Optimal harvest rates for Pacific halibut

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Abstract

Key to determining the optimal harvest rate that maximizes the long-term sustainable yield is having knowledge of stock productivity and what age, or size, of fish are being harvested by all fishing sectors. Recent size-at-age data and changes in the stock assessment model for Pacific halibut have resulted in changes in estimated productivity and selectivity for both directed fisheries and survey selectivity. Previous estimates of optimal exploitation rates are outdated and need to be revised. We develop an age- sex- and size-structured equilibrium model to investigate how variation in growth, changes in size-selectivity, size-limits, and bycatch impact estimates of optimal exploitation rates in each of the Regulatory Areas for Pacific halibut. Differences in growth rates between regulatory areas translate into as much as a 40% difference in yield per recruit. A maximum size limit of 140 cm results in little to no benefit of protecting spawning stock biomass under the current discard mortality rate of 16%. In the absence of size limits, over all yield per recruit increases but at the expense of reducing spawning biomass and changing the composition of the catch towards smaller fish. Optimal harvest rates would have to be adjusted downwards to compensate for the loss of spawning biomass. Undetected shifts in commercial selectivity towards capturing smaller/younger fish results in an upward bias in the estimates of optimal harvest rates. A reduction in bycatch rates in non-directed fisheries can lead to desirable increases in optimal exploitation rates. Conversely, unreported bycatch results in an upward bias in optimal exploitation rates. The optimal harvest rate is very sensitive to estimates of natural mortality, steepness of the stock-recruit relationship, and fisheries selectivity. The harvest control rule should be updated with changes in model structure and updated parameter estimates to ensure the harvest policy is kept up to date. Results presented are preliminary and include a number of simplifying assumptions. Recommendations concerning revisions to the optimum harvest rate will be developed over the coming year.

Introduction

The current harvest objectives for Pacific halibut are to achieve a high level of yield while at all times maintaining healthy female spawning stock biomass to ensure long-term sustainability. The current harvest policy intends to achieve a desired exploitation rate of 21.5% in regulatory Areas 2A, 2B, 2C, and 3A, and a lower exploitation rate of 16.125% in Areas 3B, 4A, 4B, and 4CDE. These harvest rates were determined using a simulation modeling approach based on the results of closed area assessments in Areas 2B, 2C and 3A (Clark and Hare, 2006) and subsequent considerations of surplus production and yield per recruit calculations in western regulatory areas, as well as, a revised definition of exploitable biomass. Since that time, there have been several significant changes to the assessment model and regulatory area management that warrant a review and update to the current harvest policy for Pacific halibut. Most significant of these aforementioned changes was the transition from several area-based assessments to a single coast-wide assessment model and apportionment. There have also been changes in mean size-at-age and fisheries selectivity for Pacific halibut, both of which have implications for optimal harvest rate calculations.

The definition of optimal harvest rate can be broadly defined as the harvest rate that would lead to maximizing the long-term yield. Optimal harvest rates can be defined in terms of specific metrics; for example, the harvest rate that maximizes the yield per recruit (F), or the harvest rate that reduces the spawning biomass per recruit to some specified level (F), or the harvest rate that maximizes the long-term sustainable yield (F). Each of these alternative harvest rate metrics requires similar biological and fisheries selectivity information, with the exception of the F which requires additional information about the relationship between spawning stock biomass and recruitment. For the purpose of this report, the harvest rate that maximizes long-term sustainable yield is what is implied with the term optimal harvest rate and is denoted herein by F.

Factors that affect the optimal harvest rate calculation fall into two general categories: 1) biological properties that define the underlying productivity of the stock, and 2) fishing related properties associated with target and non-target fisheries that catch halibut. Important biological parameters that define the optimal harvest rate include: growth parameters and the variance in size-at-age, maturity- and fecundity-at-age, natural mortality rates, the steepness of the stock-recruitment relationship, and migration rates among the various fishing grounds (Beddington and Kirkwood, 2005). Although dispersal and movement is important for determining optimal harvest rates, it is often ignored under the assumption of a unit stock (area is sufficiently large enough to ignore dispersal and migration). The vulnerability of fish to fishing gear, also known as selectivity, is also extremely important in determining optimal harvest rates (Hilborn and Walters, 1992). In general, the age-at-entry to the fishery relative to the age-at-maturity defines the optimal fishing mortality rate; as the age-at-entry to the fishery increases relative to the age-at-maturity, the higher the value of F.

The current harvest strategy for Pacific halibut also includes the use of a minimum size limit in the directed commercial longline fishery. Halibut that are below the minimum legal size of 81.3 cm total length are required to be released and the IPHC assumes a 16% mortality rate for released fish based on previous tagging studies. Changes in the size limit also have implications for the F calculations, especially if release mortality rates are significant. In general, if halibut less than the minimum size limit are routinely captured, then reducing the minimum size limit will also result in reductions in the optimal harvest rate. Note that the EBio calculation is based on all halibut greater than 66 cm (or 26 inches) so the definition of Ebio does not change with changes in size limits.

Previous studies have examined the impacts of alternative size limits on the yield per recruit and spawning biomass per recruit using steady-state or equilibrium models (Clark and Parma, 1995). Previous halibut studies have not considered the cumulative impacts of size-selective fishing on optimal harvest rate calculations for Pacific halibut. Using a minimum size limit, faster growing individuals from a given cohort would experience higher total mortality rates over their lifetime as they recruit to the legal size at a younger age in comparison to slower growing individuals. The cumulative effect of fishing mortality imposes a higher total mortality rate on faster growing halibut; remaining individuals left in the population consist of slower growing individuals (Taylor et al., 2005). The cumulative effects of size-selective fishing can, therefore, give the appearance of declining mean weight-at-age in the population.

