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[Article]

Evaluation of a Selective Flatfish Trawl and Diel Variation in Rockfish Catchability as Bycatch Reduction Tools in the Deepwater Complex Fishery off the U.S. West Coast

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Abstract.—We tested the potential of a selective flatfish trawl to reduce bycatch of slope rockfish in the upper continental slope bottom-trawl fishery (250–500 m) on the U.S. West Coast. The trawl we tested differed from typical slope trawls in that it was a low-rise, two-seam trawl with a severely cut back headrope. We used an alternate haul, randomized block design to compare catches of the experimental trawl with those of a typical four-seam, high-rise trawl and to examine diel changes in catch rates for both trawls. The experimental trawl produced catches similar to the control trawl for all commercially valuable flatfish, except arrowtooth flounder *Atheresthes stomias*, which was reduced 24%. Catches of most rockfish and roundfish were significantly reduced in the experimental trawl (50–94% depending on species). However, the catches of darkblotched rockfish *Sebastes crameri* and redbanded rockfish *S. babcocki* were not reduced significantly in the experimental trawl. Nighttime catches were reduced 30–99% for most rockfish species, the greatest reductions occurring in the experimental trawl. The large nighttime catch reduction for several rockfish species for both trawls along with no catch reduction in Dover sole *Microstomus pacificus*, suggests that fishing only at night may be a viable bycatch-reduction strategy for some rockfish species. The diel and depth-related variation in catch rates we noted for the selective flatfish trawl indicates that catches by this trawl may be especially sensitive to physical and environmental factors such as time of day, depth, or turbidity.

The U.S. West Coast bottom-trawl fishery on the upper continental slope targets sablefish *Anoplopoma fimbria*, Dover sole *Microstomus pacificus*, and shortspine thornyhead *Sebastolobus alascanus* and, at greater depths, longspine thornyhead *Sebastolobus altivelis*. This group of species is also known as the ''deepwater complex.'' In recent years, this fishery has been allowed to operate only in areas deeper than about 275–366 m because of concerns about bycatch of two overfished rockfish species, darkblotched rockfish *Sebastes crameri* and Pacific ocean perch *Sebastes alutus* (PFMC 2002; the fishing area boundaries vary seasonally). Given the depth distributions of these two rockfishes, the depth restriction should be very effective at limiting bycatch. Longer term however, the concentration of deepwater-complex fishing effort in deeper areas could lead to serious bycatch problems with other species. For example, concentrating the fishery deeper than 366 m will probably increase impacts on aurora rockfish *Sebastes aurora* and rougheye rockfish *Sebastes aleutianus*, species for which stock status is unknown (PFMC 2002). Given the low productivity of rockfishes (Clark 2002; Ralston 2002), a better solution for the deepwater-complex fishery might be to develop gears that do not efficiently capture slope rockfish species.

Comparative fishing experiments on the U.S. West Coast continental shelf have shown that the bycatch of some overfished rockfish species, notably canary rockfish *Sebastes pinniger*, can be reduced with the use of a selective flatfish trawl (King et al. 2004). The trawl tested by King et al. (2004) incorporated very low total rise and a severely cut back headrope, similar to a trawl developed in the Faroe Islands by Thomsen (1993). The bycatch for some larger species of rockfish and roundfish in this trawl was 70–90% less than in traditional trawls (i.e., less or greater percentages in this paper = the tested value minus the comparison base value/the comparison base value). The experimental results of King et al. (2004) were also verified under actual commercial fishing conditions through a large-scale exempted fishing permit fishery, demonstrating similar levels of bycatch reduction (Parker et al. 2004). As a result beginning in 2005, selective flatfish trawls are required for all trawling shallower than 183 m off Oregon and Washington. The potential for selec-

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tive trawls to reduce bycatch of bocaccio *Sebastes paucispinis* is also being tested in waters off California.

West Coast tests of selective flatfish trawls have been primarily conducted in waters shallower than 200 m. Several important slope rockfish species are primarily found deeper than 200 m. Therefore, the available data do not provide information on species such as Pacific ocean perch, yellowmouth rockfish *Sebastes reedi*, aurora, or rougheye and darkblotched rockfishes. The primary objective of this research was to test a selective flatfish trawl at the depths fished by the deepwater-complex fishery to determine if it could be effective at reducing slope rockfish bycatch.

A secondary objective of this project was to estimate the reduction in catch of shortspine thornyheads using the experimental trawl in the slope fishery. The shortspine thornyhead is not a highly productive species, based on life history characteristics and recent population trends (PFMC 2002; Ralston 2002). King et al. (2004) found the catch of large ($\geq$26 cm) shortspine thornyheads on the continental shelf to be 34% less with a selective flatfish trawl than the traditional trawl. However, as for slope rockfish, the study did not sample at the optimal depths for shortspine thornyheads. Any noted reduction in shortspine thornyhead catch in the deepwater-complex fishery should be evaluated because it could provide a useful management tool if the shortspine thornyhead stock becomes constrained or needs additional protection.

Lastly, several studies have shown dramatic changes in catchability of fishes between day and night (Casey and Myers 1998; Petrakis et al. 2001). On the west coast, the vertical distribution of widow rockfish *Sebastes entomelas* is known to change on a diel basis (Gunderson 1984). However, little is known about diel changes in vertical distribution or catchability of exploited slope species. Diel changes in catchability for darkblotched rockfish and other species could potentially be used as a bycatch management tool.

Methods

The experimental trawl design we tested has been described previously by King et al. (2004). Briefly, the trawl has a very low-rise, two-seam design, and rather than incorporating a typical ''square'' or hood, it utilizes a severely cut-back headrope to allow fish that rise to escape (Figure 1). By design, the trawl also lacks floats along the central 50% of the 40.3-m headrope to reduce visual stimuli that could cause fish to dive into the trawl. Our trawl differed from that tested by King et al. (2004) only in that it employed a rock-hopper style footrope that better matched the footropes used in the deepwater fishery. The configuration consisted of a 31.2-m chain footrope covered with rubber disks 17.8 cm in diameter, which were interspaced with single rubber disks (35.6 cm in diameter) at 58.4-cm intervals along the length of the footrope. Another chain, called the rockhopper chain, ran through the outer edge of the large disks and was covered by rubber disks 12.7-cm in diameter. A chain fishing line was attached to the rock-hopper chain with shackles spaced at 51 cm. The netting of the trawl was attached to a rope bolsh line, which was lashed to the chain fishing line. The sweeps (mud gear) between the trawl doors and the trawl bridles consisted of 110 m of 1.5-cm cable covered with 7.5-cm rubber disks. The trawl doors were 1.5 $\times$ 2.1 m AMCO V-type steel doors and were used for both trawls.

