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Comprehensive incentives for reducing Chinook salmon bycatch in the Bering Sea walleye Pollock fishery: Individual tradable encounter credits

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A B S T R A C T

After record salmon bycatch in 2007 by the Eastern Bering Sea and Aleutian Islands fishery for walleye Pollock, the North Pacific Fishery Management Council (NPFMC) concluded that additional management strategies were necessary to further control salmon bycatch. The Preliminary Preferred Alternative (PPA) was selected in April 2009 and implemented in January 2011 as Amendment 91. In this paper, we present the original comprehensive bycatch credits allocation and trading plan as designed by the first author as commissioned by the Alaskan Pollock Fleet for Chinook salmon, the Comprehensive Incentive Plan (CIP). The CIP, which uses individual (vessel-level) tradable encounter credits (ITEC), included incentives that make up the backbone of Amendment 91/PPA. While salmon bycatch has been reduced since the implementation of the PPA, the current amendment does not have individual vessel incentives that vary with the vulnerability of salmon populations. The CIP approach presented here provides robust vessel-level incentives to reduce Chinook salmon bycatch under all levels of salmon abundance, but particularly when salmon populations are at their lowest levels and are most vulnerable. The specific financial incentive structure in the full plan, with trading of by-catch liabilities among vessels, can be applied well in other fisheries where bycatch threatens both sustainability and profitability.

1. Introduction

1.1. The BSAI walleye Pollock fishery

The Eastern Bering Sea and Aleutian Islands (BSAI) fishery for walleye Pollock (*Theragra chalcogramma*) yields gross ex-vessel revenues in excess of $300 million and is arguably, the premier U.S. fishery. Over time, this fishery has slowly been rationalized, with the last major change occurring in 1998 with the passage of the American Fisheries Act (AFA) (AFA, 1998). This regulation established permanent sector allocations of the total allowable catch (TAC) in addition to placing a moratorium on the entry of new vessels, setting parameters for the formation of cooperatives within sectors and providing funds to buy out nine of the twenty-nine then active catcher-processors. All sectors quickly organized under inter-cooperative agreements – civil contracts – that created sub-sector allocations to each firm. Sub-sector allocations share many of the characteristics of individual fishing quotas (IFQs): they represent an assured opportunity to harvest a known fraction of the TAC and they can be sold or leased within their sector. Since implementation of the inter-cooperative agreements, the catcher boat and catcher processor fleets have consolidated and become more economically efficient, utilization rates (pounds of finished product per pound of fish caught) have increased, production has shifted towards higher-value product forms, and economic returns have increased (Criddle and Macinko, 2000; Anderson, 2002; Felthoven, 2002; NPFMC, 2002; Wilen and Richardson, 2008).

1.2. Chinook salmon bycatch

The walleye Pollock fishery uses mid-water trawls to target schools of fish. This fishery has very low bycatch rates (e.g., 1.1% by weight in 2006 and 1.2% by weight in 2007) and even lower

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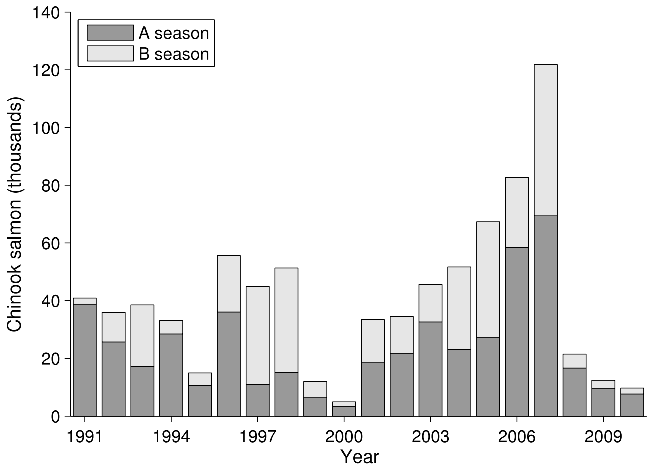

Fig. 1. Chinook salmon bycatch in the BSAI Pollock mid-water trawl fishery, 1991–2010.

discard rates (e.g., 0.28% in 2006 and 0.30% in 2007) (Hiatt et al., 2008). Nevertheless, the magnitude of walleye Pollock catches in the Bering Sea is so large that even small bycatch rates represent substantial levels of bycatch mortality. In 2007, for example, bycatch mortality included 264 mt of Pacific halibut (*Hippoglossus stenolepis*), 338 mt of Pacific herring (*Clupea pallasi*), 3.8 thousand crabs (*Paralithodes sp*., *Chionoecetes sp*., and *Lithodes sp*.), 109.1 thousand Chinook salmon (*Oncorhynchus tshawytscha*), and 83.3 thousand other salmon (*O. sp.*) (Hiatt et al., 2008). In particular, Chinook Salmon bycatch is highly variable from year to year and from the A season (January 20–June 10) to the B season (June 10–November 1) (Fig. 1), making necessary a plan to consistently regulate and lower its impact on the population.

Measures to manage Chinook salmon bycatch date back to the early 1980s when an overall cap of 55,250 Chinook salmon was set for foreign and joint-venture trawl fisheries (NPFMC, 1982, 1983, 1984). Fixed portions of the overall cap were allocated to each nation licensed to operate in the fishery. Any nation that exceeded its annual cap was prohibited from fishing in large parts of the Bering Sea for the remainder of that year. Rather than extend the fixed cap to the domestic fisheries that subsequently displaced the joint-venture fisheries, the North Pacific Fishery Management Council (NPFMC) explored a variety of fixed and triggered spatial closures (NMFS, 1995, 1999; NPFMC, 1995, 1998, 2005). Failure of these measures to avert the large bycatches observed in 2005, 2006, and 2007 provided the impetus for re-adoption of an annual hard cap on Chinook salmon bycatch mortality in this fishery (NPFMC, 2008).

1.3. Amendment 91—The preliminary preferred alternative

After record salmon bycatch in 2007, the NPFMC concluded that additional management strategies were necessary to further control salmon bycatch. The Preliminary Preferred Alternative (PPA) was selected in April 2009 and implemented in January 2011 as Amendment 91. It specified a framework under which one of two binding caps would apply, how those caps would be apportioned among the sectors, and conditions under which they could be apportioned within sectors (NPFMC, 2009).

The PPA apportions 70% of the bycatch cap to the A season and 30% to the B season. All unused A season bycatch allowances can rollover into the B season cap. These bycatch caps are broken down further into four sectors: catcher processors, mothership, shore-based catcher boats and Community Development Quota (CDQ) entities (Ginter, 1995; NRC, 1999). Although these sector allocations are primarily based on sector bycatch history (2002–2006), they also reflect Pollock allocations under the AFA. In effect, sectors with "dirty" fishing history received a somewhat smaller bycatch allocation than their proportionate share of historical bycatch. The Incentive Plan Agreement (IPA), a private contractual arrangement, provides individual incentives for sectors at all bycatch encounter levels to keep bycatch below 60,000 Chinook salmon per year. To ensure bycatch savings, the NPFMC established a sector level performance standard in which each sector's bycatch is evaluated against that sector's hard cap of 47,591 Chinook salmon. For sectors to continue to receive bycatch allocations based on an IPA's 60,000 salmon cap, sectors must not exceed its performance standard in any 3 of 7 consecutive years. If a sector fails the performance standard, it will no longer be allowed to participate in an IPA and will permanently be allocated a percentage allocation of the original 47,591 Chinook salmon hard cap. Vessels that opt out of the ICA face an open access bycatch pool equivalent to their share of an overall hard cap of 28,496 Chinook salmon.

Since the implementation of Amendment 91, Chinook salmon bycatch has declined by 59% compared to bycatch rates from 1991–2010 and in-river Chinook returns have improved in 2015–2016; however, long-term salmon management is still a major concern.

