Estimates of halibut total annual surplus production, and yield and egg production losses due to under-32 inch bycatch and wastage

Steven R. Hare

Abstract

Estimates of annual surplus production, and yield and egg losses due to bycatch and wastage of under-32 inch halibut are presented by regulatory area. A novel method is developed to decompose bycatch and wastage into sex and age components.

Introduction

Halibut biomass is estimated to have declined by 11% to 62% among IPHC regulatory areas over the past decade (Hare and Clark 2009). For the most part, the declines are not unexpected – the twin impacts of the passing through of two very large year classes (1987 and 1988) and the expansion of targeted fisheries in the previously lightly exploited western regulatory areas raised removals to historic levels that were not considered sustainable. Halibut productivity has waxed and waned over decades (Clark et al. 1999, Clark and Hare 2002) and this has presented a challenge to stabilizing removals.

Production is at the heart of a sustainable fishery. In this paper, I summarize trends in three important production quantities: i) Annual Surplus Production (ASP); ii)Yield Loss (YLoss) due to bycatch and wastage mortality of under-32 inch halibut (i.e., halibut below the commercial legal size limit); iii) lost egg production (EggLoss) due to bycatch and wastage mortality of under-32 inch halibut. Given the enormous changes in halibut growth rates, each of these quantities has changed substantially over the past few decades. The importance of each of these measures is discussed in the relevant sections.

Annual surplus production

In modern fisheries management, biomass estimates, stock status, and sustainable harvest levels are determined with highly complex stock assessment and harvest policy simulation models. However, there have been recent calls for presentation of more basic indices, such as annual surplus production plots, alongside the complex models, as a means of diagnosing stock trends (Hilborn 2001, Jacobson et al. 2001). Walters et al. (2008) aver:

> "...it is important to recognize that [surplus production] remains a fundamental (some would say the fundamental) quantity of interest in fisheries assessments aimed at determining sustainable harvest rates, target stock sizes, and possible future stock trajectories."

In this section, I describe how surplus production is estimated for Pacific halibut and present a series of biomass-productivity time-series plots for each of the regulatory areas. These plots illustrate the spatial and temporal variability in annual surplus production and its relationship to biomass and harvest.

Methods

A fishery is sustainable as long as removals are less than or roughly equal to a stock's annual surplus production. Annual surplus production (ASP) is defined as:

$$ASP_{year} = Biomass_{year+1} - Biomass_{year} + Removals_{year}$$

In other words, ASP is the level of removals that a stock can sustain and maintain biomass at a constant level. ASP is virtually never constant itself as it varies in response to a host of factors, including recruitment, growth, natural mortality, and migration. Declines in biomass occur when surplus production is negative (i.e., mortality exceeds recruitment and growth) or removals exceed surplus production. Biomass increases when ASP is positive and exceeds removals. Note that in this context, "biomass" refers to exploitable biomass (EBio), i.e., the biomass of halibut available to the commercial, recreational, and subsistence fisheries. Exploitable biomass is generally - and in the case of Pacific halibut substantially - less than total biomass (see Hare and Clark (2009)). The difference between the two biomasses is determined by the length-specific selectivity curve.

To estimate regulatory area ASP, we require area-specific estimates of exploitable biomass and removals. Coastwide exploitable biomass estimates are produced annually as part of the halibut stock assessment, and the values used for this analysis were taken from Hare and Clark (2009). The IPHC stock assessment setline survey is used to estimate the distribution of exploitable biomass (EBio) among regulatory areas. The partitioning among areas uses an equal-weighted average of the three most recent CPUE values, with each regulatory area's average CPUE weighted by bottom area (Hare 2008):

$$\mathrm{EBioFraction}_{\mathrm{RA,\,t}} = \frac{BottomArea_{RA} \times \dfrac{\sum_{y-2}^{y} CPUE_{RA,t}}{3}}{\sum_{2A}^{4CDE} \left(BottomArea_{RA} \times \dfrac{\sum_{y-2}^{y} CPUE_{RA,t}}{3} \right)}$$

where CPUE is the regulatory area (RA) average weight of all commercial legal-sized (>81.3 cm, or 32 in; O32) halibut, in net pounds per standard skate of gear, captured during the survey. The outer summation in the denominator includes all IPHC regulatory area from 2A up through 4CDE. Note that the CPUE estimate from 4CDE is derived differently from the other areas (Hare and Clark 2009) in that it relies upon the NMFS Bering Sea trawl survey. Further, the estimates of ASP presented here are not smoothed (other than what occurs as the result of the CPUE averaging) as is sometimes done to smooth out abrupt jumps (Deriso and Quinn 1983, Hilborn 2001).

The accuracy of this method for partitioning EBio depends on a key assumption, namely that catchability (the relationship between effort and catch) is constant (or nearly so) among regulatory areas. IPHC staff has conducted a number of investigations into the constant catchability assumption (Clark 2008a, Clark 2008b, Clark 2008c, Clark and Hare 2009, Hare and Clark 2009), however no definitive conclusion has been reached because there is no comprehensive technique to examine the relationship over all areas where halibut occur. To date, none of the investigations have suggested a sizable catchability difference between areas. Research on the issue of catchability is ongoing - for the time being staff will continue to use the working assumption of constant catchability. This is the same assumption adopted by all management agencies worldwide that use survey data for such purposes. As both the stock assessment and EBio partitioning require data from the setline survey (for all IPHC regulatory areas), the ASP calculations begin in 1997.

The other data required to compute ASP are total removals by regulatory area. Halibut removals are generally grouped into eight categories: commercial catch, IPHC survey catch, sport catch, personal use (subsistence) catch, O32 bycatch, O32 wastage, U32 bycatch and U32 wastage, where O32 and U32 refer to halibut over 32 inches and under 32 inches in length, respectively. This is the preferred designation over the previously used terms "legal-sized" and sublegal-sized" to refer to fish larger and smaller than the commercial legal size limit. There is no size limit in the personal use, sport, and bycatch fisheries. Only the first six of the above listed categories are summed to compute removals, as used in the ASP calculations. The reasoning is that ASP represents removals available to the targeted fisheries (bycatch is also considered a targeted fishery). Thus, for the purposes of this analysis, U32 removals are not considered part of the annual surplus production and their effect on stock productivity is considered in the section on Lost Yield and Egg production. Area-specific estimates, for the period 1997-2008, of EBio are listed in Table 1, total removals in Table 2, and ASP in Table 3.

Results

Annual surplus production is highly variable among regulatory areas as well as over time (Fig. 1). The eastern regions appear to be somewhat less variable over time and have generally higher levels of ASP. Figure 1 also shows total removals as well as average ASP and average removals over the period 1997-2008. Average total removals exceeded average ASP in all regulatory areas over the past 12 years, in line with the declining EBio trends seen coastwide (Hare and Clark 2009) The difference between the two averages was greatest in Area 3B and smallest in areas 2A and 4CDE. ASP was negative for a stretch of years in the late 1990s and early 2000s in Areas 2C, 4A, 4B, and 4CDE, and generally lower than average in the other areas, indicating that biomass levels would have declined even if removals had been strongly curtailed. It is of interest to note the estimates of surplus production produced here are roughly in line with the ranges of ASP published in the 1980s for Area 2 (Deriso and Quinn 1983) and in the 1990s for Areas 2 and 3 (Sullivan and Parma 1997). The assessment methods differ considerably among the three time periods, and the absolute biomass estimates they produce also differ substantially. ASP, however, is computed from the relative change between successive estimates and it appears that estimates of annual changes are more consistent than estimates of biomass level.

A second useful means of considering ASP is to examine plots of ASP vs. EBio (Fig. 2) These types of plots can be notoriously difficult to interpret due to factors such as regime shifts, changes in growth rates, and other forms of non-stationarity (Walters et al. 2008). Nevertheless, some general observations are worth noting. For all of the regulatory area ASP vs. EBio plots, the time trajectory is one of a clockwise loop, generally beginning in the upper right quadrant where both ASP and EBio are highest. Over the first six years or so, the trajectory proceeds clockwise, with both ASP and EBio decreasing. Over the final six years, EBio continues to decline but ASP has begun to increase. This form of ASP vs. EBio plot is termed "clockwise loop structure" by Walters et al. (2008) and they interpret this as a sequence of time-structured recruitment anomaly deviations from mean equilibrium conditions. This interpretation fits the scenario described in the introduction of the passing through of a couple of strong year classes in the halibut population. The generally upward trend in the last several data points is indicative of a stock returning to a more productive state.

Lost yield and lost egg production due to bycatch and wastage of under-32 inch halibut

Bycatch and wastage are two sources of halibut mortality that must be accounted for in halibut management. The effects of bycatch and wastage have been accounted for in different ways over the past 30 years. Bycatch compensation, i.e., reduction of yield available to the commercial fishery (Fishery Constant Exploitation Yield, or CEY), began in 1981, while wastage compensation began in 1987. In those days, the emphasis was on yield loss and it was calculated that, because the bycatch consisted mostly of small fish, each pound of bycatch resulted in an eventual loss of 1.40 pounds of yield to the commercial fishery. The recommended Total CEY was therefore reduced by 1.40 pounds for each pound of bycatch to arrive at the Fishery CEY. This reduction was calculated as a coastwide total and distributed among regulatory areas in proportion to the estimated exploitable biomass in each area. The reasoning employed was that most of the bycatch consisted of juvenile fish on the Bering Sea nursery grounds and would eventually have recruited to summer feeding stocks all along the coast more or less in proportion to the biomass of those stocks. Later in the 1980s the yield loss factor was recalculated at 1.58. Compensation for wastage, which was estimated only for over 32-inch fish, was set at one pound of yield per pound of wastage. It is important to note that wastage is presently estimated only for the commercial fishery. It is possible, and even likely, that wastage occurs in the sport and subsistence fisheries but at present there do not exist sufficient data to estimate the magnitude. Given the relative scales of the removals, sport and subsistence wastage are likely much less than commercial wastage, nonetheless it is a goal to eventually quantify the magnitude of these other forms of wastage and account for them in halibut management. The remainder of this document pertains only to commercial wastage.

