Central Coast Trawl Impact and Recovery Study: 2009-2012 Final Report

A REPORT TO THE CALIFORNIA OCEAN PROTECTION COUNCIL

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Executive Summary

This report summarizes the results of a multi-year study (June 2009 to December 2012) to assess the impacts of bottom trawling on seafloor habitats and associated biological communities. The Central Coast Trawl Impact and Recovery (CCTIR) study was funded by the California Ocean Protection Council (OPC) through a State Coastal Conservancy grant (#10-058) to The Nature Conservancy (TNC), and by private funders. This project used small foot-rope trawl gear in an experimental study conducted in unconsolidated, soft-sediment habitat on the continental shelf off of Morro Bay, California. It was a collaborative research effort that involved numerous federal, academic, NGO, and fishing partners in the design and execution of the research.

Research Objectives

The objectives of this research project were to compare any changes to the structural and biological attributes of the seafloor before and after bottom trawling at known levels of trawling effort, as well as to monitor the recovery of the seafloor post-trawling. Specifically, we assessed changes to the small-scale topographic complexity and abundance of mobile and sessile (attached) invertebrates that are important attributes of fish habitat that could be attributed to trawling impacts. The research questions that were addressed by this study included:

- How did micro-topographic complexity of the seafloor and invertebrate density differ between trawled plots and control plots over time in a depositional soft-sediment environment?
- How did spatial and temporal patterns in seafloor community structure vary under different levels of trawling intensity and over time after trawling?
- What was the catch of flatfish and bycatch of associated species using trawl gear in this soft-bottom habitat?

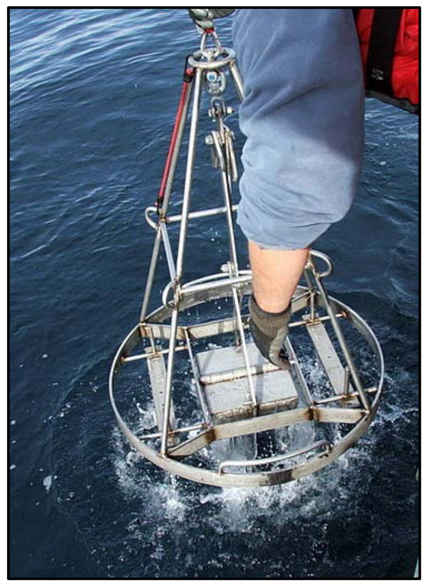
Research Design

The experimental design for this project underwent extensive peer-review by the Ocean Science Trust and external reviewers, including representatives of the fishing industry. The study area was apportioned into eight treatment plots, each measuring 1000 m x 300 m at a water depth of approximately 170 m, over soft-bottom habitat on the continental shelf. Four of the plots were selected to be trawled at specific levels of intensity (based on historical effort data), while the remaining four plots served as non-trawled control plots against which changes in the trawled plots were evaluated over time. The study employed a thirty-three foot small-footrope otter trawl for the directed trawling; this is the gear required to be used in this shelf habitat shoreward of the trawl Rockfish Conservation Area. A remotely-operated vehicle (ROV) was used to collect photographic and video data and a modified Van Veen bottom grab sampler was used to collect sediment samples in the study plots before and after trawling.