Further, previous studies have not addressed how different release mortality rates affect yield per recruit and optimal harvest rates for Pacific halibut. Coggins et al. (2007) and Pine et al. (2008) demonstrated that for a given size limit, increases in discard mortality can lower the realized yield per recruit. This is also the case if both lower and upper size limits (i.e., slot-limit) are in place, where the assumption is that an upper size limit would add additional protection to large sexually mature females.

Maximizing yield per recruit, or maximizing the total landed biomass is not always desirable from an economic perspective. In the cases where there is a differential price structure for the size of fish landed (e.g., large fish fetch a higher price per pound than small fish), it may be more desirable to fish at rates lower than in order to maximize value of all fish landed. Moreover, fishing mortality rates associated with Maximum Economic Yield (MEY) are generally lower than fishing mortality rates associated with MSY (Gordon, 1954).

In this paper, I develop an equilibrium model for Pacific halibut to examine how changes in biological components and size-specific fishing mortality impact estimates of optimum harvest rate calculations. In addition to the directed fishery, the impacts of other constant removals from non-directed fisheries (e.g., bycatch) on estimates of optimal fishing mortality rates in the directed fishery are also examined. The cumulative effects of size selective fishing on changes in mean weight-at-age are also explored. Size-at-age data from the 2011 setline survey are used to estimate growth curves for each regulatory area, and these growth curves are used to illustrate how relative differences in growth affect estimates of optimal harvest rates in each regulatory area.

Methods

Equilibrium model

At equilibrium, the annual yield is calculated as the sum over ages of the fraction of individuals that die due to fishing multiplied by the total number or biomass of individuals available for harvest. Thus the equilibrium yield equation, assuming both natural and fishing mortality occur simultaneously, can be written as:

(1)

where is the age-specific fishing mortality rate which can be parsed as , where is the age-specific fraction that is vulnerable to fishing mortality (also termed selectivity in models that do not distinguish between landed and discarded fish). It is common to use a simple parametric function (i.e., a logistic curve) to describe age-specific selectivities. For this application we use the same length-based coefficients that are internally estimated in the stock assessment model and convert these coefficients into age-based selectivities based on the mean length-at-age and the coefficient of variation in the mean length-at-age. Biomass at age () is defined as the numbers-at-age () times the average weight-at-age (). Assuming steady-state conditions, this can be expressed as the product of recruitment, survivorship, and the average weight-at-age. Assuming unfished conditions (i.e., ), survivorship to a given age is given by the following recursive equation and natural mortality rate *M*:

(2)

and survivorship under fished conditions () is given by:

(3)

The total age-specific biomass is given as:

(4)

where is the equilibrium number of age-1 recruits.

Substituting () into () and parsing fishing mortality into age-specific components yields the following expression

(5)

where is the equilibrium recruitment obtained under a fishing mortality rate . The summation term in () represents the yield per recruit (), and the yield equation simplifies to:

(6)

For a given equilibrium fishing mortality rate , the equilibrium recruitment is a function of the available spawning biomass relative to the unfished spawning biomass. For the Beverton-Holt model, this can be expressed as:

(7)

where the spawning biomass per recruit and for unfished and fished conditions, respectively, is based on the survivorship and mature female weight-at-age, or fecundity-at-age (). Two leading parameters are the unfished age-1 recruits , which serves the purpose of providing the overall population scale, and the recruitment compensation parameter κ which is defined as the relative improvement in juvenile survival rate as the spawning biomass tends to zero. For the Beverton-Holt model this can be derived from steepness as κ=4*h*/[1−*h*], (see Martell et al., 2008, for further details). Spawning biomass per recruit is given by:

(8)

(9)

Note that it is not necessary to have absolute estimates of fecundity as the units cancel out in the ratio in (). What is important is the relative egg contribution by age, and here it is assumed that fecundity is proportional to mature female body weight.

Based on equations – it is now possible to calculate the equilibrium yield given estimates of the following parameters: . The following subsections describe how these equilibrium calculations can be modified to include mortality associated with catch-release, and how the cumulative effects of size-selective fishing can lead to changes in mean size-at-age.

Including release mortality

The equilibrium model described in the previous section only considers the case in which all fish captured for a unit of fishing mortality are removed from the population and not for cases in which some fish captured will be discarded because they are not within the legal size range. To include the effects of post-release mortality associated with size limits, the vulnerability age-schedule () has to be modeled as as a joint probability, where the probability of dying due to fishing is based on the probability of capture and being retained times the probability of being captured, released, and dying after release. This joint probability is as follows:

(10)

where is the age-specific vulnerability associated with a unit of fishing mortality, is the age-specific probability of being captured by fishing gear, and are the age-specific retention and release probabilities, and λ is the probability of dying after being discarded (assumed to be 0.16 in the directed fishery).

To implement the effects of size-limits and post-release mortality rates on the equilibrium yield calculations defined in the previous section, we simply substitute () for all the terms in equations and above. In addition to calculating equilibrium yield (), the equilibrium discards can also be calculated in a similar manner as (), where the discard per recruit is defined as:

(11)

and the total discards are given by:

(12)

Note that equation represent the total biomass of discarded fish; the total discard mortality is the discard mortality rate (λ) multiplied by .

Cumulative effects of size-selective fishing

To account for variation in growth and represent the cumulative effects of size-selective fishing, the population is divided into a number of distinct groups (*G*) that each have a unique growth curve (). Growth was based on fitting a growth model to the 2011 sex-specific length-age data collected in the fishery independent setline survey (see Appendix ). The variance in length-at-age for each of the *G* groups is set to a fraction of the estimated total variance from the setline survey length-at-age data:

where is the estimated mean length-at-age, and *CV* is the estimated coefficient of variance. Partitioning growth into *G* groups that vary in the mean length-at-age only can then be integrated into the equilibrium model a series of *G* sub-populations, where each of the above calculations in equations ()-() represents sub-populations that differ only in growth and relative numerical abundance. A similar model was developed by Mulligan and Leaman (1992) for Pacific ocean perch to explain poor residual patterns obtained when fitting a standard growth curve that assumes size-at-age is normally distributed.

