# The role of catch shares in Pacific halibut bycatch reduction in the U.S. West Coast bottom trawl fishery

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## ABSTRACT

Pacific halibut (*Hippoglossus stenolepis)* are a valuable target species in the U.S. and Canada, but are also caught as bycatch in other groundfish fisheries. In 2011, a catch shares (CS) management program was implemented in the U.S. west coast limited entry (LE) bottom trawl fishery, shifting responsibility for catch limits, including P. halibut bycatch, from the fleet to individual vessels. After CS implementation, P. halibut bycatch decreased significantly from an annual mean of 312.5 metric tons (mt) (2007-2010) to 65.6 mt (2011-2014). I hypothesized that this reduction in P. halibut bycatch resulted from changes in fishing behavior initiated by the shift to CS. I evaluated changes in variables associated with P. halibut bycatch, including fishing latitude, depth, duration, and catch of correlated species, before and after CS implementation. Comparisons of associated variables under LE versus CS management showed that significant changes to all variables occurred after CS implementation. To predict and compare relative P. halibut bycatch among LE versus CS hauls, I modeled how associated variables predicted P. halibut encounters, bycatch weight, and mortality for LE data, and re-ran these models for CS data. My results indicate that the relationship between predictor variables and P. halibut bycatch changed under CS from what was observed in the LE fleet. These changed relationships suggest that fishers altered their behavior following the management shift, likely contributing to the reduction in P. halibut bycatch under CS management. This work will help the Pacific Fishery Management Council and International Pacific Halibut Commission understand how CS has changed fishing behavior and P. halibut bycatch in bottom trawl fisheries.

## INTRODUCTION

Fishers often discard portions of their catch at sea, referred to as bycatch, because some species or individuals have relatively low market value or are prohibited by law from being landed (Hall et al. 2000). Bycatch is a significant concern to fishery management and conservation efforts as it produces a number of externalities that threaten the ecological and economic sustainability of fisheries. Negative impacts include declining stock sizes, disrupted ecosystems, and conflicts among fisheries (Hall et al. 2000).

Pacific halibut (*Hippoglossus stenolepis)* are valuable to commercial, recreational, and tribal fisheries on the west coast of the U.S. and Canada, but are also bycatch in fisheries that target other groundfish species (Gustafson 2014; Clark & Hare 1998; Jannot et al. 2015). U.S. federal regulations require groundfish fishers on the U.S. west coast to discard at sea all P. halibut bycatch. The estimated rates of mortality of discarded P. halibut are gear specific (Jannot et al. 2015), but a large proportion do not survive (Gustafson 2014; Clark & Hare 1998). As a result, groundfish fisheries can significantly impact P. halibut stocks and directed fishery yields (Gustafson 2014; Clark & Hare 1998). Although fishers deploy a variety of gears in the U.S. west coast groundfish fishery—bottom and midwater trawl nets, hook and line gears, and fish pots—the bottom trawl sector is responsible for a large proportion of P. halibut bycatch and thus is the focus of this analysis (Jannot et al. 2015).

Scientific observers stationed on U.S. west coast groundfish vessels by the West Coast Groundfish Observer Program (WCGOP) collect information on bycatch of all species, with an emphasis on prohibited species and species of management concern, including P. halibut (NWFSC 2016a). Until 2011, the WCGOP aimed to maintain a minimum observer coverage rate of 20% of groundfish landings in the limited entry (LE) bottom trawl sector (Somers et al.

2015c). Starting in 2011, a catch shares (CS) management program was implemented in the U.S. west coast LE bottom trawl fishery, shifting management from fleet-wide to individual vessel-based catch limits. The CS program divides the total allowable catch of more than 70 species (including P. halibut) into individual shares by species, representing pounds (a.k.a. quota) available for a vessel to catch. Catch shares aim to increase individual fisher accountability and flexibility and end the “race for fish” that exists under more traditional, fleet-wide techniques, resulting in healthier stocks and economic benefits for fishers (NOAA 2010; NMFS 2015; Grimm et al. 2011). The CS program for the U.S. west coast groundfish fleet requires that each vessel carry a National Marine Fisheries Service-certified observer on all fishing trips, resulting in 100% CS trips observed and approximately 99% of CS hauls sampled (Somers et al. 2016).

Because U.S. west coast bottom trawl fishers are prohibited from retaining any P. halibut, this species is managed under an Individual Bycatch Quota (IBQ). Fishers with a federal groundfish permit are allocated IBQ pounds for P. halibut caught north of 40º 10’ N. latitude, taking into account gear-specific P. halibut mortality and survivorship after capture. Pacific halibut caught south of 40º 10’ N latitude are not managed with an IBQ, but the very small amount of P. halibut bycatch in this area was included in this analysis. The U.S. west coast groundfish fishery has seen a significant reduction in P. halibut bycatch since the implementation of the CS program (Jannot et al. 2015). LE vessels discarded an average of 312.5 metric tons (mt) of P. halibut per year from 2007-10, whereas CS vessels discarded an average of 65.6 mt per year from 2011-14 (Jannot et al. 2015). Although some discards survive, this dramatic reduction was also present when comparing only dead P. halibut discards (Jannot et al. 2015). This encouraging result can be used as an important lesson for successfully managing bycatch in fisheries, but also raises many questions.

To better understand the changes observed, this report considers how the fleet-level reduction in P. halibut bycatch is explained at the tow level. I address the question: what are the mechanisms that have contributed to P. halibut bycatch reduction since the implementation of the CS program in 2011? I hypothesized that a number of variables individually or jointly contributed to reducing bycatch with the management shift. These variables include location (i.e. latitude) and depth of fishing, haul duration, and retained catch of species that have previously been shown to be correlated with P. halibut bycatch (see Table 2 for a list of these species) (Heery et al. 2010). I predicted that (a) there were significant changes in these variables between LE and CS management periods and (b) changes in these variables under CS resulted in lower P. halibut bycatch relative to LE hauls. Table 1 outlines the changes to fishing variables that I predicted would contribute to reduced P. halibut bycatch under CS management. These predictions were based on relationships observed in the 2007-2010 LE data.

