# Interpreting Pacific halibut catch statistics in the British Columbia individual quota program

**Patrick J. Sullivan and Suzanne Dyner Rebert**

**Abstract**: An individual quota management program was implemented on Pacific halibut (*Hippoglossus stenolepis*) in Canada in 1991. Subsequent changes in fleet behavior influenced the interpretability of catch-per-unit-effort (CPUE) statistics. A regression analysis on Pacific halibut CPUE statistics collected from 1986 to 1994 indicates that year, season, area, vessel class, and gear type all significantly influence CPUE and that there are significant year × season, year × area, and other interactions. CPUE as an annual index of abundance appears to be influenced by changes in fish distribution and fleet behavior. Effort-weighted global CPUE estimates indicate a 38% increase in halibut density in years following implementation of the quota program, while seasonally adjusted area-weighted estimates show only a 16% increase. Two systematic scientific surveys conducted on a portion of this area in 1986 and 1993 showed a 132% increase in density, although high variation and bias in these estimates limited their significance. The composition of the fleet remained relatively stable over this period making interactions involving the factors of gear type and vessel size-class less significant. Results of this analysis proved useful in planning survey and assessment programs prior to implementing a similar quota program in Alaska.

**Résumé** : En 1991, un programme de gestion par quotas individuels était instauré pour la pêche au flétan du Pacifique (*Hippoglossus stenolepis*) au Canada. Il s'en est suivi des changements dans les modalités de pêche de la flottille, changements qui ont influé sur l'interprétabilité des statistiques relatives aux captures par unité d'effort (CPUE). L'analyse de régression des valeurs de CPUE recueillies sur la pêche au flétan du Pacifique de 1986 à 1994 nous a appris que l'année, la saison, la zone, la classe de bateau et le type d'engin influent tous de façon significative sur les CPUE et que certaines interactions (année × saison, année × zone et autres) sont significatives. Comme indice de l'abondance annuelle, le facteur CPUE semble varier en fonction des changements de la distribution des poissons et des activités de la flottille. L'estimation des CPUE globales pondérées en fonction de l'effort de pêche révèle que la densité des populations de flétans a augmenté de 38 % les années qui ont suivi l'instauration du programme de quotas, tandis que l'estimation pondérée en fonction de la zone, après ajustement pour la saison, n'a indiqué qu'une hausse de 16 %. Or, deux relevés scientifiques systématiques ont été effectués dans cette zone en 1987 et 1993 : on a mis en évidence une augmentation de la densité de 132 %, bien que la forte variation et les biais importants que comportent ces estimations en limitent la fiabilité. Comme la composition de la flottille est demeurée relativement stable pendant la période considérée, les interactions mettant en jeu le type d'engin ou la classe de bateau ont moins d'importance. Les résultats de cette analyse ont été utiles pour la planification des relevés et des évaluations qui ont précédé l'application en Alaska d'un programme de quotas comparable.
[Traduit par la Rédaction]

## Introduction

Marine fisheries have traditionally been characterized by open access with total allowable catch (TAC) attained through a variety of restrictions on season length, area, and gear type. Critics of open access note that the resulting overcapitalization of the fishing fleet has forced managers to impose shorter seasons, resulting in unnecessary human risk and often a waste of the resource. Since the early 1970s a number of factors, including extended national jurisdiction, growing rates of exploitation, and tight fishery management budgets, have induced several countries to experiment with different management techniques, including individual quota (IQ) management, which entail the allocation of individual catch limits among users.

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However, this increasingly popular management technique may also encourage changes in many aspects of fleet behavior, which must be understood if data collection, stock assessment, and enforcement of total and individual quotas are to be consistent and accurate. This paper is an examination of the effect on catch statistics of one recently instituted IQ program, the British Columbia individual vessel quota (IVQ) system for Pacific halibut (*Hippoglossus stenolepis*), which took effect in 1991 in a limited-entry fishery. Results of this IVQ program are being closely watched by managers, fishers, and other observers in Canada and the United States. Managers of halibut in the North Pacific were particularly interested in these results, because in early 1993 the U.S. Secretary of Commerce approved an IQ plan for the much larger halibut fishery in Alaskan waters that was implemented in 1995.

Because IQ management is a fairly new technique and will probably take many years to reveal its effects fully, there is still relatively little empirical information on the effect of fleet behavior under existing IQ programs around the world. Some studies, however, point to issues that warrant further investigation. Boyd and Dewees (1992) noted changes in fleet composition in the inshore New Zealand fisheries placed under IQ management in 1986. Assessments were also made by Geen and Nayar (1988) of Australia's southern bluefin tuna (*Thunnus maccoyii*) fishery, unique in its application of IQ management to a pelagic, high-seas stock, and by Gardner (1988) of Atlantic Canada's "enterprise allocation" management of offshore groundfish fisheries. The latter system, which allocated harvest rights between corporations rather than individual fishermen, was applied to a fishery already characterized by vertical integration. Peacock and MacFarlane (1986) attributed much of the difficulty with compliance problems that developed in the Bay of Fundy herring (*Clupea harengus*) purse seine fishery to regional rivalries and the failure to reduce fleet size before introducing privatization.

This paper addresses the problem of interpreting Pacific halibut catch statistics in light of changes occurring under the Canadian Pacific halibut IVQ program. Catch per unit effort (CPUE) in particular is examined to determine if annual variations in that statistic are influenced by the behavior of the fleet through timing and location of fishing, vessel size, and gear type. CPUE is used in this and other annual stock assessments as a measure of relative abundance and so plays a critical role in estimating biomass and current levels of exploitation. However, it is well known that factors outside of changes in population abundance can influence CPUE (Sampson 1991) and that these factors may reflect changes in the distribution of the stock as well as the behavior of the fleet (Quinn 1985). Under an IQ system, one might expect a shift in effort to areas with higher CPUE in an attempt to maximize catch per effort. However, conflicting objectives, such as fishing closer to home port or redirection of effort while targeting for other species, can influence this behavior.

The question for us becomes, "How do changes in fleet behavior (given the IQ program) and corresponding changes in fish distribution (independent or not of the IQ program) affect our interpretation of CPUE, and how might we account for them?" Our major interest is in the season–area effects, although we wish to account for gear and vessel effects as well if they are determined to be important. Four scenarios can be considered here: (*i*) both the fishers and the fish distribute themselves consistently by season and area across years; (*ii*) the fishers change their distribution, but the fish do not; (*iii*) the fish change their distribution, but the fishers do not; and (*iv*) both the fishers and the fish change their distribution. If the first scenario holds then a conventional estimator (e.g., simple mean log(CPUE) or effort-weighted mean CPUE as is currently used by the International Pacific Halibut Commission (IPHC) should be adequate as an index of abundance. If the second scenario holds, as it might under a change in fishery management, then accounting for changes in the fishery (e.g., the main effects: season fished, area fished, gear fished, etc.) and weighting the influence of each factor proportionally and independently of effort distribution should result in an appropriate indicator of abundance. If the third or fourth scenario holds, and fish change their distribution from one year to the next as well, then in addition to the main effects we should expect to see significant interactions between year and the remaining factors, and we will need to make some additional assumptions for our estimators to be representative of annual changes in abundance. We shall show that not only did the fishers appear to have changed their behavior in response to a change in management but that the fish likely changed in their distribution as well (although this change may not have been a response to or coincident with the change in management) and will attempt to account for these changes in our estimation.

## Materials and methods

### Data

The bilateral body responsible for the collection of halibut catch statistics, and for recommendations based on their interpretation, is the IPHC established by United States – Canadian treaty in 1923 as the International Fisheries Commission (Bell 1981). The Commission staff conducts a variety of shore-side and at-sea studies of halibut stock size, catch, age and length distribution, and migration.

The Pacific halibut is the largest member of the pleuronectid (flounder) family; it is a right-eyed flatfish that may attain a length of 2.5 m and a weight of 250 kg. However, the average fish caught today weighs approximately 20 kg. Females tend to be larger than males and have a longer life-span; halibut enter the fishery at age 8 and may live another 20 or more years.

Halibut have been pursued by hook-and-line fishers off the northwestern coast commercially since the 1880s, and the basic configuration of the gear used has not changed dramatically, although many technological advances have been made (Sullivan and McCaughran 1995). From earliest times until the 1980s the familiar J-shaped hook was used; this was replaced throughout the fleet in 1982 and 1983 by a circular hook that doubled catching power (Quinn et al. 1985). Skud (1975) developed the idea of an "effective skate" to standardize CPUE for changes in fishing practices. Today, the basic unit of effort, called a skate, is a 550-m (1800-foot) groundline with shorter lines (gangions) attached every 5.5 m (18 feet), with a circle hook on each gangion. This basic unit is used here to represent standardized effort in the Pacific halibut fishery. Customarily several skates are tied together in a "string," and the resulting groundline may be several kilometres long, with hundreds of baited hooks. Originally, gangions with hooks attached were tied onto the groundline by hand during the preparations for the fishing season; this "fixed-hook gear" is still used by some of the largest and most experienced vessels in British Columbia. Many newer entrants to the fishery favor snap-on gangions ("snap-hook gear"), which are attached to the groundline as it is deployed.

The Alaskan fleet numbers over 6000 vessels at present, while the modern British Columbia fishery operates on a much smaller scale. Limited-entry "L" licenses were assigned to 435 vessels by the Department of Fisheries and Oceans (DFO) in 1979. Even in the British Columbia case, with limited entry, incentives to maximize individual catch and effort remained. As investment in vessels and technology increased, the halibut season dwindled from 6 months in 1979 to 6 days in 1990. That year, DFO and industry representatives approved a trial IVQ plan to go into effect at the start of the 1991 season, which would be extended to seven months. Each L vessel was assigned a share of TAC based on a 70% weighting of the vessel's best historical catch over the qualifying period 1986–1989 and a 30% weighting of vessel length. These shares were originally nontransferable during the 1991–1992 trial period, except upon sale of the vessel, but DFO and industry representatives agreed to introduce transferability in the 1993 season, which was considered a third trial year.

