Exploring index-based PSC limits for Pacific halibut

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Executive Summary

In June 2015, the North Pacific Fisheries Management Council (hereafter, NPFMC or Council) reduced the Prohibited Species Catch (hereafter, PSC) limits for Pacific halibut in the BSAI groundfish fisheries from 4,426 mt to 3,515 mt. In addition to this action, the Council also requested a discussion paper exploring ways to index BSAI halibut PSC limits to a metric of halibut abundance. This discussion paper develops two general approaches for moving forward with index-based PSC limits: (1) the Council sets PSC limits independent of the IPHC harvest policies, or (2) both the Council and IPHC coordinate polices for setting annual catch and PSC limits. Both approaches could potentially satisfy management objectives of both agencies. Under option (1), it is unclear which harvesting sector might have priority access to Pacific halibut when setting PSC limits or allowable catch in the directed fishery. Option (2) would require a high-level discussion where a relative harvest intensity would be assigned to a particular sector (i.e., an allocation or catch sharing plan). It also requires a more flexible and responsive regulatory environment than currently exists.

We also introduce a new concept, termed *Fishery Footprint*, as a measure of the fisheries demand on the resource, or the amount of spawning capital used. This is analogous to the Ecological footprint; a measure of human demand on the natural capital used each year. A common type of ecological footprint is the amount of land and sea area needed to supply the resources consumed. A fishery footprint is defined as the amount of spawning capital required to replace the mortality associated with that fishery. We use the Spawning Potential Ratio (SPR) and relative Mortality Per Recruit (hereafter, MPR) from each fishery to quantify the footprint of each fishery. This concept is essential for the purposes of quantifying the relative impacts of each fishery on the future productivity of Pacific halibut and for setting sector specific harvest rates.

The overarching theme for this discussion paper is to consider how alternative options for setting PSC limits would jointly affect the long-term yield and the catch rates of Pacific halibut in the directed and non-directed halibut fisheries. For the purposes of discussion we use an example set of alternative management procedures for Pacific halibut to shed light on how the incentive

landscape in each sector is affected by changes in harvest policy. To do so, we use an age- sex-structured coastwide model that jointly considers all sources of mortality on Pacific halibut. This model is then used to determine fishing mortality rates for each sector that would jointly satisfy conservation and allocation constraints. Finally, we examine the incentive landscape under each of these options and discuss the pros and cons of allocations based on yield versus spawning capital.

Options for setting Pacific halibut PSC limits:

We discuss five alternative options for setting annual PSC limits, and much of the discussion focuses on the BSAI region. We also note that all non-catch sharing plan removals have the same general effect for all IPHC regulatory areas. They include bycatch in Area 2B, 2C, and 3A unguided sports fisheries, and PSC limits in the GOA region. The five alternative options are:

1. Status Quo. Continue using the adopted fixed PSC limits.
2. Maintain fixed PSC limits and periodically update these limits in response to changes in fishing technology and the status of the halibut resource.
3. Use empirical estimates of abundance based on fisheries independent surveys and a harvest control rule for setting BSAI PSC limits.
4. Used model-based estimates of biomass and apportionment along with a harvest control rule for setting PSC limits in each of the IPHC Regulatory Areas.
5. Integrate bycatch encounter catch rate data from commercial fisheries in the BSAI and GOA regions into the model based estimates in option 4.

Option 1 is the status quo situation where PSC limits in the BSAI remain fixed. Option 2 would maintain an annual fixed PSC limit, but periodically this limit would be updated to reflect changes in the composition of the bycatch and changes in the status of the halibut resource. Options 3-5 require a harvest rate and a biomass estimate of halibut in the 4CDE region, where the annual PSC limit = harvest rate * biomass. Option 3 discusses the potential use of empirical observations (i.e., the NMFS-EBS bottom trawl survey) as an index of abundance and its limitations. Option 4 is based on model-based estimates of apportioned vulnerable biomass, where the stock assessment model and the IPHC survey apportionment are used to determine vulnerable halibut abundance in each regulatory area. The fifth option is based on the same principle as option 4, but addition information on the bycatch encounter rates from commercial fisheries in the BSAI and GOA regions are integrated to better inform the model about the abundance of sublegal halibut that are not vulnerable to the setline survey gear used by the IPHC. These industry data would require extensive standardization to avoid mis-interpretation of industry responses to management actions and avoidance effects.

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Introduction

In January 2015, the IPHC set a catch limit for Pacific halibut of 583 mt (1,285,000 pounds) in Regulatory Area 4CDE for the directed fishery. In order to be commensurate with the IPHCs' harvest policy in this Regulatory Area, this catch limit was based on the assumption that actual bycatch in that area would be reduced by 42% from the existing 2014 PSC limits, or a 25% reduction from the measured 2014 bycatch. In June 2015, the Council reduced halibut PSC limits from 4,426 mt to 3,315 mt (a 21% reduction) for the 2016 BSAI groundfish fisheries. PSC limits for Pacific halibut in the BSAI groundfish fisheries are fixed in regulation and can only be alter Council action.

Catch limits for the directed halibut fishery in all IPHC Regulatory Areas are set on an annual basis by the Commission. The current process for setting catch limits in the directed fishery is guided by a harvest policy and a risk-based decision table that is based on the objective of keeping the Pacific halibut stock above 30% of its unfished level 80% of the time. This harvest policy was developed in 2006 (Clark and Hare, 2006). The process of setting area-specific catch limits for the directed fishery first involves determining the target catch distribution among Regulatory Areas based on apportioned biomass and the area specific target harvest rates. The total allowable catch (or TCEY in IPHC terms) for any given area includes all sources of O26 (halibut greater than 26" in length) mortality including bycatch and discard mortality in the directed fishery (also known as wastage). The next step in setting the catch limit for the directed fishery is to subtract all anticipated removals not included in CSPs from the TCEY, and the remainder (if > 0) is the directed fishery catch limit (including all CSP removals). This process of setting the annual catch limits implies priority is given to non-directed, and non-CSP halibut fisheries (e.g., unguided sport takes precedence over guided sport, bycatch takes precedence over directed fisheries).

Both the IPHC and the NPFMC use a sloping harvest control rule for setting annual catch limits (ACLs) for target fisheries (Fig. 1). If the stock status[1] falls below a threshold limit reference point, then the harvest rates are adjusted downwards to allow the stock to rebuild above the threshold limit reference point. If the stock status falls below the limit reference point, then the fishery is closed and remains closed until the stock rebuilds to the limit reference point. In contrast, the current NPFMC PSC limits for Pacific halibut are fixed and are independent of stock status. Using a fixed PSC limit and assuming the PSC limits are fully subscribed each year, the implied harvest rate associated with bycatch fisheries increases with decreasing halibut abundance. This implied harvest rate is in complete contradiction with the default harvest control rules used to set annual catch limits for directed fisheries (Fig. 1).

[1] The currency in which stock status is determined is based on the spawning stock biomass relative to the unfished level.

Developing an abundance based PSC limit would require that the PSC limits vary with halibut abundance, and, for the purposes of this discussion paper, I implicitly assume that PSC limits would decrease when estimates of stock-status decline. There are an infinite number of ways in which to create such a rule, but the simplest would be to use a fixed harvest rate to set the annual PSC limit (e.g., PSC limit = [fixed harvest rate] * [halibut abundance]). In developing such a rule for setting annual PSC limits, the obvious questions are: (1) what should the harvest rate be?, and (2) where does the estimate of halibut abundance come from? More complicated harvest control rules for setting annual PSC limits could also include caps at a given halibut abundance threshold, where the PSC limit is proportional halibut abundance below the threshold and then held constant if the status of halibut is above some threshold. Or specific harvest rates at different abundance thresholds. Note that these scenarios imply a much more flexible and responsive regulatory environment than currently exists.

A key element in the catch accounting system for PSC limits is the estimation of bycatch mortality. Estimation of total discards and bycatch mortality is based on sampling theory, or assumptions, and is not based on a 100% census: coverage rates in GOA trawl fisheries is particularly low (<30%). In the directed halibut fisheries, up until 2013, there were no observer data from which to base estimates of wastage in the directed halibut fishery. To date, estimates of wastage in each Regulatory Area are based on an assumption that the ratio of under-32 inch to over-32 inch (hereafter, U32:O32) in setline survey and an assumed average discard mortality rate of 16%[2]. Estimates of halibut bycatch mortality are based on a weighted average of the composition of the condition factors, or injury codes and condition-specific discard mortality rates developed for trawl gears and hook-and-line gears, based on observer samples. These samples are expanded up from the haul level to the entire fleet based on the percent observer coverage in a given fleet.

The use of PSC limits creates very strong incentives in the non-directed halibut fisheries to avoid catching Pacific halibut. The formation of fishery cooperatives, incentive plan agreements, sharing information on bycatch rates, and efforts to reduce discard mortality rates are just a few of the available tools industry has adopted to minimize halibut bycatch. PSC limits for Pacific halibut are based on weight. There are a number of different methods for reducing bycatch mortality which results in changing the composition of the bycatch where, for example, a 1000 pound PSC limit on average consists of 100 halibut compared to the same 1000 pound limit utilizing 200 halibut (i.e., reducing the average size from 10 lb. to 5 lb.). The net effect is an increased mortality on the number of individual fish.

[2] We do not believe that the current observer programs can accurately estimate wastage in the commercial halibut fishery. Specifically the coverage rate for vessels less than 40 feet is 0%. In 2013, roughly 50% of the vessels operating in Alaska halibut fisheries are less than 40 feet (although they harvest about 20% of the catch).

A harvest policy for a particular fishery managed under MSY-based reference points, or the proxy SPR-based reference points, is highly sensitive to the age/size at which halibut recruit to the fishery. The abundance metric in which these harvest policies are developed around is the spawning stock biomass, and in sex-structured models it is often the female spawning biomass. The spawning biomass depletion level associated with MSY (or target spawning biomass) depends on the ratio of age-at-entry to the fishery relative to the age-at-maturity. If halibut recruit to the fishing gear prior to becoming sexually mature, then the target spawning biomass associated with MSY will be larger in comparison to a gear that harvests halibut closer to the age-at-maturity. Moreover, the target harvest rate must also be reduced to ensure that the cumulative removals of sexually immature fish allow for sufficient spawning biomass to accrue to achieve the desired target spawning biomass reference points. When the age/size at entry to the fishery changes due to changes in regulations (i.e., changes in minimum size limits), or due to changes in availability (i.e., spatial redistribution of the stock), or due to gear changes that change the overall selectivity of the fishing gear (i.e., use of smaller hooks, or excluders in trawl gears), then it is essential that reference points be updated, and the associated target fishing mortality rates also be updated to ensure the harvest policy is consistent with the spawning biomass reference points. The same argument is also true when considering dynamic changes in biological parameters (e.g., changes in growth rates, alternative recruitment regimes, time-trends in natural mortality).

The choice of using MSY or an SPR proxy for setting spawning biomass reference points is largely dependent on the ability to estimate the parameters of the stock-recruitment relationship (SRR), or steepness. Specifically, the slope at the origin of the SRR is key for determining the optimum fishing mortality rate that will maximize the long-term sustainable yield. In order to reliably estimate this parameter, there is a need to obtain data during periods of low-spawning stock biomass. Management agencies tend to want to avoid driving the stock to such low abundance. An alternative is to use reference points based on the Spawning Potential Ratio (SPR) as a proxy for MSY-based reference points. Clark (1991) was the first to note that over a wide-range of life-history types and wide range of SRR, about 75% of the maximum sustainable yield is achieved if the spawning biomass is maintained in the range of about 20–60% of the unfished level. Analysis of the SRR for Pacific halibut suggests recruitment variability and trends in growth maybe just as important as the SRR. For this reason, the current harvest policy is based on a simulation study (Clark & Hare 2006) that includes both recruitment and growth variability, rather than just a simple stock recruitment relationship. The IPHC does not have a specified SPR-target reference point, but the harvest control rule does have threshold and limit reference points defined at 30% and 20% of the unfished level, respectively.

This discussion paper is organized into six sections. The first section discusses the tradeoffs between conservation objectives and long-term sustainable yields (or encounter rates) for directed and non-directed fisheries. Second, we discuss how harvest control rules are used in setting annual catch limits, and how these rules could be modified to include abundance-based PSC limits. Next we discuss the options for developing the appropriate abundance index on which to base PSC limits. Fourth, we discuss the incentive landscape under the status quo, and how to incentivize maximizing yield per recruit and minimizing mortality per recruit by basing allocative discussions on spawning capital as the currency for negotiation. Fifth, is the yield equivalence, specifically how each fishing sector (commercial, bycatch, sport, etc.) impacts the sustainable yield for other sectors, and how the important policy variables (e.g., selectivity and allocation) affect over all yield and efficiency. Finally we point out a number of critical assumptions that are necessary in quantifying bycatch impacts on the Pacific halibut stock, and list a number of research recommendations for moving forward with developing abundance-based PSC limits.

There are a number of occasions in this text in which the terms allocation, catch sharing plan, agreements, etc. are used, somewhat interchangeably. We recognize that these terms can have political connotations, and the authors (especially Martell) are in no way trying to aggravate an already politically sensitive situation. Simply put, in this document allocation is meant to imply the action or process of distribution something (catch or spawning capital) among user groups. Cooperative management is meant to imply the mutual interest between the NPFMC and the IPHC and working towards a common goal.

Tradeoffs

Current IPHC harvest policy

The IPHC harvest policy is based on a sloping harvest control rule, designed to maintain a constant harvest rate when the stock is above the threshold reference point of 30% of unfished biomass. If the stock falls below the threshold, the harvest rate is ramped down to a rate of 0 as the stock approaches the limit reference point of 20% of the unfished biomass. Using the current IPHC harvest policy, the TCEY (at the Blue Line) for Pacific halibut in each of the regulatory areas is determined by apportioning estimated coastwide biomass into each Area then multiplying that biomass by area specific harvest rates. The harvest control rule (Fig. 1) is used to determine which harvest rates to apply based on the estimated stock status (depletion of female spawning stock biomass relative to unfished). Next the harvest rate is multiplied by the biomass which results in an area specific TCEY:

TCEY = Harvest Rate * Biomass

The TCEY includes all O26 sources of mortality, including bycatch and wastage in the directed fishery, as well as, removals from recreational, charter, tribal, and Community Development Quota

(CDQ) fisheries. The next step in the process is to determine the available yield for the directed fishery (FCEY), which is given by:

FCEY = TCEY - (O26 bycatch + non-CSP removals)

Note that this current policy[3] requires the IPHC to account for other sources of removals not under its control in order to achieve its conservation mandate; what is leftover is allocated to the directed fishery.

Under a fixed PSC limit, the fraction of all halibut killed by PSC increases with decreasing halibut abundance (see PSC harvest rate in Fig 1.). In order to be consistent with the harvest policy and accommodate a constant PSC limit, the harvest rate in the directed fishery must decrease with decreasing female spawning biomass. In effect, the harvest rate for a fixed PSC limit is abundance based where the harvest rate *increases* with decreasing halibut abundance. This is qualitatively different than the harvest control rules that are used to set annual fishing rates (i.e., F_{OFL}) and Acceptable Biological Catch (ABC) in target fisheries managed under Tiers 1-3 by the Council. Thus, under fixed PSC limits for bycatch, all of the conservation burden is borne by the directed fisheries; to share in the conservation burden PSC limits would have to decrease.

Current trends in fishing intensity

The current status of the coastwide spawning stock biomass at the end of 2014 is approximately 40% of the estimated unfished biomass based on the ensemble of assessment models that were assembled in the 2015 stock assessment model (Fig. 2, taken from Stewart and Martell, 2014). Trends in the relative coastwide exploitation rates (as measured by trends in catch:setline survey WPUE) in the directed halibut fisheries increased from 1997 and peaked in 2010 (Fig. 2). In 2011, the commercial landings decreased from 49.8 Mlb to 39.6 Mlb, and this decrease was sufficient enough to reverse trends in the relative exploitation rates. Since 2010, commercial landings have decreased by over 50% to 23.7 Mlb and coastwide exploitation rates in the directed halibut fishery continue to decline. Over this same 2010-2014 window, estimates of bycatch and removals associated with sports fishing have remained relatively the same (2010: 10.3 Mlb bycatch, 7.8 Mlb sport, and in 2014: 9.3 Mlb bycatch and 7.1 Mlb sport). Trends in the relative exploitation rates for these two sectors have remained relatively constant. This gives the appearance that in recent years (since 2011) the directed halibut fishery has borne the entire conservation burden. Moreover, the

[3] Each IPHC Regulatory area has its own unique set of rules for catch allocation. For example wastage is included in the FCEY for area 2C and 3A; personal use is included in the FCEY for area 2A, etc.

