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Accounting for Bycatch in Management of the Pacific Halibut Fishery

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Abstract.—Since the 1960s, fisheries for groundfish other than Pacific halibut *Hippoglossus stenolepis* have caused an average of about 9,000 metric tons (mt, round weight) of halibut bycatch mortality every year, whereas annual directed catches of Pacific halibut have varied from 13,000 to almost 50,000 mt. About half of the bycatch consists of juvenile Pacific halibut caught in Alaska, some of which would otherwise migrate south and contribute to the fishery in British Columbia. These interceptions have long been a difficult issue for the United States and Canada. At recent levels of high juvenile abundance, the juvenile bycatch reduces coastwide recruitment by about 10%. The resulting yield loss, plus bycatch of adult fish, reduces yield to the directed fishery by about 11,000 mt per year. Migration modeling indicates that the yield loss due to bycatch occurs almost entirely in the area where the bycatch is taken. In particular, bycatch in Alaska reduces Pacific halibut yields in British Columbia by, at most, a few percent. During the 1980s and early 1990s, annual quotas in the directed Pacific halibut fishery were reduced by an amount equal to, or sometimes greater than, the *total* Pacific halibut bycatch mortality, and the quota reduction was distributed among regulatory areas in proportion to Pacific halibut exploitable biomass. At present, the Pacific halibut quota in each regulatory area is reduced by the amount of *adult* Pacific halibut bycatch mortality in that area, and the target exploitation rate is adjusted downward (slightly) to offset the bycatch mortality of juveniles.

The Pacific halibut *Hippoglossus stenolepis* is widely distributed in coastal waters of the North Pacific from the northern Bering Sea to central California on the east and south to Hokkaido, Japan, on the west. Aboriginal peoples in North America have fished halibut for thousands of years, and a commercial longline fishery has been conducted in U.S. and Canadian waters for more than 100 years. Since 1923, the Pacific halibut stock has been studied and managed by the International Pacific Halibut Commission (IPHC), making this one of the longest- and best-studied groundfish stocks in the world. Halibut assessment and management have been described by Skud (1977a), Hoag et al. (1993), and Sullivan and McCaughran (1995).

Pacific halibut bycatch was negligible until the early 1960s, when major fisheries for other groundfish species began in the Gulf of Alaska and Bering Sea (Williams et al. 1989). Since then, halibut bycatch mortality in those fisheries has averaged about 9,000 metric tons (mt) per year in round weight (Figure 1). The actual bycatch is somewhat greater, but all halibut taken as bycatch must, by law, be returned to the sea and some fish survive. Total halibut bycatch and the survival rate of discarded fish are estimated by shipboard observers. In this paper, we consistently refer to the quantities of halibut that are killed in the bycatch fisheries, and we consistently refer to both directed catch and bycatch amounts in round weight. (Many IPHC documents report present catches and even stock-size estimates in ''net weight,'' meaning headed and gutted. Net weight is 75% of round weight.)

Both the United States and Canada have adopted several management measures over the years to limit the bycatch of Pacific halibut in other groundfish fisheries. At present the total annual bycatch mortality in Alaska is capped at 7,000 mt. This total is distributed as bycatch quotas among a number of fisheries and management areas, which are closed when the bycatch quota is reached. (In some years the bycatch quotas have been inadvertently exceeded, but not by much.) Canada first imposed similar, but stricter, controls in 1996, which had the effect of reducing annual halibut bycatch in British Columbia from its previous average of about 1,000 mt to only 200 mt. There are as yet no halibut bycatch control measures in the groundfish fisheries off Washington and Oregon.

Since 1960, annual quotas in the directed Pacific halibut fishery have varied from as little as 13,000 mt (in the mid-1970s) to almost 50,000 mt (in the late 1980s). The IPHC has routinely taken bycatch into account when setting quotas, but the process

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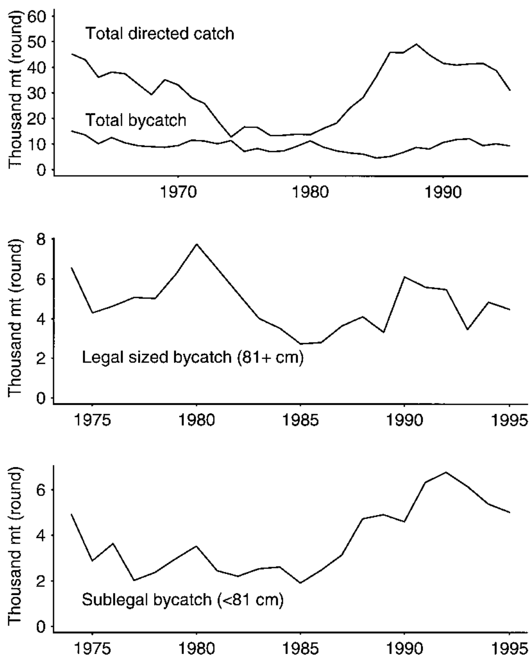

FIGURE 1.—Directed catches and bycatch mortality of Pacific halibut, 1962–1995, in metric tons (mt, round weight). The lower two panels show bycatch by size category, 1974–1995. Legal-sized fish are those above 81 cm.

has been complicated and contentious because of the uncertainty about the migration patterns of juvenile halibut and the resulting distribution of bycatch impact among IPHC regulatory areas.

During summer, Pacific halibut are distributed over the entire continental shelf of the northeast Pacific, although the distribution is patchy at the northern and southern ends of the range. In winter, adult fish congregate and spawn in deep water on the continental slope. These spawning grounds are scattered throughout the Gulf of Alaska from the Queen Charlotte Islands to the Aleutians and into the Bering Sea (Figure 2). The eggs, larvae, and postlarvae drift to the west in deep currents for about 6 months, then settle out and metamorphose on nursery grounds in the western Gulf of Alaska (west of Kodiak Island) and the eastern Bering Sea (and possibly along the coast of Russia). The juveniles spend some time on the nursery grounds, then migrate to home areas in the Bering Sea and throughout the Gulf of Alaska to as far south as Washington and Oregon, arriving by age 7 or 8. Thereafter, location changes are minimal except for the winter spawning migration (Skud 1977b). Females reach sexual maturity at ages 10–12; males sooner. It is not known whether the juveniles that migrate to a given home area are the progeny of that area's spawners.