I first described how variables that are correlated with P. halibut bycatch have changed since the implementation of the CS program. I then developed separate models for P. halibut encounters, bycatch weight, and mortality at the individual haul level in the LE fishery, and re-ran these models for CS fishery hauls. To estimate the effects of each individual variable in predicting bycatch, I used those models to derive expected P. halibut gross bycatch (herein referred to simply as “bycatch”) and dead bycatch (that is, only individuals expected to die due to interaction with fishing gear) for LE and CS data across the range of associated variable values recorded by observers. I included dead bycatch predictions in this report because IBQ pounds are allotted for dead P. halibut under CS management.

## METHODS

### *Data*

NOAA's National Marine Fisheries Service (NMFS) established the WCGOP in 2001 to improve catch and discard estimates in the U.S. west coast groundfish fishery. The WCGOP is administered by the Northwest Fisheries Science Center (NWFSC) Fishery Resource Analysis and Monitoring Division (FRAM) Fishery Observation Program (FOS), Seattle, WA. Beginning in 2002, this program required all vessels participating in the LE groundfish trawl fishery in the U.S. exclusive economic zone (EEZ) (6-370 km offshore) to carry a NMFS-certified observer when informed to do so.

Although fishers in the CS groundfish fishery may deploy any gear type—bottom trawl, midwater trawl, hook and line, or pot—I analyzed only haul-level bottom trawl observer data. Pacific halibut bycatch data were collected by observers placed on commercial bottom trawl vessels targeting groundfish by the WCGOP. Observers collected data on fishing activity, including haul locations, retained and discarded catch, and individual fish characteristics (e.g. length and weight) for high-priority species, including P. halibut. Observers also collected data on the viability of P. halibut. Observers assigned a viability to each specimen in a given haul as "excellent," "poor," or "dead" based on physical examination of individuals in-hand (see NWFSC 2016b for the gear-specific criteria observers used to rate P. halibut viability). In this analysis, all dead-condition P. halibut were considered "dead," although in practice a small proportion of dead-condition P. halibut are not actually dead upon release (see NWFSC 2016b for the mortality rates applied to each viability condition to determine dead bycatch under IBQ).

I filtered the data to include only hauls observed four years prior to and four years after the implementation of the CS program. Data collected from 2007-10 correspond to the pre-catch shares, LE bottom trawl fishery with observer coverage that varied between 17-23% of groundfish landings (Somers et al. 2015c). Data collected from 2011-14 correspond to the CS bottom trawl fishery with 100% at-sea observer coverage. Due to the increase in coverage rate with CS, significantly more hauls were observed in the CS period (35,853) than in the earlier LE period (11,127).

### *Analysis*

I first evaluated how specific variables that are correlated with P. halibut bycatch have changed at the haul-level since the implementation of CS (Table 2). I conducted Welch's *t*-tests to evaluate how means of P. halibut associated variables differed between LE and CS hauls. Overall means from 2007-10 (LE) were compared to means from 2011-14 (CS). To visualize trends, I plotted annual means from 2007-14.

I then developed three different generalized linear models (GLM's) to estimate the effects of the variables of interest on P. halibut bycatch. These three models were first fit for LE data and then re-run for CS data to compare the effects of predictors before and after the implementation of the CS program. The response variables in the three models were: probability of P. halibut encounter in a given haul; gross weight (mt) of P. halibut caught per haul; and proportion of dead P. halibut caught per haul. I used observer data to identify hauls that encountered P. halibut. Weight and mortality were each modeled using a delta model based only on hauls that encountered P. halibut (Stefánsson 1996). I used only hauls with encounters to derive predicted P. halibut bycatch weights and mortality because the majority of observed hauls had zero P. halibut bycatch, resulting in highly skewed bycatch weight and mortality distributions. Total counts of P. halibut classified as dead were summed and divided by the total number of P. halibut observed in each haul to derive proportions of dead P. halibut discarded. If sub-sampling occurred when an observer was unable to estimate the weight of all P. halibut in a given haul, the weight of P. halibut sub-sampled was expanded to estimate haul-level values. Table 2 outlines the explanatory variables used in the models. In addition to the variables of interest, I included the intended target group or species, season, and year of each haul to control for the potential effects of these variables.

Variations of the following GLM were used:

$$\begin{aligned} P = \beta_0 &+ \beta_1(\mathit{latitude}) + \beta_2(\mathit{depth}) + \beta_3(\mathit{catch\ of\ correlated\ species}) + \beta_4(\mathit{haul\ duration}) \\ &+ \beta_5(\mathit{target}) + \beta_6(\mathit{season}) + \beta_7(\mathit{year}) \end{aligned}$$

Depending on the model, *P* corresponds to the predicted probability of P. halibut encounter, P. halibut bycatch weight, or proportion of dead P. halibut per haul. Probability of encounter was modeled by the logit link following a binomial distribution. Weights were log-transformed, and then modeled by the identity link following a normal distribution. Mortality was modeled by the logit link following a binomial distribution. I developed a fourth model for counts of P. halibut caught in a given haul, but did not include it because results from the count model were similar to results from the weight model. All variables were originally included in the LE and CS base encounter models. I did not include interactions among variables because of limited sample sizes, especially in LE data. Additionally, initial analyses indicated that interactions would not significantly improve the encounter model fits, and thus were not tested for the weight and mortality models. After fitting the models, I removed the variable with the largest *P*-value and then re-fit the model, repeating this process until all variables remaining in the model were significant at $\alpha$=0.05. Consistent with the delta model concept, only variables that were significant in the encounter models were included in the weight and mortality models. Any other insignificant variables present in the weight and mortality models were removed one at a time, as described above, until all variables remaining in the models were significant.

I conducted the remainder of the analysis using methods derived from Jannot and Holland (2013). To visualize the effects of haul latitude, depth, duration, and catch of correlated species on P. halibut bycatch, I calculated P. halibut encounter, weight, and mortality predictions as a function of each explanatory variable while holding all other explanatory variables at their average values across both LE and CS hauls. To make predictions by haul duration, for example, the range of haul durations recorded by observers were used to calculate LE and CS model predictions given fixed values of the remaining explanatory variables. Weight predictions were then back-transformed and multiplied by the probability of encounter predictions to derive unbiased, unconditional expected bycatch per haul (mt). Bycatch predictions were multiplied by mortality predictions to derive unbiased, unconditional expected dead bycatch per haul (mt). To directly compare LE to CS predictions, I divided all predictions by the overall maximum value of the upper confidence interval to derive relative expected bycatch and dead bycatch. Bycatch predictions by haul duration, for example, were divided by the overall maximum value of the upper confidence interval of LE and CS predictions across the range of haul durations recorded by observers. I used the statistical program R version 3.2.1 to conduct all analyses (R Core Team 2015).