In 1990, the aim of bycatch compensation changed from compensation for lost yield to compensation for lost egg production. The rationale was that the exploitation strategy was based on maintaining, on average, an optimum spawning biomass and therefore an optimum egg production, so the logical way to compensate for bycatch was to reduce the setline quota by an amount just sufficient to result in the same level of egg production as would have occurred had there been no bycatch. Calculations showed (Sullivan et al. 1994) that the reproductive compensation factor was lower than the yield loss factor, averaging 1.00 pound of required compensation for each pound of bycatch, so from 1990 until 1996, the fishery CEY was reduced by the amount of bycatch pound for pound.

Beginning in 1997, setline yield was reduced for every pound of O32 bycatch and wastage, but not for U32 bycatch and wastage. The Total CEY reduction for O32 bycatch occurred in the regulatory area where the bycatch was taken. This was (and is) viewed as treating the O32 bycatch and wastage in manner consistent with O32 catches taken in the commercial catch. On the basis of extensive bycatch-migration modeling (Clark and Hare 1998), it was determined that the major impact of U32 bycatch (and, by implication, wastage) was primarily on the area where the bycatch was taken. The effect of U32 bycatch is to reduce recruitment to the commercial and sport fisheries, thereby impacting stock productivity, yield, and biomass levels at varying harvest rates. Thus, rather than deducting bycatch (and wastage) from available yield, the effects are incorporated into the harvest rate simulations (Clark et al. 1997, Clark and Hare 2006).

The issue of bycatch continues to be contentious and, in mid-2009, a workshop was convened to discuss the issue (IPHC Staff 2010). Further, the enormous change in growth rates has had a large impact on stock impacts of U32 catches of halibut. As background material for the workshop discussions, the yield loss and egg loss compensation calculations were updated and are presented in this section. Figure 3 presents the size distribution and estimated number of halibut lost to bycatch in 2008 (both O32 and U32 halibut are illustrated). Figure 4 presents the same information for halibut lost to commercial wastage. The methods and calculations outlined below pertain only to the U32 component of both bycatch and wastage.

Methods

The methods used here to update the yield and egg loss calculations differ somewhat from those employed in the 1980s and 1990s (Sullivan et al. 1994). Back then, a combination of length-based, unisex models and age-based, two-sex models were used to compute yield loss and recruitment losses. A new method, which allows complete sex and age based modeling is developed for the new estimates.

To estimate lost yield from the catch of halibut of a given size, I first statistically characterize the age and sex composition of the catch. For U32 bycatch and wastage, the only data that are available are estimates of numbers caught by length (in 5 cm increments). To parse out catches at length, we need to construct growth schedules (more accurately, mean size and variance at age) for males and females. A standard population dynamics model, with constant annual recruitment and constant fishing and natural mortalities is used to establish an equilibrium population structure. Within each length category the sex and age proportions can then be tabulated and with this schedule any length distribution can be parsed into its sex and age components. Of course, any bycatch or wastage size distribution likely comes from a non-equilibrium situation and will reflect different year class sizes. This method at least represents a big improvement over the decomposition method used previously, which did not account for sex-specific growth rates nor variance in size at age.

Due to the great disparity in growth rates, separate size-at-age curves must be constructed for the two sexes. For ages 2 to 11, halibut lengths (and standard deviations) were computed using halibut collected aboard the NMFS trawl surveys. Trawl-caught halibut, particularly at smaller sizes, more accurately reflect the size of halibut in the sea due to the relative uniform selectivity of trawls compared to setline gear. For IPHC areas 2 and 3, NMFS Gulf of Alaska survey data were used, while Area 4 used NMFS Bering Sea trawl survey data. Mean lengths and standard deviations for halibut 12 and older were computed from halibut caught in the IPHC setline surveys. Both sets of data are for fish caught between 2004 and 2007. Mean length at age appears to increase linearly, though at a somewhat slower rate for fish age 11 and older (Figure 5a). The same is true for standard deviation in length at age. Linear regressions were fit to estimate smooth growth parameters, with different regressions for males and females, and younger and older fish. With the mean length and standard deviation of length estimates, length distributions at age for male and female halibut were computed and are illustrated in Figure 5b.

Older fish appear in decreasing numbers in the population due to natural (M) and fishing (F) mortality and these rates affect the proportions of both sexes and ages for a given length in the population. I used an equilibrium F of 0.25 and M of 0.15 for both sexes in the calculations to determine proportions of sex and age at length. The resultant length-age-sex key is illustrated in Figure 5c. Males comprise around 55-60% of the population of halibut 30-90 cm in length. The fraction (at length) that is female then increases rapidly, generally reaching 95% by 115 cm. With this key, it is possible to take any size distribution of halibut and decompose it by sex and age group. Note that separate keys were produced for each of the IPHC regulatory areas but are not illustrated. Differences among areas do exist but are not easily deduced from visual inspection of the plots such as those presented for the coastwide growth schedules (Fig. 5). However, the area specific schedules were used in all subsequent lost yield and egg production computations. The decomposition of coastwide U32 bycatch and commercial wastage into age- and sex-specific distributions is illustrated for 2008 data in Figure 6.

With the size and age distributions, it is relatively straightforward to compute both yield loss and egg loss. An age and size-structured simulation model is used to project the distributions forward in time and lost yield is computed from the Baranov catch equation, assuming an F of 0.25.

Yield loss is defined as

$$\text{Yield Loss} = \sum_{g=1}^{2}\sum_{t=1}^{30}\sum_{a=t}^{30} N_{g,a,t}\,\frac{F_{g,a,t}sel_{g,a}}{F_{g,a,t}sel_{g,a}+m}\left(1-e^{-\left(F_{g,a,t}sel_{g,a}+m\right)}\right)W_{g,a}$$

$$W_{g,a} = 0.00000692L^{3.24}$$

Where g indexes sex, t indexes time, a indexes age and sel indicates selectivity, which is a function of length at age, and W indicates weight of halibut in net pounds as a function of length. Commercial selectivity at length is that estimated in the most recent halibut stock assessment (Hare and Clark 2009). Maximum age is 30.

A Yield Loss ratio on a pound for pound basis can then be computed as a ratio of future cumulative yield loss to the weight of the bycatch (or wastage) when taken

$$YL_{\text{ratio}} = \frac{\text{Yield Loss}}{\text{BycatchWt.}}$$

The YL_{ratio} varies with the size of fish in the catch and is greatest for catches composed of small fish and drops steadily with size (Figure 5d). Note that the YL_{ratio} to length plot is constructed by successively computing the cumulative yield loss for each separate length category. Bycatch and wastage are composed of a range of sizes - but the smaller the average size of the catch, the greater the cumulative yield loss. The YL_{ratio} drops below 1.0 around 58 cm. This is the point at which losses due to natural mortality are greater than gains from growth. It also implies that future yield from fish greater than 58 cm will be less than the yield if they were taken at 58 cm. Of course, this only takes into account yield considerations and ignores potential impacts on egg production. The dramatic decrease in growth rates seen over the past 30 years has substantially lowered the point at which the setline loss ratio drops below zero. Further, the yield loss from bycatch has also decreased. As noted earlier, when these same calculation were initially done in the 1980s, it was estimated that the commercial fishery lost approximately 1.58 pounds of catch for each pound of bycatch. These calculations show that the loss is now around 1 pound per pound of bycatch on a coastwide basis. However, it must be noted that the earlier calculations were based on the full size range of bycatch, including fish over 32 inches in length, whereas the contemporary calculations are restricted to U32 halibut. If the O32 fish were included in the contemporary calculations, the Yield Loss ratio would be even less than the approximate value of 1.0.

The calculations to determine lost egg production employ the same age and sex decompositions as are used for estimating lost yield. Lost egg production is computed by summing how many eggs would have been produced by the fish lost to bycatch or wastage, assuming the same removals due to fishing and natural mortality. The operational equations are:

$$\text{Egg Loss } = \sum_{t=1}^{30} \sum_{a=t}^{30} NF_{a,t} M_a E_a$$

$$E_a = 0.0256 L^{3.5601}$$

where *a* indexes age, *t* indexes time, M_a is fraction mature at age, NF is number of females in the population at time t and age a and E_a is Egg production at age, which is a function of length *L*. Egg Loss is then computed on a per pound of bycatch basis. An Egg Replacement ratio is computed as the ratio of Egg Loss per pound of bycatch to Egg Production per pound of commercial catch, i.e., it determines how much commercial catch must be left in the water to replace egg production lost to bycatch (or wastage).

$$ER_{ratio} = \frac{\text{Egg production/lb of bycatch}}{\text{Egg production/lb of setline catch}}$$

This ratio was the basis for bycatch compensation between 1991 and 1995. Similar to the Yield Loss ratio, Egg Replacement ratio is greatest for small fish and declines with size. However, unlike Yield Loss, there is an increase in the Egg Replacement ratio for fish of a larger size (Figure 5d). The reason for this increase at larger sizes is that above a size of about 105 cm, virtually all catch is comprised of females and the egg production per pound of bycatch of fish of this size is significantly greater than the egg production per pound of fish between 82 and 105 cm. Egg production per pound of commercial catch is generally in the range of 40,000 - 50,000 eggs. Egg production per pound of bycatch and wastage is generally around 70,000 eggs and 55,000 eggs, respectively. Thus, typical ER_{ratios} are roughly 1.8 lb/lb for bycatch and 1.2 lb/lb for wastage. The amount of commercial catch that would have to be foregone to replace lost egg production is the product of bycatch (or wastage) mortality and the ER_{ratio}.

