Effective herding of flatfish by cables with minimal seafloor contact

Craig S. Rose (contact author)[1]
John R. Gauvin[2]
Carwyn F. Hammond[1]

Email address for contact author: craig.rose@noaa.gov

[1] NOAA, National Marine Fisheries Service
Alaska Fisheries Science Center, Conservation Engineering Program
7600 Sand Point Way NE
Seattle, Washington 98115

[2] Best Use Cooperative
4241 21st Avenue West, Suite 302
Seattle, Washington 98199

Abstract—Otter trawls are very effective at capturing flatfish, but they can affect the seafloor ecosystems where they are used. Alaska flatfish trawlers have very long cables (called sweeps) between doors and net to herd fish into the path of the trawl. These sweeps, which ride on and can disturb the seafloor, account for most of the area affected by these trawls and hence a large proportion of the potential for damage to seafloor organisms. We examined modifications to otter trawls, such that disk clusters were installed at 9-m intervals to raise trawl sweeps small distances above the seafloor, greatly reducing the area of direct seafloor contact. A critical consideration was whether flatfish would still be herded effectively by these sweeps. We compared conventional and modified sweeps using a twin trawl system and analyzed the volume and composition of the resulting catches. We tested sweeps raised 5, 7.5, and 10 cm and observed no significant losses of flatfish catch until sweeps were raised 10 cm, and those losses were relatively small (5–10%). No size composition changes were detected in the flatfish catches. Alaska pollock (*Theragra chalcogramma*) were captured at higher rates with two versions of the modified sweeps. Sonar observations of the sweeps in operation and the seafloor after passage confirmed that the area of direct seafloor contact was greatly reduced by the modified sweeps.

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Otter trawling is one of the most effective methods for capturing commercial quantities of flatfish and is the principal method for flatfish harvest in Alaska waters. However, trawl fisheries have received increasing attention for their potential to affect seafloor habitats. Changes to seafloor ecosystems resulting from the passage of trawl gear have been have described in a wide range of studies (Barnes and Thomas, 2005; Lokkeborg, 2005). These include changes to infaunal (Tuck et al., 1998) and epifaunal (Kaiser et al., 1998; Prena et al., 1999; McConnaughey et al., 2000) communities, as well as indirect effects from changes to seafloor structure and resuspension of sediments (Churchill, 1989). The most common response to mitigate these problems has been closures of sensitive areas to trawling. When such areas have rough, rocky substrates, regulations requiring that trawl footrope cross-sections be below a certain size have been used to discourage fishing in these areas; the smaller footropes make nets more vulnerable to damage (Hannah, 2003; Bellman et al., 2005).

Alaskan commercial flatfish fisheries, among the largest in the world, are pursued almost exclusively with demersal otter trawls. (The exception is the fishery for Pacific halibut [*Hippogossus stenolepis*], a large, piscivorous species that is harvested by longlines.) These otter trawls generally use very long cables, herein called "sweeps," that skim the seafloor ahead and to both sides of the trawl net. In Alaska flatfish fisheries, the fishermen have used progressively longer sweeps to increase the width of their gear and, hence, the area from which flatfish are captured. These sweeps now account for the overwhelming majority of the seafloor area swept by these trawlers to capture flatfish. Although these sweeps greatly increase flatfish catches, they also account for most of the negative effects of trawling on the seafloor.

Although some reviews (Kaiser et al., 2007) have recommended development of modified fishing gear to reduce the effects of trawling on seafloor communities, studies that test such gear are just beginning to be published. He (2007) reviewed such efforts for all mobile fishing gears. A substantial effort in Europe focused on modifications for beam trawling (van Marlen et al., 2005). Guyonnet et al. (2008) described tests of modified gear that reduce the contact of the cables between trawl doors and nets with the seafloor. Although their tests were accomplished with different modifications to gear (dangling chain sections attached to neutrally bouyant rope) and in a very different fishery, their concept is very similar to the modifications we tested.

Ryer (2008) has described flatfish behaviors that are important to

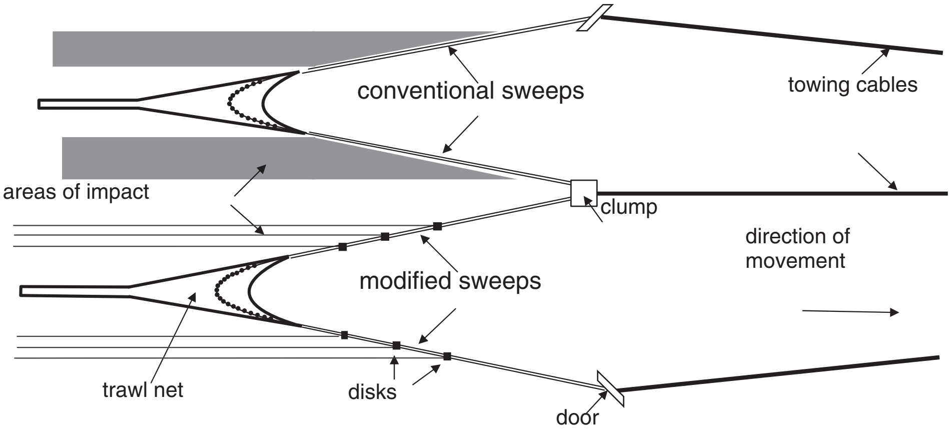

Figure 1

Diagram of the twin trawl system, complete with sweeps (conventional and modified), towed simultaneously behind a vessel and used to test whether raised trawl sweeps reduce flatfish herding. Actual total width was approximately 250 m. Shaded areas represent the area of contact with the seafloor.

their capture by trawls. Flatfish generally react to approaching objects at much closer ranges (<1 m) than do roundfish and remain very close to the seafloor when avoiding such objects. To target these behaviors, towing cables (angled toward the trawl net across the sea floor) are used in both demersal seines and otter trawls to herd flatfish into the path of a capture net. Flatfish avoid the approaching cable by continuous or burst-and-pause swimming, both of which move them gradually into the path of the capture device. Conventional sweep cables have equal diameters throughout, and no structures to interrupt their contact with the seafloor. Here, we test whether effective herding responses could be stimulated if such cables were raised a short distance above the seafloor.