## RESULTS

While there was a significantly greater chance of encountering P. halibut amongst CS vs. LE hauls ($P < 0.001$), P. halibut encounters had been increasing prior to the management change in 2011 (Fig. 1a). With CS, the probability of encountering P. halibut became stable, compared to the increasing trend in the four years prior to the management shift. Amongst hauls that did encounter P. halibut, the weight of P. halibut bycatch per CS haul was significantly less than in LE hauls ($P < 0.001$). The weight of P. halibut caught per haul dropped dramatically in 2011 and remained consistently lower than prior to CS implementation (Fig. 1b). The proportion of dead P. halibut caught per haul was also significantly lower amongst CS as compared to LE hauls ($P < 0.001$), and was overall on the decline under both LE and CS management (Fig. 1c). There was a statistically significant difference in the mean of all associated variables of interest—haul latitude, depth, duration, and catch of correlated species—when comparing overall means of hauls conducted under LE vs. CS, but plots of means by individual year illustrated more complicated trends (Fig. 2).

On average, CS hauls occurred at significantly lower latitudes relative to LE hauls ($P = 0.0013$), but there was not a dramatic, fleet-wide shift in latitude following the management change (Fig. 2a). Over the 2007-10 LE period, the average latitude of all hauls (that is, those with and without P. halibut encounters pooled together) showed a northward trend, while the average latitude of all hauls moved gradually south across CS years. The average latitude of only hauls encountering P. halibut moved north during the LE period, fluctuating between about 44 and 45° N. latitude, but shifted much farther north and remained consistently around 46° N. latitude after CS implementation.

On average, CS hauls occurred at significantly shallower depths relative to LE hauls ($P < 0.001$). The average depth of all hauls shifted from shallower to deeper depths across LE years, ranging from about 225 to over 250 fathoms (Fig. 2b). CS fishing occurred in shallower depths than LE fishing, and the average depth remained within a relatively narrow range from about 200 to 225 fathoms. This shift to shallower depths with the management shift was evident amongst both hauls that caught P. halibut and those that did not. LE hauls that encountered P. halibut fluctuated between 150 and 200 fathoms during the 2007-10 period, but the depth of CS hauls that encountered P. halibut remained relatively constant at about 150 fathoms during the 2011-14 period.

On average, CS hauls were significantly shorter than LE hauls ($P < 0.001$). All hauls pooled together were, on average, between 4.5 and 5 hours in duration under LE, with little trend over the four-year period (Fig. 2c). Hauls overall became shorter with the management shift, and average haul duration declined across CS years from about 4.4 to 4.1 hours. This shift to shorter hauls was evident amongst both hauls that caught P. halibut and those that did not. Unlike all hauls pooled together, which exhibited little trend over time under LE, hauls that caught P.

halibut varied greatly but overall became shorter in duration over time under LE, on average ranging from 3.6 to 4.5 hours. The average duration of CS hauls encountering P. halibut was relatively constant (~3.5 hours) over the 2011-14 period.

On average, CS hauls retained significantly more catch of correlated species relative to LE hauls ($P < 0.001$), but hauls from both periods retained an increasing catch of correlated species from 2007-14. The average catch of correlated species of all hauls rose from about 0.25 to 0.4 mt across LE years and 0.5 to 0.6 mt across CS years (Fig. 2d). The average catch of correlated species of only hauls that encountered P. halibut rose from about 0.5 to 1.0 mt during the LE period. In contrast, the average catch of correlated species of hauls that encountered P. halibut became relatively constant at just over 1.0 mt during CS management.

The models largely predicted lower relative P. halibut bycatch and dead bycatch for CS compared to LE hauls across the variables of interest (Figs. 3 & 4). In both the LE and CS models, haul latitude was positively correlated and haul depth was negatively correlated with P. halibut bycatch and dead bycatch (Figs. 3a, 4a, 3b, & 4b). Haul duration was positively correlated with the LE model predictions, but became insignificant in predicting bycatch and dead bycatch in the CS models (Figs. 3c & 4c). Catch of correlated species was positively correlated with bycatch and dead bycatch in both the LE and CS models (Figs. 3d & 4d).

The models suggest that the relationships between haul depth, duration, and catch of correlated species and P. halibut bycatch and dead bycatch changed with the implementation of CS. There was no noticeable change in relationship between bycatch predictions and haul latitude between the LE and CS models, but latitude had a smaller impact on dead bycatch in the CS model, as illustrated by the more gradual slope of CS dead bycatch predictions compared to LE predictions (Figs. 3a & 4a). The more gradual slopes of predicted CS P. halibut bycatch and dead bycatch relative to LE predictions indicate that haul depth had a smaller impact on bycatch and dead bycatch in the CS models (Figs. 3b & 4b). Although haul duration was positively correlated with predicted LE bycatch and dead bycatch, haul duration did not have a statistically significant impact on CS predictions (Figs. 3c & 4c). Catch of correlated species had a lower impact on P. halibut bycatch and dead bycatch in the CS models, as illustrated by the more gradual slopes of CS predictions relative to LE predictions (Figs. 3d & 4d).

## DISCUSSION

This research suggests that the fleet-level reduction in P. halibut bycatch can be explained by a haul-level reduction in bycatch. There was a dramatic reduction in the weight of P. halibut caught per haul, suggesting that individual fisher behavior, rather than a fleet-level change in fishing effort (e.g. fewer fishers participating in the fishery or fewer overall tows conducted), explains the dramatic reduction in P. halibut bycatch under CS management. Although ecological factors could also contribute to lower bycatch per haul, the coincidence of this dramatic shift with the implementation of the CS program suggests that individual fisher behavior itself changed.

