expected to decrease relative to status quo from 73% to 63% (or 74% to 61% depending on assumed selectivity), intermediate MSL result in smaller decreases. Decreasing the MSL is expected to have smaller effects on the percentage of females in the ocean with a maximum expected change from 44% to 45% if the MSL is reduced or eliminated. As noted, the largest change would be expected for age 25 where the percentage female would change from 12% (status quo) to 22% (MSL = 65 cm). However, potential reductions of the current MSL are expected to increase the proportion of immature females in the catch in those areas and widen the gap between the rate at which females are caught and the rate at which they mature. The benefits of delaying the capture of fish after maturity have being pointed out early and frequently in the history of fisheries science (Holt 1895, Hilborn and Walters 1992, Smith 1994, Myers and Mertz 1998, Parma 1998). One of the benefits of delaying capture until after fish mature is an additional level of protection for the spawning stock to uncertainty, and potential stock assessment errors. Myers and Mertz (1998) showed that a spawn-at-least-once policy could prevent a collapse of a stock even in cases when fishing mortality targets are exceeded. A spawn-at-least-once policy requires that fish become vulnerable to the commercial gear only after having spawned once. Myers and Metz (1998) analysis was based on simulated stocks with spawning stock/recruitment functional forms. Although similar spawning stock/recruitment relationships are not used for halibut, management still relies on reference points that are based on relative levels in female spawning biomass relative to unfished. A precautionary approach to fisheries management would not support potential policies that are expected to increase the risks to the stock. In the context of basic life history theory, lowering or eliminating the MSL is expected to increase the capture of immature female halibut at the area specific and coastwide levels and therefore goes against a precautionary approach. In theory, the increased capture of immature females could be offset by applying lower target harvest rates to achieve similar reductions of female spawning biomass to the status quo. In practice, the historical control of realized harvest rates has been affected by retrospective bias in the stock assessment and subject to misspecifications such as in the closed-area assessments conducted before the 2006 change to a coastwide assessment. The retrospective bias in assessment estimates has resulted in departures between realized and target harvest rates, as much as 63% higher than target at the coastwide level (Valero 2012b). Misspecification in the closed-area stock assessments resulted in realized harvest rates, estimated by recent coastwide stock assessments with survey-partitioned biomass, as much as three times higher than the target in areas 2B and 2C and as low as half the target harvest rate for Area 4 during part of the last decade (Valero 2012b).

A potential concern of the current MSL is the higher proportion of females relative to males in the commercial catch and resultant lower proportion of females in the population. However, only major changes in the commercial selectivity towards smaller sizes would result in a more balanced sex ratio of the commercial catch, with a resultant much lower target harvest rate and the risk associated with harvesting a larger proportion of immature females as much as four years before they mature. Since a harvest strategy has to make tradeoffs between conservation and exploitation, the risks associated with reducing or dropping the size limit would need to be evaluated with the potential yield gains. A single-area coastwide yield per recruit and spawning biomass per recruit was conducted along with a multi-area migratory analysis. If the yield per recruit analysis (conducted assuming that fishing mortalities can be perfectly controlled) indicated substantial potential gains in yield then consideration of further trade-offs with principles of life history theory mentioned before would have merit. However, both single area and migratory analyses indicated substantial reductions in spawning biomass per recruit associated with reductions/elimination of the MSL and no substantial increase in yield per recruit. When constraining harvest rates to produce equivalent reductions of spawning biomass per recruit to the status quo, yield per recruit is lower when accounting for reduced weight at age of the commercial catch under changing selectivities.

These results are highly sensitive to assumptions on the weight at age resulting from different selectivities. If commercial weight at age is assumed not to change even with changes in commercial selectivity then harvest rates equivalent to the status quo results in higher yield per recruit. Since current commercial weight at age is strongly influenced by the current MSL, assuming no changes in weight at age when the current MSL is either reduced or eliminated seems to be problematic. Assuming that the weight at age of the commercial catch will change seems more realistic and the approach taken here was to assume it would be that of the IPHC survey. Approaches that are more realistic were followed by Clark and Parma (1995) and Parma (1998) by using numerical integration to compute the average weight at age for males and females in the commercial catch as a function of the size at age distribution in the population, the size selectivity and the legal size limit. That approach implies modeling growth, its variability at age and the effects of size-selective fishing as part of the analysis. Previous work on the potential effects of size-selective fishing mortality on Pacific halibut found that yield per recruit analyses that ignored changes in size at age by using constant selectivities and weights at age may result in biased estimates of mean spawning biomass per recruit and serious overestimation of optimal fishing levels (Deriso and Parma 1988, Parma and Deriso 1990).

Most of the analyses and discussion in this paper reflect a comparison between the current MSL of 81.3 cm and elimination of the size limit. The analysis on gradual changes in the MSL attempts to interpolate between the extremes and consider the effect of small changes, assuming a linear decrease of weights-at-age in the catch with decreasing MSL. At the extreme MSL of 65 cm, which is similar to having no size limit, the results of the gradual analysis are similar to the other analyses: there would a loss in terms of yield per recruit when controlling for spawning biomass per recruit. Maintaining the status quo SBR would necessitate managing at a lower HR, the commercial catch would be comprised of a much larger number of small fish though there would be at most a 10% decrease in the female component of the catch as well as an increase in the proportion (at most 3%) and average age (from 13.1 to 13.6) of females the population. In one part of our analysis we estimated weight at age for ages derived from lengths, but assuming no variation in the age-length relationship. A simple linear interpolation method was used to predict how average weight at age in the commercial catch would respond to gradual changes in MSL, in other part of our analysis. Like many aspects of this modeling work attempting to estimate the effect of a changed size limit, it is uncertain how realistic the interpolated values are, although it is reasonable to assume that a MSL between the current and an eliminated MSL would result in commercial weights at age intermediate between the IPHC survey and commercial weight-at-age. Thus, while acknowledging the uncertainty of the magnitude and shape of the interpolated commercial weight-at-age, the gradual analysis suggests the following: YPR remains near, or marginally above (at most 3% higher) the status quo for a few cm below the current MSL and that the proportion of females in the catch decreases gradually from around 73% to 63%, while the proportion of females in the ocean increases at most from 44% to 45%.

Other works suggest it can be extremely difficult to measure the efficacy of size limits given the effects of non-stationary population processes such as variable recruitment and the number of years required to see an effect (Allen and Pine 2000). Analyses presented here rely on equilibrium condition assumptions. Short or medium term population projections based on recent stock assessment population estimates could be used to illustrate the effect of changing MSL. However, there are a number of population trends (e.g. size at age) and revisions of recent estimates (e.g. recruitment) that have made those projections unreliable (Valero 2012a, 2012b). In addition, requests for eliminating the size limit should be put in the context of current regulations, which at present do not regulate the characteristics of the fishing gear such as hook size and spacing. There is no guarantee that reducing or eliminating the size limit would not result on a shift towards fishing gear (for example smaller hooks, different hook spacing) that could target progressively smaller fish efficiently. It could be argued that careful monitoring of changes in commercial selectivity from potential MSL changes could be possible in areas where the commercial fishery is monitored (for example Area 2B at present). An illustration on potential problems of relying on monitoring to detect selectivity changes can be illustrated by the distribution of U32 halibut in commercial landings, along with the percentage of U32 halibut relative to the total landed by area and coastwide (Fig. 16). Even though the current MSL of 32 inches has been in place coastwide since 1974, there are substantial percentages of U32 commercially landed halibut in the catch, with one of the highest percentage (8.24% as of 2008) corresponding to the only area that is currently fully observed (Area 2B). Under these conditions, modifications of fishers behavior and resultant changes in selectivity due to changes in MSL (potentially including differences among areas) are expected to not only be unpredictable but also difficult to monitor. Finally, part of the rationale for requests to reduce or eliminate the size limit are based on recent stock assessment estimates of large and increasing trends in total halibut numbers and total biomass in spite of decreasing trends of exploitable biomass. Recent analysis show that ongoing retrospective bias in recent assessment estimates has resulted in consistent downward revisions of previous biomass estimates, along with reversing of originally increasing to revised decreasing trends, including on total biomass (Valero 2012b). Given the effects of retrospective bias and the potential effects of assumed selectivity types on trends and levels of total biomass (Valero 2012c), independent validations of the large and increasing numbers and biomass of small halibut estimated by recent stock assessments seems necessary. Overall, minor reductions in the MSL along with harvest rate reductions are expected to produce at most 3% increases in yield per recruit but greater reductions in the MSL including its elimination are expected to reduce both yield per recruit and spawning biomass per recruit. The proportion of females in the population between the extremes of current MSL and a MSL of 65cm would change from 44% to 45% for ages 6 and older, and from 12% to 22% at age 25.

References

Allen, M. and Pine, W. I. 2000. Detecting fish population responses to a minimum length limit: effects of variable recruitment and duration of evaluation. N. Am. J. Fish. Man. 20, 672-682.

Best, E. A. 1977. Distribution and abundance of juvenile halibut in the southeastern Bering Sea. Int. Pac. Halibut Comm., Sci. Rep. 62.

Bell, F. H. 1981. The Pacific halibut, the resource and the fishery. Alaska Northwest Publishing Company, Anchorage Alaska, 267 p.

Clark, W. G. and Parma, A. M. 1995. Re-evaluation of the 32-inch commercial size limit. Int. Pac. Halibut Comm. Tech. Rpt. 33: 34 p.

Clark, W. C. and Hare, S. R. 2006. Assessment and management of Pacific halibut: data, methods and policy. Int. Pac. Halibut Comm. Sci. Rep. 83.

Deriso, R. B. and Parma A. M. 1988. Dynamics of age and size for a stochastic population model. Canadian Journal of Fisheries and Aquatic Sciences. 45: 1054-1068.

Hare, S. R. 2010. Estimates of halibut total annual surplus production, and yield and egg production losses due to under-32 inch bycatch and wastage. Int. Pac. Halibut Comm. Report of Assessmnent and Research Activities 2009:323-346.

Hare, S. R. 2011. Potential modifications to the IPHC harvest policy. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2010: 177-199.

Hare, S. R. and Clark, W. G. 2008. 2007 IPHC harvest policy analysis: past, present, and future considerations. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2007: 275-295.

Hilborn, R., Skalski, J., Anganuzzi, A. and Hoffman, A. 1995. Movements of juvenile halibut in IPHC regulatory areas 2 and 3. Int. Pac. Halibut Comm. Tech. Rep. 31.

Hilborn, R. and Walters, C. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, London. 570 p.

Hoag, S. H., Myhre, R. J., St-Pierre, G. and McCaughran, D. G. 1983. The Pacific halibut resource and fishery in regulatory Area 2; I. Management and biology. Int. Pac. Halibut Comm. Sci. Rep. 67.