F/V South Bay bottom trawler

Small footrope trawl net

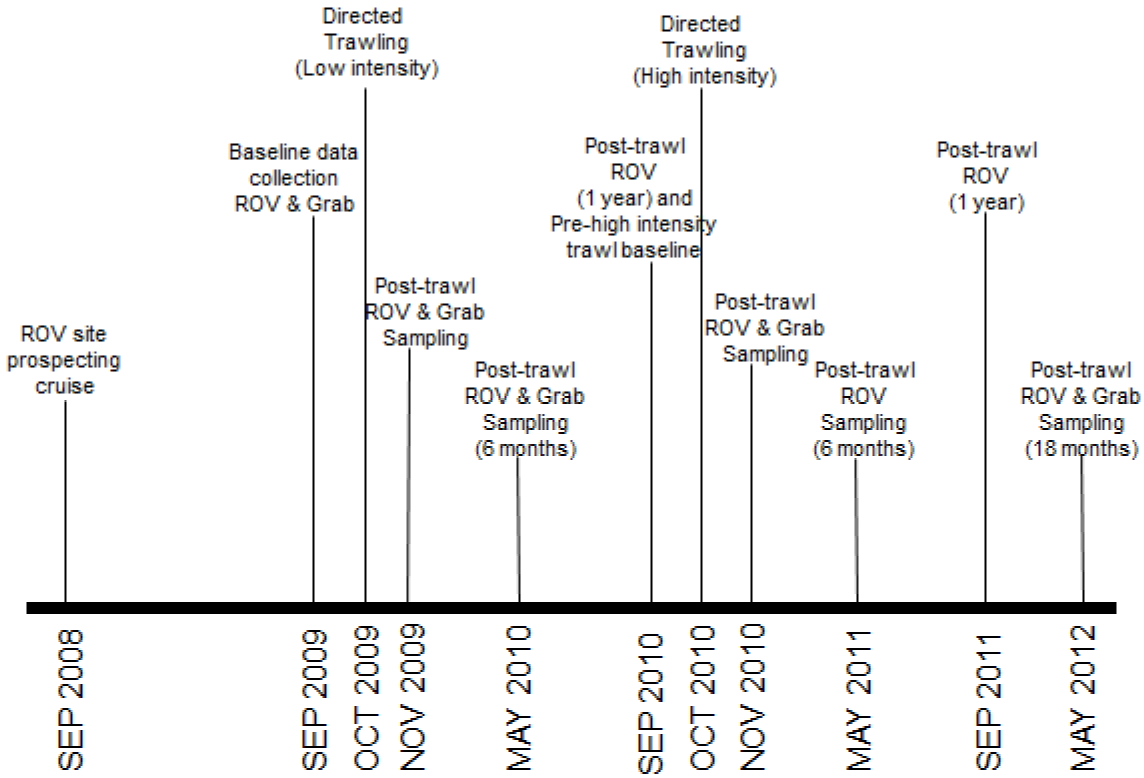
Remotely-operated vehicle



Van veen grab sampler

Research Timeline:

Pre-trawling baseline surveys were conducted in the fall of 2009. The first directed trawling treatment occurred in October 2009, with 'low-intensity' trawling equivalent to two trawl passes over the entirety of each of the four trawl treatment study plots. In October 2010 the 'high-intensity' trawling treatment was conducted, with five trawl passes over the entirety of each trawl treatment plot. Post-trawling surveys to assess impacts and recovery occurred at two-weeks, six months, and one year after each of the directed trawling efforts. A final survey to complete Year 3 of the study was conducted in May 2012, approximately one and one-half years post-high-intensity trawling.



Results and Conclusions

Our results showed that the heavy trawl doors that hold the trawl net open leave persistent scour marks in the seafloor, but there were few other measurable effects that could be attributed to the experimental trawling in this habitat. Our results on the effects of bottom trawling activity on the structural attributes of fish habitat in soft sediments of the outer continental shelf include:

- *Trawl door scour marks can persist for up to a year in unconsolidated sediments.*

  We found that tracks left in the seafloor by the heavy trawl doors scouring the seafloor, measuring as wide as 20 cm and as deep as 10 cm, persisted for at least a year following low-intensity trawling.

- *Minimal impact to micro-topographic structure on the seafloor following both low- and high-intensity bottom trawling.*

  Some smoothing out of the seafloor, as measured by reductions in bioturbated sediments, were observed in the trawled plots compared to controls; however, these minimal differences with respect to micro-topographic structure on the seafloor were statistically significant only during one sampling period.

- *No measurable impacts of bottom trawling on macro-faunal invertebrate densities*

There were no observed differences in densities of either sessile invertebrates or mobile invertebrates between the trawled or control plots that could be attributed to trawling.

- *High spatio-temporal variation in macro-faunal invertebrate densities.*

  We found that densities of both sessile and mobile invertebrates were both low in the study area, and that densities varied considerably across the study plots and between study periods. This suggests that any effects of trawling on epifaunal invertebrate communities must be considered in the context of significant background environmental variation.

