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CIRCLE HOOK SIZE AND SPACING EFFECTS ON THE CATCH OF PACIFIC HALIBUT

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ABSTRACT

Joint fishing for halibut (*Hippoglossus stenolepis* Schmidt, 1904) and sablefish (*Anoplopoma fimbria* Pallas, 1811) in Alaska in recent years has created questions about the use of fishing effort data in the halibut stock assessment. The optimum gear for halibut uses larger hooks and longer spacing than sablefish gear. We conducted a randomized block fishing experiment to estimate the relative fishing power of different hook sizes and spacings. The blocks consisted of 12 randomized treatments, each a combination of one of four hook sizes and four hook spacings. All possible treatments were not tested because some are not used in the fishery. Each treatment consisted of a single 100-hook skate of gear. Primary response variables were the weight of legal-sized halibut for commercial retention and the count of sub-legal sized fish. The experiment was conducted in a high fish density region in 2005 and in a lower fish density region in 2007. There was no evidence of an interaction effect between hook size and hook spacing in either year, for either legal-sized weight or sub-legal count. Hook size had an effect on sub-legal fish counts in both areas, with highest catches on smaller hooks, but there was evidence of a hook size effect on legal weight in the high density area. Hook spacing had an effect on weights and counts with higher catch seen on the longer spacings.

The catch of longline fishing gear is a function of multiple factors including type of bait, hook size, hook type, and hook spacing (Lokkeborg and Bjorland 1992, Lokkeborg 1994). While the influence of bait and hook types has been investigated (McCracken 1963, Saetersdal 1963, Lokkeborg et al. 1989), there has been relatively little investigation of the effects of hook spacing on catch rates or catch composition of longline gear. Recent changes in the fishery for Pacific halibut (*Hippoglossus stenolepis* Schmidt, 1904) have created the need to examine the potential effects of hook size and spacing on the fishing effort data used in the halibut stock assessment.

The International Pacific Halibut Commission (IPHC) is responsible for research and assessment of the Pacific halibut stocks in the northeast Pacific Ocean. Since the 1920s, the IPHC has applied standardizing factors to merge commercial fishing data in weight per unit effort (WPUE) calculations. A "length-standard" adopted in 1931 defined a unit of fishing gear as 1800 ft (549 m) of groundline, regardless of the number of hooks. This was replaced in 1943 by a "hooks-standard," based on 120-hook units, regardless of hook spacing. The length-standard implied that catch was solely a function of the length of gear fished. The hooks-standard implied that hooks fish independently and the number of hooks alone determined catch. In the 1970s, based on an extensive review in conjunction with experimental fishing conducted using J-hooks (Hamley and Skud 1978), the IPHC adopted a "spacing-standard," which allows for both possibilities, and defines a standard skate of gear as

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an 1800-ft (549 m)[1] skate with 100 #3 hooks. The Hamley-Skud conversion formula, which is still in use, shows catch per hook increasing with hook spacing, with the asymptote (maximum catch per hook, about 1.5× the standard) effectively reached at spacing of around 36–42 ft (10.9–12.5 m). A major change in the halibut fishery occurred in the mid-1980s with the introduction and almost overnight acceptance of the circle hook over the J-hook. This change between hook types was one of the most remarkable changes in fishing gear by an entire fleet ever observed. Changes in fishing technology normally occur over several years or even decades, but the change from J- to circle hooks occurred so rapidly that the IPHC had to conduct comparison fishing between the two hook types very quickly after 1983 to correctly interpret commercial fishery catch and effort data.

Studies in 1984 determined that circle hooks caught 2.2× the weight of fish that J-hooks caught, and this factor was then used to compare J-hook and circle hook catches. The studies also showed that length specific selectivity was also different between the hook types. In contemporary IPHC stock assessments, the effect of the hook change in the commercial fishery was accommodated by utilizing different catchability parameters for pre- and post-1983 periods. A hook spacing study using circle hook gear in IPHC Regulatory Areas 2B and 3A (Fig. 1) was attempted in 1985, but an analysis was never completed. Chen (2005) subsequently analyzed the 1985 hook spacing data, and concluded that while there was a general trend of increasing catch per hook with increasing hook spacing, this effect was not seen in all areas, and the small sample size seriously limited the statistical power of the experiment.