1.4. ICA requirements

To operate under the Inter-Cooperative Agreement (ICA) fisheries hard cap level, sectors or groups of vessels within a sector must prepare a National Oceanographic and Atmospheric Agency (NOAA) fisheries plan that demonstrates the following attributes: (1) it rewards individual vessels that successfully avoid Chinook salmon or penalizes individual vessels that fail to avoid Chinook salmon; (2) it creates incentives to avoid Chinook salmon bycatch at all levels of abundance[1] in all years; and, (3) it creates incentives that will influence fishing decisions even when bycatch is at levels below the hard cap. These requirements were established to address the negative outcomes that can occur when restrictive hard caps alone are used for managing fishery bycatch (Boyce, 1996; Abbott and Wilen, 2009). For example, fleet-wide hard caps with no individual vessel incentives to avoid bycatch can induce a careless race to fish until the bycatch hard cap is hit, thereby jeopardizing the profitability of the fleet (Boyce, 1996; Abbott and Wilen, 2009).

1.5. A comprehensive incentive plan for bycatch avoidance

In this paper, we present the original comprehensive bycatch credits allocation and trading plan, the Comprehensive Incentive Plan (CIP). The CIP, which uses Individual (vessel-level) Tradable Encounter Credits (ITEC) (Sugihara, 2007), also includes incentives that make up the backbone of Amendment 91/PPA. This approach provides robust vessel-level incentives to reduce Chinook salmon bycatch under all levels of Pollock biomass and at any rate[2] of Chinook salmon bycatch. Additionally, the incentives could act cumulatively through time to continually reduce overall Chinook salmon bycatch. The plan is flexible and could be tuned to meet predetermined performance standards through experimental implementation and monitoring. It rewards vessels with consistently low bycatch rates and penalizes those with chronic high bycatch rates (Boyce, 1996). The plan is structured so that the avoidance incentive is greatest during low encounter periods of Chinook

[1] At present, there are no estimates of Chinook salmon abundance in federal waters off Alaska.

[2] The bycatch rate is the number of Chinook salmon caught per metric ton of walleye Pollock.

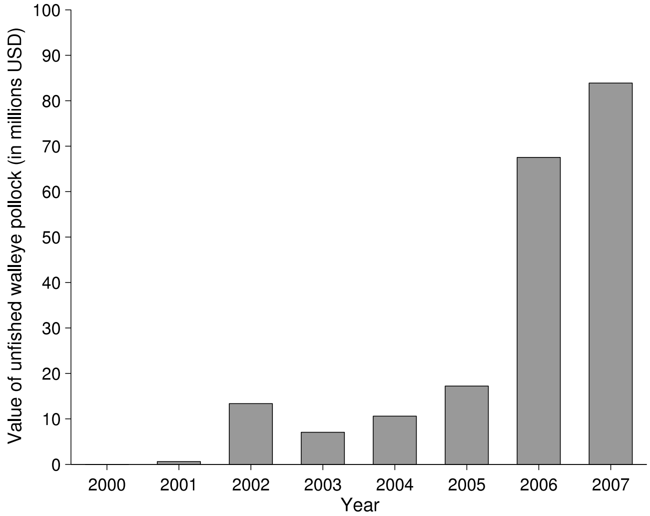

Fig. 2. Annual revenue losses for the inshore sector that would have occurred under the performance-target cap of 47,591 fish. This calculation is based on daily catch data from Sea State Inc. and assuming an ex-vessel value of $0.20/lb for the A season and $0.12/lb for the B season.

Salmon and reflects the actual industry cost of bycatch as determined by lower realizations of Pollock catch.

The incentive plan to reduce Chinook salmon bycatch examined here is analogous to regional pollution credit markets in its use of credit trading to create *short-term* individual vessel incentives to reduce Chinook encounter rates (Rico, 1995). However, stronger individual incentives come from an annual allocation scheme for ITEC that creates *long-term accountability* for bycatch behavior. These allocation incentives promote responsible behavior and operate at all levels of salmon encounter (as required under the PPA).

Specifically, this plan targets the inshore catcher-vessel sector, where daily data on Pollock harvests and Chinook salmon encounters from 2000–2007 show that, without behavioral changes, vessels will run out of credits under the simple hard cap even in low salmon encounter years. If ITEC are expensive or unavailable for sale, the cost of unfished Pollock due to a shortage of credits can be considerable (Fig. 2). The CIP creates incentives for vessel owners to have sufficient ITEC in reserve to avoid the need to buy credits, and to have the option of gaining extra revenue by selling unused credits. These aims can be accomplished through continual bycatch avoidance in order to increase ITEC allocation in future years.

2. Methods

2.1. Model specification: Basic elements of the plan

2.1.1. Initial sector allocation

Sectors are assumed to receive annual allocations of salmon encounter credits in amounts corresponding to bycatch limits (1 ITEC = 1 Chinook) described in the ICA alternative of the PPA under the industry-wide hard cap of 60,000 (NPFMC, 2009). For this analysis, the inshore catcher-vessel sector receives 33,390 credits, of which 20,916 are reserved for the A season and 12,474 credits are reserved until the start of the B season.

2.1.2. Legacy vessel allocation

Individual vessel allocations of ITEC are made separately for each season and it is assumed that 100% of any unused A season credits are carried forward to the B season as an incentive to reduce bycatch in the A season.

A key provision of the CIP is the legacy allocation rule, which rewards vessels with low Chinook salmon encounter rates with extra ITEC in future years and penalizes vessels with high encounter rates by reallocating fewer ITEC in following years. This rule creates a long-term incentive to lower bycatch so that vessels will have extra credits as insurance against future moderate to high salmon encounter years, when additional ITEC will be needed to finish harvesting a vessel's Pollock allocation. This allocation scheme uses the potential costs of unfished Pollock due to shortage of credits as an incentive for individual vessels to reduce salmon bycatch in order to obtain a maximal reserve of credits.

There are many possible implementations of a legacy allocation rule. Indeed, any rule that rewards low bycatch rates with additional credits, penalizes high bycatch rates with fewer credits, and carries forward these rewards and penalties from year to year will suffice. In our plan, we consider the following allocation scheme that distributes credits to individual vessels according to:

$$C_{s,y,i} = P_{s,y,i}F_{s,y,i}I_s \quad (1)$$

$C_{s,y,i}$ = the number of credits that vessel i receives in season s of year y

$P_{s,y,i}$ = the proportional allocation factor for vessel i in season s of year y

$F_{s,y,i}$ = the AFA cooperative catch share (fraction of the sector's Pollock quota) received by vessel i in season s of year y

I_s = the total amount of ITEC for the sector in season s

The proportional allocation factor reflects a vessel's allocation of ITEC relative to its pro rata Pollock share. During the first year of implementation, the proportional allocation factor for each vessel is unity ($P_{s,y1,i} = 1$). Thus, all vessels within a cooperative governed by an ICA would receive an ITEC allocation proportional to their Pollock allocations. In subsequent years, this proportional allocation factor will change (based on bycatch performance) and individual vessels will receive differing ITEC allocations. For vessels with the same Pollock allocation, the relative values of their proportional allocation factors will reflect their relative ITEC allocations; if one vessel's proportional allocation factor is 20% larger than the other vessel, it will receive 20% more credits than the other vessel (assuming both vessels receive the same Pollock allocation).

The proportional allocation factor for each vessel is updated according to:

$$P_{s,y,i} = \alpha + \beta P_{s,y-1,i} + \gamma Q_{s,y-1,i} \quad (2)$$

$P_{s,y-1,i}$ = the proportional allocation factor for vessel i in season s of year y
α = the constant weighting parameter
β = the legacy weighting parameter
γ = the incentive weighting parameter
$Q_{s,y-1,i}$ = the bycatch factor for vessel i in season s of year y

The constants α, β and γ are proportional weights that sum to unity (see Appendix A for a more detailed discussion).