- *No difference in the composition of infaunal invertebrates between trawled and control plots.*

  We found that species diversity in the infaunal community was low relative to other locations along the continental shelf at similar depths, and that diversity did not vary significantly between trawled and control plots immediately following low-intensity trawling.

Typical soft-bottom habitat with low and "patchy" abundance of invertebrates. Above left photo shows examples of mobile invertebrates such as a small octopus surrounded by brittlestars; above right shows an attached fleshy sea pen. Bottom left are rapidly colonizing but short-lived polychaete worms with a juvenile rockfish, and bottom right, a Petrale Sole (commercially important flatfish) surrounded by brittlestars.

Trawl door scour marks seen one-year after low-intensity bottom trawling.

In conclusion, this study showed that bottom trawling with small footrope trawl gear impacted the unconsolidated sediments of the study area via the trawl door scour marks that persisted for up to a year following trawling. However, the small reductions in micro-topographic complexity observed in trawled plots relative to control plots were generally not significant, and there were no measurable effects of trawling on densities of invertebrates, including sessile and mobile epifauana and infauna. The study area was characterized by a high degree of patchiness in space and time in the invertebrate assemblage, particularly for opportunistic species such as polychaete worms and brittlestars.

Management Implications

Trawling is still the primary way to catch flatfish and remains an important component of California's fisheries. It is important to reconcile our need for local seafood, fish landings, and fishermen's livelihoods with environmental impacts of trawling in different habitats, as well as bycatch and discard rates associated with the gear. The types of management measures this study could inform include trawl gear regulations, trawl effort controls, and spatial management of trawling to limit the footprint to avoid more sensitive habitats.

One of the great benefits of this project was the collaborative partnership that evolved among diverse stakeholders interested in moving toward a more quantitative evaluation of the impacts of bottom trawling on seafloor communities and a greater understanding of ecosystem dynamics and resilience to inform fishery management.

Introduction

Bottom trawling – where weighted nets and heavy door-spreaders are dragged across the seafloor - has been identified as a key threat to seafloor habitats. Based on limited evidence, it is thought that soft-bottom habitats tend to recover more quickly than rocky habitats (see National Research Council [NRC] 2002); however, relatively little is known about the nature of the impacts of trawling on soft-botttom seafloor communities. Currently, most flatfish — which are an important component of the groundfish fishery in California — can be caught in commercially-viable quantities only using bottom trawl gear. Understanding the impact of trawl gear on soft-bottom habitats and the time it takes those communities to recover will help us determine the most appropriate locations for bottom trawling in the "working seascape" to minimize adverse impacts on seafloor habitats, while allowing the catch of economically important fishes.

Our current understanding of bottom trawling impacts to soft sediment environments is limited both by the small number of empirical studies in these habitats and by the lack of precise estimates of fishing effort applied to the areas being studied (Collie et al 1997; Schwinghamer et al. 1998; Engel and Kvitek 1998; Watling and Norse 1998; Collie et al. 2000; Kaiser et al. 2000; Lindholm et al. 2004). To-date there are only a few trawl impact studies from the U.S. West Coast (Engel and Kvitek 1998; Hixon and Tissot 2007; de Marignac et al. 2008; Lindholm et al. 2009). These studies, while instructive, have largely been snap-shots based on limited data collected post-trawling with little knowledge of the intensity of trawling effort. Additionally, there continues to be a general paucity of relevant studies of this type on the U.S. west coast.

The Nature Conservancy (TNC) and the Institute for Applied Marine Ecology (IfAME) at California State University Monterey Bay (CSUMB), working with fishermen and other key partners, implemented a multi-year study to examine the impacts of bottom trawling on soft-bottom habitats, and the amount of time it takes for seafloor habitats to recover post-trawling. This collaborative research project is part of a larger Central Coast Groundfish Project, managed by TNC, that aims to help reform the groundfish fishery to improve the economical and environmental performance of the fishery. The goal of this collaborative research project is to inform best management practices and management decisions for bottom trawling in soft-bottom habitats along the continental shelf of California by quantifying impacts and recovery patterns after trawling.