The control trawl chosen for this experiment was a typical four-seam Aberdeen trawl designed for a much higher overall rise than the experimental trawl (Figure 2). This trawl had a footrope length of 32 m and a headrope length of 27 m, creating the typical square or overhanging hood. The control trawl had no netting in the forward part of the lower wing, creating an open space above the footrope ends, also known as a flying wing. This common feature of trawls used on the continental slope is designed to reduce damage to the net's lower wing on rough substrates. The portion of the footrope beneath the space in the lower wing panel was covered with cylindrical rubber bobbins approximately 28 cm long and 18 cm in diameter. Otherwise, the footrope configuration and sweep dimensions for the control trawl matched the experimental trawl.

We used an alternate haul, randomized block design (Burridge and Robins 2000). Alternate haul experiments often require a large number of hauls to detect moderate effects, so this experiment was divided into two stages, each consisting of several multiday cruises (June and August 2003). For the first portion of the experiment, a single-factor experimental design was employed, with trawl type randomized within blocks. For this stage of the study, all hauls were conducted during daylight hours. For the second stage, we added a second factor to investigate the effect of diel changes in trawl catchability. The four hauls within each block were randomized with respect to trawl type and night versus day. Daytime hauls occurred from

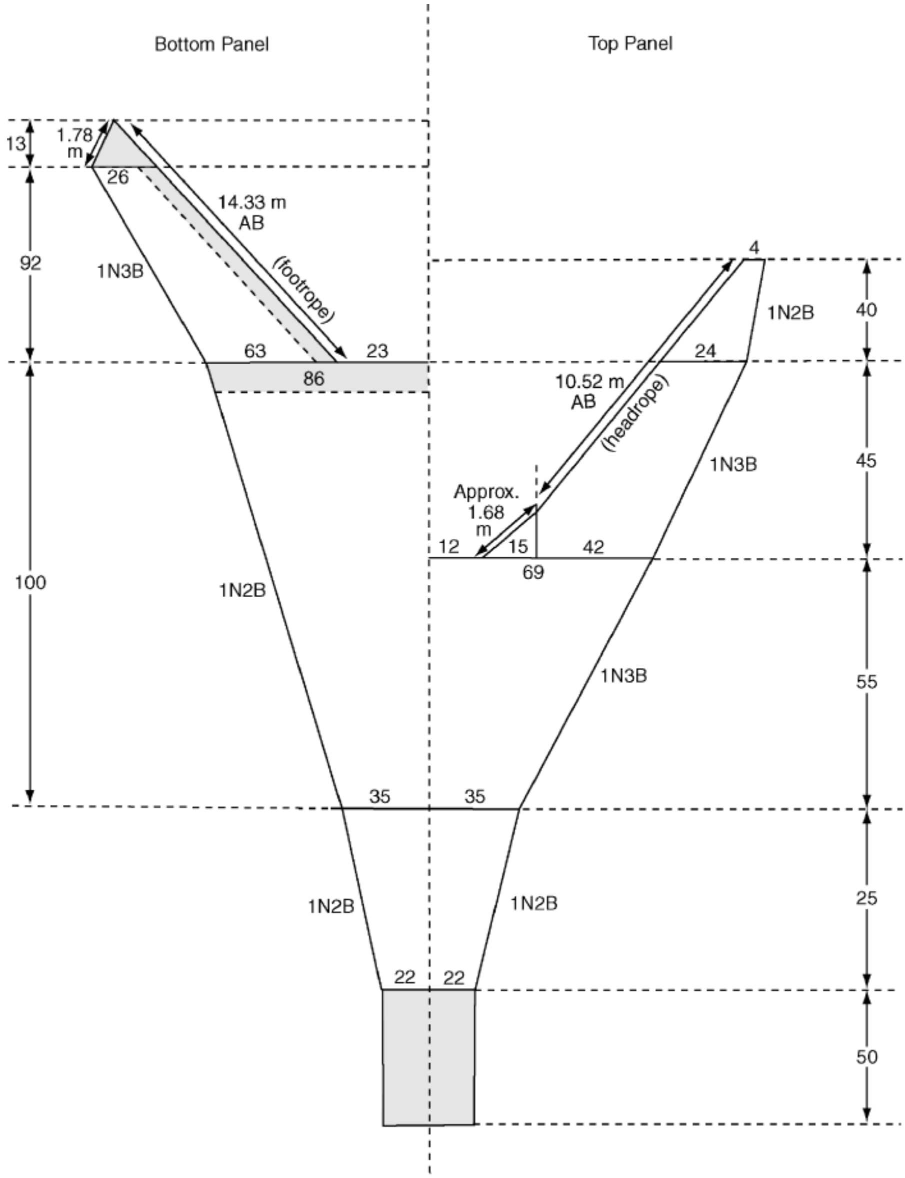

FIGURE 1.—Schematic of an experimental flatfish trawl, a two-seam Eastern 400 low-rise trawl with a cutback headrope (no hood), tested against a traditional (control) trawl (shown in Figure 2) used in the U.S. West Coast bottom-trawl fishery on the upper continental slope. Between-knot mesh size was 140 mm, except in the cod end where it was 114 mm. Mesh counts for panel widths and depths are shown. Double-mesh panels are in gray; all other mesh is single twine. Tapered panels show the ratio of bar cuts (B) to point cuts (N), as described by Motte (1980).

0900 to 1600 hours; nighttime hauls occurred from 2100 to 0400 hours. These hours precluded sampling during low-light conditions of dawn and dusk (sunrise being at about 0620 hours and sunset at about 2020 hours). For both portions of the experiment, the 30-min tows for each block were first planned on a map, such that the distance between hauls was less than about 400 m, and then, treatments were assigned randomly (Figure 3). Paired daytime or nighttime hauls were always conducted sequentially and blocks were always completed within a single 24-h period.