Results

Estimates of bycatch mortality and commercial wastage, and their size distributions, are produced annually for the stock assessment (see Figs. 3 and 4 for 2008 values). Coastwide, the number of U32 fish lost to bycatch has varied between 1.74 and 2.59 million halibut over the 1996-2008 time frame (Table 4a). Numbers lost to wastage in the commercial fishery are approximately an order of magnitude less (Table 5a). In terms of weight, the U32 bycatch has averaged about

7.5 million pounds and U32 wastage around 1.5 million pounds (Tables 4b and 5b, respectively). The coastwide trend in U32 bycatch mortality has been essentially flat, but there has been a steady increase in commercial U32 wastage mortality, as growth rates have declined and recruitment has improved.

Bycatch mortality, and the yield loss due to bycatch mortality, have shown little trend on a coastwide basis, but there have been recent modest increases in areas 3A and 4B, and high variability in areas 2C and 4A (Fig. 7). Most of the bycatch mortality and yield loss occurs in areas 3A, 3B, 4A, and 4CDE where losses are at or above one million pounds annually. $YLoss_{ratios}$ average 1.19 pounds of commercial catch per pound of bycatch, and are greater than 1.0 for all areas except 3A. The highest $YLoss_{ratio}$ is in Area 2C. The low value in 3A occurs due to the relatively large size of the bycatch and the small size at age of fish in the commercial catch. The high value of 1.47 lbs/lb in 2C is primarily due to the large size at age of halibut in the commercial catch. On a coastwide basis, the mean loss to the CEY resulting from U32 bycatch (of about 7.5 million pounds) has been around 8 million pounds annually.

Commercial wastage of U32 halibut, and its concomitant yield loss, has shown an increasing trend over the 1996-2008 time frame in all areas, except 4B where the wastage is virtually insignificant (Figure 8). The $YLoss_{ratio}$ of commercial wastage ranges from a low of 0.70 lbs/lb in 3A to a high of 1.22 lb/lbs in 2C, with a coastwide average of 0.83 lb/lbs. The reasoning for why areas 3A and 2C represent the low and high values is the same as for bycatch mortality. On a coastwide basis, the mean loss to the CEY resulting from U32 wastage (of about 1.5 million pounds) has been around 1.3 million pounds annually.

The Egg Replacement ratio quantifies how much commercial catch would need to be foregone to replace lost egg production by the stock due to bycatch or wastage. Coastwide, over the period 2002 to 2008, the ER_{ratio} was estimated to average 2.02 lb/lb of bycatch and 1.29 lb/lb of wastage. Thus, to replace the average annual lost egg production due to U32 bycatch, about 15 million pounds of commercial catch would have to be foregone annually. The 1.8 million pounds of U32 wastage would require nearly 2.5 million pounds of commercial catch be foregone annually. The exact ER_{ratios} vary annually and by area and are illustrated in Figures 9 and 10. The highest bycatch ER_{ratios} are in areas 4A and 4CDE; the lowest are in areas 2A and 2B. The highest wastage ER_{ratios} are in areas 2C and 4B; the lowest are in areas 2A and 4CDE. The areas of high and low ratios differ from those that had the highest and lowest Yield Loss ratios due to the influence of the size distribution and sex composition of the commercial catch.

Discussion

Many factors affect stock productivity, including stock size, recruitment, growth, natural mortality, and migration. Annual surplus production succinctly illustrates the annual productivity of each regulatory area integrating each of these factors. However, ASP does not in itself provide guidance on whether the level of EBio that produced ASP was "ideal". A higher or lower EBio would produce a higher or lower ASP and a separate analysis must determine the target level of biomass or harvest rate. Further, ASP provides no guidance or information on spawning biomass levels. The one generalization that perhaps can be made is that if ASP is negative or very low, then it is most likely that removals at existing levels will lead to stock declines. A positive, or large ASP, can mean either that removals can be increased or the stock is quite low and the EBio is rebuilding but the foregoing warning concerning the "ideal" or target level of biomass should be heeded.. Thus, while ASP and its variability are of interest, it is but one factor to consider in establishing sustainable harvest levels and yields.

The calculations and results for Yield Loss and Egg Replacement ratios presented here do not consider the effects of migration. Each area's bycatch and wastage - and the resultant impacts - were confined to the area of capture. Area 4CDE, for example, has a large bycatch and the impacts of that bycatch are illustrated as being very substantial for Area 4CDE. However, in all likelihood, much of the Yield and Egg Production loss are in areas "downstream" since Area 4CDE is a net exporter of migratory fish, particularly those comprising the U32 category. Consideration of the effects of migration on the distribution of Yield and Egg Production Loss is the focus of a companion RARA report to this one (Valero and Hare 2010). Another issue not considered in this analysis is the mismatch in timing between loss of yield or eggs due to bycatch and wastage and compensation. Both yield and egg loss would occur several years in the future while compensation acts in the current year to replace the future losses. The ongoing calculations that would be required to exactly compensate in real time for past losses would be considerable. If bycatch and wastage are roughly constant over time then compensating presently for current bycatch and wastage levels then the timing issue is less problematic, because in an equilibrium setting, present compensation exactly replaces past losses. Further work on the timing issue is possible but is not currently perceived to be a pressing issue.

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Table 1. Estimates of Exploitable Biomass (in M net lbs) among IPHC regulatory areas for the period 1997-2008.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1997	4.827	46.318	70.502	177.031	133.280	48.038	45.690	48.015	573.701
1998	4.909	47.110	71.707	180.058	135.558	48.860	46.471	48.836	583.510
1999	4.950	37.230	55.762	165.478	138.178	53.925	40.792	66.105	562.418
2000	4.782	33.061	46.652	146.486	133.035	52.507	36.469	66.771	519.763
2001	4.690	26.612	34.847	128.951	121.805	51.502	31.241	65.856	465.504
2002	4.909	28.689	35.173	125.125	114.394	45.633	29.082	57.940	440.945
2003	4.614	28.319	37.131	130.976	97.903	37.333	24.277	49.308	409.861
2004	3.988	26.802	37.257	126.316	88.834	30.774	19.230	48.576	381.776
2005	3.407	25.196	33.950	128.571	77.099	27.112	14.447	44.704	354.486
2006	3.307	23.975	30.293	129.102	71.091	24.306	13.272	40.157	335.503
2007	3.117	23.020	26.649	132.468	64.362	20.474	13.101	35.565	318.756
2008	2.763	19.923	24.822	122.468	59.689	16.026	13.809	30.099	289.600
2009	2.907	27.041	26.749	134.674	63.775	18.173	18.369	32.956	324.644

Table 2. Estimates of Total Removals (in M net lbs) among IPHC regulatory areas for the period 1997-2008.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1997	1.262	13.754	12.370	31.862	9.920	3.941	3.546	5.505	82.160
1998	1.689	14.529	13.146	32.122	12.002	4.820	3.245	5.493	87.046
1999	1.567	14.011	12.453	31.018	14.686	5.572	3.935	6.589	89.831
2000	1.486	12.288	11.165	25.997	16.152	6.228	5.295	6.318	84.929
2001	1.790	11.798	10.719	27.970	17.036	5.817	4.884	6.896	86.910
2002	1.653	13.821	11.054	28.619	18.099	5.859	4.292	6.267	89.664
2003	1.607	13.475	11.465	29.700	17.803	5.611	4.101	5.472	89.234
2004	1.713	14.251	14.028	32.773	15.909	4.174	3.026	4.906	90.780
2005	1.511	14.700	14.197	33.611	13.617	3.958	2.262	5.791	89.647
2006	1.561	14.265	13.851	32.593	11.370	4.070	1.826	5.461	84.997
2007	1.509	11.811	12.346	34.198	9.793	3.563	1.747	5.863	80.830
2008	1.342	9.809	10.100	31.506	11.450	3.589	1.991	5.544	75.331

Table 3. Estimates of Annual Surplus Production (in M net lbs) among IPHC regulatory areas for the period 1997-2008.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1997	1.345	14.546	13.575	34.889	12.199	4.762	4.327	6.326	91.968
1998	1.730	4.649	-2.799	17.542	14.621	9.885	-2.435	22.761	65.955
1999	1.399	9.842	3.343	12.026	9.544	4.154	-0.388	7.255	47.176
2000	1.394	5.838	-0.640	8.462	4.921	5.223	0.068	5.404	30.670
2001	2.009	13.875	11.045	24.144	9.625	-0.052	2.724	-1.020	62.351
2002	1.359	13.451	13.012	34.469	1.608	-2.441	-0.513	-2.365	58.580
2003	0.981	11.958	11.591	25.040	8.733	-0.949	-0.945	4.740	61.149
2004	1.131	12.645	10.721	35.029	4.174	0.512	-1.757	1.034	63.489
2005	1.412	13.479	10.540	34.141	7.609	1.152	1.087	1.244	70.665
2006	1.371	13.310	10.207	35.959	4.641	0.238	1.655	0.869	68.250
2007	1.155	8.714	10.519	24.198	5.120	-0.885	2.455	0.397	51.673
2008	1.486	16.927	12.027	43.713	15.536	5.737	6.550	8.401	110.376