The proportion of recruitment to each of these *G* groups is assumed to be normally distributed with 99.7% of all individuals falling within 3 standard deviations of the mean asymptotic length. There are no assumptions about the composition of the spawning stock biomass and recruitment into each of these groups (i.e., no genetic selection effects due to fishing is assumed), and irrespective of spawning stock size, recruitment to each of these groups follows the same normal distribution. Genetic extensions could be included to examine fishery induced evolution, if desired.

The per recruit functions described in the previous equations are then modified to include both the age- and size-effect. For example, the spawning biomass per recruit described in () is now calculated as:

(13)

where and computed over *G*=11 discrete intervals from -1.96 to 1.96. In other words, the equilibrium population consists of 11 discrete sub-populations that differ only in their mean length-at-age and the relative abundance of each sub-population follows a normal distribution. In such a case, non-zero fishing mortality () would then impose differential total mortality, where faster growing individuals would be subjected to a higher overall over its lifetime relative to slower growing individuals because they recruit to the size-selective fishery at a younger age. The use of multiple groups to represent cumulative size-selective fishing effects also assumes there is no compensation in growth rates as densities are reduced through fishing. Although not implemented here, density effects on growth could easily be accommodated in this model.

Life-history parameters

For this paper, the assumed natural mortality and selectivity parameters are listed in Table 1. Estimated growth parameters for each regulatory area are summarized in Table in Appendix . Sexual maturity for female halibut was assumed to be a logistic function of age, where the age-at-50% maturity is 10.91 years and the standard deviation is 1.406 years. Relative fecundity-at-age is assumed to be proportional to mature female weight-at-age. The allometric length-weight relationship (*a*,*b* parameters in ) was assumed to be the same for both sexes (Table ).

The two key parameters that define the underlying stock-recruitment relationship in this model are: , the unfished spawning stock biomass, and steepness (*h*) which is defined as the fraction of unfished recruitment that is obtained when the spawning stock biomass is reduced to 20% of its unfished state. Normally these two parameters are obtained by fitting a stock-recruitment relationship to the historical estimates of spawning biomass and recruitment numbers (usually integrated within the stock assessment model). The current assessment model for Pacific halibut has no built in stock recruitment relationship at this time, so these parameters are not readily available. In the absence of and *h* estimates, was arbitrarily set at 100 pounds, and a steepness value of 0.75 was chosen somewhat arbitrarily because estimates of were fairly similar to those obtained for Areas 3A, 2B and 2C by Clark and Hare (2006). Note also, that in arriving at a value of 0.75 for steepness, no bycatch was assumed for the non-directed fisheries (i.e., bycatch for the trawl fishery was set equal to 0). If bycatch was included in the initial development of the model, the assumed value of steepness would likely be higher to compensate for recruitment loss associated with bycatch of juvenile halibut.

Optimal fishing rates

To determine the fishing mortality rate that would maximize the relative yield in each regulatory area, a discrete range of equilibrium fishing mortality rates was used to calculate equation () and the value of that corresponds to the maximum was then set equal to for that regulatory area. The relationship between and is then plotted for each regulatory area (also referred to as equilibrium yield curves).

Note that in the equilibrium model presented here, fishing mortality is modeled as an instantaneous rate for the purposes of partitioning total mortality into additive components of natural mortality, fishing mortality, and discard mortality. The relationship between the optimal fishing mortality rates and discrete exploitation rates () in Clark and Hare (2006) and this paper is approximately:

The equilibrium yield curves obtained for each regulatory area assume no migration between each regulatory area, and for the purposes of this paper, are effectively treated as closed populations. Therefore, a single value of is used for all regulatory areas and we only report the relative yields per 100 pounds of unfished spawning biomass. The other reason for assuming the same scaling and steepness parameter is that it also allows for direct comparisons of yield-per-recruit, spawning biomass per-recruit, discards per-recruit etc. in response to differences in size-at-age (growth) in each regulatory area.

Scenarios

A combination of policy parameters in the equilibrium model were explored to examine the implications of changing fishing regulations on optimal harvest rate calculations. Also the sensitivity of optimal harvest rates to alternative assumptions about discard mortality rates, steepness, or the effects of bycatch non-directed fisheries was also examined. In addition to the base scenario (S1, Table ), eight additional scenarios were examined to explore the effects of minimum and maximum size limits (S2, S3), a 10 cm shift in commercial selectivity towards smaller fish (S4), other mortality associated with non-directed fisheries that remove a constant catch (S5), and sensitivity to size-dependent natural mortality (S6, S7) and steepness (S8, S9).

The intention of scenarios 2 and 3 is to examine how the overall equilibrium yield, yield-per-recruit, spawning biomass per-recruit, and estimates of F would change with changes in size limits. Similarly, how would these same variables change if the fishery targeted smaller fish (S4)? In the case of Scenario 4, the same size-based selectivity coefficients are used, but the liner interpolation over size is shifted to 50–120 cm from the status quo of 60–130 cm. In other words, if a 100 cm female had a selectivity of 0.535 in the base scenario, is S4 it has a selectivity of 0.535 at 90 cm.