Interestingly, Hamley and Skud (1978) developed their formula in response to a trend toward wider hook spacings in the commercial fishery. Common hook spacings went from 9 ft (2.7 m) in the 1920s, to 13 ft (4.0 m) in the 1930s, and by the late 1950s, the predominant rig was 18-ft (5.5 m) gear. By the 1970s, 21-, 24-, and 26-ft (6.4, 7.3, and 7.9 m, respectively) gear were in use in the commercial fishery. The adoption of individual quota (IQ) management for halibut and sablefish (*Anoplopoma fimbria* Pallas, 1814), together with coincident seasons for these species, has resulted in an increased amount of mixed-target or combination fishing for both halibut and sablefish in Alaska. The optimum gear for the two species is quite different, with sablefish gear using smaller #5 or #6 circle hooks and short 36–48 in (91–122 cm) spacing, while optimum gear for halibut may be larger #3 circle hooks with 15–18 ft (4.6–5.5 m) spacing.

Adjustments are made for hook spacing relative to the standard 1800-ft (549 m) 100-hook skate in IPHC stock assessments. This is also the gear used on IPHC standardized stock assessment surveys, which provide a fishery-independent index of relative abundance. However, the adjustments are based on the relationship derived from the hook-spacing experiments conducted in the 1970s using J-hooks, and no adjustment of WPUE for hook size is made. There is concern that smaller hooks may affect size selectivity, hence WPUE. The increased use of combination gear for sablefish and halibut fishing within the commercial fishery prompted the IPHC to investigate the relationship of catching power and selectivity by these different gear types. Therefore, the IPHC conducted fishing experiments using different combinations of hook sizes and hook spacings during the summers of 2005 and 2007. The

1 The North American halibut fishery is conducted and regulated using English units of measurement. For familiarity to the user community for this fishery, the English units that pertain to regulatory or management features of the fishery are used, with metric equivalents introduced at first usage, and all other non-regulatory units are presented in metric format.