Bottom trawling for groundfish occurs, or has occurred, on much of the continental shelf and upper slope area of the west coast over the last 80-100 years, with little information on impacts of that fishery to inform spatial management. Collecting data and information on the impacts of trawling on soft-bottom habitats, and the time it takes for seafloor communities to recover, will provide a foundation to advance spatial planning in the ocean and help reduce conflicts between conservation and fishing.

The continental shelf in California is dominated by soft-bottom habitats and very little is known about the background environmental variability or the impact of fishing gear on the habitats and associated species. One of the defining characteristics of this project was that we experimentally controlled the effort applied to the trawled study plots in partnership with local fishermen. The vast majority of studies worldwide, and all of the studies on the west coast (including studies by PI Lindholm in northern California), have been conducted without the ability to control this critical factor and have instead been forced to site their studies opportunistically in areas where specific quantitative data on trawling effort were not available.

The research questions addressed by this study include:

- How did micro-topographic complexity of the seafloor and invertebrate density differ between trawled plots and control plots over time in a depositional soft-sediment environment?

- How did spatial and temporal patterns in seafloor community structure vary under different levels of trawling intensity and over time after trawling?

- What was the catch of flatfish and bycatch of associated species using trawl gear in this soft-bottom habitat?

This research was funded by the California Ocean Protection Council (OPC), through a State Coastal Conservancy grant, two private foundations (Kabcenell Family Foundation and the Seaver Institute), and through in-kind contributions of project partners. The study design was reviewed by the California Ocean Science Trust team, an external review panel of scientists and gear experts, and local fishermen who provided important input on the research. The project represented a broad collaborative partnership among non-profits, state and federal agencies, academia, and members of the fishing community. The research effort involved key staff and resources from:

- The Nature Conservancy (TNC): TNC managed the research project and provided scientific design and support; funding and fund-raising; use of a federal trawl permit and trawl vessel; use of a remotely-operated vehicle (ROV); and contracts with partners. Dr. Mary Gleason, TNC's lead marine scientist in California and an expert on disturbance ecology, was a co-prinicipal investigator on this study. Steve Rienecke, a fishery biologist, assisted with field operations and data analysis.
- Institute for Applied Marine Ecology (IfAME), California State University Monterey Bay (CSUMB): Dr. James Lindholm, Rote Distinguished Professor of Marine Science and Policy, is an expert on trawling impacts and has conducted similar studies on soft-bottom habitats elsewhere. He was co-principal investigator and lead on study design and analyses. Donna Kline assisted with oversight of field operations, data collection, and analyses on all videographic and still photographic data.
- Marine Applied Research and Exploration (MARE): Dirk Rosen and staff provided operational support for the ROV system and associated technology.
- Central Coast commercial fishermen: Several Central Coast fishermen collaborated in the design of the study and implementation of the field research or directed trawling including: the late Ed Ewing, Tim Maricich, David Wainscott, Gordon Fox, Michelle Leary, and Mark Tognazzini and their crew members.

- Monterey Bay National Marine Sanctuary (MBNMS): Dr. Andrew DeVogelaere and other staff from MBNMS provided scientific input and coordinated use of NOAA resources (ship time, equipment, and crew) to support the research effort.
- National Marine Fisheries Service (NMFS): Dr. Elizabeth Clarke and other NMFS staff provided design and analytical advice, as well as analytical support for the project.

Methods

Study Site: The study site was located on the outer-continental shelf in Estero Bay in a primarily soft-sediment, depositional environment approximately eight nautical miles offshore from the town of Morro Bay, California. This site was selected based on site-prospecting and baseline surveys conducted aboard NOAA's *R/V Fulmar* using the *ROV Beagle* in September 2008, and in consultation with some members of the commercial fishing community in Morro Bay. It was located in a relatively productive area just shoreward of the Rockfish Conservation Area and the shelf-slope break in an area that was historically trawled for flatfish (Petrale Sole, Dover Sole, English Sole). Trawling had since ceased in the area and the experimental site had not been trawled since before 2000, based on conversations with staff at NMFS who have access to Vessel Monitoring System data, and local fishermen.