I originally predicted that fishers changed their behavior in terms of haul location, depth, duration, and catch of correlated species following the management shift, but I largely did not see shifts in these variables that I expected would contribute to lower P. halibut bycatch. LE haul data suggested that lower latitudes are associated with lower P. halibut bycatch, however there was not a dramatic, southward movement in haul location following the management shift. Fishers did begin fishing farther south over time under CS, but this trend was not consistent across the fleet. CS hauls that encountered P. halibut, in fact, overall occurred farther north relative to LE hauls with encounters. LE haul data also suggested that shallower depths and larger catch of correlated species contribute to larger P. halibut bycatch, but CS hauls occurred at overall shallower depths and retained larger catch of correlated species following the management shift. Finally, LE haul data suggested that shorter haul durations are associated with lower P. halibut bycatch. Haul duration became an insignificant explanatory variable in the CS models, but CS tows were significantly shorter than LE tows. More consistent shorter tows could explain why haul duration became insignificant in predicting CS bycatch and dead bycatch.

The relationship between these variables and predicted P. halibut bycatch and dead bycatch changed such that the models largely predicted lower relative bycatch and dead bycatch for CS as compared to LE hauls across the range of observed predictor values, and such that haul latitude, depth, duration, and catch of correlated species had smaller impacts on CS predictions. For example, the data suggest that fishing in shallower depths would increase P. halibut bycatch. However, CS fishers appear to have changed their behavior such that, although they fished at overall shallower depths relative to LE fishers, the models consistently predicted lower bycatch and dead bycatch across the majority of depths recorded by observers. Fishers under CS management also altered their behavior such that hauls occurring at incrementally shallower depths resulted in smaller increases in CS bycatch and dead bycatch predictions compared to those in LE.

The results of this analysis mean that I can only speculate at the exact behavioral mechanisms that produced the observed changes in relationships between the haul-level variables of interest and predicted P. halibut bycatch and dead bycatch, and how these changes may have contributed to the dramatic reduction in P. halibut bycatch following the management shift. It is possible that shorter haul durations allowed fishers to actively avoid P. halibut and other non-targeted quota species. Shorter tows likely allowed them to more effectively track catch composition and leave “hotspot” areas in which they encountered P. halibut. It is also possible that fishers deployed bycatch reduction devices (BRD’s), which exclude species of management concern such as P. halibut (Lomeli & Wakefield 2015). The use of BRD’s could also explain why haul duration became insignificant in predicting CS bycatch, as these devices may effectively exclude P. halibut regardless of how long a trawl net is deployed. It is worth noting that any changes fishers made to fishing behavior following the management shift were not necessarily solely due to P. halibut IBQ’s, as fishers must take into account a range of species’ quotas under CS.

The weight model fits were low for both LE and CS data (adjusted $R^2$-values of 0.11 and 0.05 respectively). These were the best fits generated using the data recorded and variables studied; however, such fits are typical of fishery-dependent data. These models were not used to make precise predictions, but rather to evaluate relationships between explanatory variables and predictions and to make general comparisons between LE and CS trends. The poor fits suggest that P. halibut bycatch is not very predictable, especially in terms of the variables we have quantified. It follows that, from a management perspective, simply regulating the variables examined in this study may not be the most effective means of further reducing P. halibut bycatch. Alternative to implementing technical regulations, managers could incentivize stronger P. halibut avoidance through lowering IBQ's. Fishers have successfully reduced P. halibut bycatch at the haul level under CS in spite of changes to associated variables that LE haul data suggested increase bycatch. Insofar as lower IBQ's remain economically feasible, fishers could continue making decisions and modifying behavior in the ways that have been effective since the management shift, be it through shorter tows, the use of BRD's, or a change to some other variable I have yet to identify.

## CONCLUSION

As often happens in ecological research, I found that the answer to the question, "what mechanisms have contributed to P. halibut bycatch reduction since the implementation of the catch shares program?", is more complicated than I originally predicted. Pacific halibut bycatch has declined at the haul level, but I did not see the shift in predictors (i.e. fishing behavior) that I expected. Instead, my results indicate that fishers changed behavior such that the relationships between the variables of interest and bycatch and dead bycatch predictions changed. Not only did the models largely predict lower CS P. halibut bycatch and dead bycatch across the range of haul latitude, depth, and catch of correlated species values recorded by observers, but haul depth, duration, and catch of correlated species had a smaller impact on bycatch and dead bycatch in the CS as compared to LE models. Looking forward, collaborating with the fleet and conducting interviews with fishers could provide insight into the specific changes in fishing behavior that effectively contributed to reducing P. halibut bycatch. Identifying and quantifying these less obvious changes in fishing behavior will be important to future management efforts for bycatch of P. halibut and other species.

