Abstract—Surveys with a remotely operated vehicle (ROV) at four mud-habitat sites with different histories of ocean shrimp (*Pandalus jordani*) trawling showed measurable effects of trawling on macroinvertebrate abundance and diversity. Densities of the sea whip (*Halipteris* spp., *P*<0.01), the flat mud star (*Luidia foliolata*, *P*<0.001), unidentified Asteroidea (*P*<0.05), and squat lobsters (unidentified Galathoidea, *P*<0.001) were lower at heavily trawled (HT) sites, as was invertebrate diversity based on the Shannon-Wiener index. Sea cucumbers (unidentified Holothuroidea) and unidentified corals (Hydrocoralia) were observed at lightly trawled (LT) sites but not at HT sites. Hagfish (*Eptatretus* spp.) burrows were the dominant structural feature of the sediment surface at all sites and were more abundant at the HT sites (*P*<0.05), a result potentially related to effects from fishery discards. Substantial heterogeneity was found between the northern and southern site pairs, indicating high site-to-site variability in macroinvertebrate densities in these deep (146–156 m) mud habitats. Two of the study sites were closed to trawling in June 2006. The data from this study can be used in combination with future surveys to measure recovery rates of deep, mud, seafloor habitats from the effects of trawling, thus providing a critical piece of information for ecosystem-based management.

Effects of trawling for ocean shrimp (*Pandalus jordani*) on macroinvertebrate abundance and diversity at four sites near Nehalem Bank, Oregon

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Intensive fishing with bottom trawls and dredges can have significant effects on some types of seafloor habitats (Auster et al., 1996; Collie et al., 1997). The reduction in habitat complexity that can result from trawling is of particular concern because of the potential for reductions in fish production at impacted sites (Lindholm et al., 1999). In continental shelf waters off the United States west coast (excluding Alaska), the effect of mobile fishing gears on seafloor habitats has received very little study. The research that has been conducted has focused on effects from otter trawls used to harvest groundfish (Engel and Kvitek, 1998; Hixon and Tissot, 2007). However, the principal trawl fishery currently operating on soft-bottom habitats on the outer continental shelf in these waters is the fishery for ocean shrimp (*Pandalus jordani*). Habitat impacts from ocean shrimp trawls are likely to be different from those from groundfish trawls (Gibbs et al., 1980; Kaiser et al., 2002). Ocean shrimp trawls are considered to be semipelagic gear: they comprise a footrope system that incorporates a chain or cable groundline partially covered with 6.4-cm diameter rubber discs, but are configured to elevate the fishing line of the net about 35–70 cm above the bottom (Hannah and Jones, 2000, 2003). No studies of the physical effects of ocean shrimp trawling on the seafloor ecosystem have been conducted. We report here on the first such study examining the condition of mud-seafloor habitats in the areas primarily impacted by ocean shrimp trawling.

The lack of research on the effects of trawling on some U.S. west coast seafloor habitats has been caused, in part, by a lack of suitable control sites that have not been previously trawled (Engel and Kvitek, 1998). However, some of the areas of rocky habitat that have been recently closed to trawling also contain limited sections of soft-bottom habitat that have been historically trawled, but that are now closed to trawling. The closure of these areas creates an opportunity to study habitat impacts from chronic trawling by examining how these areas recover after closure, in comparison to nearby areas of similar habitat that continue to be trawled. One such area is a section of mud habitat that has historically been trawled for ocean shrimp but is now enclosed within the Nehalem Bank Essential Fish Habitat no-trawl zone (Fig. 1) that was closed to trawling in June 2006. One objective of this study was to conduct an
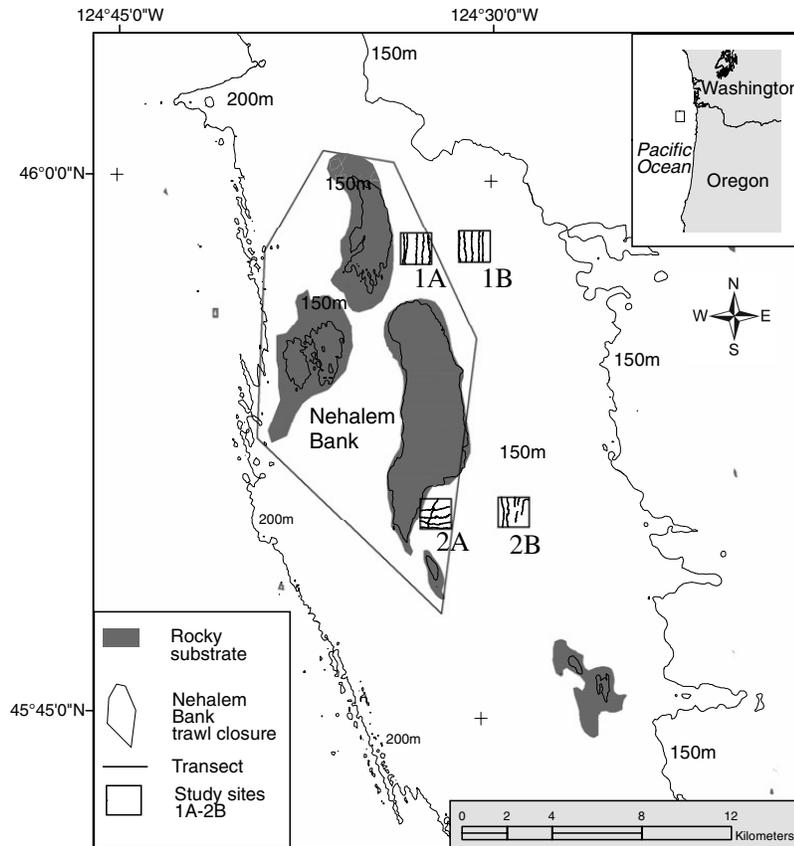
Figure 1