Like most flatfish fisheries, those in Alaska operate on seafloors consisting of unconsolidated mixtures of sand and mud. The potential for reducing damage to the physical and biological features of these habitats by raising sweeps a short distance off the bottom is dependent on the presence of low vertical relief or flexible structures of the bottom relief. This modification would likely not prevent damage to high relief and rigid or fragile features more common on rockier substrates. For the modifications tested here to be effective, their effects on both catch rates and seafloor features need to be examined.

To develop practical modifications for the trawl systems used in Alaska's flatfish fisheries, we convened a series of meetings with trawler captains and gear manufacturers. For initial study, they recommended raising the sweeps slightly above the seafloor, allowing small and flexible animals and other habitat structure to pass beneath. In the current study we examine the proposed change, focusing on determining which adjustments maintain catch rates and on using direct observations to demonstrate reduced seafloor contact.

Methods

To test the effect of the modified sweeps on their ability to herd flatfish, we used a twin trawl system (Fig. 1). A twin trawl system tows two separate trawls, including sweeps, simultaneously on parallel, adjacent tracks. Close proximity and simultaneous operation assure that both nets encounter very similar compositions of fish species at similar abundances. Therefore differences in catch are principally due to differences in the capture effectiveness of the two trawls. The only difference between the trawls in this experiment was the use of the elevating disks on the sweeps of the trawls.

Twin trawl tests

Field experiments were conducted during September 2006 in the eastern Bering Sea onboard the FV *Cape Horn*. The *Cape Horn* is a 47-m trawler processor, active in the mixed groundfish fisheries of the Bering Sea. This vessel was equipped for a twin trawling system, with an extra winch and towing cable. The sweeps and trawls were towed with conventional trawl doors on each side and a weight (clump) in the middle. Both doors and the clump were towed from three separate cables that were adjusted so that both sides fished evenly. Towing sites were selected to provide commercial catch rates of a mixture of the four principal flatfish species of the Bering Sea shelf: yellowfin sole (*Limanda aspera*); northern rock sole (*Lepidopsetta polyxystra*); flathead sole (*Hippoglossoides elassodon*);

and arrowtooth flounder (*Atheresthes stomias*). Towing continued through both day and night periods, reflecting commercial practice. All of the tows were in areas with bottom substrates composed of mixtures of sand and mud (McConnaughey and Smith, 2000).

The trawls were identical two-seam nets with 200-mm mesh in the forward portions and equipped with 130-mm codends. The mouth opening of each net was much wider (25 m) than high (3 m). Similar nets in a single trawl configuration are used to target flatfish on the eastern Bering Sea shelf. The distances between each of the doors and the central clump were monitored for equality with acoustic measurement systems and were each approximately 80 m. Both nets were equipped with sensors that indicated the direction of water flow in relation to the center of the headrope. The three towing cables were adjusted to keep that flow perpendicular to the headropes of both nets and to keep their door-clump openings equal, assuring comparable fishing characteristics for both fishing systems.

The sweeps were 180-m long and were composed of 5-cm (2-inch) diameter combination rope constructed of steel cable covered with polyethylene fiber. This is the most common sweep material currently used in U.S. Bering Sea flatfish fisheries. Sweeps used on vessels to target flatfish on the eastern Bering Sea shelf are 200 to 450 m long (C. Rose, unpubl. data). The sweeps of the two adjacent trawls had to be about half as long as those used with commercial single trawls, because the entire twin trawl system is similar in width to a conventional single trawl. The shorter sweep lengths were necessary to assure that the angle of the test sweeps to the direction of towing was similar to that common in the fishery. In this field study, clusters of disks (disk clusters) were attached over the experimental sweeps at 9-m (30-ft) intervals (Fig. 2). The disks were either 15, 20, or 25 cm (6, 8, or 10 inch) in diameter attached to 5-cm (2 inch) diameter sweeps, creating nominal clearance between the cables and the seafloor of 5, 7.5, and 10 cm (2, 3, and 4 inch), respectively. Nominal clearances are those immediately adjacent to a disk when the disk is resting on a hard surface. The pressing of disks into the seafloor and the sagging of sweeps between elevating devices would affect actual clearances. For stability, disk clusters were approximately the same length as their diameter. These disk clusters were fixed in position with a combination of clamps and rope seizings, which were run through the sweep cable to prevent the clusters from sliding along the cable. Disk clusters were installed on the aft 90 m of the modified sweeps. Halfway through each experiment, the sweeps were switched between the two trawl nets, but each trawl net remained in place.