The migration of juveniles from the western nursery grounds to their home areas appears to be

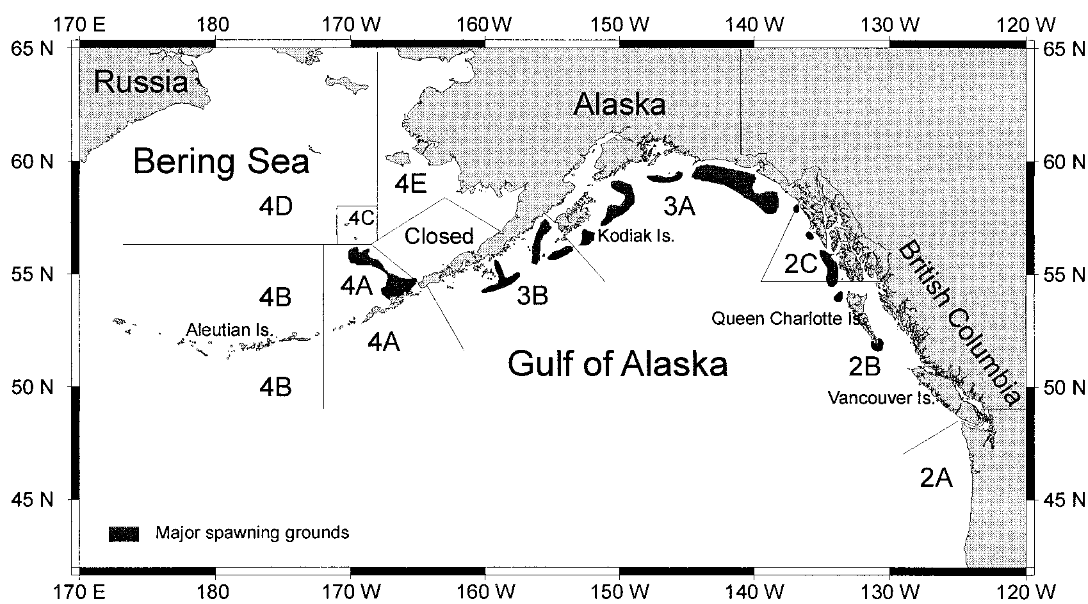

FIGURE 2.—The Gulf of Alaska and Bering Sea, showing the International Pacific Halibut Commission (IPHC) regulatory areas and major spawning grounds of Pacific halibut (from St-Pierre 1984).

unidirectional. Juvenile fish marked in the northern Gulf of Alaska have been recovered there and to the south, but hardly ever from the western Gulf of Alaska or the Bering Sea. Similarly, juveniles marked in British Columbia are almost always recovered in British Columbia (or farther south), but almost never in Alaska.

The commercial Pacific halibut fishery is conducted mainly in spring and summer when the adult fish are feeding on the continental shelf in their home areas. Owing to the selectivity of longline gear for larger fish and the commercial minimum size limits, the commercial catch consists almost entirely of fish 8 years old and older (i.e., fish that have completed their migration).

Pacific halibut bycatch in other fisheries includes both adults that have completed their migrations and juveniles that may or may not have completed their migrations. The bulk of the trawl bycatch, for example, is made up of fish of ages 4–6. Thus, many of the juveniles in the bycatch are fish that have been intercepted in the course of their migration, and their capture has the effect of reducing recruitment to the adult stock in the area to which they are migrating, which is not necessarily the area of capture.

Despite a recent decrease in growth rates, the size of juvenile halibut when they complete their migration (at ages 7–8) still corresponds approximately to the minimum size limit in the commercial fishery, which since 1974 has been 81 cm. As a reasonable approximation, therefore, bycatch of fish above the legal size limit can be considered to affect only the stock in the area where the bycatch is taken, whereas bycatch of sublegal fish may reduce recruitment in other areas.

Directed catches and bycatches were both quite stable in the first half of the 1990s, as illustrated by the weights (Table 1) and length frequencies (Figure 3) of halibut in the 1995 catches. Coastwide, bycatch in weight was about a third as much as the directed removals and was almost equally divided between legal-sized fish and sublegal fish. However, there were large differences between areas; for example, the bycatch of legal-sized fish was more than half the size of the directed catches in the International Pacific Halibut Commission (IPHC) Area 2A and Area 4, and more than half of the coastwide bycatch of sublegals was taken in Area 4, mainly in the Bering Sea trawl fisheries.

Management of the directed fishery by the IPHC is based on the distribution of legal-sized fish in summer, when the fishery takes place. That is, a management stock consists of the adult fish that feed in a given home area in the summer (and remain there year after year, leaving only for a winter migration to a spawning area on the continental slope). Each year the IPHC sets a quota for each of the regulatory areas shown in Figure 2. In doing so it has to allow for the effect of bycatch in all areas on the stock in each area, which in the case of sublegal bycatch is neither obvious nor easy to calculate. For example, the effect of a given level of bycatch in the Bering Sea on recruitment to British Columbia clearly depends on the age composition of the bycatch, the migration schedule of juveniles, and the abundance of eventual British Columbia recruits relative to eventual Alaska recruits in the Bering Sea. There is a good deal of uncertainty about all of these estimates.

TABLE 1.—Coastwide removals of Pacific halibut in 1995, by International Pacific Halibut Commission (IPHC) regulatory area. Catches are metric tons (mt) round weight. The directed catch includes all directed commercial, sport, and subsistence catches. Legal-sized fish are those at least 81 cm long.

IPHC area	Directed catch (mt)	Bycatch in other fisheries (mt): Legal size	Bycatch in other fisheries (mt): Sublegal size
4 (Bering Sea and Aleutians Islands)	3,004	1,989	3,268
3B (western Gulf of Alaska)	1,811	581	478
3A (northern Gulf of Alaska)	13,869	1,077	706
2C (Southeast Alaska)	6,007	175	35
2B (British Columbia)	6,627	425	492
2A (Washington and Oregon)	362	224	37
All areas	31,680	4,471	5,016

In this paper we review existing knowledge of the distribution and migration of juvenile Pacific halibut, outline a model of juvenile migration, and report area-by-area impacts of juvenile bycatch corresponding to a range of plausible migration schedules. In the last section we review how the IPHC has actually adjusted quotas to account for bycatch in the past, and how it does so at present.