The current IPHC data most directly affected by IVQ management are those collected through port sampling, which involves copying vessel log-book information as well as sampling length measurements (for weight estimation) and extracting otoliths (for age determination). A random sample of the catch is taken from each vessel as it unloads its fish, while from log books and landing statistics catch is tallied with statements of effort, area fished, and gear used. The day when fish are caught is also recorded on log books and here is summarized by season (i.e., spring, March–May; summer, June–August;

**Fig. 1.** International Pacific Halibut Commission statistical areas.

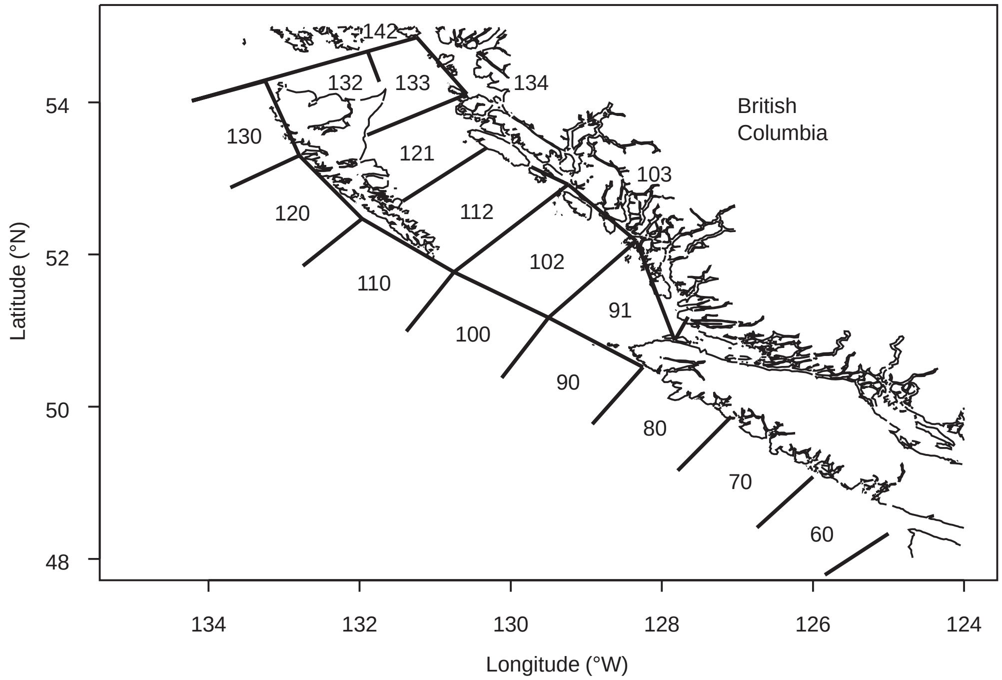



**Table 1.** Vessel class identifier indicating vessel size as defined by corresponding vessel length range.

| Vessel class | Length range (m) |
|---|---|
| A–B | 3–9 |
| C–D | 9–12 |
| E–F | 12–15 |
| G–H | >15 |

fall, September–November). Vessels fall into eight length-classes, A through H, based on 1.5-m (5-foot) increments, which have been consolidated into four paired classes here for analysis (Table 1). The areas used are 97 km wide (60 mile wide) IPHC statistical areas numbered 60 through 142, arrayed along the coasts of British Columbia's mainland and Vancouver and the Queen Charlotte Islands (Fig. 1). A vessel's fishing location is determined by log records of Loran readings and (or) latitude–longitude determination, and sometimes by references to physical features of the coastline.

Details of the IVQ program included several provisions for monitoring and enforcing individual landings; these data have proven essential to the functioning of IQ programs worldwide (Rebert 1993). Monitoring of individual landings is conducted by a private contractor under DFO's aegis, while enforcement officers are DFO employees budgeted under a federal grant matching IVQ fees collected from fishermen. The IVQ program provides for a consultative body of fishers, the Halibut Advisory Board, whose members are elected by and from IVQ shareholders. More information on the Canadian halibut IVQ program can be found in Turris (1994) and more on its subsequent socioeconomic effects in Casey et al. (1995).

## Methods

A synoptic approach is taken to explore the influence of various factors on CPUE by use of a linear model that incorporates the factors of interest. Results from the analysis will indicate which factors play a major role in interpreting this statistic, and a graphical analysis of the distribution of fleet effort will indicate how severe these influences are likely to be. The significant factors and interactions shall be employed to highlight fleet behavior and fish distribution patterns that likely affect the conventional CPUE indexes of abundance. Alternative estimators and alternative information sources are examined in light of these factors.

The natural log of CPUE, defined as the catch of halibut in kilograms per skate (the standardized unit of effort), is modeled as a function of five explanatory factors and their interactions:

$$\log(CPUE) = \beta_0 + Y\beta_1 + A\beta_2 + S\beta_3 + G\beta_4 + V\beta_5 + \sum_i \sum_{j>i} X_{ij}\,\beta_{ij} + \varepsilon$$

The form of the equation reflects the multiplicative influence that each of the factors has on the CPUE abundance index (Gavaris 1980). The explanatory factors are families of indicator variables representing the effects of year, *Y*; area, *A*; season, *S*; gear, *G*; and vessel, *V* (Table 2). The year factor *Y*, for example, is a $n \times (k_1 - 1)$ matrix of 0s and 1s, with $k_1 = 9$ being the number of levels (years) used in the analysis and *n* being the number of observations. Elements of the matrix are set to 1 for the factor level corresponding to the observation and set to 0 otherwise. Only $k - 1$ levels need to be represented to fully specify the model. The coefficient $\beta_1$ is then a vector of length $k_1 - 1$, with each element corresponding to one level represented in the factor *Y*. The interaction terms $X_{ij}$ represent the elementwise product of each level of each factor (e.g., $Y \times V$, $Y \times G$,..., $A \times V$). The coefficient of the interaction term $\beta_{ij}$ is a vector of length $(k_i - 1) \times (k_j - 1)$ corresponding to the product of the number of elements contained in the *i*th and *j*th components. The term $\varepsilon$ represents independent and identically distributed Gaussian error.

A linear model was chosen as the most parsimonious approach to take in detecting a change that might influence current abundance indexes. While nonlinear and higher order effects are possible, we feel a simpler approach should be employed at least initially. A linear relationship between catch and effort exists for halibut under the current level of exploitation; thus, CPUE (the ratio of catch to effort) was chosen over regressing catch against effort as a covariate for greater interpretability and added parsimony.

Determining the significance of interactions is a key component of this analysis. In particular, an interaction involving the year effect can

**Table 2.** Factors and number of levels within each factor included in the analysis (e.g., there are 17 different statistical areas represented) and a brief definition of the factor levels.

| Factor | No. of levels | Description |
|---|---|---|
| Area | 17 | See Fig. 1 |
| Gear | 2 | Fixed-hook, snap-hook |
| Season | 3 | Spring, summer, fall |
| Vessel | 4 | A–B, C–D, E–F, G–H |
| Year | 9 | 1986–1994 |

potentially lead to spurious trends in CPUE as a measure of annual abundance. Conventional estimators (e.g., mean log(CPUE), or effort-weighted CPUE, ΣCatch/ΣEffort) that ignore such interactions, which result from changes in fleet and fish behavior, can lead to erroneous assessments of fish abundance.

A stepwise approach is used to find the significant model components. A step consists of adding a factor (e.g., *Y*, the year effect) to the model and testing for significance of the addition relative to a previously specified model (e.g., the null model with no factors or the model determined to be the most significant representation from the prior step). The factor or interaction selected for addition is chosen based on its relative significance given the prior model, as based on the partial *F*-test statistic

$$(1) \qquad F = \frac{\mathrm{SSE}_{\mathrm{prior}} - \mathrm{SSE}_{\mathrm{proposed}}}{\mathrm{df}_{\mathrm{prior}} - \mathrm{df}_{\mathrm{proposed}}} \div \frac{\mathrm{SSE}_{\mathrm{proposed}}}{\mathrm{df}_{\mathrm{proposed}}}$$

where SSE is the sum of squared error and df is residual degrees of freedom for the prior and proposed models. Once a factor or interaction is determined to be significant enough to add, it is added and the factors already present in the model are tested for their continued significance with the new factor present (and if no longer significant are removed and returned to the pool of factors to be considered). The addition of another element from the remaining pool of factors or interactions is then considered, thus beginning a new step in the process. The procedure ends when none of the remaining factors are found to be statistically significant (at the 0.05% level). Main effects are examined first, followed by interactions.

The $C_p$ statistic (Mallows 1973):

$$(2) \qquad C_p = \frac{\mathrm{SSE}_{\mathrm{proposed}}}{\mathrm{MSE}_{\mathrm{full}}} - (n - 2p)$$

where $n$ is the number of observations and $p$ is the number of parameters used in the proposed model, is calculated after application of the stepwise regression for use in comparing the relative significance of different model formulations to the full model. Here the full model is defined to be the final model selected through the stepwise process:

$$(3) \qquad \mathrm{MSE}_{\mathrm{full}} = \frac{\mathrm{SSE}_{\mathrm{final}}}{\mathrm{df}_{\mathrm{final}}}$$

## Results

### Regression analysis

Results of the stepwise linear fit to the data indicate that area and season play a major role in the interpretation of CPUE (Table 3). Furthermore, all single factors added were significant to model fit (at the 0.05 level) with area being the most informative. Six of a possible 10 interaction terms were found to be significant; four involved year. Season and area were found to have statistically significant interactions together and in combination with the year effect (Table 4). Season and area also appeared to interact significantly with vessel type. Statistically significant but lower level interactions appeared between year, vessel, and gear. No higher order interactions were examined.

Observed log(CPUE) was compared with predicted log(CPUE) under the full model to validate the Gaussian assumption (Fig. 2). Half of the 8141 observations occurred between 4 and 5 log(CPUE) (i.e., between 54 and 148 kg/skate) with fewer data points and somewhat greater variance observed for lower values. A root transformation such as that suggested by Quinn (1985) or Richards and Schnute (1992) might have made the variance more homogeneous, but the log transformation leads to a more intuitive interpretation of results relative to standard CPUE statistics and the multiplicative nature of the factors. The factors and interactions chosen for inclusion in the stepwise regression and their relative ranking in significance were the same regardless of the transformation used (i.e., log, square-root, or fifth-root, which results in a residual distribution that is closest to being Gaussian).

### Season and area effects

Commercial catch statistics on percent effort expended by year and season indicate a shift in seasonal effort (Fig. 3). Effort occurred primarily during the spring and summer seasons in 1986, 1987, and 1988, then summer and fall in 1989, the years when the time–area closures were in effect. The year just prior to implementation of the IVQ program, 1990, was unusual in that, after the catch limit was set, the fleet was split, half fishing during spring landing dates and half fishing during summer, with a "clean-up" fishery by the entire fleet for the remaining quota in fall. During the initial year of the IVQ, 1991, harvest shifted later to summer and fall and then shifted back in subsequent years when the majority of effort was expended during the initial opening period of spring.

Generally, summer catch rates appear to be somewhat higher across years compared with those shown in spring and fall (Fig. 4), but fishing during periods when higher catch rates occur does not seem to be the overriding objective of the fleet when they have the option to choose. Discussions with fishers and processors suggest that the shift to fishing in later periods in 1991 was due to fishers waiting for the price to increase, while the strategy in later years was to fish early, prior to the Alaskan opening (in early June) and just after winter closures, when demand for halibut was greatest. Fishing dates, catch limits, and landed catch for the entire Canadian fleet indicate the management constraints imposed on the fleet over the period of the study (Table 5).

The shift in effort by area is also noteworthy (Fig. 5). Most of the effort occurs in the northern and central waters off British Columbia and the Queen Charlotte Islands (i.e., Fig. 1, areas north of 110) prior to 1991, while a greater amount of effort is observed along the outer shelf (e.g., areas 100 and 130) and further south (areas south of 110) thereafter.

A comparison of catch rates across all IPHC regulatory areas indicates that halibut densities are generally greater in the north and central regions of the Gulf of Alaska than they are to the south off British Columbia, averaging 190 kg/skate for commercial halibut fishing in the central Gulf between 1986 and 1994, while averaging 66 kg/skate commercially off British Columbia. Similar gradients appear on a smaller scale within British Columbian waters (Fig. 6) with CPUE decreasing north to south (e.g., areas 130–142 relative to areas 60–91) and offshore to inshore (e.g., 100–102–103 and 130–132–

**Table 3.** Results of the stepwise regression.

| Factor | Regression df | Residual SS | Residual df | $F$ | $P$ | Mallow's $C_p$ |
|---|---|---|---|---|---|---|
| Intercept | 1 | 6349 | 8140 | — | — | 3381 |
| Year | 8 | 6294 | 8132 | 25 | <0.000 01 | 3297 |
| Area | 16 | 5054 | 8116 | 114 | <0.000 01 | 1079 |
| Season | 2 | 4987 | 8114 | 54 | <0.000 01 | 962 |
| Gear | 1 | 4959 | 8113 | 46 | <0.000 01 | 913 |
| Vessel | 3 | 4902 | 8110 | 31 | <0.000 01 | 816 |
| Year × season | 12 | 4772 | 8098 | 18 | <0.000 01 | 604 |
| Season × vessel | 6 | 4720 | 8092 | 15 | <0.000 01 | 521 |
| Area × season | 32 | 4632 | 8060 | 5 | <0.000 01 | 426 |
| Area × vessel | 47 | 4549 | 8013 | 3 | <0.000 01 | 369 |
| Year × area | 128 | 4374 | 7885 | 2 | <0.000 01 | 307 |
| Year × vessel | 24 | 4342 | 7861 | 2 | 0.000 1 | 297 |
| Year × gear | 8 | 4328 | 7853 | 3 | 0.002 | 288 |

**Note**: Significant factors and interactions are shown with the sum of squares (SS) and the residual degrees of freedom (df) at each stage of the fit. The partial $F$-test statistic and associated $P$ value for the proposed factor relative to the prior model fit are also given along with the $C_p$ statistic to allow comparisons of the relative contribution of each factor or interaction with the full model at each step in the process. Once entered, none of the factors or interactions was dropped because of lack of significance resulting from subsequently added factors.