The bycatch factor, Q, is computed as a monotonic function of a vessel's bycatch rate with the following properties: vessels with an average bycatch rate (across all vessels within the same sector) will have $Q = 1$; vessels with higher than average bycatch rate will have $Q < 1$; and vessels with lower than average bycatch rate will have $Q > 1$. The behavior of Eq. (2) is designed such that the proportional allocation factor for vessels with average bycatch rate approaches 1 over time (i.e., ITEC pro-rata to Pollock share). The proportional allocation factor for vessels with lower than average bycatch rates will converge to a value > 1 (with exact value dependent upon bycatch history and parameterization). Similarly, the proportional allocation factor for vessels with higher than average bycatch rates will approach to a value < 1. A particularly nice property of this formula is the presence of asymptotic bounds for P that constrain how much ITEC can vary for any vessel (see Appendix A).

The formula in Eq. (2) is presented in a flexible form to emphasize the fact that with monitoring and feedback, parameters can be adjusted to both reflect and respond to varying magnitudes of bycatch reduction (i.e., changing the incentive structure) to meet performance standards. We note, however, that the actual magnitude of bycatch reduction resulting from any plan involves human behavior, which cannot be known *ex ant* e, except, perhaps, through experimental implementation.

2.1.3. Example parameterization

For all the results presented, we will consider the case where the bycatch function is of the following form:

$$Q_{s,y-1,i} = 1 - \delta z_{s,y-1,i} \tag{3}$$

$z_{s,y-1,i}$ = the z-score (clipped to finite values) for vessel i's bycatch rate relative to the other vessels in the sector
δ = a weighting parameter for the bycatch factor

The weighting parameter, δ, determines the maximum and minimum values for Q, affects the magnitude of fluctuations in proportional allocation factor from year to year, and sets the asymptotic bounds for the proportional allocation factor (see Appendix A).

We consider the following parameterization scheme (although many others are possible with qualitatively similar behavior but slightly different incentive structures): $\alpha = \beta = \gamma = 1/3$, and where $\delta = 2/3$. That is:

$$P_{s,y,i} = \left(\frac{1}{3}\right) + \left(\frac{1}{3}\right) P_{s,y-1,i} + \left(\frac{1}{3}\right) Q_{s,y-1,i} \tag{4}$$

and

$$Q_{s,y-1,i} = 1 - \left(\frac{2}{3}\right) z_{s,y-1,i} \tag{5}$$

This weighting scheme produces a lower bound of 2/3 and an upper bound of 4/3 for P, meaning that a vessel can neither lose nor gain more than 1/3 of its initial allocation (assuming its Pollock share remains constant). A range of 2/3 in the proportional allocation factor is reckoned to provide sufficient motivation for the incentives to be effective but can be adjusted as necessary through tuning of the parameters.

2.1.4. Scaling for vessel size to place small independent vessels on a level playing ground with large vessels and firms

Based on sampling error theory, it is to be expected that the variance in bycatch rates between vessels varies between smaller and larger vessels (Wiens, 1989). Smaller vessels are expected to have higher variability due to smaller sample sizes, increasing their risk of accidentally running into pockets of Chinook salmon and running out of ITEC purely as a result of bad luck. Meanwhile, larger vessels or companies with multiple vessels can average such unusual hauls over a large number of total hauls and total Pollock catch. We tested this assumption using historical data across the Inshore Catcher-Vessel sector, the Mothership sector, and the Catcher-Processor sector, and found our assumption to be true (Fig. 3). Hence, the legacy allocation model was corrected to reflect this difference in bycatch variability across vessel size (see Appendix A for details).

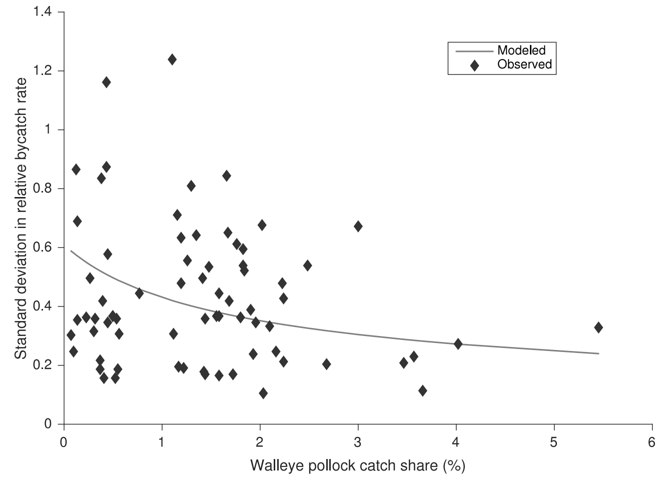

Fig. 3. Smaller vessels show higher variability in bycatch rates. (based on annual data from 2003–2007).

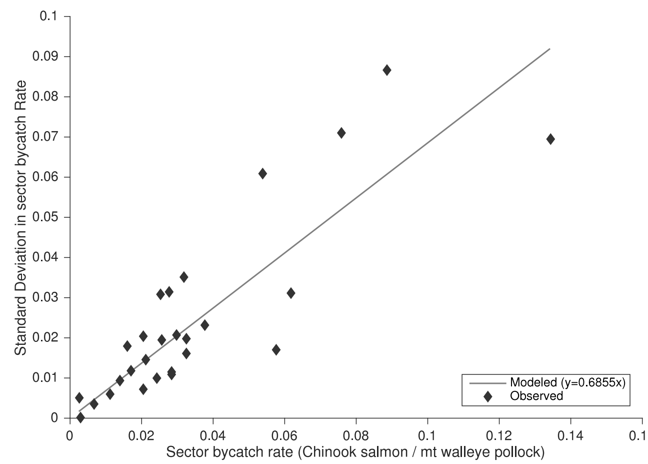

Fig. 4. Standard deviation of bycatch rates as a function of sector total bycatch rate. (Annual data from multiple sectors provided by Sea State, Inc.).

Scaling to avoid penalizing competitive improvement through time. In addition to various forms of sampling variation, the variance in bycatch rates between vessels could also reflect consistent behaviors shown by vessels that can directly influence bycatch rates (e.g., caution in gear deployment, choices of fishing location, tow speed, timing, etc.) (Branch et al., 2006).

One expectation of the CIP is that the variance in the distribution of bycatch rates among vessels will decrease over time as vessels adopt bycatch reducing operational strategies. As this happens, an increased proportion of the variation in bycatch rates will be due to random chance rather than operational choices of individual vessels (Fig. 4). The legacy allocation model was also corrected to account for this variability (see Appendix A for details).

2.2. Transfer rules

2.2.1. ITEC supply and pricing considerations

Here we expose the proposed rules to regulate ITEC trading. The price of encounter credits will likely be determined by market perceptions of supply and demand, which in turn will be driven mainly by the perceived risk of running out of ITEC before completing one's Pollock harvest. Vessels are likely to offer ITEC for sale only after completing their Pollock harvest, when there is no risk of

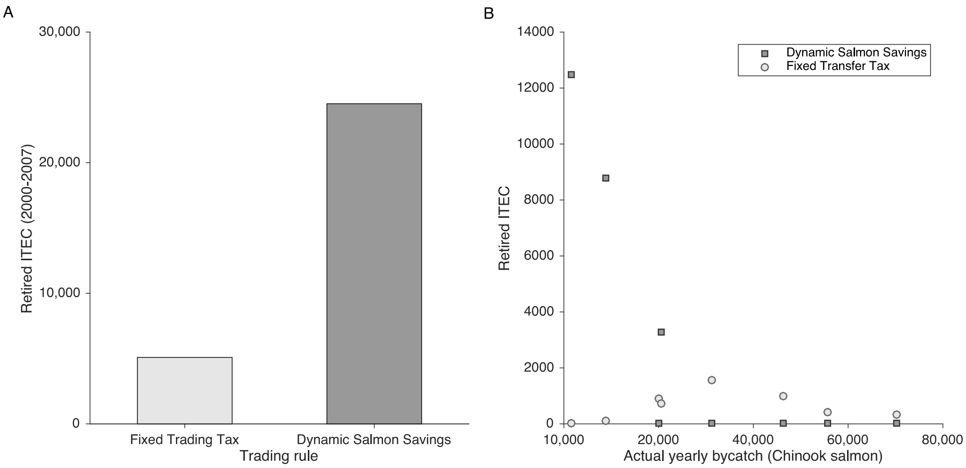

Fig. 5. (A) Number of retired credits over eight years (2000–2007) under two different transfer rules: Fixed Transfer Tax and Dynamic Salmon Savings. (B) Number of retired ITEC vs. yearly bycatch (proxy for salmon abundance). More ITEC are retired during low salmon abundance years using Dynamic Salmon Savings.