Table 4a. Estimated number, in millions, of under-32 inch halibut bycatch mortality in non-directed fisheries.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1996	0.019	0.022	0.020	0.359	0.269	0.419	0.029	0.752	1.889
1997	0.019	0.017	0.029	0.398	0.212	0.566	0.018	0.772	2.032
1998	0.034	0.017	0.023	0.292	0.163	0.397	0.029	0.846	1.801
1999	0.031	0.014	0.025	0.333	0.197	0.604	0.016	0.942	2.162
2000	0.026	0.016	0.027	0.334	0.172	0.446	0.023	0.917	1.960
2001	0.026	0.004	0.047	0.413	0.267	0.219	0.026	0.734	1.737
2002	0.027	0.017	0.062	0.397	0.558	0.721	0.015	0.950	2.747
2003	0.029	0.020	0.053	0.431	0.288	0.508	0.008	0.952	2.289
2004	0.027	0.021	0.055	0.557	0.227	0.509	0.011	0.866	2.272
2005	0.015	0.028	0.053	0.484	0.207	0.450	0.010	0.998	2.245
2006	0.032	0.023	0.024	0.531	0.203	0.419	0.068	1.287	2.586
2007	0.032	0.023	0.024	0.495	0.180	0.423	0.095	1.142	2.414
2008	0.026	0.010	0.024	0.529	0.193	0.321	0.062	0.935	2.100

Table 4b. Estimated weight, in millions of net pounds, of under-32 inch halibut bycatch mortality in non-directed fisheries.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1996	0.140	0.133	0.111	1.297	0.972	1.582	0.160	2.708	7.102
1997	0.140	0.106	0.157	1.415	0.714	1.543	0.098	2.230	6.403
1998	0.248	0.096	0.123	1.192	0.657	1.297	0.157	2.030	5.799
1999	0.226	0.085	0.127	1.602	0.992	1.586	0.073	2.141	6.833
2000	0.188	0.102	0.141	1.606	0.863	1.335	0.106	2.330	6.670
2001	0.192	0.028	0.158	1.392	1.045	0.934	0.145	2.177	6.070
2002	0.171	0.092	0.174	1.121	1.205	1.697	0.081	2.038	6.578
2003	0.199	0.115	0.197	1.613	1.064	1.571	0.039	2.349	7.146
2004	0.181	0.121	0.205	2.084	0.837	1.574	0.053	2.136	7.189
2005	0.103	0.165	0.197	1.810	0.765	1.392	0.050	2.461	6.942
2006	0.197	0.143	0.127	1.912	0.892	1.063	0.193	3.217	7.744
2007	0.197	0.146	0.127	1.781	0.792	1.075	0.270	2.855	7.244
2008	0.157	0.064	0.128	1.905	0.852	0.814	0.176	2.337	6.432

Table 5a. Estimated number, in millions, of under-32 inch halibut wastage mortality in the directed commercial fishery.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	All
1996	0.000	0.027	0.017	0.046	0.009	0.002	0.003	0.001	0.105
1997	0.000	0.036	0.020	0.061	0.024	0.004	0.004	0.002	0.152
1998	0.000	0.039	0.021	0.068	0.032	0.006	0.004	0.003	0.172
1999	0.000	0.039	0.023	0.071	0.043	0.008	0.005	0.004	0.194
2000	0.000	0.034	0.020	0.056	0.054	0.011	0.006	0.005	0.186
2001	0.001	0.034	0.021	0.067	0.065	0.012	0.006	0.006	0.211
2002	0.001	0.041	0.023	0.075	0.078	0.014	0.005	0.006	0.244
2003	0.001	0.044	0.024	0.078	0.087	0.016	0.004	0.006	0.259
2004	0.002	0.051	0.033	0.090	0.089	0.014	0.003	0.007	0.287
2005	0.002	0.057	0.039	0.099	0.084	0.014	0.002	0.007	0.304
2006	0.002	0.060	0.043	0.099	0.079	0.016	0.001	0.008	0.309
2007	0.002	0.063	0.039	0.136	0.066	0.021	0.003	0.011	0.341
2008	0.002	0.035	0.031	0.133	0.104	0.021	0.003	0.014	0.344

Table 5b. Estimated weight, in millions of net pounds, of under-32 inch halibut wastage mortality in the directed commercial fishery.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	All
1996	0.002	0.184	0.115	0.323	0.059	0.016	0.017	0.009	0.726
1997	0.002	0.248	0.136	0.426	0.161	0.029	0.029	0.016	1.048
1998	0.002	0.275	0.147	0.473	0.218	0.039	0.025	0.019	1.198
1999	0.003	0.276	0.154	0.491	0.296	0.055	0.031	0.029	1.335
2000	0.003	0.240	0.135	0.393	0.370	0.072	0.041	0.033	1.287
2001	0.005	0.236	0.143	0.459	0.443	0.080	0.038	0.040	1.442
2002	0.009	0.286	0.155	0.516	0.528	0.092	0.032	0.040	1.658
2003	0.009	0.302	0.165	0.530	0.593	0.104	0.029	0.038	1.770
2004	0.011	0.343	0.225	0.612	0.597	0.085	0.018	0.043	1.933
2005	0.013	0.388	0.260	0.659	0.558	0.093	0.012	0.047	2.030
2006	0.014	0.410	0.283	0.667	0.511	0.101	0.009	0.051	2.045
2007	0.016	0.438	0.267	0.918	0.423	0.132	0.018	0.074	2.286
2008	0.015	0.262	0.212	0.924	0.681	0.133	0.019	0.091	2.337

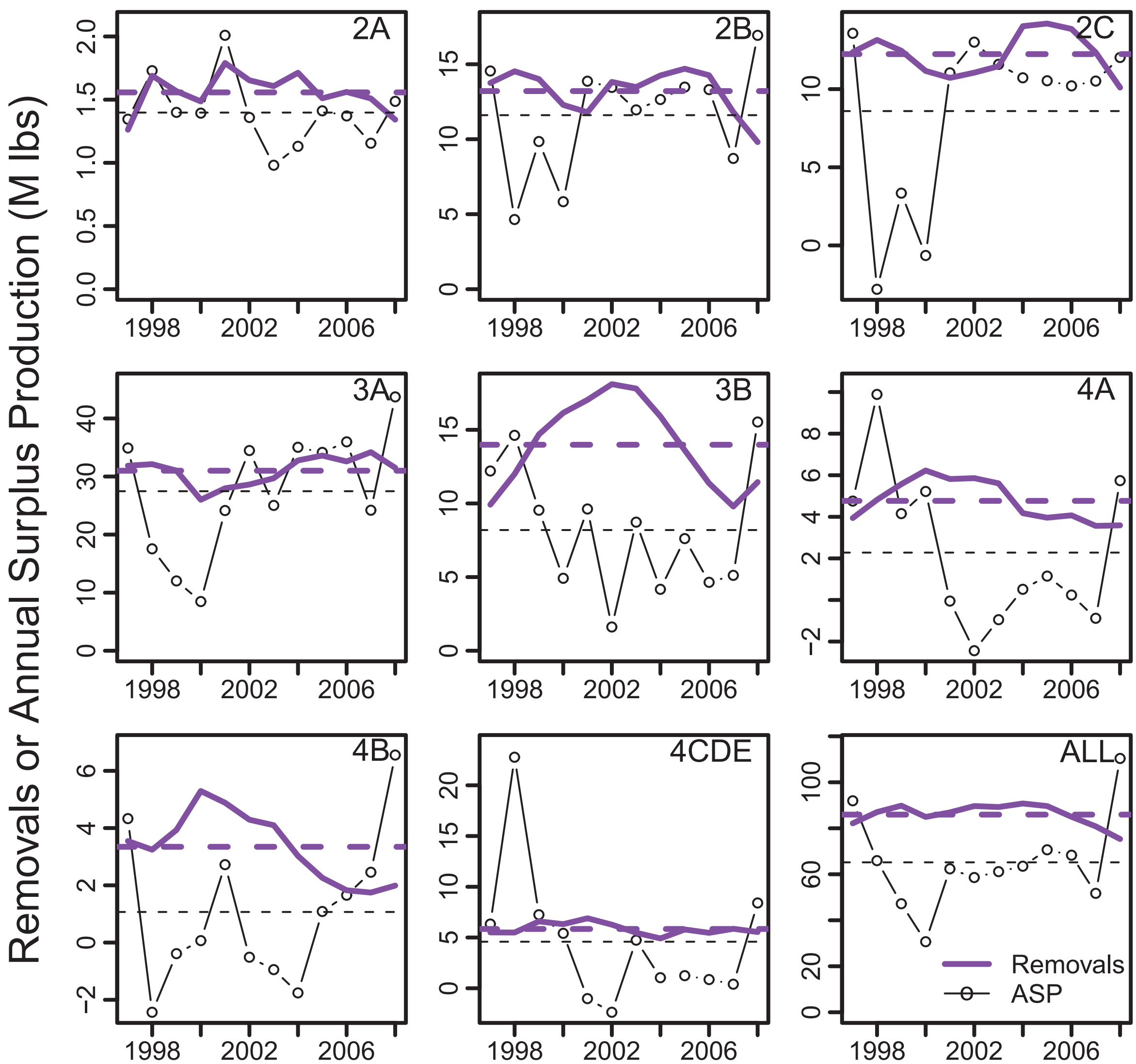

Figure 1. Estimated annual surplus production (ASP) and total removals for all IPHC regulatory areas, 1997-2008. The dashed lines indicate mean values for removals (thick line) and ASP (thin line) over the time period.

