Effect of migration on lost yield, lost spawning biomass, and lost egg production due to U32 bycatch and U32 wastage of Pacific halibut

Juan L. Valero and Steven R. Hare

Abstract

During the last 60 years, annual catches in the directed commercial Pacific halibut fishery have ranged from about 20 million pounds to about 75 million pounds, whereas bycatch mortality of halibut in non-directed fisheries has averaged about 14 million pounds per year. Treatment of bycatch in IPHC management has changed over time from different forms of explicit area-specific quota deductions to the implementation of the current method, which is based on a harvest rate adjustment, in the late 1990s. The current method deducts O32 bycatch from area-specific quotas and incorporates U32 bycatch in the determination of the target harvest rate. At that time, migration modeling of U32 bycatch indicated that the impact of U32 bycatch was largely confined to the area where the bycatch was taken. However, this approach assumed that ontogenetic halibut migration ceased by the time halibut became available to commercial gear, an assumption that has been refuted by a recent extensive tagging program. Here we report preliminary results on the impact of U32 bycatch and U32 wastage on lost yield (LY), lost spawning biomass (LSBio), and lost egg production (LE) in light of the improved understanding of halibut migration. Preliminary results suggest that coastwide impacts on LY, LSBio and LE are similar with or without accounting for migration of U32 bycatch and U32 wastage. However, area specific impacts on LY, LSBio, and LE vary by area when accounting for migration. The effect of migration is to decrease impacts of U32 bycatch and U32 wastage on Area 4 and to increase impacts on other areas, particularly Area 2. Much of the impact of U32 bycatch is determined to be on areas outside of where the bycatch was taken. In contrast, most of the impacts of U32 wastage are determined to be from local wastage.

Introduction

The Pacific halibut (*Hippoglossus stenolepis*) is distributed in the north Pacific from Hokaido, Japan to northern California, U.S. (Clark and Hare 2006). The International Pacific Halibut Commission (IPHC) studies and manages halibut from the Bering Sea to northern California (Fig. 1). Halibut abundance changes along its geographic range, with the current center of abundance located around Kodiak Island (Area 3A, Fig. 1) in the Gulf of Alaska (Clark and Hare 2006). During summer, halibut are distributed on the continental shelf, but during the winter mature halibut migrate to spawning grounds located in deeper waters (St. Pierre 1984). Recent archival tagging has identified winter spawning migrations as long as 1200 km as well as some degree of site fidelity to summer areas (Loher 2008). After spawning, halibut eggs and larvae are carried by prevailing currents north and westward towards the western Gulf of Alaska and the Bering Sea. Juvenile halibut undertake an ontogenetic eastward-southward migration that counters the drift of eggs and larvae (Skud 1977, Hilborn et al. 1995).

The commercial fishery that targets Pacific halibut is considered to have started in 1888 near the area around Cape Flattery off the northwest coast of Washington State (current IPHC regulatory area 2A, Fig. 1). Since the late 1950s, annual commercial removals ranged from about 20 million pounds (mid 1970s) to about 75 million pounds (late 1980s and early 2000s). Pacific halibut bycatch was negligible until the development of large scale trawling for other groundfish resources in the late 1950s. Since that time, the bycatch of Pacific halibut in non-directed fisheries has constituted a major source of mortality, averaging about 14 million pounds per year, to the coastwide population (Williams 2009). The manner in which bycatch has been accounted for in Pacific halibut management has changed over time (a comprehensive history of the treatment of bycatch can be found in Clark and Hare, 1998). During the 1980s quotas were adjusted to compensate for lost yield; during the early 1990s compensation focused on lost egg production. Reductions were calculated as a coastwide total and deducted on an area basis in proportion to estimated distribution of exploitable biomass. During the late 1990s halibut bycatch under (U32) and over (O32) the 32 inch minimum commercial size started to be treated differently. O32 bycatch was treated the same as other area-specific removals whereas U32 bycatch was incorporated in the evaluation of the target harvest rate. At that time, migration modeling of U32 bycatch indicated that the impacts of U32 bycatch were largely confined to the area where the bycatch was taken (Clark and Hare 1998). However, this approach assumed that ontogenetic halibut migration ceased by the time halibut became available to commercial gear, an assumption that has been refuted by a recent extensive tagging program (Webster and Clark 2007). Here we report preliminary results on the impact of U32 bycatch and U32 wastage on yield (LY), spawning biomass (LSBio), and egg production (LE) in light of the improved understanding of halibut migration.

Materials and Methods

This work uses a sex-specific, age-structured, multi-area model with migration similar to that described in Valero and Hare (2009, 2010). The model includes ages one to 50, which is an accumulating age or plusgroup. Sex-specific size at age, maturity at age, and selectivity (survey and commercial) at size are the same as in Hare (2010). The model used here includes six areas: Area 4 (a combination of IPHC regulatory Areas 4A, 4B, and 4CDE) and regulatory Areas 3B, 3A, 2C, 2B, and 2A (Fig. 1). The basic equation describing population dynamics is

$$N^U_{a+1,s,t+1,i} = e^{-(M+S^f_{a,s}F_{t,i})}\sum_{k=1}^{K}\Theta_{a,i}(k \to i)N^U_{a,s,t,k}$$