(or cost associated with) running out of credits. The specific market conditions will then be entirely dependent on the frequency of salmon encounters throughout the season, which will determine the likelihood that a vessel will sell ITEC.

We examine two types of transfer rules for ITEC: "Buy side" transfer rules and "Sell side" transfer rules.

2.2.2. Buy side transfer limits

To ensure that a poorly performing vessel (one at the 2/3 allocation level, $P = 2/3$) can never obtain more than its original allocation through purchase, we recommend the following buy side transfer limit: "in each season only an amount less than 1/3 of a vessel's credits allocation for that season may be purchased". This means that the worst performers (with lower allocations) will be able to buy fewer credits, while the better performers (with larger initial allocations) are further rewarded with the ability to potentially buy more if needed. This fixed buy side transfer limit is likely to encourage the transfer of Pollock catch shares to "clean" boats who experience unfortunate pockets of Chinook salmon rather than transfer of ITEC to vessels with historically high bycatch rates.

2.2.3. Sell side transfer limits

To limit the transfer of all unused ITEC from cleaner vessels to poorly performing vessels and protect Chinook salmon in low abundance years, we propose two alternative sell side transfer limits. These are Fixed Transfer Tax (FTT) and Dynamic Salmon Savings (DSS). Below we explain what each one encompasses and how they could be estimated.

2.2.4. Fixed Transfer Tax

A fixed sell side transfer tax could be implemented as a monetary or ITEC-based tax on all transfers. With a FTT, a fixed percentage of credits are retired for every ITEC transaction. For our simulation, we used a FTT rate of 20%: if a vessel wished to buy 100 credits, 20% or 20 credits would be retired as the "transfer tax", so that a total of 120 credits would be removed from a seller's pool of ITEC, but only 100 would be transferred to the buyer.

2.2.5. Dynamic Salmon Savings (DSS)

We suggest DSS as another transfer rule that is adaptive to different levels of salmon encounter and will apply to each vessel after it completes its Pollock harvest. This is an adaptive rule designed to create more protection during times of low encounters as compared to FTT rules. In order to implement a DSS strategy, it is necessary to estimate a sector specific Salmon Saving Rate (SSR), which refers to a percentage of the original quota that each vessel needs to have as a reserve and cannot be sold before the final SSR is estimated. The sector specific SSR calculated near the end of the B season is intended to limit the possible abuse of abundant ITEC during low salmon abundance years, while not adversely affecting the completion of Pollock harvest.

DSS consists of two parts. The first part is a provisional savings rule that applies to vessels that sell credits before the SSR is calculated. The provisional savings rule requires that ITEC savings must be held in reserve to meet the maximum SSR. This promotes salmon savings early in the year. For example, if a cap is set so that the maximum SSR is 50%, then prior to setting the dynamic savings rule (e.g., throughout the A season), vessel owners can only sell up to 50% of their residual ITEC. Thus, if a vessel wishes to sell 50 credits early in the year, it must keep an additional 50 credits *in reserve* until the SSR is calculated. This reserve acts as a conservative salmon savings rule governing transfers until the SSR is computed. It operates like "tax withholding" and protects Chinook salmon from exploitation due to excess ITEC until the SSR is posted.

The second part of DSS is the calculation of the SSR in the B season. Numerical experiments with the Inshore sector daily data over an eight-year period suggest that calculating the SSR when 2/3 of the B season sector Pollock quota are caught (2/3 sector TAC) gives the best result for estimating the credits needed to complete the season (see Appendix B for details on calculating the SSR). This is the "estimated total sector bycatch for the B season". This estimate normally occurs between August 29 and Sept 16. We examined the number of credits retired under FTT and DSS schemes and report the results in Fig. 5.

2.2.6. Estimated benefits from simple model without by-catch reduction incentives

Trading encounter credits without explicit incentives to avoid bycatch can increase industry revenues and reduce fleet bycatch. We estimated the potential value of recovered walleye Pollock by applying the following rules: ITEC are only traded after a vessel has finished its Pollock quota for the season; and ITEC are transferred as soon as they are needed and are made available to the vessel(s) that have run out of ITEC and for whom the intrinsic value (non-market value) is highest. The results are presented in Fig. 6.

2.2.7. Hypothetical modeling with incentives

The actual year-to-year magnitude of bycatch reduction in any plan cannot be known *ex ante*. However, for heuristic purposes, we illustrate a plausible outcome using a simple behavioral model

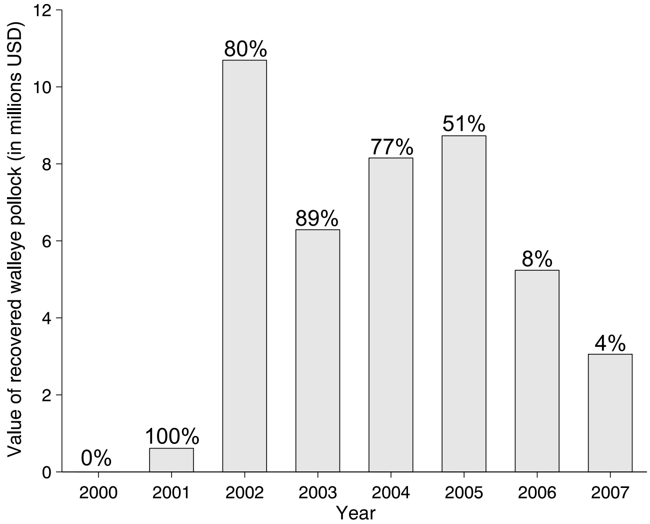

Fig. 6. Potential revenue recovered (for the Inshore sector) from trading ITEC under the PPA performance-target cap. Numbers on top of the bars represent the percentage recovered out of the lost revenue. Even without explicit incentives to avoid bycatch, trading by itself can help to maximize industry revenues.

to simulate the evolution of bycatch patterns. We hypothesized that vessels with high bycatch rates (low Q) would have greater incentive to reduce bycatch rates as a result of the punishment from having ITEC allocation reduced in future years.

Using observed changes in bycatch rates in the inshore sector over the period 2000–2007, we established 25% as an upper bound on the potential change in bycatch rates.[3] This 25% was then scaled by the relative values of Q for each vessel: vessels with a lower value of Q (i.e., relatively high bycatch) were simulated to have greater reductions in bycatch due to a greater incentive to make up for bad performance in the prior year.

The incentive to reduce bycatch is modeled as a function of bycatch rates:

$$incentive_{s,y,i} = \psi/(1 + Q_{s,y,i}) \tag{6}$$

where ψ is the maximum yearly change in bycatch rate and is parameterized as 0.25. Then:

$$incentive\ multiplier_{s,y,i} = 1 - incentive_{s,y,i} \tag{7}$$

and the cumulative incentive multiplier (CIM) is simply:

$$CIM_{s,y+1,i} = CIM_{s,y,i}(incentive\ multiplier_{s,y,i}) \tag{8}$$

$$CIM_{s,y+1,i} = 1 \tag{9}$$

and the incentive adjusted bycatch is:

$$incentive\ adjusted\ bycatch_{s,y,i} = CIM_{s,y,i}(actual\ bycatch_{s,y,i}) \tag{10}$$

Thus, the estimated bycatch levels decrease over time depending on the incentive for each vessel in each year. The actual reduction per year varies between 18.75% and 9.375%, depending on the value of Q, where larger reductions occur for smaller values of Q (high bycatch rates) and smaller reductions occur for larger values of Q (low bycatch rates).