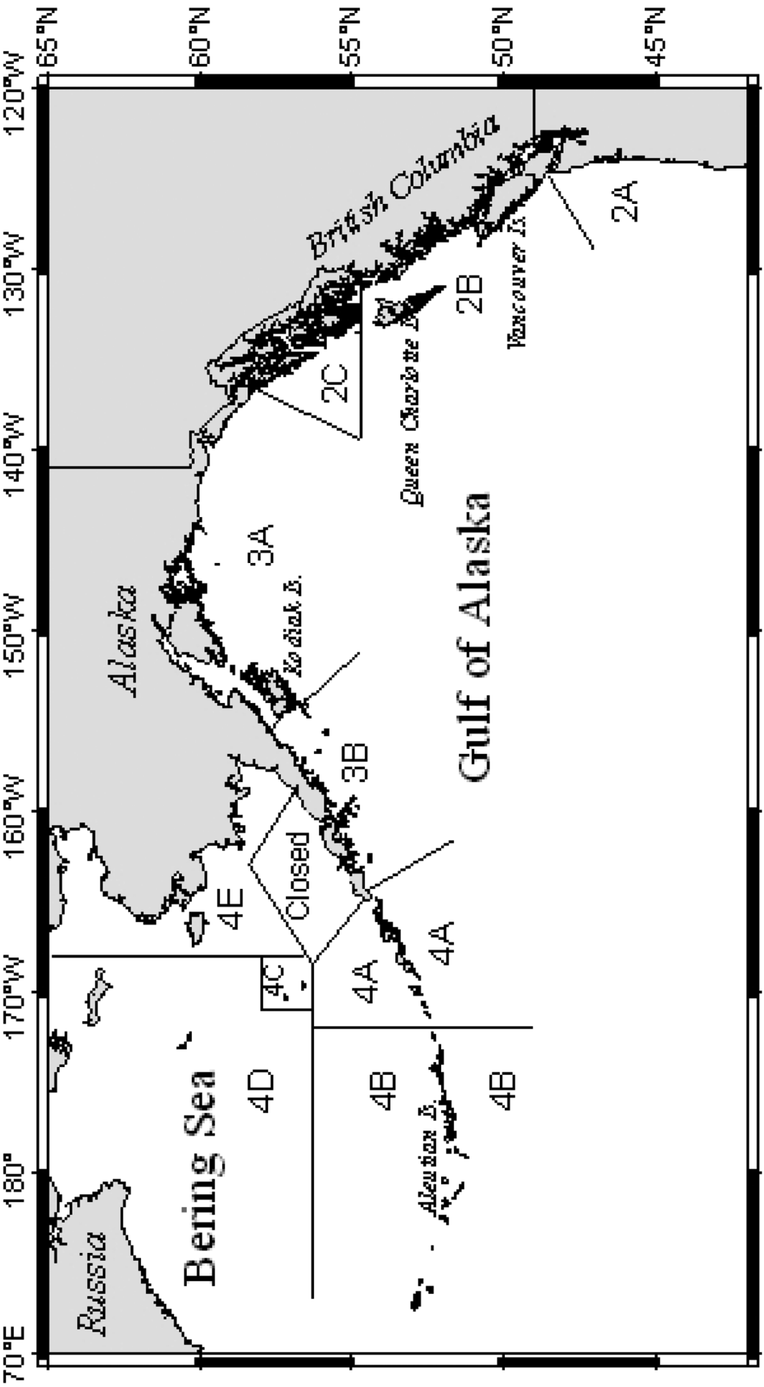

Figure 1. International Pacific Halibut Commission Regulatory areas.

2005 study was conducted in IPHC Regulatory Area 3A (Fig. 1), where halibut densities are relatively high. The 2007 study was conducted in the relatively lower-density IPHC Regulatory Area 2C (Fig. 1). In 2005, the commercial fishery WPUEs were 446 lb (202 kg) per skate and 203 lb (92 kg) per skate in Areas 3A and 2C, respectively.

Methods

Experimental Design.—The experimental design was the same for both experiments, and required the successful hauling of 44 strings of gear. The sample size for the experiment was based on an analysis of 2003 survey data for Areas 3A and 3B. With a significance level of $\alpha = 0.05$ and power of 0.90, a sample size of 480 skates (40 12-skate sets) was required to have a minimum detectable difference of 60 lb (27 kg) per skate. Fishing locations were based around IPHC setline survey grid stations in the experimental areas.

The experiment was a randomized block design, with two factors, hook size and hook spacing. The four levels of hook size were #3 (largest) to #6 (smallest) hooks (alternate designations are hook sizes 16/0–13/0). The four spacing levels were 18, 12, 9, and 3.5 ft (5.5, 3.6, 2.7, and 1.1 m). All possible combinations of hook size and spacing were not fished. While all these hook sizes or spacings are present to some extent in the commercial fishery, almost none of the large-hook gear is fished on short spacings, and likewise almost none of the small hooks are fished on long spacings. The 12 combinations tested in the experiments are shown in Table 1.

For each day's fishing, two strings of 12 100-hook skates were set, with the hook and spacing factors randomized by skate within each string. The order of the skates in each set was determined by reference to a random setting order table. Twelve skates of each gear were included in each string, representing one each of the twelve hook size and spacing combinations. The primary response variables were the catch rate of halibut 32 in (81.3 cm, FL) or larger (O32, legal for commercial retention), expressed as weight per skate (WPUE) and the count of fish <32 in FL (U32) expressed as numbers per skate (NPUE).

Note that the skates were a standard number of hooks rather than a standard length. Therefore, the length of the skates varied from 1800 ft (100 hooks at 18 ft spacing) to 350 ft (100 hooks at 3.5 ft spacing). The length of each string was approximately 12,700 ft (3871 m), about equivalent in length to seven standard IPHC survey skates (1800 ft each). Hook size, spacing, gangion type, and length were constant within a skate, i.e., each of the 12 skates was a unique combination of hook size and spacing, with standard 24-in (61-cm), 60-thread count, hard-lay gangions (after tying) on all gear. The vessel was responsible for construction of the gear and for rigorous gear maintenance before each resetting of the gear. Hook counts were conducted on all gear prior to setting to ensure adherence to the 100-hook per skate specification. Damaged or missing hooks or gangions were replaced prior to setting.