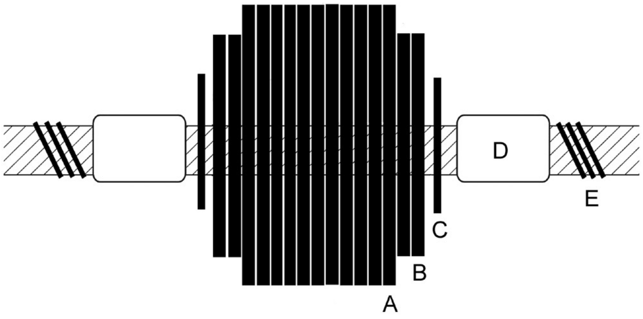

Figure 2

Schematic diagram of a cluster of disks (disk cluster) attached to trawl sweeps to raise the sweeps above the seafloor to test whether this gear modification reduces flatfish herding. Rubber disks (**A**, 20 cm-diameter, and **B**, 15 cm-diameter) were installed over the sweep cable, between clamps (**D**) that fix their location on the cable. Steel washers (**C**) prevented rubber disks from passing over clamps. Ropes seized over and tucked through cable (**E**) blocked clamps from shifting.

Catches from each trawl were kept separate throughout the sampling process. As catches entered the sampling area, they passed across a motion-compensated flow scale which provided a total catch weight. All individuals of four flatfish species (yellowfin sole, northern rock sole, flathead sole, and arrowtooth flounder) and two gadids (Pacific cod [*Gadus macrocephalus*] and Alaska pollock [*Theragra chalcogramma*]) were sorted into separate holding bins. These are the principal flatfish and gadid species harvested from the eastern Bering Sea shelf. Fish from each bin were then run across a second flow scale to measure the weight of each of these species. During the sorting of catch from each trawl, 50–150 fish of each species were sampled and their fork lengths were measured to 1-cm intervals to determine their size composition. These length samples were periodically taken from the catch as it passed through the sorting area to avoid bias in case fish size varied between parts of each catch. Because of their large size, limited holding space and handling requirements precluded adequate length sampling of Pacific cod.

Tows were planned to last 2 hours, unless catch sensors indicated substantial catches (>8 metric tons [t] per net) before that time. Actual tow durations ranged from 33 to 150 minutes. We eliminated hauls where debris (e.g., crab pots) was large enough to clog the net, or where gear components became entangled, because such conditions could influence gear performance and the size and composition of the resulting catch. Tow locations were selected in order to encounter commercial concentrations of the major flatfish species of the eastern Bering Sea shelf. Environmental parameters at the trawl, including depth, temperature and light level, were sampled throughout the experiment with a Mk9 logger (Wildlife Computers, Redmond, WA) mounted at the center of the trawl's headrope.

We used a high-resolution, rapid-update sonar (SoundMetrics DIDSON, Dual-frequency IDentification SONar, Lake Forest Park, WA) to observe how the sweep modifications affected seafloor contact. This was mounted in a protective sled, which was towed both behind the sweeps, to show interactions between the sweeps and the seafloor, and, separate from the trawl, across the track of a previous haul, to show marks left on the seafloor. These observations were made only on sweeps with the 20-cm disks. The sled was also towed across tracks from previous trawl tows with conventional and modified sweeps and was equipped with a video camera for detailed imagery.

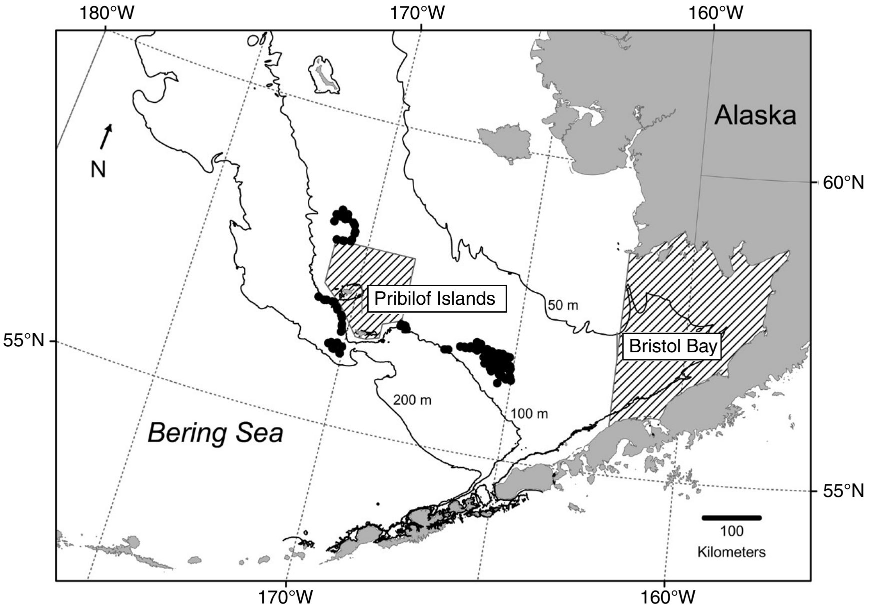

Figure 3

Fishing locations (●) in the eastern Bering Sea for the 2006 tests of the effects of raised sweeps on flatfish herding. Regions shaded with diagonal lines are areas of trawl closures around the Pribilof Islands and in Bristol Bay. Contour lines indicate depths.

To estimate the proportional change in catch due to the sweep modifications, the difference between the natural logarithms of the catch weights from modified and unmodified trawls (Log*Dif*) was calculated for each species from each twin-trawl haul:

$$\text{Log}Dif = \ln(Catch_{modified}) - \ln(Catch_{unmodified}). \qquad (1)$$

This statistic, equivalent to the logarithm of the ratio between catches with modified and unmodified nets, was appropriate because absolute catch sizes were uncontrolled and varied widely. A statistic based on subtracting the untransformed trawl catches, like that for an ordinary paired *t*-test, would have varied proportionally to absolute catch rates, whereas catch ratios, as measured by Log*Dif*, were independent of the fish densities encountered during each tow. Averages and confidence intervals of Log*Dif* were computed for each species and sweep modification. To report these results as ratios, the averages and confidence intervals were then back-transformed with the exponential function. Catch results were only used for species with more than a minimal catch (>10 fish) in both nets. The null hypothesis that the sweep modifications did not affect catch was tested with a *t*-test of whether average Log*Dif* was different from 0, equivalent to a paired *t*-test for differences between the log-transformed catches.