Map of the study area at Nehalem Bank, Oregon, showing the four study sites (1A, 1B, 2A, and 2B) where the effects of ocean shrimp (*Pandalus jordani*) trawling on macrobenthos and seafloor habitat were evaluated. The Nehalem Bank trawl closure is also outlined.

initial survey of the condition of two sites within this closed area to monitor changes over time (sites 1A and 2A, Fig. 1). We also surveyed two nearby sites that remain open to ocean shrimp trawling as control sites (sites 1B and 2B, Fig. 1).

In the absence of true control sites that have not been trawled, researchers studying trawl effects on habitat have resorted to comparing habitat condition across a gradient of trawling intensity (Thrush et al., 1998; Kaiser et al., 2000). The mud-habitat sites within the Nehalem Bank trawl closure area (sites 1A and 2A, Fig. 1) have not been as heavily trawled for ocean shrimp as have the two nearby mud seafloor sites that are closer to the center of the ocean shrimp trawl grounds (sites 1B and 2B, Fig. 1).

A second objective of this study was to compare the condition of the seafloor habitat and macrobenthos for the four sites to determine if current differences may be related to the amount of prior trawling. The nature of differences between these four sites, if related to trawling history, could be useful in developing hypotheses regarding expected changes within the closed areas over time.

Materials and methods

Study area and field surveys

Nehalem Bank is a 74.6 km² rocky outcrop composed of sandstone and siltstone located off northern Oregon, between the 150- and 200-m depth contours (Lanier, 2006). Our study sites comprised four square sections of mud habitat (1850 m wide) in the vicinity of Nehalem Bank, two within and two outside the area recently closed to trawling (Fig. 1). Our study design was chosen primarily to provide a detailed baseline survey of the limited areas of soft-bottom habitat that are enclosed within the Nehalem Bank trawl closure area (Fig. 1) so that the process of habitat recovery from physical trawl impacts can be examined in future studies. Accordingly, our design was much more spatially restricted than would be optimal for a study aimed primarily at quantifying the effects of trawling history on habitat and associated fauna. However, the contrast in trawling history between the eastern and western pairs of sites allowed for an analysis of how trawling may have impacted these sites.

We used trawl logbook data from the state of Oregon as one indicator of the history of trawling at the four study sites. Data for vessels that landed shrimp in other states were considered minimal and not included here because of a lack of availability of Washington and California ocean shrimp logbook data after 1992 (Hannah, 1999). The logbook information provides only haul start locations and not actual trawl paths; therefore it must be regarded as a crude index of the level of trawling at these sites. However, the pattern of the data that is available indicates that all four study sites have been predominantly impacted by ocean shrimp trawls. Ocean shrimp trawl start locations (starts) within these four sites from 1988 through 2007 averaged between 0.65 and 8.25 starts/yr (means for 5–year periods are shown in Fig. 2A), whereas groundfish trawl starts/yr averaged from 0.05 to 0.35 starts/yr. The dominance of ocean shrimp trawling at these sites is also understated by these averages because the available shrimp trawl logbook data are a subsample of the total ocean shrimp trawl effort (26–75% of total effort included; Hannah, 1995) whereas the groundfish trawl data represent a more complete census. The logbook data also show a large difference in ocean shrimp trawling history between each of the site pairs with similar latitude (between 1A and 1B, and between 2A and 2B in Fig. 2A). For the northern pair, the easternmost site (1B) has received on average, about seven times more ocean shrimp hauls than the western site (1A). The easternmost southern site (2B) has received an average of about six times more ocean shrimp hauls than the more western site (2A). Hereafter the two eastern sites will be referred to as heavily trawled (HT) and the western sites as lightly trawled (LT).