All strings were set in parallel berthings, >1 and <3 nmi apart, in a similar depth stratum. Two 12-skate sets (24 skates total) were made per day and were treated as a single station. Station positions were occupied progressively to avoid depletion issues. Setting began at approximately 5:00 AM local time or at first light each morning. When all strings were set, the vessel returned to the first string and began hauling after the set had been soaking at least 5 hrs. During hauling, all halibut were brought aboard. U32 fish, which were not part of a 10% random sample that were aged, were measured and returned to the water unharmed. All O32 halibut and some bycatch (Pacific cod, *Gadus macrocephalus* Tilesius, 1810 and rockfish, *Sebastes* spp.) caught on all skates were retained and sold to offset charter costs. Experimental response variables for halibut were length on all fish, sex, and maturity on all O32 fish, and a 10% random sample for sex, maturity, and age of U32 fish. All station and fishing data were collected to conform to IPHC assessment survey fishing standards (Clark and Hare 2006).

The 17.7-m F/V Free to Wander was chartered to conduct the experiment in IPHC regulatory Area 3A (central Gulf of Alaska) in July–August 2005 and the 18.3-m F/V Proud Venture was chartered to conduct the hook size and spacing experiment in IPHC regulatory

Table 1. Block design for the hook size and spacing experiments on catch of Pacific halibut.

Hook spacing	Hook size			
	#6	#5	#4	#3
3.5 ft (approximately 1.1 m)	×	×		
9 ft (approximately 2.7 m)	×	×	×	×
12 ft (approximately 3.7 m)	×	×	×	×
18 ft (approximately 5.5 m)			×	×

Area 2C (southeastern Alaska) during July–August 2007. The vessels were supplied with a suggested list of 50 fishing locations, which had survey WPUE averaging in the top 40%–85% in the IPHC Areas in the 3-yr period 2004–2006. The chartered vessel was responsible for completing all experimental sets effectively. Sets were considered effective if the vessel properly set the gear and hauled back within 24 hrs. Situations resulting in the data from a set being deemed ineffective for the experiment and requiring re-setting of the string included loss of function of ≥33% of the total number of hooks for a string. Loss of function could be the result of lost gear, snarls, shark or mammal depredation, or excessive amphipod predation activity.

The fishing gear was provided as half skates coiled in tubs. During setting, a weight of approximately 2.3–4.5 kg was snapped on the groundline at each skate junction. A color coding system was devised to mark each skate end using colored twine to represent both the hook spacing and hook size on that gear. This was combined with a series of plasticized charts, which used both colors and text to specify the randomized order for the day's fishing. All gear was hand-baited with the same bait used in standard IPHC grid charters; frozen chum salmon (*Oncorhynchus keta* Walbaum, 1792), grade number 2 semi-bright, or better. The crews were responsible for cutting the salmon into pieces sized between 0.1 and 0.15 kg for baiting the gear. Bait cutting was monitored by IPHC staff to ensure the bait size was consistent across all gear types.

Catch rates are expressed here as catch per 100-hook skate. The standard measure of catch per unit effort used by the IPHC for both the commercial fishery and IPHC setline survey is catch per standard skate. A standard skate is one hundred #3 (16/0) hooks at 18-ft (5.5 m) spacing. In these experiments, we express catch rate as catch per 100 hooks, although the spacing (hence length of skate) varies among experimental treatments. However, each skate is 100 hooks, providing a consistent metric for comparison.

Data Analysis.—To test for effects of hook size and spacing on halibut catch, we modeled total weight of the catch of O32 halibut and number of U32 fish caught separately for each experiment. Models included hook size and spacing effects, with their interactions, and accounted for the effects of depth (quadratic effect), differences among sets (first blocking variable), and the order of the skates (second blocking variable). Weight data for O32 fish were analyzed by fitting a general linear model using least squares through an analysis of variance (ANOVA), with weight per 100 hooks (skate) square-root transformed prior to analysis to ensure that the assumptions of homogeneity of variance and normality were met. The U32 NPUE data were modelled by fitting a generalized linear model with log link (Poisson regression), with log (number of hooks/100) as an offset term (i.e., count/100 hooks is modelled). *F*-tests that allow for overdispersion in the data were used to test for significant effects on U32 NPUE.

Because some treatment combinations are missing, the tests of hook size and spacing effects depend on the order in which the terms appear in the models. For example, if hook size is added first, we are testing hook size without allowing for the effect of hook spacing, and vice versa. A more appropriate test comes from fitting the model twice, and testing each effect having allowed for the other. For example, if hook size 3 has a lower mean than other sizes, but this size was never used with hook spacing 4, then the mean for hook spacing 4 will appear higher relative to other hook spacing means, because they do include data from hook size 3. Testing hook spacing without accounting for the effect of hook size would be misleading in this case.