Holt, E. W. L. 1895. An examination of the present state of the Grimsby trawl fishery with especial reference to the destruction of immature fish. Journal of Marine Biology Association of the United Kingdom. **5**:337–447.

Myers, R. A. and Mertz, G. 1998. The limits of exploitation: a precautionary approach. Ecological Applications 8 (Suplement): S165-S169 .

Myhre, R. J. 1974. Minimum size and optimum age of entry for Pacific halibut. Int. Pac. Halibut Comm. Sci. Rep. 55, 15 p.

Parma, A. M. 1998. Re-evaluation of the 32-inch commercial size limit. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 1997: 167-202.

Parma, A. M. and Deriso, R. B. 1990. Dynamics of age and size composition in a population subject to size-selective mortality: effects of phenotypic variability in growth. Canadian Journal of Fisheries and Aquatic Sciences 47: 274-289.

Quinn, T. J., Deriso, R. B. and Hoag, S. H. 1985 Methods of population assessment of Pacific halibut. Int. Pac. Halibut Comm. Sci. Rep. 72.

Ricker, W. E. 1969. Effects of size-selective mortality and sampling bias on estimates of growth, mortality, production, and yield. J. Fish. Res. Board Can. 26: 479-54 1.

Ricker, W. E. 1981. Changes in the average size and average age of Pacific salmon. Can. J. Fish. Aquat. Sci. 38: 1636-1656.

Smith, T. D. 1994. Scaling Fisheries: The Science of Measuring the Effects of Fishing, 1855–1955. Cambridge University Press, 392p.

Valero, J. L. 2012a. Projections of Pacific halibut coastwide exploitable biomass using alternative methods and assumptions. Report of Assessmnent and Research Activities 2011: 267-280.

Valero, J. L. 2012b. Harvest policy considerations on retrospective bias and biomass projections. Report of Assessmnent and Research Activities 2011: 311-330.

Valero, J. L. 2012c. Progress in the development of a management strategy evaluation for Pacific halibut. Report of Assessmnent and Research Activities 2011: 281-310.

Valero, J. L. and Hare S. R. 2010a. Exploring effects of fishing and migration on Pacific halibut dynamics with Widget 2. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009:209-240.

Valero, J. L. and Hare S. R. 2010b. Effect of migration on lost yield, lost spawning biomass, and lost egg production due to U32 bycatch and U32 wastage of Pacific halibut. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009:309-321.

Valero, J. L. and Hare S. R. 2011. Evaluation of the impact of migration on lost yield, lost spawning biomass, and lost egg production due to U32 bycatch and wastage mortalities of Pacific halibut. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2010: 261-280.

Valero, J. L and Webster, R. A. 2012. Current understanding of Pacific halibut migration patterns. Report of Assessmnent and Research Activities 2011: 341-380.

Webster, R. 2009. Analysis of PIT tag recoveries through 2008. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008:213-220.

Webster, R. A. and Clark W. G. 2007. Analysis of PIT tag recoveries through 2006. Int. Pac. Halibut Commission. Report on Assessment and Research Activities 2006: 129-138.

Webster, R. A., Clark, W. G., and Leaman, B. M. (in prep). Pacific halibut on the move: a renewed understanding of adult migration from a coastwide tagging study.

Table 1. Coastwide yield per recruit and female spawning biomass per recruit under status quo (MSL: 81.3, commercial selectivity as estimated for 2008-2010 and target harvest rate of 0.215) and assuming commercial selectivity changes to either the 2008-2010 estimated IPHC survey selectivity or a modified 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes. Weight at age of the catch is either that of the commercial catch for 2008-2010 (08-10 Commercial) or that of the 2008-2010 IPHC survey (08-10 Survey and 08-10 Commercial shift).

		Yield per recruit		Spawning biomass per recruit	
Selectivity	**HR**	**lb**	**Relative to status quo**	**Relative to max**	**Relative to status quo**
08-10 Commercial	*0.215*	4.14	1.00	0.37	1.00
08-10 Survey	*0.215*	4.01	0.97	0.31	0.82
08-10 Commercial shift	*0.215*	4.72	1.14	0.17	0.47

Table 2. Coastwide yield per recruit and female spawning biomass per recruit under status quo (MSL: 81.3, commercial selectivity as estimated for 2008-2010 and target harvest rate of 0.215) and status quo equivalent scenarios assuming commercial selectivity changes to either the 2008-2010 estimated IPHC survey selectivity or a modified 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes. Status quo equivalent scenarios use HR that reduces spawning biomass per recruit to the same level as the status quo. Weight at age of the catch is either that of the commercial catch for 2008-2010 (08-10 Commercial) or that of the 2008-2010 IPHC survey (08-10 Survey and 08-10 Commercial shift).

		Yield per recruit		Spawning biomass per recruit	
Selectivity	**HR**	**lb**	**Relative to status quo**	**Relative to max**	**Relative to status quo**
08-10 Commercial	0.215	4.14	1.00	*0.37*	1.00
08-10 Survey	0.165	3.67	0.89	*0.37*	1.00
08-10 Commercial shift	0.101	3.75	0.91	*0.37*	1.00

Table 3. Coastwide yield per recruit and female spawning biomass per recruit under status quo (MSL: 81.3, commercial selectivity as estimated for 2008-2010 and target harvest rate of 0.215) and assuming commercial selectivity changes to either the 2008-2010 estimated IPHC survey selectivity or a modified 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes. Weight at age of the catch is that of the commercial catch for 2008-2010 for all scenarios.

		Yield per recruit		Spawning biomass per recruit	
Selectivity	**HR**	**lb**	**Relative to status quo**	**Relative to max**	**Relative to status quo**
08-10 Commercial	*0.215*	4.14	1.00	0.37	1.00
08-10 Survey	*0.215*	5.03	1.22	0.31	0.83
08-10 Commercial shift	*0.215*	6.82	1.65	0.18	0.47

Table 4. Coastwide yield per recruit and female spawning biomass per recruit under status quo (MSL: 81.3, commercial selectivity as estimated for 2008-2010 and target harvest rate of 0.215) and status quo equivalent scenarios assuming commercial selectivity changes to either the 2008-2010 estimated IPHC survey selectivity or a modified 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes. Status quo equivalent scenarios use HR that reduces spawning biomass per recruit to the same level as the status quo. Weight at age of the catch is either that of the commercial catch for 2008-2010 for all scenarios.

		Yield per recruit		Spawning biomass per recruit	
Selectivity	**HR**	**lb**	**Relative to status quo**	**Relative to max**	**Relative to status quo**
08-10 Commercial	0.215	4.14	1.00	*0.37*	1.00
08-10 Survey	0.166	4.52	1.09	*0.37*	1.00
08-10 Commercial shift	0.101	4.97	1.20	*0.37*	1.00

Table 5. Summary statistics for the two Selectivity Patterns of the analysis on gradual changes in MSL. These values correspond to the "x's" in Figures 14 and 15. Status quo is highlighted. Abbreviations are as follows: minimum size limit (MSL), harvest rate (HR), yield-per-recruit (YPR), average weight in the catch (AWC), relative numbers in catch (RNIC), discard-per-recruit (DPR). See text for details and interpretation.

Selectivity Pattern A

MSL	HR	YPR	AAFS	AWC	RNIC	DPR
65	0.187	3.513	13.39	17.05	32.7	0.082
66	0.188	3.563	13.38	17.52	31.0	0.085
67	0.190	3.615	13.36	17.98	29.5	0.089
68	0.191	3.655	13.35	18.48	27.4	0.094
69	0.193	3.698	13.33	18.96	25.7	0.099
70	0.194	3.728	13.33	19.47	23.3	0.105
71	0.196	3.760	13.31	19.97	21.3	0.112
72	0.197	3.780	13.30	20.50	18.8	0.121
73	0.199	3.803	13.28	20.99	16.7	0.134
74	0.201	3.819	13.27	21.50	14.4	0.148
75	0.203	3.831	13.25	22.01	12.1	0.164
76	0.204	3.836	13.25	22.50	9.8	0.179
77	0.206	3.847	13.23	22.95	8.0	0.194
78	0.208	3.852	13.22	23.42	5.9	0.211
79	0.210	3.854	13.20	23.90	3.9	0.230
80	0.212	3.852	13.19	24.38	1.8	0.249
81	0.214	3.849	13.18	24.85	-0.2	0.269
82	0.216	3.819	13.16	25.07	-1.9	0.281
83	0.218	3.785	13.15	25.31	-3.6	0.294
84	0.220	3.748	13.14	25.57	-5.6	0.309
85	0.223	3.714	13.12	25.83	-7.4	0.326

Selectivity Pattern B

MSL	HR	YPR	AAFS	AWC	RNIC	DPR
65	0.116	3.696	13.67	16.18	50.0	0.000
66	0.119	3.740	13.63	16.79	46.3	0.000
67	0.123	3.789	13.59	17.38	43.2	0.000
68	0.127	3.829	13.55	17.97	40.0	0.000
69	0.131	3.860	13.51	18.56	36.6	0.000
70	0.136	3.894	13.47	19.13	33.7	0.001
71	0.141	3.918	13.43	19.70	30.6	0.007
72	0.146	3.930	13.39	20.28	27.3	0.018
73	0.152	3.944	13.35	20.84	24.3	0.032
74	0.158	3.947	13.31	21.40	21.2	0.050
75	0.164	3.941	13.29	21.97	17.9	0.071
76	0.171	3.935	13.25	22.52	14.8	0.097
77	0.179	3.928	13.21	23.05	12.0	0.124
78	0.186	3.902	13.20	23.60	8.6	0.157
79	0.195	3.884	13.16	24.13	5.7	0.192
80	0.204	3.854	13.14	24.65	2.7	0.233
81	0.214	3.822	13.12	25.17	-0.2	0.278
82	0.225	3.754	13.09	25.46	-3.1	0.323
83	0.237	3.685	13.07	25.75	-6.0	0.372
84	0.249	3.607	13.05	26.04	-9.0	0.425
85	0.263	3.529	13.03	26.32	-11.9	0.486