We chartered the fishing vessel *Persistence* out of Newport, Oregon, to conduct this experiment.

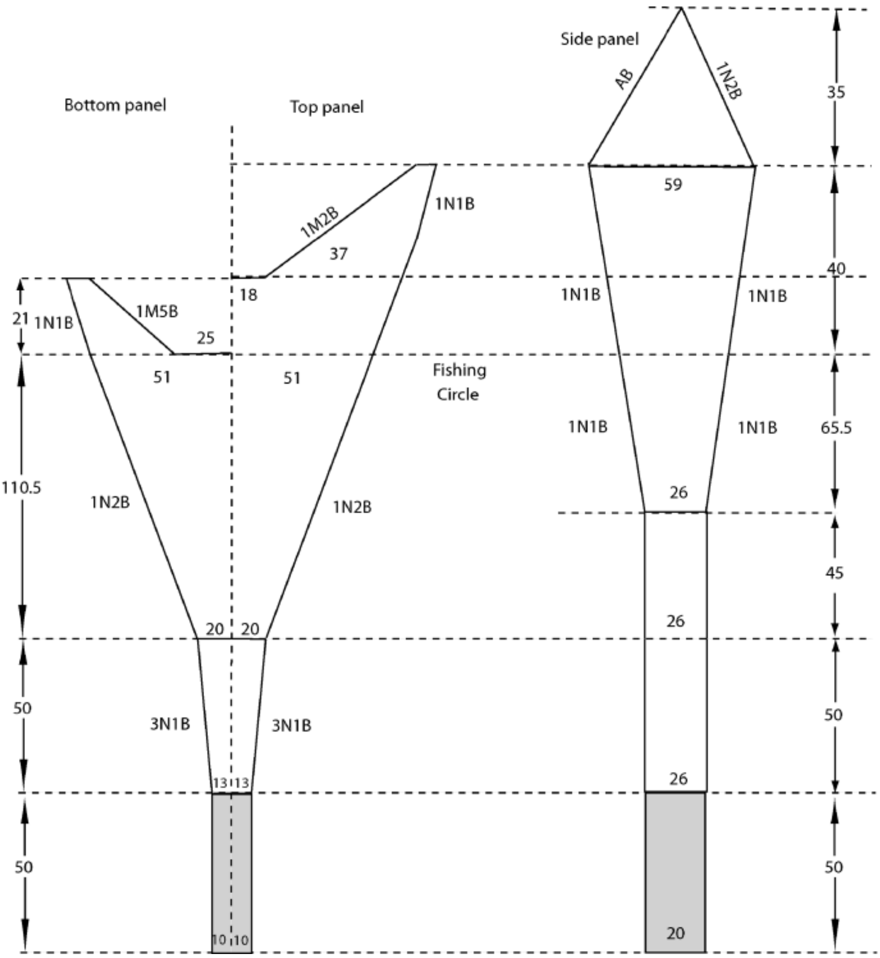

FIGURE 2.—Schematic of a traditional (control) trawl, a modified four-seam Aberdeen high-rise combination trawl with an overhanging ''square'' or hood, used in the U.S. West Coast bottom-trawl fishery on the upper continental slope. Between-knot mesh size was 203 mm forward of the fishing circle and 140 mm elsewhere. Mesh counts (c) for panel widths and depths are shown. Double-mesh panels are in gray; all other mesh is single twine. Tapered panels show the ratio of bar cuts (B) to either point cuts (N) or mesh cuts (M), as described by Motte (1980).

The *Persistence* is a steel-hulled boat having an overall length of 23.2 m, a 625-hp engine, and twin net reels. Trawl configuration was measured for both trawls using a SIMRAD ITI acoustic trawl mensuration system. The rise of the headrope at the center and the distance between the wingtips was measured for both trawls. Stability, uniform bottom contact, and correct trawl configuration were confirmed using underwater video before commencing experimental tows. A recording inclinometer (also called a bottom contact sensor) was attached to the centerline mesh just behind the footrope to measure the actual time on bottom (TOB) for each haul.

For each haul, total count and weight (kg) by species were recorded. Lingcod *Ophiodon elongatus* were counted, weighed, and immediately released. Pacific halibut *Hippoglossus stenolepis* were measured (cm, total length) and released; their weights were obtained from a length–weight conversion chart. Because a complete census of fish lengths for every tow was not practical, individual lengths for the most common species were subsampled from each haul to examine any difference in trawl selectivity; rockfish were also separated into large (≥26 cm; marketable) and small (<26 cm; (unmarketable) categories before weighing.