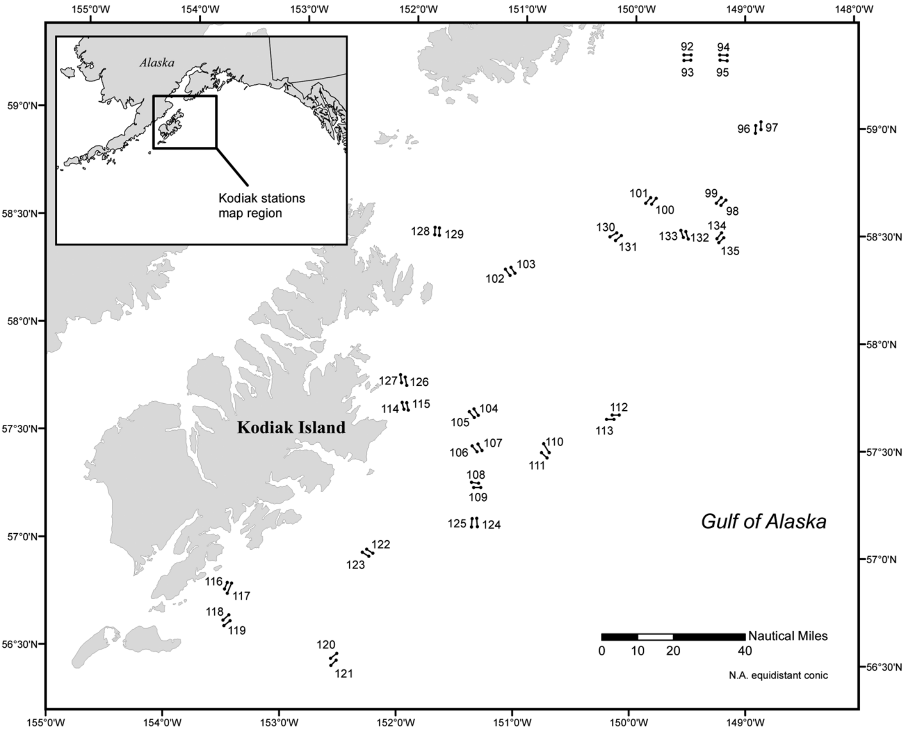

Figure 2. Location of experimental fishing locations in the high halibut density area (International Pacific Halibut Commission Regulatory Area 3A). Numbers indicate set number during the experimental cruises.

Results

For each experiment, 44 sets were successfully completed, involving the occupation of 22 station locations. In the 2005 experiment (Area 3A, high density area, Fig. 2), the gear caught 10,408 O32 halibut, with an estimated weight of 89,023 kg, and 6074 U32 halibut. Mean fishing depth ranged from 64 to 269 m. Eight skates were deemed ineffective due to degree of hook snarls. All other skates were effective. In the 2007 experiment (Area 2C, low density area, Fig. 3), the gear caught 3325 O32 halibut with an estimated weight of 18,579 kg, and 1303 U32 halibut. Mean fishing depth ranged from 69 to 247 m.

For each experiment, data are presented as treatment means (back transformed in the case of O32 WPUE) calculated at the mean depth, for the first skate of the first set. No error bars are presented because due to the blocked design, treatment differences are precisely estimated, but treatment means may not be. The differences between treatment means are of interest here, not the treatment means themselves, and the inclusion of error bars can lead to misleading comparisons of treatments. Instead, tables of treatment differences with standard errors are included to aid in the interpretation of the statistical results.