**Table 4.** Rank in significance of the interaction term and significance level of the full model when compared with a model with the indicated interaction term eliminated.

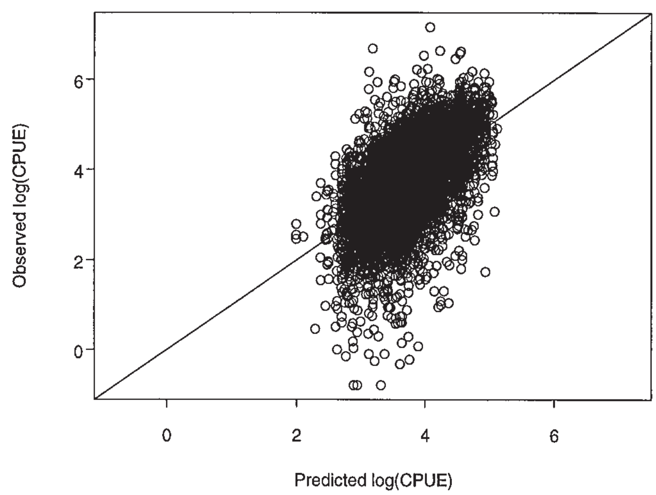
| Factor | $F$ | $P$ |
|---|---|---|
| Year × season | 16 | <0.000 01 |
| Year × area | 2 | <0.000 01 |
| Season × vessel | 13 | <0.000 01 |
| Area × season | 4 | <0.000 01 |
| Area × vessel | 3 | <0.000 01 |
| Year × vessel | 2 | 0.000 2 |
| Year × gear | 3 | 0.001 |

133–134). These patterns are confirmed by data collected from the 1993 IPHC systematic survey (Fig. 7), although an examination of the 1986 survey results would indicate that this has not always been the case.

The shift in effort to areas along the outer shelf is consistent with the objective of increasing fishing efficiency through an increase in CPUE, but shifts in effort to the south are more consistent with the aim of reducing costs by fishing closer to home port. Obviously the fishers may be trying to satisfy several different objectives. Regardless of the motivation, the net effect is a shift in the distribution of the fleet.

The observed shift in effort by season and area coupled with the significance of season and area as factors in the regression analysis indicates that changes in fleet distribution will likely influence conventional CPUE estimates. The average across years of the differences between the maximum and minimum value within a season (or area) is useful for determining the magnitude that changes in effort could have on global estimators under a catch-rate maximizing objective. An examination of seasonal means (Fig. 4) indicates an average maximum difference of 0.32 in log(CPUE) (corresponding to a 38% change in CPUE) by season within year, with at most a 0.54 difference in log(CPUE) (70% change in CPUE). In contrast, an examination of area means (Fig. 6) indicates greater disparity with an average maximum difference of 1.6 log(CPUE) (a 500% change in CPUE) with at most a difference of 1.8 log(CPUE)

**Fig. 2.** Observed log(CPUE) versus predicted log(CPUE) under the full model. The diagonal line is the 1:1 ratio.




(600% change in CPUE). Consequently, a shift in effort by area potentially has seven times the impact that a shift in season could have.

There is also a contrast in trend by year from north to south worth noting. Mean log(CPUE) for area 130 and north under the full model all appear below the reduced model in years prior to 1990, while they all appear above the reduced model after 1990 (Fig. 6). The opposite trend is observed in means for areas 90 and south. This contrast, indicated by the interaction between year and area, indicates a difference in annual trend north to south that cannot be accounted for under any of the remaining factors. It will be important to account for this contrast in trend as we shall see later.

The significance of the year × season and year × area interaction terms indicates that the nature of these effects must be addressed if we hope to use CPUE as an index of annual abundance. Changes in fleet behavior were expected in response to the new management program, as such changes had often occurred in the past (Sullivan and McCaughran 1995). However,

**Fig. 3.** Pacific halibut commercial effort in percent by season by year for the seasons spring, summer, and fall. Inset text indicates the year and total effort expended in thousands of skates.

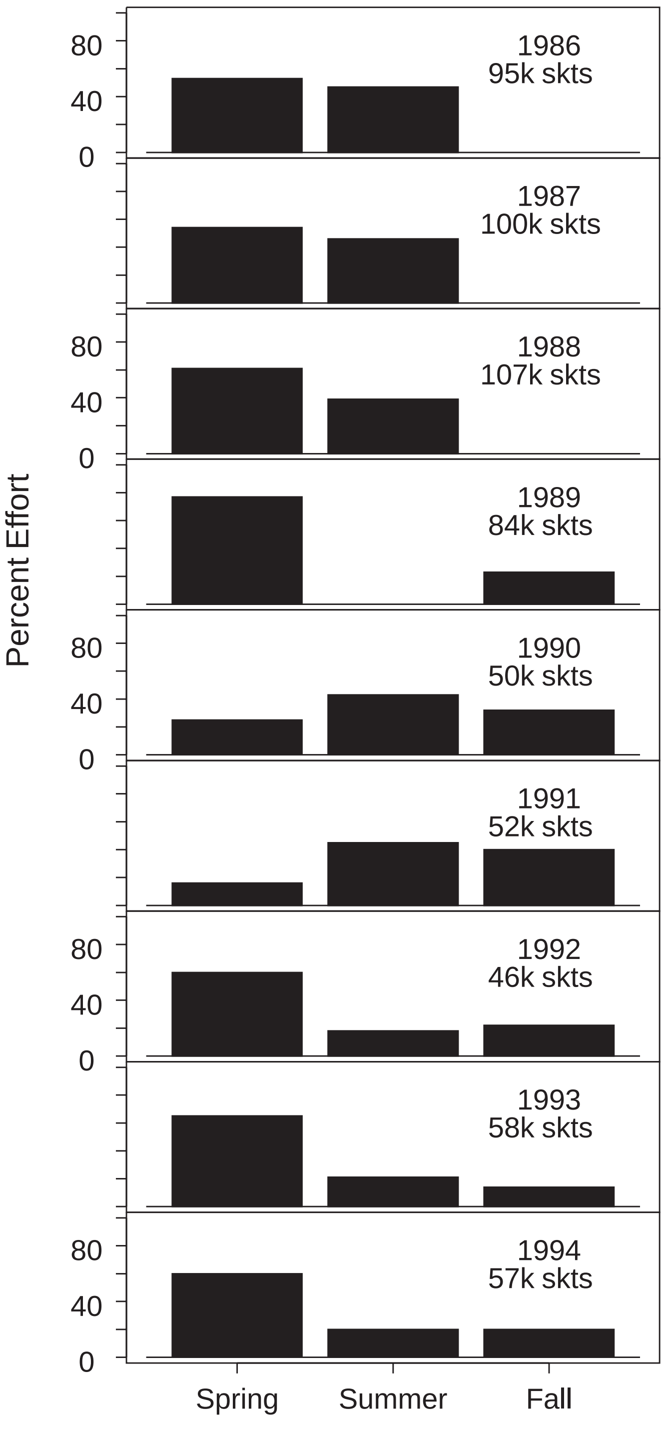
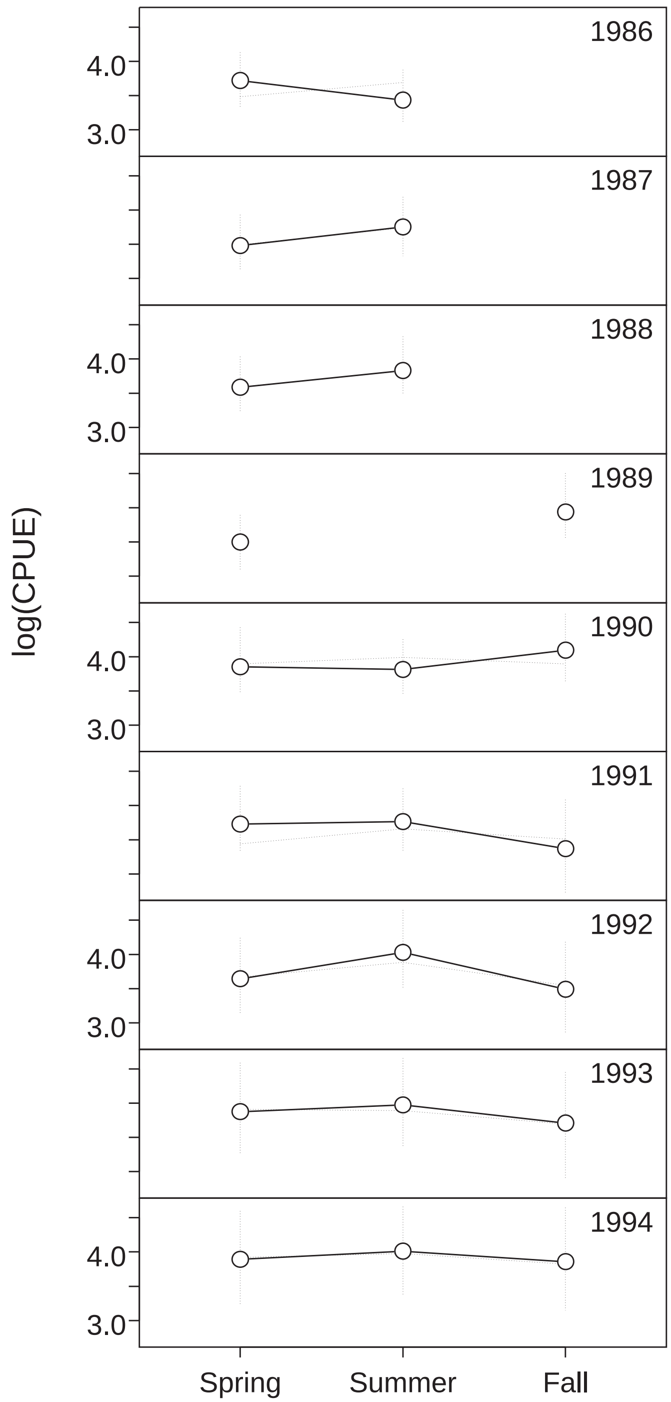



**Fig. 4.** Mean log(CPUE) by year for seasons spring, summer, and fall under the full model (circles with solid line) contrasted with a reduced model where year × season interaction term is dropped (broken line). Interquartile range of raw data shown by vertical broken lines represents the middle 50% of the data.




with regard to fish distribution on the grounds, significant fine-scale changes in distribution patterns were not anticipated. Halibut are known to conduct large-scale migrations (St.-Pierre 1984) but generally are believed to do so only during the winter spawning period and to return to their feeding grounds in spring and summer in time for the fishing season (Skud 1977). The regression analysis indicates that season and area show the greatest degree of interaction with year. Thus, not only is it likely that a modification in fleet behavior has occurred (i.e., fishing through the years differently across season and area), it is as likely that changes in fish distribution patterns have occurred (i.e., fish appearing in areas or seasons