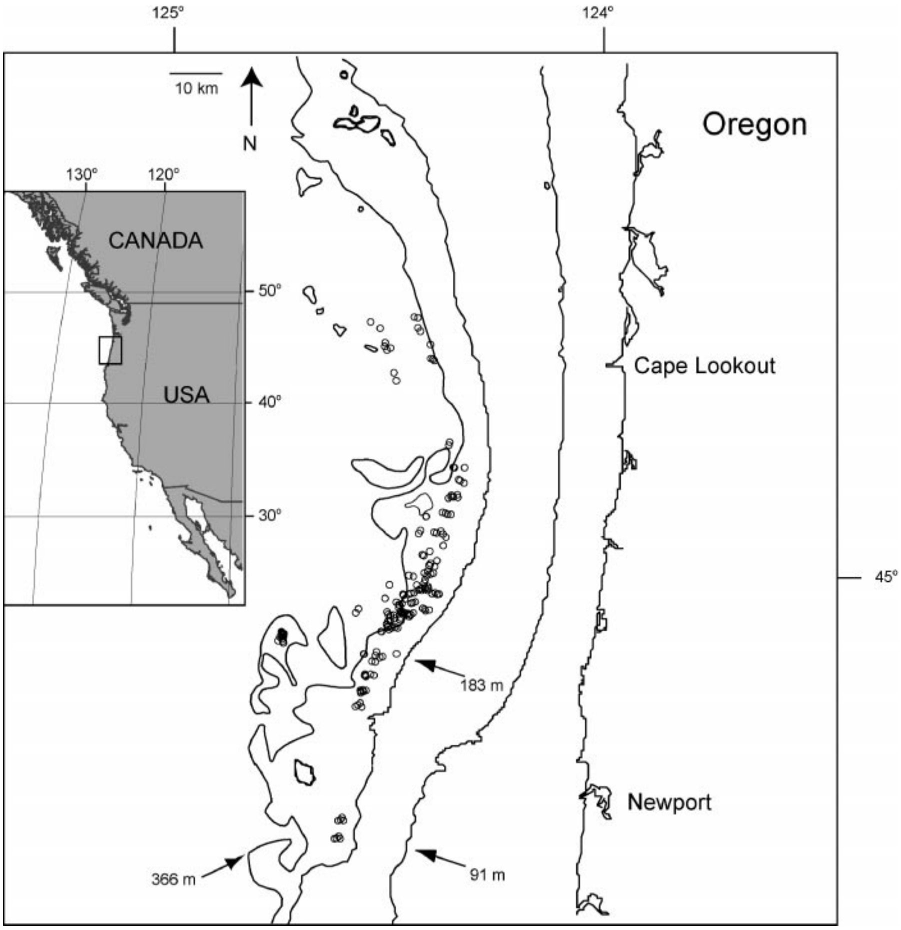

FIGURE 3.—Haul locations along the Oregon coast where a conventional slope trawl was compared with an experimental trawl in 2003; depths ranged from 225 to 443 m.

Catch for each haul was standardized to a haul duration of 30 min TOB. Daytime catches were then compared using the nonparametric Wilcoxon's signed rank test. A nonparametric test was selected because of the high frequency of zero catches encountered for some species. Although some parametric methods can be used to analyze these data, the results are more difficult to interpret and often still do not meet parametric assumptions. We chose nonparametric techniques in all cases, except for those requiring a two-factor test; for those we used an analysis of variance (ANOVA) on log-transformed data for species that were captured in all hauls. We estimated the percent reduction in catch in the experimental trawl using the ratio of means approach (Ye 2002). No correction was made for differences in swept area or volume for the two trawls because, although of similar size, their shapes were so different that swept area or volume was not a particularly useful concept, especially for such a range of species types (King et al. 2004).

Although we did not anticipate a depth effect a priori, we looked for changes in performance of the experimental trawl by comparing daytime mean catch rates of both trawls over the range of depths fished. We divided the daytime catch data into three depth bins that provided roughly equal numbers of hauls per bin: 225–291, 292–347, and 348–443 m. For species that occurred in all of the hauls (no zero tows), we then conducted a two-factor ANOVA on log-transformed catch data to test for the significance of depth effects and trawl–depth interactions.

To compare day and night catches, we used the Wilcoxon's signed rank test for paired tows, and analyzed the data from the experimental and control trawls separately. These comparisons included

TABLE 1.—Comparison of trawl mensuration data for control (standard) and experimental trawls tested on the U.S. West Coast continental slope. Tow duration is the time the footrope was in contact with the sea floor.

Trawl variable	Control		Experimental	
	Mean	SE	Mean	SE
Tow duration (min:s)	36:07	0.002	38:03	0.02
Headrope height (m)	4.5	0.601	1.3	0.119
Wing spread (m)	20.2	0.606	20.8	0.764

a relatively small number of tows, so we limited the analysis to commonly occurring species (present in five or more hauls). With small sample sizes, the statistical power of this analysis was very limited. Only strong effects were likely to be detected, and negative findings were not considered very meaningful.

Length data collected from daytime hauls were analyzed using the nonparametric Mann–Whitney *U*-test to examine differences in mean length between the control and experimental trawls. This nonparametric test was used to address the nonnormality of multimodal length data.

Results

Field sampling resulted in 74 successful blocks comparing the experimental and control trawls during daylight hours, a total of 148 hauls. An additional 32 hauls were completed at night. Combining these with the corresponding daytime hauls resulted in 16 blocks, or 64 hauls (32 for each trawl) comparing daytime and nighttime catches. The depths fished ranged from 225 to 443 m for the daytime hauls, and 225 to 320 m for the day–night comparison hauls.

Mensuration gear documented a large difference in headrope height between the experimental and control trawls, the headrope of the control trawl running 4.5 m off-bottom versus 1.3 m for the experimental trawl (Table 1). Wing spread of the two trawls was similar (20 m); however, the very different shape of the two trawls makes this comparison not particularly meaningful. The low-rise nature of the experimental trawl required a spread measurement be taken very close to the sea floor, whereas the flying wing employed in the control trawl required that the measurement be taken from the upper wing or several meters above the bottom. The TOB data showed that both trawls were on bottom about 6–8 min longer than the target tow time of 30 min and that the experimental trawl had a higher mean TOB than the control trawl (about 2.0 min longer; Table 1). Underwater video observations showed no obvious problems in the shape or stability of either trawl.

Catch

Control and experimental trawl catches for commercially valuable flatfish such as Dover sole, petrale sole *Eopsetta jordani*, and rex sole *Glyptocephalus zachirus* were similar (Table 2, $P > 0.05$). Given the low statistical power in alternate haul experiments, this is probably best interpreted as an indication that any difference in catch for these species is probably of small magnitude. Two notable exceptions were arrowtooth flounder and Pacific halibut, which were 24% and 46% less, respectively, in the experimental trawl. In contrast, the catch of slender sole, a small flatfish that is generally not marketable, was 89% greater in the experimental trawl (Table 2, $P < 0.001$). Catches of sablefish and large shortspine thornyheads, the other two primary target species of the deepwater-complex fishery, were both about 50% less in the experimental trawl ($P < 0.001$), but the catch of small shortspine thornyheads was similar for both trawls ($P > 0.05$).