To conduct seafloor habitat surveys of the four sites, we chartered the 21-m shrimp fishing vessel *Miss Yvonne*, out of Newport, OR. Video surveys were conducted with a Phantom HD2+2 (Deep Ocean Engineering, San Leandro, CA) remotely operated vehicle (ROV) during 20–23 June 2007. Using this system, we gathered standard-resolution video and GPS location data along each of 21 transects (Fig. 1), which were viewed and recorded in real time. The transects were spaced systematically across each site; however, actual transect paths were dependent on the prevailing direction of vessel drift. Thus, they varied in orientation and in some instances were divided into segments because of unusable portions (Fig. 1). Lighting was provided by two 200W lights (Nuytco Research Limited Newtlite, North Vancouver, BC). This system is also equipped with two parallel forward-facing lasers (15 mW, red), situated 10 cm apart and aligned with the central axis of the primary camera (forward facing oblique), that can be used for scaling the field of view and objects viewed by the camera.

All four sites at Nehalem Bank had similar depth ranges (Table 1). The areas and linear distances surveyed were also similar, with the exception of site 2B, where an equipment malfunction resulted in a lack of
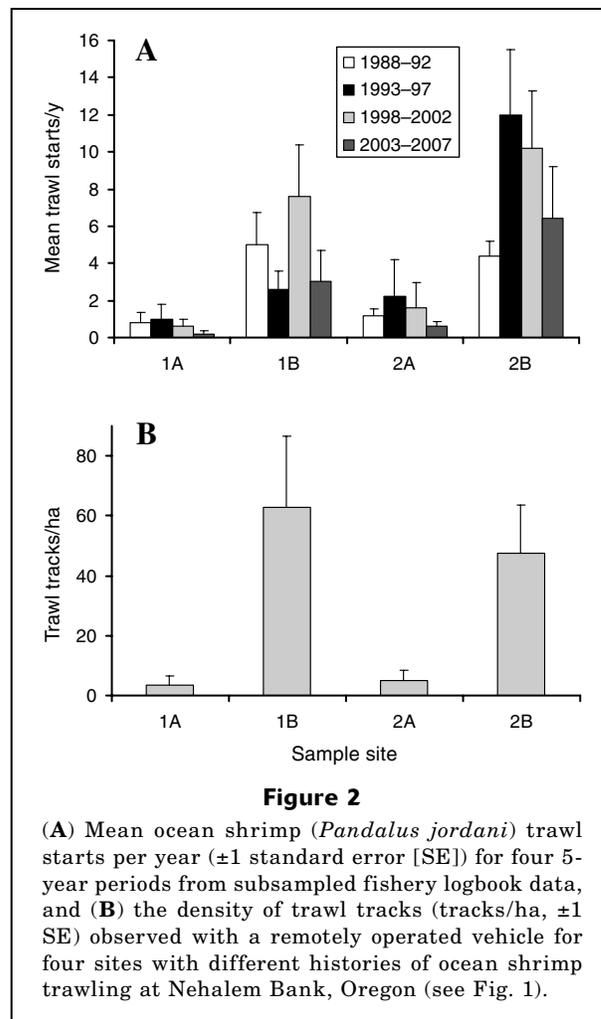
Figure 2

(**A**) Mean ocean shrimp (*Pandalus jordani*) trawl starts per year (±1 standard error [SE]) for four 5-year periods from subsampled fishery logbook data, and (**B**) the density of trawl tracks (tracks/ha, ±1 SE) observed with a remotely operated vehicle for four sites with different histories of ocean shrimp trawling at Nehalem Bank, Oregon (see Fig. 1).

ROV position data for a portion of two transects, reducing the linear distance surveyed to 7.11 km in comparison to about 9.30 km for each of the other sites.

Video analysis

Processing of video data began with an initial review of the tapes to identify usable segments for quantitative analysis. Only short segments of video proved unusable, because of poor visibility, or because the ROV was either too far above the bottom, off the intended transect, or briefly pulled sideways by the research vessel. This initial review identified start and stop times of each usable segment for subsequent quantitative analysis (Table 1). Transects for which we report data are composites of these large segments of usable video data.

Organisms, and other features, including trawl tracks and biogenic features such as hagfish (*Eptatretus* spp.) burrows, were enumerated from the video only if they were in view at the vertical center of a standard video screen (50% line), where the lasers were also aligned. This approach avoided an unrealistic extension of the top of the camera's estimated field of view beyond the

Table 1

Depth range (m), number of transects surveyed, and area (ha) and linear distance (km) of transects surveyed with remotely operated vehicle at the four mud seafloor sampling sites at Nehalem Bank, Oregon (see Fig. 1), June 2007.

Sampling site	Depth range (m)	Number of transects	Area surveyed (ha)	Distance surveyed (km)
1A	148.3–154.4	5	1.51	9.25
1B	150.5–153.8	5	1.23	9.30
2A	149.4–155.7	5	1.16	9.30
2B	146.2–156.0	6	0.76	7.11

practical limits of visibility. As organisms crossed the 50% line, they were counted and visually identified to the lowest taxonomic level possible, with the exception of pandalid shrimp, which were very numerous but were not counted. Large white sea whips were all recorded as *Halipteris* spp.; however, some of the smaller specimens may actually have been *Stylatula* spp. Hagfish burrows were too numerous to count completely throughout the video footage and therefore were subsampled by randomly selecting three two-minute segments per videotape (26.2-min average duration) and counting all of the burrows in these subsamples.