**Table 5.** Catch limit, fishing dates, and estimated catch for each year of the analysis.

| Year | Catch limit (t) | Opening date | Closing date | Fishing days | Catch (t) |
|---|---|---|---|---|---|
| 1986 | 5079 | May 3 | May 11 | 8 | |
| | | June 8 | June 15 | 7 | |
| | | | | | 5088 |
| 1987 | 5215 | May 2 | May 10* | 8 | |
| | | June 16 | June 21* | 5 | |
| | | August 22 | August 25 | 3 | |
| | | | | | 5556 |
| 1988 | 5669 | May 6 | May 14 | 8 | 3144 |
| | | August 19 | August 25 | 6 | 2688 |
| | | | | | 5832 |
| 1989 | 4535 | April 25 | May 3 | 8 | 3259 |
| | | September 9 | September 12 | 3 | 1471 |
| | | | | | 4730 |
| 1990 | 3537 | April 16 | April 20 | 4 | 1157 |
| | | June 14 | June 18 | 4 | 1383 |
| | | September 13 | September 15 | 2 | 1347 |
| | | | | | 3887 |
| 1991 | 3356 | May 1 | November 30 | 213 | 3252 |
| 1992 | 3628 | March 8 | October 31 | 237 | 3460 |
| 1993 | 4672 | March 1 | October 31 | 244 | 4821 |
| 1994 | 4535 | March 1 | November 15 | 259 | 4494 |

**Note**: The Pacific halibut IVQ was initiated in British Columbia in 1991.
*Vessels could fish in either the May or June opening but not both.

**Table 6.** Mean log(CPUE), sampling effort, and bottom area by IPHC statistical area and year.

(A) Mean log(CPUE) (logarithm of kilograms per skate)

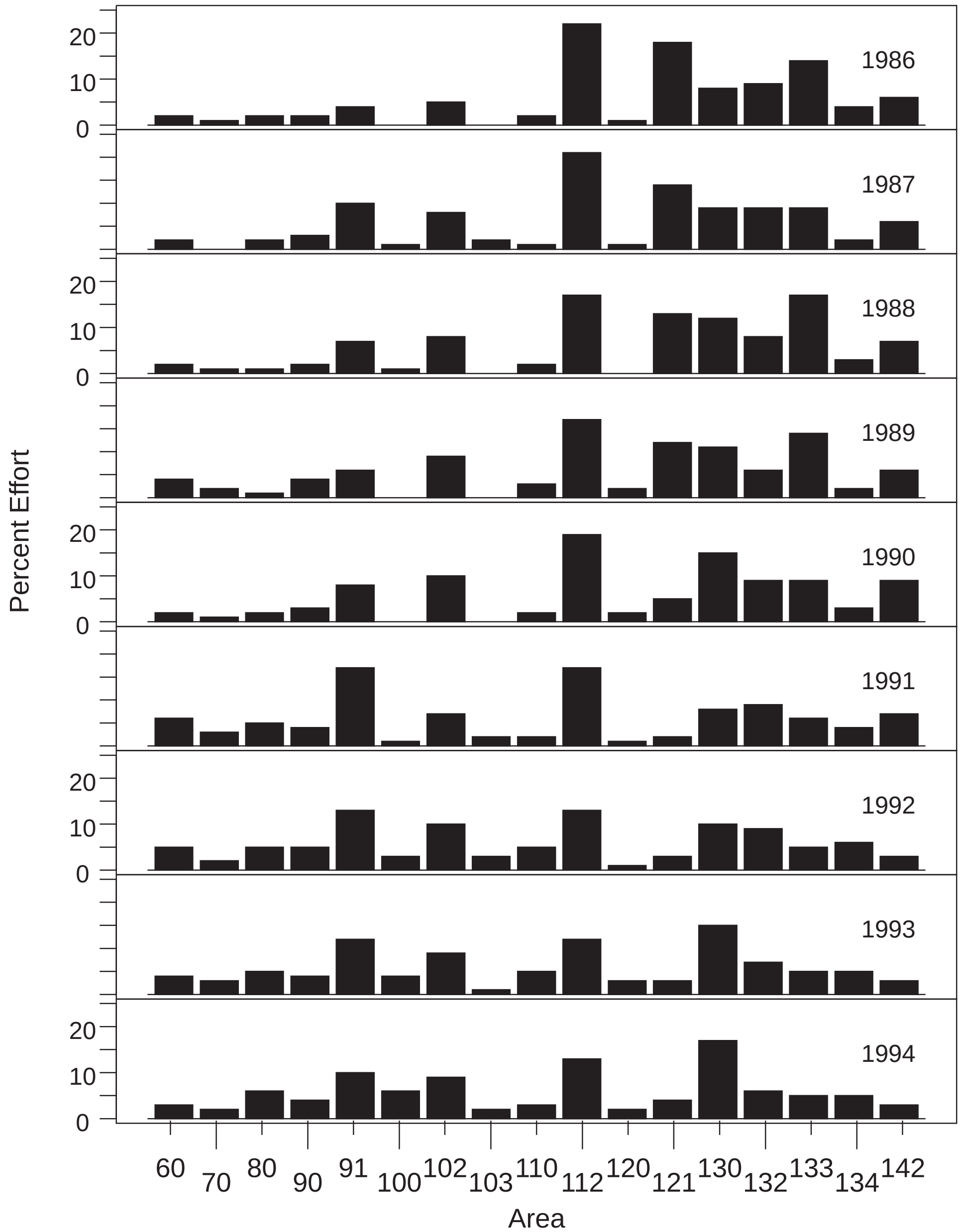
| IPHC area | Bottom area (km$^2$) | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|---|---|---|---|---|---|
| 60 | 4351 | 3.48 | 3.19 | 3.08 | 3.44 | 4.01 | 2.92 | 2.83 | 3.03 | 3.20 |
| 70 | 4280 | 3.19 | 3.07 | 3.29 | 3.33 | 3.69 | 2.94 | 3.31 | 3.09 | 2.71 |
| 80 | 2185 | 3.82 | 3.52 | 3.42 | 3.43 | 3.80 | 3.43 | 3.79 | 4.00 | 3.92 |
| 90 | 8500 | 3.57 | 3.52 | 3.53 | 3.62 | 3.63 | 3.28 | 3.36 | 3.49 | 3.45 |
| 100 | 9393 | 3.73 | 3.61 | 3.82 | 3.75 | 4.03 | 3.45 | 3.64 | 4.13 | 4.20 |
| 110 | 641 | 3.60 | 3.93 | 3.96 | 4.23 | 4.27 | 4.07 | 4.02 | 3.99 | 3.78 |
| 112 | 7890 | 3.62 | 3.54 | 3.69 | 3.67 | 4.09 | 3.67 | 3.73 | 3.99 | 3.93 |
| 120 | 665 | 3.76 | 3.61 | 4.49 | 4.04 | 3.88 | 3.90 | 4.13 | 4.33 | 4.10 |
| 121 | 5079 | 3.62 | 3.63 | 3.50 | 3.48 | 3.65 | 3.18 | 3.46 | 3.50 | 3.43 |
| 130 | 2485 | 3.93 | 3.93 | 4.15 | 4.13 | 4.26 | 4.36 | 4.54 | 4.62 | 4.54 |
| 132 | 5991 | 3.38 | 3.70 | 3.64 | 3.35 | 3.75 | 3.74 | 3.72 | 3.71 | 3.81 |
| 142 | 2540 | 3.67 | 3.89 | 3.94 | 3.93 | 4.11 | 4.07 | 4.30 | 4.64 | 4.53 |

(B) Sampling effort (skates hauled)

| IPHC area | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|---|---|---|---|---|
| 60 | 1 637 | 1 647 | 1 543 | 2 439 | 934 | 2984 | 2561 | 1903 | 1760 |
| 70 | 871 | 305 | 532 | 1 227 | 268 | 1301 | 1158 | 1576 | 1089 |
| 80 | 1 232 | 1 043 | 1 058 | 973 | 878 | 2206 | 2411 | 2509 | 3274 |
| 90 | 4 563 | 8 553 | 7 194 | 6 765 | 4560 | 9969 | 8911 | 8218 | 7212 |
| 100 | 4 079 | 7 083 | 6 571 | 6 320 | 4273 | 4796 | 7834 | 7799 | 8637 |
| 110 | 1 606 | 980 | 1 150 | 1 856 | 980 | 1086 | 2253 | 2487 | 1544 |
| 112 | 16 460 | 14 191 | 12 314 | 10 960 | 8040 | 7956 | 6287 | 6331 | 6773 |
| 120 | 800 | 998 | 81 | 1 195 | 976 | 706 | 473 | 1608 | 983 |
| 121 | 13 428 | 9 638 | 9 499 | 8 094 | 2043 | 1041 | 1244 | 1411 | 1862 |
| 130 | 5 957 | 6 279 | 8 704 | 7 320 | 6355 | 3842 | 4683 | 7842 | 8488 |
| 132 | 19 703 | 13 113 | 20 462 | 14 257 | 8560 | 9080 | 9600 | 8674 | 8042 |
| 142 | 4 313 | 3 802 | 4 987 | 4184 | 3740 | 3189 | 1396 | 1317 | 1581 |

**Note**: Bottom area is the area for depths less that 900 m and is assumed to be a constant relative measure of habitat for Pacific halibut.