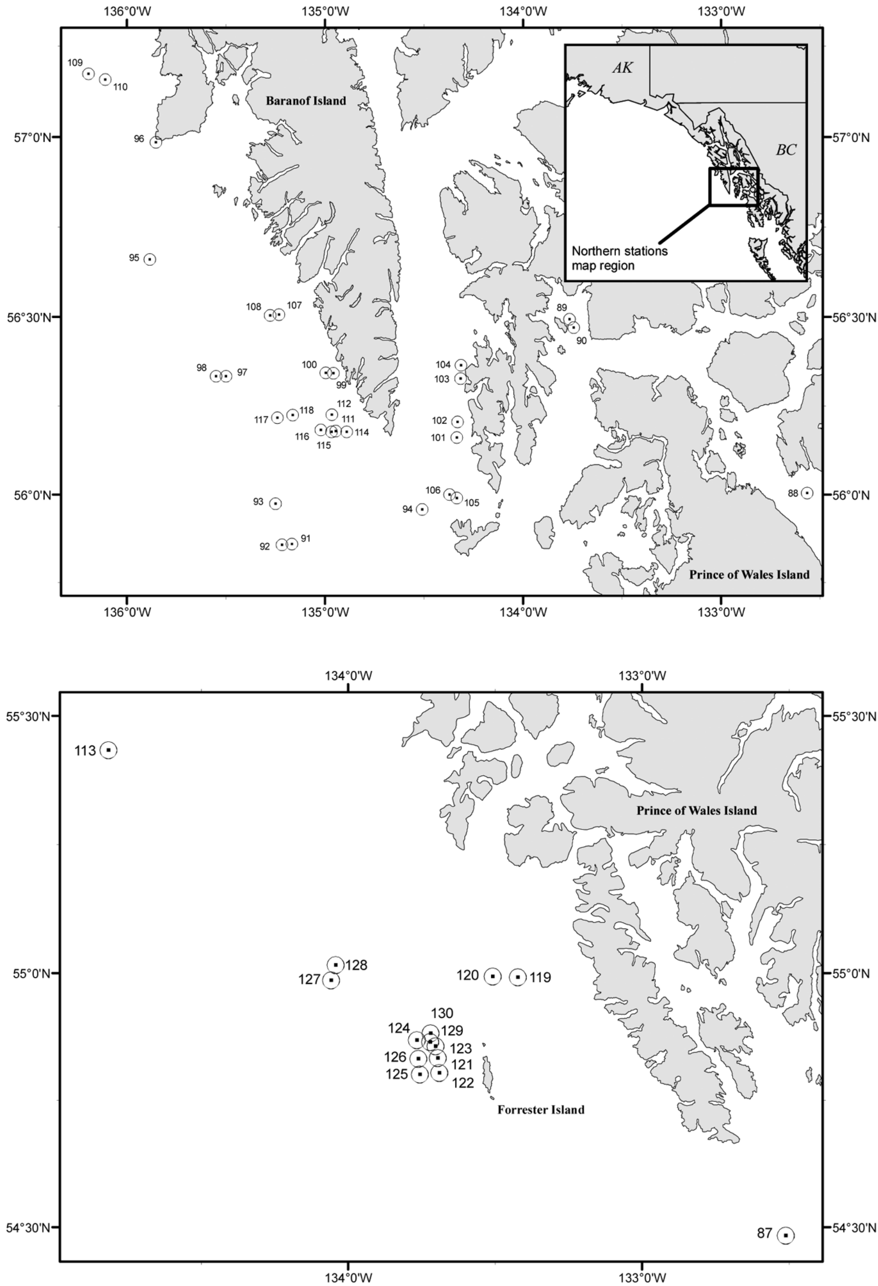

Figure 3. Location of experimental fishing locations in the low halibut density area (International Pacific Halibut Commission Regulatory Area 3A). Numbers indicate set number during the experimental cruises.