These dynamics are then incorporated into the simulation and run forward to produce the results shown in Figs. 7 and 8.

[3] We computed the median values of changes in bycatch rates for individual vessels across 8 years of data. The minimum of these median values was around 50%; as a conservative estimate, we set half of that, 25%, as the maximum possible reduction in bycatch attributable to behavior (with the majority of vessels in the simulation reducing bycatch far less).

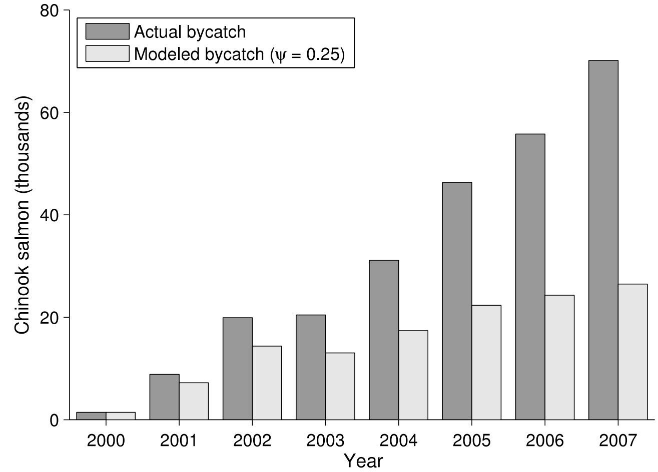

Fig. 7. Effects for the Inshore sector of cumulative market incentives for reducing Chinook salmon bycatch.

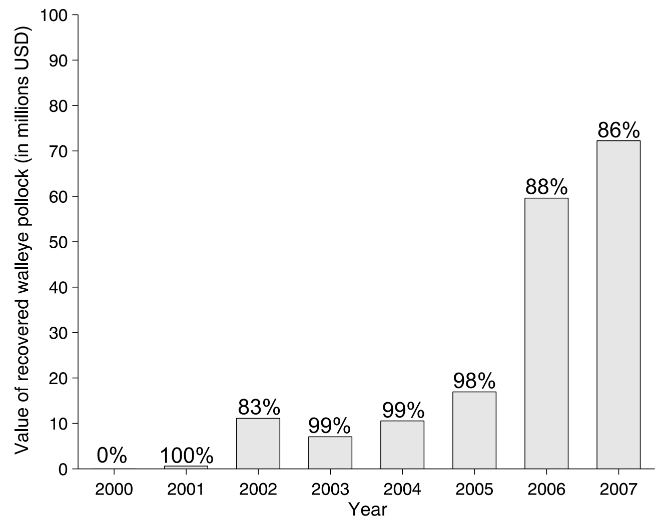

Fig. 8. Potential revenue recovered (for the Inshore sector) from trading ITEC and modeled incentives to avoid bycatch under the PPA performance-target cap. Numbers on top of the bars represent the percentage recovered out of the lost revenue.

3. Results

3.1. Historical data

Data from 1991–2010 show the variability of annual salmon bycatch spanning from 4,961 to 121,758 individuals when accounting for both, A and B seasons (Fig. 1). Such levels of bycatch frequently limit the ability of fishing vessels to fish all of their Pollock quota, incurring losses of up to 83.9 million USD per year for the entire fleet (Fig. 2). Our framework proposes a mechanism to incentivize the reduction of bycatch by implementing a competition-based incentives system, primarily supported by the creation of ITEC. This system is intended to continuously improve total bycatch of the fleet, as well as allow a recovery of Pollock value that would otherwise be lost with a fixed quota.

3.2. Fixed Transfer Tax vs. Dynamic Salmon Savings systems

In our simulations of the number of credits retired under a FTT scheme and DSS for the inshore catcher-vessel sector, we found that a FTT scheme would have retired a total of 5089 ITEC between 2000–2007. In contrast, a DSS scheme could have retired a total of 24,517 ITEC in the same period of time, almost 5 times more credits than FTT over a span of just eight years (Fig. 5A). We also found that a DSS scheme is particularly effective during years of low salmon encounter, with up to 12,483 ITEC retired per year (Fig. 5B).

3.3. Estimated benefits from simple model without by-catch reduction incentives

By applying the simple rules described in the methods where ITEC are only traded after a vessel has finished its Pollock quota and transferred as soon as they are needed, we estimated that the industry could have recovered a minimum of 0.6 million USD in 2001 and a maximum of 10.7 million USD in 2001 (Fig. 6). In 2001, this value would have represented a recovery of 100% of the amount that was lost due to shortage of bycatch quota (Fig. 2), while in 2007 it would have represented just 3.6% of the lost value. On average, 58% of the lost value could have been recovered throughout the whole time period.

3.4. Estimated benefits with modeled incentives

We also estimated the total bycatch and recovered value from unfished walleye Pollock following our full incentives structure, where $\psi = 0.25$. We estimated that a minimum of 0.6 million USD would have been recovered in 2001 from the walleye Pollock fishery, while a maximum of 72.2 million USD could have been recovered in 2007 (Fig. 8). Such recoveries represent 100% and 86% of the reported lost values for the fishery in those years respectively. Additionally, on average 94% of the lost value could have been recovered throughout the whole time period.

4. Discussions

4.1. Legacy Allocation Rule

In this work, we present a comprehensive incentive plan to reduce Chinook salmon bycatch in the Alaskan Pollock fishery through the allocation and trading of Individual Tradable Encounter Credits (ITEC). One of the key points of our proposal is the legacy allocation rule, which promotes continuous competition among individual vessels, fostering consistent bycatch reductions. For example, if a vessel is near the top of the pack (i.e., one of the highest proportional allocation factors), it will remain near the top of the pack only if it performs consistently well relative to the fleet. If such a vessel experiences an average bycatch rate, its proportional allocation factor will decrease in subsequent years. The CIP is designed so that vessels are unable to "slack off" and still maintain an augmented ITEC allocation. Increased allocation ($P > 1$) can only be maintained through continuously low bycatch rates, and so incentives to reduce bycatch are always present. Furthermore, because vessels with low bycatch rates receive proportionally more credits than vessels with high bycatch rates as a result of reallocation, the cleaner fishing vessels will be able to realize more of their Pollock share, causing bycatch rates for the fleet as a whole to continuously decrease. Conversely, if a vessel is at the bottom of the pack in terms of bycatch avoidance, it will remain there only if it stays at the bottom relative to other vessels in each year. It can dig out of this hole by consistently moving its behavior closer to the mean. This constant competition will stimulate a steady decline in the industry average bycatch rate.

The second term of the allocation formula (2) is the legacy component that incorporates past behavior into the calculation of ITEC allocation for the current fishing season. This component serves an important function in moderating the long-term effects of bycatch performance on ITEC reallocation to promote consistent bycatch reduction over multiple fishing seasons. One of the problems with any performance-based reward/penalty system is that the measurement of performance is always subject to noise. In this case, random variation in bycatch rates (e.g., sampling error or bad/good luck) can be difficult to separate from variation due to operational choices. The legacy component addresses this problem by causing the reward/penalty for bycatch behavior to decay with time. This has two effects: (1) fluctuations in bycatch rate due to chance events will wash out over time and (2) rewards/penalties compound only as a result of consistently low or high bycatch. Additionally, the legacy component guarantees that even in low salmon encounter years, individual vessels will not abuse the high availability of ITEC and increase by-catch because initial allocation in following years will be dependent on their previous year performance.