Differences in the catch of slope rockfish species in the selective flatfish trawl were highly species-specific and size-specific. Catches of rougheye and aurora rockfish, large Pacific ocean perch, and splitnose rockfish were 57–94% less in the experimental trawl (Table 2). Catch of yellowmouth rockfish and large sharpchin rockfish were much less in the experimental trawl, but the differences were not statistically significant, suggestive of a lack of statistical power for fish that occurred in just a few hauls (<12 blocks). Significant differences in catch were not found for large darkblotched rockfish, redbanded rockfish, or large rosethorn rockfish. Because darkblotched rockfish were caught in 59 blocks and redbanded rockfish in 56 blocks, it's unlikely that these two species escape from the experimental trawl in significant numbers. Most of the smaller, bottom-oriented rockfish showed no significant difference in catch between the two trawls ($P > 0.05$). Notable exceptions included small splitnose rockfish, which were reduced 36% in the experimental trawl, and small rosethorn rockfish and greenstriped rockfish, which increased 85% and 106%, respectively. Most of the other fish species encountered did not show significant differences in catch between the two trawls. Exceptions were Pacific hake and sandpaper skate, which were reduced 86% and 35%, respectively, in the experimental trawl.

TABLE 2.—Comparison of mean catch (kg/haul) between the experimental trawl and control trawl using Wilcoxon's signed rank test. Species were captured off the Oregon coast in 148 paired daytime tows during summer months in 2003. Percent difference is the experimental trawl catch minus the control trawl divided by the control trawl (×100). The sample size, *N*, refers to the total number of blocks in which the species was captured in at least one haul.

Species	Mean catch (SE)		Percent difference		
	Control	Experimental	(+ or −)	*P*-value	*N*
Flatfish					
Dover sole	35.61 (3.34)	36.73 (3.36)	+3	0.6145	74
Slender sole *Lyopsetta exilis*	0.16 (0.03)	0.30 (0.06)	+89	0.0005	67
Arrowtooth flounder	57.58 (6.74)	43.72 (5.70)	−24	0.0001	74
Petrale sole	0.82 (0.29)	0.57 (0.17)	−31	0.5699	22
Rex sole	7.25 (1.12)	8.19 (1.42)	+13	0.9890	73
Pacific halibut	26.33 (13.04)	14.22 (9.67)	−46	0.0016	16
Roundfish and rockfish					
Pacific hake *Merluccius productus*	25.74 (3.57)	3.57 (0.11)	−86	0.0001	69
Sablefish	81.28 (8.26)	40.68 (5.79)	−50	0.0001	74
Lingcod	0.85 (0.32)	1.01 (0.45)	+19	0.7938	20
Rougheye rockfish	2.86 (0.86)	1.24 (0.41)	−57	0.0247	36
Shortspine thornyhead					
Large (≥26 cm)	16.49 (1.97)	7.94 (1.14)	−52	0.0001	74
Small (<26 cm)	7.98 (0.75)	7.68 (0.76)	−4	0.7814	74
Rosethorn rockfish *Sebastes helvomaculatus*					
Large (≥26 cm)	0.75 (0.26)	1.39 (0.53)	+85	0.1354	19
Small (<26 cm)	0.10 (0.04)	0.19 (0.07)	+85	0.0076	15
Splitnose rockfish *Sebastes diploproa*					
Large (≥26 cm)	1.15 (0.40)	0.20 (0.07)	−83	0.0001	42
Small (<26 cm)	5.15 (1.47)	3.28 (1.43)	−36	0.0001	60
Aurora rockfish	0.43 (0.27)	0.03 (0.02)	−92	0.0180	7
Greenstriped rockfish *Sebastes elongatus*	0.17 (0.09)	0.35 (0.19)	+106	0.0146	15
Darkblotched rockfish					
Large (≥26 cm)	6.18 (1.60)	6.49 (1.58)	+5	0.5973	59
Small (<26 cm)	0.50 (0.14)	0.66 (0.24)	+31	0.7935	32
Sharpchin rockfish *Sebastes zacentrus*					
Large (≥26 cm)	4.70 (1.95)	1.24 (0.60)	−74	0.0995	12
Small (<26 cm)	0.52 (0.28)	0.18 (0.07)	−65	0.3329	10
Redbanded rockfish *Sebastes babcocki*					
Large (≥26 cm)	0.87 (0.13)	0.69 (0.13)	−20	0.3524	56
Small (<26 cm)	0.12 (0.02)	0.10 (0.02)	−13	0.4645	42
Pacific ocean perch					
Large (≥26 cm)	15.42 (5.66)	0.89 (0.21)	−94	0.0001	50
Small (<26 cm)	0.09 (0.04)	0.01 (0.02)	−93	0.4631	17
Yellowmouth rockfish	2.27 (1.41)	0.15 (0.06)	−93	0.1614	8
Other fish					
Longnose skate *Raja rhina*	15.31 (3.34)	16.40 (3.63)	+7	0.8883	64
Sandpaper skate *Bathyraja interrupta*	2.53 (0.38)	1.65 (0.25)	−35	0.0372	58
Spotted ratfish *Hydrolagus colliei*	1.52 (0.24)	1.86 (0.33)	+22	0.2608	50
Bigfin eelpout *Aprodon cortezianus*	0.42 (0.05)	0.59 (0.08)	+41	0.0657	61
Spiny dogfish *Squalus acanthias*	1.26 (0.29)	1.26 (0.37)	0	0.7115	38

TABLE 3.—Comparison of mean lengths by species between daytime control and experimental trawls on the U.S. West Coast continental slope in 2003. Samples size, *N*, refers to the total number of each species that was measured during the daytime experiment in both trawls.

Species	Mean length (cm)		Mann–Whitney *U*-test	
	Control	Experimental	*P*-value	*N*
Flatfish				
Dover sole	38.0	38.3	0.4644	3,000
Arrowtooth flounder	43.0	41.9	0.3148	2,560
Rex sole	30.2	30.5	0.0065	2,778
Pacific halibut	108.4	107.2	0.9784	198
Roundfish and rockfish				
Sablefish	54.1	52.6	0.0001	3,166
Rougheye rockfish	46.5	44.8	0.2126	214
Shortspine thornyhead	25.7	24.1	0.0001	7,230
Rosethorn rockfish	27.3	27.2	0.8995	337
Splitnose rockfish	21.9	20.5	0.0001	1,704
Darkblotched rockfish	29.0	28.4	0.0062	1,509
Sharpchin rockfish	29.0	27.6	0.0001	700
Redbanded rockfish	29.0	28.7	0.9761	326
Pacific ocean perch	36.0	32.6	0.0001	730
Yellowmouth rockfish	44.9	44.3	0.2951	115

Length

A comparison of daytime mean lengths between trawls showed no meaningful differences in average size for flatfish (Table 3). For rockfish and roundfish, numerous species differed significantly in mean length between the two trawls, larger fish being caught in the control trawl. The largest mean differences were observed for Pacific ocean perch (3.4 cm), shortspine thornyheads (1.6 cm), splitnose rockfish (1.4 cm), sharpchin rockfish (1.4 cm), and sablefish (1.5 cm).