where $N^U_{a,s,t,i}$ is numbers of fish (U denotes either U32 bycatch or U32 wastage) at age a, sex s, year t, and area i; M is natural mortality (fixed at 0.15yr^{-1}, the value used in the assessments); $S^f_{a,s}$ is the selectivity of the commercial fishery for age a and sex s, $F_{t,i}$ is the fishing mortality rate for year t and area i, $\Theta_{a,i}$ is a matrix of annual migration rates among areas. Migration is assumed to occur instantaneously at the beginning of the year, before any source of mortality occurs. Analysis of traditional (Hoag et al. 1983, Quinn et al. 1985) and PIT tag (Webster and Clark 2007, Webster 2010) recoveries suggest that the fraction of fish migrating is a function of fish size/age, with smaller/younger fish more likely to migrate than larger/older fish. We use three migration scenarios. The first scenario has no migration ("NM"), produced to compare results obtained by Hare (2010). In the second scenario, ("1M") fish of all sizes migrate following a single migration matrix based on results of the PIT tag model (Webster 2009). In the third scenario ("2M"), migration of halibut smaller than 65cm is based on tagging results of juveniles (Hilborn et al. 1995) whereas migration of halibut larger than 65cm is based on PIT tag model results (Webster 2009).

We used this model in two ways. In order to explore the effect of different migration scenarios on the expected unfished distribution of biomass, we initialized the model using a relative distribution of age one halibut (Fig. 2) based on IPHC juvenile trawl surveys (Best 1977) and ran the model to equilibrium conditions under the two migration scenarios (1M and 2M). On the other hand, to evaluate the impacts of U32 bycatch on metrics of interest, the model was initialized instead with the 1996 to 2008 average numbers of bycaught U32 halibut by age, sex, and area reported by Hare (2010). The same calculations were made for the 1996 to 2008 average U32 wastage. The model was run with a fishing mortality rate of F=0.25. Computationally, the model keeps track of where (on a regulatory area basis) U32 fish, had they not being killed as bycatch or wastage, would have migrated and be caught by the commercial fishery (LY) or survive and contribute to spawning biomass (LSBio) and egg production (LE). The calculated impacts are cumulative over the life span of the age classes represented in the U32 removals (bycatch or wastage) and are equivalent to annual impacts assuming a constant level of U32 removals over time. Metrics were computed as follows. Commercial catch in numbers of fish (*U* denotes either U32 bycatch or U32 wastage), at age *a*, sex *s*, year *t*, and area *i* ($C^U_{a,s,t,i}$) is calculated using the Baranov catch equation:

$$C^U_{a,s,t,i} = \frac{F_{t,i} S^f_{a,s} N^U_{a,s,t,i}}{M + S^f_{a,s} F_{t,i}} \left[1 - e^{-(M + S^f_{a,s} F_{t,i})} \right]$$

Catch in weight is given by:

$$Y^U_{a,s,t,i} = C^U_{a,s,t,i} w^f_{a,s}$$

Lost yield is defined as:

$$LY^U_i = \sum_{t=1}^{50} \sum_{a=t}^{50} \sum_{s=1}^{2} Y^U_{a,s,t,i}$$

where $w^f_{a,s}$ is the average weight at age *a* for sex *s* in the fishery. Female Spawning Biomass for year *t* and area *i* ($SBio_{t,i}$) and lost spawning biomass ($LSBio_i$) are given by:

$$SBio^U_{t,i} = \sum_{a=1}^{50} N^U_{a,1,t,i} w^s_{a,1,i} Mat_a$$

$$LSBio^U_i = \sum_{t=1}^{50} SBio^U_{t,i}$$

where $N^U_{a,1,t,i}$ is the number at age *a* of females (*s* = 1) for year *t* and area *i*; $w^s_{a,1,i}$ is the average weight at age *a* for females in area *i*, and Mat_a is maturity at age. Given fecundity at age by area ($Fec_{a,i}$) and average length at age of females by area ($L_{a,1,i}$), egg production ($E^U_{t,i}$) is given by:

$$E_{t,i}^{U} = \sum_{a=1}^{50} N_{a,1,t,i}^{U} Fec_{a,i} Mat_{a}$$

$$Fec_{a,i} = 0.0256 L_{a,1,i}^{\;3.5601}$$

Lost egg production (LE_{i}^{U}) was calculated as:

$$LE_{i}^{U} = \sum_{t=1}^{50} E_{t,i}^{U}$$

In order to make comparisons easier between the metrics of interest, both lost egg production and lost spawning biomass are reported in terms of the equivalent foregone commercial yield required to replace their losses.

Preliminary results and on-going work

Preliminary results of the simulation approach presented here produced expected halibut biomass distributions under no fishing (Fig. 3) that are similar to those obtained by Valero and Hare (2009, 2010) and also to the earliest available estimates of halibut relative distribution (Thompson and Van Cleve 1936, see Fig. 3 bottom panel). A considerably larger proportion of the coastwide distribution is expected in Area 2 under no fishing conditions (Fig. 3) than what is currently estimated to be there by recent methods (Clark and Hare 2006, Hare 2010). This is consistent with the long history of exploitation of Area 2 and the higher than expected realized harvest rates resulting at least in part from the use of closed-area assessments. The expected distribution of biomass is similar between the scenarios of one or two migration matrices, although the scenario with two migration matrices produces a larger proportion of expected biomass in Area 2 (Fig. 3).

Coastwide impacts on LY, LSBio, and LE are similar with or without accounting for migration of U32 bycatch and U32 wastage (see left panels of Figs. 4, 6, 7, and 8). Coastwide differences among scenarios with different specification of migration are due to area differences in size at age, as fish moving between areas change their size at age relationship accordingly. The overall pattern of U32 mortality impacts on spawning biomass and egg production are very similar, and that is expected since both are close to cubic functions of mature female fish size, only differing between the coefficients of weight and fecundity.