We estimated the area of the belt transects surveyed by combining information on the change in position of the ROV over time and the width of the camera field of view at the 50% line. The on-ground width of the camera's field of view was calculated by measuring the distance between the two laser dots (mm) on a standard video screen every 30 seconds (based on the imprinted video time stamp) and applying an established relationship between the screen laser width and the on-ground width of view of the camera. Position data for the ROV were smoothed with a 9-point moving average before the distance covered in each 30-second interval was measured. A simple straight line "distance traveled" was calculated for each 30-second interval based on the smoothed position data at the start and end points of the interval. This distance was then multiplied by the average of the two estimates of the width of view at the start and end of each 30-second interval to approximate the total area surveyed. These areal estimates were then summed across all reviewed 30-second intervals to estimate the area in each belt transect.

To determine how ocean shrimp trawling may have affected the size distribution of sea whips, we measured the approximate size of all sea whips as they were enumerated at the 50% line. The measurement was taken when the base of the organism was at the 50% line, expressed as a multiple of the laser width separation (10 cm) in that video frame. Frequently, with the base of large sea whips positioned at the 50% line, only the bottom portion of the sea whip was visible. In these instances, the visible portion of the sea whip was measured and recorded as a minimum measurement, but was not excluded from the analysis.

Statistical analysis

We compared the densities of invertebrates and physical bottom features, such as hagfish burrows and trawl tracks, between LT and HT sites (Fig. 1) using analysis of variance (ANOVA). Trawling history (LT or HT) and block (northern or southern station pair) were treated as main effects with interaction, and transects were treated as replicate samples. Although our primary interest was the effect of trawling on seabed structure and structure-forming invertebrates, we included in our statistical analysis all fish and invertebrate groups that were encountered in at least 50% of the transects, according to the approach of McConnaughey et al. (2000). Density data were transformed by using Box-Cox transformations with a displacement of 0.001 before ANOVA. The Box-Cox transformation employs a log-likelihood function to find a power transformation that best normalizes the data (Sokal and Rolf, 1981; McConnaughey et al., 2000). The residuals from each ANOVA were tested for normality with the Shapiro-Wilk goodness-of-fit test. Box-Cox transformations successfully normalized the density data for all of the taxa we compared statistically, with the exception of Dungeness crab (*Cancer magister*) and hagfish, as well as for the physical features we enumerated (trawl tracks and hagfish burrows). Sea whip length data were not adequately normalized by transformation ($P < 0.01$). For data that were not successfully normalized ($P > 0.05$), nonparametric Wilcoxon rank sum tests were applied to the northern and southern station pairs separately by using JMP® 6 statistical software (SAS Institute, Inc., Cary, NC). To compare the invertebrate species diversity between LT and HT sites, we calculated the Shannon-Wiener diversity index (Pielou, 1969) as well as species richness, defined as the number of species or taxonomic groups encountered at each site per unit of area sampled (Fig. 1).

Results

Hagfish burrows were very abundant and were the dominant structural feature of the sediment surface at all four sites (Fig. 3A). These burrows were mounds in the seafloor, with cone-shaped depressions in the center, ranging in diameter from approximately 10 to 60 cm. We