4.2. Sell side transfer rules. Fixed vs. DSS plans

Without a transfer mechanism, some individual vessels will run out of ITEC, resulting in a portion of the walleye Pollock TAC that could go unfished leading to significant revenue losses for the fishery (Fig. 3). The risk of catastrophic losses due to unharvested walleye Pollock in any given year should provide strong financial motivation for industry to adopt a plan for transferring ITEC, in addition to incentivizing individual vessels to lower bycatch rates so that they may insure themselves against revenue loss (via increased ITEC allocation and/or reduced need for ITEC). Thus, the second component of our management proposal is the regulation of ITEC trading through buyer and seller rules. These rules should prevent the abuse of ITEC in low salmon encounter years, especially at the end of the season, and to help promote the completion of the fleet's Pollock quota by allowing transfers between vessels. We propose that ITEC prices will be market driven, as a combination of demand throughout the season and salmon encounter rates. For example, as individual vessel owners become sellers of surplus ITEC towards the ends of the season, the supply of ITEC will increase, which will put downward pressure on ITEC's prices. During times of moderate to high Chinook salmon encounters, this rising supply will be met with rising demand and prices could actually increase towards the end of the season.

On the sellers' side, we explored two strategies: Fixed Transfer Tax (FTT) and Dynamic Salmon Savings (DSS). We found that a FTT would not be desirable in this industry as it can potentially limit the Pollock harvest that might otherwise occur if ITEC were optimally distributed with a DSS plan. A FTT is also not desirable for Chinook salmon conservation as it is dependent upon transfers taking place. During years of low salmon encounter, very few transfers will take place, reducing the effectiveness of a FTT when it is most needed. Transfers of ITEC would occur more frequently and in greater volume during years of moderate to high salmon encounter; at these times, a fixed transfer tax would increase the burden of an already limited ITEC supply. Conversely, a DSS plan could help to reduce bycatch on average by 63% and recover Pollock fishery value in up to $25 million dollars annually.

4.3. Differences with current implementation in the Alaskan Pollock fishery

The Comprehensive Incentive Plan provides a combination of short-term and long-term incentives to promote bycatch reduction of individual vessels. These incentives come in the form of changes in ITEC allocation based on bycatch performance (long-term incentives) and additional profits or expenses from the trading of ITEC (short-term incentives). These broad incentives have been mirrored in the Preliminary Preferred Alternative (PPA), a simplified version of the suggested CIP for the BSAI Pollock fishery that was implemented in 2011 (UCBA, 2009). While the exact implementation details differ, the SSIP exhibits an incentive structure broadly analogous to the CIP: namely a future increase in the availability of credits for low rates of Chinook salmon bycatch and the inclusion of a market for trading credits. However, one key difference between these plans is the presence of direct competition between vessels in the CIP plan to encourage continuous lowering of fleet-wide bycatch rates. Whereas vessels continually compete to lower bycatch regardless of its actual level in the CIP, vessels participating in the SSIP do not directly compete with each other but create a reserve of Salmon Savings Credits (similar to ITEC) by having bycatch below a fixed performance. Under the PPA, vessels which have high bycatch rates (relative to the fleet), but which do not exceed their pro-rata allocation of the 47,591 hard cap, are not penalized with a reduced allocation in future years. Vessels are only penalized with a reduced allocation if they purchase credits from other vessels. Although eliminating head-to-head competition between individual vessels reduces the incentive towards cumulative lowering of bycatch rates, the simplified credit system under the PPA may help minimize the possibility of any idiosyncratic behaviors arising from competition. Regardless of details, in principle, comprehensive incentive programs that have an allocation component and a trading component represent an effective rational framework for controlling bycatch with simple economic incentives, particularly if the trading leads to transparent organized markets that enhance industry revenues and reduce the costs of regulation and enforcement.

4.4. Enforcement and compliance

As expected from any management plan that limits fishing activities and given the restrictions imposed by Amendment 91 on the Bering Sea pollock fishery, there was an increase in under- and misreporting on the amount of Chinook salmon bycatch. Given this, in 2011 there were some significant changes in the monitoring requirements in the Bering Sea pollock fishery to enable Chinook salmon bycatch accounting. These changes include: (1) requirements for 100-percent observer coverage for all vessels and processing plants; (2) salmon retention requirements; (3) specific areas to store and count all salmon, regardless of species; (4) video monitoring on at-sea processors; and (5) electronic reporting of salmon by species by haul (for catcher/processors) or delivery (for motherships and shoreside processors) (NPFMC, 2015). In recent years, NMFS has identified problems with ensuring that all species of salmon are retained and counted, thus the enforcement and compliance discussions are still going on and being revised to further improve the applicability of the management regulations (NPFMC, 2015).

4.5. Future scalability to multiple species

The CIP framework for bycatch reduction is both general and scalable. It can be extended to other bycatch species within an individual fishery or across multiple fisheries to further increase industry efficiency. This benefit is analogous to that seen in New Zealand from multispecies trading of fishery quotas (Dewees, 1998).[4] It arises when ITEC for multiple bycatch species can be traded between vessels that have complementary needs (e.g., excess species B ITEC can be traded for limiting species A ITEC, and this can occur in principle across vessels, sectors, and fisheries where bycatch patterns may be conducive to such optimizations). Such trading can diminish the unfair economic penalties associated with random high encounters in one particular bycatch species at one particular location, and lead to higher overall industry operating efficiency (as well as lower overall bycatch rates). Indeed, the classical theme of increasing economic efficiency through organized trading of substitutable or fungible assets can be further complemented by the implementation of a tradable catch-share market across fisheries where the beneficial permutations only multiply. Analogous to ITEC, trading multispecies catch shares on an organized exchange can address variability in the spatial and temporal distribution of marine fish stocks.

5. Conclusions

Despite improvements in Chinook salmon bycatch numbers since the implementation of the PPA as Amendment 91 in 2011, we believe that the original comprehensive management strategy plan proposed in this study would further reduce by-catch if implemented correctly. It is difficult to tell, however, whether the complex nature of human behavior and relationships would allow this to happen. Our proposal encompasses two main components: the legacy allocation and trade system. Together, the legacy component and organized transparent markets can enhance industry rationality, increase efficiency and profits, and reduce the costs of regulation and ease of enforcement. Thus, insofar as they help to catalyze organized markets, fungible assets such as CIP ITEC can be transformative, leading the way to better resource stewardship, lower industry risk, and higher profits not only for the case presented in this study, but possibly for other fisheries around the world where by-catch limits their overall profitability.

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Appendix A. Technical issues regarding the allocation formula

Here we examine several properties of the allocation equation:

$$P_{s,y,i} = \alpha + \beta P_{s,y-1,i} + \gamma Q_{s,y-1,i} \tag{2}$$

Scaling.

The proportional allocation factor is transformed into number of credits via Eq. (1)

$$C_{s,y,i} = P_{s,y,i} F_{s,y,i} I_s \tag{1}$$

[4] Consider an example where there are two vessels in the same fishery with multiple bycatch species: vessel 1 is better at avoiding bycatch of species A and vessel 2 is better at avoiding bycatch of species B. The vessels can trade respective ITEC allocation with each other to maximize their catch and balance their bycatch obligations.

$C_{s,y,i}$ = the number of credits that vessel i receives in season s of year y
$P_{s,y,i}$ = the proportional allocation factor for vessel i in season s of year y
$F_{s,y,i}$ = the AFA cooperative catch share (fraction of the sector's Pollock quota) received by vessel i in season s of year y
I_s = the total amount of ITEC for the sector in season s

Because different vessels have different shares of the Pollock catch, it is possible for the amount of ITEC distributed within a sector to be different from the sector and season appropriate fraction of the target bycatch level of 47,591. In other words, if all smaller vessels fish with lower bycatch rates and larger vessels fish with higher bycatch rates, then the subsequent reallocation will increase the allocation for the smaller vessels and decrease the allocation for the larger vessels by a fractional amount. This will result in a net decrease in allocated credits for the sector, since the amount gained by the smaller vessels is lower than the amount lost by the larger vessels. Conversely, a net increase in credit allocation for the sector can occur if the larger vessels tend to fish with lower bycatch rates.

There is a negligible,[5] but non-zero possibility that the reallocation would distribute more than a sector's share of the 60,000 hard cap. In such a situation, the amount of ITEC to be distributed can simply be scaled to the 60,000 level. Additionally, sectors may choose to scale the amount of ITEC to the 47,591 level in order to meet the performance criterion of not exceeding the 47,591 target more than three years over any consecutive seven year period.