On the other hand, area-specific impacts on LY (Figs. 4-5), LSBio (Fig. 6), and LE (Fig. 7) vary by area and also by source of U32 mortality (bycatch or wastage) when accounting for migration. The effect of migration is to decrease impacts of U32 bycatch and U32 wastage on Area 4 and to increase impacts in other areas, particularly Area 2. Most of the impacts of U32 bycatch are determined to be from out of area bycatch (Fig. 5). In contrast, most of the impacts of U32 wastage are determined to be from local wastage (Fig. 9). This contrast is attributable to the younger ages of the U32 bycatch compared to the ages of the U32 wastage (Fig. 10). The younger the source of mortality, the more migration is expected to occur before that component would have become available to the commercial halibut fishery and therefore result in yield lost.

Previous bycatch-migration modeling (Clark and Hare 1998) indicated that the impact of U32 bycatch was largely confined to the area where the bycatch was taken. Conversely, our results indicate considerable impacts of out of area U32 bycatch on areas eastward to where the U32 bycatch mortality occurs. This difference is attributable to the use of different assumptions on halibut migration between the modeling approaches. Based on data available at the time, Clark and Hare (1998) assumed that by age 8 the ontogenetic halibut migration had ceased. Our assumptions on migration are based on an improved knowledge from the recent PIT tag study. By consequently allowing migration to continue at older ages, the out of area effects of U32 bycatch are determined to be larger than previously reported. The larger age composition of U32 wastage results in mostly local effects on the area where U32 wastage occurs. This is consistent with previous work showing that the effects of varying harvest rates on the commercial fishery on upstream areas have negligible effects on yield lost to downstream areas (Valero and Hare 2009, 2010).

Results presented in this work are preliminary and extensive analyses are still being conducted. We have run sensitivities to some of the assumptions of the model such as the effect of using alternative migration scenarios and different size at age relationships. Preliminary results indicate that there is some variability in the results depending on the assumptions made (as expected), however the overall pattern still holds. A full report on the impacts of U32 bycatch and U32 wastage is anticipated in the following year.

References

Best, E. A. 1977. Distribution and abundance of juvenile halibut in the southeastern Bering Sea. Int. Pac. Halibut Comm., Sci. Rep. 62.

Clark, W. G. and Hare, S. R. 1998. Accounting for bycatch in management of the Pacific halibut fishery. N. Am. J. Fish. Mgmt. 18: 809-821.

Clark, W. C. and Hare, S. R. 2006. Assessment and management of Pacific halibut: data, methods and policy. Int. Pac. Halibut Comm. Sci. Rep. 83.

Hare, S.R. 2010. Estimates of halibut total annual surplus production, and yield and egg production losses due to under-32 inch bycatch and wastage. Int. Pac. Halibut Comm. Report of Assessmnent and Research Activities 2009:323-346.

Hoag, S. H., Myhre, R. J., St-Pierre, G. and McCaughran, D. G. 1983. The Pacific halibut resource and fishery in regulatory Area 2; I. Management and biology. Int. Pac. Halibut Comm. Sci. Rep. 67.

Hilborn, R., Skalski, J., Anganuzzi, A. and Hoffman, A. 1995. Movements of juvenile halibut in IPHC regulatory areas 2 and 3. Int. Pac. Halibut Comm. Tech. Rep. 31.

Loher, T. 2008. Homing and summer feeding site fidelity of Pacific halibut (*Hippoglossus stenolepis*) in the Gulf of Alaska, established using satellite-transmiting archival tags. Fish. Res. 92: 63-89.

Quinn, T. J., Deriso, R. B. and Hoag, S. H. 1985 Methods of population assessment of Pacific halibut. Int. Pac. Halibut Comm. Sci. Rep. 72.

St. Pierre, G., 1984. Spawning locations and season for Pacific halibut. Int. Pac. Halibut Comm. Sci. Rep. 70.

Skud, B. E. 1977. Regulations of the Pacific halibut fishery, 1924-1976. Int. Pac. Halibut Comm. Tech. Rep. No. 15.

Thompson,W. F. and Van Cleve, R. 1936. Life history of the Pacific halibut - Distribution and early life history. Int. Fisheries Comm. Rep. 9.

Valero, J. L. and Hare S. R. 2009. Exploring effects of fishing and migration on the distribution of Pacific halibut. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008:265-298.

Valero, J. L. and Hare S. R. 2010. Exploring effects of fishing and migration on Pacific halibut dynamics with Widget 2. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009:209-240.

Webster, R. A. and Clark W. G. 2007. Analysis of PIT tag recoveries through 2006. Int. Pac. Halibut Commission. Report on Assessment and Research Activities 2006: 129-138.

Webster, R. 2009. Analysis of PIT tag recoveries through 2008. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008:213-220.

Webster, R. 2010. Analysis of PIT tag recoveries through 2009. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009: 177-186.

Williams, G. H. 2009. Incidental catch and mortality of Pacific halibut, 1962-2008. Report on Assessment and Research Activities 2009: 299-312.