Distribution and Migration of Juvenile Halibut

Despite having released and recovered large numbers of marked juvenile Pacific halibut over the years (Trumble et al. 1990), the IPHC staff has not been able to obtain reliable estimates of migration rates from marking data. The most ambitious effort along these lines was the release of about 55,000 marked juvenile halibut in the northern Gulf of Alaska in 1980–1981. A thorough analysis of the recovery data (Hilborn et al. 1995)

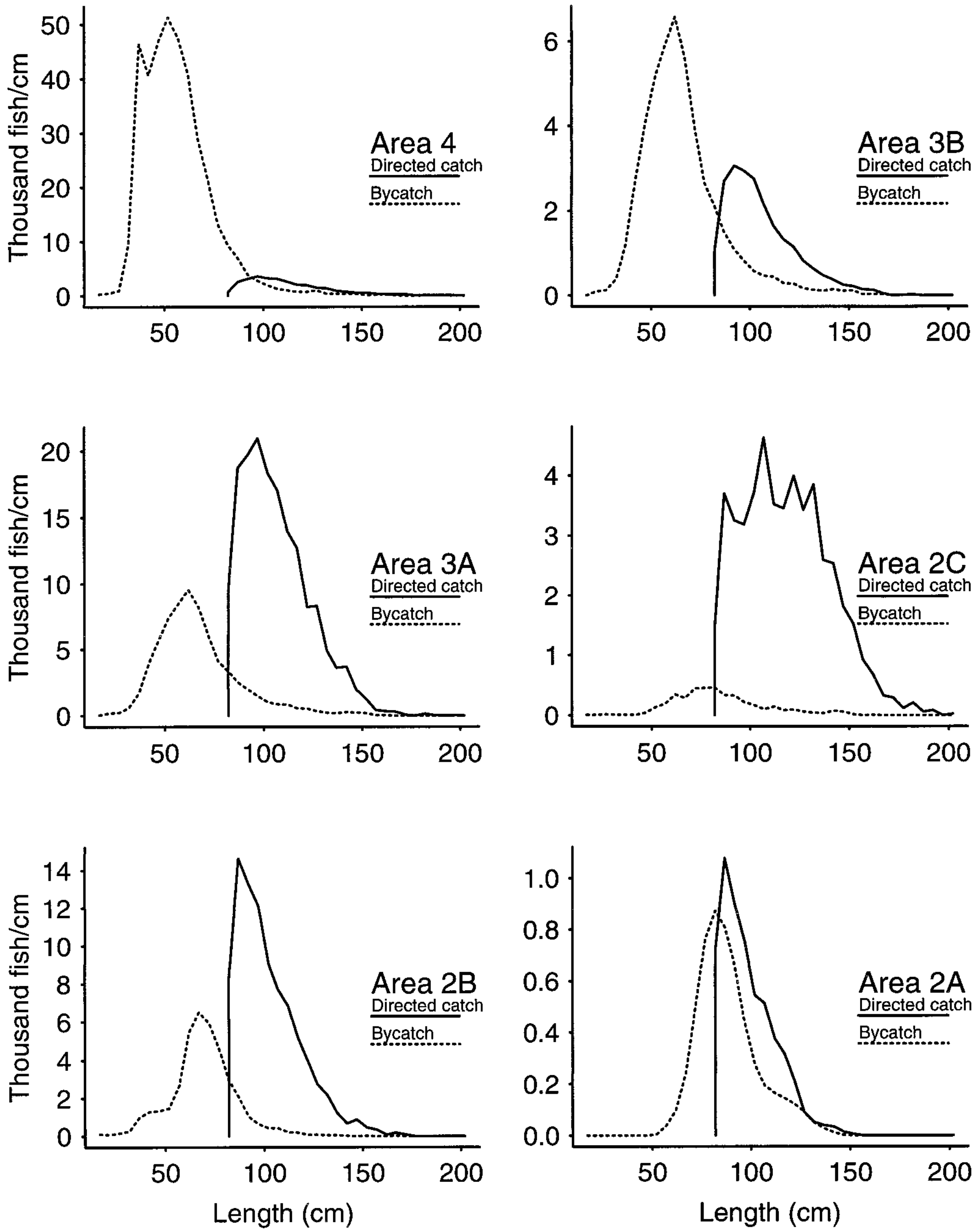

FIGURE 3.—Length frequencies of the directed fisheries and the bycatch in 1995, by IPHC regulatory area (see Figure 2). The commercial longline fishery was subject to an 81-cm minimum size limit.

showed that, in statistical terms, migration rates were highly confounded by other factors that affect recovery rates in different areas and years, such as fishing effort, selectivity, tagging mortality, and reporting rates by fishers. For example, there were fewer recoveries than expected from southeastern Alaska (Area 2C, hereafter referred to as SE Alaska) relative to the number of recoveries in south-central Alaska (Area 3A) and British Columbia (Area 2B), but that probably resulted from having insufficient IPHC samplers on hand to redeem tags in SE Alaska ports. Similarly, the increase in re-

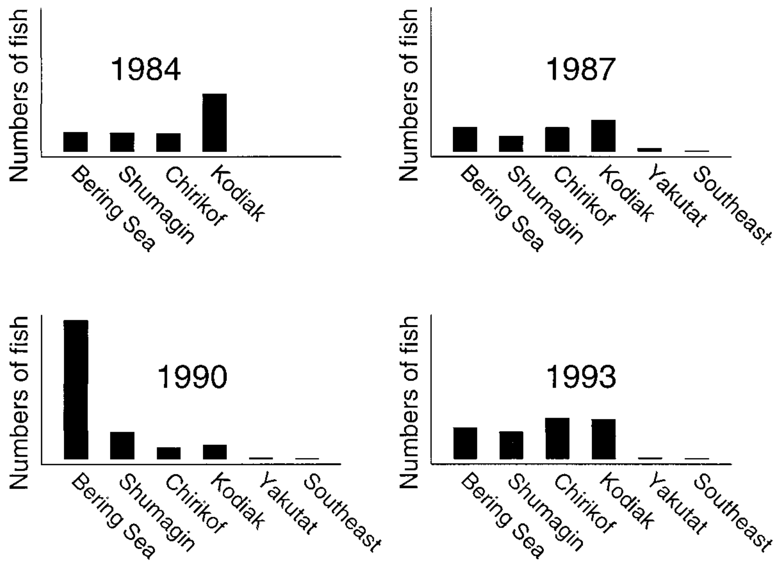

FIGURE 4.—Relative numbers of age 2–4 Pacific halibut in the National Marine Fisheries Service trawl surveys by International North Pacific Fisheries Commission (INPFC) area. Shumagin area is IPHC Area 4A plus western Area 3B; Chirikof is eastern Area 3B; Kodiak is western Area 3A; Yakutat is eastern Area 3A; and southeast is Area 2C.