The study plots were situated at a depth of 160-170 meters and were located to avoid an area where a number of undersea cables were installed. The study site and eight study plots (each approximately 1 kilometer by 300 meters in size) are shown in Figure 1, as are reference sites along the same contours surveyed in May 2012.

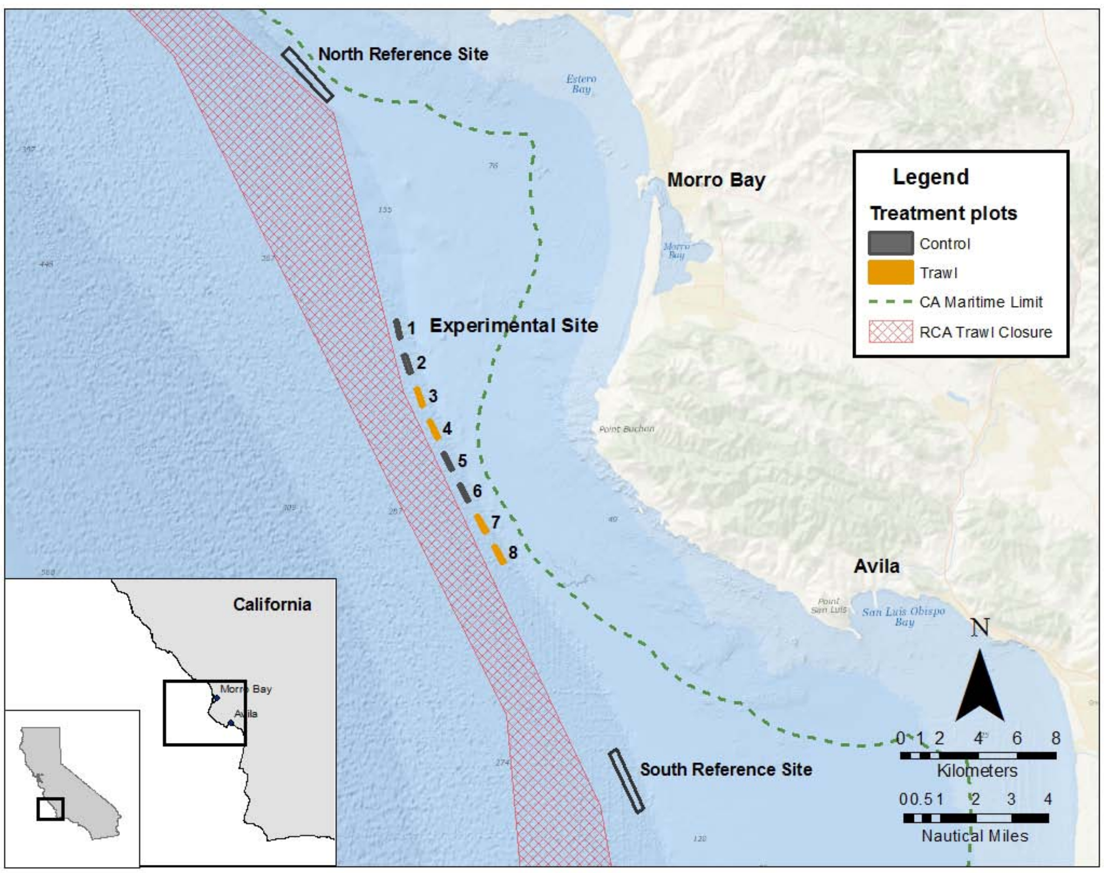


Figure 1. The study plots include four control plots (black) and four treatment plots (yellow filled) that were subjected to directed trawling of known intensity in October 2009 and 2010. For logistical reasons related to the directed trawling, trawled plots were located adjacent to one another. North and South Reference sites were surveyed in May 2012.

Research Objectives: The objective of this research project was to compare any changes to the structural (micro-topographic complexity) and biological (mobile and sessile macro-invertebrates) attributes of fish habitat across a gradient of bottom trawling effort, ranging from no recent trawling (control) to low-intensity trawling to higher intensity trawling.