Depth

Dover soles, arrowtooth flounder, sablefish, and large and small shortspine thornyheads were captured in all daytime blocks, facilitating statistical analysis of trawl–depth interactions. Trawl-depth interactions were statistically significant ($P < 0.05$) only for sablefish and shortspine thornyheads (Figure 4). All of the trawl–depth interactions indicated that the experimental trawl became relatively less effective at capturing these species as depth increased beyond about 347 m.

Diel Effects

Analysis of the performance of the two trawls showed that all of the statistically significant differences ($P < 0.05$) involved reductions in night catches for both trawls (Tables 4, 5), but the reduction for the experimental trawl was much greater for most species. The reductions in flatfish catch at night with the selective flatfish trawl were large: Dover sole (47% less), arrowtooth flounder (79%). and rex sole (90%). The control trawl showed smaller nighttime reductions in catch rate for flatfish, ranging from 0% for Dover sole, to 28% for rex sole, 45% for arrowtooth flounder, and up to 57% for slender sole.

Rockfish catch reductions at night were dramatic for the experimental trawl, ranging from 90% for darkblotched rockfish ($P < 0.01$) up to 100% for redbanded rockfish ($P < 0.05$) and Pacific ocean perch ($P < 0.05$). For the control trawl, the reductions in rockfish catches at night were more modest, ranging from no significant difference for redbanded rockfish and Pacific ocean perch ($P > 0.05$) up to 92% for small splitnose rockfish ($P < 0.01$). Notably, catch rates for small and large darkblotched rockfish were both reduced 86% at night in the control trawl ($P < 0.05$).

Reductions in nighttime catch rates for sablefish (79% less) and shortspine thornyheads (90–91%) were of similar magnitude and were much smaller in the control trawl (Tables 4, 5). Other species encountered, including Pacific hake and lingcod, generally followed the same pattern, except for longnose skates and sandpaper skates, which showed no significant differences ($P > 0.05$) between daytime and nighttime catches in either trawl.

Only minor changes in mean length (<1 cm) were observed between day and night tows, except for two species. Pacific ocean perch were 5.3 cm larger in night control trawl catches (Mann–Whitney *U*-test, $P < 0.05$, $N = 26$). Rex sole were 1.5 cm larger in the experimental trawl ($P < 0.01$,

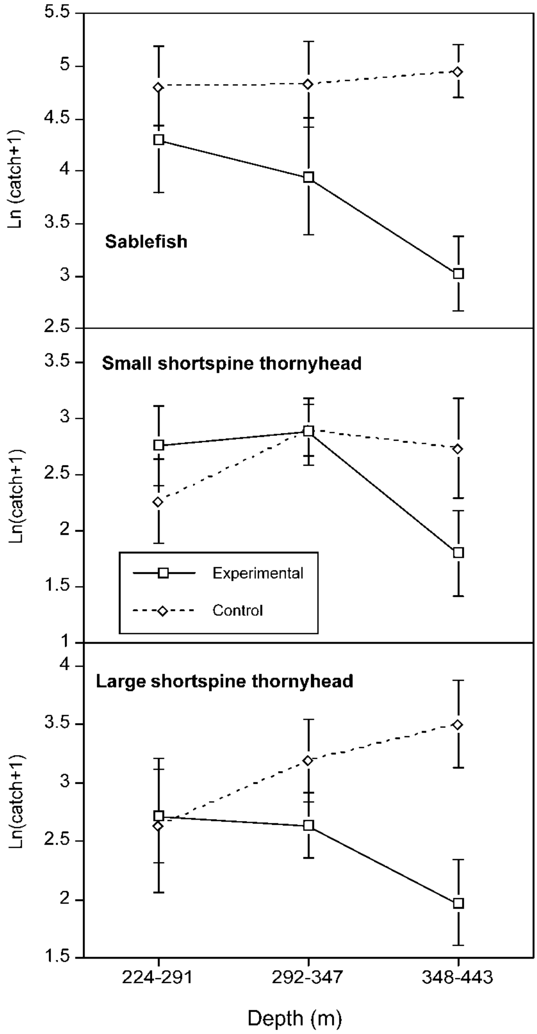

FIGURE 4.—Log$_e$ mean catch rates by trawl and depth bin, for sablefish and large (≥26 cm) and small (<26 cm) shortspine thornyheads taken in trawls on U.S. West Coast upper continental slope in 2003.

$N = 438$) and 0.91 cm larger in the control trawl at night ($P < 0.001$, $N = 756$).

Discussion

The experimental trawl was effective at reducing catches of slope rockfish species that were similar in size and ecology to those escaping in the shelf experiment (King et al. 2004), with the notable exception of darkblotched and redbanded rockfish. The large reduction in catch of Pacific ocean perch, Pacific hake, rougheye rockfish, aurora rockfish, and splitnose rockfish, along with no reduction in catch for most flatfish species supports the idea that group- and species-specific behaviors can be utilized to change relative selectivities in mixed-species fisheries. If scalable, the results also suggest that the selective flatfish trawl might be useful in reducing bycatch of these slope rockfish species in the deepwater complex fishery, but not without some impact on the catch rates for some target species, and not without major reductions in nighttime catch efficiency.