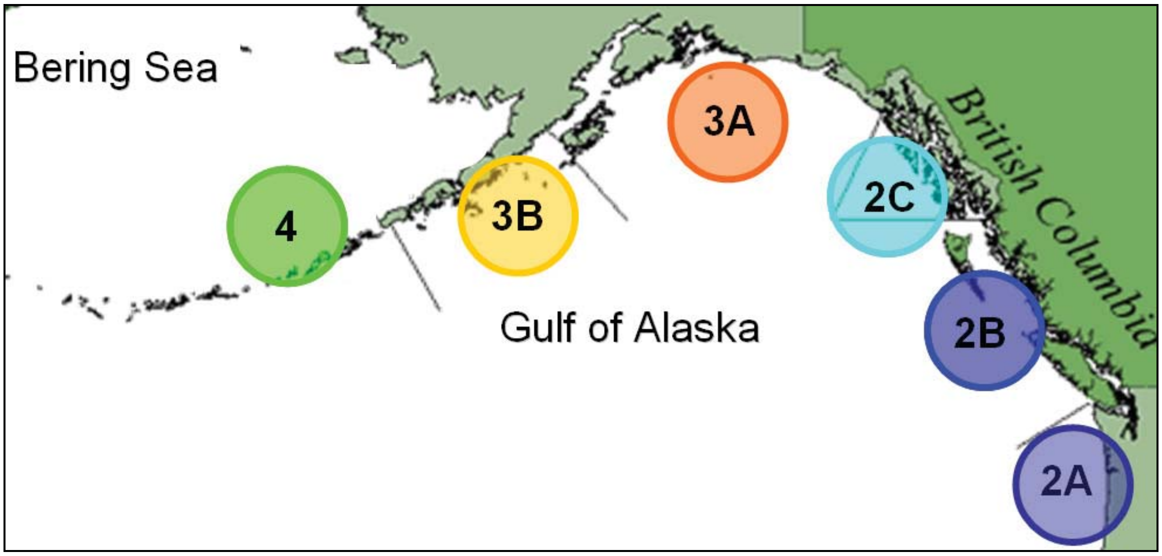

Figure 1. Map of areas included included in the simulation model. Areas 3B to 2A are IPHC regulatory areas, area 4 is a combination of 4A, 4B and 4CDE areas

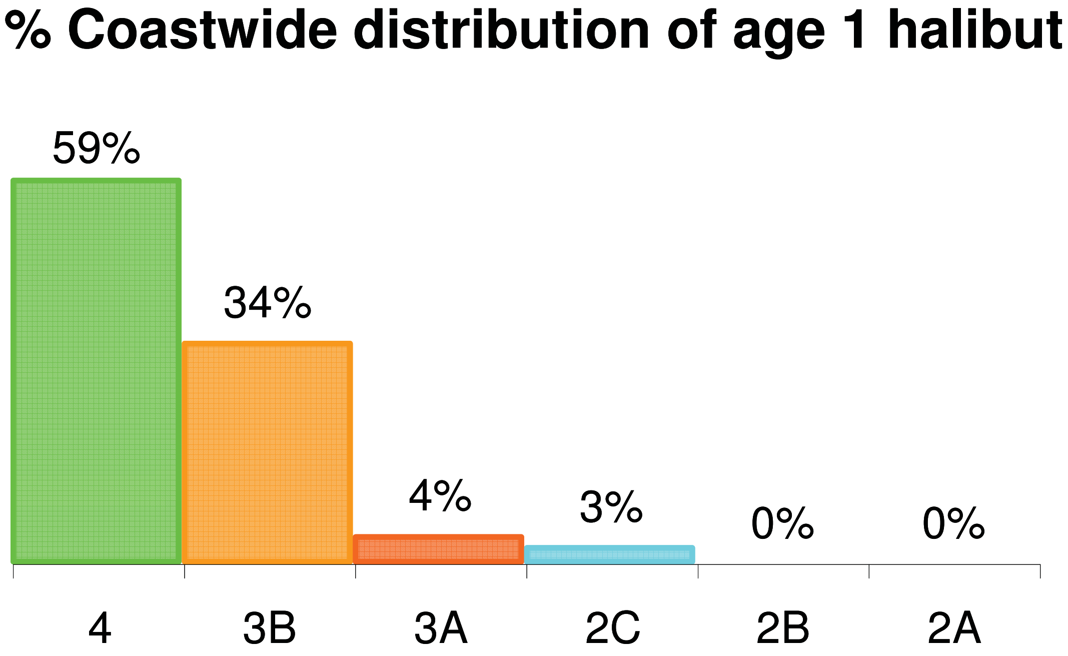

Figure 2. Percentage coastwide distribution of age 1 halibut based on IPHC juvenile surveys.