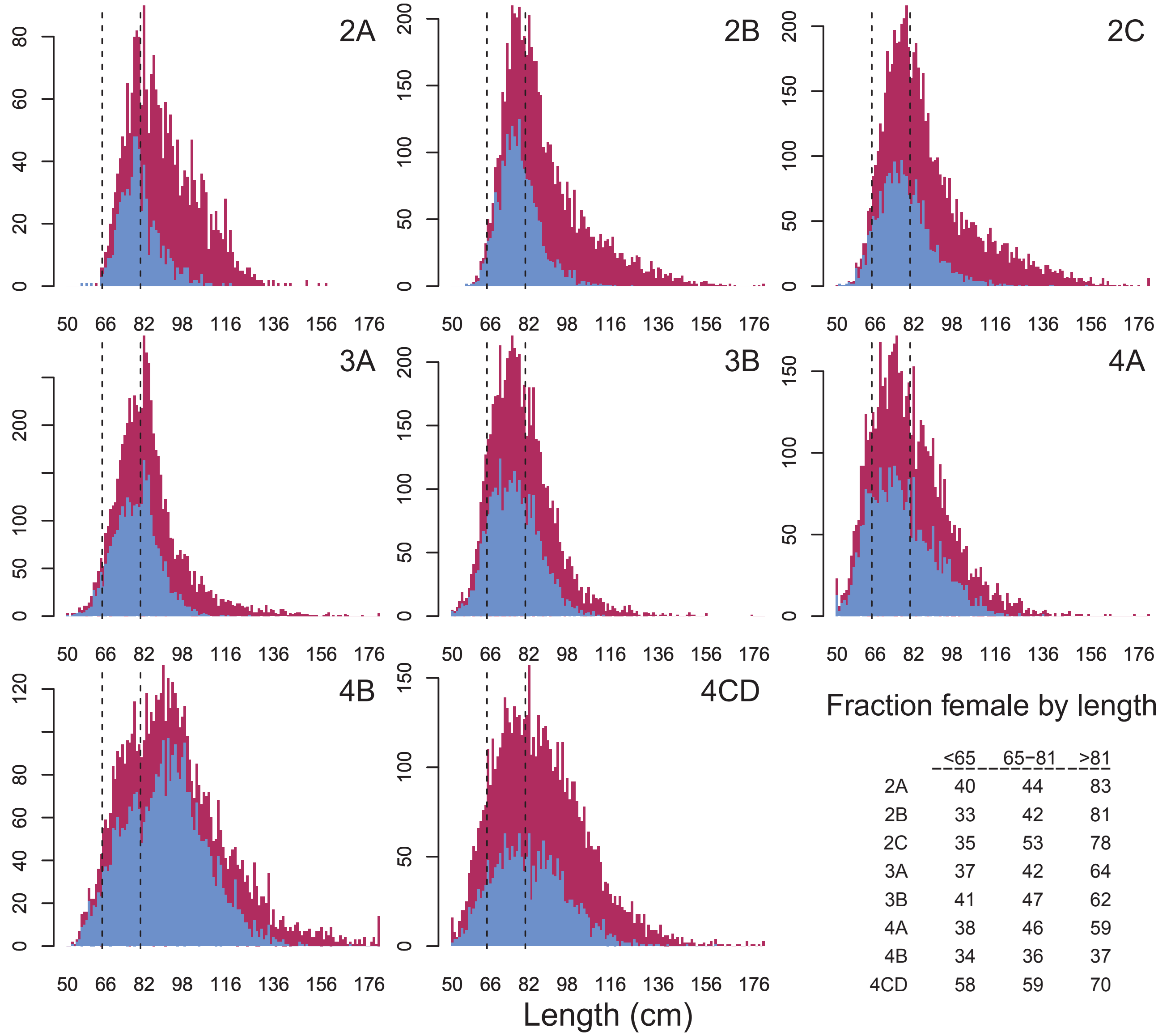
Table 6. Summary of sex-specific compositions of yield-per-recruit (YPR), numbers in catch (NIC) and numbers in the ocean (NIO). Values for YPR, NIC and NIO are percentages and values correspond to "status quo equivalents" of minimum size limit (MSL) and harvest rate (HR). See text for details and interpretation.

Selectivity Pattern A

		Females			Males		
MSL	HR	YPR	NIC	NIO	YPR.M	NIC.M	NIO.M
65	0.187	76.6	62.8	45.4	23.4	37.2	54.6
66	0.188	76.6	63.2	45.3	23.4	36.8	54.7
67	0.190	76.7	63.7	45.2	23.3	36.3	54.8
68	0.191	76.8	64.2	45.1	23.2	35.8	54.9
69	0.193	77.0	64.7	45.0	23.0	35.3	55.0
70	0.194	77.3	65.3	45.0	22.7	34.7	55.0
71	0.196	77.6	65.9	44.9	22.4	34.1	55.1
72	0.197	77.9	66.6	44.8	22.1	33.4	55.2
73	0.199	78.3	67.2	44.7	21.7	32.8	55.3
74	0.201	78.6	67.9	44.6	21.4	32.1	55.4
75	0.203	79.0	68.5	44.6	21.0	31.5	55.4
76	0.204	79.5	69.3	44.5	20.5	30.7	55.5
77	0.206	79.9	70.0	44.4	20.1	30.0	55.6
78	0.208	80.4	70.8	44.4	19.6	29.2	55.6
79	0.210	80.9	71.5	44.3	19.1	28.5	55.7
80	0.212	81.3	72.1	44.3	18.7	27.9	55.7
81	0.214	81.8	72.9	44.2	18.2	27.1	55.8
82	0.216	82.3	73.7	44.1	17.7	26.3	55.9
83	0.218	82.8	74.5	44.1	17.2	25.5	55.9
84	0.220	83.3	75.3	44.0	16.7	24.7	56.0
85	0.223	83.7	75.9	44.0	16.3	24.1	56.0

Selectivity Pattern B

		Females			Males		
MSL	HR	YPR	NIC	NIO	YPR.M	NIC.M	NIO.M
65	0.116	73.1	61.4	45.5	26.9	38.6	54.5
66	0.119	73.6	62.1	45.4	26.4	37.9	54.6
67	0.123	74.1	62.8	45.2	25.9	37.2	54.8
68	0.127	74.6	63.5	45.1	25.4	36.5	54.9
69	0.131	75.2	64.2	45.0	24.8	35.8	55.0
70	0.136	75.8	65.0	44.9	24.2	35.0	55.1
71	0.141	76.4	65.8	44.8	23.6	34.2	55.2
72	0.146	77.0	66.6	44.7	23.0	33.4	55.3
73	0.152	77.6	67.5	44.6	22.4	32.5	55.4
74	0.158	78.3	68.3	44.5	21.7	31.7	55.5
75	0.164	78.9	69.2	44.4	21.1	30.8	55.6
76	0.171	79.6	70.0	44.3	20.4	30.0	55.7
77	0.179	80.2	70.9	44.3	19.8	29.1	55.7
78	0.186	80.9	71.8	44.2	19.1	28.2	55.8
79	0.195	81.5	72.6	44.1	18.5	27.4	55.9
80	0.204	82.1	73.4	44.1	17.9	26.6	55.9
81	0.214	82.7	74.3	44.0	17.3	25.7	56.0
82	0.225	83.2	75.1	43.9	16.8	24.9	56.1
83	0.237	83.8	75.9	43.9	16.2	24.1	56.1
84	0.249	84.4	76.6	43.8	15.6	23.4	56.2
85	0.263	84.9	77.4	43.8	15.1	22.6	56.2



Fraction female by length

	<65	65−81	>81
2A	40	44	83
2B	33	42	81
2C	35	53	78
3A	37	42	64
3B	41	47	62
4A	38	46	59
4B	34	36	37
4CD	58	59	70

Figure 1. Illustration of sex ratio at length of halibut caught (and sexed) on the IPHC setline survey between 2009 and 2011. Male frequencies are in blue, females in red. Vertical lines indicate lengths of 65 and 81.3 cm.

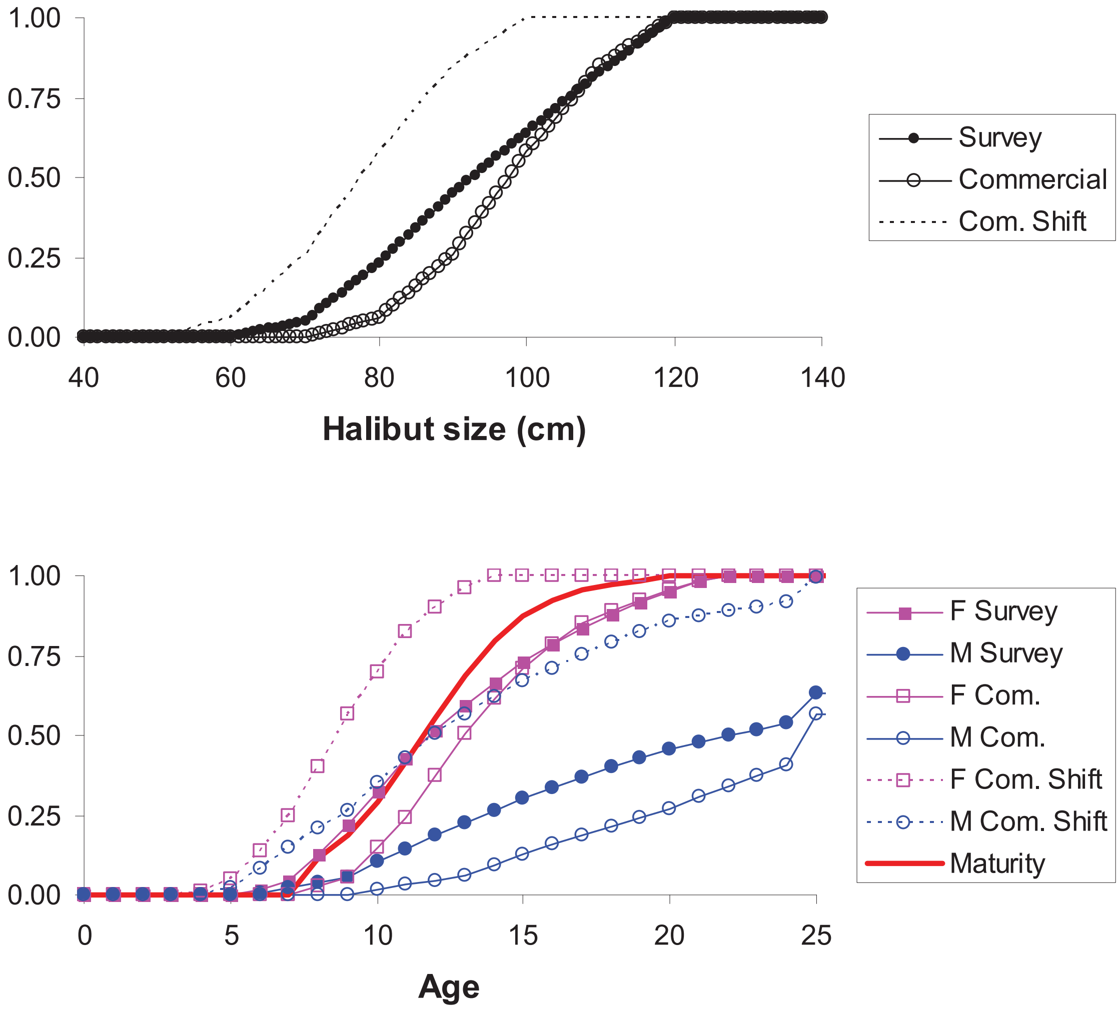


Figure 2. Coastwide selectivity at length for the commercial fishery (Commercial), the IPHC survey (Survey) and that assumed under a reduction in MSL (Com. Shift).