Upper and lower bounds for proportional allocations.

When the weightings are such that $\alpha = \gamma$ the asymptotic lower and upper bounds on P will depend only on the bounds for Q. Thus, for both Eqs. (3) and (4) the bounds for P are the same (2/3,4/3) when the bounds for Q are [1/3, 5/3] (obtained when $\delta = 1/3$).

Specific forms for the bycatch function Q.

In general, Q can be any monotonic function that rewards low bycatch behavior and that penalizes high bycatch behavior. The performance measure chosen here involves computing a z-score for bycatch rate and converting via linear scaling (Figs. A-1). Vessels with $z < -2$ receive a $Q = 5/3$, and vessels with $z > 2$ receive a $Q = 1/3$. Vessels with $-2 < z < 2$ have $Q = 1 - 1/3z$. Note that this penalty function provides equal incentive for the vast majority ($-2 < z < 2$) of vessels, since the slope of Q is constant for these vessels. Here, the incentive is directly related to the slope of the penalty function: a greater slope indicates a greater change in credit reallocation for the same change in bycatch rate.

An alternative bycatch function was considered that uses each vessel's z-score to compute a cumulative p-value based on a normal distribution (Figs. A-2). This bycatch function would create the highest incentives for vessels near the mean bycatch rate: these vessels can move up and down in Q value more quickly than vessels at the extremes because of the steepness in the penalty function near the mean. However, this type of bycatch function would provide the least incentive for vessels at the extremes to change behavior, whereas a linear function like the one above would be viewed as being fair to all vessels.

[5] Note that $60{,}000/47{,}591 \approx 1.26$. Since the maximum proportional allocation factor (given our parameterization) is 4/3, distributing at the 60,000 level would require the vessels that comprise ~93% of the Pollock TAC to be at the upper limit and the remaining ~7% at the lower limit.

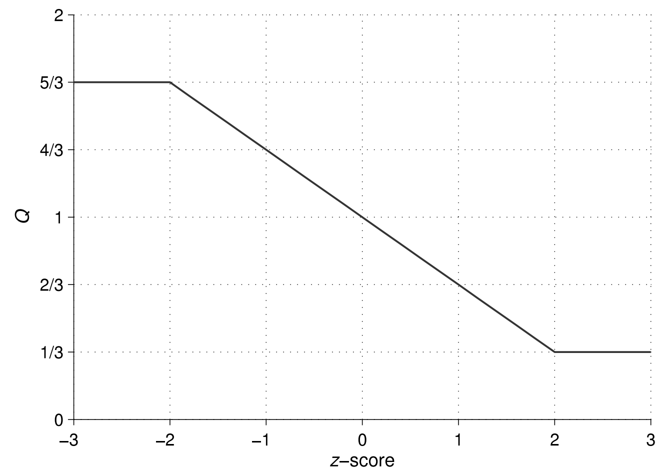

Fig. A-1. A linear penalty function capped at z-scores of +2 and −2. Because the slope of the penalty function is equal for $-2 < z < 2$, most vessels have equal incentive to reduce bycatch.

Computation of z-scores.

The variance in bycatch rates between vessels can be attributed, in part, to chance encounters with pockets of Chinook salmon, and in part to choices by vessel operators that directly influence bycatch rates (e.g., caution in gear deployment, towing speed, choice of fishing location, timing).

One reasonable expectation of the CIP is for the distribution of bycatch rates among vessels to decrease over time as vessels exploit the same behavioral changes to reduce bycatch rates. A larger proportion of the variation in bycatch rates would then be due to random chance and not intentional behavior on the part of vessels. Since z-scores are scaled to the standard deviation of the bycatch rates, large fluctuations in z-scores may occur due to random chance. To mitigate this problem, we use an estimated standard deviation based upon a sector-wide bycatch rate (equivalent to a weighted average of individual vessel's bycatch rates). This calculation is based on historical data across the Inshore Catcher-Vessel sector, the Mothership sector, and the Catcher-Processor sector (Fig. 5).

Because small vessels are subject to more sampling error (Fig. 4), we also use a corrected standard deviation to reduce the effects of random noise due to vessel size. This random noise varies with the inverse square root of $1 + F_{s,y,i}$. Where $F_{s,y,i}$ is the AFA cooperative catch share of vessel i), thus we correct the standard deviation using:

$$\sigma_{s,y,i} = \sigma_{s,y}\sqrt{(1 + 1\backslash n_{s,y})}/\sqrt{(1 + F_{s,y,i})}$$

Where $n_{s,y}$ is the number of vessels in the sector for season s of year y. The adjusted standard deviation, $\sigma_{s,y,i}$, is then used in place of the normal standard deviation, $\sigma_{s,y}$, to calculate the z-score for vessel i.

Convergence rates.

The legacy weighting parameters, β and γ in Eq. (2), affect the rate at which a vessel can change its proportional allocation factor, P, from year to year. The graphs below (Fig. A-3) show the extreme cases realized by two different weighting schemes: (1/3, 1/3, 1/3) and (1/4, 1/2, 1/4).

In the "equal" weighting scheme (1/3, 1/3, 1/3), the legacy component receives less weight than in the "augmented" weighting scheme (1/4, 1/2, 1/4), and incentives are increased (larger yearly changes in allocations). However, fluctuations in allocation due to

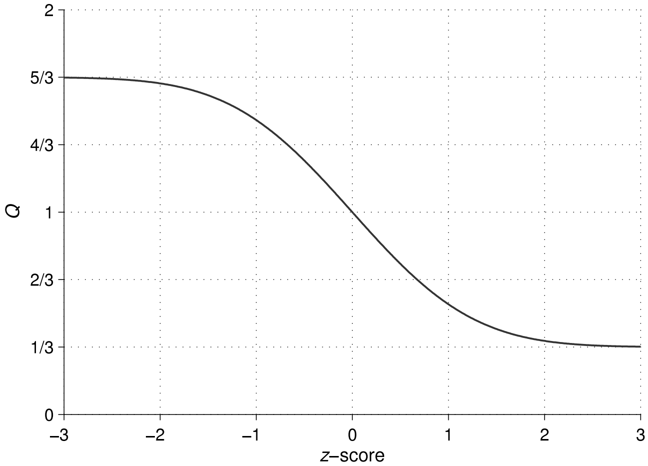

Fig. A-2. A penalty function based on the cumulative distribution function for a Gaussian distribution. The slope is highest in the middle; therefore, the incentives are largest for vessels with average bycatch rates.

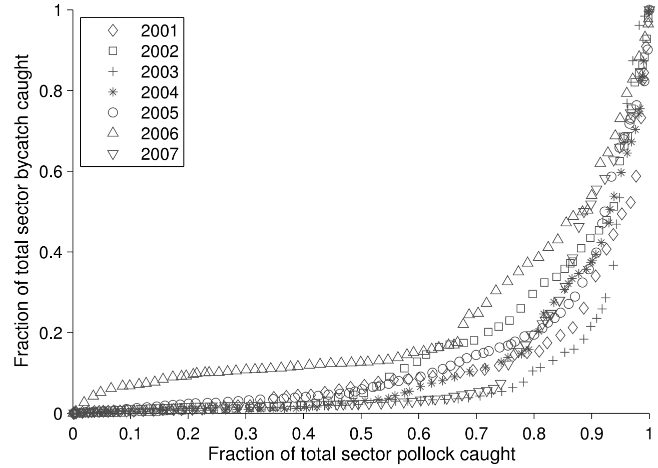

Fig. B-1. Cumulative bycatch as a function of Pollock harvested during the B season.

random noise affecting bycatch rates are also magnified, which decrease the incentives associated with consistent behavior, and should be taken into account when choosing a weighting system.

Alternative parametrizations and parameters' tuning.