Figure 3

(**A**) Numbers of hagfish (*Eptatretus* spp.) burrows (thousands/ha, ±1 standard error [SE]) and (**B**) the Shannon-Wiener diversity index for all invertebrate species and species groups at two lightly and heavily trawled sites at Nehalem Bank, Oregon (see Fig. 1).
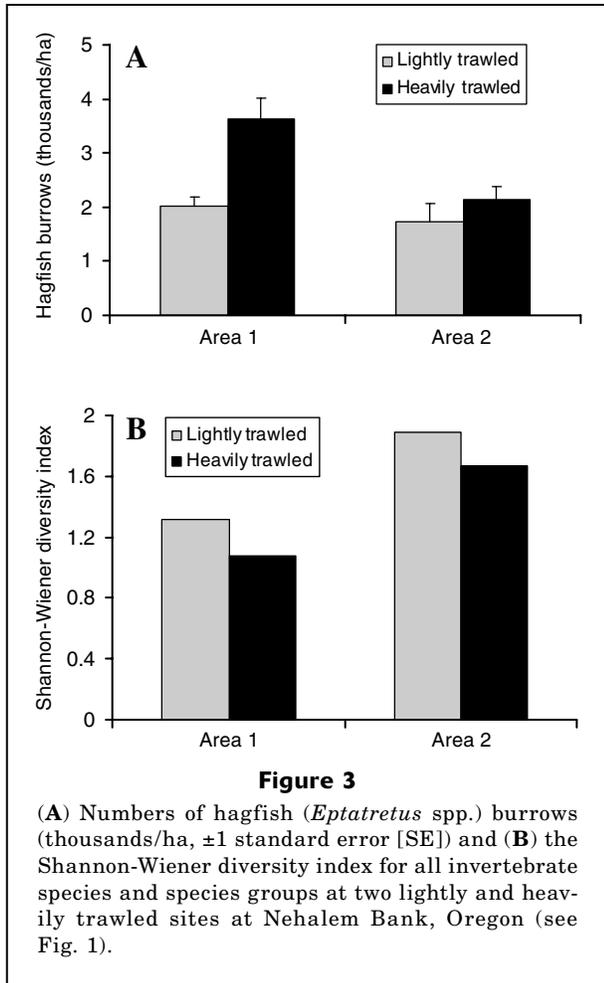
occasionally observed hagfish using the burrows. Counts of trawl door tracks, by site, corresponded generally with the average index of trawling history from logbook data (Fig. 2), however the trawl track data indicated more trawling at site 1B than at 2B and the logbook data indicated more trawling at 2B. The trawl door tracks that we observed were relatively large features in this very flat mud habitat, consisting of linear furrows about 0.2–0.5 m deep. The habitat at all four sites appeared very similar, but a few very small, low-relief, rocky outcrops were noted within site 1A. The most abundant benthic macroinvertebrates that we observed were sea whips and orange sea pens (*Ptilosarcus gurneyi*) at the two northern sites and sea whips and heart urchins (*Brisaster* spp.) at the two southern sites (Table 2). Unidentified flatfish, eelpouts (Zoarcidae), Pacific hake (*Merluccius productus*), and rockfishes (*Sebastes* spp.) were the most abundant fish species observed at the four sites (Table 2).

Analysis of variance showed substantial heterogeneity between the northern and southern site pairs, confirming the appropriateness of using the blocking variable. Sea whips and orange sea pens were more abundant at the northern sites (Table 2, blocking variable $P<0.001$), whereas heart urchins, squat lobsters (Galathoidea spp.), Pacific hake, eelpouts, juvenile rockfish, and skates (Rajidae) were more abundant at the southern sites (blocking variable $P<0.05$). The density of hagfish burrows was higher at the northern sites (Fig. 3A, blocking variable $P<0.001$). The density of trawl tracks was not significantly different between northern and southern site pairs (Fig. 3B, blocking variable $P>0.05$).

Statistically, trawling history (LT or HT) accounted for some of the heterogeneity between sites. The HT sites had more hagfish burrows (Fig. 3A, $P<0.05$) and trawl tracks (Fig. 2B, $P<0.01$) contributing to physical complexity, but had reduced densities of sea whips (Table 2, $P<0.01$). Densities of the orange sea pen were also lower at HT sites, but the difference was not statistically significant. The apparent influence of trawling history on the density of sea whips was much greater at the southern sites (interaction $P<0.01$), indicating that the effect of ocean shrimp trawling on sea whips could be variable between areas and possibly density dependent, having greater impacts at sites that are less favorable habitat for sea whips. It is also possible that this interaction indicates differences in sea whip abundance between sites that are unrelated to trawling history.

Several other benthic macroinvertebrates were observed at lower densities at the HT sites (Table 2) (indicating negative effects from chronic trawling) such as the flat mud star (*Luidia foliolata*, $P<0.001$), unidentified sea stars (Asteroidea, $P<0.05$), and squat lobsters (unidentified Galathoidea, $P<0.001$). The reduction in squat lobster density from trawling was greatest at the southern sites, where squat lobster densities were also the highest (interaction $P<0.05$), again indicating variability in how trawling influenced macroinvertebrate density between sites. Although their numbers were not tested statistically, sea cucumbers (unidentified Holothuroidea) and unidentified corals (Hydrocoralia) were observed at both LT sites (present in <50% of transects) but were not observed at either of the HT sites. Three taxonomic groups of fish were also observed at lower densities at HT sites, including juvenile rockfish ($P<0.01$), eelpouts ($P<0.01$), and skates ($P<0.05$).

Wilcoxon rank sum tests showed that for the southern sites, mean sea whip length was greater at the HT site ($P<0.001$) because of a relative lack of smaller individuals (Fig. 4). The difference in mean length between the northern HT and LT sites was not significant ($P>0.05$). Although not tested statistically, sea whips were much larger at the northern than at the southern sites where their densities were lower (Fig. 4).