covery rates that occurred during the first few years after the IPHC began to give out coveted hats instead of modest cash payments as a reward for redeemed tags probably was the result of increased reporting rates. Because the effect of events such as these are indistinguishable from actual migration data, we conclude that migration rates are poorly determined by the recovery data.

Although recoveries of marked fish have not yielded all the information that was hoped for, they have provided some useful information. Other data sources, such as those summarized below, have also helped to reveal some of the general features of juvenile distribution and migration.

Ocean Circulation

The general circulation of ocean currents in the Gulf of Alaska is counterclockwise, so most Pacific halibut postlarvae can be expected to settle to the bottom around Kodiak Island and westward. Kodiak Island is about how far the currents would carry a halibut hatched off the Queen Charlotte Islands (the southeasternmost major spawning area) during the 6 months that it spends in midwater as an egg, larva, and postlarva. This hypothesis was corroborated by an ichthyoplankton survey in May–June 1986 in which stations were fished from Dixon Entrance (above the Queen Charlotte Islands) around the Gulf of Alaska and into the Bering Sea. Significant numbers of halibut postlarvae were caught only at stations around Kodiak Island, to the west of Kodiak, and into the Bering Sea (St-Pierre 1989).

NMFS Trawl Surveys

The U.S. National Marine Fisheries Service (NMFS) conducts trawl surveys of the eastern Bering Sea every year and of the Gulf of Alaska every third year. In addition to some large Pacific halibut, the survey trawl catches large numbers of juvenile (ages 2–6) fish, an age- and size-group that is not caught by the setline gear used in IPHC surveys. Thus the NMFS trawl surveys supply information on the distribution of juveniles that is not available from any IPHC data. Determination of relative abundance of halibut in the International North Pacific Fisheries Commission (INPFC) areas during the last four surveys (1984–1993; Figure 4) has shown that very few small halibut (ages 2–4) were caught east of Kodiak Island. This is not to say that none are there; IPHC trawl surveys have found small halibut in the Yakutat, SE Alaska, and Queen Charlotte Island regions, but the gulfwide NMFS survey results indicate that the proportion of juveniles east of Kodiak is small.

Another interesting feature of the NMFS data (Figure 4) is that in most years the Bering Sea accounted for only a small part of the total juvenile abundance, although it was long considered to be the major nursery area. The exceptional year was

1990, when the large 1987 year-class was present as 3-year-olds. Overall, the proportion of juvenile Pacific halibut in the Bering Sea for the four survey years was about 40%, but if 1990 is excluded, the proportion drops to 20%. In 1990, about 60% of the juveniles were located in the Bering Sea. It is possible that during periods of high recruitment a higher proportion of juveniles are in the Bering Sea, but it is also possible that periods of high recruitment are precisely the periods when large numbers of postlarvae are swept into the Bering Sea.

Recoveries of Marked Juveniles

As mentioned above, recoveries of marked juveniles indicate that the migration from nursery grounds in western Alaska to their eventual home areas is unidirectional. Juveniles marked in the Bering Sea (Area 4) have been recovered from all parts of the range. Juveniles marked in the western Gulf of Alaska (Area 3) have been recovered there and to the east and south, but almost never from the Bering Sea or Aleutians (Area 4). Similarly, juveniles marked in British Columbia (Area 2B) have been recovered there and to the south, but almost never from Alaska. Thus, it appears that early in life, say by age 2, the eventual recruits to Area 4 are all located in Area 4, whereas the eventual recruits to the management stocks in Areas 2 and 3 are distributed between Area 3 and Area 4 in some proportion.

At age 2, the eventual recruits to Area 2 and Area 3 may be unevenly mixed on the nursery grounds in Area 3 and Area 4. For example, it is plausible that at age 2 the future Area 2B recruits, having been spawned in northern British Columbia and SE Alaska, will be found mostly in the western Gulf of Alaska rather than the Bering Sea, whereas a higher proportion of future Area 3 recruits, having been spawned in the northern and western Gulf of Alaska, will be found in the Bering Sea. If that were true, future Area 2B recruits would be less numerous relative to future Area 3 recruits in the Bering Sea than in the Gulf of Alaska. Consequently they would be relatively less numerous among recoveries of adult fished marked as juveniles in the Bering Sea than among recoveries of adult fish marked as juveniles in the Gulf of Alaska. But there is no difference in relative recoveries: releases of marked juveniles in both the Bering Sea (Area 4) and the Gulf of Alaska (Area 3) resulted in about three times as many recoveries from Area 3 as from Area 2B (Table 2). This implies that future Area 2 and Area 3 recruits are well mixed (i.e., distributed in the same proportions) on the nursery grounds in the western Gulf of Alaska and the Bering Sea.

TABLE 2.—Numbers of Pacific halibut marked as juveniles in the Bering Sea (Area 4) and northern Gulf of Alaska (Area 3) and later recovered as adults in the directed setline fishery.

	Marking area:	
Recovery area	Area 4	Area 3
Area 4	354	0
Area 3	89	417
Area 2C	19	57
Area 2B	31	136
Area 2A	10	9

Stock-Specific Estimates of Abundance and Distribution at Age 8

Every year the IPHC staff estimates the abundance of Pacific halibut (ages 8 and older) in each regulatory area by fitting a size- and age-structured model to historical data series from the commercial fishery and IPHC setline surveys. Among other things, the annual stock assessment provides estimates of year-class strength at age 8 in each IPHC regulatory area (i.e., for each management stock) and, therefore shows the eventual distribution of Pacific halibut after they have completed their migration from the nursery grounds to their home areas. The assessment does not produce estimates of juvenile abundance (ages 1–7) because fish younger than age 8 are quite rare in both survey and commercial setline catches.