IPHC does not have authority to change bycatch limits, or recreational catch limits on an area-by-area basis, they only have the authority to change annual catch limits in the directed halibut fishery.

The proportions of the total mortality accounted for by directed and non-directed fisheries has changes substantially over time (Fig. 3) but the most important component of these changes is the resulting proportional mortality rates on the stock that result. Specifically, how the trends in exploitation rates for each sector vary with trends in abundance (Fig. 2).

Catch composition

Another tradeoff that needs to be taken into consideration when developing a long-term sustainable harvest policy for halibut is the composition of the catch. The age-at-entry to a fishery relative to the age-at-maturity is a critical ratio in determining sustainable harvest rates. This is true for both MSY-based and SPR-based reference point calculations. If halibut are captured before they become sexually mature then the harvest rate for that fishery must be lower relative to a fishery that captures halibut after they become sexually mature. Recall that the female spawning biomass is used as a measure of stock status (i.e., used to determine if the stock is overfished). If two or more fisheries are impacting a different demographic, then the fishery that has a lower average age/size in the catch will affect all other fisheries and will have the most significant impact on the Spawning Potential Ratio (SPR) per unit of mortality. A simple metric for understanding the importance of catch composition is the number of halibut required to make up a metric ton.

Key to developing a harvest policy for Pacific halibut that tries to jointly addresses the objectives of all sectors is understanding that the fishing mortality imposed by each participant affects all other participants. A model for evaluating alternative bycatch policies, alternative size-limits, and all other management-related variables must jointly assess all sources of mortality and future impacts on the spawning stock biomass. The age- and sex-structured model detailed in Appendix A is based on a set of simultaneous equations that can be used for developing harvest policies for Pacific halibut, and can account for fisheries interactions.

Harvest Control Rules

Sloping harvest control rules

Both the IPHC and the NPFMC use a “sloping harvest control rule” (HCR, see Fig. 1) for setting annual catch limits for the directed halibut fishery and other target fisheries managed under the Council. There is no formal harvest control rule specified for setting annual PSC limits. The PSC limits for Pacific halibut are set by the Council and are static (i.e., is not based on the current abundance of Pacific halibut). The implied harvest rate associated with fixed PSC limits, if the PSC limits are fully subscribed, increases with decreasing halibut abundance. Qualitatively, this implied policy is exactly opposite of the sloping HCR used to set annual catch limits for directed fisheries, and leaves the impression that bycatch fisheries are given priority access over directed fisheries. As shown in Figure 1, a fixed PSC limit implies an inverse abundance-based harvest rate, where the harvest rate increases as the Pacific halibut stock decreases. Such a policy would likely delay re-building the halibut stock, should it fall to low levels, and also severely restrict opportunities for a directed fishery.

Adopting an abundance-based PSC limit could potentially resolve the problem of increasing bycatch mortality rates during periods of low halibut abundance. However, the shape of the harvest control rule must contain a fixed harvest rate during periods of low abundance to be consistent with the implied benefits of a sloping harvest control rule. There are an infinite number of possibilities for specifying a harvest control rule for setting PSC limits and here we discuss three general rules: (1) the status quo policy of a fixed PSC-limit, (2) a policy based on a fixed harvest rate for setting annual PSC limits, and (3) a policy based on a fixed harvest rate with a PSC cap, where the PSC limit would be fixed if halibut abundance is above some pre-determined threshold (Figure 4). These harvest control rules are examples of the status quo, and two alternative rules that could be used for setting abundance-based PSC limits.

The implied harvest and PSC limits based on the harvest control rules specified in Figure 4 are shown in Figure 5. In the case of the directed halibut fishery, the fishery would be closed when the spawning stock biomass is less than 20% of its unfished state, between 20%-30% catches increase linearly, and if the stock status is greater than 30%, the catch limit is proportional to the projected vulnerable biomass (Fig. 5). Under the stats quo scenario, PSC limits are fixed and are independent of the stock status. Using a fixed harvest rate for setting annual PSC limits results in limits that are directly proportional the stock status. Lastly, the third harvest control rule is a hybrid of the status quo and a fixed harvest rate, where annual PSC limits are fixed when the stock is at or above a 40% stock status threshold, and is proportional to abundance using a fixed harvest rate when the stock is less than 40% of its unfished state.

Developing a harvest control rule for setting annual PSC limits

Key features that would need to be specified in developing a harvest control rule for setting annual PSC limits are: (1) the maximum harvest rate, (2) the stock-status limits and thresholds that specifies transitions in the harvest rates, (3) the stock-status limit where the bycatch fishery would be severely restricted, or even closed. Note that none of the rules shown in Figure 4 specify a limit-reference point for setting PSC limits, and in these cases it is assumed that non-directed fisheries would continue to operate in the absence of a directed halibut fishery. Based on the current HCR used by the IPHC, catch limits in the directed halibut fishery would be set to 0 if the stock status falls below 20% of its estimated unfished state.

The implied allocation of the Pacific halibut resource to the directed fisheries and bycatch fisheries is not static under any of the harvest control rules shown in Figure 4. Under a fixed PSC limit (status quo) and using the 30:20 harvest control rule for setting the total mortality, the proportion of the total halibut mortality (in pounds) increases in the bycatch fisheries as halibut abundance decreases (Fig. 6, left panel). If the halibut stock falls below the threshold reference point, then the harvest rate in the directed fishery declines sharply and the proportion of halibut mortality quickly shifts solely to bycatch fisheries.

Under a fixed harvest rate policy for setting PSC limits, the proportion of mortality (in pounds) in directed and bycatch fisheries remains constant as long as the halibut stock remains above the threshold limit reference point (Fig. 6, middle panel). If the stock is below the threshold then the implied allocation shifts towards the bycatch fisheries. Adding a cap for the PSC-limit when the stock status us greater than the target (arbitrarily assumed to be 40% of unfished biomass in Fig. 4) places an upper bound on the PSC-limits and the implied allocation decreases in the bycatch fishery during periods of high halibut abundance (Fig. 6, right panel).

Figures 5 and 6 examine the relative impacts on the annual catch limits in directed and bycatch fisheries over the entire range of stock status. They do not characterize the fishery impacts on the halibut stock, specifically the impacts on stock productivity as measured by the Spawning Potential Ratio (SPR). To characterize the impacts on SPR, the composition (age or size) of the catch needs to be taken into consideration.

Tradeoffs in the Spawning Potential Ratio

The Spawning Potential Ratio (SPR) is a unique metric in that it integrates all sources of fishing related mortality into a single metric and has been widely adopted throughout the United States since the mid 1990s as the basis for fisheries reference points (Goodyear, 1993; Mace and Sissenwine, 1993). The definition of SPR is: the average fecundity of a recruit over its lifetime when the stock is fished divided by the average fecundity of a recruit over its lifetime when the stock is subject only to natural mortality (i.e., unfished). Key to understanding this definition is the phrase “recruit over its lifetime”. The average fecundity over the lifetime of a recruit depends on: (1) how long the average recruit lives, and (2) the relative differences in fecundity between ages. Note that SPR is a ratio, and therefore the absolute units of fecundity (e.g., eggs per gram of mature female biomass) cancel out, but the relative differences in fecundity between age-classes are important. In the case of Pacific halibut, the IPHC assumes that fecundity is proportional to sexually mature female biomass. For the unfished case, the average fecundity per recruit is a function of the natural mortality rate and the mature weight-at-age of female halibut. The SPR is based on the relative differences in survivorship between fished and unfished populations, as fecundity-at-age (f_a) is assumed to be the same in both fished and unfished conditions:

$$SPR = \frac{\phi_e}{\phi_E}$$

where

$$\phi_e = \sum_{a=1}^{A} \hat{\iota}_a f_a \qquad (1)$$

$$\phi_E = \sum_{a=1}^{A} \iota_a f_a$$

In Eq. (1) the survivorship to age a (ι_a) for unfished conditions is based on the estimate of age-specific natural mortality for Pacific halibut, and for fished conditions is based on age-specific estimates of total mortality (natural mortality plus the additional age-specific fishing mortality rates summed across all fisheries). A more detailed explanation of survivorship is provided in Appendix A. The salient point is that the composition of the catch can have profound effects on the estimates of SPR and the derived SPR-based reference points used in the harvest control rule.

To illustrate this point consider the following simple example. Consider two fisheries (A and B) each harvesting 1000t of halibut. In fishery A, half the catch (by weight) consists of sexually mature fish, and in fishery B 95% of the catch consists of sexually mature fish. Which fishery, A or B, has a larger impact on the SPR? Based on how the question is posed, some might argue that fishery B has a larger impact because the vast majority of the fish caught are sexually mature. But recall that SPR is based on the life-time reproductive output; therefore, fishery A has a larger impact on the SPR because half of the biomass has been removed prior to becoming sexually mature and this results in a smaller numerator in the SPR calculation (Eq. 1). Moreover, although both fishery A and B each remove 1000t of halibut from the population, fishery A would remove a larger number of individuals (because 1/2 the catch is not sexually mature) relative to fishery B. Therefore, fewer individuals would survive to maturity and grow to larger sizes.

SPR-based reference points are commonly used in developing harvest control rules because they require less information than MSY-based reference points. The use of MSY-based reference points in lieu of SPR-based reference points is applicable; however, reliable estimates of the stock recruitment relationship are required to derive robust MSY-based reference points. If any given fishery in a complex decides to alter the composition of their catch, then the SPR-based reference point calculations need to be updated to reflect the changes in survivorship-at-age. The same is true for MSY-based reference points. For example, if the composition of the catch shifts towards smaller fish (i.e., reducing the minimum size limit for Pacific halibut) then the fishing mortality rate that would maintain the same target SPR would have to decrease to accommodate the increase in mortality rates on sexually immature fish.

Abundance Index for Area 4CDE

In setting annual abundance-based PSC limits, the harvest rates for each sector would be determined by the aforementioned harvest control rule, but the first question is what should be used as the index of abundance for setting annual PSC limits? Second question, what harvest rate should be used to calculate the PSC limit once the abundance index has been established? The Bering Sea shelf covers the vast majority of IPHC Area 4CDE. There is an annual trawl survey that is conducted each year and is used to provide, *inter-alia*, an area-swept estimate of halibut abundance. The IPHC also conducts annual fisheries independent surveys in the BSAI region, but the survey is limited to the slope region > 75 fm in Regulatory Areas 4A and 4D. In 2006 and 2015, survey calibration experiments with the NOAA trawl survey were conducted by the IPHC to make better use of the NMFS trawl survey data for estimating annual halibut abundance in area 4CDE. Norton Sound surveys are also used (Webster and Stewart, 2015).

For the NPFMC, the question of what abundance index to use for setting annual catch limits in non-halibut directed fisheries depends on the Tier determination for the stock. For Tier 3 stocks or higher, the harvest rate used in calculating the Over Fishing Limits (OFL) and Acceptable Biological Catch (ABC) is based on the status of the spawning stock biomass. This harvest rate is then multiplied by the projected vulnerable biomass which is a function of the estimated fisheries selectivity. The IPHC uses a similar approach for calculating the “Blue Line” catch limit recommendations, but also develops a more detailed risk-based decision table to provide advice for setting annual catch limits. Due to large uncertainty in estimates of partially recruited cohorts, there is increasing uncertainty that the annual catch limit will actually achieve the intended harvest rate objective as catches are projected beyond cohorts already observed. This is exactly the same problem with setting annual PSC limits for Pacific halibut in BSAI as there are few fisheries-independent data and large uncertainty associated with the abundance of halibut size-classes encountered by the groundfish trawl fishery.

We discuss three potential avenues to pursue in developing an abundance index for the BSAI region: (1) use the EBS trawl survey data as the index, (2) use model-based estimates that integrate both the IPHC setline survey data and the EBS trawl survey data, and (3) same as option 2, but also integrate fishery-dependent information. The pros and cons of each of these approaches will be discussed further.

NMFS-EBS bottom trawl survey

The NMFS-EBS trawl survey has been conducted annually since 1979 and is an important source of abundance information for groundfish stocks in the Bering Sea. The survey is conducted on a 20 NM grid and covers a large portion of the Bering Sea shelf that is not surveyed by the IPHC annual set line survey. Area-swept estimates of halibut biomass from the EBS trawl survey between 1982 and 2015 have increased over this time period (Fig. 7); whereas, trends in estimates of female halibut spawning stock biomass have been decreasing since the late 1990s.

The IPHC setline survey does not extend into the EBS shelf region, and therefore, the NMFS-EBS trawl survey is the only source of fisheries-independent information on abundance. It would be useful if this index could provide information on future recruitment to the coastwide Pacific halibut stock. Unfortunately, there is no lag relationship between the trends in Pacific halibut numbers and the estimates of age-0 recruits. In fact the relationship is negative (correlation lag 0-4 years: -0.426 -0.365 -0.318 -0.209 -0.133), suggesting that in years with above average cohort strength in Pacific halibut, the abundance index in the NMFS-EBS trawl survey would decrease in the subsequent years when this year class recruits to the trawl survey gear. If the EBS trawl survey index was used for setting a proportional abundance-based PSC limits, then the concern would be that in years with a low EBS-trawl survey abundance, the PSC limits might be overly restrictive from the perspective of the coastwide halibut stock, and vice versa. Further research is warranted on investigating the relationship between the NMFS-EBS trawl survey abundance and coastwide recruitment of Pacific halibut.

Model based estimates

The second option is to use a model-based estimate of biomass as the source of abundance information for setting annual PSC limits. In this case, estimates of vulnerable biomass (i.e., the sum of products of numbers-, weight-, and selectivity-at-age) would be based on the stock assessment model used to estimate halibut abundance. There are two issues with this approach: (1) lags associated with estimating the relative cohort strengths prior to recruiting to the setline survey gear, and (2) how to apportion biomass in each of the regulatory areas.

Estimating the relative abundance of a specific brood year, or cohort, depends on having reliable age-composition information from all sectors to determine the age-at-entry to the fishery, or sector-specific selectivity. Pacific halibut recruit to the setline survey gear relatively late (6-8 years at 50% selectivity) in comparison to the trawl gear (2-4 years at 50% selectivity). This difference between selectivities creates a lag in which, for example, the true impact of the bycatch fishery wont be known for a number of years after the fishery occurred. The larger the difference in age-at-entry between the two gear types, the longer the lag period. This issue is not unique to setting PSC limits, this same lag exists in setting annual catch limits for directed fisheries, as it often takes a number of years before the estimates of relative cohort strength stabilize. A potential solution for the lag in information is to adopt a harvest control rule that would buffer for the effects of lags (e.g., sloping harvest control rules and the analogous buffers used by the Council do this).

Biomass apportionment for Pacific halibut is based on the relative abundance (WPUE) in the IPHCs' annual setline survey, and this apportionment is based on distribution of legal sized halibut, termed O32 (Webster and Stewart, 2015). In the BSAI region, much of the bycatch is of sublegal sizes and the setline survey is not a reliable index for halibut less than 26-inches due to the selectivity of the long-line gear. At present the IPHC deducts the total O26 bycatch from the TCEY, which is based on the apportioned O32 biomass. An additional assumption is that U26 fish will redistribute and be observed again before harvest. In short, the IPHCs' harvest policy is not affected by the amount of U26 bycatch; one reason why the IPHC is transitioning to an SPR-based mortality index.

If the process for setting annual catch limits in a given regulatory area, or region, is to use a harvest rate and estimate of vulnerable biomass, then the estimate of vulnerable biomass would be based on the selectivity curve for that particular fishing sector, or particular regulatory area. The process used by the IPHC for setting area-based annual catch limits first apportions the survey biomass into each regulatory area, these proportions are then multiplied by the area-specific target harvest rates, which results in a distribution of Total Constant Exploitation Yield (TCEY, Table 1). This TCEY distribution is then multiplied by the coastwide TCEY which results the total catch for each Regulatory Area. A similar process could be used for apportioning the biomass pool that is vulnerable to the bycatch fisheries.