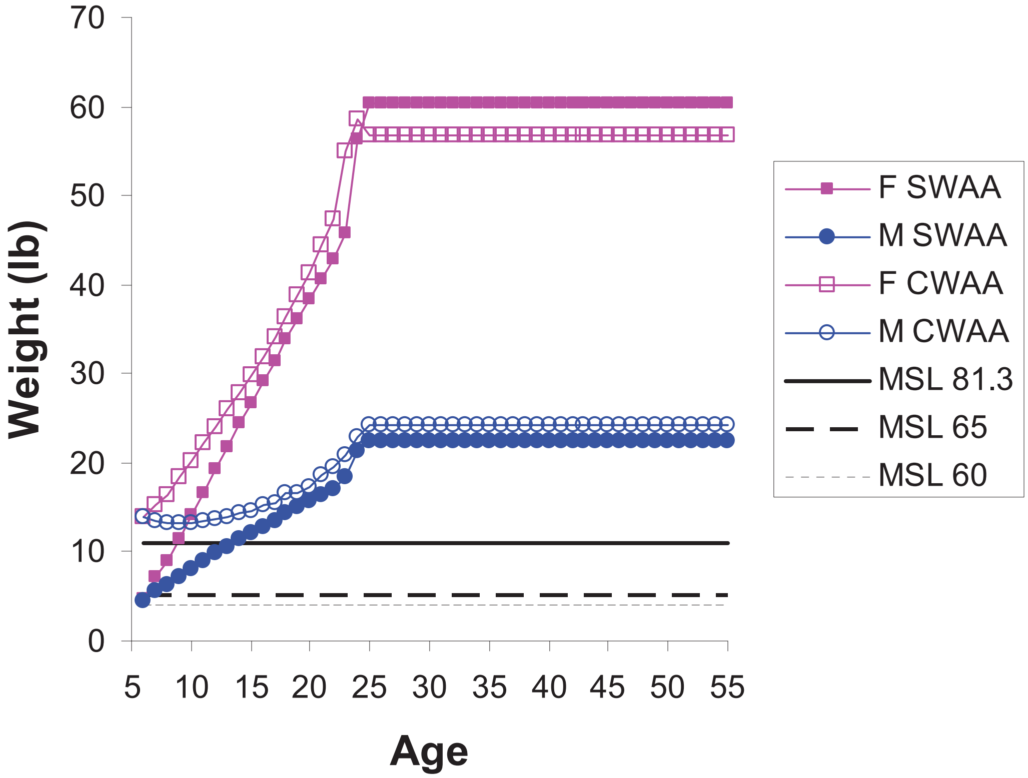


Figure 3. Observed weight-at-age in commercial (CWAA) and survey (SWAA) catches of female (F) and male (M) halibut. Horizontal lines represent average weights of halibut corresponding to MSL of 81.3 cm (solid line), 65 cm (dashed line) and 60 cm (dotted line).

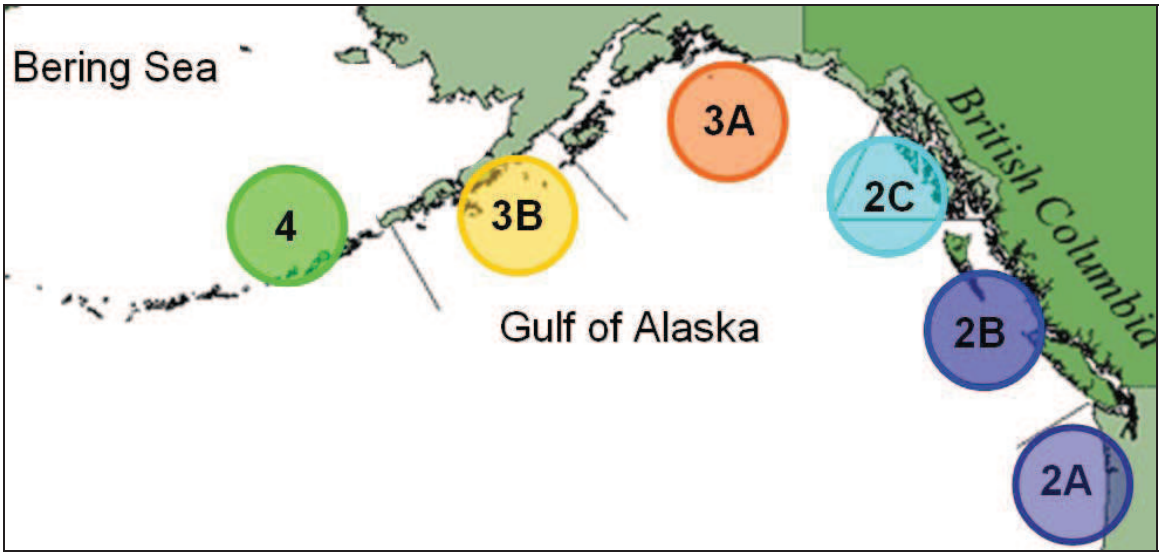


Figure 4. Map of areas included included in the migratory spatially structured model. Areas 3B to 2A are IPHC regulatory areas, area 4 is a combination of 4A, 4B and 4CDE areas.

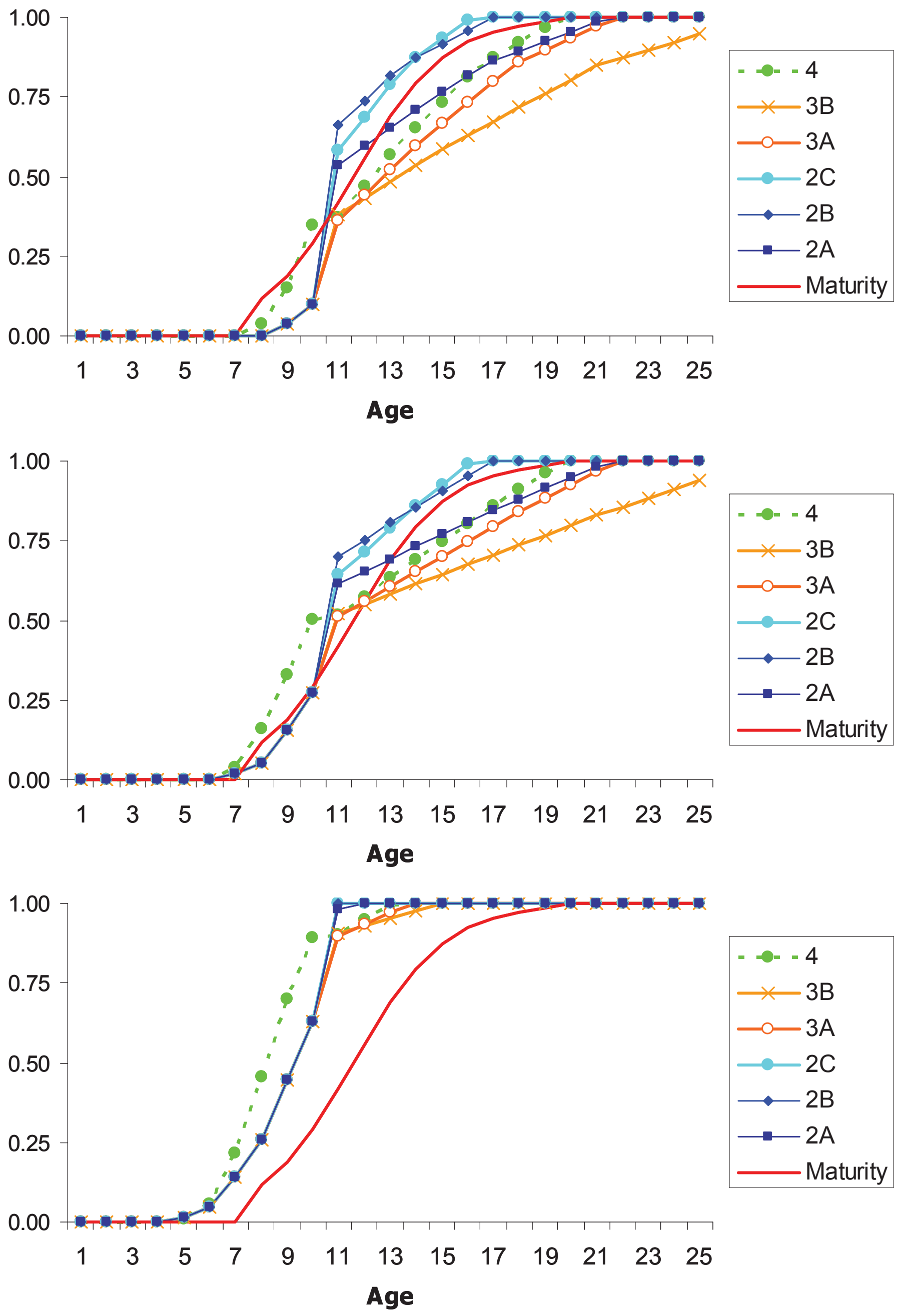


Figure 5. Female selectivities at age corresponding to selectivities at length estimated for the commercial fishery (Top), the IPHC setline survey (Center) and one resulting from shifting the commercial fishery 20 cm towards smaller sizes (Bottom). The red line (no marker) represents female maturity.

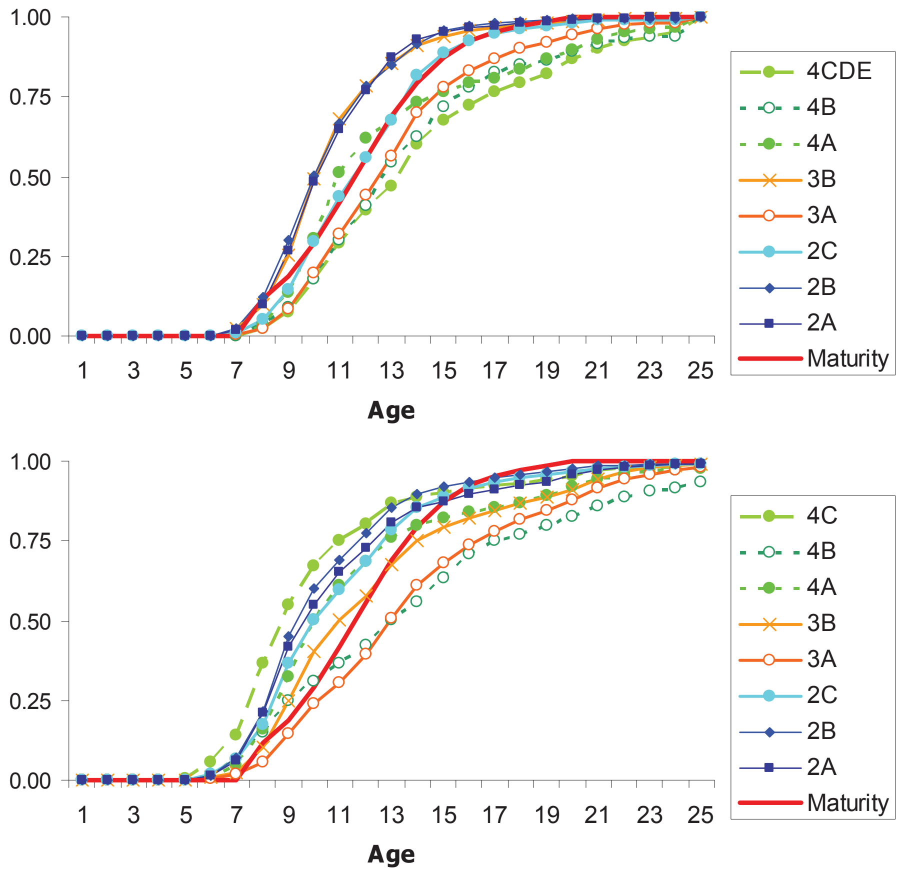


Figure 6. Female cumulative age distributions for the commercial fishery (Top) and the IPHC setline survey (Bottom) during 2009. The red line (no marker) represents female maturity.