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# FIGURES & TABLES

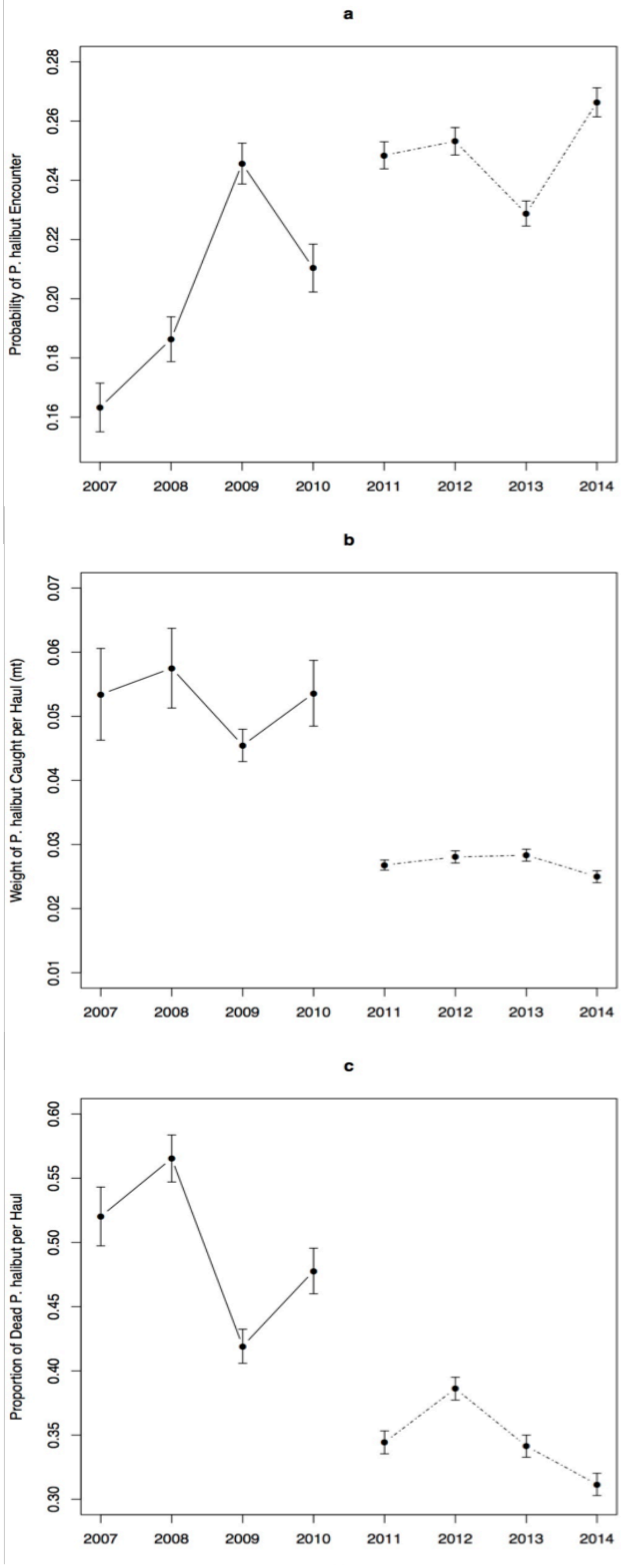

**Figure 1. Probability of encounter, weight of P. halibut caught (given encounter), and proportion of dead P. halibut caught (given encounter) per haul by year. Means and standard errors are shown. The solid line denotes LE means; the dotted line denotes CS means.**

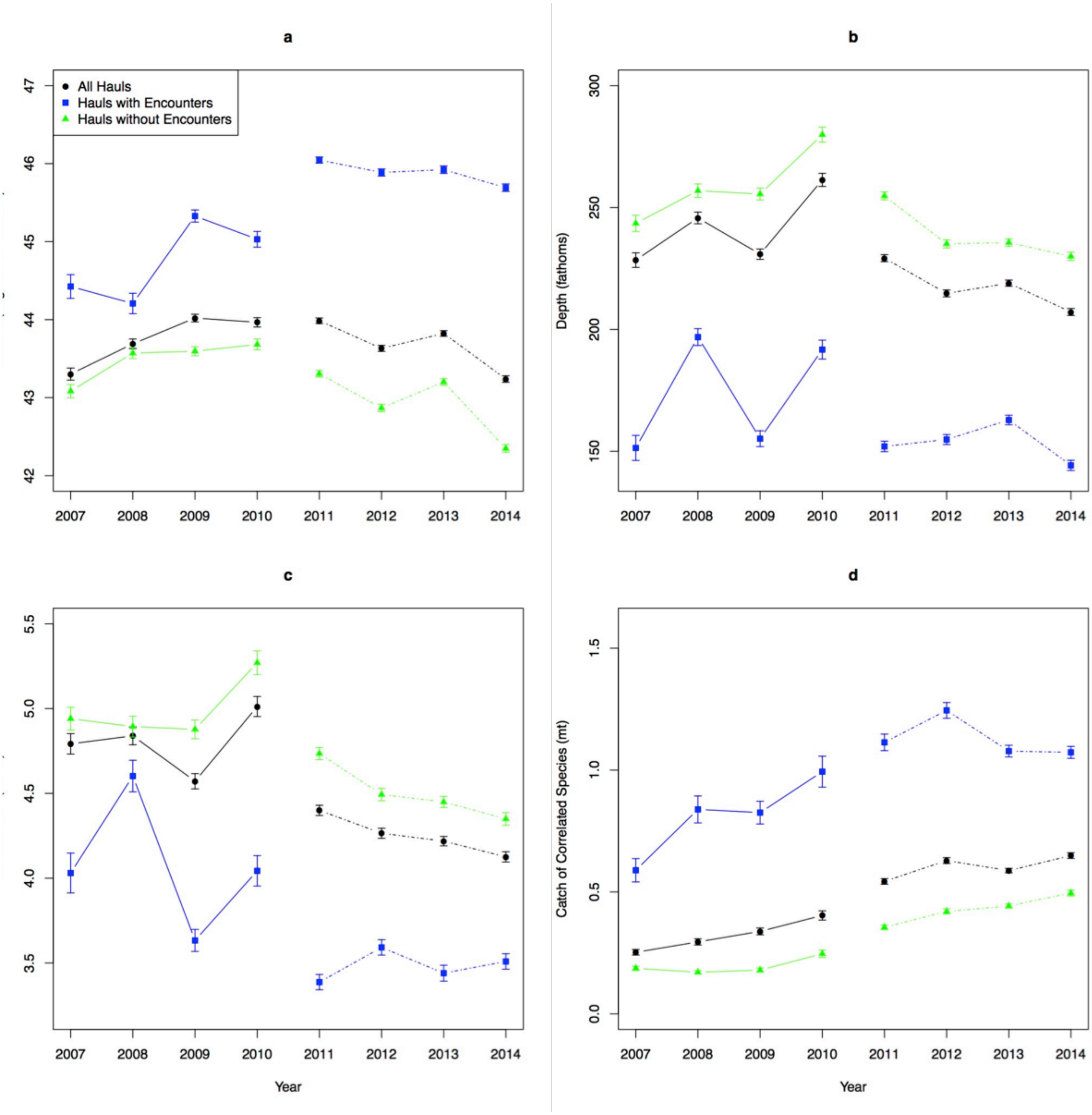

**Figure 2. Predictor variables by year across all hauls, hauls with P. halibut encounters, and hauls without P. halibut encounters. Means and standard errors are shown. Solid lines denote LE means; dotted lines denote CS means.**