Invertebrate diversity based on the Shannon-Wiener diversity index was higher at the LT sites (Fig. 3B) and generally higher at the southern sites because of reduced dominance of sea whips (Table 2). Species richness per unit of area surveyed was greatest at the two southern sites and was not consistently reduced at HT sites (13.8 and 17.1 taxonomic groups/ha at sites 2A and 2B, 9.3 and 10.6 taxonomic groups/ha at 1A and 1B, respectively). The absolute number of taxonomic groups was highest at the LT sites. Fourteen and 16 of the 17

Table 2

Mean densities (number/ha) and standard errors (SE) of epibenthic macroinvertebrates (pandalid shrimp excluded) and fish at four mud-habitat sites with different histories of ocean shrimp (*Pandalus jordani*) trawling off the northern Oregon coast (see Fig. 1). *P*-value shown is for the effect of trawling history (lightly or heavily trawled) on density in a two-factor analysis of variance on Box-Cox transformed data (ns=nonsignificant at *P*>0.05, nt=not tested, nm=not meaningful).

Taxon				Density (number/ha)				
1A		1B		2A		2B		
Mean	SE	Mean	SE	Mean	SE	Mean	SE	*P*-value
Invertebrates								
Halipteris spp. (sea whips)	452.9	51.2	459.5	46.9	190.1	10.0	60.4	11.8	0.0025
Ptilosarcus gurneyi (orange sea pen)	141.8	48.6	100.8	9.2	26.9	9.7	14.5	4.1	ns
Stylasterias forreri (fish-eating star)	21.1	3.4	28.0	6.7	19.8	3.9	28.0	7.4	ns
Luidia foliolata (flat mud star)	28.8	4.1	9.7	1.9	27.2	3.5	7.8	2.8	0.0001
Unidentified Asteroidea (sea stars)	3.3	1.0	4.2	1.9	6.8	0.9	2.0	2.0	0.0236
Brisaster spp. (heart urchins)	103.6	42.9	44.8	7.1	92.6	14.1	96.4	14.9	ns
Cancer magister (Dungeness crab)	2.9	1.4	2.5	1.0	9.0	3.7	4.5	3.1	ns[1]
Unidentified Ophiuroidea (basket stars)	7.9	2.9	4.9	1.6	0.0	nm	0.0	nm	nt
Unidentified Galatheoida (squat lobsters)	2.0	0.9	0.8	0.8	92.0	10.9	4.5	3.1	0.0003
Rossia spp. (bobtail squid)	2.4	1.2	3.2	1.9	3.9	2.1	2.0	2.0	nt
Unidentified Octopodidae	0.0	nm	0.0	nm	0.0	nm	0.7	0.7	nt
Unidentified anemone	6.7	4.0	2.5	1.0	0.0	nm	0.0	nm	nt
Unidentified corals (Hydrocoralia)	1.4	1.4	0.0	nm	0.9	0.9	0.0	nm	nt
Unidentified Echinoida (sea urchins)	1.4	1.4	0.0	nm	23.6	13.2	2.0	2.0	nt
Unidentified Holothuroidea (sea cucumbers)	0.6	0.6	0.0	nm	11.9	2.0	0.0	nm	nt
Unidentified invertebrates	2.0	0.9	0.9	0.9	6.4	2.7	2.9	1.9	nt
Fishes								
Unidentified flatfish	359.1	44.4	315.7	24.8	322.3	22.2	458.7	34.4	ns
Merluccius productus (Pacific hake)	143.8	65.6	188.6	18.1	340.3	19.7	269.0	47.6	ns
Zoarcidae (eelpouts)	341.3	41.4	101.4	13.9	325.3	52.0	337.6	74.5	0.0051
Sebastes spp. (rockfishes)	55.7	9.0	20.9	7.8	94.1	16.7	62.2	7.9	0.0025
Eptatretus spp. (hagfishes)	1.4	0.9	3.9	1.8	7.2	2.3	10.2	3.5	ns[1]
Raja spp. (skates)	6.9	2.8	0.8	0.8	13.9	2.0	10.9	5.6	0.02
Unidentified roundfish	3.1	2.1	0.0	nm	19.2	18.2	6.1	2.3	nt
Anoplopoma fimbria (sablefish)	1.4	1.5	0.9	0.9	2.0	1.3	6.1	2.9	nt
Hippoglossus stenolepis (Pacific halibut)	0.0	nm	0.0	nm	2.7	1.7	0.0	nm	nt
Microstomus pacificus (Dover sole)	6.1	6.0	0.0	nm	9.4	5.8	3.1	2.1	nt
Hydrolagus colliei (spotted ratfish)	7.2	3.0	0.0	nm	62.1	15.3	0.7	0.7	nt
Sebastes elongatus (greenstriped rockfish)	1.3	0.8	0.0	nm	1.2	1.2	0.0	nm	nt
Cottidae (sculpins)	0.0	nm	1.6	1.0	0.0	nm	1.4	1.4	nt
Agonidae (poachers)	23.0	4.1	11.3	3.2	0.0	nm	0.0	nm	nt
Unidentified fish	0.0	nm	0.0	nm	0.0	nm	2.0	2.0	nt

[1] Not normalized by Box-Cox transformation, but ns in both Wilcoxon tests.

taxonomic groups identified in Table 2 were present at sites 1A and 2A, respectively, whereas only 13 of these groups were recorded for sites 1B and 2B.