An example of applying this apportionment procedure is shown in Figure 9, where the apportioned vulnerable biomass implied by the assumed selectivity curves for the coastwide commercial and bycatch fleets (taken from the IPHCs' stock assessment model for Pacific halibut). The selectivity curve for the bycatch fishery is assumed to be the same for both sexes; whereas, the selectivity curve for males in the commercial fishery is modeled as an offset to the female selectivity curve and males are never more than 40% selected at any age. Moreover, these selectivity curves represent the coastwide average selectivity by fleet and sex, and do not necessarily reflect what the true selectivity curve is in a specific Regulatory Area. Another way to think of this is that the bycatch series in Figure 9 represents the biomass of all halibut ages-3 and older, and the Commercial series represented ages 10 and older. The salient point is that halibut recruit to the bycatch fleet at least 7-10 years prior to recruiting to the commercial fishery; therefore, the vulnerable biomass available to bycatch fisheries is substantially larger than what is available in the directed commercial fisheries with a 32-inch minimum size limit.

There are a number of issues, however, in adopting this approach for setting annual PSC limits: (1) the setline survey does not index halibut less than 26-inches very well, (2) the apportioned biomass is in part based on the assumption of average recruitment for age-classes that are not fully recruited to the setline survey, (3) the lags associated with the previous assumption are affected by the intended target harvest rate for the bycatch fisheries, and (4) the selectivity assumed for any given area is actually a weighted average of all the bycatch fleets (trawl, hook & line, and pot gear) and the proportions differ by Regulatory Area. The following paragraphs discuss in more detail issues (2)-(4).

Recall that the setline survey is used to apportion the biomass in each of the regulatory areas based on the target TCEY distribution (i.e., Table 1). The WPUE series in each of the regulatory areas is the best available index of abundance for fish greater than 26-inches; therefore, the TCEY distribution is really looking at the distribution of near-legal sized halibut, and is not providing any information about the distribution of age-3 to age-7 halibut. If the coastwide TCEY consists of biomass that is vulnerable to bycatch and is multiplied by a TCEY distribution that is based on setline survey, then a large fraction of that vulnerable biomass (i.e., the differences between the commercial and bycatch biomass in Fig. 9) is based on estimates of long-term average recruitment. In other words, there are no fisheries-independent data to inform the relative abundance of cohorts that have not recruited to the setline survey but are vulnerable to bycatch. It will take a number of years before the relative abundance of recruited cohorts that are vulnerable to bycatch are reliably estimated by the IPHC setline survey.

The aforementioned lag in indexing the relative abundance of each cohort through the setline survey is less important if the target bycatch harvest rate is low in comparison to a high target harvest rate for bycatch fisheries. This is akin to the status quo situation in which the fixed PSC limit is less of a concern during periods of high halibut abundance in comparison to periods of low halibut abundance. The conservation concern is that if the PSC limits are based on average recruitment, and it takes 10 years to determine the strength of the cohort, then during periods of below average recruitment the harvest rates associated with bycatch will be higher than intended. The counter concern is that if there is an above average recruitment event, then the PSC limits will be set too low, and the non-retention fisheries will be highly constrained due to high encounter rates with an above average recruitment event.

The biomass apportionment example in Figure 9 assumes that all bycatch fisheries in all regulatory areas have the same age-specific selectivity coefficients. This assumption is fine in the coastwide assessment model as all of the data are catch weighted by area. However, this assumption is not appropriate for developing abundance-based PSC limits. In this case, it would be better to use a fleets as areas model to bring more spatial resolution to the area-specific differences in selectivity relative to the coastwide stock. The IPHC has already adopted this approach for its ensemble of assessment models, but there is still more work to be done. Moreover, the NPFMC actually allocates the 3,515 mt PSC limit to four different sectors (Amendment 80 cooperatives, 1,745 mt;

BSAI trawl limited access, 745 mt; longline fisheries, 740 mt; and CDQ fisheries, 315 mt), and each of these sectors has different selectivities. In practice, it would be appropriate to separate the bycatch fleet into groups that have, or are assumed to have, similar selectivities and develop harvest control rules for setting PSC limits on a sector-by-sector basis in each of the IPHC Regulatory Areas.

Integrating industry and observer data

There is a large potential source of information on the relative abundance of sub-legal cohorts that could be obtained through additional examination of data collected by industry and observer programs. The primary concern with these data is they are not obtained from a systematic or stratified random sampling procedure. The addition of these data as a source of abundance information is likely to introduce bias due to non-random sampling. However, the composition information collected from observer sampling would be informative about trends in selectivity and provide information about the relative strength of cohorts by tracking modes, if they exists, over time. This effort would require extensive data standardization to avoid mis-interpretation of management and avoidance effects.

The scale at which fisheries-dependent data should be included should not be limited to just the BSAI region. Pacific halibut disperse over a very large area, in relatively short periods of time early in life, and then probably undergo seasonal spawning migrations and continued diffusion after they become sexually mature around age-11. Composition data from bycatch fisheries should be analyzed from both the BSAI and GOA regions, as both of these areas combined are probably more informative about total coastwide recruitment, than just the composition information from the BSAI region alone, due to the movement of halibut in and out of various Regulatory Areas in Alaska.

Incentive Landscape

Are current policies for PSC incentivizing growth overfishing?

The very idea of a placing catch limits on certain non-target species in any fishery creates the incentive to avoid and or reduce discard mortality, but only if these limits actually constrain the fishery from harvesting its entire quota each year. PSC limits for Pacific halibut in the BSAI are sufficiently constraining for a number of non-target fisheries using trawl gear and or hook & line gear. Faced with these constraints, there have been large investments in technology and gear innovations that reduce halibut bycatch through avoidance and letting halibut escape trawl nets. Moreover, the Amendment-80 cooperatives are also collaborating with NMFS to modify observer procedures and protocols to allow for deck sorting of halibut with the objective of reducing discard mortality rates. Under these experimental fishing permits, the trawl codend is emptied on deck and the crew spends upwards of 20-30 minutes sorting through the catch and removing halibut, then sampling for viability analysis, and finally releasing the halibut overboard. The goal of the deck sorting program is to reduce the overall discard mortality rate for trawl caught halibut. Hook & line fisheries are required to use careful release methods and are discouraged from using other devices for releasing halibut. Many of the non-target fisheries participate in incentive plan agreements that permits rapid sharing and dissemination of bycatch information such that individuals can avoid areas high encounter rates. The trawl industries have made substantial investments in gear innovations with the advent of excluders; but, the use of these devices usually also results in a loss of the target species, especially in other flatfish fisheries (i.e., rock sole, yellowfin sole) and requires even more fishing effort to land their target species quotas. One concern with these innovations to reduce bycatch mortality and having a fixed PSC limit in place is that the fixed PSC-limits based on weight are incentivizing growth over-fishing.

For example, trawl excluders developed for Pacific halibut are very effective at removing larger halibut from the gear and less effective at removing smaller halibut. If an excluder device can effectively reduce the halibut encounter rate, as measured in kg/hour, by say 50%, then in theory, the use of the device could effectively double the fishing effort without exceeding the halibut PSC limit. But also note that the use of this device is also going to change the selectivity of the trawl gear such that the composition of the bycatch has shifted towards smaller halibut. A simple metric for monitoring the composition of the bycatch is the number of halibut per ton. At present, the bycatch selectivity curve used in the IPHC stock assessment model catches about 450 halibut per metric ton (about a 4.9 pound average round weight). If the selectivity curve were exclude larger halibut and the average weight of the bycatch was reduced to roughly three pounds round weight, then bycatch metric increases to roughly 730 halibut per metric ton. So given a BSAI PSC limit of 3,515 mt the current coastwide bycatch selectivity would translate into a bycatch mortality of 1.57 million individual halibut. If industry adopted the use of excluders that changes the composition of the catch to 730 halibut mt^{-1} and the PSC limit was fully utilized, this would result in a bycatch of over 2.56 million individual halibut. In both of these examples, a total of 3,515 mt of bycatch mortality was taken, but the use of excluders results in the loss of nearly a million additional halibut from the stock.

With any sort of biomass-based PSC limit in place, there is a strong incentive to reduce the encounter rate of halibut as measured by units of weight. The previous example is just one of many ways in which the composition of the bycatch would shift towards smaller individuals. Hook & line fisheries can use smaller, softer, hooks that would not support the weight of large halibut, or haul back the gear at high speed, etc. The point is that a fixed PSC limit based on weight creates an incentive to growth overfish in bycatch fisheries. There are two solutions to deal with the increase risk of growth overfishing and still maintain the same target SPR: 1) reduce the target fishing mortality rates in the directed fishery, or 2) reduce the PSC limit in the bycatch fisheries.

Allocations based on yield versus spawning capital

In developing a harvest policy for any fishery there are two key components: (1) stock reference points (i.e., target, threshold, and limit reference points) that trigger certain management actions, and (2) determining the appropriate fishing mortality rates for each sector given the biological parameters of the stock, and parameters that describe the fishery impact on the stock (i.e., selectivity, discard mortality rates, allocations or catch proportions). The setting of stock reference points is largely a policy decision, and in many cases there are default limits specified in legislation. Estimation of biological parameters for a stock and parameters that describe the fishery effects is done by fitting stock assessment models to fishery-independent and fishery-dependent data. The key variables that determine the target harvest rate (which corresponds to the target reference point) for each fishery are: fisheries selectivity and how the catch is apportioned among the different fishing sectors. These sector allocations are almost always result in conflict as it involves trading off catch in one sector to accommodate the catch in another sector. Moreover, removals by each of the different fishing sectors does not necessarily translate into the same impact on the stock; the only case in which there would be a direct pound-for-pound impact would the case where the selectivities are identical (i.e., using very similar gears, or terminal fisheries such as salmonids) .

Typically, catch allocations are based on maintaining the same proportion of the total catch (in weight) in each fishing sector. For example, if 80% of the Pacific halibut catch was allocated to the directed fishery and 20% to bycatch. Given a 20 million pound TCEY, 16 million pounds would go to the directed fishery and 4 million as bycatch. But due to differences in selectivity, both of these sectors would have different proportional impacts on the population numbers. In fact, it might be possible that 80% of the total number of individuals die due to bycatch if the average weight of the bycatch is 80% less than the average weight of the directed fishery. These differences in selectivity have differential impacts on the Spawning Potential Ratio (SPR), and as a consequence, any time there is a change in selectivity in one or more sectors, the target harvest rates should be updated to reflect these changes. We also note here that the target harvest rates should be updated in responses to changes in other variables as well (i.e., changes in growth, natural mortality, etc), and not just limited reallocation or changes in selectivity.

An alternative to maintaining the same catch proportions based on yield, is to maintain the same proportional impacts on the stock. The SPR is used by both the IPHC and the NPFMC for setting reference points and (1-SPR) is a measure of fishing intensity that integrates over size- or age-specific total mortality rates from multiple fisheries (Goodyear, 1993). The NPFMC uses SPR=35% as its proxy for MSY-based reference points. The IPHC does not have a defined target SPR, but the threshold SPR is 30% and the limit reference point is SPR=20%. In other words, both the NPFMC and the IPHC are trying to set catch limits such that the impacts of all sources of fishing mortality leave behind some target fraction of the Spawning Potential for future generations. If for example, the target SPR for Pacific halibut is SPR_{target}=40%, this implies that 60% (1-SPR) of the spawning potential is harvested by all sectors combined. The idea of maintaining the same proportional impacts on the stock would be to allocate a fraction of the (1-SPR_{target}) to each sector. We use the term *fishery footprint* as a measure of the fisheries demand on the resource, or the amount of spawning capital required to support a particular fishery. This is akin to the Ecological Foot print, which is a measure of human demand on the natural capital used each year.

To maintain the same proportional impacts on the stock by each sector, the relative footprint of each sector would be held constant from year-to-year. This also changes the currency for allocation discussions. Rather than allocating a fraction of the total available yield to each sector based on some agreement between the various agencies, the allocation discussion would now focus on what fraction of the SPR should be allocated to each sector. These sorts negotiations are usually based on the historical removals by each of the sectors. The historical footprint of each of the fishing sectors can also be calculated based on the stock assessment model results (e.g., see Table 2 for the breakdown of the 2014 halibut fishery). For example, in 2014 the commercial fishery landed roughly 59% of the 42,512 million pounds of halibut mortality and utilized about 22% of the spawning capital. In comparison, coastwide estimates of bycatch resulted in 22% of the halibut mortality, and utilized about 29% of the spawning capital (Table 2).

A historical comparison of the catch proportions and the corresponding footprints of each fishing sector can be used to illustrate the relative trends in the implied allocations over time (Fig. 10). The trends in the catch proportions and fisheries footprints are similar due to the assumption of constant selectivity in the coastwide bycatch fishery. The proportion of the SPR utilized by each sector has varied the most in the commercial fishery, with footprints ranging from 22% in 2014 to 40% in 2004 when commercial fishery yield peaked at 75.4 million pounds (Fig. 11). In the bycatch fisheries, historical footprints have ranged between 21% in 1998 to 29% in 2012. Footprints in the sport sector have range between 4% in 1999 to 8.3% in 2007, and in the Personal use category range between 0.3% and 1.5% in 1997 and 2013, respectively (Fig. 11). These historical comparison of catch proportions and relative footprints are useful in the context of negotiation at the coastwide scale. It would be more appropriate to break these down into smaller spatial scales, at least at the scale of the IPHC Regulatory Areas, when it comes to making area specific catch sharing plans.

The incentive structure is very different if catch sharing plans are based on allocating total mortality to each sector versus allocating a portion of the fisheries footprint to each sector. The following examples illustrate how these two distinctly different policies create differing incentive structures. As mentioned in section on tradeoffs, the current policy of fixed PSC limits creates the incentive to reduce encounter rate in bycatch fisheries if these fisheries are in fact constrained by halibut bycatch. This also incentivizes growth overfishing, where the use of excluders or other size-selective fishing gear modifications would shift the composition of the bycatch to smaller fish, resulting in increasing the numbers of individuals taken while still remaining below the biomass based PSC limit. Moreover, as halibut abundance decreases fishing intensity in bycatch increases, if the PSC limit is fully utilized. Under an abundance-based PSC limit, the same incentive still exists; however, fishing intensity would not increase during periods of declining abundance as the PSC limits would, in theory, also decline. How would the harvest policy for all sectors have to change to accommodate a change in the composition of bycatch, or a reduction in discard mortality rates? How would the harvest policy have to change if there was a reduction in the minimum size limit in the commercial fishery? The answers to these questions depend on three variables: (1) what is the catch sharing arrangement between sectors, (2) if allocations are based on catch, or spawning capital, and (3) what is the target reference point.

To illustrate how the incentive landscape changes when allocations are based on spawning capital versus yield, we use the age-sex-structured model described in Appendix A to compare 3 alternative harvest policies with the current status quo. For this example, the model is used to determine the appropriate SPR-based reference points under the assumption that F_{SPR}=35% is the target reference point[4]. For the status quo procedure, bycatch is fixed at the 2014 estimate of 9.315 Mlb, and the proportions of the available total catch (after bycatch has been accounted for) remains the same in the Commercial, Sport and Personal use sectors. Yield-based allocations are based the observed catch proportions in 2014 where the commercial fishery is allocated 59% of the total yield and bycatch fisheries are allocated 22% of the total yield (Table 2). Using these same yield proportions, we also calculate the relative fisheries footprint under the 2014 catches and use these proportions for spawning-capital-based allocations (see footprint in Table 2). For each of these alternative management procedures, we compare how the long-term yield differs under fixed-allocations based on yield, and under fixed-allocations based on spawning capital. We also compare the expected catch rates in each sector, as well as, how the composition of the catch, as measured by the number of halibut per ton, might change under these alternative harvest policies.

If the catch sharing plan is based on yield allocations for each of the sectors, then the proportional changes in long-term yield is the same across all sectors. For example, removing the size-limit in the commercial fishery may result in a 9.4% increase in the long-term yield for the

[4] Setting the target reference point is also a policy decision, alternatives could also include MSY-based reference points.

directed commercial fishery, but this benefit also accrues to all sectors due to fixed yield allocations in the catch sharing plan (Table 3). Similarly, the use of excluders results in a 7.6% decrease in all sectors due to the fixed sector allocations. Reducing the discard mortality rate in the bycatch fisheries by 50% effectively changes the composition of the halibut stock due to increased survival of smaller halibut. The average size in the population decreases due to the increase in survival rates (i.e., the age-structure of the population is less truncated).