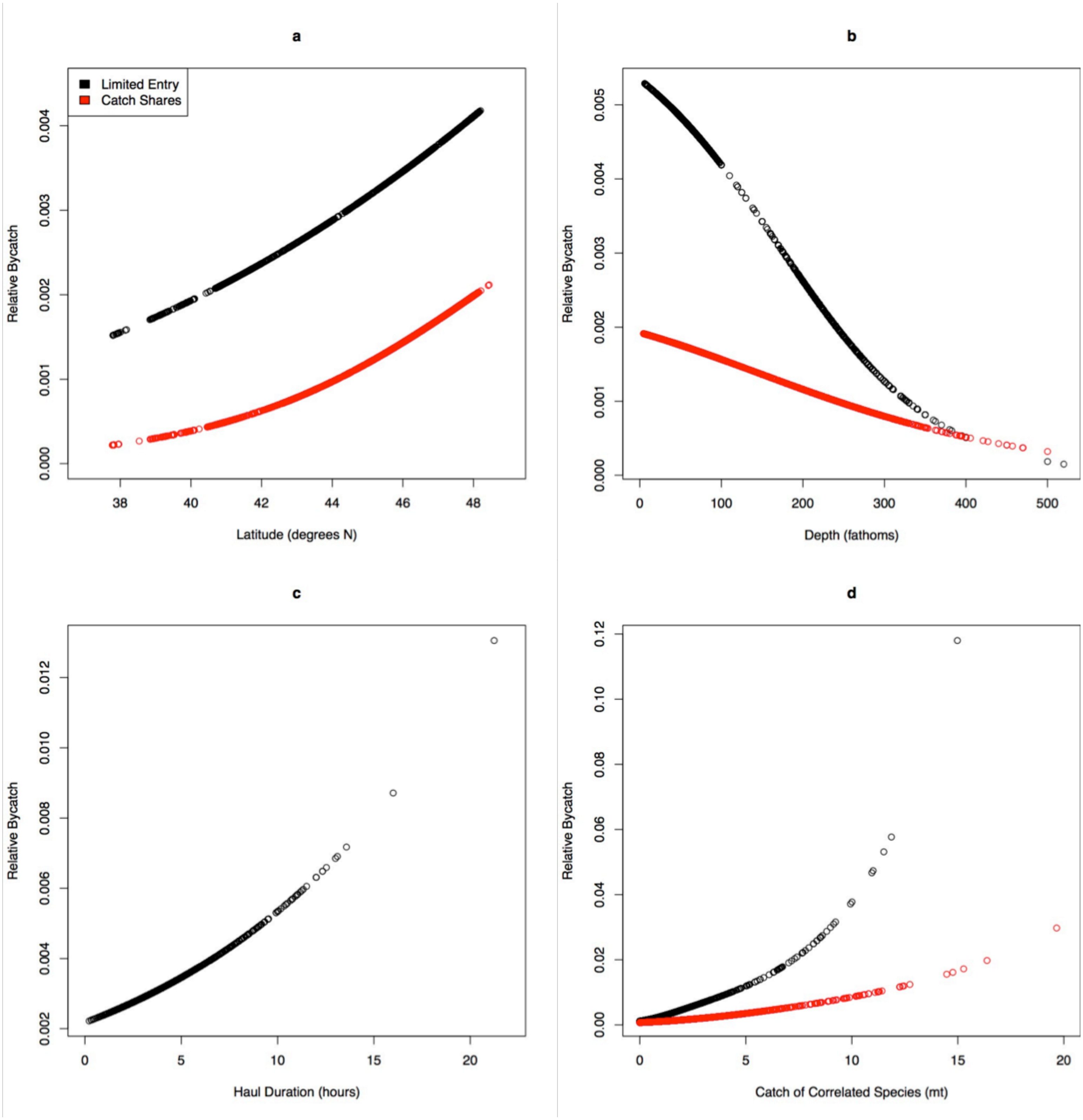

**Figure 3. Predicted relative bycatch of P. halibut by explanatory variable holding all other variables at their averages. Black points denote relative P. halibut bycatch predictions based on the LE models. Red points denote relative P. halibut bycatch predictions based on the CS models. There are no CS data for relative P. halibut bycatch predictions by haul duration because haul duration was an insignificant predictor of bycatch in the CS models.**