The relative abundance of 8-year-olds among regulatory areas does not appear to have varied greatly since the early 1980s, when there was an increase in abundance in Alaska relative to British Columbia. The most recent estimates, based partly on the assessment itself and partly on survey coverage of lightly fished areas, indicate that Area 4 receives about 30% of the total number of 8-year-olds, Area 3B 20%, Area 3A 30%, Area 2C 10%, Area 2B 10%, and Area 2A 1%.

Conclusions Regarding Juvenile Distribution and Migration

The information given so far indicates that all but a small proportion of juvenile Pacific halibut are in the western Gulf of Alaska and the Bering Sea at age 2, that the future recruits to Areas 2 and 3 are well mixed throughout the nursery grounds, and that all of the Area 4 recruits are restricted to nursery grounds in Area 4. The proportion of postlarvae that settle out in the Bering Sea appears to be variable. In our studies it ranges from 20% to 60% and the overall average is 40%. Migration from the nursery grounds in western Alaska to the home areas is unidirectional, taking place between ages 2 and 8. The eventual distribution of 8-year-olds among areas is reasonably well known from the annual stock assessment; however, the timing of the migration from the nursery grounds to the home areas is not known.

Alternative Models of Juvenile Migration

To calculate the impact of bycatch in a given area on the various management stocks, we need to know the stock composition of the bycatch in that area. In the case of the Bering Sea (Area 4) bycatch, for example, we need to know what proportion of the fish in the bycatch are bound to migrate and recruit to British Columbia (Area 2B), what proportion to SE Alaska (Area 2C), and so on. In addition, the impact depends on the size composition of the bycatch. The Area 2B juveniles in the Bering Sea must have a different size composition from, say, the Area 4 juveniles because the Area 2B juveniles must migrate out of the Bering Sea over time whereas the Area 4 juveniles accumulate there. The end result is that the Area 2B juveniles in the Bering Sea are smaller on average than the Area 4 juveniles, both in the sea and in the bycatch.

To calculate impacts, therefore, we need to know the stock composition of the juveniles in each size-group in the bycatch in each regulatory area (or, equivalently, the relative abundance and geographic distribution of each age-group of each stock's juveniles). This is a level of detail far exceeding what we now know or may ever know about the initial distribution of juvenile Pacific halibut and the timing of their migration between ages 2 and 8. Therefore, we calculated a range of migration schedules that incorporate the known general features of juvenile migration summarized above and that bracket a plausible range of values for initial distribution and migration timing. We have used the best information available, but this part of the exercise is inevitably uncertain and is sure to remain so.

As an example, Table 3 shows one of the schedules constructed to describe the migration of Area 2B recruits from nursery grounds in western Alaska to Area 2B. Each row of the table gives the proportional distribution of a particular age-group in each of the regulatory areas (each row thus sums to one). Initially, at ages 1 and 2, the bulk of the fish are in Area 4 (32.5%) and Area 3(51.5%). By age 7 most them have reached Area 2B (75%), and by age 8 all are there. The important features of a schedule like this are given below.

TABLE 3.—Sample schedule describing the migration of juvenile Pacific halibut from their nursery grounds in western Alaska (mostly) to Area 2B (British Columbia). Each row of the table gives the proportional distribution of that age-group among regulatory areas, so each row sums to one.

Age-group	Proportion of age-group located in:				
	Area 4	Area 3	Area 2C	Area 2B	Area 2A
1	0.325	0.515	0.055	0.105	0
2	0.325	0.515	0.055	0.105	0
3	0.263	0.470	0.078	0.190	0
4	0.188	0.425	0.088	0.300	0
5	0.125	0.363	0.100	0.413	0
6	0.087	0.250	0.100	0.563	0
7	0.025	0.175	0.050	0.750	0
8	0	0	0	1.00	0

Initial proportion in the Bering Sea.—Because of the large bycatch of small fish in the Bering Sea, the proportion of Area 2B fish placed there initially (at ages 1 and 2) has a large effect on the calculated impact of Bering Sea bycatch on the Area 2B stock. The trawl survey results show that, at most, 60% of all juveniles are in the Bering Sea initially. The Area 4 stock itself accounts for about 30% of 8-year-olds coastwide and, because the Area 4 juveniles do not migrate out of Area 4, at least half of the 2-year-olds in the Bering Sea. To make up the other half of the upper limit of 60% in the Bering Sea requires no more than about half of the juveniles of the Area 2 and Area 3 stocks, which account for 70% of 8-year-olds coastwide. A range of 10–50% of Area 2B recruits in Area 4 at age 2 therefore seems reasonable; some of them must be there to account for the tag returns, and no more than about half could be there (along with the same proportion of Area 3 recruits) and still leave enough juveniles in the Gulf of Alaska to account for the trawl survey results. To the extent that Area 4 recruits sustain a higher mortality owing to the large bycatch in Area 4, they must constitute a higher coastwide proportion than 30% at age 2, and the proportion of 2B recruits in Area 4 at age 2 must be less than the values calculated above. The upper end of the range of values used may, therefore, overestimate the impact of Area 4 bycatch on Area 2B recruits, and underestimate the impact on Area 4 recruits.

Initial proportion in the home area.—Placing more fish initially in the home area naturally reduces the impact of bycatch elsewhere. All of the data indicate that the proportion of Area 2B recruits located in Area 2B at ages 1–3 is low, but it is not zero. In this schedule it is set at 10%; extreme values of 1% and 20% were also used. Fish not placed initially in the Bering Sea or in the home area are placed mostly in Area 3, and a small bridging proportion is placed in Area 2C.

Timing of migration to the home area.—Moving Area 2B recruits quickly out of Alaska (especially out of Area 4) tends to reduce the impact of Alaska bycatch, whereas retaining them longer in Alaska increases the impact. A wide range of timings is possible, and there are no good data for choosing among them. This part of the location schedules is quite speculative, and we have simply tried to set up a reasonable range of possibilities, all of which move the fish from their initial distribution at age 2 to their home area by age 8.