To test whether the sweep modifications affected the size-selectivity for different fish species and to minimize variability, we pooled fish into three size classes for each species, except for arrowtooth flounder, where a wide size range made four size classes more appropriate. The size-class boundaries were set so that approximately one-third (one-fourth for arrowtooth flounder) of the fish in the combined control catches were in each category. To maintain consistency with the weight-based analysis of overall catch, and because the Alaska trawl fleet classifies fish sizes by weight, the boundaries of the size classes were defined by individual weights instead of lengths, and the catches of each size class were computed as weights, instead of numbers. Length-weight functions from the annual Bering Sea shelf trawl survey (NMFS, unpubl. data[1]) were used to convert the sampled lengths to their corresponding weights. The catch of each size class was estimated by expanding the proportion of that size class, by weight, from the sample of catch for that species. As with the total catch data, averages and confidence intervals were calculated. We used analysis of variance to test for differences between size classes for each combination of species and for each sweep modification.

Results

From 6 to 23 September 2006, 61 successful twin trawl hauls were conducted, including 19, 26, and 16 hauls with experimental sweep clearances of 5, 7.5, and 10 cm, respectively. Depths at these tow sites (Fig. 3) ranged from 70 to 117 m, and bottom temperatures ranged from 2.5° to 5.5°C.

Sonar imagery during towing showed that unmodified sweeps produced a continuous cloud of disturbed sediment due to contact with the seafloor. Variation in the density of that cloud appeared to result from contact with high and low spots on the seafloor, and rapid oscillation of strong and weak cloud intensity appeared to be due to vibration of the sweeps. In contrast, the sediment cloud from the modified sweep appeared only directly behind the disk cluster. The only clouds from the

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[1] NMFS, Alaska Fisheries Science Center, RACE Division, 7600 Sand Point Way NE, Seattle, WA

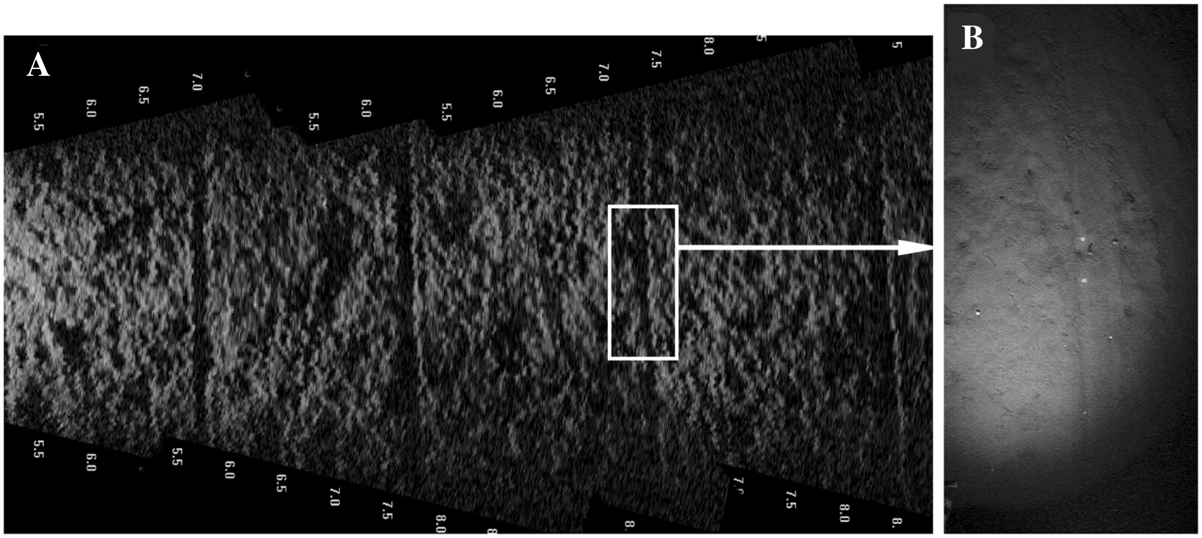

Figure 4

(**A**) Sonar and (**B**) video imagery of the seafloor after passage of the raised otter trawl sweeps. Video picture was taken as the seafloor sled passed over the location indicated on the sonar image. Otter trawl sweeps were raised with widely spaced disk clusters, which caused the parallel tracks seen in the sonar image and the flattened swath in the video image.

sweeps themselves were brief puffs after contact with high spots on the seafloor. Areas covered by the modified sweeps showed marks from the disk clusters that were approximately 10-cm wide separated by seafloor indistinguishable from unaffected areas (Fig. 4A). This disk cluster mark was approximately 5% of the 2-m interval between marks. This spacing is much shorter than the 9-m spacing on the cable because sweeps are sharply angled to their direction of movement (angle-of-attack). Images of such tracks from the video (Fig. 4B) showed a flattening of very low-profile surface textures.