Discussion

The data presented here indicate that fishing with ocean shrimp trawls in the deepwater mud habitats near Nehalem Bank has reduced invertebrate diversity and negatively impacted the abundance of several common macroinvertebrate taxa, such as sea whips, sea cucumbers, flat mud stars, sea stars, and squat lobsters (Table 2). For sea cucumbers and squat lobsters, the negative effects on abundance are probably a result of both capture in ocean shrimp trawls and mortality from physical damage caused by trawl doors and groundlines. For the other taxa, the physical effects of trawl doors and groundlines are probably most important. The four Nehalem Bank sites studied here represent a small

Figure 4

Length frequency of sea whips (*Halipteris* spp.) measured in multiples of the 10-cm interlaser width of a remotely operated vehicle at four sites with different histories of ocean shrimp trawling at Nehalem Bank, Oregon (see Fig. 1).
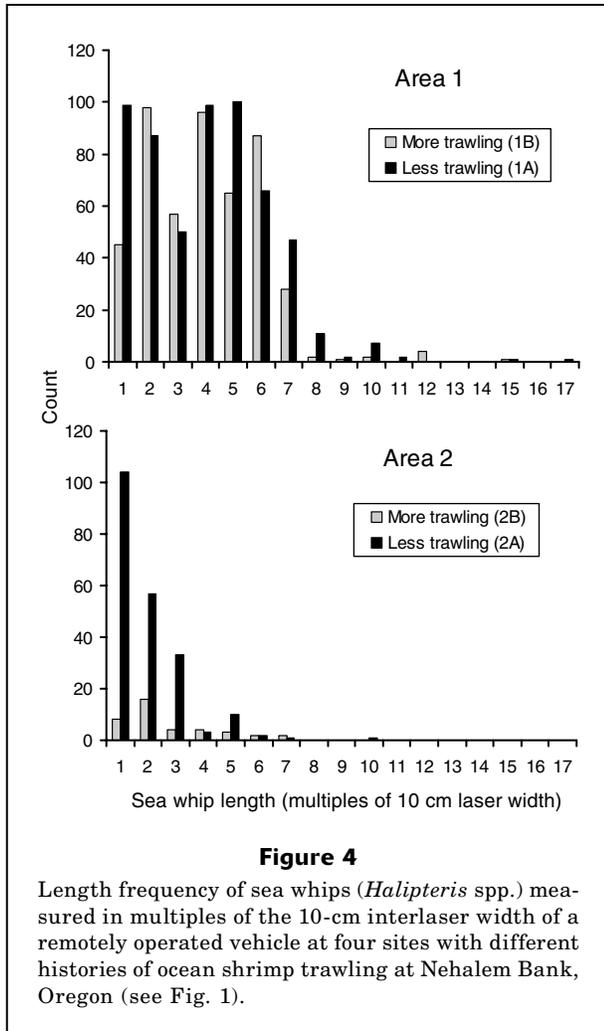
portion of the mud-seafloor habitat that receives some trawling annually for ocean shrimp, which in waters off Oregon can be more than 550,000 ha when ocean shrimp stock abundance is high (Hannah, 1995). Densities of many invertebrate taxa were very different at the northern and southern site pairs in this study, indicating a need for more spatially extensive research to understand the impacts of ocean shrimp trawling on habitat over a fishery scale (Thrush et al., 1998; Kaiser, 2003). The statistical significance of the interaction terms in the two-factor ANOVAs for sea whips and squat lobsters shows that the long-term fishery-scale effects of ocean shrimp trawling may depend on other habitat-specific influences on invertebrate density, in addition to fishery-related factors. More extensive sampling is needed to determine if other heavily trawled areas most closely resemble site 1B, site 2B, or something else entirely.

The changes we observed in HT sites at Nehalem Bank were less extreme than those attributed to groundfish trawling in other U.S. west coast studies (excluding Alaska). Engel and Kvitek (1998) studied HT and LT bottom trawl sites in more sandy habitats

at slightly shallower depths in California, and found large reductions in most of the large epifaunal species or species groups at HT sites (50–90% reductions, Fig. 4 in Engel and Kvitek, 1998). Hixon and Tissot (2007) studied sites of mud habitat with different trawling histories off southern Oregon at deeper depths than those of our study. They found a large reduction in macroinvertebrate abundance on trawled seafloors, including an almost complete elimination of *Stylatula* spp., as well as a major shift in the dominant invertebrate taxa. Interpretation of their study however, is complicated by the fact that the sites they compared had nonoverlapping depth ranges (their "trawled" site was 274–361 m deep, "untrawled" site was 183–215 m deep), confounding depth and trawling-related effects on the biota. The diversity of macroinvertebrates was generally lower at HT than at LT Nehalem Bank sites in our study; however, most taxa were not as severely reduced as those in the studies by Engel and Kvitek (1998) and Hixon and Tissot (2007). Also, some species or groups that are considered vulnerable to trawl effects, like sea whips (Wilson et al., 2002) and orange sea pens, were found in both HT sites at Nehalem Bank and were abundant in HT site 1B (Table 2). Moreover, the invertebrate taxa found at all four Nehalem Bank sites were similar, except for the notable absence of sea cucumbers and unidentified corals at HT sites, a likely effect of the trawl fishery.