The study incorporated a “Before-After-Control-Impact” (BACI) design (Manly 2009) where monitoring was conducted before directed trawling, within 2-weeks after trawling, and 6-months, 1-year and 1.5 years after trawling to provide a time series for assessing impacts and recovery relative to control plots.

The pre-trawling and post-trawling monitoring efforts utilized two primary sources of data (Figure 2):

- Visual surveys with a Remotely-Operated Vehicle (ROV) to capture video and still photo images

- Grab samples of benthic sediment and infauna

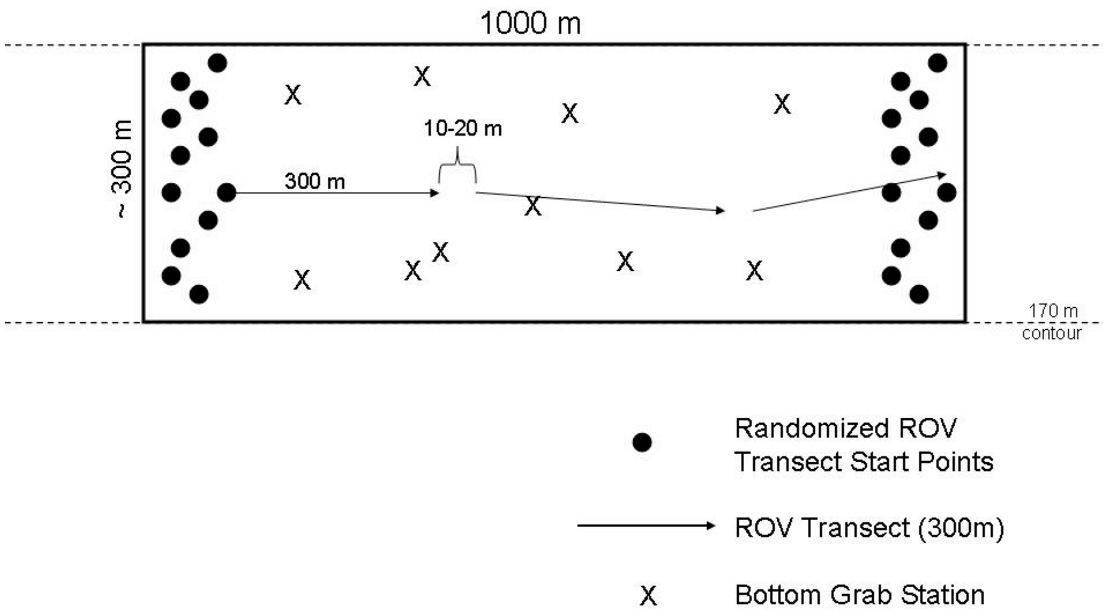


Figure 2: Idealized schematic of a study plot depicting 1) a set of randomized ROV transect start points, 2) a minimum of three ROV transects with 10-20 m separation between, and 3) randomized grab sample locations. The same scheme was used for both control and trawled plots.

Visual surveys with a Remotely Operated Vehicle: The TNC *ROV Beagle* was configured with two video cameras (forward-oblique and down-looking), a down-looking digital still camera, two down-looking lasers for image calibration, and two forward-looking lasers for estimating size of organisms and data collection area. The ROV was equipped with an altimeter and was “flown” at an altitude of approximately 0.6 – 0.8 m above the seafloor.

Each ROV transect was ~300 m in length (20 minutes in time); this length was determined based on species and habitat accumulation curves plotted from data in soft sediment communities (Lindholm et al. 2004; Lindholm et al. 2009) and from a review of preliminary data collected at the study site in the Fall of 2008. Transects were begun at randomly selected starting points located at the northwest or southeast ends of each treatment plot and followed the isobath; the precise direction of each transect depended on local conditions (winds, currents, etc.) at the time of the dive. A minimum of three, and up to six, transects were flown in each study plot during each sampling period. In May 2012, additional reference sites were added to the north and south of the study area to better characterize the unconsolidated habitat at this depth contour (Figure 1). Six ROV transects (each also ~300m in length) were conducted at each reference site for comparison to the observations at the primary study site.