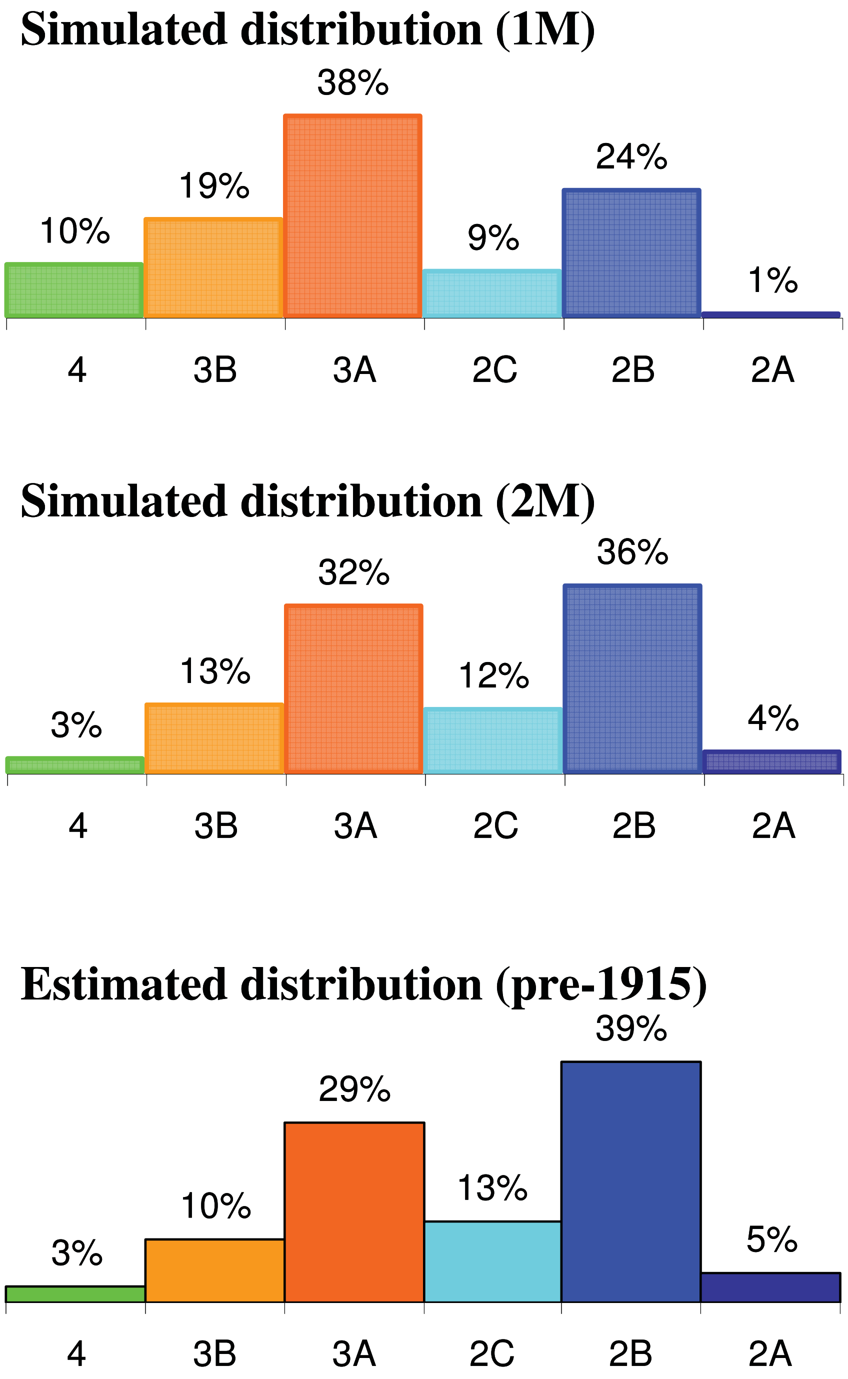

Figure 3. Simulated distribution of biomass expected at equilibrium unfished conditions when assuming halibut migration is specified by one migration matrix for all fish sizes (1M, top panel) or two migration matrices based on fish size (2M, middle panel). Bottom panel is the earliest available estimate of biomass distribution of Pacific halibut (based on Thompson and Van Cleve 1936).

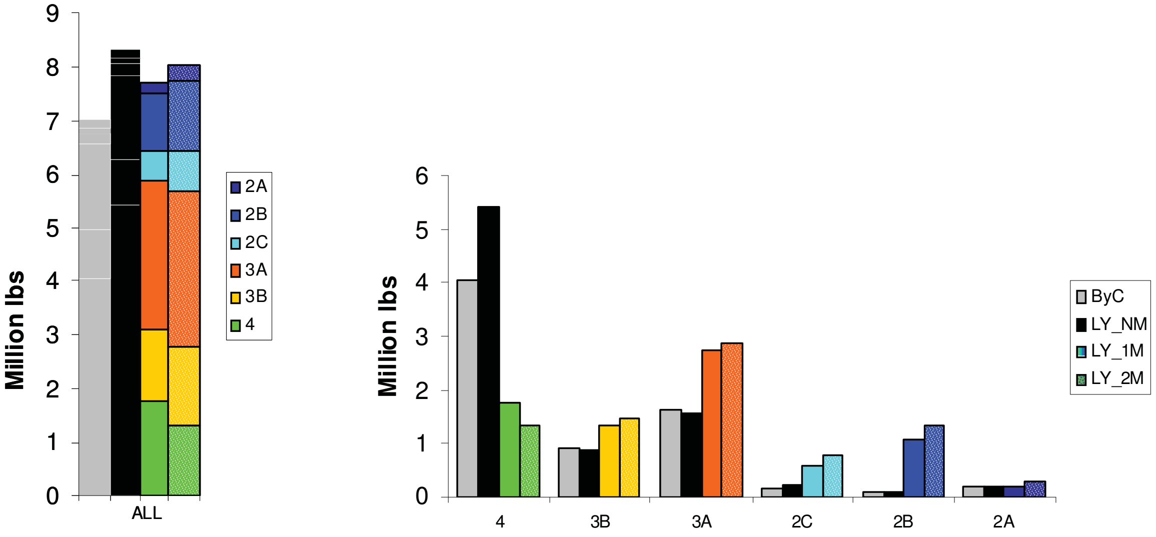

Figure 4. Total ("ALL", left panel) and area-specific ("4" to "2A", rigth panel) average 1996-2008 U32 bycatch ("Byc", grey colored first column series) in million pounds. The second column series (black color) is the resultant lost yield when migration ("LY_NM") is not taken into account. The third series represents lost yield with a common migration matrix ("LY_1M"). The last series represents lost yield with two migration matrices based on fish size ("LY_2M"). Colors in the last two series correspond to the areas where yield is lost.