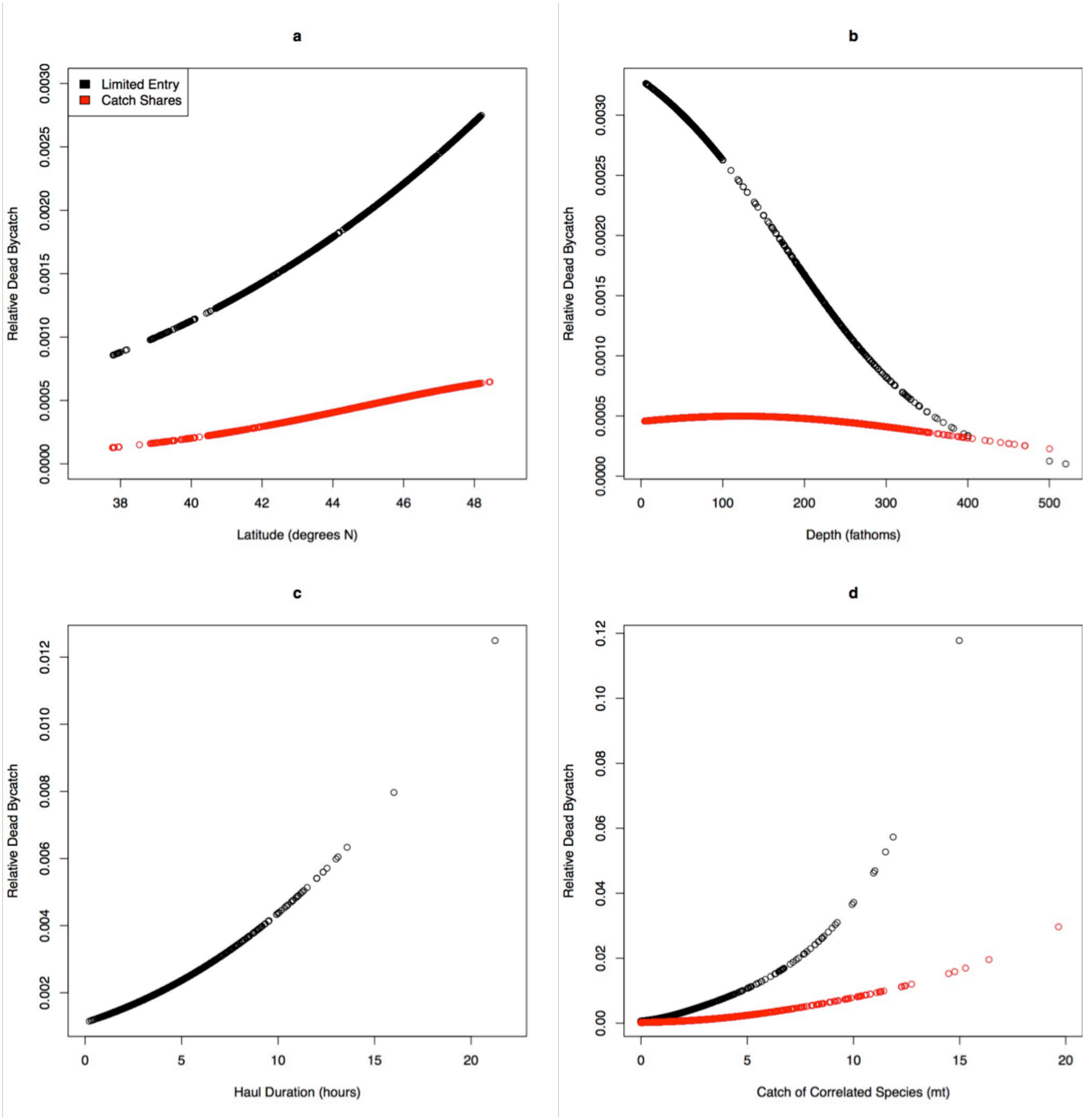

**Figure 4. Predicted relative dead bycatch of P. halibut by explanatory variable holding all other variables at their averages. Black points denote relative dead P. halibut bycatch predictions based on the LE models. Red points denote relative dead P. halibut bycatch predictions based on the CS models. There are no CS data for relative dead P. halibut bycatch predictions by haul duration because haul duration was an insignificant predictor of dead bycatch in the CS models.**

**Table 1. Changes in haul-level variables of interest that corresponded to less bycatch in LE hauls and resulting predictions for how these variables would change with the shift to CS.**

| Variable | LE Data | CS Prediction |
|---|---|---|
| **Latitude** | ↓ latitude = ↓ bycatch | ↓ latitude |
| **Depth** | ↑ depth = ↓ bycatch | ↑ depth |
| **Haul duration** | ↓ haul duration = ↓ bycatch | ↓ haul duration |
| **Catch of correlated species** | ↓ catch of corr. species = ↓ bycatch | ↓ catch of corr. species |

**Table 2. Explanatory variables and metrics used to analyze factors associated with P. halibut bycatch.**

| Variable | Description | Units / Values | Purpose |
|---|---|---|---|
| **Latitude** | The average latitude of the haul. | Degrees N. latitude | Predictor |
| **Depth** | The average depth of the haul. | Fathoms | Predictor |
| **Catch of correlated species** | The weight of species that have been found to be correlated with P. halibut catch (arrowtooth flounder, petrale sole, lingcod, Pacific cod, skates, yellowtail rockfish, and Pacific ocean perch) (Heery et al. 2010). | Metric tons | Predictor |
| **Haul duration** | The duration of the haul from gear deployment time to gear retrieval time. | Hours | Predictor |
| **Target** | The intended target group or species as communicated to the observer by the captain or another crew member. We consolidated these data into six groups based on species that are commonly fished together. “Other” denotes species that did not obviously fit into one of these groups and “Unknown” denotes hauls for which the observer recorded “unknown” or did not record a targeted species. | Flatfish, rockfish, skate & grenadier, dover-thornyheads-sablefish, other, unknown | Control |
| **Season** | The season in which the haul occurred. | Jan-Mar,<br>Apr-Jun,<br>Jul-Sep,<br>Oct-Dec | Control |
| **Year** | The year in which the haul occurred. | 2007 – 2014 | Control |

**Table 3 (a-f). Summary of model coefficient estimates, standardized estimates, standard errors, variance inflation factors, ANOVA-generated *P*-values, and model fits. Encounter model fits are described by an accuracy rate (the proportion of hauls for which the model correctly predicted a P. halibut encounter). Weight model fits are described by an adjusted $R^2$-value. Viability model fits are not listed because no common metric was found for evaluating the fit of a GLM for proportions following a binomial distribution.**

**a. LE Encounters**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| z \|) |
|---|---|---|---|---|---|
| **Intercept** | -3.93 | 0.00 | 0.464 | | < 2e-16 |
| **Latitude** | 0.11 | 0.84 | 0.010 | 1.15 | < 2e-16 |
| **Depth** | -0.01 | -3.40 | 0.000 | 4.28 | < 2e-16 |
| **Duration** | 0.07 | 0.51 | 0.014 | 1.68 | 2.17e-7 |
| **Catch of correlated species** | 1.02 | 1.99 | 0.048 | 1.06 | < 2e-16 |
| **Target** | | | | 3.72 | |
| Flatfish | -0.60 | -0.51 | 0.103 | | 4.56e-9 |
| Rockfish | -1.19 | -0.39 | 0.277 | | 1.92e-5 |
| SG | 1.35 | 0.12 | 0.784 | | 0.086 |
| Other | -0.90 | -0.77 | 0.106 | | < 2e-16 |
| Unknown | -0.72 | -0.08 | 0.526 | | 0.171 |
| **Season** | | | | 1.43 | |
| 2 | -0.99 | -1.18 | 0.082 | | < 2e-16 |
| 3 | -1.05 | -1.17 | 0.091 | | < 2e-16 |
| 4 | -0.54 | -0.51 | 0.090 | | 1.97e-9 |
| **Year** | | | | 1.09 | |
| 2008 | 0.29 | 0.31 | 0.087 | | < 0.001 |
| 2009 | 0.54 | 0.64 | 0.079 | | 8.35e-12 |
| 2010 | 0.37 | 0.38 | 0.089 | | 3.27e-5 |
| | | | | **Accuracy** | 0.81 |