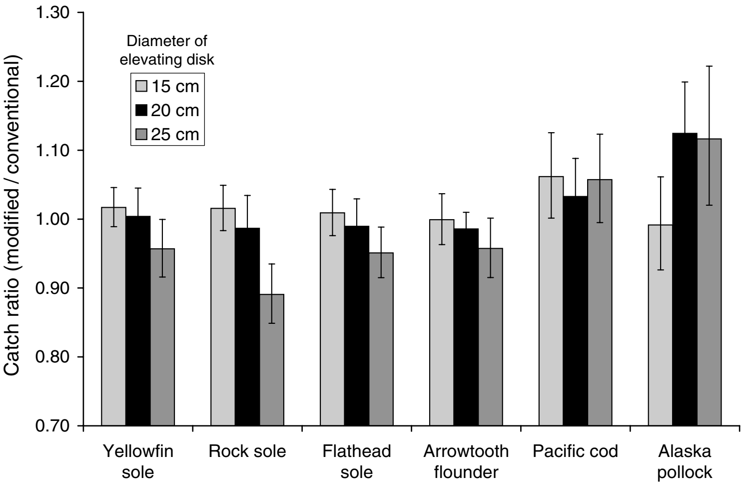

Figure 5

Estimates of and 95% confidence intervals for the ratios of fish catches with the modified trawl sweeps raised to three different heights off the seafloor to fish catches with conventional sweeps for the four principal flatfish species (yellowfin sole [*Limanda aspera*]; northern rock sole [*Lepidopsetta polyxystra*]; flathead sole [*Hippoglossoides elassodon*]; arrowtooth flounder [*Atheresthes stomias*]); and two principal gadid species: Pacific cod (*Gadus macrocephalus*); and Alaska pollock (*Theragra chalcogramma*) taken in Bering Sea trawl fisheries.

The use of 15-cm disks on the sweeps did not cause significant differences in catch rates (Log*Dif* was not different from 0) for any of the six species, and only the pollock catch rate changed (12% increase, $P=0.007$) with the 20-cm disks (Fig. 5). Northern rock sole and flathead sole catches both decreased significantly (–11%, $P<0.001$, and –5%, $P=0.02$, respectively) when the 25-cm disks were used, whereas pollock catch increased again (+12%, $P=0.03$). Decreases for the other two flatfish were also observed—although not statistically significant at the 0.05 level ($P=0.08$ for arrowtooth flounder and $P=0.07$ for yellowfin sole). A consistent decrease in the mean relative catch with increasing disk size for all of the flatfish species, although only significant for the largest disks, indicates that smaller effects may have occurred for the smaller disks that could not be statistically detected in our experiment. Pacific cod catches did not change significantly with any of the modifications.

For evaluating the likelihood of substantial losses of catch, the confidence intervals provide more information than the basic significance tests alone. For example, the lower confidence bounds for the effects of 20-cm disks on flatfish catches leave only a 2.5% (1 of 40) probability that catch losses would exceed 4–6%. Corresponding "worst case" losses for the 15-cm disks were even smaller. Similarly, although none of the Pacific cod catch results passed the threshold of a 95% two-tailed probability of being different from no change, all three of the confidence intervals were almost entirely above a value of 1. Therefore, a trawler could implement one of these modifications with little expectation of catching fewer Pacific cod and with a reasonable chance of slight increases in Pacific cod catch.

The size composition of each species from the unmodified nets (Fig. 6) showed truncation at the lower end of the size distribution, owing to use of large mesh in the body of the net (20 cm, stretch measure), intermediates (14 cm) and codends (15 cm) that release smaller fish. Although the proportions varied somewhat between experiments, each study encountered a representative range of sizes available to the commercial fishery.

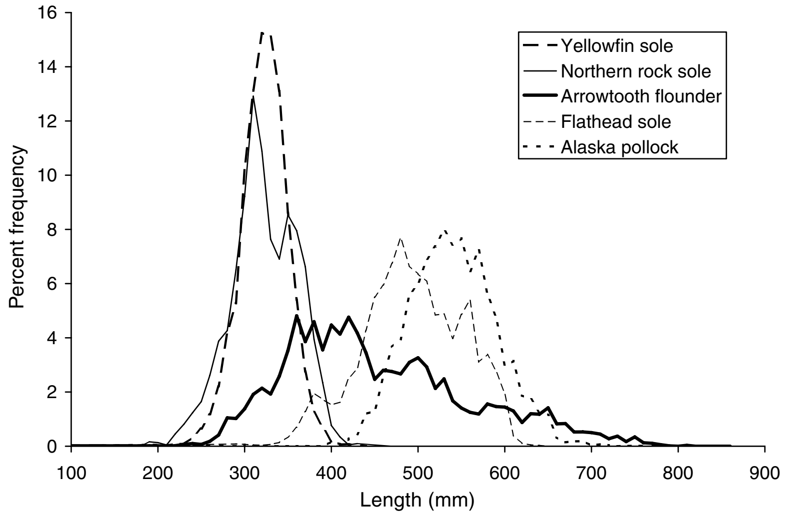

Figure 6

Size compositions for flatfish and gadid species taken during tests of whether raised trawl sweeps reduce herding of fish. Yellowfin sole (*Limanda aspera*); northern rock sole (*Lepidopsetta polyxystra*); flathead sole (*Hippoglossoides elassodon*); arrowtooth flounder (*Atheresthes stomias*); Pacific cod (*Gadus macrocephalus*); and Alaska pollock (*Theragra chalcogramma*).

ANOVA tests for differences in catch effects between major size classes (thirds or quartiles of control size frequencies) revealed no significant differences for any of the flatfish species (Fig. 7). One significant difference ($P=0.04$) was detected for pollock in sweeps with the smallest disks (15 cm), attributable to a lower catch rate of the smallest pollock. Confidence intervals were included in Figure 7 to aid comparisons between size groups within species and sweep modification classes. Confidence intervals were wider for the largest and smallest categories because few individuals from these ranges were encountered in some tows, increasing variability, whereas all tows had substantial numbers of fish in the central ranges.