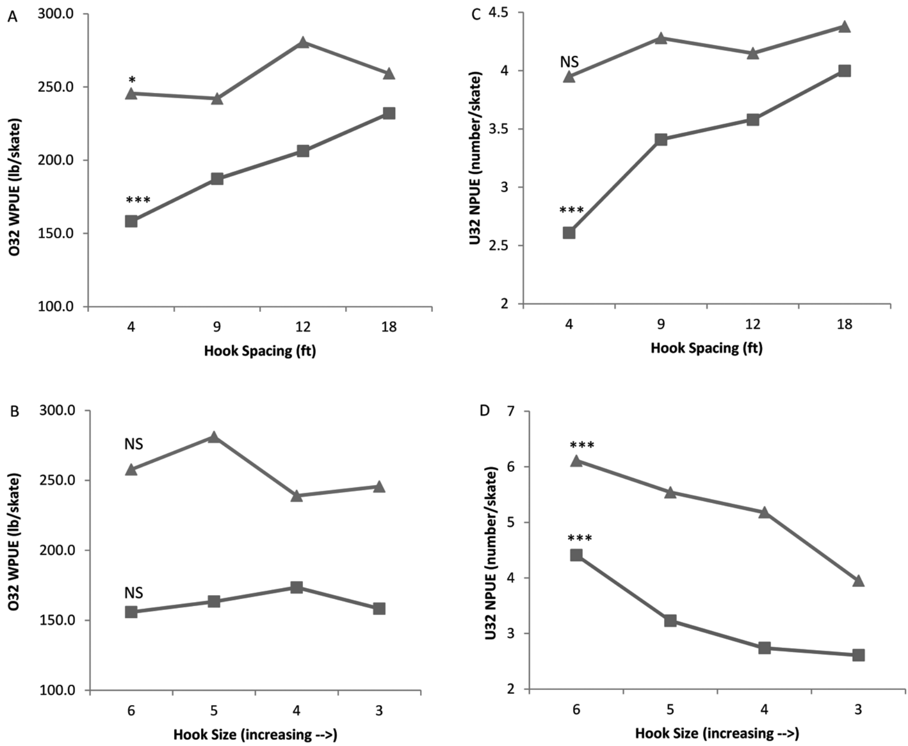

Figure 4. O32 halibut weight per unit effort as a function of (A) hook spacing and (B) hook size. U32 numbers per skate as a function of (C) hook spacing and (D) hook size. Experiments were conducted in low density (■) and high density (▲) areas. * indicates $P < 0.05$, *** indicates $P < 0.001$.

O32 Halibut WPUE, High Density.—There was no evidence of an interaction between hook size and hook spacing ($F_{5,460} = 1.61$, $P = 0.16$), and for simplicity, the remainder of the results come from a model with the interaction omitted (we note that some combinations of factors were missing from the experiment, and for all analyses, the interaction result only applies to those combinations that were included). There was a significant spacing effect ($F_{3,465} = 3.52$, $P = 0.015$) on the O32 WPUE, but the effect of hook size was marginally non-significant ($F_{3,465} = 2.53$, $P = 0.057$; Fig. 4A,B): 12 ft spacing led to higher catches than other spacings, with the lowest catches coming from 4 and 9 ft. Estimated treatment differences (on square root scale) and standard errors are presented in Table 2, and are adjusted for depth, sets, and skates.

O32 Halibut WPUE, Low Density.—As with the high density data, there was no evidence of an interaction between hook size and hook spacing ($F_{5,460} = 0.52$, $P = 0.76$). Hook spacing ($F_{3,465} = 5.73$, $P = 0.001$), but not hook size ($F_{3,465} = 0.79$, $P = 0.50$) significantly influenced catch weight (Fig. 4A,B). Indeed, the effect of hook spacing was strong and linear across the range of spacing treatments: catch was greatest with a spacing of 18 ft, and diminished with decreasing distance between hooks (Table 3, Fig. 4A,B).

Table 2. Estimated treatment differences (standard deviations): O32 weight per unit effort (lb per skate, square root transformed), high halibut density area. The values are a contrast of the treatment in the row with that in the column: a positive number means the row treatment had a higher mean.

Hook size		4	5	6
	3	0.21 (0.45)	–1.10 (0.50)	–0.39 (0.50)
	4		–1.32 (0.50)	–0.61 (0.50)
	5			0.71 (0.45)

Hook spacing		9	12	18
	4	0.11 (0.52)	–1.09 (0.52)	–0.44 (0.67)
	9		–1.20 (0.39)	–0.54 (0.51)
	12			0.65 (0.52)

U32 Halibut NPUE, High Density.—There was no evidence for an interaction between hook size and spacing ($F_{5,460}$ = 1.89, P = 0.095), and the remainder of the results are from models fitted without an interaction term. Catch of U32 halibut did not vary significantly with hook spacing ($F_{3,465}$ = 1.02, P = 0.38), but was significantly influenced by hook size ($F_{3,465}$ = 23.7, P < 0.001; Fig. 4C,D). The tables of treatment comparisons show only small differences among the spacing treatments, but a clear pattern of greater U32 catch with decreasing hook size (Table 4, Fig. 4D).