Using similar reasoning, we drew up four alternative location schedules to encompass the plausible range of juvenile migration schedules for each management stock. The four schedules represented the extreme values of two tunable parameters: degree of ''Beringness'' and speed of migration to the home area (''quickness''). The Beringness parameter was used to set initial proportion by area with the two extreme settings referred to as ''Bering'' and ''local.'' At the Bering end, the maximum proportion of 2-year-olds was placed in the Bering Sea and the minimum in the home area. At the local end of the scale, the reverse was true. The quickness parameter was used to set how rapidly the juveniles would move from the nursery grounds to their home areas, and ranged from ''slow'' to ''fast.'' At the slow end, fish linger in the nursery grounds in Areas 4 and 3, and move slowly to their home area. At the fast end, they get under way earlier and move faster. Calculated out-of-area bycatch impacts are greatest under the Bering–slow schedule, and least under the local–fast schedule. We also constructed an ''intermediate'' schedule, which was simply the midpoint of what we regarded as the plausible range of the two tuning parameters.

Calculation of Stock-Specific Impacts

We used the migration model and recent estimates of recruitment at age 8 to each management stock (regulatory area) to calculate stock-specific impacts of the 1995 bycatch. Basically, we took a single year-class and simulated its migration from ages 2 through 8, calculating how many juveniles of each management stock would be lost to bycatch in each regulatory area if the 1995 bycatch amount and size composition were repeated every year in every regulatory area. This is a fair estimate of bycatch impacts in the early 1990s because neither bycatch nor recruitment varied greatly during those years.

Our migration model allocates bycatch mortality among management stocks by calculating the stock composition of every age-group in the regulatory area where the bycatch is taken and then apportioning the estimated bycatch mortality by age-class among stocks in proportion to their abundance in that regulatory area. The age composition of the bycatch is estimated by applying a length–age key to the reported length distribution. Because juvenile halibut grow rapidly, there is little overlap between the length ranges of successive age-groups, so in this case a length–age key is reliable.

To keep track of the relative abundance by age of every stock in every regulatory area, we begin with the estimated absolute number of each stock at age 1, distributed according to one of the migration schedules. At each age (1–8), we subtract natural mortality and bycatch mortality in each regulatory area, and then redistribute the fish according to the migration schedule to obtain the absolute abundance at the next age in every regulatory area. In principle the calculations are straightforward, but in practice they are complicated by the effect of bycatch mortality on both the proportional distribution of age-groups among areas and on the relative abundance of the various stocks as juveniles.

The location schedules developed earlier (Table 3) are reasonable when viewed as examples of how juveniles would migrate in the absence of bycatch. Each schedule implies a set of age- and area-specific migration rates, and using those rates in the absence of bycatch will generate the given location schedule. For example, the location schedule for Area 2B recruits in Table 3 shows that between ages 3 and 4, the proportion of 2B juveniles present in Area 2B itself will rise from 0.19 to 0.30, an increase of 0.11. Under unidirectional migration, this increase will be drawn first from Area 2C, and then from Area 3 if needed. Of all the Area 2B recruits only 0.078 are in Area 2C at age 3, so the migration rate of 2B recruits from 2C to 2B at age 3 is 100%. An additional 0.032 (0.110 − 0.078) must come from Area 3, where 0.47 are located at age 3, so the migration rate of 2B recruits from Area 3 to Area 2B at age 3 is 6.8% (0.032/0.47).

However, using those same migration rates and allowing for the actual age- and area-specific bycatch will result in a different location schedule. For example, a heavy bycatch mortality in Area 4 at age 5 will affect the distribution of age 6 fish among areas, and that has to be accounted for in the calculations. We do that by using the migration rates implied by each location schedule, rather than the location schedule itself, to calculate the distribution of each stock at each age sequentially.

Estimates of the absolute abundance of each stock at age 8 are available from the annual stock assessment. The *absolute coastwide abundance* at age 1 at any given level of bycatch can be back-calculated by a simple cohort analysis, but the *absolute abundance of each stock* at age 1 will depend on the distribution of bycatch impacts among stocks. Because the calculation of bycatch impacts requires an estimate of the absolute abundance of each stock at age 1, the model has to be run iteratively to locate the stock-specific values of abundance at age 1 that will result in the correct values at age 8, given the migration schedule in effect and the distribution of bycatch by area and size. The procedure is similar to (but simpler than) the measurement error model of migratory catch–age analysis described by Quinn et al. (1990).

In effect, the model estimates stock-specific abundance at age 1 by cohort analysis (back-calculating from age 8). A migration schedule that allocates more bycatch mortality to a given stock increases the removals that go into the cohort analysis and, therefore, the estimate of abundance at age 1. An important consequence of this part of the calculation is that the estimates of stock-specific bycatch mortality rates turn out to be much less variable (among migration schedules) than absolute bycatch impacts because higher absolute impacts generate higher stock-specific estimates of abundance at age 1.

The effect of the 1995 sublegal bycatch mortality on recruitment to each stock, for each of the migration schedules discussed above, is shown in Table 4. Coastwide, juvenile halibut suffer a bycatch mortality of 1–3% per year; the higher rates fall on ages 4–6. The cumulative effect over ages 2–8 is to reduce year-class strength by about1.8 million 8-year-olds, or by about 10% at recent levels of recruitment. The impact does vary substantially among areas, but it is not very sensitive to the migration schedule used for the calculations. Sublegal bycatch reduces recruitment to the Area 4 stock by 15–20%, but to Area 2 and 3 stocks by only about 5–10%. For every stock except 2C (where bycatch is very low), most of the recruitment loss due to sublegal bycatch results from sublegal bycatch in that area itself, rather than from interceptions of migrating juveniles in other areas. In particular, even under the Bering–slow migration schedule, which maximizes interceptions, the sublegal bycatch in Area 4 only reduces recruitment in Areas 2 and 3 by about 3%. Similarly, sublegal bycatch in all of Alaska (Areas 3 and 4, plus Area 2C) reduces recruitment to British Columbia (Area 2B) by about 5%, at most, whereas at the 1995 bycatch level, the sublegal bycatch in British Columbia itself reduced recruitment by about 8%.