It's not surprising that a change in policy for one fishing sector would have impacts on the catch rate for that particular sector; but quantifying the impacts on the catch rates of other sectors as a consequence, is necessary to determine the appropriate sector-specific harvest rates that are consistent with the target reference point and the catch sharing plan. For example, reducing the minimum size limit in the commercial fishery would have a substantial impact on the catch rates of legal size halibut. Using the expected catch rates shown in Table 4, commercial catch rates would increase from 325 to 450 (a 27% increase). This change in the composition of the catch also changes the available composition to other fisheries (Table 5), which can have minor impacts on their catch rates as measured in units of weight per effort. For the cases presented in Table 4, there is relatively little indirect effects on the catch rates associated with changes in size limits, using excluders, or reducing discard mortality rates. Where the major impacts would occur is the case in which there is a fixed PSC limit, and that limit does not change with changes in fisheries selectivity. This is an example of how changes in policy for one fishery can affect the long-term catch rates in other fisheries.

Reducing or removing the minimum size limit for Pacific halibut, and maintaining the same distribution of catch across all sectors that was observed in the 2014 fishery, results in an overall increase in the fishery footprint for the commercial fishery. As a consequence, the composition of catch in the commercial fishery will consists of a higher proportion of smaller fish; the expected number of halibut per ton increases from 128 to 161 pieces. This shift in catch composition requires more of the spawning capital relative to the other sectors (Fig. 12), assuming no policy changes in those sectors, and therefore the target fishing mortality rate for the directed commercial fishery must be reduced. As result of this policy change, the proportion of the total mortality associated with the commercial fishery is reduced, and the other sectors benefit from the reduced total mortality rate given the catch sharing plan.

If the bycatch fisheries changed the composition of the catch towards a larger number of smaller halibut that, the overall footprint increases (Fig. 12), resulting in reduced yields in the other sectors due to effects of growth overfishing. As a consequence, the harvest policy in other sectors has to change to accommodate both the target reference point and maintain the same catch proportions in the catch sharing plan. In contrast, reducing the discard mortality rate by 50% through careful release and deck sorting efforts allows the target fishing mortality rate for bycatch fisheries to increase by approximately 184% (Table 6). Assuming fishing mortality is proportional to fishing effort, the net effect would allow the bycatch fisheries a significant increase in fishing effort without exceeding the PSC limits.

If the catch sharing plan is based on fixed allocations of spawning capital to each of the sectors, then there is a much stronger incentive to reduce the discard mortality rate in bycatch fisheries rather than develop gear innovation that would change the composition of the bycatch and increase the impact on the SPR. For example, the results in Table 6 suggest that fishing effort would increase by 129% with the use of excluders; whereas, reducing the discard mortality rates by 50% would result in a 190% increase in fishing effort. In the directed commercial fishery, fishing effort would have to decrease by 30% (i.e., 69.9% of the status quo effort, Table 6) if there was no minimum size limit to accommodate the overall increase in the footprint that would occur (Fig. 12). The net result in this case is a similar yield in the directed fishery, but an significant increase in the commercial CPUE (Table 4).

The salient point to make in the comparison between yield-based allocations versus spawning capital-based allocations is the differences in the incentive landscape. Under the yield-based allocations, bycatch fisheries are incentivized to reduce the weight of the bycatch which results in increased growth overfishing and reducing the overall total yield summed across all sectors. Under the spawning capital-based allocation, there is a stronger incentive for bycatch fisheries to reduce the discard mortality rate, rather than avoid large halibut (Table 6). Moreover, under the spawning capital-based allocation, if any one sector can reduce its overall footprint (by maximizing the yield per recruit, or minimizing its mortality per recruit) then all other sectors benefit from this savings. A win-win situation. Under the yield-based allocations, changes in behavior, or gear innovations, only translates into net benefits to all other sectors if the modification results in reducing the impacts on the spawning capital. But in this case, the incentive in bycatch fisheries is to shift the composition of the catch and increase the overall fishery footprint.

Yield Equivalence

In cases where there are two or more fishing sectors with different selectivities there is a need to understand the equivalent impacts on the stock, specifically the metric that is used for allocation. For example, the IPHC began compensating for bycatch in 1981, where the equivalent O32 yield was reduced to account for the projected bycatch. For the component of the bycatch that is of legal size, this compensation is a 1:1 tradeoff. Compensating for halibut of sublegal size requires an estimate of the future losses of legal sized halibut. For example, the IPHC currently assumes that one pound of bycatch that is less than 26-inches in length translates into one pound of legal catch (32-inches or greater) in the directed fishery under the assumption that the fishing mortality rate is 0.25 (Hare 2010). This relationship was developed back in 2009 based on the size-at-age at the time. Closer inspection of the analysis performed by Hare (2010) reveals that there are a number of important variables that go into calculating the pound for pound impacts of bycatch on the directed fishery. These variables include: size-at-age, the sex ratio of the catch, average recruitment, natural mortality rates, migration and movement in and out of each regulatory area, fisheries selectivity, discard mortality rates, the target harvest rate, and the ratio of bycatch:retained catch. A number of these variables have changed since this analysis was conducted, including: size-at-age, selectivities for all sectors, and the ratio of bycatch:retained catch. Also the methods used by Hare (2010) is based on the cumulative yield lost over the life-time of a cohort relative to the weight of the bycatch, and does not account for the cumulative effects of bycatch removals each year, or removals from other sectors. These fisheries interactions are critical for establishing appropriate reference points, and for mitigating the effects of bycatch on directed halibut fisheries.

Fisheries Interactions

Another way to look at the yield equivalence is the look at the distribution of catch limits across sectors when each sector is systematically removed from the harvest policy calculations. In other words, how much more yield could be obtained in the commercial, sports, and personal use fisheries if there was no bycatch? Then sequentially repeat this analysis by removing the commercial fishery, the sports fishery, and so on. Table 7 summarizes the relative precent increase in long-term yield for all other sectors by systematically removing each sector and updating the harvest policy calculations. For example if the bycatch fisheries did not exists, yield in commercial, sport and personal sectors would all increase by 28% (Table 7, first column second row). Similarly, if the sport fishery did not exist, then yields in all other sectors would increase by 25%.

Changes to the harvest policy in one or more sectors also impacts all other sectors, and these impacts differ between allocation methods. For example, if there were no size limit in the commercial fishery, then the relative effects of bycatch are more pronounced; catch limits in all other sectors would increase by 34% rather than 28% under a yield based allocation. If, however, allocations are based on maintaining the same footprint in each sector, then the effects of removing bycatch would result in a 39% increase in yield for all other sectors. Both the no size limit (NSL) and excluder scenarios (EXL) involve changing the composition of the catch (via changes in fisheries selectivities). Reducing discard mortality rates (DMR) assumes there is no change in the composition of the catch. If the composition of the fishery induced mortality does not change, then the relative effects of removing each fishery is the same for yield-based allocation versus footprint-based allocation. For example, if the discard mortality rate in the bycatch fishery is reduced by 50%, then removing the commercial fishery results in a ~90% increase in yield for all other sectors in both allocation schemes (Table 7).

Previous analyses have examined the yield loss ratio on a pound for pound basis (Sullivan, 1994, Hare 2010). Specifically, for each pound of bycatch what is equivalent yield lost to the directed fishery. Sullivan (1994) concluded that one pound of bycatch resulted in 1.58 pounds of lost yield in the directed fishery. Prior to the Sullivan (1994) analysis, the directed fishery annual catch limits were reduced by 1.40 pounds for each pound of bycatch. Hare (2010) examined the bycatch impacts at the 32-inch size limit threshold and concluded that each pound of U26 bycatch translates into 1 pound of O32-inch lost yield in the directed fishery. Taking the results used to produced the summary statistics in Table 7, we've calculated a similar pound for pound impact of bycatch on all other sectors (Fig. 13). For example, assuming a target SPR of 35% and the same 2014 distribution of catches, the long-term average yield in the commercial fishery is 24.98 Mlb given 9.3 Mlb bycatch. Setting the bycatch to 0 and re-calculating the long-term average yields results in a long-term average yield of 31.88 Mlb for the commercial fishery; this represented an increase of 6.91 Mlb. The overall pound for pound impact (of all sizes) is 6.91 of potential lost yield divided by 9.32 Mlb of bycatch, or 0.74 pounds per pound of bycatch (Fig. 13). Another important point to note is that the calculations involved in the example shown in Figure 13 maintains the same proportions of the total catch (which would be specified in a catch sharing plan). In other words, in the previous example where each pound of bycatch reduces the commercial fishery by 0.74 pounds, it also reduces the sports fishery by 0.21 pounds, and personal use by 0.03 pounds. These proportional reductions are equivalent to the proportions specified in the catch sharing plan, or allocation agreement.

Pound for pound impacts are very sensitive to the composition of the catch in each sector. In general, higher mortality rates on small fish result in larger pound for pound impacts in other sectors. This is true regardless if allocations are based on yield or spawning capital. For example, under the management procedure where there are no size-limits in the commercial fishery, one pound of bycatch is equivalent to 0.91 pounds in the commercial fishery (Fig. 13). The reason for this change is that under a no size-limit policy the composition of the commercial catch would shift to a smaller average size and more closely resemble the composition of the bycatch fishery. If both fisheries have the same catch composition (i.e., the same selectivity) then the pound for pound impact is 1.0.

Based on the example in Figure 13, one obvious question is why are the pound for pound impacts so much larger if the composition of the bycatch shifts towards smaller sizes (EXL procedure), or the discard mortality rate is reduced by 50% (DMR procedure). The answer is due to the substantial increase yield in the commercial fishery associated with removing the bycatch fishery that has a very high mortality per recruit. For example, under the target SPR of 35% and using the 2014 distribution of catch by sector for an allocation arrangement, the long-term sustainable yield for the commercial fishery is 23.08 Mlb and bycatch is 8.61 Mlb. Absent the bycatch sector in the harvest policy calculations, the commercial sector long-term yield would increase by 12.67

Mlb to 35.75 Mlb. In other words, the 8.61 Mlb of bycatch results in a loss of 12.67 Mlb in the commercial fishery, or a loss of 1.47 pounds per pound of bycatch. Similarly, reductions in the discard mortality rate (DMR) by 50% in the bycatch sector also result in substantial increases in long-term yield for the commercial sector in the absence of bycatch (an increase of 13.21 Mlb with 9.14 Mlb of bycatch).

In summary, the yield equivalence, or pound for pound impacts of one fishing sector on another fishing sector is not a simple calculation that only involves differences in selectivity between sectors. The relative impacts depend on a number of factors that are under management control including: the harvest policy, changes in selectivity (incl. size limits) in any one sector, allocation or catch sharing plans, discard mortality rates. There are also a number of biological variables that affect yield equivalence, including natural mortality rates (incl. age-specific natural mortality rates), changes in size-at-age, maturity schedules and movement rates among Regulatory Areas.

Critical Assumptions

One of the critical assumptions in the harvest policy model (Appendix A) used to for generating these examples is that natural mortality is independent of age or size. That is, an age-1 female halibut has the same natural mortality rate as an age-15 female halibut, currently assumed to be 0.15^{-yr}. If natural mortality rates decreases with age, then a large number of young halibut taken as bycatch would otherwise die from natural causes (Fig. 14). The pound for pound impacts of bycatch are negated if the contrast in age-specific natural mortality rates is large. Based on the alternative structural assumption about age-specific natural mortality rates (Fig. 14), the impacts of one pound of bycatch reduces the commercial yield by 0.74 pounds; whereas, under size-dependent natural mortality bycatch impacts are less (1 pound of bycatch translates into 0.39 pounds of lost yield in the directed fishery).

Another critical assumption is growth rates, and size-at-age, are independent of halibut density (i.e., no density-dependent growth). The current harvest policy for Pacific halibut was developed assuming that growth was density-dependent, where halibut grew faster at low densities, and slower at high densities. Recent trends in size-at-age, and declining adult density suggests that this relationship no longer holds. But the salient point from a harvest policy perspective is that bycatch of small halibut could potentially reduce the overall density, leading to compensation in halibut growth rates. If this were in fact the case, the effects of bycatch reducing juvenile densities in the Bering Sea could lead to compensation in halibut growth rates further negating the impacts of bycatch on the directed fisheries.

The combined effects of density-dependent growth and size-specific natural mortality rates could be used to effectively hide the effects of juvenile bycatch on the directed fishery. At one extreme, if compensation in growth and size-specific natural mortality were strong, juvenile bycatch could even enhance the directed fishery (akin to pruning a fruit tree to increase fruit production). These are structural assumptions (density-dependent growth and size-dependent natural mortality) in the population model, and it is also reasonable to argue that natural mortality is not constant across ages, and growth is not independent of density; in the absence of data both hypotheses are equally likely. The important question is not which hypothesis is correct, but what are the consequences if the assumption is incorrect. There is often an asymmetrical cost associated with these alternative assumptions (Walters and Martell, 2004) and its generally less risky to assume a constant natural mortality rate and density-independent growth.

One of the primary assumptions in the example harvest policy calculations is that the catch limits (including bycatch PSC limits) are fully utilized. This is a necessary assumption when developing a harvest policy for Pacific halibut. It would be inappropriate to develop a harvest policy assuming that only a fraction of the PSC limits would actually be utilized, just as it would be inappropriate to assume that only a fraction of the annual catch limit in the directed fishery would be utilized. In practice, if there are significant savings in the PSC limits, or other sectors for that matter, the harvest policy would err on the conservative side. If the policy was developed on 80% of the PSC limit, then the harvest policy would be more risk prone, because estimates of optimal fishing mortality rates in the directed fishery would be based on a 20% reduction in the PSC limits. Moreover, if bycatch is anticipated to be well below the PSC limits, then the equivalent yield (see section on Yield Equivalence) could be transferred/traded/reallocated to other sectors.

Research Recommendations

There are a number of options for setting abundance-based PSC limits for Pacific halibut presented in this discussion paper, and we are not advocating the adoption of any option without evaluating the potential consequences. There are a number of issues that need to be examined in more detail. Below are a number of recommendations that we feel are worth exploring before proceeding with adopting abundance-based PSC limit. We also note that a number of these recommendations are not necessary if the Council and IPHC choose to maintain the status quo.

Harvest policy

- Use a computer simulation framework (i.e., management strategy evaluation) to examine the performance of alternative harvest control rules and catch sharing plans for setting PSC limits.
    - Develop management objectives for directed and non-directed halibut fisheries.
    - Develop a set of performance metrics for directed and non-directed halibut fisheries which are related to these objectives.

  - Requires an operating model for Pacific halibut stocks, and other BSAI groundfish stocks, such that policy impacts on directed and non-directed halibut fisheries can be evaluated.
  - Examine alternative harvest control rules for setting annual catch limits in directed and non-directed halibut fisheries.
- All of the examples in this document examine these issues from the perspective of the IPHC harvest policy (i.e., long-term equilibrium perspective). This is necessary, as there is no allocation agreement or catch sharing plan in place between the IPHC and the NPFMC. Its not likely that any one of these alternative policies could be implemented without a more detailed investigation on the short-term costs of actually implementing a new policy. A more detailed study on alternative strategies from transitioning from the current status quo to a new policy are just as important.

Economic & Social impacts

- What are the social and economic impacts of alternative policies for setting PSC limits?
  - Examine the social and economic tradeoffs over a range of PSC limits and how they impact the economics of the directed fishery and non-directed fisheries.
  - Economic impacts of coastal Alaskan communities under alternative PSC limits.
  - Social and economic impacts in the directed and non-directed halibut fisheries.

Spatial scale

- The analysis of alternative harvest policies should be conducted at finer spatial scales, at least at the IPHC Regulatory Area, instead of a coastwide harvest policy analysis.
  - Implications of movement/migration on the area-specific harvest rates.
  - Spatial scale of the fisheries objectives: maximize total yield in each Regulatory Area will be highly dependent on movement among IPHC Regulatory Areas.
  - Downstream effects of bycatch. E.g., foregone yield in Area 3 as a consequence of bycatch in Area 4?