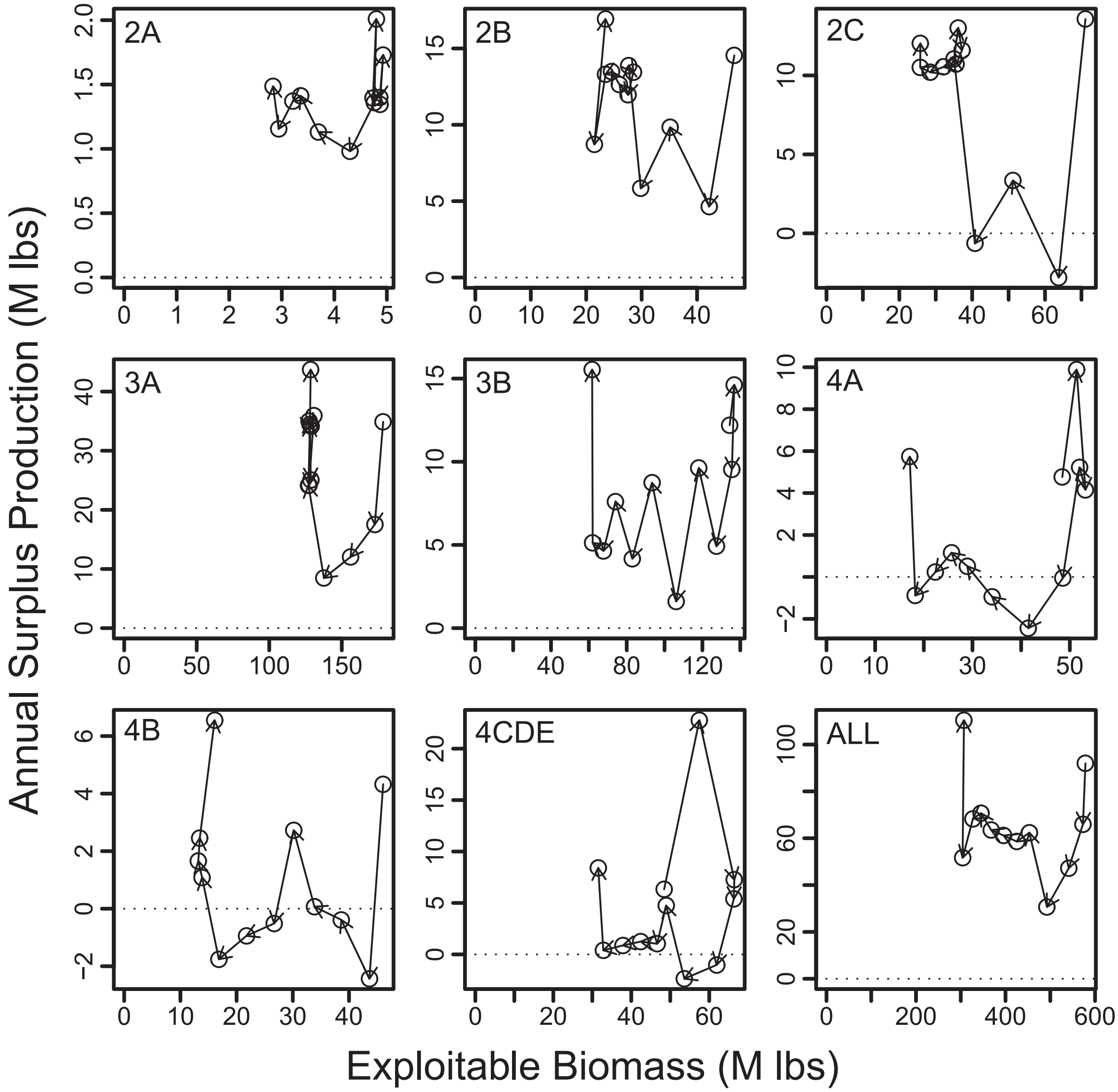

Figure 2. Relationship between Exploitable Biomass and Annual Surplus Production over the period 1997 (originating circle) to 2008 (concluding circle).

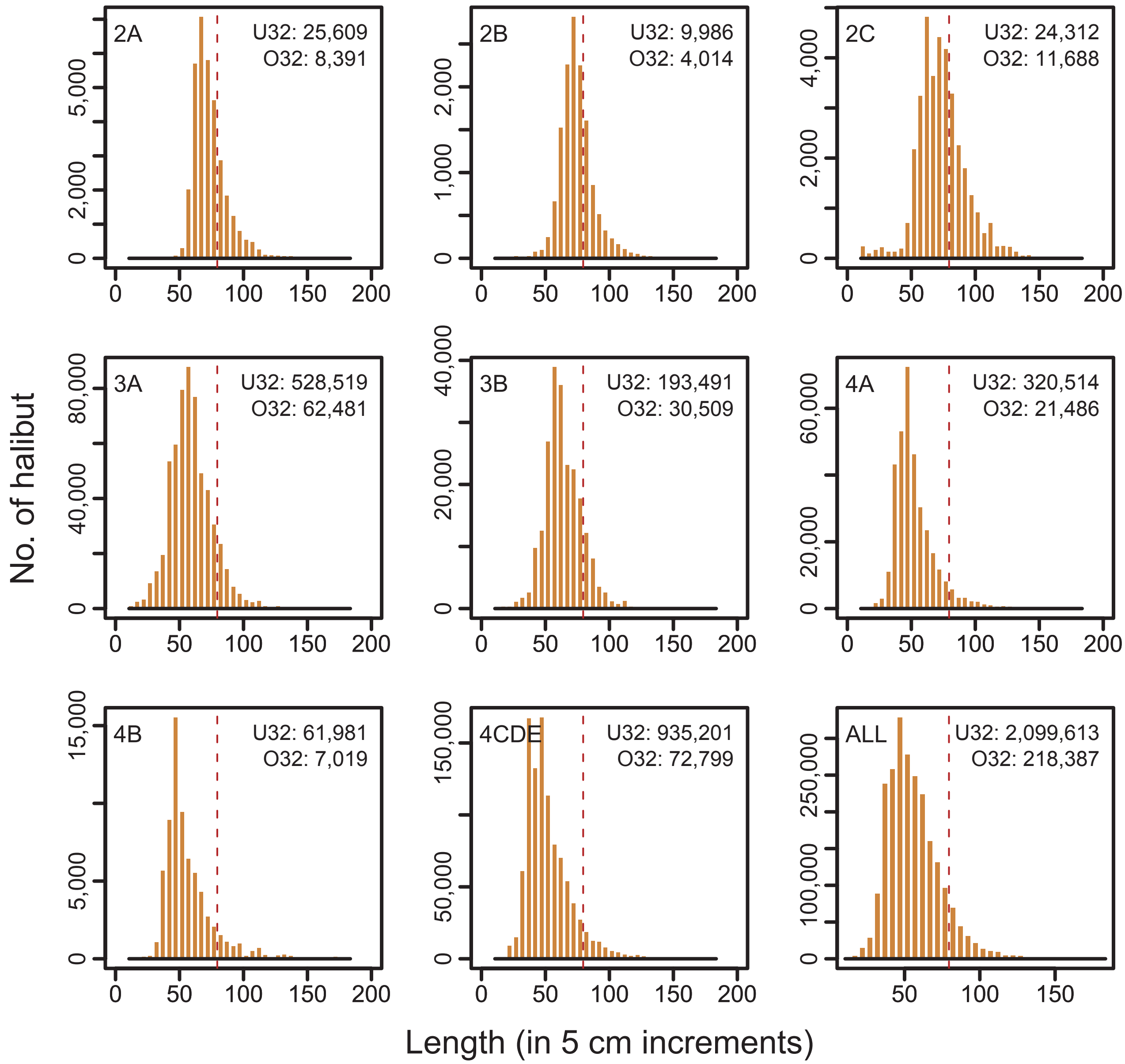

Figure 3. Estimated size distribution of bycatch by regulatory area, for 2008. The vertical line separates the under-32 inch (U32) halibut and over-32 (O32) inch halibut. Estimated numbers of U32 and O32 halibut killed as bycatch are also listed.