In scenario S5, the bycatch from a non-directed trawl fishery is assumed to be constant, irrespective of the density of halibut on the trawl grounds (a worst-case scenario). Also, bycatch is not expected to result in additional compensation in juvenile survival rates for new recruits (i.e., there is no impact on steepness of the stock-recruit relationship). In the case of constant bycatch, the fishing mortality rate is expected to decrease exponentially with increasing halibut density. For example, if the bycatch fisheries discard a fixed amount of 1 million pounds of dead halibut each year and the equilibrium biomass is 10 million pounds, then the corresponding fishing mortality rate of the bycatch fishery is proportional to 1/10, or 0.1. If, however, the equilibrium biomass is at a lower level, e.g., 2.5 million pounds, then the equilibrium fishing mortality rate is proportional to 1/2.5, or 0.40. To approximate the exponentially increasing effect of a fixed level of bycatch, the equilibrium biomass for a given directed fishery mortality rate () was approximated as . In other words, for increasing values of , the approximate equilibrium biomass declines to 0.15; the corresponding bycatch fishing mortality is then given by:

It was also assumed that bycatch from the directed trawl fisheries selected fish of small and intermediate sizes. This selectivity was approximated with a double logistic function with the size at 50% selectivity at 61 cm for the ascending limb and 81.3 for the descending limb, and a standard deviation of 0.1 cm (knife-edge) for both ascending and descending portions of the curve. In reality, the actual selectivity curves could differ markedly, and the appropriate size-composition data would have to be integrated into the assessment model to estimate selectivity parameters for a discard fishery.

In scenarios 6 and 7, natural mortality is assumed to be size-dependent where small halibut have a higher natural mortality rate than larger halibut (S6), or natural mortality rates increase with increasing size (S7). In both scenarios 6 and 7, the average natural mortality rate is approximately 0.15 when integrated over all size classes.

Lastly, scenarios 8 and 9 are intended to demonstrate how sensitive the reference fishing mortality rate calculation is to the assumed value of steepness in the stock assessment model. This is akin to the range of recruitment values used in the Clark and Hare (2006) simulation study where no density-dependent effects on recruitment were assumed.

Results

Growth

Size-at-age data in each of the regulatory areas has very marked differences in both the mean length-at-age, and the distribution of age-classes (Fig. ). Male and female halibut in Area 2A are fast growing but tend to have a much smaller asymptotic size than halibut sampled in other regulatory areas. Moreover, the age-composition in Area 2A is truncated relative to other regions, with very few fish older than 17 years. The coefficient of variation in length-at-age is much higher in Areas 2B and 2C, especially for females. Estimated growth rates for female halibut in these two areas is nearly linear for younger ages, and on average older halibut in these regions are much larger in comparison to other regions with old female halibut. Area 4B is also another anomaly in that the age-distribution is much older, especially for males, with many sampled individuals beyond age 20. Additional details about the growth model and estimated model parameters are found in Appendix .

We note here that estimated growth parameters in Figure are biased due to size-based selectivity in the setline survey and potentially contaminated due to the cumulative effects of size-selective fishing. Nonetheless, the relative differences in growth rates in each of the regulatory areas is what is important in this analysis.

Area-specific estimates of F

The relative equilibrium yield versus fishing mortality rate in each of the regulatory areas (Fig. ) demonstrate the relative differences in expected yield based only on differences in halibut growth (size-at-age) in each of the regulatory areas. For each of the regulatory areas shown in Figure , a minimum size limit of 81.3 cm exists, steepness is fixed at an arbitrary value of 0.75, size-selectivity is the same in each area, and natural mortality rates are the same (*M*=0.15) for all areas. The only biological difference between regulatory areas is the growth rate. For each recruiting halibut in a specific regulatory area, the maximum yield per recruit would be obtained in Area 2A. Halibut in Area 2A are very large at younger ages and more vulnerable to the fishing gear (selectivity) at an age when they are numerically more abundant.

In contrast, in Area 4C halibut obtain very large sizes, but the growth rate is much slower in comparison to 2A so fewer individuals are available to be harvested and less yield per recruit is obtained in this area. The net result of this difference in growth rates is that estimates of F are lower in Area 4C relative to Area 2A (Fig. and Table ). The difference in early growth between 2A and 4C translates into roughly 40% more yield per recruit in Area 2A.

Equilibrium yield curves for each regulatory area under each of the 9 alternative scenarios are shown in Figure and the corresponding estimates of optimal exploitation rates () are summarized in Table . Relative to the current harvest rate policy of 21.5% and 16.125%, estimates of optimal exploitation rates for Areas 2B and 2C are below the current 21.5% value. However, recall that this is based on the assumption of a Beverton-Holt stock recruitment relationship with a steepness value set at an arbitrary level of 0.75. The utility of S1 is to serve as a baseline in which to compare impacts of alternative size limits and model assumptions on the estimates of optimal exploitation rates that would maximize the average long-term yield in each of the statistical areas.

The maximum size limit scenario results in slight increases in the estimates of in areas where halibut grow to a sufficiently large size to benefit from such protection (Table ). Imposing a maximum size limit does not result in any yield benefits in any of the regulatory areas (Scenario S2, Table ). In fact, in Areas 2A and 3B, there is a very small probability that an individual halibut would survive and grow to surpass the upper legal size limit of 140 cm. There is only a minor improvement in the relative spawning biomass in Areas 2A and 3B associated with a maximum size limit of 140 cm (Table ). Whereas, there is a further reduction in the spawning biomass depletion in areas where halibut grow beyond the 140 cm maximum size limit and fishing at , and the amount of spawning biomass reduction is proportional to the discard mortality rates.

If size-limits were removed altogether, and there is no change in the size-selectivity of the commercial fishery, then estimates of would have to be reduced (S3, Table ) in order to compensate for the increased total mortality rate associated with retaining fish smaller than 81.3 cm. Relative increases in overall yield do occur with the removal of the minimum size limits, as the yield per recruit in each area increases, with the exception of Area 4B. However, this modest increase in overall yield does come at the expense of reducing spawning stock biomass, as well as, reducing the average size of landed fish.

Scenario 4 represents a shift in the commercial selectivity towards smaller fish, and the net impact of this shift is a reduction in the values for each regulatory area, as well as, decreases in the overall landed yield (Tables and ). Recall that this scenario was run with the current minimum size limit of 81.3 cm in place and serves to show that minimum size-limits alone does not afford protection of spawning stock biomass if discard mortality rates are greater than 0. Although corresponding increases in spawning biomass are observed in Table for scenario 4, this increase owes to the reduction in that would be required to maximize yield if selectivity were to shift towards smaller fish.