Discussion

Flatfish can be effectively herded by trawl sweeps and with greatly reduced seafloor contact. Significant catch reductions, averaging 5% for flathead sole and 11% for rock sole, were only detected when 25-cm disks were installed that raised the sweeps 10 cm above the substrate at the ends of each 9-m section. No detectable catch reductions occurred during tests with smaller clearances (5 and 7.5 cm). Confidence intervals indicated only a 2.5% probability of catch reductions greater that 5% with 7.5-cm clearances. Nor did sweeps with such clearances appear to change size selectivity significantly.

Flatfish exhibit predator avoidance behaviors that allow them to be effectively herded by the sweeps. In contrast to roundfish, flatfish cease movement when a predator is detected and only flee upon very close approach (Ryer, 2008). Therefore, observed flatfish reactions to trawl gear (Main and Sangster, 1981; Rose, 1996; Ryer and Barnett, 2006) mostly occur at horizontal ranges of much less than 1 m. However, because conventional fishing gear has either continuous or closely spaced contact with the seafloor, there has been little or no information to assess the role of gear contact or proximity to the seafloor in either initiating or sustaining the flight behaviors that result in herding. Given the cryptic behaviors of flatfish, we could not assume that stimuli several centimeters above the seafloor would be as effective as those that would directly contact flatfish on the seafloor. The current results demonstrate that flatfish do respond with effective herding behaviors to sweep cables displaced from the seafloor by 5 to 10 cm. Even the largest of the flatfish encountered here would not have contacted the raised sweeps if they remained resting on the seafloor. At the highest clearance (10 cm), slightly reduced catches indicated that the flight response began to break down and some of the flatfish were not herded as well as with the conventional sweeps. Winger et al. (2004) found that flatfish size

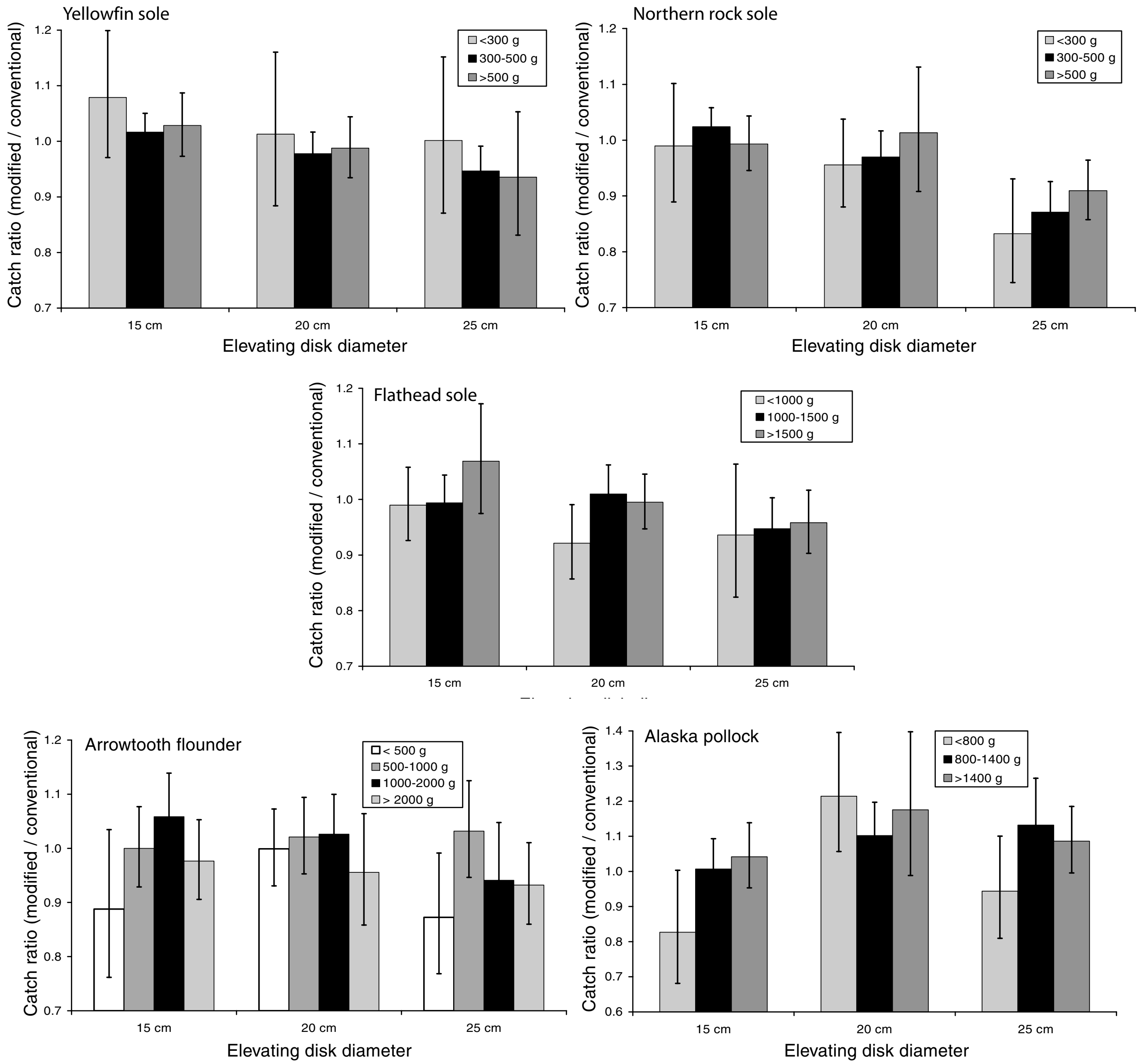

Figure 7

Estimates of and 95% confidence intervals for ratios of fish catches during tests with modified trawl sweeps raised to three different heights off of the seafloor to catches with conventional sweeps for broad size classes of four principal flatfish species and a principal gadid species taken in Bering Sea trawl fisheries: yellowfin sole (*Limanda aspera*); northern rock sole (*Lepidopsetta polyxystra*); flathead sole (*Hippoglossoides elassodon*); arrowtooth flounder (*Atheresthes stomias*); and Alaska pollock (*Theragra chalcogramma*).