Uncertainty in demographic parameters

- It's entirely possible to build a model in which bycatch effects are minimized by introducing size-dependent natural mortality rates and density-dependent growth in Pacific halibut. In this case, the bycatch fisheries are effectively removing fish that would likely die from natural causes anyways, thus negating the effects of bycatch. In addition, having density-dependent growth, where halibut grow faster at lower densities would further compensate for bycatch losses. If the combined effects of size-dependent natural mortality and density-dependent growth are significant, it's possible that the bycatch fisheries could enhance the directed commercial fishery. This is a very important question from a policy and bycatch management perspective, but very difficult to obtain the necessary data to measure size-dependent natural mortality and density-dependent growth. The more important question to address, that is quantifiable, is what are the consequences if either of these assumptions are wrong?

  - Use a factorial design with an operating model to address size-dependent & independent natural mortality rates, density-dependent and -independent growth and examine consequences of each assumption.

- The same arguments in the previous bullet point hold true for size-dependent discard mortality rates.

Acknowledgements

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Table 1. Survey-based apportionment calculations for 2015 (see Webster and Stewart, 2015 for details), target harvest rates for each regulatory areas, and the apportioned target TCEY distribution based on the harvest rate policy.

	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
Apportionment	2.2%	14.8%	15.1%	33.5%	12.1%	6.7%	3.8%	11.9%	100.0%
Target Harvest Rate	21.5%	21.5%	21.5%	21.5%	16.1%	16.1%	16.1%	16.1%	19.6%
TCEY Distribution	2.4%	16.2%	16.5%	36.6%	9.9%	5.5%	3.1%	9.8%	100.0%

Table 2. Halibut mortality (million pounds) by sector for all regulatory areas combined, along with the proportion of the yield and the relative footprint of each sector based on the catch distribution and fishery selectivities by sector in 2014.

Fishery	Yield (1000 lb)	Proportion of Yield	Footprint
Commercial	24,977	59%	22%
Bycatch	9,315	22%	29%
Sport	7,083	17%	8%
Personal	1,137	3%	2%
TOTAL	42,512	100%	60%

Table 3. A comparison of long-term annual yield (million net pounds) at FSPR=35% where the same 2014 catch proportions are maintained (YPR allocation), or maintaining the same impact on the spawning capital, for three alternative management procedures: no minimum size limit, use of excluders in trawl gears, and reducing discard mortality rates in bycatch fisheries by 50%.

		Allocation based on YPR			Allocation based on Spawning Capital		
Sector	Staus Quo	No Size Limit	Excluder	DMR	No Size Limit	Excluder	DMR
Commercial	24.977	27.335	23.076	24.237	24.203	26.821	24.062
Bycatch	9.315	10.195	8.606	9.039	11.242	6.036	9.149
Sport	7.083	7.752	6.544	6.873	8.618	7.613	6.841
Personal	1.137	1.244	1.004	1.103	1.378	1.224	1.102
TOTAL	**42.5**	**46.5**	**39.2**	**41.3**	**45.4**	**41.7**	**41.2**

Table 4. Expected catch rate at FSPR=35% for each sector given the 2014 catch proportions, or the 2014 impacts on the spawning capital for three alternative management procedures and the status quo.

		Allocation based on YPR			Allocation based on Spawning Capital		
Sector	Staus Quo	No Size Limit	Excluder	DMR	No Size Limit	Excluder	DMR
Commercial	325	450	325	329	450	325	329
Bycatch	334	332	168	172	332	168	172
Sport	258	255	258	263	254	257	263
Personal	396	392	396	409	392	396	409
Average	**328**	**357**	**287**	**293**	**357**	**287**	**293**

Table 5. Expected number of halibut per ton at FSPR=35% for each sector given the 2014 catch proportions or the 2014 impacts on spawning capital for three alternative management procedures and the status quo.

		Allocation based on YPR			Allocation based on Spawning Capital		
Sector	Staus Quo	No Size Limit	Excluder	DMR	No Size Limit	Excluder	DMR
Commercial	128	161	128	131	161	128	131
Bycatch	465	468	771	464	468	770	464
Sport	158	157	158	160	157	157	160
Personal	205	205	204	207	205	204	207
Average	**239**	**248**	**315**	**241**	**248**	**315**	**241**

Table 6. Expected change in fishing effort required to achieve sector-specific harvest rate objectives relative to the status quo effort based on a FSPR=35% harvest policy.

	Allocation based on YPR			Allocation based on Spawning Capital		
Sector	No Size Limit	Excluder	DMR	No Size Limit	Excluder	DMR
Commercial	79.0%	92.4%	95.8%	69.9%	107.4%	95.1%
Bycatch	110.1%	184.2%	188.2%	121.4%	129.2%	190.5%
Sport	110.7%	92.4%	95.0%	123.1%	107.5%	94.5%
Personal	110.7%	92.5%	94.1%	122.7%	107.8%	94.0%
Average	**102.6%**	**115.4%**	**118.3%**	**109.3%**	**113.0%**	**118.5%**

Table 7. Relative percent increase in long-term yield (columns) when a specific sector (row) is removed from the harvest policy calculations assuming an FSPR=35% target. For example, if the commercial was removed, yield in all other sectors would increases by 131% under the Status Quo (STQ) procedure, if bycatch was removed all other sectors would increase by 28%.

		Allocation based on YPR			Allocation based on MPR		
(-) Sector	STQ (%)	NSL (%)	EXL (%)	DMR (%)	NSL (%)	EXL (%)	DMR (%)
Commercial	131%	94%	90%	90%	75%	122%	89%
Bycatch	28%	34%	55%	54%	39%	33%	55%
Sport	25%	31%	19%	19%	36%	23%	19%
Personal	2%	3%	2%	2%	3%	2%	2%

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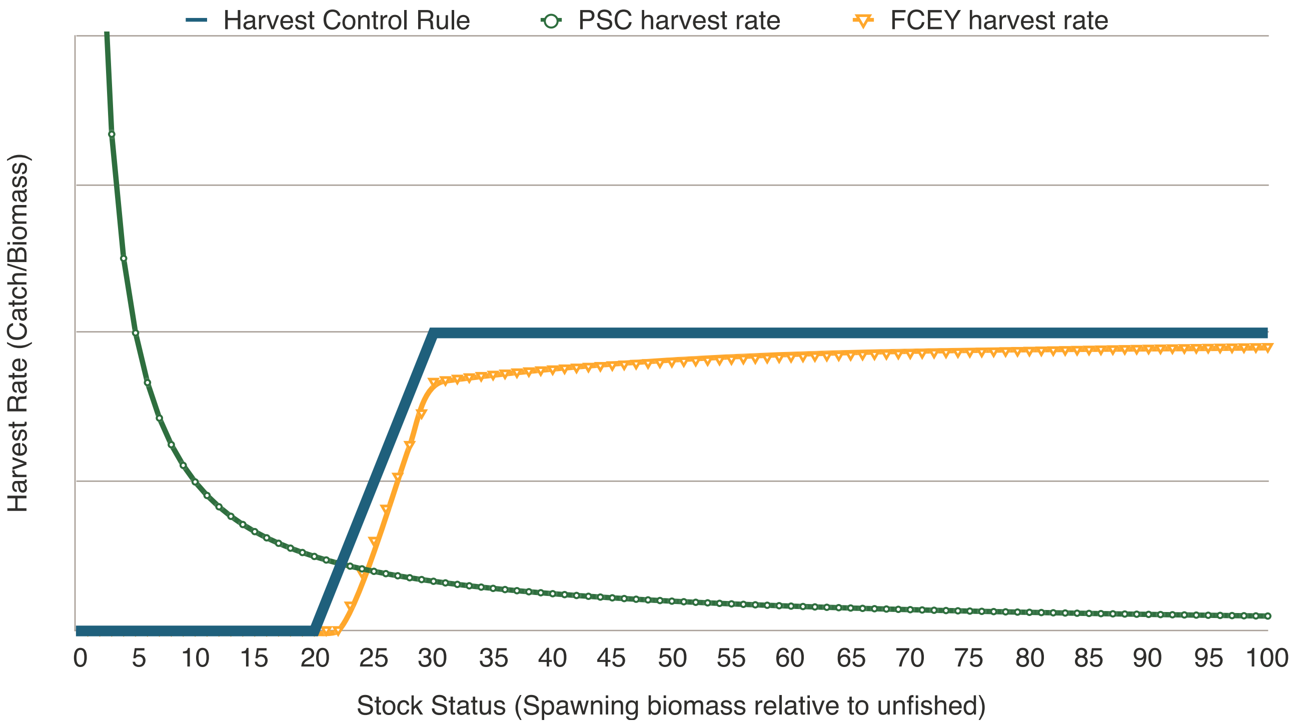


Figure 1. The 30:20 sloping harvest control rule used by the International Pacific Halibut Commission for setting the annual harvest rate to compute the annual catch limit for all fisheries and the implied harvest rate for the directed fishery (FCEY) and fixed PSC limits.

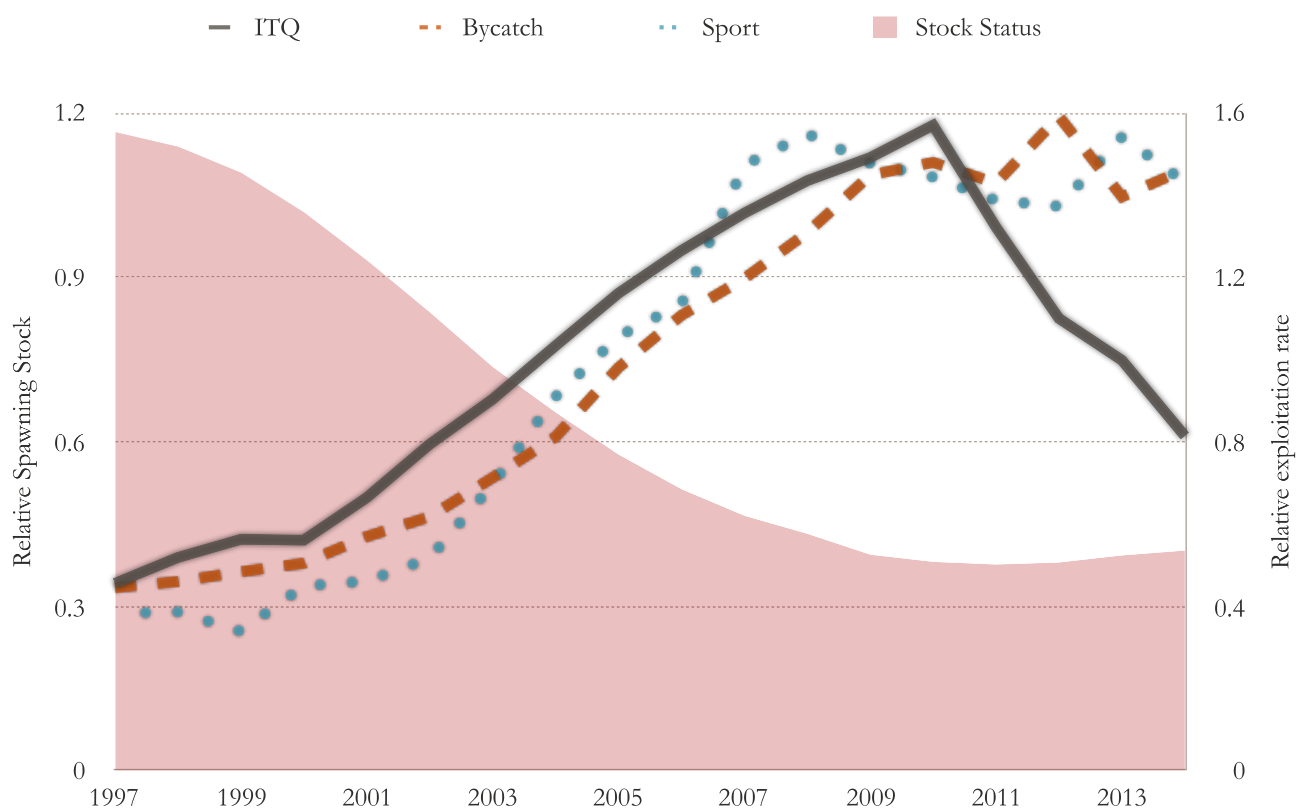


Figure 2. Trends in coastwide spawning biomass and relative exploitation rates (catch/set-line survey wpue scaled to have a mean = 1.0 for each catch vector) for directed halibut fisheries (ITQ, including wastage), all sources of bycatch, and sport fisheries.

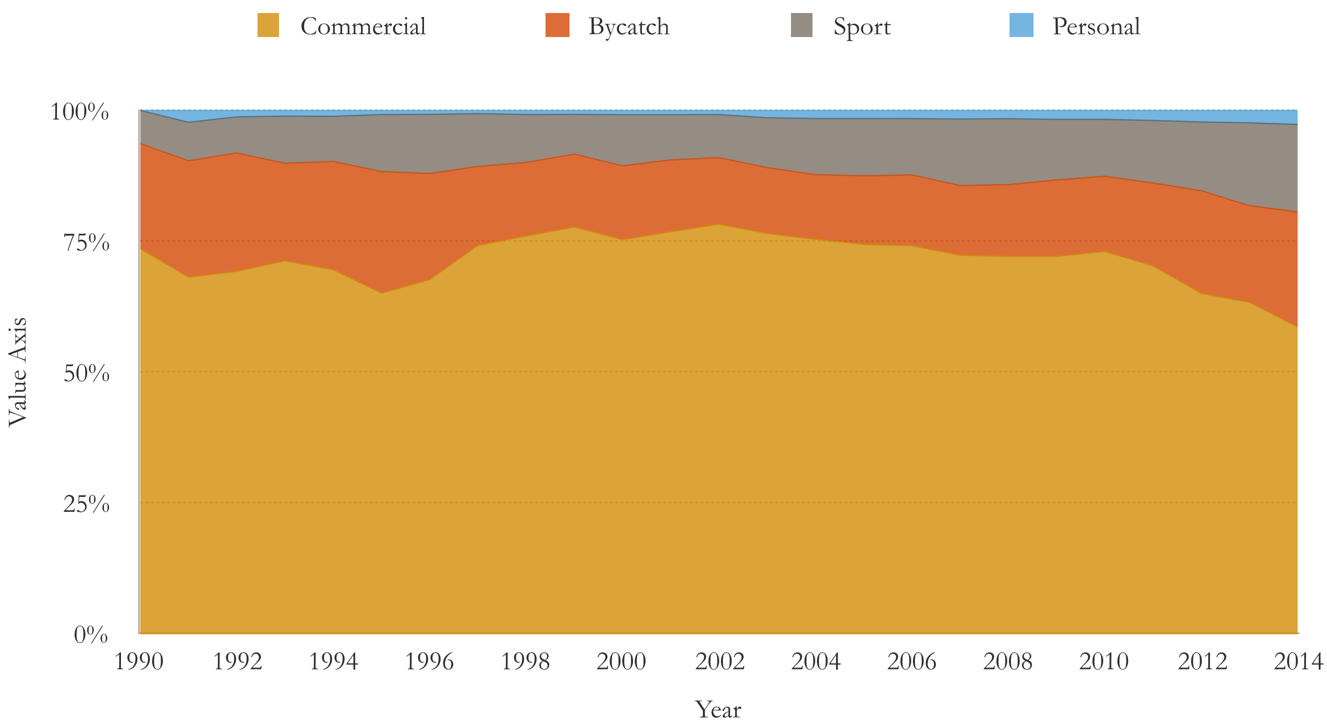


Figure 3. Proportion of the total halibut mortality in pounds taken by each fishing sector (Commercial sector includes wastage) between 1990 and 2014.