**b. CS Encounters**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| z \|) |
|---|---|---|---|---|---|
| **Intercept** | -11.32 | 0.00 | 0.305 |  | < 2e-16 |
| **Latitude** | 0.26 | 2.18 | 6.23e-3 | 1.22 | < 2e-16 |
| **Depth** | -6.06e-3 | -1.83 | 2.28e-4 | 3.29 | < 2e-16 |
| **Catch of correlated species** | 0.38 | 0.92 | 1.42e-2 | 1.09 | < 2e-16 |
| **Target** |  |  |  | 3.30 |  |
| Flatfish | 0.14 | 0.10 | 5.37e-2 |  | 0.008 |
| Rockfish | -0.97 | -0.46 | 0.108 |  | < 2e-16 |
| SG | -0.43 | -0.06 | 0.198 |  | 0.029 |
| Other | -0.49 | -0.46 | 5.05e-2 |  | < 2e-16 |
| Unknown | -10.73 | -0.41 | 93.57 |  | 0.909 |
| **Season** |  |  |  | 1.48 |  |
| 2 | -0.29 | -0.31 | 4.03e-2 |  | 4.59e-13 |
| 3 | -0.43 | -0.45 | 4.54e-2 |  | < 2e-16 |
| 4 | -0.51 | -0.46 | 4.65e-2 |  | < 2e-16 |
| **Year** |  |  |  | 1.06 |  |
| 2012 | -0.84 | -0.08 | 3.95e-2 |  | 0.034 |
| 2013 | -0.23 | -0.24 | 3.86e-2 |  | 1.34e-9 |
| 2014 | 0.11 | 0.10 | 4.01e-2 |  | 0.007 |
|  |  |  |  | **Accuracy** | 0.71 |

**c. LE Weight**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| t \|) |
|---|---|---|---|---|---|
| **Intercept** | -5.90 | 0.00 | 0.411 | | < 2e-16 |
| **Latitude** | 0.04 | 0.09 | 0.009 | 1.07 | 3.31e-6 |
| **Depth** | -2.02e-4 | -0.02 | 3.23e-4 | 1.82 | 0.531 |
| **Duration** | 0.06 | 0.11 | 0.013 | 1.45 | 6.65e-6 |
| **Catch of correlated species** | 0.23 | 0.26 | 0.017 | 1.07 | < 2e-16 |
| **Season** | | | | 1.44 | |
| 2 | -0.13 | -0.05 | 0.069 | | 0.066 |
| 3 | -0.17 | -0.06 | 0.073 | | 0.023 |
| 4 | -0.23 | -0.07 | 0.075 | | 0.002 |
| | | | | **$R^2$-value** | 0.11 |

**d. CS Weight**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| t \|) |
|---|---|---|---|---|---|
| **Intercept** | -5.21 | 0.00 | 0.223 | | < 2e-16 |
| **Latitude** | 0.02 | 0.04 | 0.005 | 1.05 | 2.69e-5 |
| **Depth** | 7.93e-4 | 0.08 | 1.29e-4 | 1.61 | 8.08e-10 |
| **Catch of correlated species** | 0.12 | 0.18 | 7.25e-3 | 1.02 | < 2e-16 |
| **Season** | | | | 1.67 | |
| 2 | -0.13 | -0.07 | 0.029 | | 4.24e-6 |
| 3 | -0.01 | -3.49e-3 | 0.034 | | 0.833 |
| 4 | -0.22 | -0.08 | 0.035 | | 4.40e-10 |
| | | | | **$R^2$-value** | 0.05 |

**e. LE Mortality**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| z \|) |
|---|---|---|---|---|---|
| **Intercept** | 0.42 | 0.00 | 0.344 |  | 0.217 |
| **Latitude** | -0.04 | -0.25 | 7.42e-3 | 1.22 | 4.84e-8 |
| **Depth** | 3.94e-3 | 0.90 | 3.53e-4 | 3.35 | < 2e-16 |
| **Duration** | 0.17 | 0.86 | 9.72e-3 | 1.26 | < 2e-16 |
| **Catch of correlated species** | -0.15 | -0.50 | 9.33e-3 | 1.19 | < 2e-16 |
| **Target** |  |  |  | 3.23 |  |
| Flatfish | 0.20 | 0.20 | 0.055 |  | 4.10e-4 |
| Rockfish | -0.58 | -0.12 | 0.237 |  | 0.014 |
| SG | -0.37 | -0.06 | 0.403 |  | 0.363 |
| Other | 0.50 | 0.51 | 0.067 |  | 8.36e-14 |
| Unknown | -0.95 | -0.13 | 0.525 |  | 0.070 |
| **Season** |  |  |  | 2.25 |  |
| 2 | -0.68 | -0.80 | 0.053 |  | < 2e-16 |
| 3 | -0.48 | -0.50 | 0.062 |  | 6.97e-15 |
| 4 | -0.22 | -0.20 | 0.062 |  | 4.12e-4 |
| **Year** |  |  |  | 1.51 |  |
| 2008 | -0.28 | -0.28 | 0.058 |  | 1.58e-6 |
| 2009 | -0.33 | -0.39 | 0.053 |  | 5.16e-10 |
| 2010 | -0.46 | -0.47 | 0.059 |  | 6.71e-15 |

**f. CS Mortality**

| Variable | Estimate | Std. Estimate | Std. Error | VIF | Pr (>\| z \|) |
|---|---|---|---|---|---|
| **Intercept** | 3.56 | 0.00 | 0.306 |  | < 2e-16 |
| **Latitude** | -0.12 | -0.64 | 6.38e-3 | 1.21 | < 2e-16 |
| **Depth** | 3.87e-3 | 0.91 | 2.63e-4 | 4.09 | < 2e-16 |
| **Catch of correlated species** | 0.22 | 0.72 | 7.59e-3 | 1.10 | < 2e-16 |
| **Target** |  |  |  | 3.88 |  |
| Flatfish | -0.73 | -0.64 | 0.046 |  | < 2e-16 |
| Rockfish | 0.08 | 0.02 | 0.114 |  | 0.484 |
| SG | -0.09 | -0.02 | 0.140 |  | 0.528 |
| Other | -0.13 | -0.15 | 0.047 |  | 6.26e-3 |
| **Season** |  |  |  | 2.18 |  |
| 2 | 0.56 | 0.63 | 0.037 |  | < 2e-16 |
| 3 | 0.80 | 0.89 | 0.045 |  | < 2e-16 |
| 4 | 0.94 | 0.78 | 0.043 |  | < 2e-16 |
| **Year** |  |  |  | 1.16 |  |
| 2012 | 0.13 | 0.13 | 0.034 |  | 2.74e-4 |
| 2013 | 0.06 | 0.06 | 0.035 |  | 0.093 |
| 2014 | -0.06 | -0.07 | 0.037 |  | 0.086 |