The yield loss to the Pacific halibut fishery resulting from bycatch consists of two parts: the yield that would have been obtained from the sublegals in the bycatch if they had survived and recruited to the fishable stock, and the immediate loss of legal-sized fish in the bycatch. Among sublegals, growth exceeds natural mortality, so the yield loss in weight is somewhat larger than the bycatch mortality in weight. (The scaling factor depends on the size composition of the bycatch, so it varies among areas and years.) These two

TABLE 4.—Proportional recruitment reductions due to sublegal Pacific halibut bycatch taken in 1995. Bering–slow is the migration schedule that maximizes interceptions. Local-fast is the migration schedule that minimizes interceptions. Intermediate is the schedule between these two. Stock refers to the IPHC area where the fish will spend most of its adult life; so for example, under the Bering-slow migration schedule, juvenile bycatch taken in Area 4 reduces recruitment to the Area 4 stock by 0.150 (15%) and to the Area 2B stock by 0.032 (3.2%).

	Area where sublegal bycatch was taken					
Stock	4	3	2C	2B	2A	Coast-wide
Bering-slow migration schedule						
Area 4	0.150					0.150
Area 3	0.032	0.050				0.082
Area 2C	0.031	0.019	0.002			0.052
Area 2B	0.032	0.014		0.081		0.128
Area 2A	0.033	0.015		0.009	0.067	0.124
Intermediate migration schedule						
Area 4	0.180					0.180
Area 3	0.014	0.053				0.067
Area 2C	0.014	0.014	0.002			0.030
Area 2B	0.015	0.010		0.084		0.109
Area 2A	0.015	0.011		0.013	0.069	0.107
Local-fast migration schedule						
Area 4	0.204					0.204
Area 3		0.057				0.057
Area 2C		0.008	0.002			0.010
Area 2B		0.006		0.086		0.092
Area 2A		0.006		0.011	0.073	0.090

TABLE 5.—Yield loss in metric tons (mt) round weight due to sublegal and legal-sized bycatch of Pacific halibut taken in 1995. Interception refers to bycatch of migrating sublegals before they reach their home area. Local bycatch means bycatch within the home area of a stock. The ranges result from using different migration schedules that result in different distributions of impacts among areas; the total (coastwide) yield losses (6,136 mt and 4,471 mt) are known and are the same for all schedules.

	Yield loss (mt) due to:				
	Sublegal bycatch				
Stock	Interception	Local	Combined	Legal-sized bycatch, local only	Total yield loss (mt)
Area 4		2,692–3,980	2,692–3,980	1,989	4,681–5,969
Area 3	7–910	1,407–1,533	1,539–2,316	1,658	3,197–3,974
Area 2C	43–286	10	53–296	175	228–471
Area 2B	32–277	480	512–757	425	937–1,182
Area 2A	9–33	39	48–72	224	272–296
Coast wide	91–1,506	4,628–6,042	6,136	4,471	10,607

components of yield loss, and the overall total for each stock have been calculated (Table 5). The range of values shown for the sublegal component in each area results from uncertainty about the migration schedule and consequently the distribution of the yield loss, not from any uncertainty about the total (coastwide) yield loss. That total (6,136 mt) is the same for all migration schedules, as is the legal-sized bycatch in each regulatory area.

Interceptions of migrating juveniles account for, at most, about 15% of the total yield loss due to bycatch (1,506 out of 10,607 mt), and probably much less. The rest of the yield loss results from bycatch of sublegal- and legal-sized fish in their home areas. Roughly speaking, therefore, it can be said that around 90% of the yield loss due to bycatch occurs in the area where the bycatch is taken.

IPHC Quota Adjustments to Account for Bycatch

Since the early 1980s, the IPHC harvest strategy for the directed Pacific halibut fishery has been to apply a constant exploitation rate (formerly 30–35%, presently 20–25%) to the estimated exploitable biomass in each regulatory area. This produces a recommended level of total removals from each area. Sport and subsistence catches, wastage in the halibut fishery (due to lost gear), and a bycatch adjustment are then subtracted from the total to arrive at the recommended commercial setline quota in each area. (Strictly speaking, this is only the staff's recommendation. The Commissioners can and sometimes do depart from the staff's recommendations, but seldom by very much.)

The target exploitation rate is based on estimates of historical spawning biomass and subsequent recruitment of 8-year-olds throughout the Gulf of Alaska (Areas 2 and 3). The recruitment estimates include an upward adjustment for the recruits lost to sublegal bycatch. In other words, the spawner–recruit estimates show what the productivity of the spawning stock would have been in the absence of sublegal bycatch. Until 1997 the choice of a target harvest rate was similarly based on yield calculations that assumed there would be no sublegal bycatch in the future. The bycatch adjustment used in calculating quotas, therefore, had to correct for the effect of sublegal bycatch on stock productivity as well as the effect of interceptions. It also had to allow for the effect of bycatch of legal-sized fish in each area.

From 1981 to1996, the bycatch adjustment was a deduction from setline quotas of an amount equal to, or sometimes greater than, the current bycatch amount. This adjustment was called ''bycatch compensation,'' the idea being first to calculate what the quota would be with no bycatch, and then to compensate the stock for whatever level of bycatch was taken.

In the early 1980s, the bulk of the bycatch was taken in foreign and joint venture trawl fisheries in the Bering Sea. The primary management concern was yield loss, and it was calculated that each kilogram of bycatch (sublegal and legal sized combined) resulted in an eventual loss of 1.58 kg of yield to the setline fishery, so the setline quotas were reduced each year by 1.58 times the current bycatch amount (Quinn et al. 1985). In the long term, the effect of this adjustment was to maintain exploitable stock biomass at the level it would have reached if fished at the target exploitation rate with no bycatch.

The setline quota reduction was calculated as a single coastwide total and was distributed among regulatory areas in proportion to estimated exploitable biomass. The Bering Sea was then thought to be the nursery area for the bulk of the juveniles coastwide, and the bycatch consisted mainly of juveniles in the Bering Sea, so the yield loss due to bycatch would be roughly proportional to the biomass in each area. In principle it would have been preferable to use this kind of adjustment only for the sublegal component of the bycatch and to reduce quotas (kilogram for kilogram) of legal-sized bycatch in each regulatory area, but data on the length composition of the bycatch were lacking for several areas and fisheries, so this level of detail was not feasible.