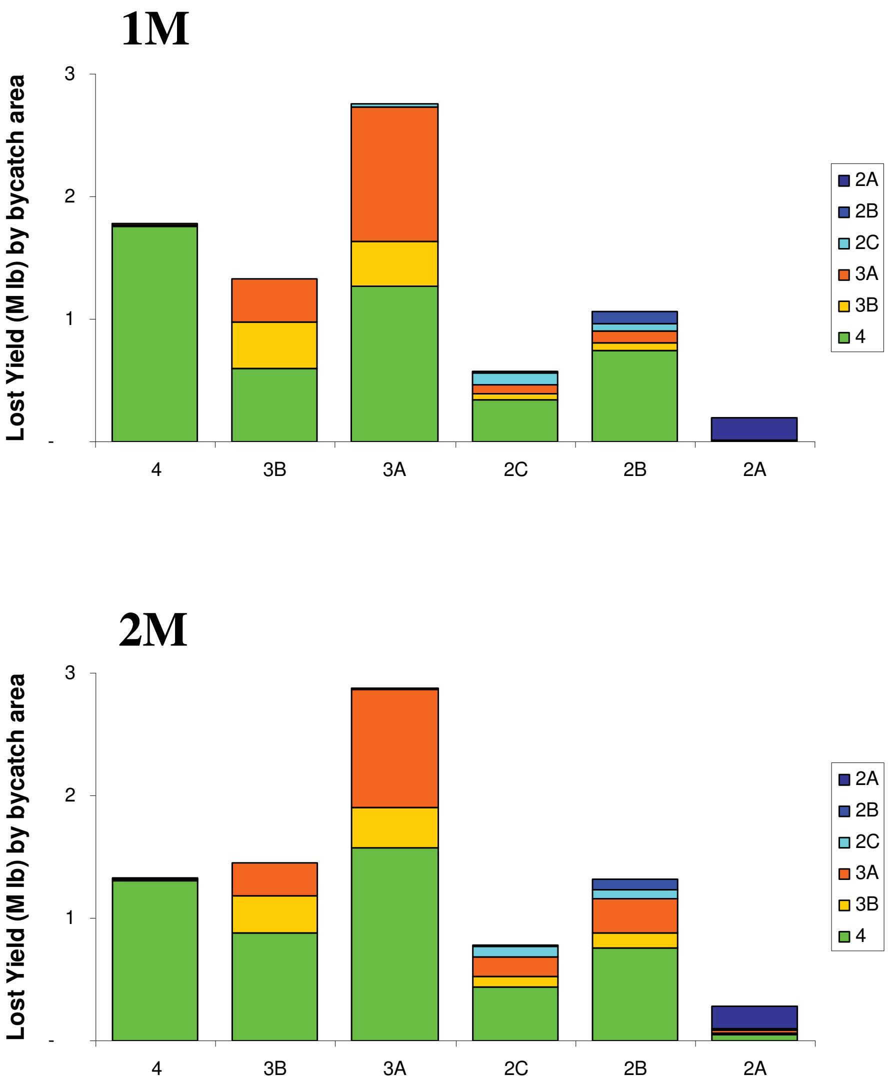

Figure 5. Lost yield in millions of pounds in each area due to U32 bycatch. Colors represent the area where U32 bycatch mortality occurred. Top panel (1M) corresponds to the one migration matrix scenario, bottom panel corresponds to the two migration matrices scenario (2M).