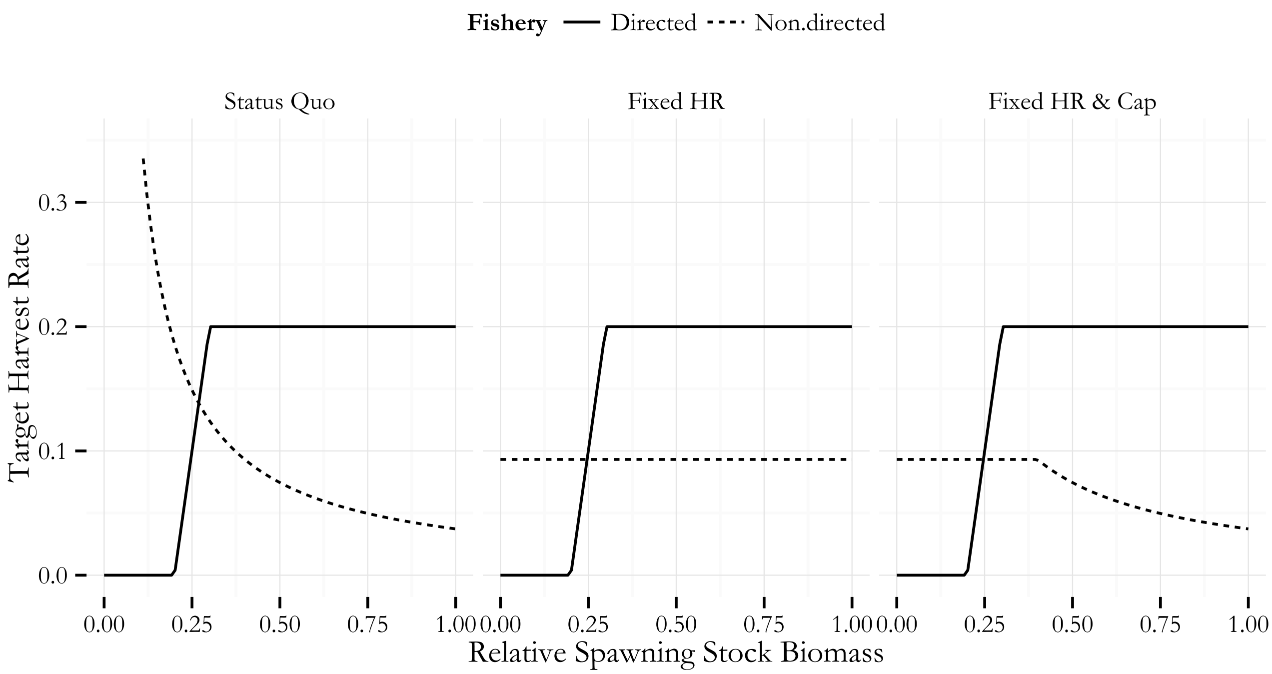


Figure 4. Examples of the three alternative harvest control rules for setting annual PSC limits for Pacific halibut overlaid on the current harvest control rule (30:20 rule) used by the IPHC for setting total catch limits (ITQ).

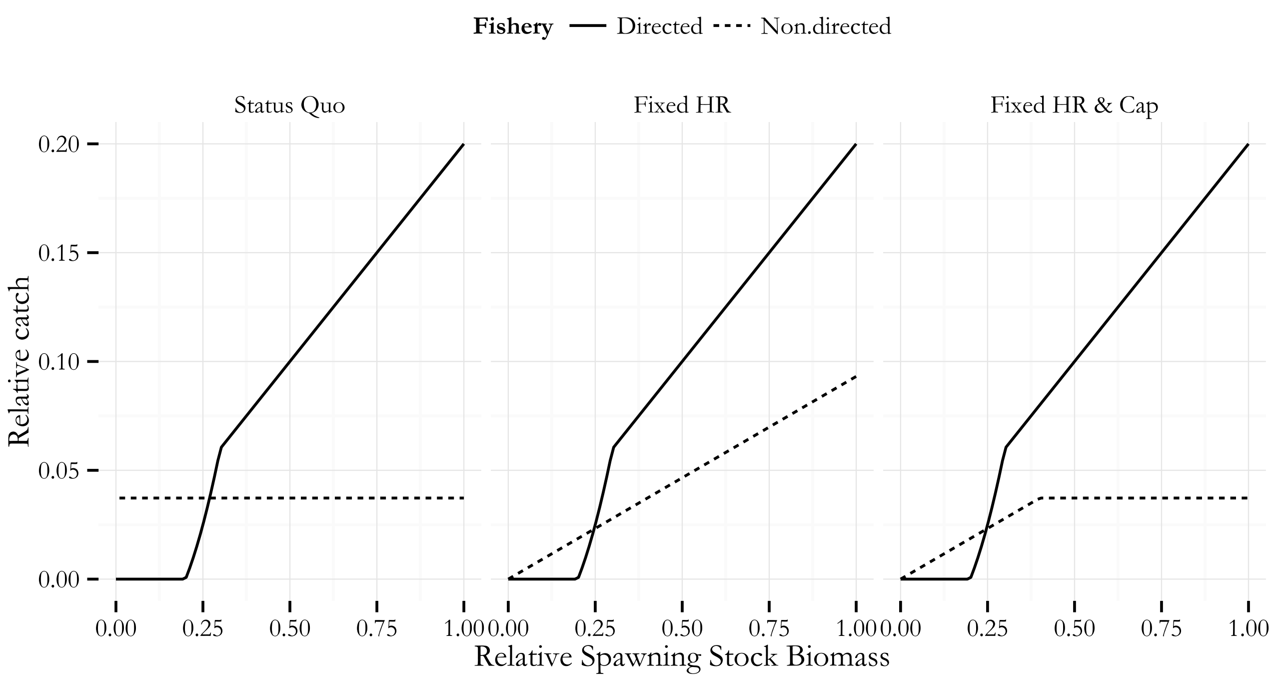


Figure 5. Examples of the relative catch limits as a function of spawning stock status based on the harvest control rules presented in Figure 4.

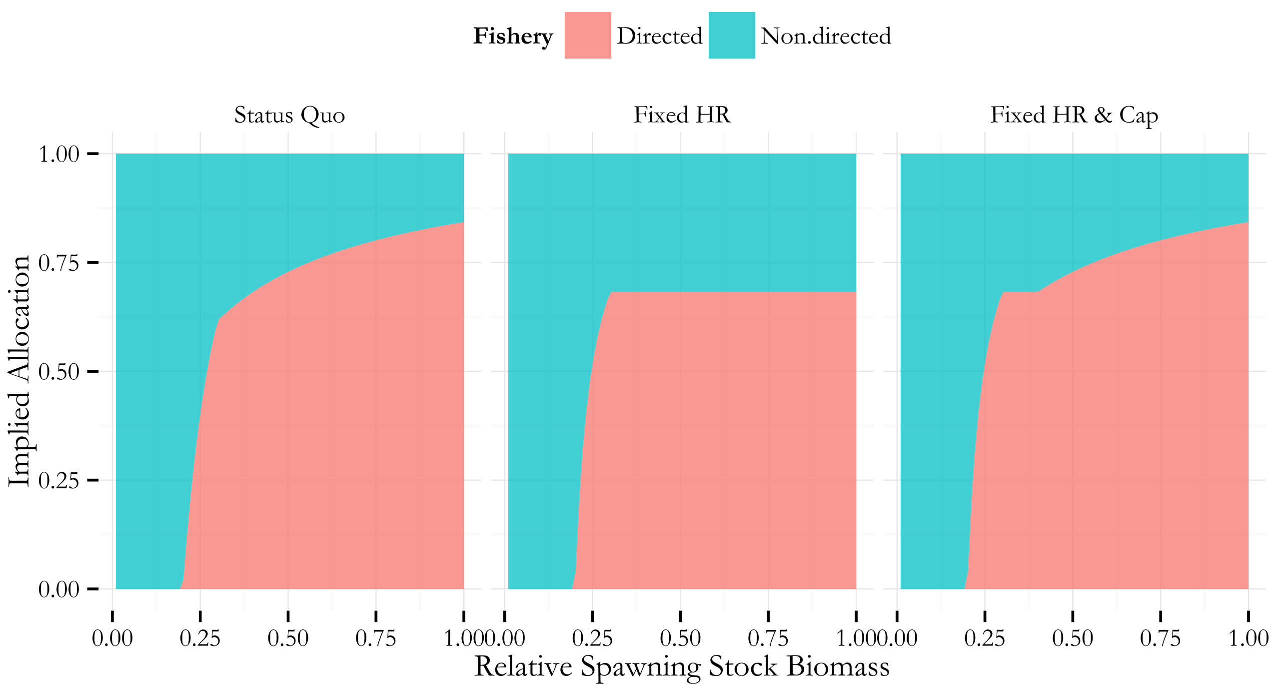


Figure 6. Implied allocation of halibut mortality (in pounds) based on the harvest control rules specified in Figure 4.

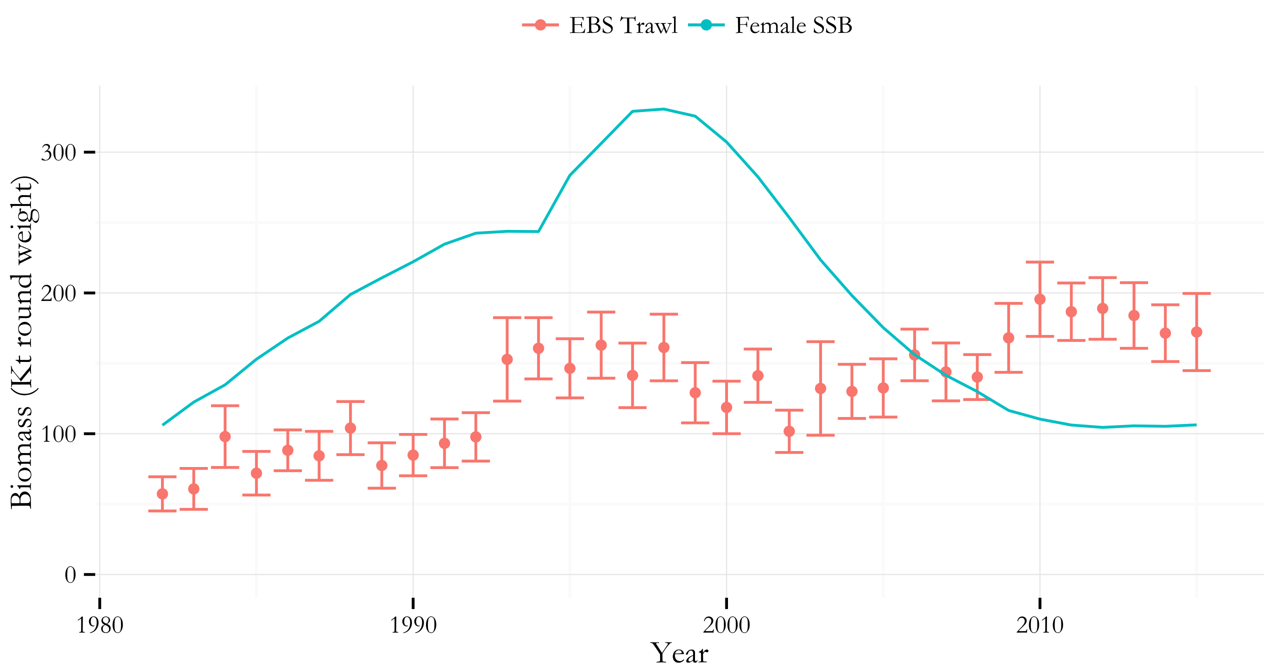
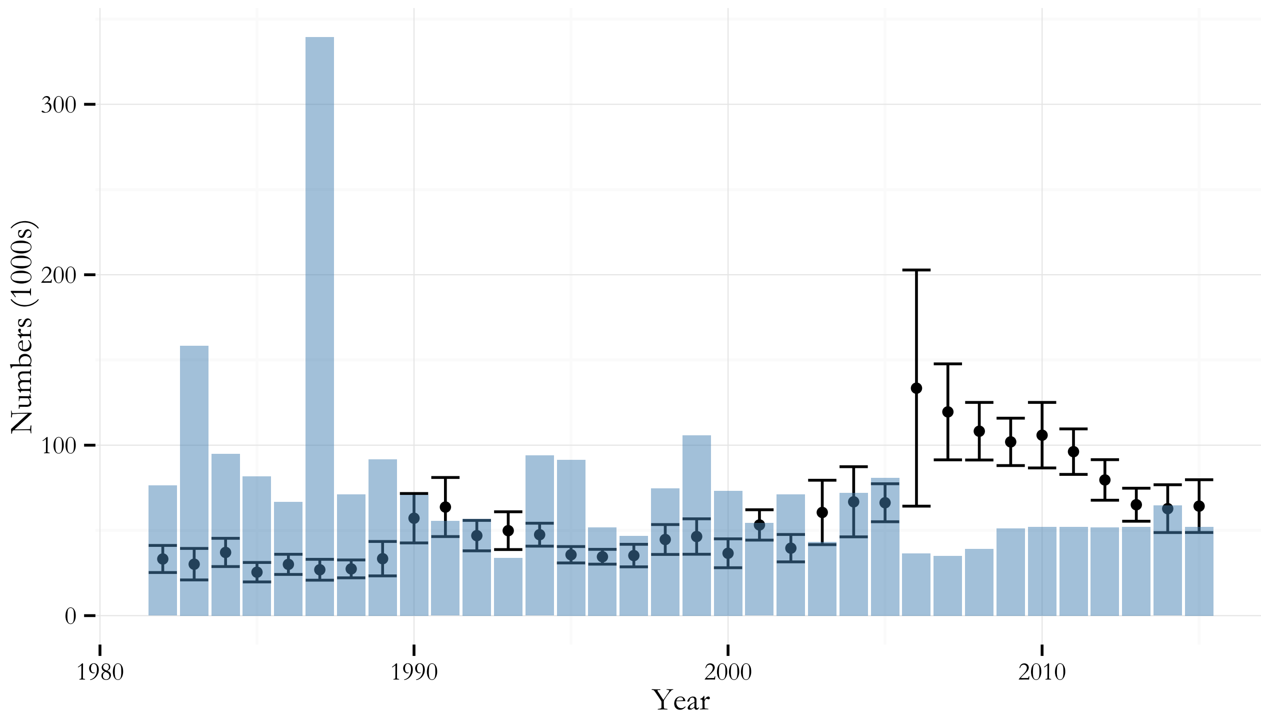


Figure 7. Area swept estimates of halibut biomass based on the NMFS-EBS bottom trawl survey and estimates of female spawning stock biomass from the 2014 long time series coastwide assessment model.



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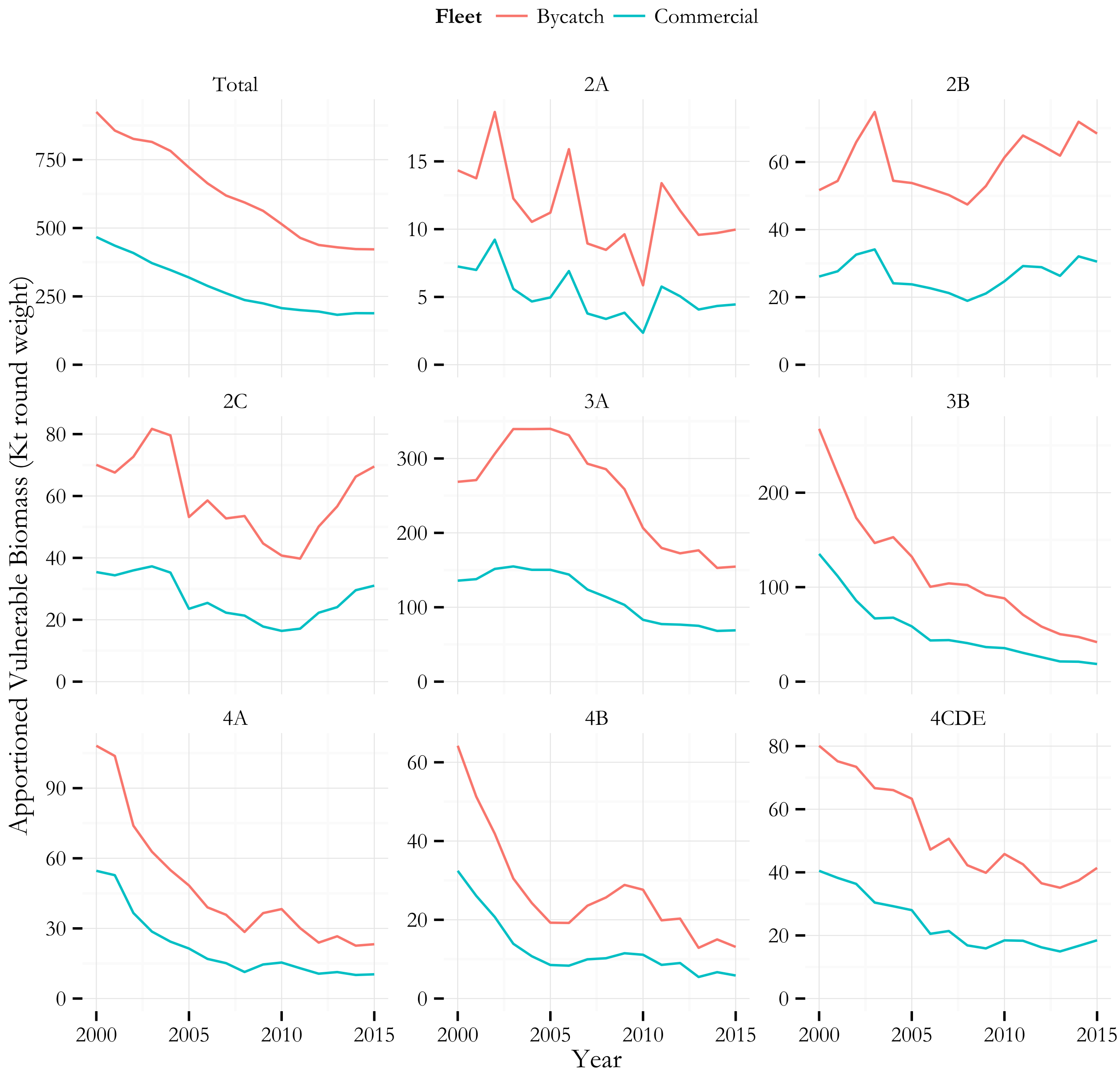

Figure 9. Apportioned vulnerable biomass based on the selectivity curves of the coastwide bycatch fishery and the retained portion of the commercial fishery between 2000 and 2015. The bycatch fishery "sees" more biomass because the fish recruit at age-3 in comparison to ages 8-12 in the commercial fishery.