Although the analyses presented here are based on the parameters given in Eqs. (4) and (5), different parameterizations are possible that will alter the incentive structure of the plan. In particular, a higher weight given to the legacy component β is a way to minimize the random effects of sampling error in bycatch rates (bad luck encounters) and emphasize the more consistent intentional behavioral component of variation in bycatch rates among vessels. Because the yearly changes are smaller, vessels must do consistently well in order to obtain the maximum possible increase in ITEC allocation. Similarly, vessels that initially have high bycatch are given more opportunities to improve over time. That is, a larger value for β in Eq. (1) helps to sort out the behavioral component from the chance component in determining relative ITEC allocations.

Conversely, a larger value for γ creates stronger short-term incentives to reduce bycatch, as the yearly changes in proportional allocation factor will be larger. Because these weights (α, β, and γ) must sum to unity, they should be viewed as tradeoffs between guaranteed ITEC allocation (α), rewarding/punishing consistent bycatch behavior (β), and rewarding/punishing yearly bycatch behavior (γ).

Appendix B. Technical issues regarding the Fixed Transfer Tax and Dynamic Salmon Savings

Fixed Transfer Tax.

With a Fixed Transfer Tax (FTT), a fixed percentage of credits are retired for every ITEC transaction. For our simulation, we used a FTT rate of 20%: if a vessel wished to buy 100 credits, 20% or 20 credits would be retired as the "transfer tax", so that a total of 120 credits would be removed from a seller's pool of ITEC, but only 100 would be transferred to the buyer.

Dynamic salmon savings.

Under a Dynamic Salmon Savings rule, a percentage of a vessel's remaining credits are retired when that vessel finishes fishing its Pollock quota: this percentage is the Salmon Savings Rate (SSR).

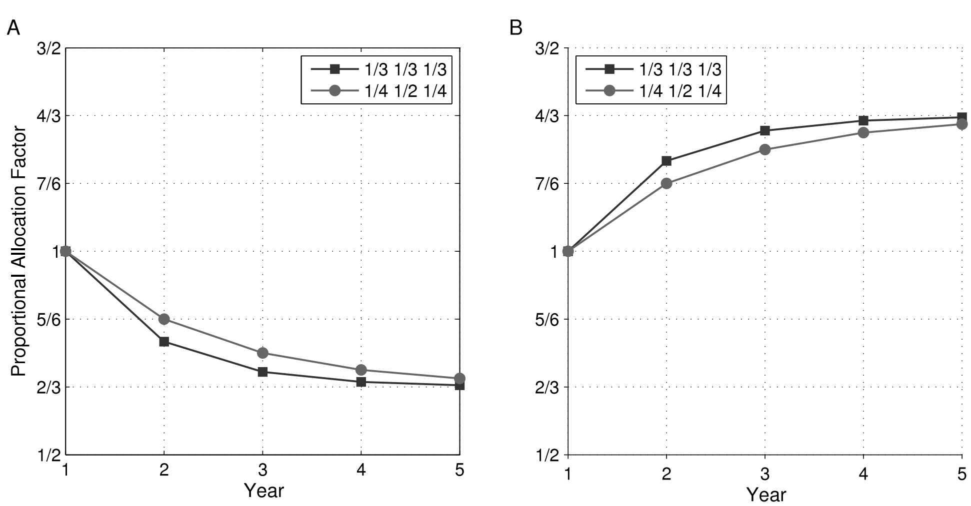

Fig. A-3. (A) Comparison of two weightings of the legacy component, with $Q = 1/3$. (B) Comparison of two weightings of the legacy component, with $Q = 5/3$. In both (A) and (B), convergence to the bounds is slower under the "augmented" weighting scheme (1/4, 1/2, 1/4).

Table B-1
Calculation of SSR for the Inshore Catcher-Vessel sector for years 2000–2007.

Dynamic salmon savings rate (at end of B season)							
Year	A	B	C	D	E	F	G
2000	16-Sep	9859	254	7286	2573	26.1%	711
2001	11-Sep	9812	277	7493	2319	23.6%	2743
2002	5-Sep	10236	1655	19895	(9659)	0.0%	9622
2003	2-Sep	10801	256	7304	3497	32.4%	7144
2004	31-Aug	9716	1890	22010	(12294)	0.0%	20924
2005	29-Aug	9668	4142	42278	(32610)	0.0%	33734
2006	10-Sep	9703	3591	37319	(27616)	0.0%	21179
2007	2-Sep	9826	1465	18185	(8359)	0.0%	33813

A = date when 2 / 3 walleye Pollock caught
B = sector credits remaining (includes 100% carry-forward from A season)
C = bycatch caught (up to the date in A)
D = predicted total bycatch with buffer (for season) (computed as D = 9 C + 5000)
E = estimated surplus credits (computed as E = B − D)
F = allowable salmon savings rate (computed as F = E / B)
G = actual total bycatch (for season)

To prevent vessels from selling credits before finishing fishing and avoiding having credits retired, it is additionally required that vessels who sell credits before finishing fishing reserve the appropriate fraction of credits corresponding to the SSR (or the maximum upper bound on SSR if the SSR has not yet been determined). In our simulation, we used 50% as the maximum upper bound on SSR.

Provisional salmon savings rule.

Note that prior to the completion of fishing and having credits retired based on the SSR, vessels may still transfer credits if an appropriate number of credits are set aside to cover eventual retirement. For example, if a cap is set so the largest Salmon Savings Rate is 50% (a number that historically will not limit the harvest), then prior to setting the SSR, boats that have finished fishing early can only sell up to 50% of their remainder credits. This means that if a vessel wishes to sell 50 credits early in the season, it must keep 50 ITEC in reserve until the SSR has been determined.

Calculating a savings rate.

Numerical experiments with the Inshore daily data suggest that calculating the savings fraction when 2/3 of the sector Pollock quota are caught (2/3 sector TAC) gives the best result in terms of estimating the credits needed to complete the season. This is the "estimated total sector by-catch for the B season". This estimate normally occurs between August 29 and Sept 16 (see Fig. B-1 and Table B-1). This tends to happen later in low salmon abundance years (when fewer transfers are needed) and occurs earlier in moderate to high abundance years.

The "estimated number of surplus credits" in the Table B-1 is the (current number of credits for the sector on the date that the salmon savings rate is calculated) − timated total B season bycatch for the sector + buffer). Here the buffer is 5000, to account for error in the estimates of total sector by-catch.

The final "allowable salmon savings rate" would then be (the number of estimated surplus credits) / (current number of credits for the fleet). It is called an" allowable salmon savings rate" in that under this SSR, the Pollock harvest for the sector would not be limited by the availability of salmon encounter credits. These numbers are shown in the table below. In high abundance years the SSR is 0% and in low salmon abundance years the allowable SSR can be as high as ∼30.0%. That is, in the year 2000, we would be confident of fishing the entire Pollock quota (with margin for error) if the SSR were set at 30.0%. However, such a high rate would put a damper on trading before the rate was posted (albeit, in 2000 no transfers were ultimately necessary).

Table B-2
Number of retired ITEC vs. yearly bycatch (proxy for salmon abundance) for two different sell side transfer rules.

	Retired credits	
Total bycatch	Fixed transfer tax	Dynamic salmon savings
1454	0	12483
8866	91	8776
19923	910	0
20471	735	3258
31136	1563	0
46354	1010	0
55782	437	0
70148	343	0

Simulation results.

Annual data for quantities of ITEC retired as a function of annual bycatch (a proxy for salmon abundance) under both the FTT and DSS schemes are shown in Fig. 5 and Table B.2. Not only is the total quantity of credits retired through DSS higher for this eight-year period (2000–2007), but the quantity of ITEC retired is high in years of low salmon abundance: precisely when the potential for abusing extra ITEC is the highest. Conversely, the quantity of credits retired through FTT is highest in years of intermediate abundance: when the most transactions take place (due to a balance of availability and demand). Increasing the FTT rate to recover more ITEC has the potential of reducing credit transfers in mid-abundance years. The subsequent revenue loss can be extreme if a high FTT rate is chosen.

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