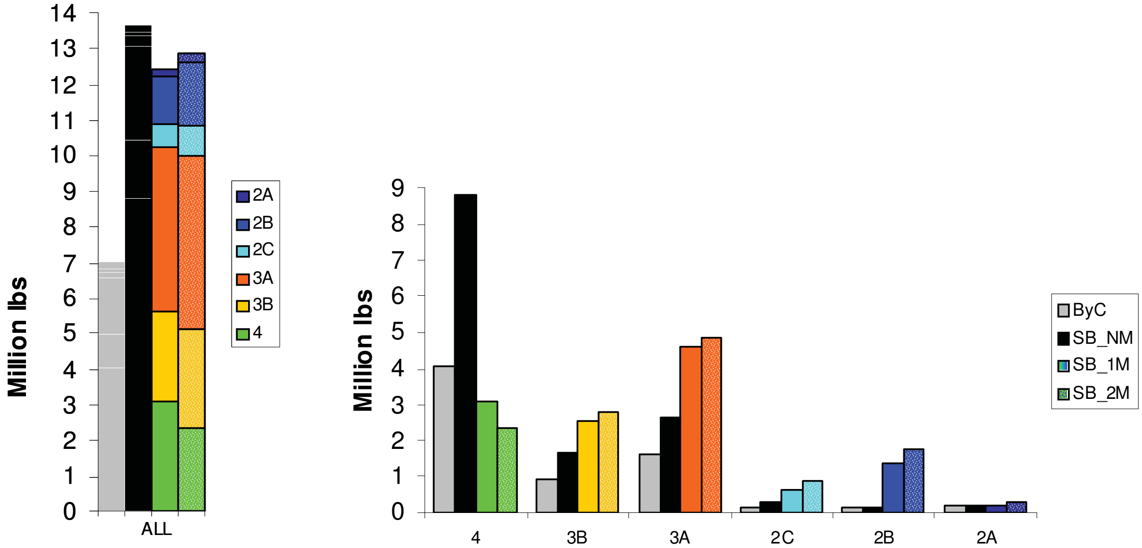

Figure 6. Total ("ALL", left panel) and area specific ("4" to "2A", rigth panel) average 1996-2008 U32 bycatch ("Byc", grey colored first column series) in million pounds. The second column series (black color) is the resultant lost spawning biomass when migration ("SB_NM") is not taken into account. The third series represents lost spawning biomass with a common migration matrix ("SB_1M"). The last series represents lost spawning biomass with two migration matrices based on fish size ("SB_2M"). Colors in the last two series correspond to the areas where spawning biomass is lost.

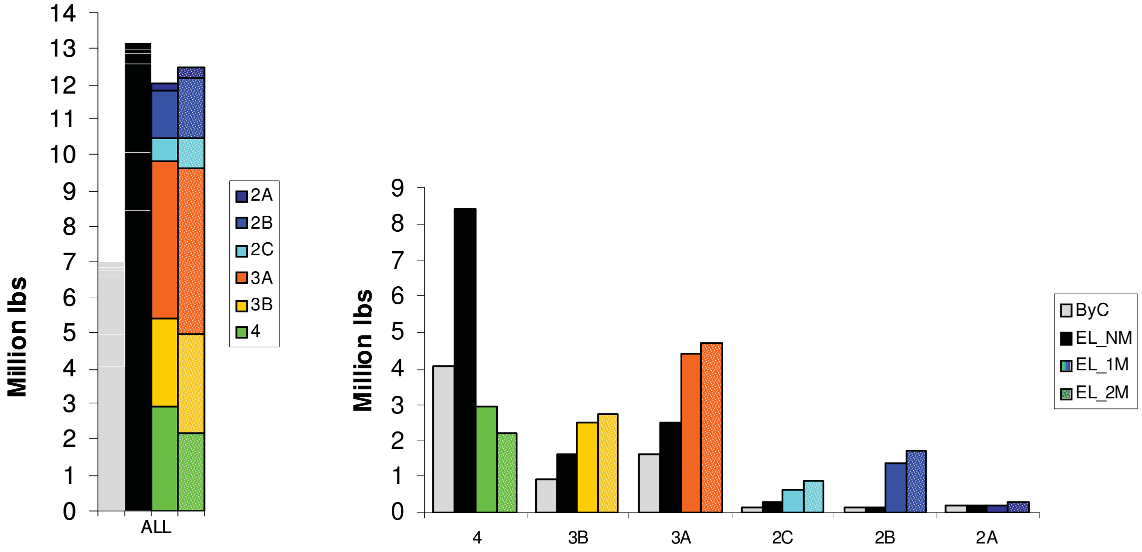

Figure 7. Total ("ALL", left panel) and area specific ("4" to "2A", rigth panel) average 1996-2008 U32 bycatch ("ByC", grey colored first column series) in million pounds. The second column series (black color) is the resultant egg loss when migration ("LE_NM") is not taken into account. The third series represents egg loss with a common migration matrix ("LE_1M"). The last series represents egg loss with two migration matrices based on fish size ("LE_2M"). Colors in the last two series correspond to the areas where egg production is lost.

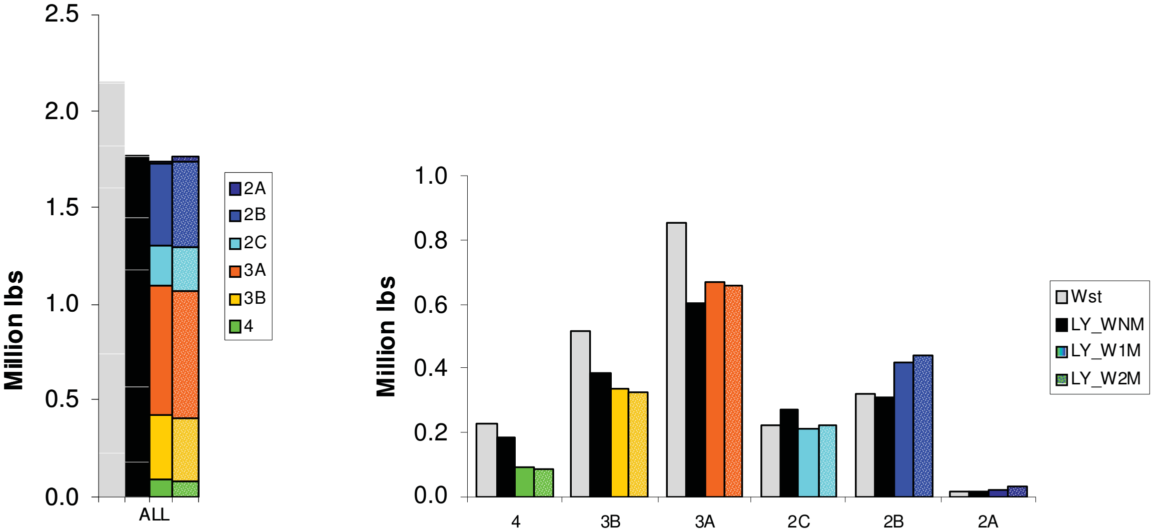

Figure 8. Total (“ALL”, left panel) and area specific (“4” to “2A”, rigth panel) average 1996-2008 U32 wastage (“Wst”, grey colored first column series) in million pounds. The second column series (black color) is the resultant lost yield when migration (“LY_WNM”) is not taken into account. The third series represents lost yield with a common migration matrix (“LY_W1M”). The last series represents lost yield with two migration matrices based on fish size (“LY_W2M”). Colors in the last two series correspond to the areas where yield is lost.