The effects of other discard mortality, from non-directed fisheries, also plays a role in harvest policy calculations. In scenario 5, a constant total harvest of 2 Mlb (i.e., bycatch from a trawl fishery) was imposed as an increasing fishing mortality rate with increasing directed . In this scenario, a constant level of bycatch results in a dramatic reduction in overall yield in the directed fishery (Table ) and a reduction in the optimal harvest rate () that would produce the maximum sustainable yield in the directed fishery. For example, in Area 2A, 2 lb of bycatch would reduce the directed yield by 1.41 lb if fishing at the optimal fishing mortality rate (Table , scenario S5).

In the case where bycatch fisheries remove a fixed amount, the mortality rate increases with declining stock size. Whereas, in the directed fishery, annual catches would scale down with reductions in exploitable biomass, and fishing mortality rates would scale down if the spawning biomass falls below B. Note also that estimates would increase if efforts were made to reduce bycatch in non-directed fisheries.

Sensitivity to assumed parameter values

Scenarios 6 and 7 examine how sensitive MSY-based reference points are to estimates of natural mortality rates. The current assessment model assumes natural mortality is independent of size/age. These two scenarios examine a size-effect in natural mortality. In general, if *M* is size/age independent, the increasing *M* results in increases in the estimates of , and vice versa (Walters and Martell, 2004). Also increases in *M* results in a decrease in MSY and the spawning biomass at . If *M* is size-dependent and decreases with size, estimates of also decrease, and vice versa. Natural mortality also plays a role in the general scaling of MSY; as fewer older fish are available for harvest due to high natural mortality rates, then the value of MSY decreases. Hence mis-specification of *M* can lead to biased estimates of other reference points (e.g., unfished spawning biomass ).

Lastly, estimates of are very sensitive to the steepness of the stock-recruitment relationship. With increasing steepness the corresponding estimates of also increase, and vice versa. The resilience of the stock to over-fishing decreases with decreasing values of steepness, the overall yield declines and there are fewer recruits per unit of spawning biomass (i.e., lower stock productivity).

Wastage in the directed fishery

In all scenarios where size limits exist, wastage in the directed fishery increases with increasing fishing mortality. Under the current status quo scenario (S1), the long-term average wastage in the directed fishery is estimated to be less than 5% of the total landed yield in each of the regulatory areas if fishing mortality rates are less that 0.25 (Fig. ). Note that for the purposes of this paper, as well as for the wastage estimates that go into the stock assessment model, it is assumed that the selectivity of the commercial fishery is the same as the estimated selectivity curve in the setline survey.

The use of an upper size limit (S2), results in increased wastage over the status quo scenario, but only in areas where halibut attain sufficiently large sizes. At low equilibrium fishing mortality rates wastage in Areas 2B, 2C, 4B and 4C are greater than 10% of the landed catch due to large halibut (greater than 140 cm) in these regions (Fig. ). As fishing mortality rates increase and erode the size structure, wastage rates decline and effectively become the same as that of a minimum size limit only.

In scenario 4, where the commercial selectivity curve was shifted by 10 cm towards smaller fish, the long-term average wastage in the directed fishery more that doubles what is currently assumed under the status quo scenario (Fig. ). Note that a minimum size limit of 81.3 cm is also maintained in the S4 calculations. Lastly, I also note here that under Scenario 3 (not shown in Fig. ), there is no wastage, as it is assumed that all fish harvested are landed.

Changes in mean weight-at-age

Mean size-at-age is predicted to decline with increasing size-selective fishing mortality, especially for age-classes that are fully recruited to the fishing gear (Fig. ). Ages less than 8 years are not expected to show much of a change in the mean weight-at-age because they are only partially recruited to the gear, and have not been subjected to intense fishing mortality.

There are substantial differences in how the predicted mean weight-at-age would change with increasing fishing mortality across regulatory areas. This is a result of differences in growth rates among regulatory areas. Despite these differences, the general pattern of cumulative size-selective fishing results larger changes in mean size for older individuals and little to no change for age classes that are not subject to intensive fishing. Similar patterns are also evident in the raw size-at-age data collected from the setline survey (Fig. ). In recent years, exploitation rates in Area 2B are estimated to be greater than the target rate of 21.5%. Mean weight-at-age for age-6 fish in Area 2B have varied little between 2002 and 2006; whereas there has been a decline in mean weight-at-age for ages 10 and 14 between 2007 and 2009 (Fig. ). There is considerable variability in the observed size-at-age data from the set line survey in all of the regulatory areas.

Discussion

Factors that affect estimates of optimal harvest rates come in two general forms: (1) biological components that define the underlying productivity of the stock, and (2) fishery components that affect size-at-entry and size-specific mortality. The former cannot be directly managed but must be taken into consideration in harevst policy, especially if there are temporal changes in stock productivity. The latter can be directly controlled through a variety of tools that limit gear specifications, size limits, or even areas fished, to control size-at-entry into the fishery and reduce post release mortality rates. In the case of Pacific halibut, there have been recent changes in size-at-age and there is also considerable variation in the size-at-age among the regulatory areas. Optimal harvest rate calculations for each of the regulatory areas will have to be updated frequently owing to continued changes, and differences, in size-at-age among regulatory areas. Also, any changes in fisheries operations or changes in fishery regulations (e.g., change in size limits or bycatch) will also affect optimal harvest calculations. In general, the underlying parameters that define the harvest control rule should be updated on a routine, or even annual, basis to ensure that biological and technological changes are taken into account to ensure harvest policy is kept up to date.