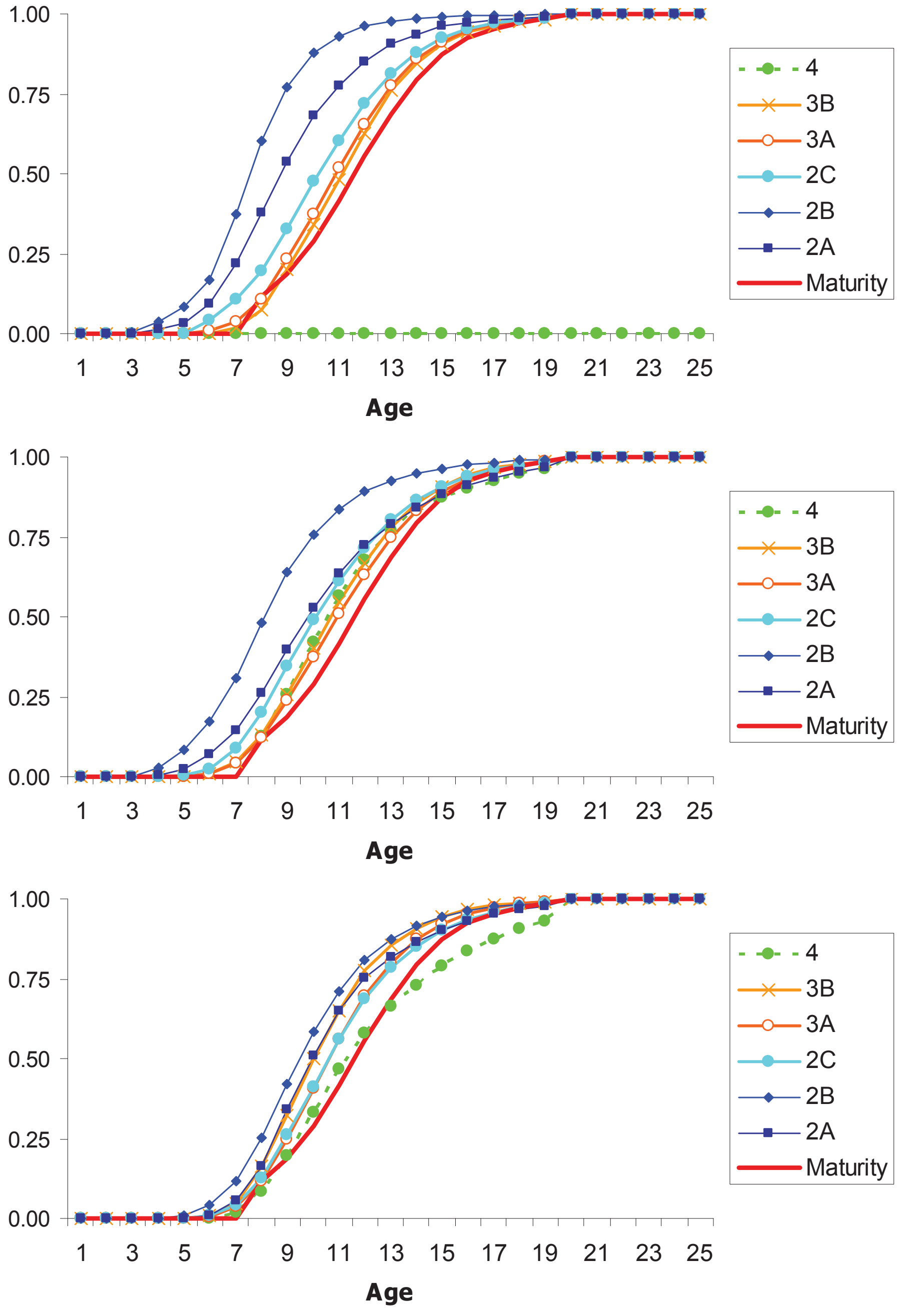


Figure 7. Cumulative age distributions for the commercial fishery during time periods of different minimum size limits (MSL): No MSL during 1935-1939 (Top), MSL: 65 cm during 1945-1973 (Center) and MSL: 81.3 cm during 1974-1990 (Bottom). The red line (no marker) represents female maturity.

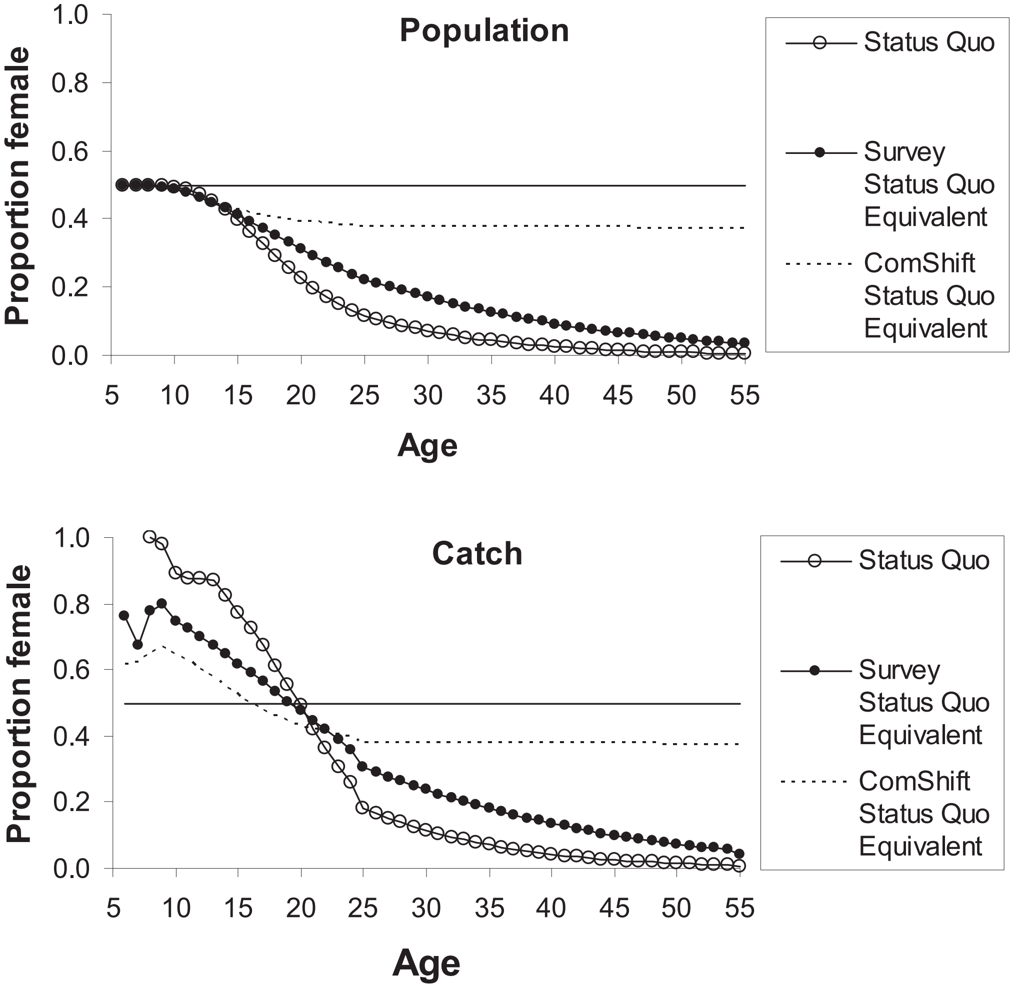
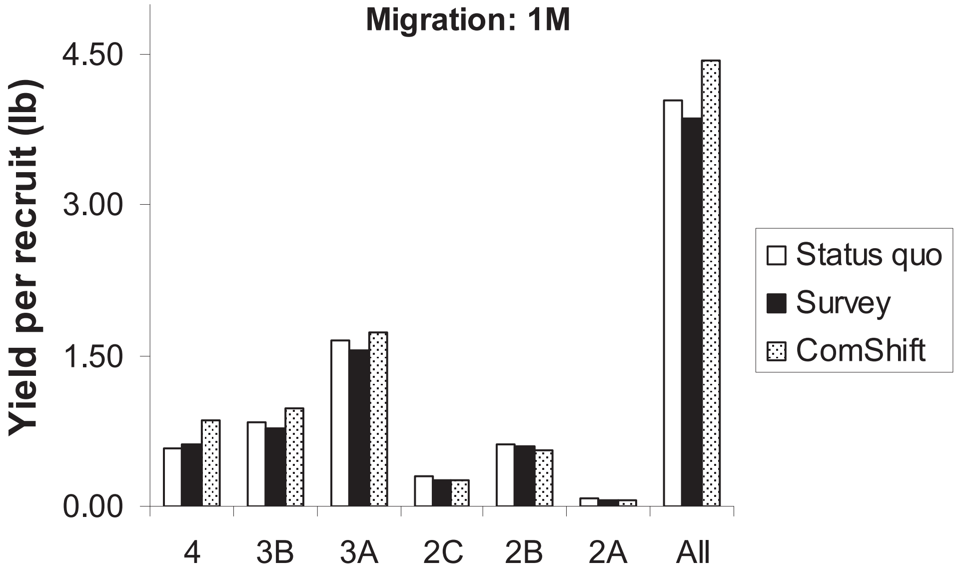


Figure 8. Proportion of female halibut in the population (Top) and in the commercial catch (Bottom) under three scenarios: 2008-2010 commercial selectivity, size limit of 81.3, HR: 0.215 (Status Quo), commercial selectivity equal to the 2008-2010 IPHC survey selectivity and HR: 0.165 (Survey Status Quo Equivalent), commercial selectivity shifted 20 cm towards smaller sizes and HR: 0.101 (ComShift Status Quo Equivalent). Status Quo equivalent HR are calculated to result in equivalent spawning biomass per recruit reductions compared to the status quo.