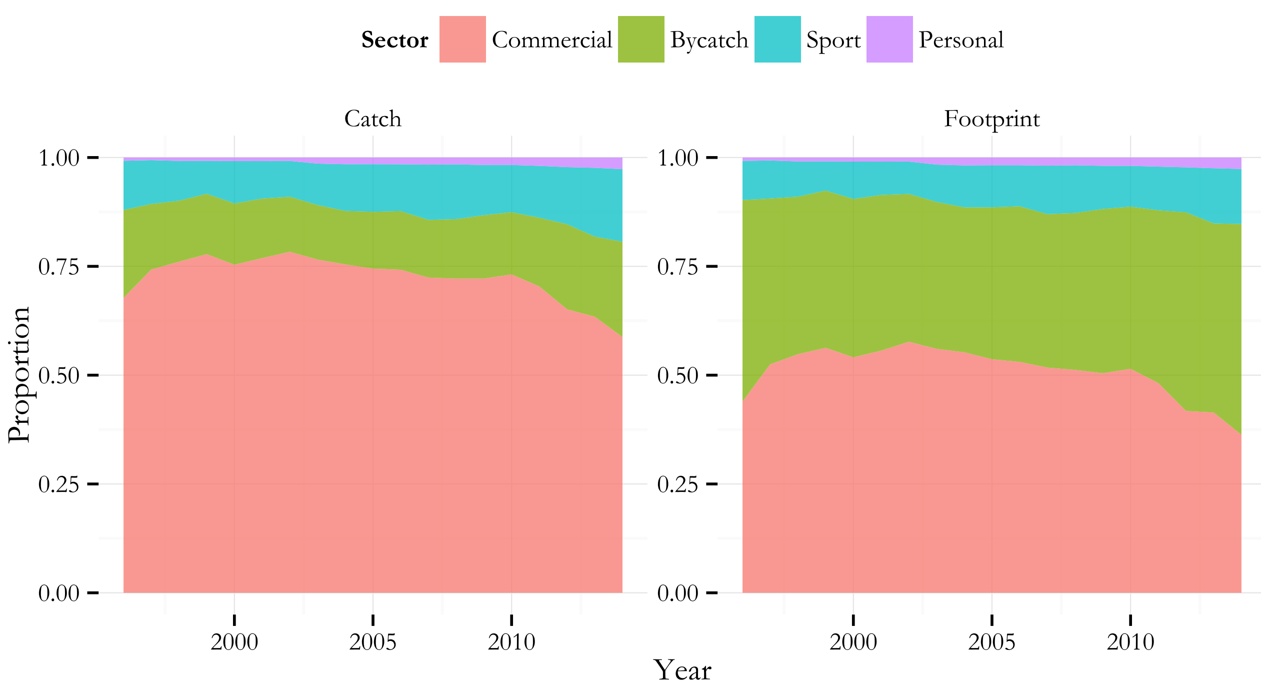

Figure 10. Proportions of the total catch and fishery footprint between 1996-2014 by sector.

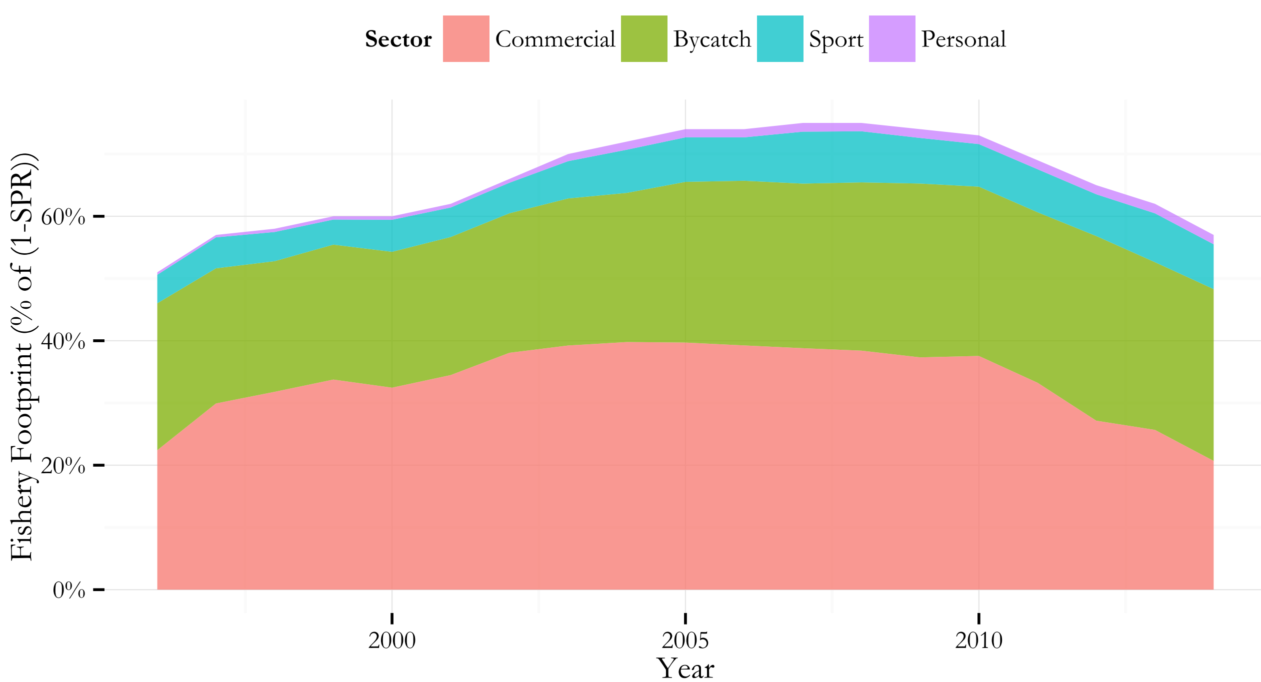

Figure 11. Trends in the fishery footprints for commercial, bycatch, sport and personal use.

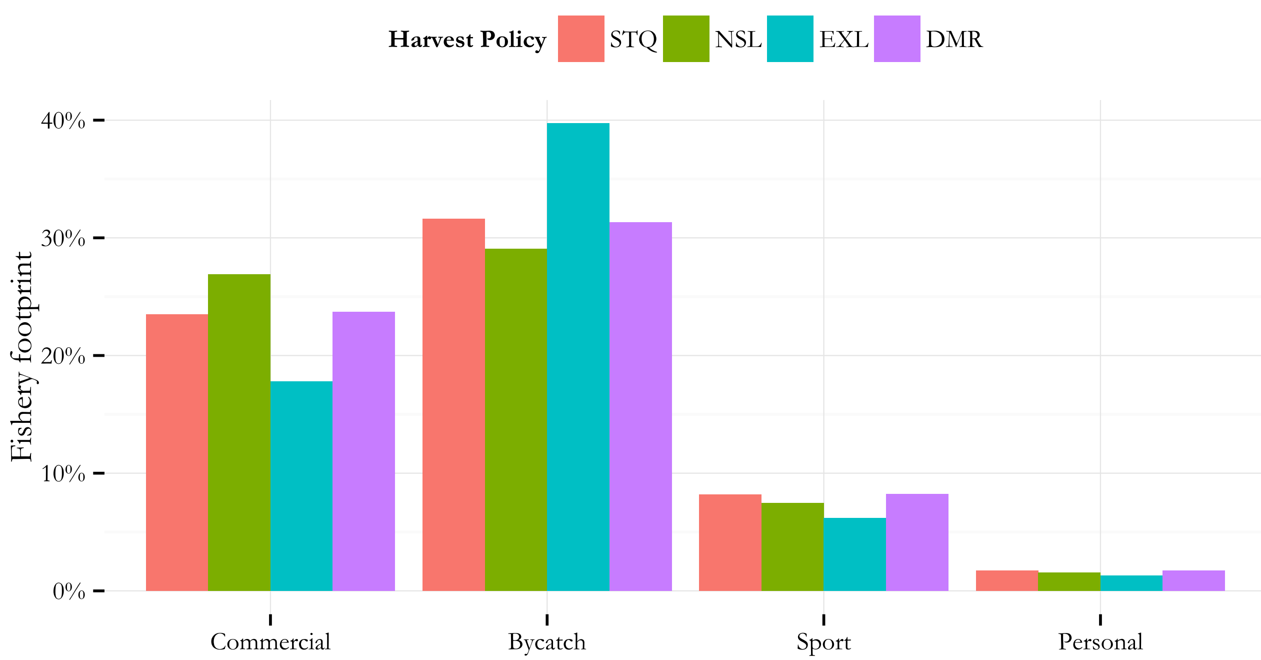

Figure 12. Relative impacts on the Spawning Potential Ratio based on the 2014 catch proportions for the status quo, and three alternative harvest policies, under the working assumption that the target SPR reference point is F_{SPR}=35%.

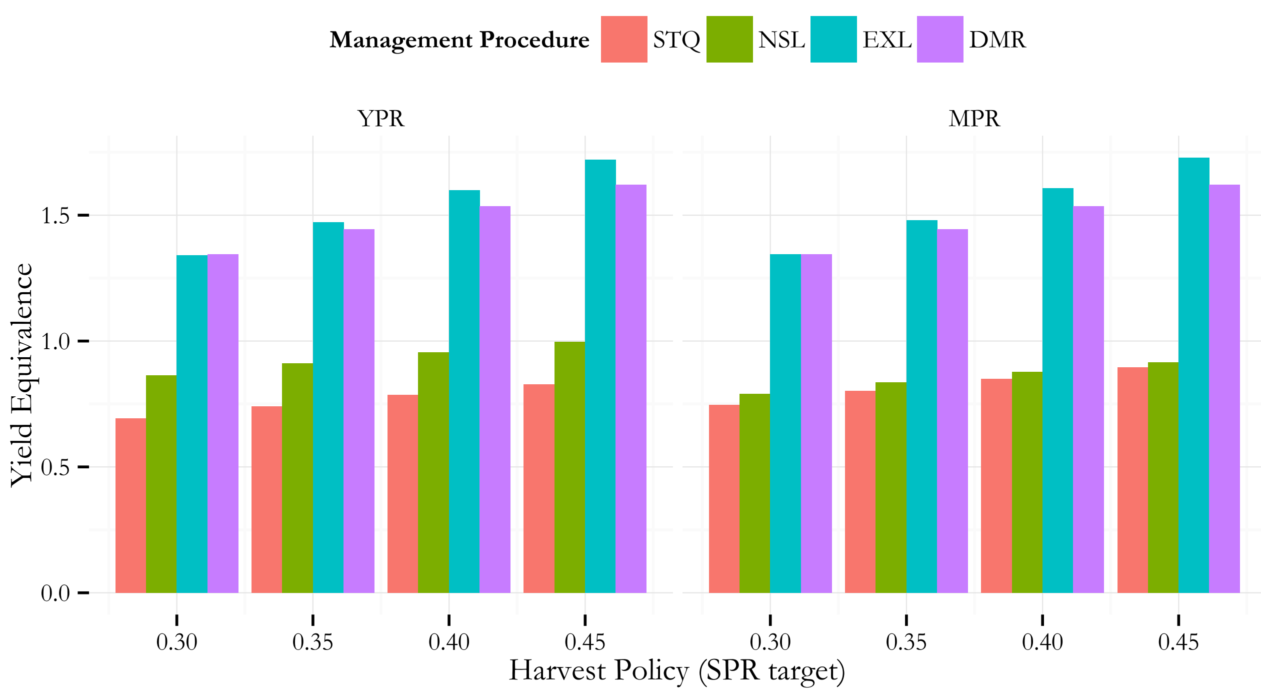

Figure 13. Equivalent yield for each pound of bycatch (coastwide) for all other sectors (commercial, sport, and personal use) based on the 2014 catch distributions, selectivities from the IPHC stock assessment, versus alternative harvest policies (based on target SPR) and alternative management procedures (Status quo, No Size Limit, Excluders, and Discard Mortality Rate reductions). Left panel reflects yield based allocations and on the right, fishery footprint allocations.

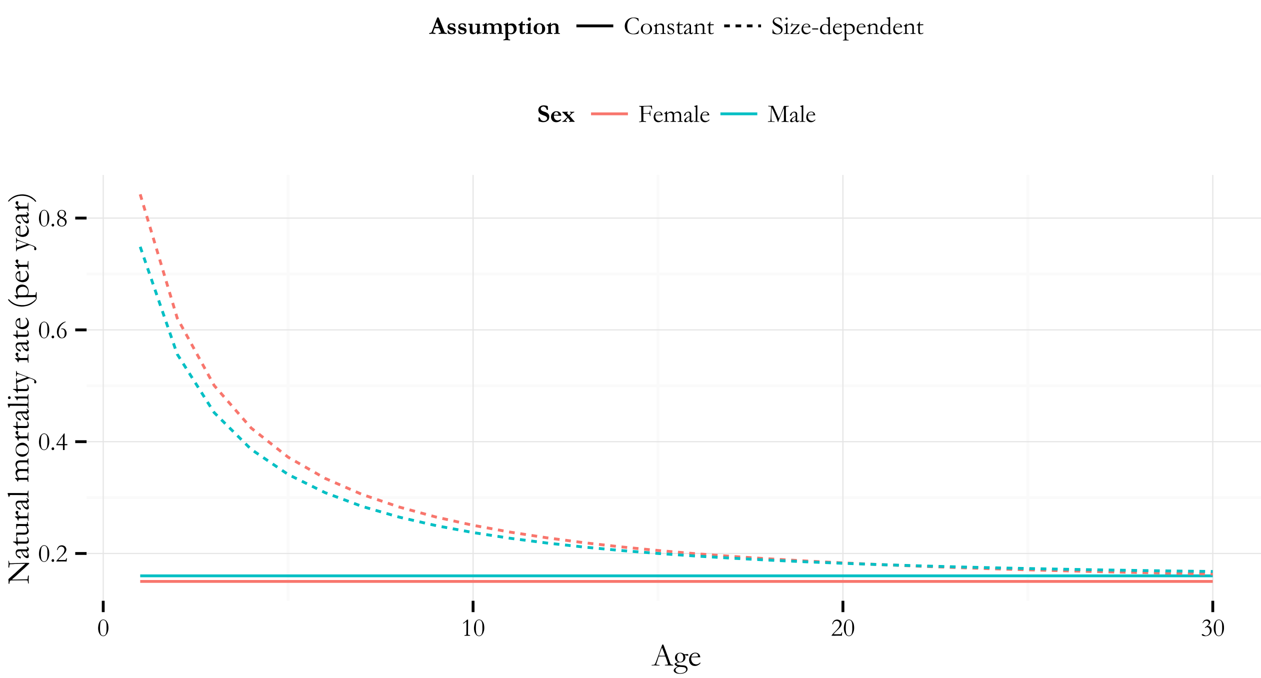

Figure 14. Example of a age-dependent natural mortality rate for male and female. Based on a constant natural mortality rate, the pound for pound impacts of bycatch on commercial yield is 1:0.74. In contrast with size-dependent natural mortality, the pound for pound impact is 1:0.39.