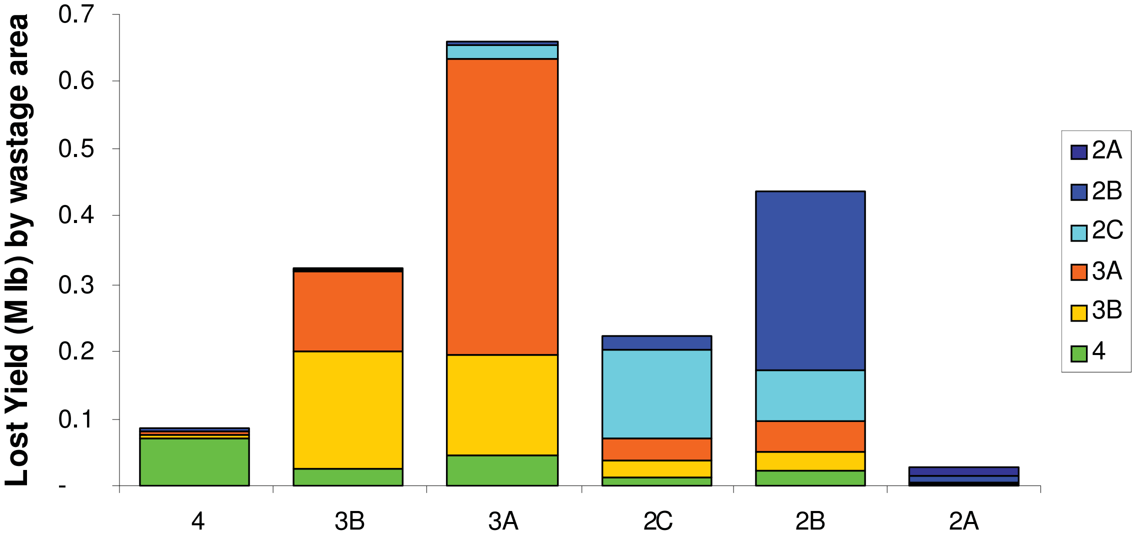

Figure 9. Lost yield in millions of pounds in each area due to U32 wastage. Colors represent the area where U32 wastage mortality occurred.

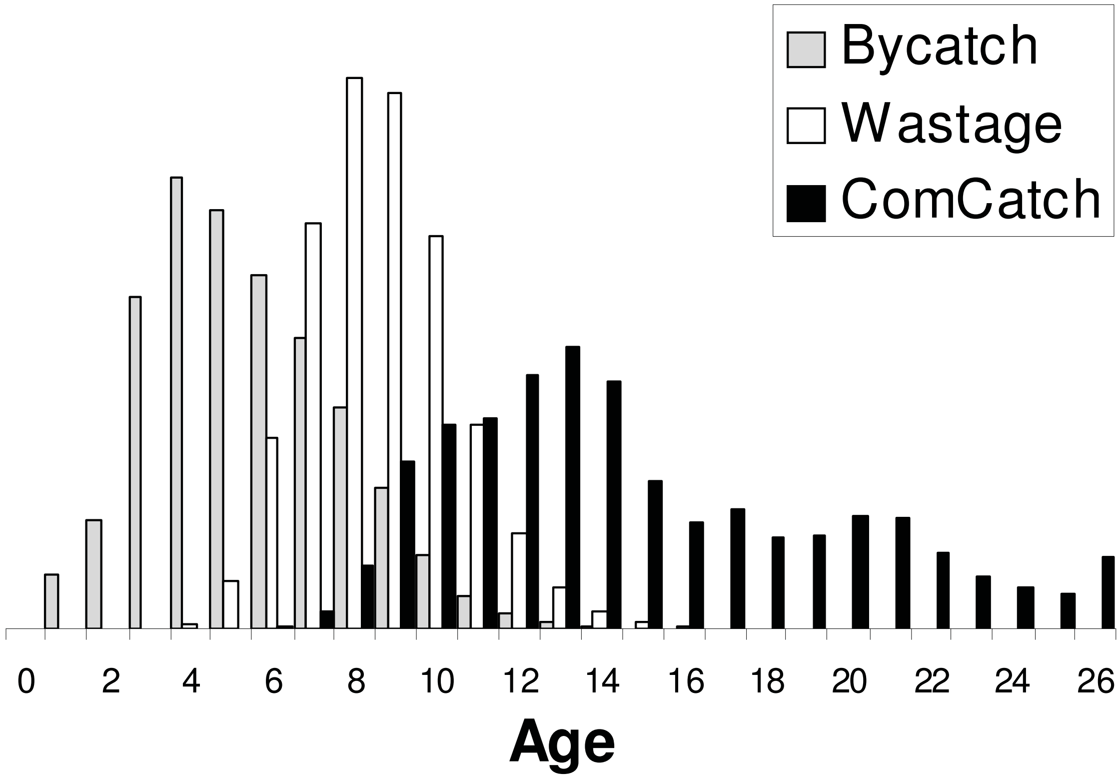

Figure 10. Age distributions of bycatch, wastage and commercial catch during 1996-2008.