affected behavioral responses to approaching sweeps, including tailbeat frequency and swimming endurance. Although any of these behaviors could affect herding-related capture rates, the current study did not indicate behavioral differences between size classes in response to the elevated sweeps.

We followed commercial practices in the gear type used, weight-based catch metrics, towing durations, catch handling, and round-the-clock operations. This procedure was undertaken to increase the relevance of our results to those with the greatest stake in deciding on the use of these modifications: the fishermen and fishing companies. Fishermen actively participated in designing the gear modifications and in conducting the research.

To examine consequences of using modified sweeps in the fishery and to improve precision, all tows were analyzed together, including day and night tows, even though light levels affect the herding process (Ryer and Barnett, 2006). The effects of light on flatfish herding are analyzed and reported in a separate paper (Ryer et al., 2010).

Although not the focus of this study, an unexpected result was the increase in pollock catches that occurred with two of the sweep modifications. Pollock herd differently from flatfish, reacting to stimuli at much greater distances (Rose, 1996). The forward sections of the most modern pollock trawls have "meshes" that are more than 25-m long. Although large groups of pollock could easily swim through such meshes, they still avoid the netting and are eventually herded into parts of the net that physically restrain them. These nets would not work if pollock herded only at short ranges. Separation of the sweeps from the seafloor, or the disk clusters themselves, could have increased visibility of the sweeps, which may have enhanced pollock herding. Both factors would be reduced at the smallest disks, where herding improvement was not detected.

Sonar observations of the elevated sweeps showed that their interaction with the seafloor was radically changed. The continuous sediment clouds produced along the entire length of the unmodified sweeps were, for the modified sweeps, reduced to isolated clouds behind each disk, indicating substantial reductions in the area of direct contact. Therefore, any effects based on direct contact, as well as resuspension of sediments, should have been greatly reduced. The sonar images of the seafloor after passage of the sweep showed that the contact area of the disks was approximately 5% of the total swept area. Seafloor texture between the disk tracks was indistinguishable from unaffected areas, but areas covered by conventional sweeps showed slight smoothing. The seafloor directly contacted by the disks was uniformly smoothed. Although the texture change due to conventional sweeps appeared slight, the resuspension observed during fishing indicated some disturbance of the bottom and we believe that the substantial reduction of contact due to using the disks more than compensates for any increased disturbance to the small area directly under the disks.

In another recent study (Guyonnet et al., 2008), the concept of slightly raising trawl sweeps, therein called "legs," was also applied to reduce their impact on the seafloor. Instead of disk clusters, Guyonnet et al. used neutrally buoyant sweep material that was weighted only by dangling chains attached every 50 cm. They also found no significant effects on catch composition or size selectivity for target animals. They found that damage to benthic animals was reduced with the alternative gear.

Our results alone, although promising, do not address the full potential of sweep modifications to reduce the effects on the seafloor of trawling for Bering Sea flatfish. Although creating several centimeters of separation between the sweeps and the seafloor greatly reduces the potential for damage to infauna and small epifauna, it does not prevent contact with seafloor features and animals larger than that spacing. The vulnerability of ecosystem features to trawling operations is a function of the amount of damage caused by each trawl exposure (e.g., the proportion of a particular species in the path of a trawl that dies due to trawl contact) and the frequency and coverage of the trawling effort. An analysis of such factors for the Bering Sea shelf highlighted structure-forming animals as the seafloor feature most vulnerable to trawling.[2] The structure-forming animals of the eastern Bering Sea shelf are generally small and flexible; therefore it is quite conceivable that creating a space below the sweeps could also reduce damage to these animals. That potential is being examined by the authors in a subsequent study that will focus on how these sweep modifications change damage rates to structure-forming animals of the Bering Sea shelf.

Successful gear modifications for reducing trawling effects on seafloor habitats would add a habitat protection option in addition to area closures and gear switching. Closures of areas to trawling can move fishing effort from productive grounds, and therefore can increase the total effort required or concentrate fishing and its effects in the remaining fishing grounds (Fujioka, 2006). The list of alternative gear for harvesting these flatfish is quite limited and none are without some negative effects on habitat. With beam trawling, herding sweeps are not used to concentrate fish into the path of the capture device. Therefore, the entire area from which fish are collected is swept with the capture net itself. Studies to reduce the effects of beam trawls on habitat have focused on other stimuli to move fish from the seafloor into the net (van Marlen et al., 2005). The capture process for demersal seines is similar in many ways to that of Alaska otter trawls with long sweeps—weighted cables are pulled across the seafloor to herd fish into the path of a capture net. Demersal entangling nets depend on natural movements of the fish to bring them to the gear, and therefore they are effective only during periods when fish are actively moving. They are still unlikely to produce catch rates similar to those produced with trawls unless vast fleets of nets are deployed. Such extensive net deployments would exacerbate the most notable problem with demersal entangling nets—ghost fishing of derelict and lost gear. Finally, although longline fishing is the foundation for one of the most successful commercial flatfish fisheries (Pacific halibut), most flatfish species are not of the size and do not have a predatory diet that make longlines particularly effective.