**Fig. 5.** Pacific halibut commercial effort in percent by area by year for IPHC statistical areas shown in Fig. 1.



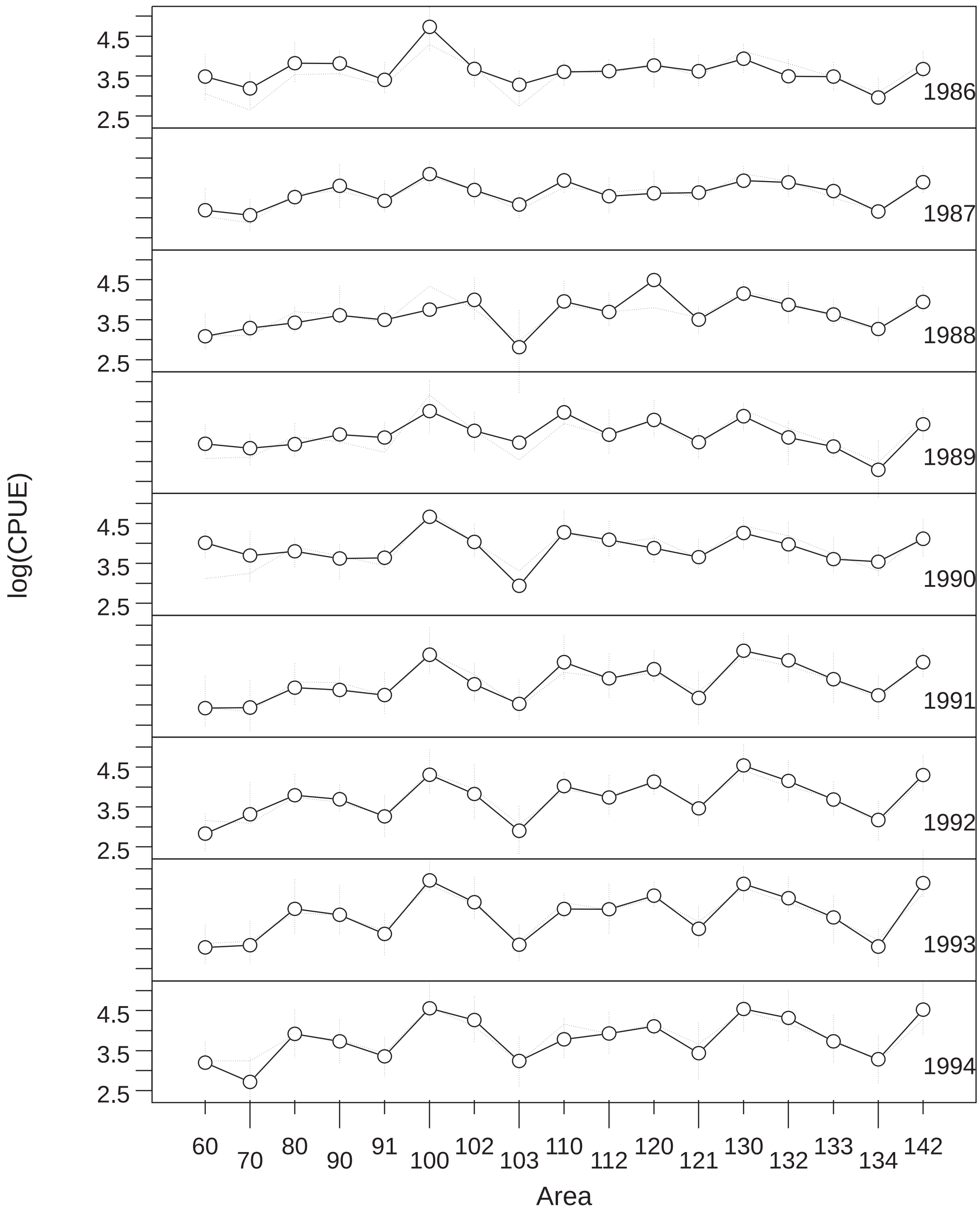

differently across years). Both these factors likely alter abundance indices in ways that are different from how indices would change if they were a function of year (regional abundance) alone and independent of the remaining factors.

To examine the influence this has on the abundance index we examine relative changes in cell means as influenced by the interaction component, much as we did when considering main effects. We do this by looking at predicted cell means across factors under the full model, and note the most significant changes in the residual sum of squares resulting from an interaction being excluded and then attempt to broadly interpret the practical significance of these effects.

Differences in the season × year interaction term, though statistically significant, like the season main effect appeared to be small in a practical sense (Fig. 4). The two most significant changes in the residual sum of squares between the full model and a model excluding the year × season interaction term were the 1986 spring and summer effects (20 and15%, respectively, of the overall change in the residual sum of squares), followed closely by seasonal differences from the full model in 1990 and 1991 (14 and 23%, respectively). The greatest change in mean, however, corresponds only to about an 0.2 difference in log(CPUE) resulting in about a 20% difference in catch rate.

The greatest year–area specific changes occur in 1986 – area 132 and 1990 – area 60 each making up about 5% of the overall change in residual sum of squares. Note how, over the years 1986–1990, areas 100 and south have higher predicted catch, while areas 130–142 have slightly lower catch rates under the full model, and that in later years (1991–1994), the

**Fig. 6.** Mean log(CPUE) by year for IPHC statistical areas under the full model (circles with solid line) contrasted with model where year × area interaction term is dropped (broken line). Interquartile range of raw data is shown by vertical broken lines. Statistical areas (Fig. 1) shown along the bottom axis increase by tens in number going south to north and by ones going offshore to inshore. Higher means are observed outside relative to inside, and north relative to south. Departures of the reduced model from the full model indicate degree of interaction. Relative trends in mean log(CPUE) observed over time (going down the figure) indicate that the full model shows a steeper increase with time in the north and a steeper decline in the south than what one might expect on average under the reduced model.



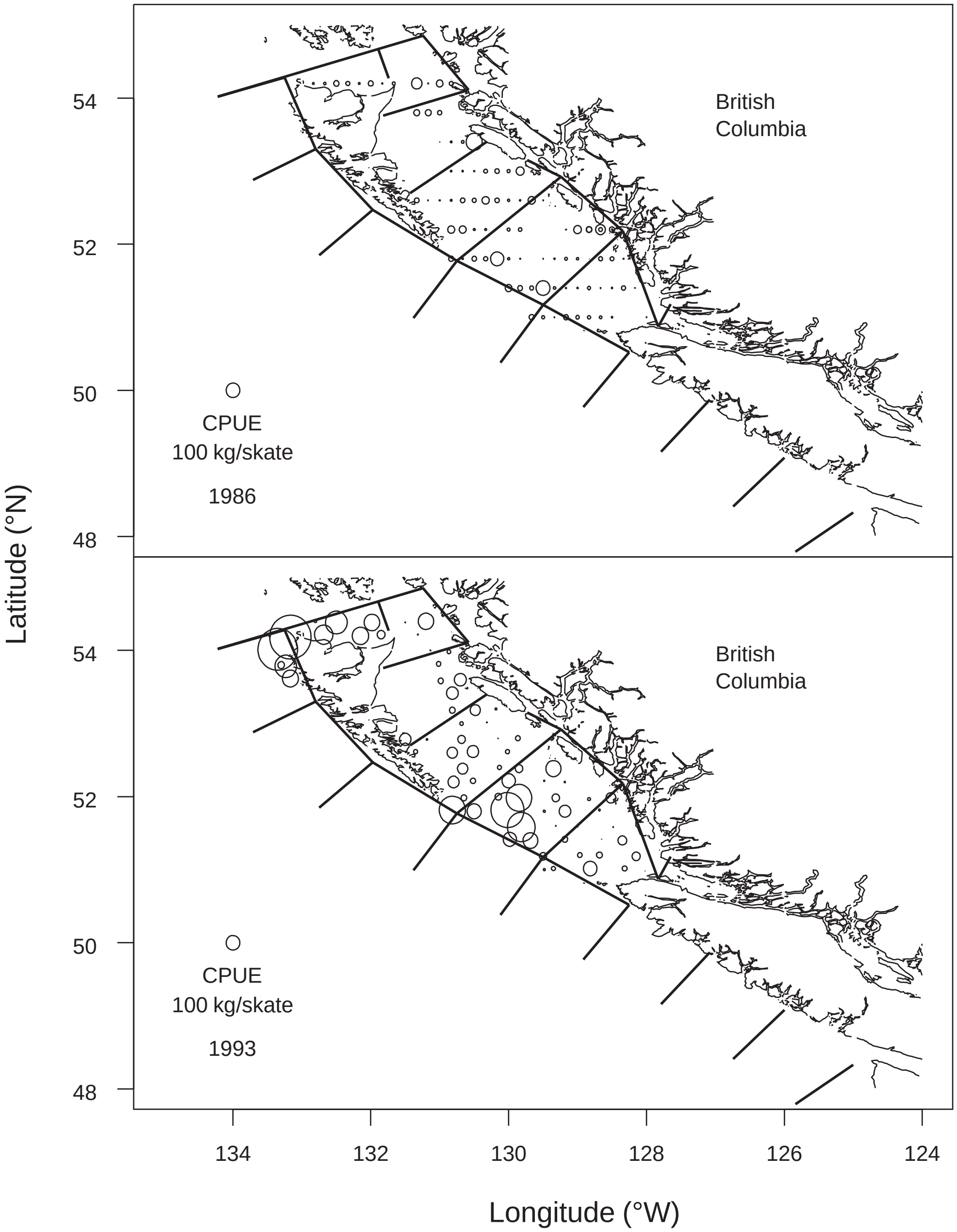

pattern is reversed. The net effect is a steeper upward trend in the northern areas with, if anything, a decreasing trend in the south in later years, consistent with the shift in fish distribution observed in the 1986–1994 IPHC scientific surveys.

Examination of the season–area effect fills out the picture on halibut distribution patterns (Fig. 8). The most significant changes to the sum of squares occurred in the summer and fall season–area combinations (greatest change in sum of squares: 12% summer – area 60; 9% fall – area 91 and summer – area 100). In particular, catch rates in offshore areas 60, 70, 100, 110, 120, and 130 were lower in summer under the full model and shifted higher in the fall. These trends are likely indicative of the change in distribution that takes place throughout the year after, and then prior to, the spawning migration runs. The north–south offshore–inshore pattern in catch rate previously discussed can still be seen and likely reflects habitat availability.

### Vessel and gear-type effects

Changes in the composition of the fleet over the 1986–1994

**Fig. 7.** Pacific halibut CPUE by station across areas for setline scientific surveys conducted in 1986 and 1993. The radius size of the circle indicates measured CPUE level.

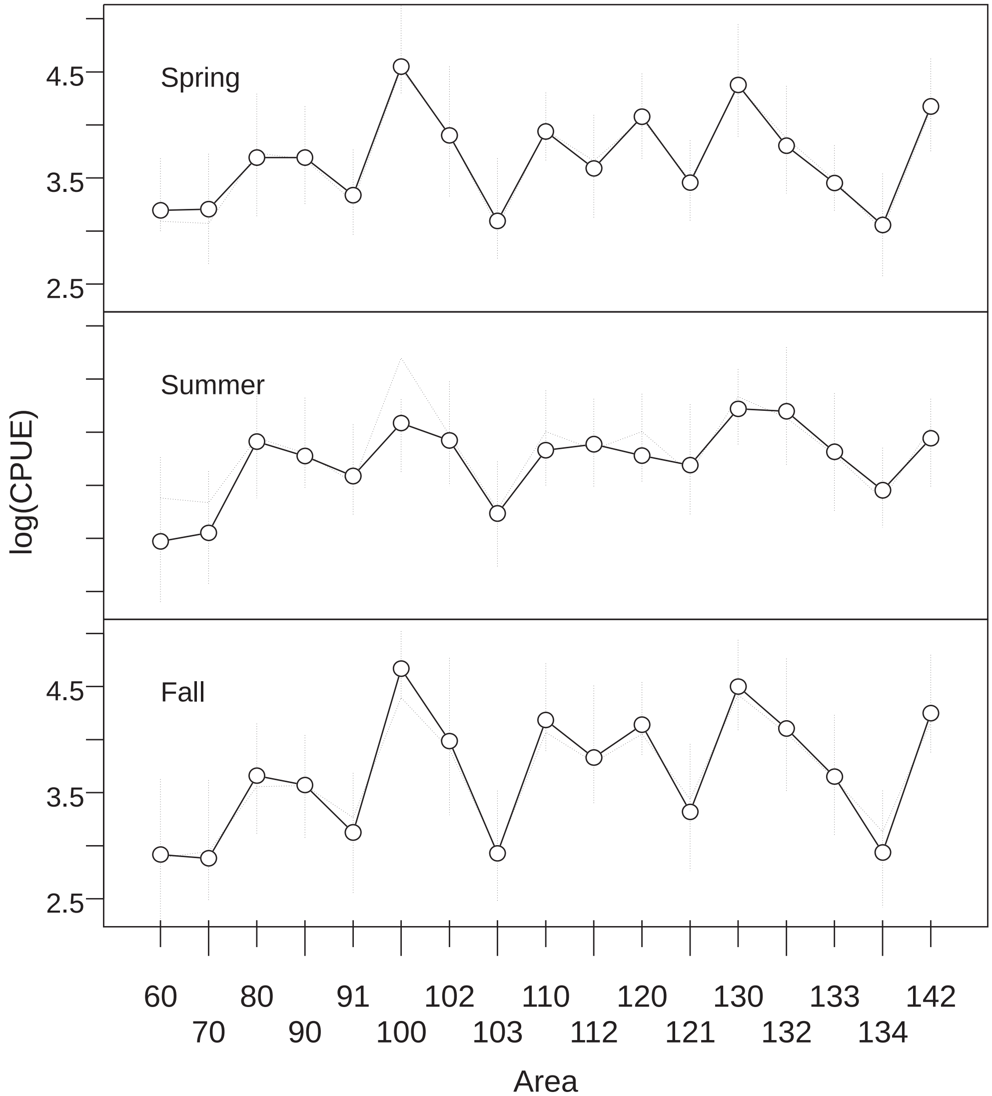



period as indicated by the distribution of effort among vessel classes and gear type, though they exist, are not as striking as those observed by area or season and are consistent with the fleet's static nature under limited entry (Figs. 9 and 10). It is apparent that the fleet is composed of three nearly equal divisions of effort between the larger vessel classes (C–D, E–F, and G–H) and is close to 80% snap-hook gear.