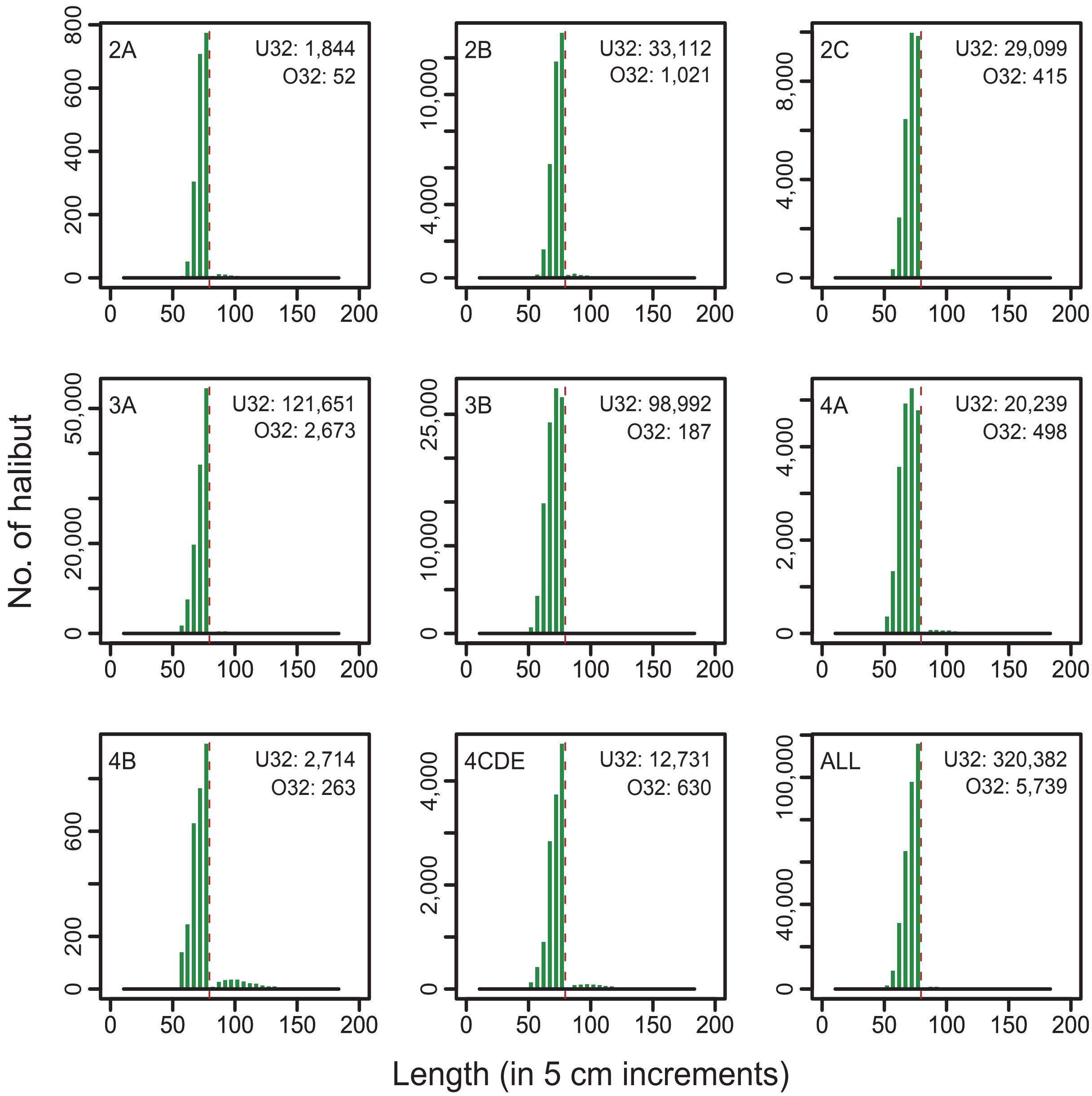

Figure 4. Estimated size distribution of wastage by regulatory area, for 2008. The vertical line separates the under-32 inch (U32) halibut and over-32 (O32) inch halibut. Estimated numbers of U32 and O32 halibut killed as wastage are also listed.

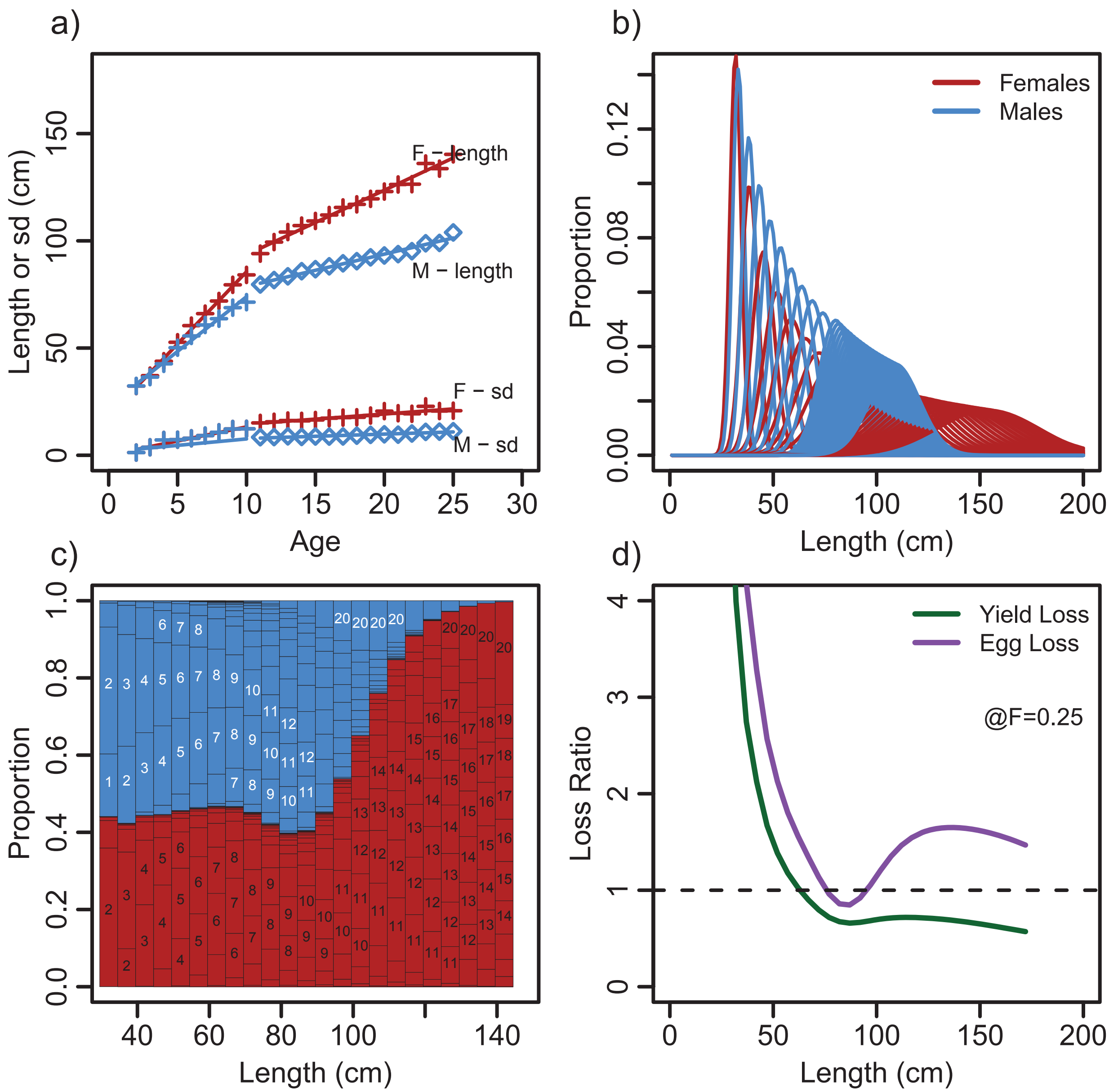

Figure 5. Summary plot for model developed to decompose catch at length data to sex and age based values. Results here are for coastwide size at age data. Separate analyses and plots were produced for all areas (but not shown here). Panel a) illustrates mean length and standard deviation at length for male and female halibut, along with fitted regressions. Panel b) shows resultant size distributions at age using parameters from regressions. Panel c) illustrates equilibrium proportions at sex (blue is male, red is fenale) and age (values shown inside bars) for 5-cm length intervals, assuming an M of 0.15 and F of 0.25. Panel d) illustrates how the yield loss and egg loss ratios are related to length. The values illustrated are for an equilibrium fishing mortaltiy rate of 0.25. The meaning of the loss ratio differs for the different types of losses (see text for details).