Each ROV transect consisted of continuous video and digital-still photographs recorded on digital tape and electronic file. Each video transect was treated as a series of non-overlapping video frames (or quadrats). The size of a down-looking video frame at a height of 0.75 m from the seafloor was approximately 0.40 m^2. Still photographs were taken at approximately 1-minute intervals along each transect for a minimum of 20 photographs. Each still photograph covered an area of approximately 0.42 m^2. Paired parallel lasers (10-cm spacing) are used to indicate a consistent reference for still photographs (to maintain constancy in area of coverage for each image) and to size individual organisms where desired.

Micro-topographic complexity of the seafloor: The primary form of micro-topographic complexity of the seafloor at this depth and geography was bioturbated sediments. Bioturbation in this context referred to changes in the plane of the sediment (including ridges, burrows, mounds and holes) created by the movement of organisms on (such as seastars and fishes) or through (such as heart urchins) the upper centimeters of the seafloor at the sediment-water interface. These small features resulting from bioturbation can serve as habitat for small demersal fishes from a variety of species (including many flatfishes found in the study area). Video imagery and digital-still photographs were used to assess the spatial extent of micro-topgraphic complexity cover in each of the eight study plots. The percent area covered by micro-topgraphic complexity was quantified for each still photo using a digitally rendered 5 cm grid that was superimposed over each photo.

Epifaunal Macro-Invertebrates: Digital still photos were also used to assess the abundance and density of epifaunal invertebrate species (macro-invertebrates that live on top of the sediment and include both sessile and mobile species) in each study plot. Sessile organisms were assessed in downward video as well because they were not well-represented in the digital stills. Sessile, erect epifaunal organisms that extend above the plane of the seafloor (such as sea pens, sea whips, and anemones) can provide habitat structure for fishes and mobile invertebrates. Counts (and ultimately densities) were made of each identifiable organism in each photograph (identified to the lowest taxonomic level possible).

Fishes: Though this was primarily a study of fish habitat rather than of fishes themselves, we collected information on all fishes (i.e. flatfishes, eel pouts, rockfishes) observed in still photographs (and to some extent video imagery). Individuals of all observed fishes were identified to the lowest taxonomic level possible and were measured when the entire fish was present within the frame of the photo. These data represent an opportunity to explore fish-habitat associations with the seafloor in unconsolidated sediments and will be analyzed as part of future research efforts.

Grab samples**:** Protocols for the collection and analysis of seafloor sediment and infaunal invertebrate organisms using grab samples were developed based on similar studies conducted by PI Lindholm in northern California (de Marignac et al. 2009) and the Gulf of Maine (Grannis 2001). Up to five bottom grab samples were collected using a 0.1 m^2 Van Veen bottom grab at randomly selected locations within each study plot using a Latin square design (Montgomery 2012) to achieve equal distribution across plots.

The grab sampling was conducted from a separate collaborative fishing vessel than the vessel used to support ROV surveys. Samples were live-sieved in the field through a 1.0-mm mesh screen and preserved in 10%-buffered formalin. All infaunal samples were transferred to 70% ethanol after returning to the laboratory, where animals were sorted from sample debris under a microscope and identified to the lowest taxonomic level possible. An additional sub-sample for grain-size analysis was removed from the homogenate and placed in a 500-mL plastic jar with lid and stored frozen.

Directed trawling**:** The directed bottom trawling was conducted by experienced trawl fishermen using a TNC-owned federal trawl permit and vessel (F/V *South Bay*). The trawl gear employed was thirty-three foot small footrope (<8 inches) gear (described in Appendix II). Regulations require this gear to be used on the shelf shoreward of the trawl Rockfish Conservation Area where this study took place.

The vessel made multiple passes over each trawled plot in a pattern analogous to 'mowing the lawn' (Figure 3). The four experimental trawled plots were first trawled at a low (2x) level of intensity in October 2009 and again at a high (5x) level of intensity in October 2010. These levels of trawl effort were determined based on meetings with NMFS staff and their review of historical trawl effort aggregated by fishing block along the Central Coast (Jan Mason, NMFS, personal communication). Our two trawling intensities (2x and 5x) were selected to reflect both the actual range of historical trawling effort in the vicinity and to capture the potential intensity of effort in the future. Due to logistical constraints we could not separate the two trawling intensities in space but only in time; thus the low-intensity trawling was conducted in Year 1 while the higher intensity trawling followed in Year 2 of the study in the same previously trawled plots.