The findings of this study were generally consistent with data from the previous tests of the selective flatfish trawl on the continental shelf (King et al. 2004; Parker et al. 2004). Those studies showed that catches of flatfish, skates, lingcod and small rockfish were maintained in the selective flatfish trawl, while less demersal rockfish escaped the trawl readily, as did Pacific hake, large shortspine thornyheads and Pacific halibut. A few species were present at the depths sampled in both experiments. One seeming discrepancy between the results of this study and those of King et al. (2004) is the reduction in sablefish catch we observed on the slope, while sablefish catch increased with the selective trawl in the shelf experiment. However, in King et al. (2004) the control trawl used had a much shorter footrope than the selective flatfish trawl (20 m for control, versus 31.2 m for experimental), which was not corrected for using swept area. The wider spread may account for the higher catch of sablefish. In this experiment, the footropes were similar in length, and the reduction in sablefish catch in the selective flatfish trawl is a composite of low escapement at shallow depths and greater escapement as depth increased (Figure 4). Additionally, the sablefish captured in this study were larger than those encountered in the shelf experiment; an average length of 54 cm versus 48–49 cm in the shelf tests (King et al. 2004). Larger fish have better chances of escaping a low-rise, cut-back trawl because of superior swimming abilities (Wardle 1975; He 1993).

The selective flatfish trawl altered the catch ratios of the principal target species toward lower catches of shortspine thornyhead and sablefish in relation to Dover sole. The trawl also became less effective for sablefish and shortspine thornyheads as depth increased. If use of this trawl were limited to depths outside normal darkblotched rockfish habitat, our data suggest an operator could use the selective flatfish trawl to manipulate the relative catches of Dover sole, shortspine thornyheads and sablefish to match landing limits by targeting different depths. However this increased control over

TABLE 4.—Comparison of mean experimental trawl catch (kg/haul) between daytime and nighttime hauls, using a Wilcoxon's signed rank test, after adjustment for trawl time on bottom. Species were captured off the Oregon coast in 32 paired tows during summer months in 2003. Percent change is the night catch minus the daytime catch divided by the daytime catch (×100). The sample size, *N*, refers to the total number of blocks in which the species was captured in either daytime or nighttime hauls.

Species	Mean catch (SE) Night	Mean catch (SE) Day	Percent difference (+ or −)	*P*-value	*N*
Flatfish					
Dover sole	34.38 (5.07)	64.78 (8.11)	−47	0.0011	16
Slender sole	0.05 (0.02)	0.38 (0.16)	−87	0.0258	14
Arrowtooth flounder	15.18 (2.21)	70.91 (14.43)	−79	0.0005	16
Petrale sole	0.30 (0.18)	0.66 (0.23)	−54	0.0687	8
Rex sole	0.49 (0.15)	4.74 (1.30)	−90	0.0013	16
Pacific halibut	2.48 (0.92)	1.67 (1.42)	+48	0.3105	7
Roundfish and rockfish					
Pacific hake	0.05 (0.05)	0.57 (0.19)	−91	0.0180	7
Sablefish	9.20 (1.60)	43.21 (9.96)	−79	0.0011	16
Lingcod	1.34 (0.75)	4.23 (1.92)	−68	0.0284	9
Rougheye rockfish	0.03 (0.03)	0.35 (0.20)	−92	0.1380	5
Shortspine thornyhead					
Large (≥26 cm)	1.68 (0.42)	18.18 (4.11)	−91	0.0004	16
Small (<26 cm)	0.88 (0.28)	8.84 (2.48)	−90	0.0006	16
Splitnose rockfish					
Small (<26 cm)	0.07 (0.03)	10.26 (5.70)	−99	0.0015	14
Darkblotched rockfish					
Large (≥26 cm)	1.21 (0.76)	12.56 (4.02)	−90	0.0107	13
Small (<26 cm)	0.17 (0.06)	2.01 (1.05)	−92	0.0499	12
Redbanded rockfish					
Large (≥26 cm)	0.00 (0.00)	0.52 (0.13)	−100	0.0051	10
Small (<26 cm)	0.00 (0.00)	0.12 (0.04)	−100	0.0117	8
Pacific ocean perch					
Large (≥26 cm)	0.00 (0.00)	0.18 (0.07)	−100	0.0431	5
Other fish					
Longnose skate	18.64 (5.49)	14.33 (4.36)	+30	0.3454	13
Sandpaper skate	1.78 (0.46)	1.26 (0.29)	+41	0.2775	16
Spotted ratfish	0.60 (0.19)	3.30 (0.92)	−82	0.0092	14
Bigfin eelpout	0.13 (0.04)	0.90 (0.28)	−86	0.0010	14
Spiny dogfish	0.09 (0.09)	2.82 (0.79)	−97	0.0015	13

catch composition would come at the expense of much lower catch rates for almost all species at night.

Changes in trawl catchability can be attributed to at least two factors, fish being available in the volume sampled by the trawl and trawl efficiency at capturing the available individuals (Shepherd and Forrester 1987; Michalsen et al. 1996). Any change in vertical distribution relative to the trawl height can change the numbers of individuals vulnerable to capture. Diel variation in catch rates in other areas has been attributed to the vertical migrations of some species (Engås and Soldal 1992; Korsbrekke and Nakken 1999). Comparable information for the U. S. West Coast does not exist, however hydroacoustic studies off British Columbia suggest several rockfish species aggregate on the bottom during the day and then disperse and move up into the water column at night (Leaman et al. 1990). Several studies have also documented vertical migration in deepwater species of *Sebastes* in the Atlantic (Atkinson 1989; Aglen et al. 1999). The consistent daytime performance of the control trawl across depths at which light levels become greatly reduced suggests that the nighttime decreases in rockfish catch rates could be related to a diel change in vertical distribution. This conclusion is contradicted by other west coast work examining near-bottom rockfish distribution suggesting most rockfish are less active and closer to substrate at night as observed from remotely operated vehicles (T. Hart, NOAA, personal communication). It is possible that nighttime excursions off bottom, beyond the view of bottom-tracking submersibles, or reaction to vehicle presence could bias those observations (Adams et al. 1995). Although the mechanism is uncertain, the greatly reduced nighttime catch rates for several

TABLE 5.—Comparison of mean control trawl catch (kg/haul) between daytime and nighttime hauls, using Wilcoxon's signed rank test, after correction for trawl time on bottom. Species were captured off the Oregon coast in 32 paired tows during summer months in 2003. Percent change is the night catch minus the daytime catch divided by the daytime catch (×100). The sample size, *N*, refers to the total number of blocks in which the species was captured in either daytime or nighttime hauls.