Implementing the trawl gear modifications described here would require some adaptations in equipment and handling methods for fishermen. The volume of the elevating devices would require additional space on deployment reels or net drums, thus requiring either that sweep lengths be shortened to fit onto the reels or larger reels be installed on vessels. The disks would

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[2] Final environmental impact statement for essential fish habitat identification and conservation in Alaska. April 2005 [online]. http://www.fakr.noaa.gov/habitat/seis/efheis.htm.

also complicate deployment and retrieval because they do not wrap as evenly onto reels as unmodified sweeps. Potential advantages with the use of disks would include longer usability of sweeps and reduced drag (improved fuel efficiency), both due to reduced contact of the sweeps with the seafloor. An important factor in identifying these implementation and operational issues early, as well as in the development of potential solutions, has been the direct participation of the fishing industry in this research and our ability to conduct these tests under conditions identical to most of the important operational aspects of the commercial fishery.

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Literature cited

Barnes, P. W., and J. P. Thomas (eds.).
2005. Benthic habitats and the effects of fishing. Am. Fish. Soc. Symp. 4, 890 p.

Bellman, M. A., S. A. Heppell, and C. Goldfinger.
2005. Evaluation of a US west coast groundfish habitat conservation regulation via analysis of spatial and temporal patterns of trawl fishing effort. Can. J. Fish. Aquat. Sci. 62:2886–2900.

Churchill, J. H.
1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. Cont. Shelf Res. 9:841–865.

Fujioka, J. T.
2006. A model for evaluating fishing impacts on habitat and comparing fishing closure strategies. Can. J. Fish. Aquat. Sci. 63:2330–2342.

Guyonnet, B., J. Grall, and B. Vincent.
2008. Modified otter trawl legs to reduce damage and mortality of benthic organisms in North East Atlantic fisheries (Bay of Biscay). J. Mar. Syst. 72:2–16.

Hannah, R. W.
2003. Spatial changes in trawl fishing effort in response to footrope diameter restrictions in the U.S. west coast bottom trawl fishery. N. Am. J. Fish. Manag. 23:693–702.

He, P.
2007. Technical measures to reduce seabed impact of mobile fishing gears. *In* Bycatch reduction in the world's fisheries (S. J. Kennelly ed.), p. 141–179. Springer, New York.

Kaiser, M. J., D. B. Edwards, P. J. Armstrong, K. Radford, N. E. L. Lough, R. P. Flatt, and H. D. Jones.
1998. Changes in megafaunal benthic communities in different habitats after trawling disturbance. ICES J. Mar. Sci. 55:353–361.

Kaiser, M. J., N. Graham, C. S. Rose, and P. H. Weibe.
2007. Ecosystem-sensitive approaches to fishing: reconciling fisheries with conservation through improvements in fishing technology. ICES J. Mar. Sci. 64:1610–1611.

Lokkeborg, S.
2005. Impacts of trawling and scallop dredging on benthic habitats and communities. FAO Fish. Tech. Paper 472, 58 p. FAO, Rome.

Main, J., and G. I. Sangster.
1981. A study of the fish capture process in a bottom trawl by direct observations from a towed underwater vehicle. Scott. Fish. Res. Rep. 23, 24 p. Marine Scotland, Aberdeen.

McConnaughey, R. A., C.B. Dew, and K. Meir.
2000. An examination of chronic trawling effects on soft bottom benthos in the eastern Bering Sea. ICES J. of Mar. Sci. 57:1377–1388.

McConnaughey, R. A., and K.R. Smith.
2000. Associations between flatfish abundance and surficial sediments in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. 57:2410–2419.

Prena, J., P. Schwinghamer, T. W. Rowell, D. C. Gordon, K. D. Gilkinson, W. P. Vass, and D. L. McKeown.
1999. Experimental otter trawling on a sandy bottom ecosystem of the Grand Banks of Newfoundland: analysis of trawl bycatch and effects on epifauna. Mar. Ecol. Progr. Ser. 181:107–124.

Rose, C. S.
1996. Behavior of North Pacific groundfish encountering trawls: applications to reduce bycatch. *In* Solving bycatch: considerations for today and tomorrow, p. 235–241. Alaska Sea Grant College Program Report 96-03, Univ. Alaska, Fairbanks.

Ryer, C. H.
2008. A review of flatfish behavior relative to trawls. Fish. Res. 90:138–146

Ryer, C. H., and L. A. K. Barnett.
2006. Influence of illumination and temperature upon flatfish reactivity and herding behavior: Potential implications for trawl capture efficiency. Fish. Res. 81:242–250.

Ryer, C. H., C. S. Rose, and P. S. Iseri.
2010. Flatfish herding behavior: diel patterns of trawl sweep efficiency as inferred from field and laboratory manipulations. Fish. Bull. 108:145–154.

Tuck, I. D., S. J. Hall, M. R. Robertson, E. Armstrong, and D. J. Basford.
1998. Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. Mar. Ecol. Progr. Ser. 162:227–242.

van Marlen, B, M. J. N. Bergman, S. Groenwold, and M. Fonds.
2005. New approaches to the reduction of non-target mortality in beam trawling. Fish. Res. 72:333–345.

Winger, P. D., S. J. Walsh, P. He, and J. A. Brown.
2004. Simulating trawl herding in flatfish: the role of fish length in behavior and swimming characteristics. ICES J. Mar. Sci. 61:1179–1185.