In this paper, we examined how changes in stock productivity and size-selectivity interact with estimates of fishing mortality rates that maximize long-term sustainable yields. This was approximated using an age- and sex-structured equilibrium model conditioned on regulatory area size-at-age data from the 2011 setline survey and parameters from the most recent stock assessment. The previous harvest policy was based on a stochastic simulation model for Pacific halibut that is now dated because of: (a) continued changes in size-at-age for Pacific halibut, (b) a transition from area-based assessments to a coast-wide model, (c) recent recognition that fishery and survey selectivity must vary over time in the coast-wide assessment due to changes in the distribution of the stock, and (d) reduction in the bycatch levels in non-directed fisheries. There have been previous equilibrium-based models for the development of harvest policy for Pacific halibut (e.g., Clark and Parma, 1995), but these models did not explicitly consider the effects of wastage and bycatch on optimal harvest rates. Moreover, previous analyses were also limited to the core halibut areas (2B, 2C and 3A). This study attempts to address some of these shortcomings, but is still incomplete.

At this point, this analysis should be considered a work in progress for the sole reason that a key population parameter (i.e., steepness) that defines the underlying stock productivity is not yet available for the new coast-wide assessment. The steepness parameter was arbitrarily set at a value of 0.75 and was chosen because it resulted in estimates of that are similar to those obtained by Clark and Hare (2006). Nevertheless, the relative changes in among regulatory areas based on differences in growth rates would not differ if a reliable estimate of steepness was available. Also critical to optimal harvest rate calculations is the area-based selectivity. At present, the coast-wide assessment model explicitly assumes size-based selectivity for each fishing gear does not vary by regulatory area, yet it is allowed to vary over time due to shifts in the distribution of the stock. In comparison to differences in size-at-age, regulatory area differences in selectivity-at-age relative to maturity-at-age will also have a large impact on estimates of area specific optimal exploitation rates. The previous closed-area assessment models estimated marked differences in selectivity among regulatory Areas 2B and 3A (Clark and Hare, 2006). The transition to a coast-wide model introduced a new assumption that size-based selectivity is the same for all regulatory areas.

One issue, that has not been examined here, and has very important harvest policy implications is the initial recruitment and movement of halibut among regulatory areas. Area-specific optimal harvest rates are sensitive to movement of halibut among regulatory areas. There has been a considerable effort in this regard to understand the movement of halibut (e.g., Loher and Seitz, 2006; Webster, 2009) and what the potential implications are for harvest policy (Valero and Hare, 2009, 2010). In general, areas with a net migration loss are nearly equivalent to having a higher natural mortality rate in a closed area model. The harvest policy implications in such a case would be to harvest at a higher rate, but the total removals would would scale down. The opposite is true for an area that has a net migration increase, harvest at a lower rate, but the scale of the harvest increases due to immigration to the area. If however, the objective is to maximize the yield from all areas combined, then the optimal harvest rate calculations are much more complex involving dispersal kernels for new recruits and age-specific migration transition matrices. Under such circumstances it is not possible to make generalized statements about how optimal harvest rates would change because the answer depends on the relative migration coefficients among the regulatory areas and the initial distribution of new recruits. Valero and Hare (2010) had made progress in this area and their early conclusions suggested that harvest policies to the north of Area 2 would have fairly severe implications for Area 2 itself due to downstream migration of halibut into this area.

It is intuitive to think that imposing a maximum size limit would afford protection to sexually mature fish that grow beyond the size limit and that this would lead to an increase in spawning biomass (or reduce the level of depletion). This does occur, but only if there is a very low discard mortality rate associated with releasing fish. In the case examined here, with 140 cm size limit and fishing at , the spawning biomass in each regulatory area remains nearly the same or declines in comparison to no maximum size limit. The reason for this decline is related to a discard mortality rate of 0.16 per year, the relatively low number of halibut currently growing to this size, and under MSY-based harvest policies, values of would increase in areas where halibut grow to sufficient size and a maximum size limit is used in the harvest policy.

Shifts in the directed commercial selectivity schedule towards smaller halibut pose a conservation concern if the discard mortality rate is greater than 0, even if minimum size limits are in place. If individual IFQ holders are not accountable for their discard mortality of undersized fish, then fishing can continue until their quota is filled with legal-sized halibut. If there is a shift towards catching smaller fish, or the probability of capturing a legal-size fish in a given area is low, then the corresponding increase in discard mortality results in a higher overall total mortality rate that may not be accounted for if the shift in selectivity goes undetected. This is of particular concern in the current assessment of Pacific halibut, where the wastage calculation assumes the commercial fishery selectivity is the same as the top 33% of the setline survey WPUE (Gilroy and Hare, 2009). Moreover, estimated commercial selectivity is based on composition data from port samples, not fish sampled on the boats at sea when the gear is being retrieved. In other words, the wastage calculation in the directed fishery is based on a tenuous assumption about how the commercial gear selects fish less than 81.3 cm.

The harvest policy implications of undetected changes in selectivity and estimates of optimal exploitation rates are somewhat insensitive if the discard mortality rates are low or even negligible. If under-sized fish are handled with extreme care such that survival rates are near 100%, then the previous discussion about uncertainty in commercial selectivity for under-size fish is moot. Moreover, the estimate of wastage would consist only of lost or abandoned gear. However, if the release mortality rates are appreciable, then estimates of optimum harvest rates must also include release mortality associated with size-limits (Goodyear, 1993; Coggins et al., 2007). In general, as the size limit increases the optimum fishing rate that would maximize yield increases exponentially. This relationship is also the same for the fishing mortality rate that would deplete the spawning biomass to some target level. The exponential increase in occurs when individuals have had at least one chance to spawn before they become vulnerable to fishing. Pine et al. (2008) demonstrated that as the release mortality rates increase, the potential of a minimum size limit to hedge against overfishing decreases as the release mortality rates increase.