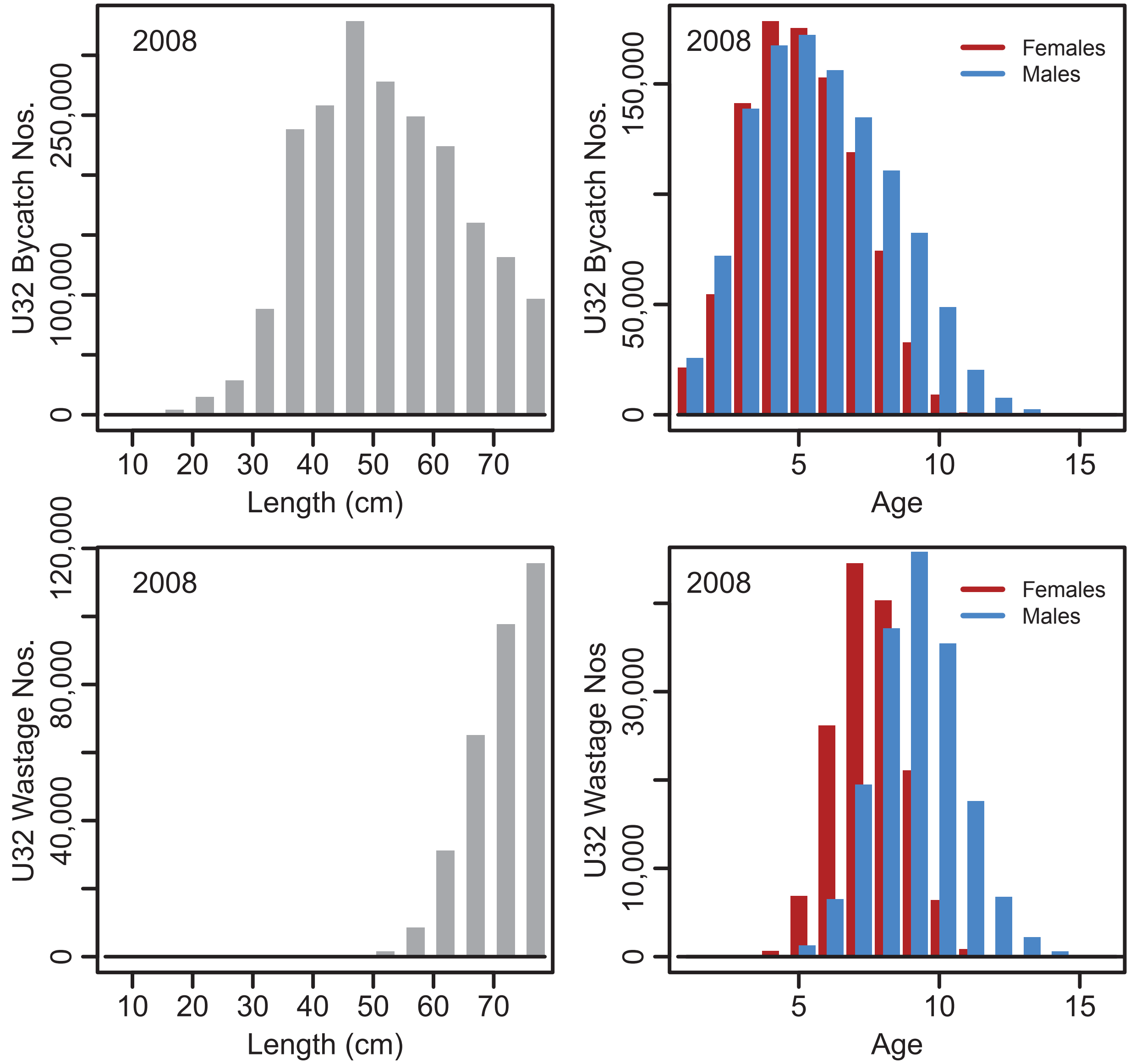

Figure 6. Under-32 (U32) length frequency distributions (left panels) for bycatch and wastage and the resultant decomposed age and sex distributions. These figures are for coastwide 2008 data. The coastwide age and sex distributions were assembled by decomposing length frequency distributions for each regulatory area and then summing across areas.

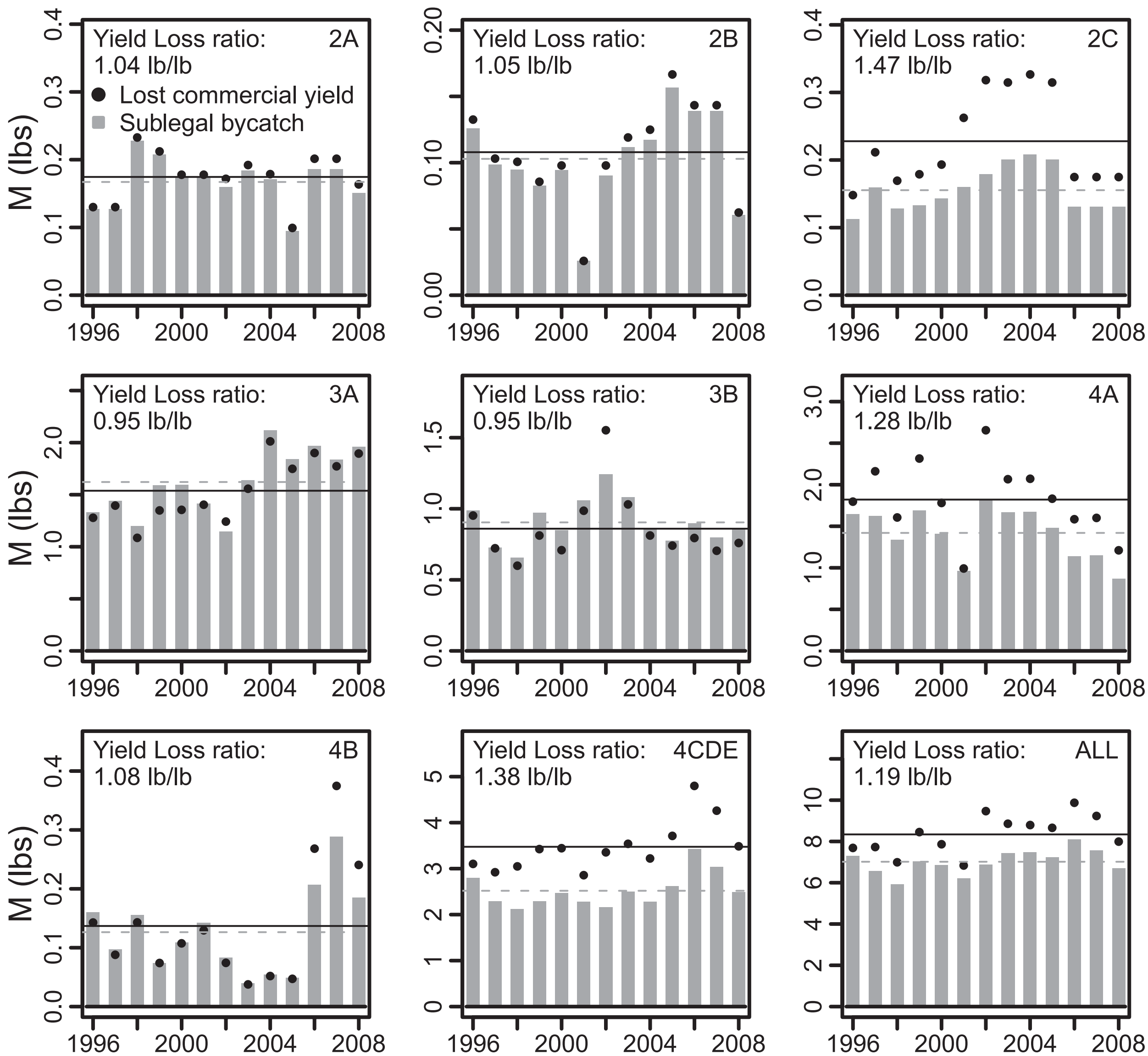

Figure 7. Illustration of impact of under-32 inch bycatch on future yield by regulatory area. The bars show estimated annual bycatch mortality, dots show estimated lost yield. Lost yield is estimated using growth models developed individually for each regulatory area. The dashed horizontal line is the average U32 bycatch over the 2002-2008 period; the solid horizontal line is the average yield loss over the same time frame.

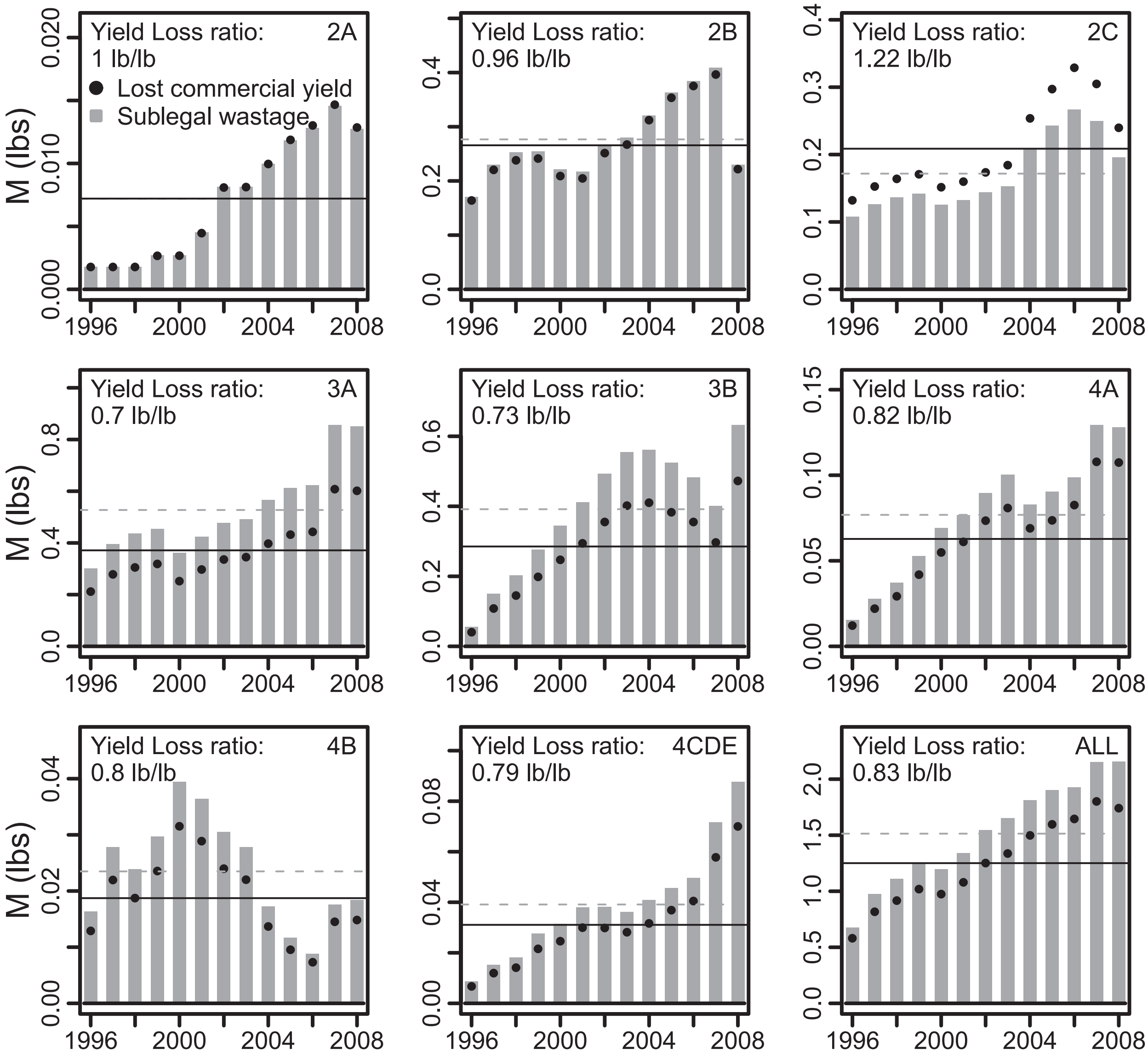

Figure 8. Same as Figure 2, but showing results for under-32 inch wastage in the commercial fishery.