Three interaction terms are associated with vessel size-class. Differences in the mean between the full model and models where the interactions with season, year, and area are removed, though statistically significant, result in deviations of lesser magnitude. Seasonal catch rates by vessel class are relatively flat showing no obvious trends (Fig. 11). The most significant changes associated with the vessel × season interaction occur during the fall and summer for vessel class A–B (37% of the change in residual sum of squares) and during the spring and summer for the largest vessel size-class G–H (30% of the change). However, these result in a difference in nominal CPUE of at most 35% for the A–B class and, at most, 13% for the G–H class. The magnitude of the G–H class change and the level of effort present for the A–B class reduce the significance of any differences occurring here.

Although yearly trends suggesting interaction by vessel class seem strong (Fig. 12), most of this contrast is explained by differences in time and location of fishing as the slight differences between the full and reduced model would indicate. Vessel class G–H, for example, has a 24, 37, and 39% distribution of effort among southern, middle, and northern

**Fig. 8.** Mean log(CPUE) by season for IPHC statistical areas under the full model (circles with solid line) contrasted with model where season × area interaction term is dropped (broken line). Interquartile range of raw data is shown by vertical broken lines.




areas, respectively, while vessel class E–F has a 33, 34, and 33% distribution, respectively. Thus, the larger sized vessel class more strongly follows the increasing CPUE trends observed in the north. Fourteen percent is the maximum difference in catch rate between the full and reduced model for vessel class G–H, with differences generally less than 5% for classes C–D and E–F.

Vessel–area means (Fig. 13) indicate greater area-to-area variability in the catch rate within the A–B size-class and a reduction in catch rate under the full model for the larger sized vessel class G–H in inside waters (i.e., areas 103, 112, 121, 132, 133, and 134). Area 132, in particular, shows the greatest change (15%) in residual sum of squares between the full and reduced model and indicates a 26% decline in CPUE over what one would expect on average for that area. Such differences are not unexpected given the access and maneuverability that vessels of different sizes have in areas with differing degrees of depth and shelter, but to what extent this affects annual trends in abundance is not clear.

The main effect of gear type on catch rate seems to indicate that fixed-hook gear is about 8% more efficient at catching halibut than snap-hook gear in British Columbia after accounting for all remaining factors (Fig. 14). Myhre and Quinn (1984) in their analysis of halibut catch rates within the Canadian commercial fleet noted that fixed-hook gear was about 20% more efficient. The difference in efficiency is apparently related to the manner in which the gear is employed and is not due to the intrinsic nature of the gear itself. The differences in trends that are accounted for by the year × gear interaction seem to occur broadly around the management transition period, do not appear to affect long-term trends, and do not appear to be a consequence of the change in management itself.

## Accounting for effects on abundance indices

Scenario 4, that both the fish and the fishers changed in their distribution over time, seems likely to have occurred. Both the fish and fishers redistributed over season and area. Area had the greatest influence in a practical sense, while the short-term

**Fig. 9.** Pacific halibut commercial effort in percent by vessel size-class by year for size-classes A–B, C–D, E–F, and G–H as shown in Table 1.

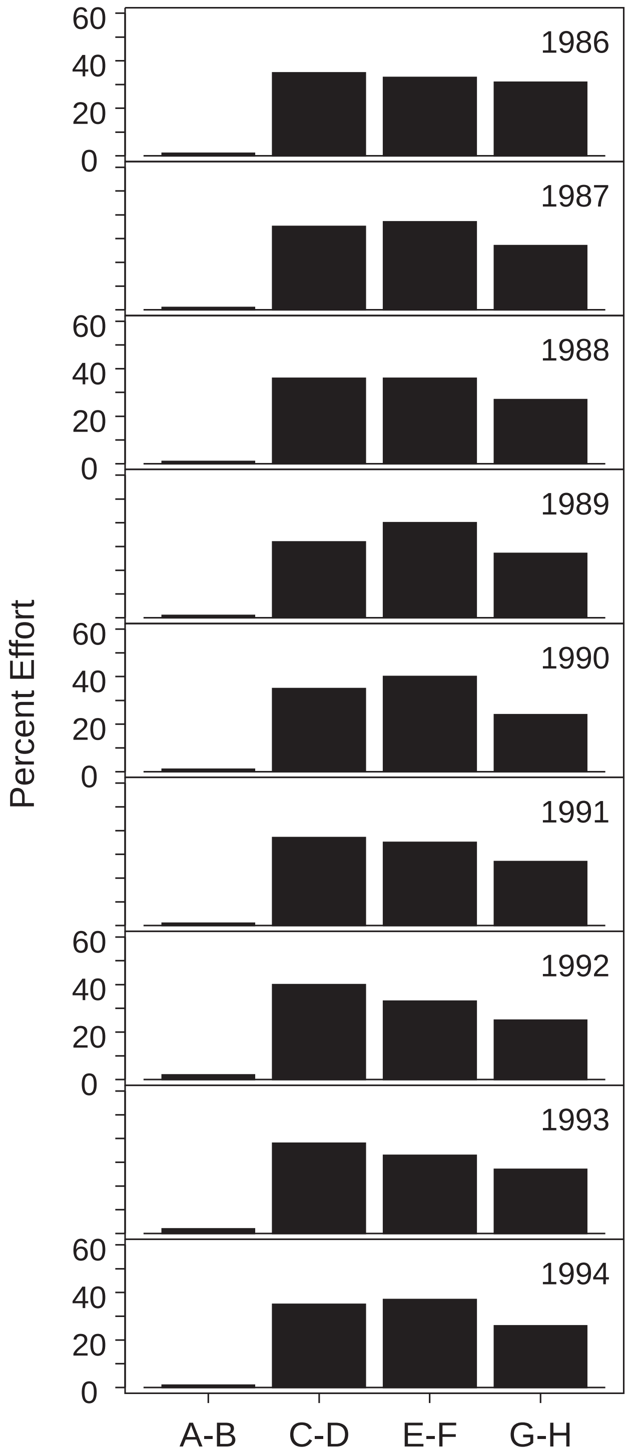
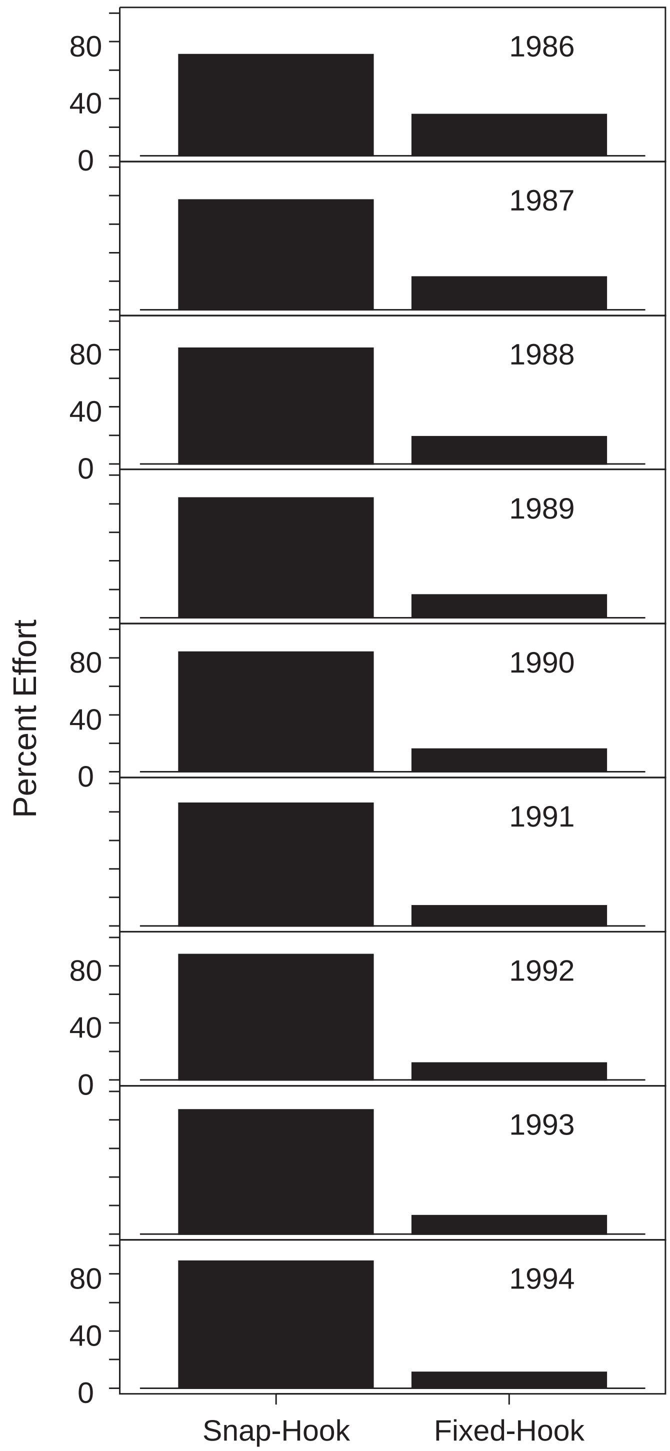



**Fig. 10.** Pacific halibut commercial effort in percent by gear type by year for snap-hook and fixed-hook gear.




and long-term time × area interactions appear to indicate small-scale dynamics of the fish on the grounds.

Vessel size and gear type also influenced CPUE. Their influence, however, did not broadly affect trends in CPUE over the 9-year period of this study nor did changes in the composition of the fleet suggest that they should. Vessel and gear factors should be monitored and accounted for where appropriate, but here we shall address these effects secondarily to the area–season effects.

An alternative estimator is now considered, which accounts for the redistribution of fish and effort by season and area. This alternative differs from those examined by Quinn et al. (1982) in that the seasonal effect is incorporated. We shall assume that all fish are present on the grounds over the length of the fishing period, although they may not have the same distribution by

**Fig. 11.** Mean log(CPUE) by vessel size-class for seasons of spring, summer, and fall under the full model (circles with solid line) contrasted with model where vessel class × season interaction term is dropped (broken line). Interquartile range of raw data is shown with vertical broken lines.