Smoothing of the sea bed and related physical reduction in habitat complexity noted in some other studies of bottom-fishing impacts (Auster et al., 1996; Collie et al., 1997; Engel and Kvitek, 1998) were not seen at the HT sites at Nehalem Bank. Instead, we found an increased roughness of surface topography resulting from more trawl tracks, similar to the findings of Tuck et al. (1998), along with more hagfish burrows, and increasing habitat complexity. However, our ROV video was mostly useful for detecting large topographic features like trawl tracks and hagfish burrows and therefore we may have missed changes in microtopography caused by trawling. Schwinghammer et al. (1996) and Kaiser et al. (2002) have argued that detecting the physical effects of trawling on habitat is highly dependent on the scale of measurement.

The moderate reductions in macroinvertebrates and lack of a reduction in physical habitat complexity from ocean shrimp trawling at Nehalem Bank could also be related to factors that are specific to the ocean shrimp fishery. The effect of trawling on seafloor habitats depends on local factors, such as gear, the spatial and temporal intensity of the fishery, the type of habitat, and the types of organisms normally found in that area (Jones, 1992; MacDonald et al., 1996). The semipelagic trawl gear used to fish for ocean shrimp has the potential for lower impacts on habitat and macroinvertebrate populations than typical bottom trawl gear because the net itself is not in contact with the seafloor and thus reduces capture efficiency for demersal fish and benthic macroinvertebrates (Hannah and Jones, 2003). The intensity of U.S. west coast ocean shrimp and bottom

trawl fisheries is also low in comparison to that of trawl fisheries in other areas, such as the Gulf of Mexico and New England (NRC, 2002). Effort in the ocean shrimp trawl fishery has also been reduced recently by a vessel buyback program that has reduced fleet size. Macroinvertebrate populations in the HT sites at Nehalem Bank may have recovered somewhat from the impacts of the heaviest trawling during earlier years (Fig. 2A). However, recovery is not likely to be a significant factor for *Halipteris* spp., which are believed to be very long-lived (Wilson et al., 2002). The deep mud habitats being trawled for ocean shrimp have low levels of natural disturbance and are considered some of the most vulnerable to the negative effects of physical disturbance and are expected to have long recovery times (Jones, 1992; Kaiser, 1998; Tuck et al., 1998; Kaiser et al,. 2002; Dernie et al., 2003). Over time, additional surveys of the Nehalem Bank sites should provide insight into both recovery time and the condition of fully recovered mud-seafloor habitats (recently closed sites 1A and 2A) as well as continued changes in areas that experience additional trawling (e.g., sites 1B and 2B).

Our data indicate that the effect of the ocean shrimp fishery on the complexity of mud-seafloor habitats near Nehalem Bank may be a mixture of physical and long-term ecological effects. The increased density of hagfish burrows at HT sites was unexpected. This finding conflicts with most other trawl-impacts studies that evaluated biogenic features in soft-bottom habitats (Auster et al., 1996; Simpson and Watling, 2005; Stone et al., 2005). One possible explanation for this difference is that through fishery removal of hagfish predators and competitors, or from supplementation of hagfish food resources with discards, the ocean shrimp fishery is creating conditions that favor the growth and survival of hagfish. This hypothesis is in general agreement with the findings from other studies that have shown benefits for scavenger populations as a result of trawling (Groenewold and Fonds, 2000; Rumohr and Kujawski, 2000), and is consistent with what little is known about hagfish food habits (Martini et al., 1997). It is unknown how increases in hagfish populations may have in turn influenced other aspects of the benthic ecology of the ocean shrimp grounds; however, it is possible that this ecological effect could generate changes that are equivalent to, or greater than, the direct physical effects of trawling. If fishery discards are stimulating hagfish population growth, it is possible that this effect will diminish over time because fish bycatch in the ocean shrimp fishery has been reduced roughly 66–86% (in terms of weight) by the requirement (since 2002) that vessels use approved bycatch reduction devices (Hannah and Jones, 2007).

To adequately understand and manage the ecosystem effects of trawl fisheries will require a great deal of information, well beyond basic information on removals and the physical effects of trawl footropes and doors. To prevent long-term detrimental effects from trawling, information on recovery times of macroinvertebrate populations is critical. The data developed here provide an opportunity for follow-up studies to better understand the recovery of macrobenthos and other changes in habitat after the cessation of trawl impacts at the Nehalem Bank closed area (Fig. 1). They also provide a starting point for understanding the effects of the ocean shrimp trawl fishery on the ecosystem.

Acknowledgments

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