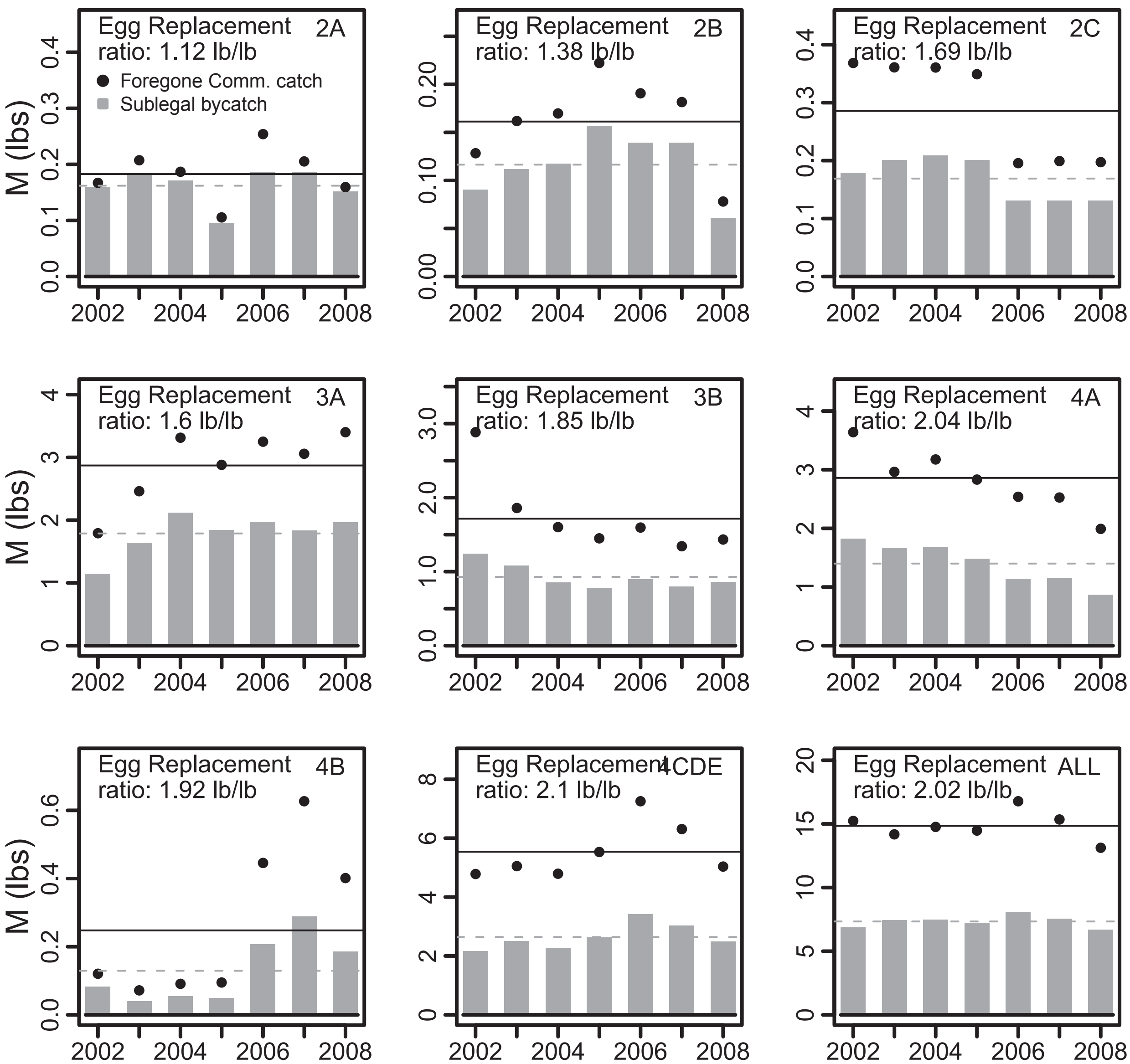

Figure 9. Illustration of impact of under-32 inch (U32) bycatch on amount of commercial catch that would have to be foregone to replace lost egg production. The bars show estimated annual bycatch mortality, dots show amount of commercial catch that would have to be foregone. The egg replacement is how the amount of commercail catch that must be foregone per pound of bycatch and it estimated using growth models develeoped individually for each regulatory area. The dashed horizontal line is the average U32 bycatch over the 2002-2008 period; the solid horizontal line is the required foregone commercial catch over the same time frame.

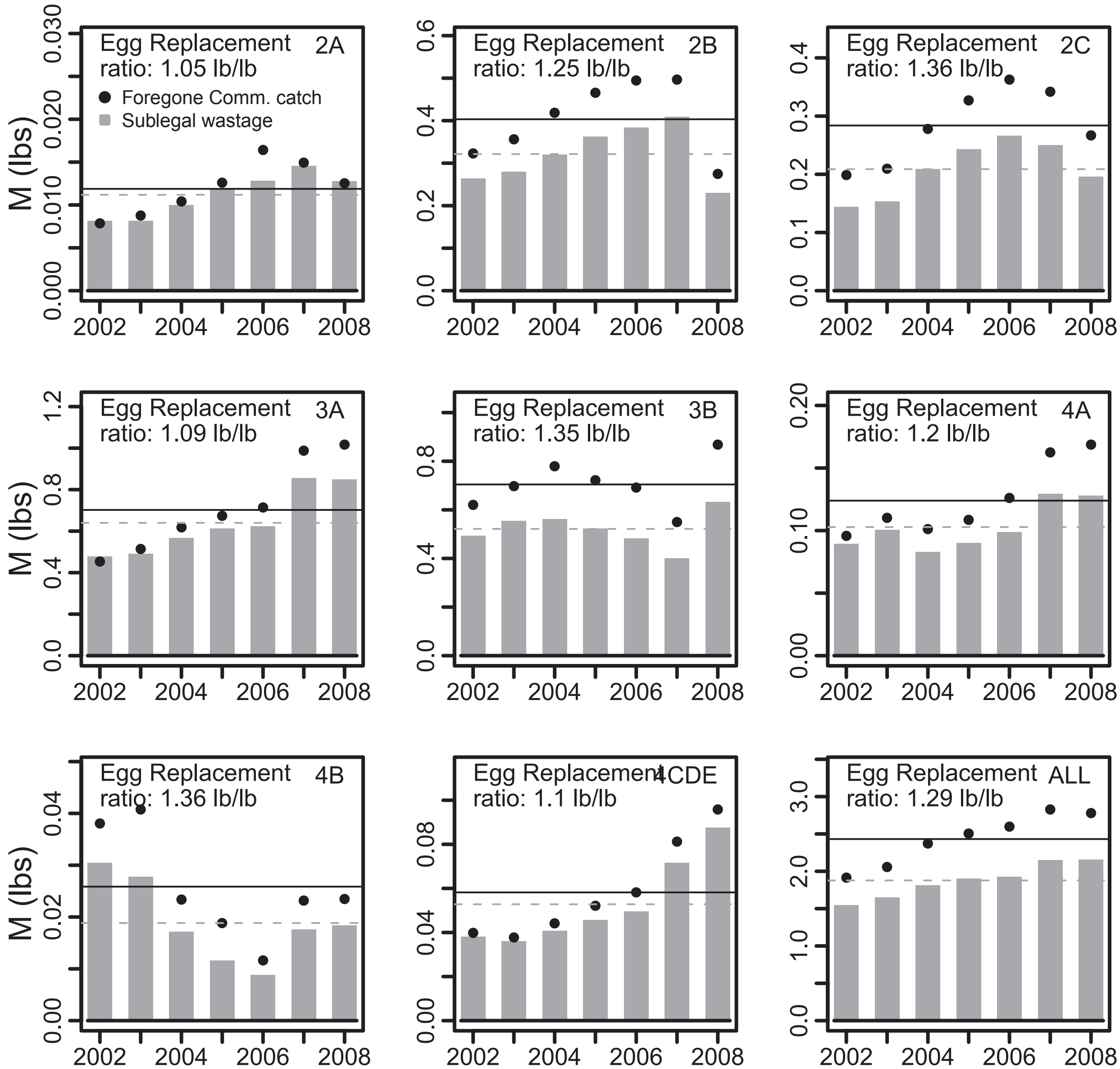

Figure 10. Same as Figure 9, but showing results for under-32 inch wastage in the commercial fishery.