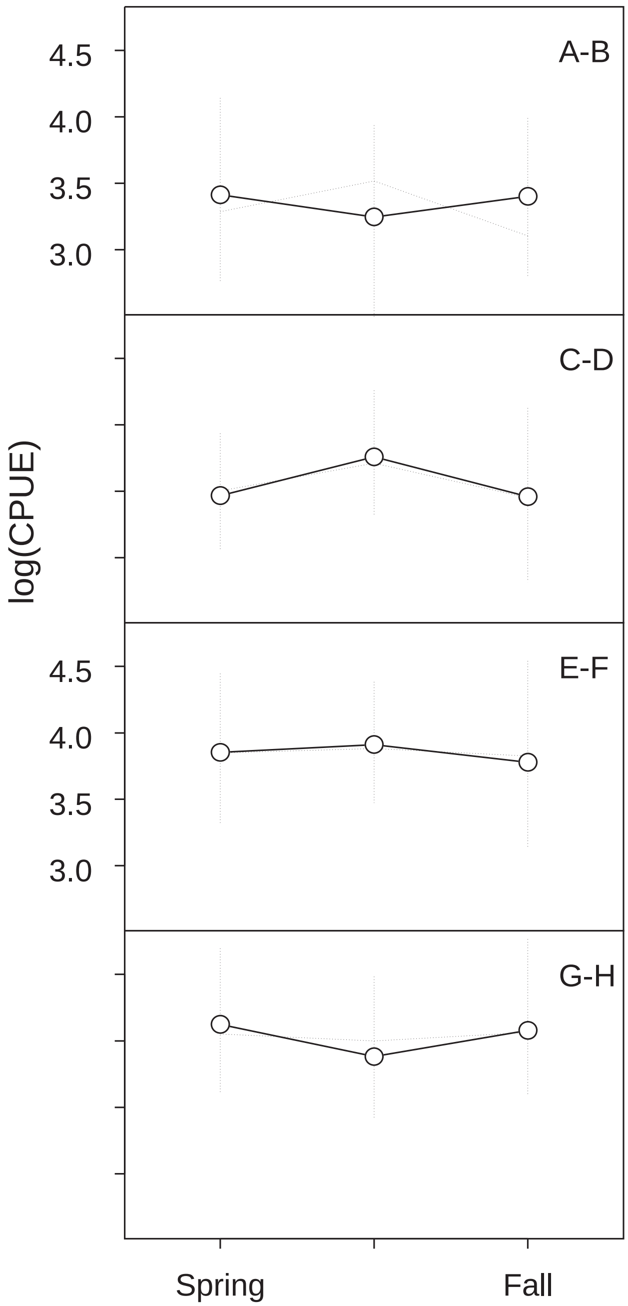
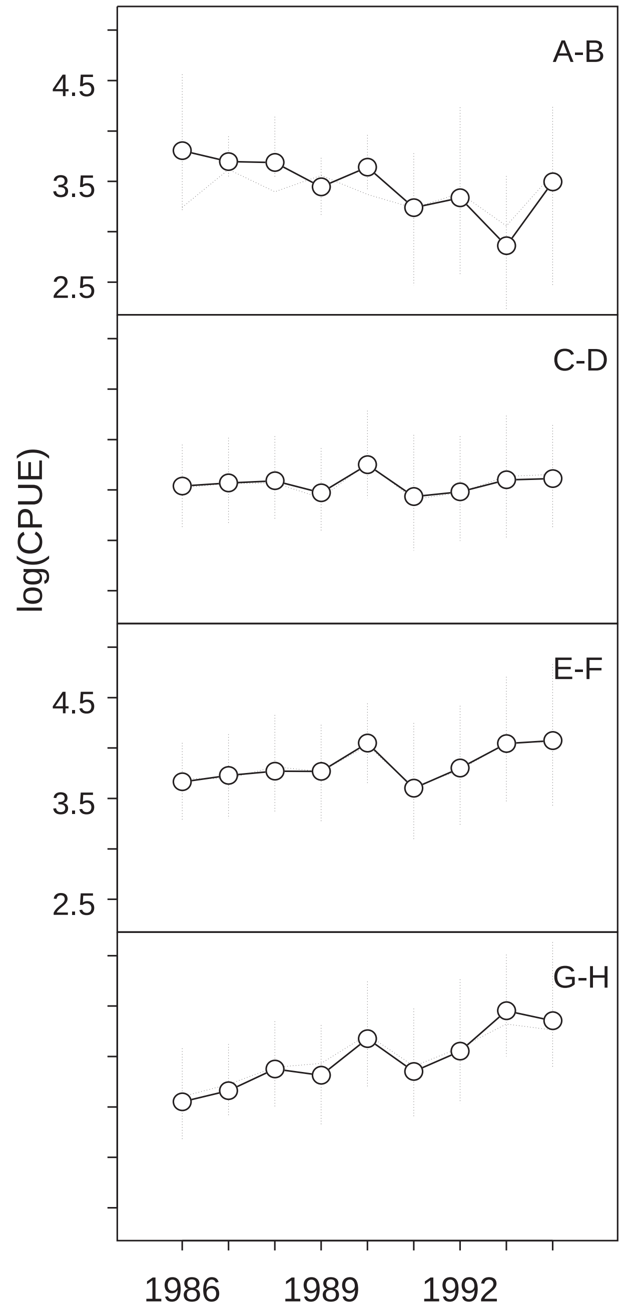


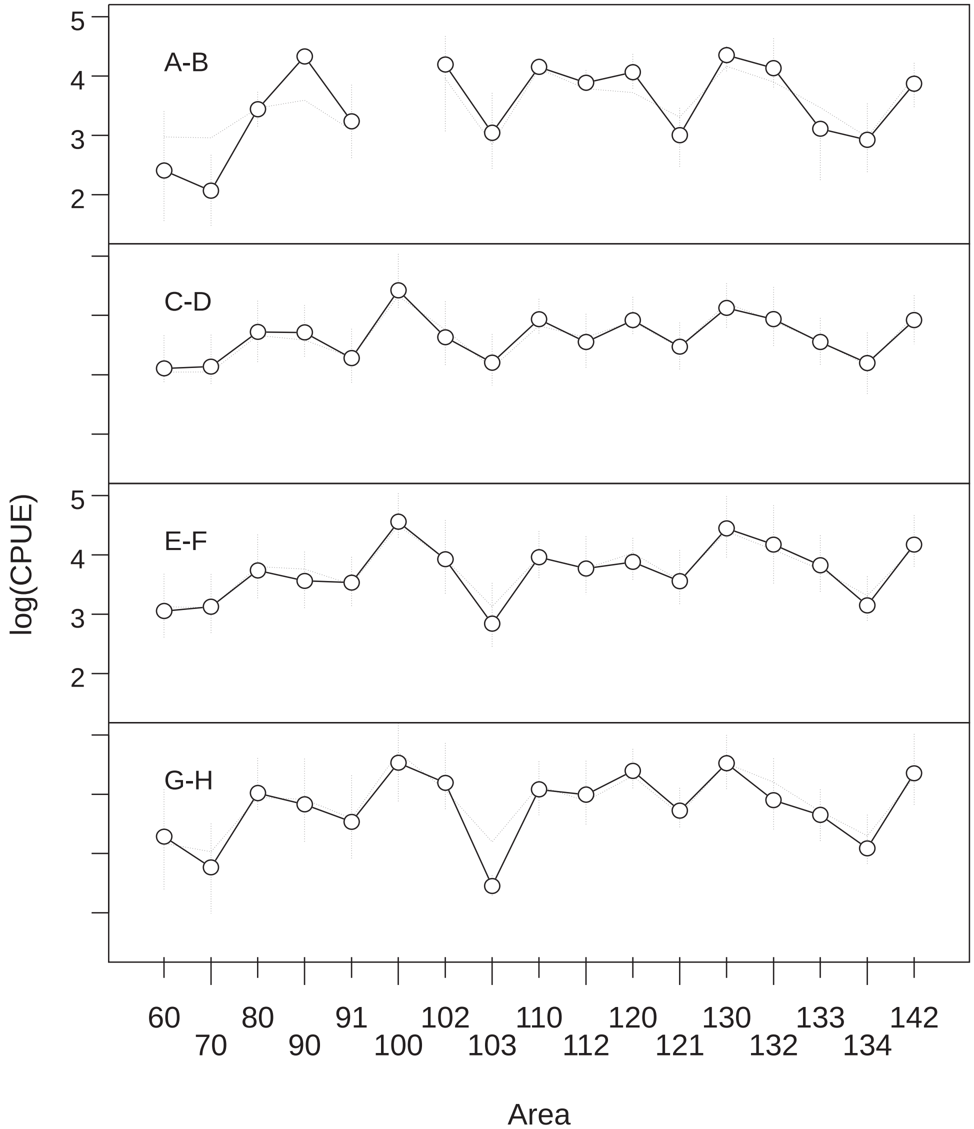

**Fig. 12.** Mean log(CPUE) by vessel size-class for years 1986–1994 under the full model (circles with solid line) contrasted with model where vessel class × year interaction term is dropped (broken line). Interquartile range of raw data is shown with vertical broken lines.




area across seasons. Given the smaller influence the seasonal main effect had on CPUE and the nearly balanced redistribution that occurs in catch rates across areas by season within years (Figs. 4, 6, and 8), it seems that this assumption will be adequate, letting the area main effect and interactions reflect a redistribution of a constant abundance across areas by season within year.

There are several conventional methods for estimating annual stock trends using CPUE statistics. These include simple annual averages, weighted annual averages (weighting by effort or by area), and annual averages derived from coefficients determined through regression or ANOVA. These approaches can be applied to the variable or a transformation of the variable (e.g., log(CPUE)) and can incorporate other kinds of adjustments, as for example, those due to known changes in catchability (Quinn et al. 1985). For Pacific halibut, area-based weighting was compared with effort-based weighting for untransformed CPUE (Quinn et al. 1982). In that study it was found that while area-based weighting is unbiased, effort-based weighting is more precise with minimal bias provided there are no substantial changes in CPUE and effort among

**Fig. 13.** Mean log(CPUE) by vessel size-class for IPHC statistical areas under the full model (circles with solid line) contrasted with model where vessel class × area interaction term is dropped (broken line). Interquartile range of raw data is shown with vertical broken lines.




areas. Regression analysis applied annually to CPUE data might be considered a better approach (Hilborn and Walters 1992) in that the influence of other factors can be regularly and systematically taken into account by incorporating additional variables into the model. However, when interactions occur, as is the case for halibut, regression analysis might be better used to diagnose influential factors, which then can be accounted for prior to computing abundance index estimates.

Because fishing on halibut occurs annually in virtually all areas in British Columbia, area-based weighting schemes are appropriate to consider. Because the fall seasonal effect for the years 1986–1988 is lacking, only spring and summer effects are considered. An equal weighting by season and weighting proportional to bottom area (as a measure of habitat) is applied to log(CPUE) and contrasted with the approach currently employed for Pacific halibut, namely effort weighting of the untransformed CPUEs ($\sum_i E_i \mathrm{CPUE}_i = \sum_i C_i / \sum_i E_i$). Weighting schemes applied to the log(CPUE)s ($\sum_i w_i \ln(\mathrm{CPUE}_i)$, where $\sum_i w_i = 1$) represent geometric means taken on the untransformed CPUEs with exponents equaling the weights ($\prod_i \mathrm{CPUE}_i^{w_i}$). All estimates are given in log units and are normalized to the average of the effort-weighted estimates for comparison of trends. Effort weights change annually and are derived from annual logbook data. Bottom-area weights represent long-term estimates and are fixed over the years examined (Hoag et al. 1997). Bottom area is measured in marine square kilometres from the coastline to a depth of approximately 900 m. Bottom area, interpreted as habitat, measured in this way occupies 50–80% of the measured bottom area in statistical areas 110 and north and occupies 0–50% of the measured bottom area in statistical areas south of 110, indicating a decrease in available habitat moving south.