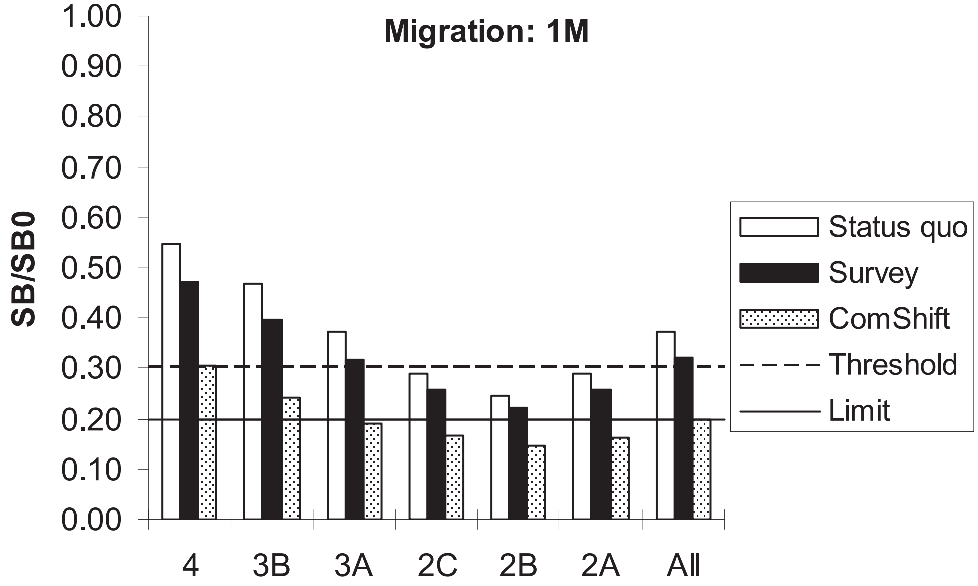
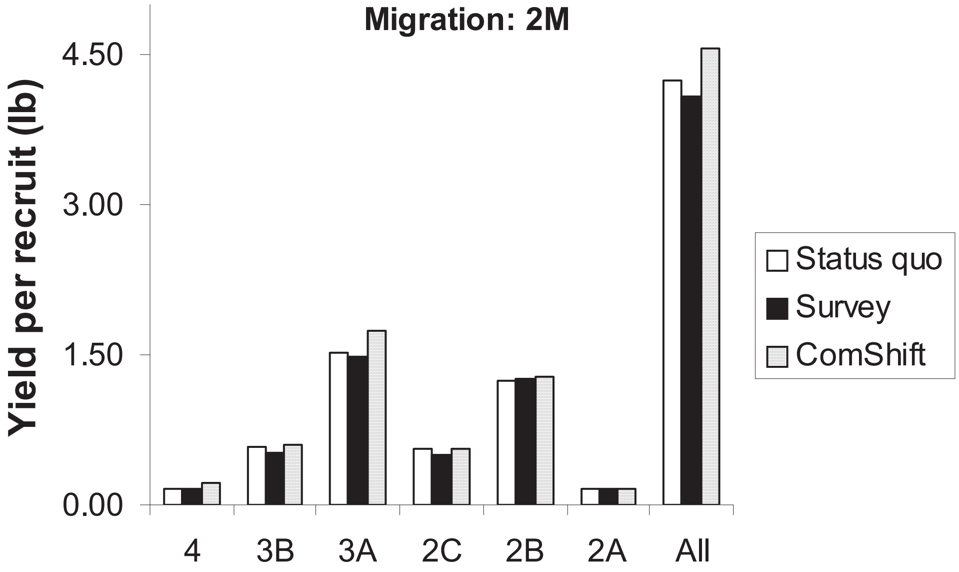


Figure 9. Yield per recruit (Top) and spawning biomass per recruit relative to unfished conditions ("SB/SB0", Bottom) at the coastwide ("All") and area specfic level, corresponding to the 1 migration matrix scenario ("1M") and harvest rate of 0.215. Selectivity of the commercial fishery is either the average for 2008-2010 with MSL: 81.3 ("Status quo"), the 2008-2010 average IPHC survey selectivity ("Survey") or the 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes ("ComShift"). Weight at age of the commercial catch is that of the 2008-2010 IPHC survey except for the Status quo where it is that of the 2008-2010 commercial catch.



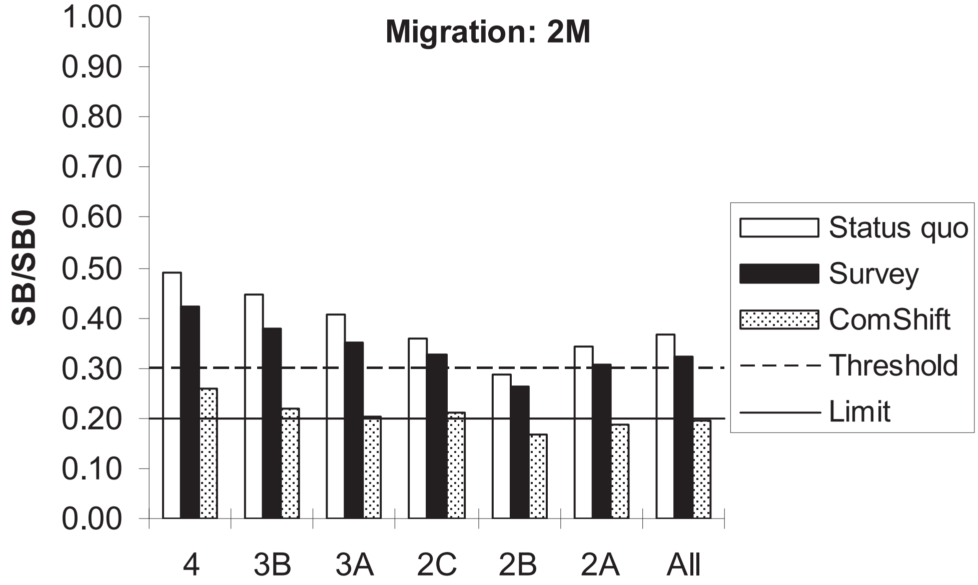


Figure 10. Yield per recruit (Top) and spawning biomass per recruit relative to unfished conditions ("SB/SB0", Bottom) at the coastwide ("All") and area specfic level, corresponding to the 2 migration matrices scenario ("2M") and harvest rate of 0.215. Selectivity of the commercial fishery is either the average for 2008-2010 with MSL: 81.3 ("Status quo"), the 2008-2010 average IPHC survey selectivity ("Survey") or the 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes ("ComShift"). Weight at age of the commercial catch is that of the 2008-2010 IPHC survey except for the Status quo where it is that of the 2008-2010 commercial catch.

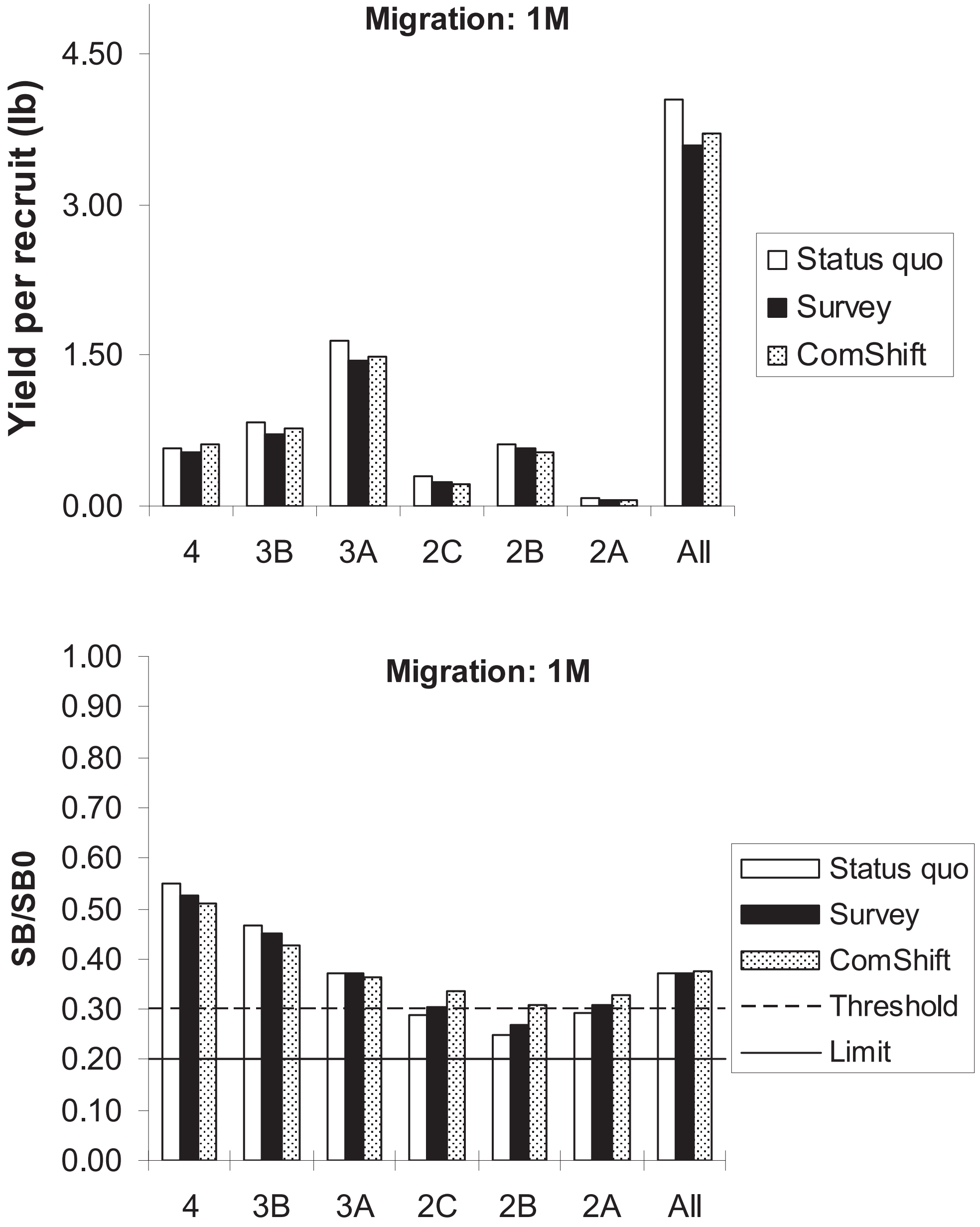


Figure 11. Yield per recruit (Top) and spawning biomass per recruit relative to unfished conditions ("SB/SB0", Bottom) at the coastwide ("All") and area specfic level, corresponding to the 1 migration matrix scenario ("1M"). Selectivity of the commercial fishery is either the average for 2008-2010 with MSL: 81.3 ("Status quo"), the 2008-2010 average IPHC survey selectivity ("Survey") or the 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes ("ComShift"). Weight at age of the commercial catch is that of the 2008-2010 IPHC survey except for the Status quo where it is that of the 2008-2010 commercial catch. Coastwide harvest rate set at a level that results in equivalent coastwide SB/SB0 to the Status quo (HR: 0.215). Equivalent HR are 0.17 for "Survey" and 0.11 for "ComShift".