Appendixes

Contents

Appendix A. Model description

An equilibrium age- and sex-structured model was developed for this analysis. The following description is broken down into three parts, age- and sex-schedule information for Pacific halibut, a description of the equilibrium model for exploring an SPR-based harvest policy, and a description of the algorithm used to determine F* and fishing mortality rate multipliers under alternative allocation agreements.

Age- Sex-schedules

For halibut size-at-age, a parametric growth function (Eq. A2.1) was fitted to size-at-age data collected from the Pacific halibut fishery in 2014 where the mean length-at-age was assumed to be normally distributed. We used the same coast-wide size-at-age data that is used in the Pacific halibut stock assessment document. Estimated growth parameters for male and female halibut are summarized in Table A.1.

Table A.1. Assumed von Bertalanffy growth parameters for female and male halibut obtained by fitting a growth model [L = Linf * (1 - exp(-k * (age - to)))] to 2014 coast-wide size-at-age data used in the 2014 stock assessment and the instantaneous natural mortality rate. The allometric parameters are used to convert length-at-age to average weight-at-age [W = a * L b].

Parameter	Female	Male	Asexual
Asymptotic Length (Linf)	151 cm	103 cm	-
Growth coefficient (k)	0.0795	0.0975	-
Time at zero length (t0)	-0.597	-1.234	-
Allometry scale (\alpha)	-	-	6.92E-06
Allometry power (b)	-	-	3.24
Natural Mortality Rate (M)	0.15	0.16	-
Age @ 50% maturity	11.6 years	-	-
Age @ 95% maturity	16.8 years	-	-

It should be noted that these parameter estimates do not necessarily reflect the individual growth, but rather reflect the current size-at-age patterns at a coast-wide perspective. The actual size-at-age data could be substituted here, but for the purposes of exploring how the SPR-based reference points are sensitive to changes in size-at-age, it is more convenient to use a parametric growth function to describe size-at-age.

Survivorship to a given age is a function of the instantaneous natural mortality rate, which is assumed to be sex-specific. There is also a provision in the model to allow for size-dependent natural mortality rates where instantaneous natural mortality rates decrease or increase with size. For an unfished population the survivorship to age a is given by Eq. (A2.5) in Table A.2. Under fished conditions, survivorship also includes age-specific fishing mortality by each of K fishing fleets (Eq. A2.6). a

Table A.2. Age-schedule information, where a is the index for age, and A is the plus group age. For clarity, the index for sex-structure is omitted. Length-at-age, survivorship and selectivity are all sex-specific in the age-structured equilibrium model.

Growth & allometry

$$l_a = l_\infty(1-\exp(-k(a-t_0))) + \epsilon_a \quad \text{(A2.1)}$$

$$w_a = \alpha(l_a)^\beta \quad \text{(A2.2)}$$

$$f_a = \frac{w_a}{1+\exp(-(a-a_h)/g_h)} \quad \text{(A2.3)}$$

Survivorship

$$M_a = \hat{M}\left(\frac{\ln(t_2)-\ln(t_1)}{k}\right)^c$$

where

$$t_1 = \exp(k(a+1)) - 1$$

$$t_2 = \exp(k(a+2)) - 1 \quad \text{(A2.4)}$$

$$\iota_a = \begin{cases} 1 & , a=1 \\ \iota_{a-1}\exp(-M_{a-1}) & , 1<a<A \\ \dfrac{\iota_{a-1}\exp(-M_{a-1})}{1-\exp(-M_a)} & , a=A \end{cases} \quad \text{(A2.5)}$$

$$\hat{\iota}_a = \begin{cases} 1 & , a=1 \\ \hat{\iota}_{a-1}\exp(-M_{a-1}-\sum_k f_k v_{a-1,k}) & , 1<a<A \\ \dfrac{\hat{\iota}_{a-1}\exp(-M_{a-1}-\sum_k f_k v_{a-1,k})}{1-\exp(-M_a-\sum_k f_k v_{a,k})} & , a=A \end{cases} \quad \text{(A2.6)}$$

Fisheries selectivity

$$v_{a,k} = \left(\frac{1}{1-\gamma}\right)\left(\frac{1-\gamma}{\gamma}\right)^{\gamma} \frac{\exp(\tau\gamma(\mu - x_a))}{(1+\exp(\tau(\mu - x_a))} \quad \text{(A2.7)}$$

$$s_{a,k} = v_{a,k}\,(r_{a,k} + (1 - r_{a,k})\delta_k)$$

where

$$r_{a,k} = \frac{1}{1+\exp(-(l_a - \text{MSL})/\sigma_a)} - \frac{1}{1+\exp(-(l_a - \text{USL})/\sigma_a)} \quad \text{(A2.8)}$$

$$\sigma_a = 0.1 l_a$$

Fishery selectivity

Fisheries selectivity is modeled as a joint probability distribution where both the size at capture and the size-at-retention are used to compute the age-specific selectivity. The probability of capturing an individual of a given age a in fishery k is given by (A2.7), and the probability of an individual dying due to fishing is given by the joint probability defined in (A2.8), where sa,k is the age-specific fisheries selectivity which includes both the probability of being captured (va,k) and the probability of retaining an age-a individual given it was captured (ra,k). MSL and USL are the minimum and optional upper size limits for Pacific halibut.

A flexible exponential logistic function (Thompson, 1994) was used to approximate the selectivity functions used for size-selective fishing. The assessment model actually uses age-based selectivity that varies over time. For this work it is necessary to consider length-based selectivity to understand the relative impacts of changing size-limits and the cumulative effects of size-selective fishing. The exponential logistic model is defined by (A2.7). The three parameters for this function (μ, τ and γ) were estimated by fitting the above model to the age-based selectivity curves used in the 2014 stock assessment model using least squares. The function is conditioned on the mean length-at-age la and . Note that $\gamma = 0$ represents the standard asymptotic logistic function and $\gamma >$ 0 implies some level of dome-shaped selectivity. Lastly, selectivity for ages greater than 15 years of age (+ Age, or asymptotic age) are assumed to be the same as age 15. Estimated parameters for the selectivity functions are listed in Table A.3 along with the asymptotic age, minimum size limit and assumed discard mortality rate (DMR).

The retention probability ($r_{a,k}$) is a function of the mean and standard deviation in length-at-age and the legal size-limit(s) for a given fishery k. A logistic function is used model the probability of retaining a halibut of a given age, where the standard deviation in the 50% retention probability is approximated by the standard deviation in length-at-age, which is assumed to have a coefficient of variation equal to 0.1.

It is also possible to substitute this simplification with an empirical age-length key, or a parametric age-length key, rather that using a simple logistic function to approximate the probability of a given age being greater than, or less than, the legal size-limit(s).

Table A.3. Selectivity parameters for each gear type, the plus group age in which the same selectivity is assumed for all ages and older, the minimum size limit and the assumed discard mortality rate (DMR).

Fishery	mu	tau	gamma	+ Age	Size Limit (cm)	DMR (δ_k)
Commercial (ITQ)	68.326	3.338	0.000	30	82	0.16
Bycatch (PSC)	38.409	4.345	0.072	15	NA	0.80
Sport (SPT)	69.838	5.133	0.134	15	82	0.20
Personal use (PER)	69.838	5.133	0.134	15	NA	0.00

Equilibrium Model

Equations for the full age-structured equilibrium model are documented in Table A.4, where the index for sex is omitted from the equations for clarity. For example age-specific total mortality rates (Z_a) are calculated independently based on sex-specific natural and fishing mortality rates. Two key input parameters into this model are the unfished recruitment (R_0) and the steepness (h) of the stock-recruitment relationship. Steepness is only absolutely necessary if MSY-based reference points are desired, and less essential if the harvest policy is based on SPR-based reference points.

Age-specific Rates

Age specific total mortality rate is defined by (A4.1), and the annual survival rate is given by (A4.2). O_a is the annual discrete mortality rate (A4.3). The following two terms are the age-specific fractions of the total mortality in numbers (A4.4) associated with fishery k, and the age-specific fractions of total mortality in units of weight (A4.5). All of these quantities serve as temporary vectors for the incidence functions and their derivatives.

Incidence Functions

The incidence functions represent an approximation to the integral of the life-time contribution to various quantities such as yield or spawning biomass. For example, for each recruit the life-time reproductive output can be measured as the sum of products between the survivorship to a given age and the age-specific female mature biomass (A4.6). The life-time reproductive output in a fished population is defined by the survivorship under some non-zero fishing mortality rate (A4.7). Equations (A4.8) and (A4.9) represent the age-specific vulnerable numbers and age-specific vulnerable biomass, respectively, for a given fishery k.

Per-Recruit Functions

The spawning potential ratio is represented as the ratio of female spawning stock biomass relative to the expected female spawning stock biomass subject only to natural mortality. This ratio is computed using the female spawning biomass per recruit. The spawning potential ratio (SPR) is given by Eq. A4.10. In deriving the mortality and yield per recruit for fishery k, the underlying model assumes that both fishing mortality and natural mortality are occurring simultaneously. The Mortality Per Recruit (MPR_k) in fishery k is defined by the product of fishing mortality rate in fleet k, and numbers per recruit that die due to fishing (A4.11). Similarly, the Yield Per Recruit (YPR_k) is the product between fishing mortality rate in fleet k and the age-specific weight (A4.12).

Equilibrium Outputs

All equilibrium model outputs are based on per-recruit functions and the corresponding equilibrium recruitment that results from the vector of fishing mortality rates f_k. The previous pre-recruit functions allow for the calculation of absolute yield, biomass, and mortality in terms of numbers by multiplying the equilibrium recruitment. To calculate the equilibrium recruitment, the underlying structural model is the Beverton-Holt model parameterized using steepness and the unfished recruitment (A4.13) and uses the inverse of the SPR as the basis for spawning stock status. The equilibrium biomass for a given vector of fishing mortality rates is given by (A4.14). The long-term sustainable yield in units of weight for fishery k is given by (A4.15), and in absolute numbers is given by (A4.16).

Table A.4. Age-structured equilibrium model in which harvest policy calculations are based on. For clarity, the index for sex is omitted.

Age-specific rates	
$Z_a = M_a + \sum_k f_k s_{a,k}$	(A4.1)
$S_a = \exp(-Z_a)$	(A4.2)
$O_a = 1 - S_a$	(A4.3)

$P_{a,k} = \frac{s_{a,k} O_a}{Z_a}$	(A4.4)
$Q_{a,k} = w_a P_{a,k}$	(A4.5)
Incidence functions	
$\phi_E = \sum_{a=1}^{A} \iota_a f_a$	(A4.6)
$\phi_e = \sum_{a=1}^{A} \hat{\iota}_a f_a$	(A4.7)
$\phi_{P_k} = \sum_{a} \hat{\iota}_a P_{a,k}$	(A4.8)
$\phi_{Q_k} = \sum_{a} \hat{\iota}_a Q_{a,k}$	(A4.9)
Per-recruit functions	
$\text{SPR} = \frac{\phi_e}{\phi_E}$	(A4.10)
$\text{MPR}_k = f_k \phi_{P_k}$	(A4.11)
$\text{YPR}_k = f_k \phi_{Q_k}$	(A4.12)
Equilibrium outputs	
$R_e = R_0 \frac{\kappa - \phi_E/\phi_e}{\kappa - 1}$ where $\kappa = \frac{4h}{1-h}$	(A4.13)
$B_e = R_e \phi_e$	(A4.14)
$Y_k = R_e\,(\text{YPR}_k)$	(A4.15)
$P_k = R_e\,(\text{MPR}_k)$	(A4.16)

Algorithm for Estimating f_k given a target SPR (F*)

The equilibrium model defined in Table A.4 requires a vector of fishing mortality rates (f_k) in order to determine the age-specific fishing mortality rates via the survivorship calculations in

(A2.6) and the defined selectivity curve for fishery *k*. From the perspective of a single fishing fleet, represented by a single selectivity curve, determining the fishing mortality rate that achieves the target SPR is fairly straight forward. The simplest approach is to loop over discrete values of the fishing mortality rate and calculate the corresponding SPR ratio and determine which fishing mortality rate corresponds to the target SPR. Let F* denote the fishing mortality rate that corresponds to the target SPR; this is also termed $F_{SPRxx\%}$ and is used as a proxy for F_{MSY}, where xx corresponds to the target SPR. In the case of two or more fisheries, including bycatch users, determining F* is not so straight forward and the algorithms differ for dealing with fixed PSC limits or abundance-based PSC limits. The NPFMC uses 35%as the default Target SPR, the Pacific Fisheries Management Council (PFMC) using a default Target SPR of 40%, and the IPHC does not have a specified target SPR but instead uses

Fixed PSC limits

For a fixed PSC limit for a specified fishing fleet, the corresponding fishing mortality rate for that fleet has to be calculated conditional on the fishing mortality rates of other fleets and the target SPR. One approach to this numerical problem is to use non-linear optimization to estimate the vector of fishing mortality rates that satisfies two constraints based on (1) the target SPR, and (2) the PSC limit. For example, consider minimizing the following quadratic function:

$$g(\vec{f}) = (\phi_e(\vec{f})/\phi_E - \text{SPR}^\star)^2 + \sum_{PSC_k \neq 0} (Y_k(\vec{f}) - \text{PSC}_k)^2 \qquad \text{(A1)}$$

where SPR* is the target SPR. Equation A1 is a function of the vector of fishing mortality rates (f_k) and can have an infinite number of solutions in cases where there are no catch limit constraints (i.e., PSC limits) for all but one of the fisheries. For example, consider the case of three fisheries (e.g., commercial halibut fisheries, recreational fisheries, and bycatch fisheries) that each have their own unique fisheries selectivities, and the bycatch fishery has a fixed PSC limit of say 100 units. From this 100 units, the fishing mortality rate for the bycatch fishery is largely determined by the PSC limit, but it's also determined by the relative fishing mortality rates of commercial and sport fisheries, and more importantly how the composition of the catch (via selectivity) differs between these gear types and how the catch is divided among these two gear types. This is the primary challenge in developing a harvest policy when there are no catch sharing agreements or sector-based allocations. If, however, there are catch sharing agreements or allocations, then Equation A1 does have a unique solution and can be used to estimate the vector of f_k's.

Assuming there is some sort of catch sharing, or allocation, agreement in place, then to proceed with estimating the corresponding fishing mortality rates that is internally consistent with achieving the SPR target is done by minimizing (A1). If there are *K* fishing fleets, and at least one of these fleets is allowed to harvest annually the PSC limit, the estimating the vector of fishing mortality rates proceeds with an initial guess for F*, and then determine the fleet specific fishing mortality rates conditional on the differences in selectivity and allocation (A_k) using the following algorithm:

Step 1: set initial values of $\lambda_k = 1$

$$f_k = \lambda_k F^\star$$

Step 2: calculate survivorship using (A2.6)

Step 3: calculate incidence function (A4.9)

Step 4: update λ_k based on allocations that have no PSC limit (Algorithm 1)

$$\lambda_k = \frac{\phi_{Q_k}}{\left(\sum_k \frac{A_k}{\phi_{Q_k}}\right)\sum_k \phi_{Q_k}}, \quad \text{where } A_k \text{ is the allocated proportion}$$

Step 5: repeat steps 2-4, until λ_k have stabilized (4-8 iterations).

The use Algorithm 1 converges in just a few iterations depending on how different the selectivities are among fishing fleets and the differences in allocations. The F* multiplier (λ_k) can only be calculated for cases in which there is no fixed PSC limit.

Abundance Based PSC limits

For cases in which the abundance-based PSC limits are based on a fixed exploitation rate policy (i.e., the PSC limit is based on a harvest rate that is a function of stock status), there also needs to be some sort of allocation (A_k) arrangement, and these allocations can be based on yield in units of weight, or in numbers of individual halibut, or based on spawning capital. The same Algorithm 1 can be used to solve for the corresponding fishing mortality rates for each fleet, but the objective function is simplified to only address the target SPR*.

$$g(F^\star, A_k) = (\phi_e(F^\star, A_k)/\phi_E - \text{SPR}^\star)^2 \qquad \text{(A2)}$$

where F^* is average fishing mortality rate for all fleets combined given the allocation arrangement (A_k).

References

Thompson, G. 1994. Confounding of gear selectivity and the natural mortality rate in cases where the former is a non-monotonic function of age. Canadian Journal of Fisheries and Aquatic Sciences, 51(12):2654–2664.