U32 Halibut NPUE, Low Density.—As with the high density data, there was no evidence for an interaction between hook size and spacing ($F_{5,460}$ = 1.87, P = 0.099). There is strong evidence of both a spacing and hook size effect on catch of U32 halibut ($F_{3,465}$ = 6.64, P < 0.001 and $F_{3,465}$ = 20.09, P < 0.001, respectively; Fig. 4C,D). The tables of treatment comparisons clearly show that in 2007, the catch of U32 halibut increased with both decreasing hook size and increasing hook spacing (Table 5, Fig. 4C,D).

Discussion

Our results show a significant and strong effect of hook spacing for O32 WPUE in both areas and U32 WPUE in the low density area. In contrast, the effect of hook size was much weaker, with no significant effect on O32 WPUE in either area. However, hook size significantly influenced U32 NPUE in both areas. The lower effect of hook

Table 3. Estimated treatment differences (standard deviations): O32 weight per unit effort (lb per skate, square root transformed), low halibut density area. The values are a contrast of the treatment in the row with that in the column: a positive number means the row treatment had a higher mean.

Hook size		4	5	6
	3	–0.60 (0.47)	–0.21 (0.52)	0.09 (0.52)
	4		0.39 (0.52)	0.69 (0.52)
	5			0.30 (0.45)

Hook spacing		9	12	18
	4	–1.12 (0.54)	–1.81 (0.54)	–2.68 (0.71)
	9		–0.69 (0.41)	–1.56 (0.54)
	12			–0.87 (0.54)

Table 4. Estimated treatment differences (standard deviations): U32 numbers per skate, high halibut density area. The values are a contrast of the treatment in the row with that in the column: a positive number means the row treatment had a higher mean.

Hook size	4	5	6
3	–0.27 (0.05)	–0.34 (0.05)	–0.44 (0.05)
4		–0.07 (0.05)	–0.17 (0.05)
5			–0.10 (0.04)

Hook spacing	9	12	18
4	–0.08 (0.05)	–0.05 (0.54)	–0.10 (0.07)
9		0.03 (0.04)	–0.02 (0.05)
12			–0.06 (0.06)

size on O32 WPUE may be related to the standardized bait used in our experiment. The standard baits were larger than would normally be used on the smallest hooks. Johannesson (1983; cited in Lokkeborg and Bjordal 1992) also found that larger baits selected for larger cod, irrespective of hook size.

The much greater effect of hook spacing on both O32 WPUE and U32 NPUE in the low density area merits commentary. The density and amount of baits provided by the experimental skates on the fishing grounds were the same for both experiments. Therefore, the treatment effects can be expected to depend entirely on the conditions in the two areas. The decreased number of baits provided by the larger-spaced skates should result in more competition for available baits, hence larger fish should be caught on skates with larger spacing even if fish densities were the same in each experimental area. Conditions of lower fish density generally imply less productive habitat and more competition. If so, we should expect that the largest fish will be the successful competitors in such environments and that low density environments will have fish of larger average size. Lokkeborg and Bjordal (1992) presented similar views that a more scattered distribution is characteristic of larger fish, larger fish have greater feeding ranges, and the presence of larger fish (cod) reduces the number of smaller fish. Indeed, for our two experimental areas, the mean O32 fish caught in the high density area was 19.1 lb (approximately 8.66 kg), while that in the low density area was 27.0 lb (approximately 12.25 kg). By extension, we should expect that O32 WPUE will increase more with increased hook spacing (greater bait competition yielding larger fish) in low density environments than in high density environments.

Table 5. Estimated treatment differences (standard deviations): U32 numbers per skate, low halibut density area. The values are a contrast of the treatment in the row with that in the column: a positive number means the row treatment had a higher mean.

Hook size	4	5	6
3	–0.05 (0.07)	–0.21 (0.08)	–0.52 (0.07)
4		–0.16 (0.08)	–0.48 (0.08)
5			–0.32 (0.08)

Hook spacing	9	12	18
4	–0.26 (0.08)	–0.31 (0.08)	–0.43 (0.11)
9		–0.05 (0.06)	–0.16 (0.08)
12			–0.11 (0.08)

These results are somewhat reassuring in terms of the current treatment of data from the commercial fishery, when incorporated into the IPHC stock assessment. The current practice is to standardize commercial fishery data to the IPHC standard 100 hook skate with 18-ft spacing, but to make no corrections for hook size variation. With no evidence of a hook size effect on O32 catch, our results indicate that relative abundance estimates from the commercial fishery have little or no bias as a result of variation in hook sizes.

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