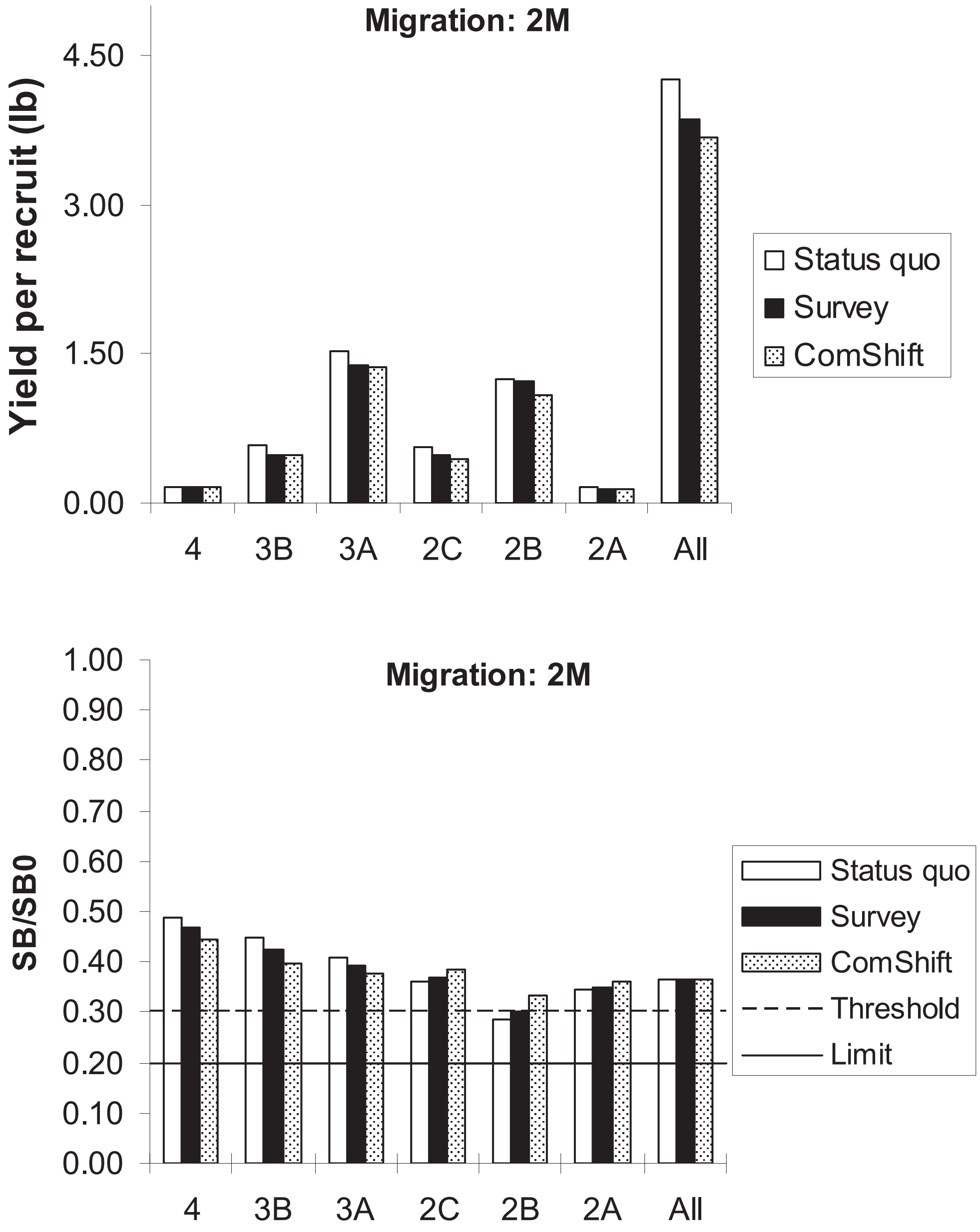


Figure 12. Yield per recruit (Top) and spawning biomass per recruit relative to unfished conditions ("SB/SB0", Bottom) at the coastwide ("All") and area specfic level, corresponding to the 2 migration matrices scenario ("2M"). Selectivity of the commercial fishery is either the average for 2008-2010 with MSL: 81.3 ("Status quo"), the 2008-2010 average IPHC survey selectivity ("Survey") or the 2008-2010 commercial selectivity shifted 20 cm towards smaller sizes ("ComShift"). Weight at age of the commercial catch is that of the 2008-2010 IPHC survey except for the Status quo where it is that of the 2008-2010 commercial catch. Coastwide harvest rate set at a level that results in equivalent coastwide SB/SB0 to the Status quo (HR: 0.215). Equivalent HR are 0.18 for "Survey" and 0.11 for "ComShift".

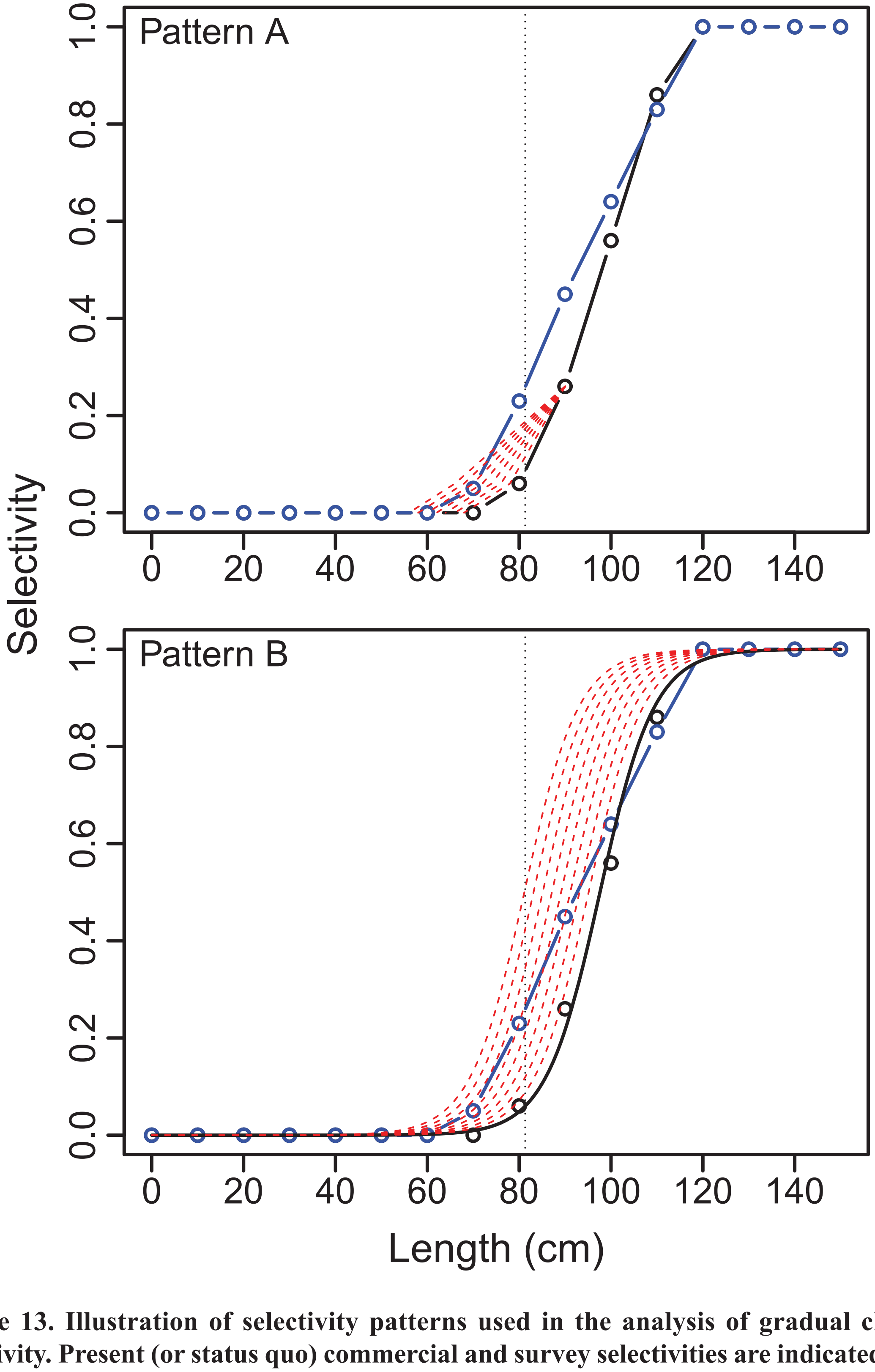


Figure 13. Illustration of selectivity patterns used in the analysis of gradual changes in selectivity. Present (or status quo) commercial and survey selectivities are indicated by black circles/lines and blue circles/lines, respectively. Dashed red lines are shown for selectivity patterns corresponding to sequential two-cm reductions in the size limit.