At that time it was estimated that about 20% of the exploitable biomass was in Area 2B (British Columbia), so the 2B quota was reduced by an amount equal to about 20% of 1.58 times the coastwide bycatch mortality, even though only about 10% of the bycatch was taken in Area 2B. This substantial and disproportionate impact of U.S. (mainly Bering Sea) bycatch on Canadian setline quotas was a highly contentious issue for the IPHC and the governments.

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 that the reproductive compensation factor was lower than the yield loss factor, averaging 1.00 kg of required compensation for each kilogram of bycatch mortality, so from 1990 through 1996 the setline quota was reduced by the amount of bycatch mortality kilogram for kilogram. The reduction was still calculated as a coastwide total and distributed among regulatory areas in proportion to the exploitable biomass in each area (Sullivan et al. 1994). In the long term, the effect of this adjustment was to maintain the spawning biomass at the level it would have reached if fished at the target exploitation rate with no bycatch.

During the first half of the 1990s both countries implemented domestic observer programs that now provide good and reasonably complete information on the length composition of the bycatch. In addition, data from the lengthening series of NMFS trawl surveys showed that the western Gulf of Alaska rather than the Bering Sea usually held the bulk of juvenile Pacific halibut, and both NMFS and IPHC surveys indicated that total halibut abundance in the Bering Sea–Aleutian Islands region was higher than had been estimated previously by the annual stock assessment. When used in the migration model described above, all of this information indicated that the impact of sublegal bycatch falls largely on the stock in the area in which the bycatch is taken.

On the basis of these findings, the IPHC in 1997 adopted a new method of handling bycatch in setting quotas. The bycatch of legal-sized fish in each regulatory area is now treated just like other noncommercial removals—as a quota deduction for that regulatory area. The mortality due to sublegal bycatch is now incorporated into the population model that is used to evaluate alternative exploitation rates, so an allowance for sublegal bycatch is contained in the chosen rate. There is no explicit adjustment for sublegal bycatch in the quota-setting process.

As mentioned previously, the cumulative prerecruit mortality due to sublegal bycatch is now 5–10% for the Area 2 and Area 3 stocks, and 15–20% for the Area 4 stock. The IPHC staff's evaluation of alternative harvest rates is based on spawner–recruit data for Areas 2 and 3 combined, so a working value of 10% was used in developing recommendations for 1997.

As a practical matter, this addition to the population model has little influence on the eventual choice of a harvest rate. Its effect is to reduce the slope parameter of the estimated spawner-recruit relationship by 10%, and a difference of 10% is minor in comparison with the general uncertainty about the form and parameter values of the relationship. Moreover, in the vicinity of the optimum exploitation rate, yield is not very sensitive to the precise value of the exploitation rate, so a rate that is optimum for a prerecruit bycatch mortality of 10% will still perform very well if the true value is really 5% or 20%. This means that the chosen exploitation rate will perform well even if prerecruit bycatch mortality is only roughly estimated or variable among years and regulatory areas as, in fact, it is.

Discussion

Bycatch in other groundfish fisheries substantially reduced yield to the directed Pacific halibut fishery over the last few decades, and it continues to do so. The IPHC staff has estimated the long-term potential productivity of the stock as 30,000–40,000 mt/year, so at recent levels of bycatch the yield loss has amounted to about a third of potential production (11,000 mt/year). Obtaining good estimates of bycatch mortality, and accounting for it somehow in setting quotas for the directed fishery, are clearly essential to good management.

Whereas the coastwide impact of bycatch is known, the distribution of the impact among regulatory areas is uncertain because the migration patterns of juveniles are uncertain. The bycatch compensation procedures used by the IPHC in the 1980s and early 1990s distributed quota reductions in proportion to biomass. There was some justification for this approach, and it certainly served its purpose for the stock as a whole, but it was quite controversial, mostly because of the disproportionate levy on the Canadian fishery to compensate for bycatch in Alaska. Distributing the quota reductions according to the results of the migration modeling reported above might be less controversial, but probably not much less, because the underlying migration schedules are invented, and at best, they can only provide a range of values. Another, more subtle drawback of the compensation procedures was that they were formulated and implemented separately from the harvest strategy, and their effect on yield was not considered when formulating the harvest strategy. However, the adjustment of quotas for bycatch does, in fact, affect yield as well as biomass, and so it was a part of the harvest strategy.

The main advantage of accounting for sublegal bycatch by including that mortality in the population model used to choose the target harvest rate, is that now the treatment of bycatch is an integral part of the harvest strategy. The effects of all sources of mortality on both biomass and yield are considered simultaneously, and the Commissioners can consider both when choosing a harvest rate that achieves the best balance of their management objectives, which include maintaining a healthy level of spawning biomass along with obtaining a high and stable yield. In equilibrium conditions, it can be expected that the addition of sublegal bycatch mortality to the population model would result in the choice of a slightly lower target harvest rate, but that might not happen when the stock is at a high level of abundance, as it is now.

Another advantage of the present procedure is that it does not explicitly reduce the setline quota in one regulatory area to account for bycatch in another regulatory area. The only explicit quota reduction is for the bycatch of legal-sized fish within each regulatory area. That avoids some controversy, even though changing the procedure has in no way reduced the yield loss resulting from sublegal bycatch.

Now that the sublegal- and legal-sized components of bycatch are being treated separately, the impact of juvenile interceptions in Alaska on yield in British Columbia appears much smaller than it appeared to be during the 1980s, for several reasons. In the 1980s all bycatch was treated as an interception, and there was a tendency to think of it as being all juveniles, even though then, as now, about half by weight was legal-sized fish. Also, the migration modeling showed that, for a range of plausible migration schedules, the impact of juvenile bycatch was largely confined to the area where the bycatch was taken. These model results were reinforced by recent survey results which indicate that the Area 4 stock is relatively larger than previously thought. In the workings of the model, that shifted more of the large juvenile bycatch in the Bering Sea to the Area 4 stock itself. Finally, the staff's estimates of coastwide Pacific halibut abundance approximately doubled in 1997 when the assessment procedure was reworked to adjust for the large decrease in halibut growth that occurred between the 1970s and the 1990s. This effectively halved the estimate of the coastwide recruitment reduction due to juvenile bycatch, reducing it from 20% to 10%.

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