If the observed changes in size-at-age are a result of cumulative size-selective fishing, then the largest changes in size-at-age would be expected in areas with higher fishing mortality rates. In closed populations, the variance in size-at-age for older fish is expected to decrease with increasing fishing mortality rates. Areas 2B and 2C are thought to have fairly high fishing mortality rates based on the results of the stock assessments and biomass apportionment (Hare, 2012). Based on the size-at-age data from the setline survey, the largest variance in size-at-age is found in Areas 2B and 2C, suggesting that these areas either have a low exploitation rates or are heavily influenced by migration from adjacent areas that have lower exploitation rates.

In the very near future, the Pacific halibut assessment model is likely to evolve to a more implicit spatial representation where estimated selectivities by regulatory area may differ. Given that steepness is unknown, and selectivity likely differs by regulatory area, it is not recommended to change the current harvest policy until, at a minimum, these two issues have been addressed. Preferably, the full suite of biological factors, including dispersal of recruits and migration, and factors that affect selectivity would be included in the harvest policy analysis.

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A Estimation of Growth

A requirement for the yield per recruit analysis is an estimate of the mean size-at-age. A generalized growth model was fit to the length-at-age data obtained from the 2011 setline survey data. The generalized growth model has four unknown parameters:

(14)

where and are the estimated mean lengths of age-2 and age-20 halibut, respectively, ϱ is the growth coefficient, and *b*>0 describes how the growth rate varies with age. Note that the *b*=1 case is equivalent to the von Bertalanffy growth curve (von Bertalanffy, 1938). The parameterization in equation is numerically stable for use in non-linear estimation and the corresponding von Bertalanff growth model,

the parameter transformations are as follows:

(15)

(16)

(17)

(18)

Note that if the parameter *p*=1, the growth model corresponds to the standard von Bertalanffy growth model. If *p*<1, then the growth rates are greatly accelerated at younger ages and vice-versa if *p*>1.

The growth model defined in () was simultaneously fit to length-age data partitioned by sex and regulatory area. Sex-specific growth parameters were assumed independent, and growth parameters for each regulatory area were estimated as a deviate from the coast wide mean growth rate. For example the mean length for age-2 fish is computed as where *h* and *i* indexes sex and regulatory area, respectively, is the estimated coast wide mean length at age-2, and is an estimated deviate from the mean with the additional constraint that . Residual deviations between observed and predicted length-at-age were assumed to be normally distributed and parameter estimation was carried out using a maximum likelihood approach with non-informative priors on all estimated quantities.

Maximum likelihood estimates of growth parameters by sex are listed in Table . Estimates of asymptotic lengths for females ranged from 126.1 cm for Area 2A to 199.5 cm for Area 4C, for males asymptotic lengths ranged from 97.0 cm in are 3B to 126.8 cm in Area 4B. Growth coefficients for females averaged 0.0775 and for males averaged 0.0811. Growth rates in Area 2A are greatly accelerated relative to the standard von Bertalanffy growth curve at younger ages (*p*<1) in Area 2A, whereas growth rates for females are reduced in all other areas (*p*>1). Also note that estimates of the *p* parameter are heavily confounded with estimates of asymptotic length, especially in areas where data from large–older fish are lacking.

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Table 1: Natural mortality rate and size-specific selectivity coefficients (scaled to the maximum estimated coefficient) used in the equilibrium model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  | Sex-specific | |
| Parameter | Symbol | Value | Female | Male |
| Unfished spawning biomass |  | 100 |  |  |
| Steepness | *h* | 0.75 |  |  |
| Natural mortality | *M* |  | 0.15 | 0.1439 |
|  |  |  | 145 | 110 |
|  | *k* |  | 0.10 | 0.12 |
| Age-at-50% maturity |  |  | 10.91 |  |
| Std Age-at-50% maturity |  |  | 1.406 |  |
| Length weight scale | *a* | 6.821e-6 |  |  |
| Length weight power | *b* | 3.24 |  |  |
| Selectivity coefficients | | | Female | Male |
|  |  | 60 | 0.000 | 0.000 |
|  |  | 70 | 0.153 | 0.132 |
|  |  | 80 | 0.310 | 0.243 |
|  |  | 90 | 0.441 | 0.367 |
|  |  | 100 | 0.535 | 0.535 |
|  |  | 110 | 0.610 | 0.694 |
|  |  | 120 | 0.695 | 0.848 |
|  |  | 130 | 0.785 | 1.000 |

Table 2: Parameter settings for alternative model scenarios. See text for description of scenarios; *h* is the steepness of the stock-recruitment relationship, *M* is the natural mortality rate for females, SL corresponds to size limit, DM is discard mortality rate, size shift in selectivity (cm), and other mortality is the range of instantaneous mortality rates from non-directed fisheries.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | *h* | *M* | Min SL | Max SL | DM | Selectivity shift | Other Mortality |
| S1 | 0.75 | 0.15 | 81.3 | ∞ | 0.16 | 0 | 0 |
| S2 | 0.75 | 0.15 | 81.3 | 140 | 0.16 | 0 | 0 |
| S3 | 0.75 | 0.15 | 0 | ∞ | 0.16 | 0 | 0 |
| S4 | 0.75 | 0.15 | 81.3 | ∞ | 0.16 | -10 cm | 0 |
| S5 | 0.75 | 0.15 | 81.3 | ∞ | 0.16 | 0 | 0.02–0.153 |
| S6 | 0.75 | 0.23–0.12 | 81.3 | ∞ | 0.16 | 0 | 0 |
| S7 | 0.75 | 0.12–0.23 | 81.3 | ∞ | 0.16 | 0 | 0 |
| S8 | 0.85 | 0.15 | 81.3 | ∞ | 0.16 | 0 | 0 |
| S9 | 0.65 | 0.15 | 81.3 | ∞ | 0.16 | 0 | 0 |

Table 3: Estimates of optimal exploitation rates for each regulatory area and scenario combination. Scenario descriptions are found on page .