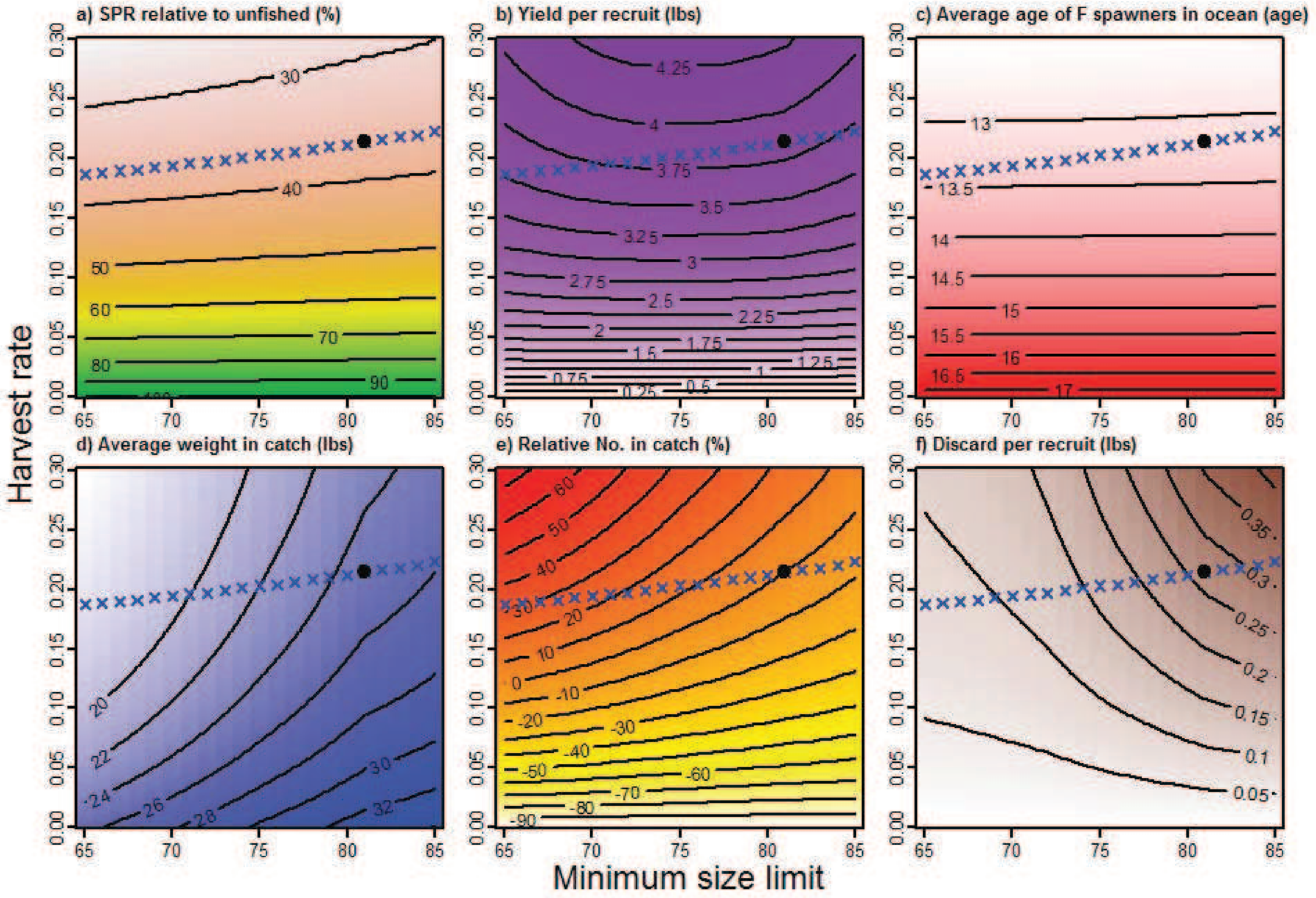


Figure 14. Summary results for gradual changes in selectivity and assumed gradual changes in commercial weight at age using Selectivity Pattern A. See text for details.

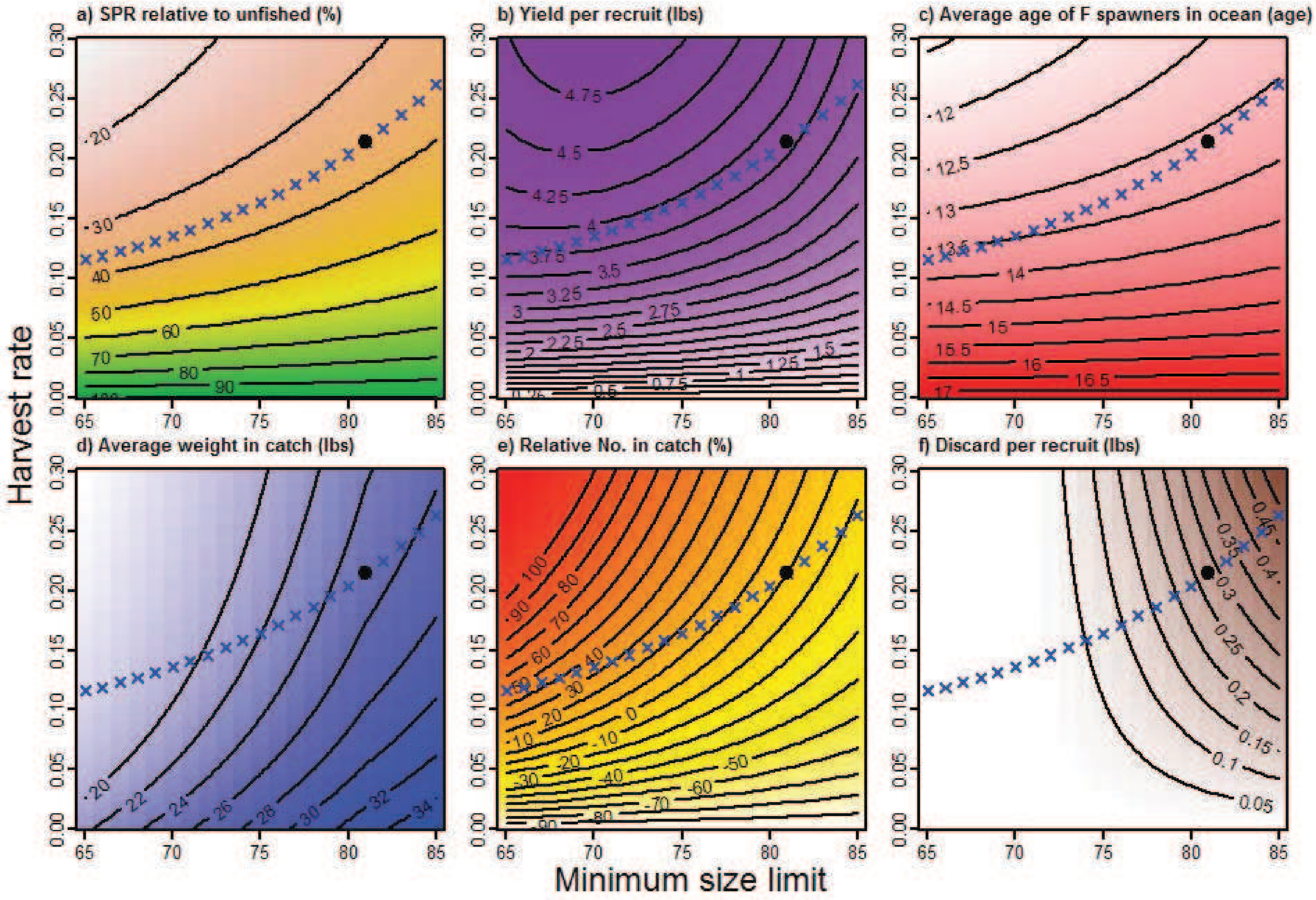


Figure 15. Summary results for gradual changes in selectivity and assumed no changes in commercial weight at age using Selectivity Pattern B. See text for details.

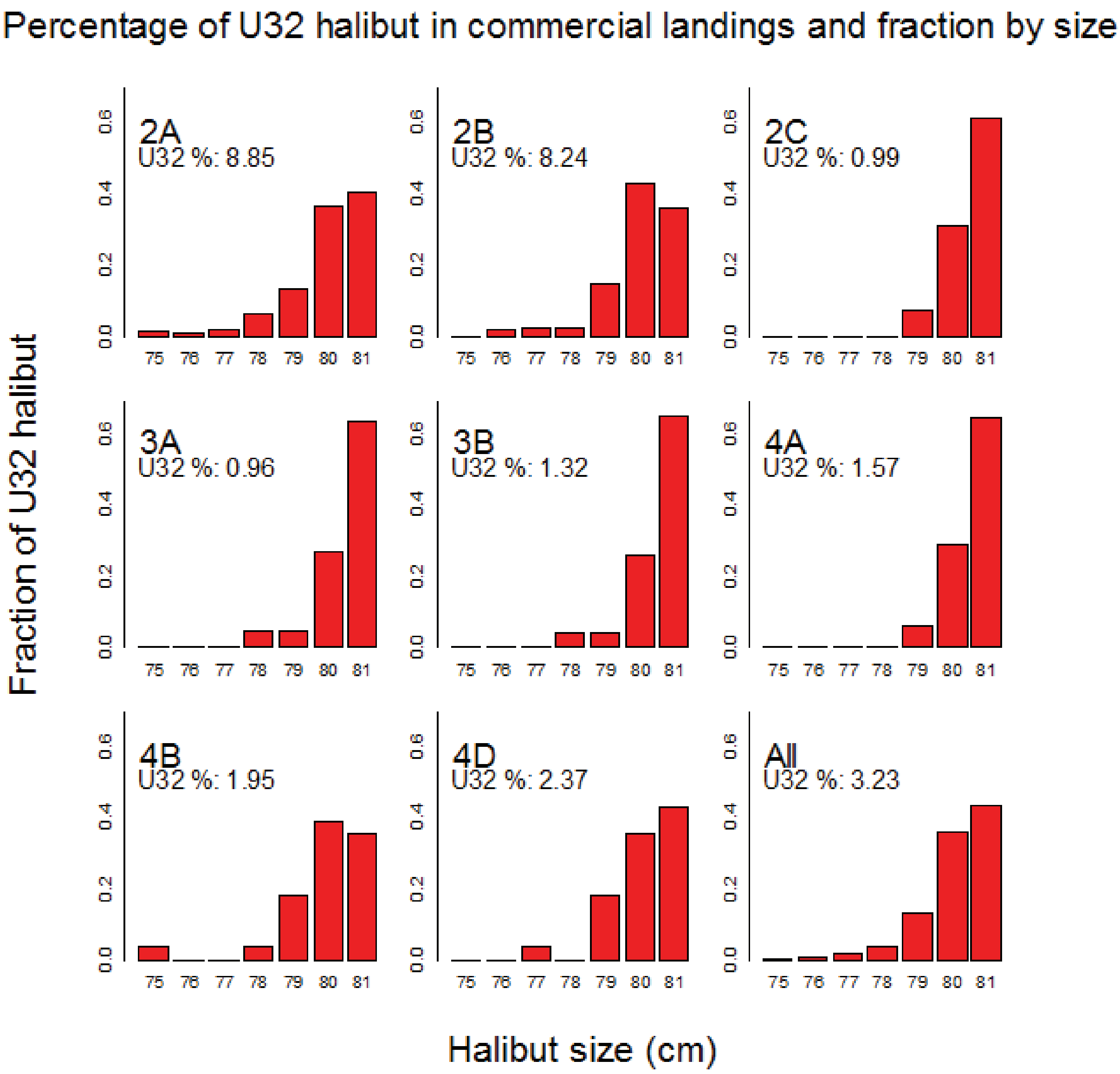


Figure 16. Size distribution of commercially landed halibut below the current 32 inch (U32) minimum size limit for each IPHC regulatory area and coastwide ("All") during 2008. U32% is the percentage of halibut under 32 inches relative to total numbers commercialy landed in 2008.