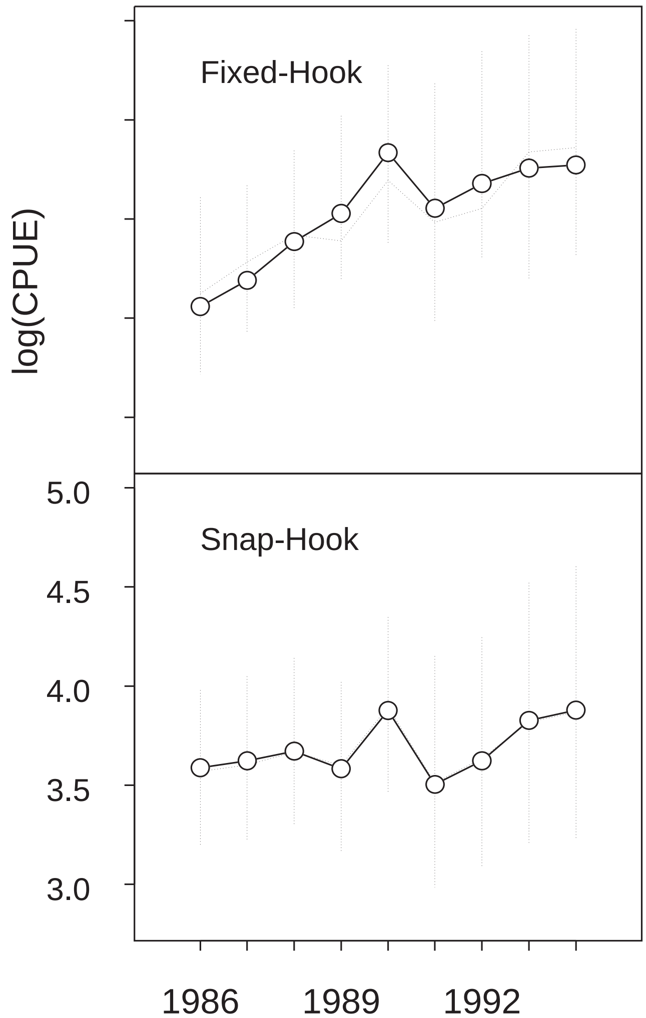
It is assumed that, while all halibut are present on the grounds, they may redistribute by area between seasons. This is why, after area weighting within each season, the seasonal trends are averaged. Here we give equal weighting to the spring and summer observations and exclude the fall observations as there are not enough fall data for years prior to onset of the IVQ. Other unequal but constant weightings might be used, but at present we have no reason to prefer the information gathered in one season over the other. Obviously effort weighting by year cannot be used, as shifts in effort between seasons with differing means (though slight) would lead to erroneous trends in the global indices. Averaging in this way is analogous to treating the seasonal area-weighted trends as independent indexes of abundance.

Effort-weighted estimates increase over time, while area-weighted seasonally adjusted estimates also increase but to a lesser extent (Fig. 15). The effort-weighted CPUE is what is currently used as an indicator of trend in IPHC stock assessments. Here it shows a 0.32 increase in log(CPUE) corresponding to a 38% increase in CPUE estimated for years prior to 1990 relative to years after 1990, whereas the area weighted log(CPUE) estimate shows a 0.15 increase in log(CPUE), corresponding to a 16% increase in CPUE over those same years. The difference in trends in the two commercial CPUE estimators is influenced by both level of effort and amount of habitat by area (Table 6). Despite the increases in effort seen in the southern areas with lower CPUE (IPHC areas 70, 80, and 90), there has been greater increase in effort in the northern offshore areas (IPHC areas 100, 110, 120, and 130), where CPUE is generally the highest and percent habitat is generally greatest. The net effect of the interarea movement of vessels and effort is higher CPUE, although the difference is not as high as might have been expected had the shift to grounds with higher CPUE been greater. The IPHC summer setline survey indices, in contrast, go from 2.93 to 3.77 log(CPUE) (adjusted to mean commercial log(CPUE) in Fig. 15) for an increase of 0.84 in log(CPUE) between the two periods, corresponding to a 132% increase in CPUE. This trend appears sharper but is not significantly different than the one indicated by the log-effort-weighted estimates. Furthermore, the survey may be biased in that it has been conducted only in the northern areas, whereas we have seen in the regression analysis the trends are more sharply increasing. Indeed, when habitat weighting for areas 80 and south are set to zero the seasonally adjusted area-weighted estimates for 1986 and 1993 are within the 95% confidence bounds of the survey estimates (adjusted to mean commerical log(CPUE)). Thus, the surveys as they are currently conducted may be more indicative of dynamics in the north than they are of the entire area.

## Discussion

Any change in management will cause a change (anticipated or not) in fishing behavior and consequently can bring about a change in catch statistics. In 1991, an IQ-management program was implemented on the commercial Pacific halibut fishery in Canada, and a similar program has more recently been implemented in Alaska. Factors critical to the interpretation of Pacific halibut catch statistics include year, area, season, gear type, and vessel size. It is often assumed that, all other factors being equal, annual changes in CPUE should reflect year-to-year changes in abundance. However, standard measures of CPUE (e.g., simple averages or effort-weighted estimates) can be affected by changes in fleet behavior, which interact with factors related to abundance. Further complications arise in the use of these standard measures when the factors interact between themselves and in particular when there is an interaction with year.

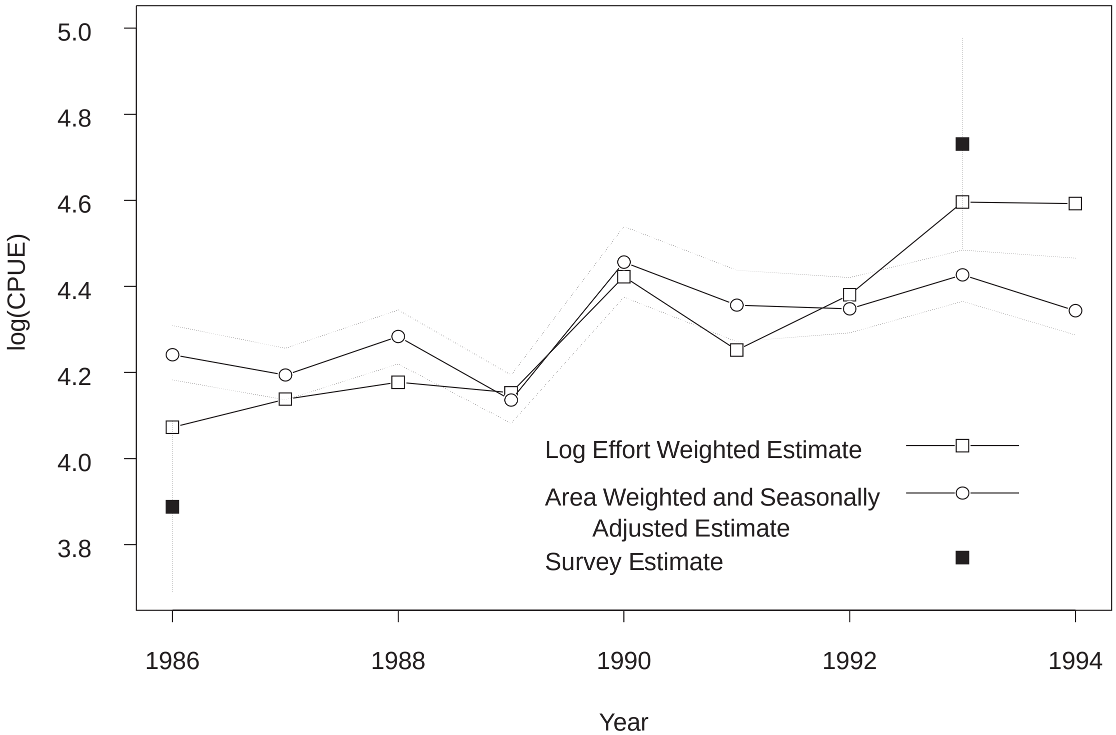
**Fig. 14.** Mean log(CPUE) by gear type for years 1986–1994 under the full model (circles with solid line) contrasted with model where gear type × year interaction term is dropped (broken line). Interquartile range of raw data shown with vertical broken lines.




In the Canadian commercial Pacific halibut fishery there are factors other than global abundance that affect CPUE and interactions exist between these factors. The expansion of time available to fish under the IVQ program has brought about a shift in effort by the fleet to areas of higher CPUE and to areas closer to home port. In addition, halibut distribution on the grounds appears to have changed by season and area.

To address these dynamic changes and their influence on CPUE as an index of abundance, a seasonally adjusted area-weighted estimator was explored. The season–area weighted estimates showed half the increase in relative abundance when compared with the effort-weighted CPUE estimates currently used by IPHC. Area × season interactions, although statistically significant, appeared to represent a redistribution of abundance on the grounds, and so were dealt with using a simple season–area weighting under that assumption. The IPHC scientific setline survey CPUE indices also showed an

**Fig. 15.** Estimated trends in log(CPUE) using different weighting schemes. Solid lines with circles represent seasonally adjusted area-weighted estimates, with 95% bootstrapped confidence intervals represented by broken lines. Log of effort-weighted estimator on the untransformed CPUE variable is shown by the broken line with points indicated by an open square. The 1986 and 1993 IPHC scientific setline survey estimates of log(CPUE) are given by a solid square, with error bars representing 95% confidence intervals.




increase that differed from the proposed abundance index but was not significantly different from the effort-weighted index. It seems that both the survey and the effort-weighted indices overemphasize abundance trends evident in the north and may not adequately reflect abundance trends over the entire area.

Fixed-gear vessels in the British Columbia halibut fleet have, on average, higher catchability than snap-gear vessels. Previous studies show that, while there is no intrinsic difference in fishing efficiency between the two gear types, how they are used may be what influences catchability. The Canadian fleet is made up largely of snap-gear vessels, and this level of use does not appear to be changing at present. In anticipation of such changes, however, it would be appropriate to account for the gear composition of the fleet in a manner similar to that used for the season effect. And, because the year × gear interaction is of lower significance it seems reasonable that the two gear types can be treated as separate indices of abundance (once the season and area effects have been resolved). Pooling the indexes with equal or some other subjective but constant weighting scheme would work as well provided both gear types are present in all time–area cells to be used.

Similar arguments can be used in addressing the vessel size effects. Different trends in catchability appear by vessel size, but the effect can be mostly accounted for by season–area differences in effort distribution, and what cannot be is relatively minor and does not appear to affect long-term trends. Therefore, a season–area based weighting should be adequate here as well, again provided the composition of the fleet does not change dramatically. This last assumption should remain valid in Canada, where entry into the fleet has been limited since 1979, but may not hold true in Alaska where limited entry has only recently been implemented in conjunction with the IQ.

In anticipation of the implementation of a Pacific halibut IQ program in Alaskan waters, several steps were taken to address some of the problems and issues raised in this analysis. Annual scientific setline surveys of halibut grounds in Alaska were proposed for years prior to and after initiating the Alaskan IQ program. This was done in an attempt to gather CPUE information independent of changes in fleet composition or behavior with greater coverage of the grounds both by area and by season. The surveys were expanded to include all areas within a regulatory region so that coverage would be complete and interarea differences within year could be better monitored. Regarding data collected from the commercial fleet, port samplers were asked to take more detailed descriptions of set locations and gear configuration to allow analysis at a finer scale. The individual quota program in Alaska was implemented simultaneously for both Pacific halibut and sablefish (*Anoplopoma fimbria*). Consequently port samplers were asked to determine target species, so that grounds and density differences could be delimited for the two populations while the fleet fished for both.

Given the limits that exist in the resources of time and money and given the complexity of biological systems, it does not seem reasonable to expect that transition periods in nature and in management will always be recognized, tracked, and accounted for. But due consideration should be given to collecting high quality information on a variety of measures that can be used to monitor changes in the system.

## Acknowledgements

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