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | 2A | 2B | 2C | 3A | 3B | 4A | 4B | 4C | 4D |
| S1 | 0.248 | 0.197 | 0.180 | 0.297 | 0.318 | 0.260 | 0.180 | 0.176 | 0.300 |
| S2 | 0.248 | 0.221 | 0.221 | 0.300 | 0.321 | 0.271 | 0.225 | 0.237 | 0.304 |
| S3 | 0.221 | 0.180 | 0.163 | 0.256 | 0.275 | 0.229 | 0.168 | 0.163 | 0.260 |
| S4 | 0.201 | 0.163 | 0.151 | 0.229 | 0.245 | 0.209 | 0.155 | 0.151 | 0.233 |
| S5 | 0.168 | 0.137 | 0.133 | 0.172 | 0.185 | 0.168 | 0.137 | 0.133 | 0.176 |
| S6 | 0.180 | 0.133 | 0.120 | 0.193 | 0.205 | 0.163 | 0.124 | 0.111 | 0.193 |
| S7 | 0.213 | 0.176 | 0.168 | 0.252 | 0.275 | 0.233 | 0.172 | 0.172 | 0.256 |
| S8 | 0.260 | 0.209 | 0.197 | 0.289 | 0.311 | 0.264 | 0.197 | 0.189 | 0.293 |
| S9 | 0.155 | 0.129 | 0.120 | 0.180 | 0.193 | 0.163 | 0.124 | 0.120 | 0.180 |

Table 4: Relative change in yield by regulatory area in comparison to S1 (status quo) for each of the alternative scenarios while fishing at rates defined in Table (MSY based fishing mortality).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | 2A | 2B | 2C | 3A | 3B | 4A | 4B | 4C | 4D |
| S1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S2 | 0.00 | -0.17 | -0.27 | -0.01 | 0.00 | -0.04 | -0.33 | -0.41 | -0.01 |
| S3 | 0.65 | 0.30 | 0.11 | 0.85 | 0.78 | 0.28 | -0.01 | 0.04 | 0.45 |
| S4 | -0.04 | -0.03 | -0.02 | -0.14 | -0.15 | -0.09 | -0.04 | -0.04 | -0.14 |
| S5 | -1.41 | -0.84 | -0.69 | -1.41 | -1.44 | -1.12 | -0.71 | -0.61 | -1.47 |
| S6 | -0.72 | -0.83 | -1.00 | -0.86 | -0.89 | -0.98 | -1.00 | -1.00 | -0.91 |
| S7 | 0.32 | 0.38 | 0.48 | 0.24 | 0.24 | 0.40 | 0.45 | 0.44 | 0.26 |
| S8 | 1.10 | 0.72 | 0.66 | 0.57 | 0.55 | 0.63 | 0.69 | 0.49 | 0.60 |
| S9 | -1.13 | -0.76 | -0.69 | -0.87 | -0.88 | -0.82 | -0.78 | -0.60 | -0.92 |

Table 5: Relative spawning biomass while fishing at for each scenario and regulatory area.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | 2A | 2B | 2C | 3A | 3B | 4A | 4B | 4C | 4D |
| S1 | 23.8 | 25.5 | 25.8 | 26.0 | 26.8 | 26.9 | 27.6 | 28.3 | 27.1 |
| S2 | 23.9 | 24.4 | 24.2 | 25.7 | 26.6 | 26.2 | 25.5 | 25.4 | 26.9 |
| S3 | 22.6 | 24.5 | 25.4 | 23.0 | 23.5 | 25.0 | 27.0 | 27.6 | 24.4 |
| S4 | 24.8 | 26.1 | 26.7 | 27.5 | 28.3 | 27.7 | 27.8 | 28.8 | 28.5 |
| S5 | 26.0 | 27.7 | 26.8 | 29.4 | 30.1 | 29.0 | 28.4 | 29.2 | 30.4 |
| S6 | 24.1 | 25.9 | 25.7 | 26.0 | 26.6 | 27.2 | 26.7 | 28.2 | 27.3 |
| S7 | 25.7 | 27.7 | 28.0 | 28.7 | 29.3 | 29.0 | 28.7 | 30.0 | 29.7 |
| S8 | 20.5 | 22.4 | 22.4 | 24.3 | 25.1 | 24.7 | 24.1 | 25.6 | 25.6 |
| S9 | 29.2 | 29.5 | 29.7 | 30.4 | 31.3 | 30.8 | 30.7 | 31.8 | 31.9 |

Table 6: Estimated growth parameters for each regulatory area based on fitting a 4 parameter growth model to the 2011 size-at-age data from the setline survey.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Reg. |  | | *k* | |  | | *p* | |
| Area | Female | Male | Female | Male | Female | Male | Female | Male |
| 2A | 126.1 | 99.3 | 0.105 | 0.095 | −2.30 | −4.53 | 0.983 | 0.818 |
| 2B | 165.3 | 107.6 | 0.076 | 0.069 | −4.62 | −7.45 | 1.499 | 0.986 |
| 2C | 192.2 | 104.3 | 0.063 | 0.110 | −6.08 | −3.65 | 1.736 | 1.296 |
| 3A | 147.6 | 97.8 | 0.057 | 0.073 | −5.81 | −4.25 | 1.167 | 0.733 |
| 3B | 135.6 | 97.0 | 0.073 | 0.083 | −4.33 | −4.90 | 1.252 | 0.995 |
| 4A | 153.6 | 107.0 | 0.073 | 0.086 | −5.16 | −3.94 | 1.601 | 1.202 |
| 4B | 167.3 | 126.8 | 0.109 | 0.080 | −4.75 | −3.60 | 2.830 | 1.203 |
| 4C | 199.5 | 125.7 | 0.079 | 0.068 | −5.86 | −11.21 | 2.717 | 2.185 |
| 4D | 153.4 | 114.6 | 0.064 | 0.065 | −6.23 | −4.61 | 1.530 | 0.953 |