Species	Mean catch (SE)		Percent difference (+ or −)	*P*-value	*N*
	Night	Day			
Flatfish					
Dover sole	61.26 (12.91)	61.45 (10.20)	0	0.9176	16
Slender sole	0.07 (0.03)	0.17 (0.08)	−57	0.2343	16
Arrowtooth flounder	52.50 (9.75)	94.90 (16.02)	−45	0.0013	16
Petrale sole	0.74 (0.25)	0.63 (0.32)	+18	0.6744	8
Rex sole	3.01 (0.75)	4.20 (0.70)	−28	0.0229	16
Pacific halibut	8.88 (3.62)	4.90 (2.21)	+81	0.2135	9
Roundfish and rockfish					
Pacific hake	25.59 (5.05)	34.94 (6.41)	−27	0.0703	16
Sablefish	84.59 (16.24)	101.68 (12.80)	−17	0.1961	16
Lingcod	2.01 (0.68)	3.37 (1.30)	−40	0.1823	11
Shortspine thornyhead					
Large (≥26 cm)	16.38 (3.19)	33.95 (5.58)	−52	0.0006	16
Small (<26 cm)	6.22 (1.20)	9.45 (1.81)	−34	0.0262	16
Splitnose rockfish					
Large (≥26 cm)	0.18 (0.10)	0.59 (0.19)	−70	0.0844	12
Small (<26 cm)	1.07 (0.20)	14.16 (5.38)	−92	0.0008	16
Darkblotched rockfish					
Large (≥26 cm)	1.40 (0.34)	10.21 (4.67)	−86	0.0072	16
Small (<26 cm)	0.15 (0.07)	1.10 (0.51)	−86	0.0469	10
Redbanded rockfish					
Large (≥26 cm)	0.81 (0.24)	1.12 (0.34)	−27	0.7764	15
Small (<26 cm)	0.03 (0.03)	0.05 (0.02)	−24	0.5002	5
Pacific ocean perch					
Large (≥26 cm)	0.35 (0.20)	0.24 (0.10)	+47	0.8886	8
Other fish					
Longnose skate	14.65 (4.34)	16.92 (5.07)	−13	0.4703	14
Sandpaper skate	1.82 (0.36)	1.80 (0.35)	+1	0.7960	16
Spotted ratfish	1.37 (0.49)	2.60 (0.48)	−47	0.0409	15
Bigfin eelpout	0.22 (0.08)	0.42 (0.11)	−48	0.0962	14
Spiny dogfish	0.27 (0.13)	2.95 (0.74)	−91	0.0030	13

rockfish species in our control trawl, along with the lack of a reduction in Dover sole catch, suggests that fishing conventional trawls for deepwater complex species only at night might be an alternative rockfish bycatch reduction strategy.

Another factor influencing catchability is trawl capture efficiency for individuals that are available to the trawl. Light availability on the sea bottom on the upper continental slope is strongly depth dependent, as these depths include the transition to the aphotic zone, depending on the magnitude of seasonal turbidity (Parsons et al. 1984). Laboratory studies have shown that in the absence of light, fish behavior towards a trawl often shifts from a typical optomotor response to an erratic response (Kim and Wardle 2003; Olla et al. 1997). The loss of optomotor response may also prevent schooling fish from reacting *en masse*, resulting in more individual erratic responses to the trawl or sweeps (Olla et al. 2000; Walsh and Godø 2003). Instead of directed evasive movements based on visual cues, they may respond to other cues or fail to detect the trawl until struck by it (Glass and Wardle 1989). The low wings of this experimental trawl, along with the cut-back headrope, make it easy for fish to escape, and allows them more time to do so because the headrope is so far behind the footrope. Individuals responding with any significant vertical movement would likely escape the experimental trawl but be captured in the control trawl. This is a likely behavioral pattern for sablefish, given the catch patterns observed in this study.

In addition to erratic behavior resulting in some vertical movement and escape over the headrope or wings, a related change in trawl efficiency may be a decline in sweep-induced herding behavior in the absence of light. The effect would be decreased catch in both trawls at night, as observed with arrowtooth flounder. We did not observe higher catches of flatfish and skates at night as reported by Casey and Meyers (1998) or Walsh (1988). However, as they point out, the behaviors resulting in diel patterns in catchability are species-specific and may even be regionally related or linked to feeding behavior. Herding effects do not explain the strong differences in catch between the control and experimental trawls at night, which are more likely to be linked to vertical movement or distribution. No data exist suggesting species such as rex sole or Dover sole become more vertically active at night, but this behavior would be consistent with the catch patterns we observed.

Many studies have documented diel changes in the size selectivity of trawls, likely due to reduced time to react at night and the limited swimming abilities of smaller fish (Beamish 1966; Petrakis et al. 2001). We did not observe any biologically meaningful changes in fish size between day and night in either trawl, with the possible exception of rex sole. This species showed a significant, but modest, increase in size at night in both trawls, consistent with increased escape rates of smaller fish. Clearly, trawl performance should be evaluated on a species-specific basis. For many species, the performance of low-rise cut-back trawls may be more light dependent than typical trawls, and performance may fall off greatly at night, at great depth, or in turbid conditions. Further developments in selective trawl design for the deepwater complex fishery will depend on learning more about near-bottom vertical distribution of these various slope species and the behaviors they demonstrate when encountering a trawl both in the daytime and at night.

Management Implications

Developing strategies to reduce bycatch of the myriad of slope rockfish species taken in the deepwater complex trawl fishery will be challenging, and may require some reduction in catch rates for target species. This research suggests two additional tools that could be useful for varying the species composition captured in this fishery. Clearly, selective flatfish trawls could reduce bycatch of Pacific ocean perch and rougheye, splitnose and aurora rockfishes. However catches of some currently depressed rockfish species, including darkblotched rockfish, would not be reduced. With selective flatfish trawls, catch rates of sablefish and large shortspine thornyhead would also be reduced: an effect that could be useful if these two stocks decline to a point where they require additional protection. The effectiveness of nighttime trawling as well as trawling at depths greater than 347 m would also decline sharply with selective flatfish trawls. Another approach, allowing conventional trawls to fish only at night, could be used to reduce the bycatch of darkblotched rockfish, but will also reduce catch rates of important target species, such as shortspine thornyhead and arrowtooth flounder.

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