The trawling effort was carefully monitored by project staff and a NOAA-trained Groundfish Observer to ensure accurate trawling inside the trawl treatment plots and to record trawl catch. All species caught were recorded and identified to the lowest taxonomic level possible.

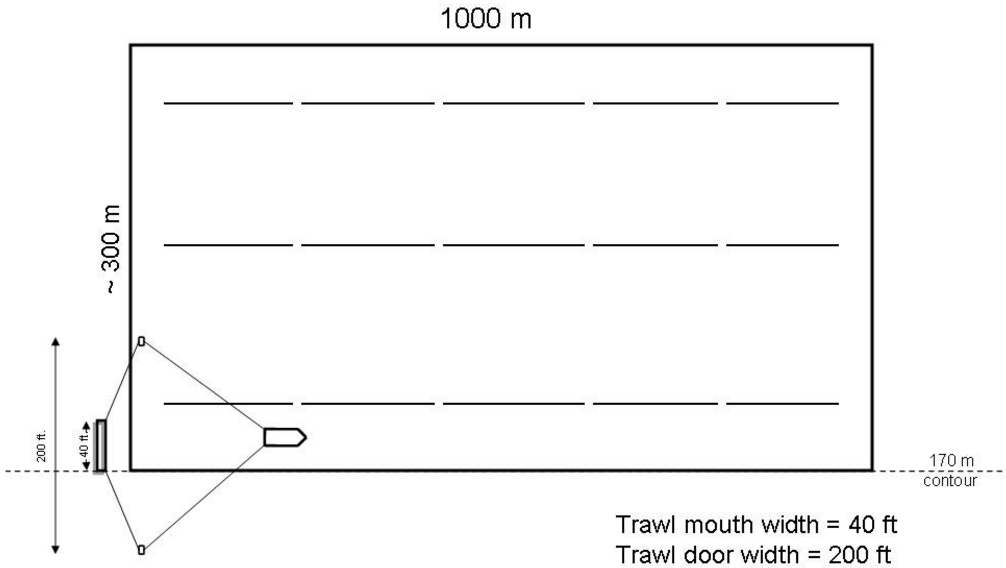


Figure 3. Idealized schematic depicting the planned distribution of bottom trawling effort across each of the eight study plots. Dotted lines represent the planned path of the bottom trawl based on the width of the footrope.

Data Analyses**:** This study incorporated a "Before-After-Control-Impact" (BACI) design (Manly 2009). Multiple metrics were used to compare trawled and control plots to test for differences between pre-trawling (before) condition and to track the trajectories of communities at each location over time following trawling at the two different intensities (after-control-impact).

Digital-still photographs or downward video were used to quantify the primary metrics of the study, including percent cover of micro-topographic complexity of the seafloor and the density of epifaunal invertebrate species in each study plot. Epifaunal invertebrates were further sub-divided into mobile and sessile macro-invertebrates (>10cm). Every organism occurring was counted and identified to the lowest taxonomic level possible. Densities were calculated based on the total area of all photographs within each transect.

Density of mobile invertebrates was assessed in both still and video imagery for the first two surveys (Sep 2009, Nov 2009), and when no difference in mean estimates were found (t=1.434, p=0.356) subsequently only in the digital stills. Downward-looking continuous video imagery was used to estimate the density of sessile invertebrates and larger scale (>20 cm) seafloor habitat attributes that were clearly visible but were not well-sampled by the still photographs.

Digital-still photographs were also used to quantify the spatial extent of micro-topographic complexity in each of the eight study plots. The percent area covered was quantified for each still photo using a digitally rendered 5 cm grid that was superimposed over each photo. Any cell in which micro-topographic features were evident was counted.

Preliminary analyses included a Generalized Linear Model with repeated measures ANOVA (Manly 2009; Zar 2010) to statistically compare any differences in square-root, arcsine transformed percent cover of micro-topographic complexity, density of mobile epifaunal macro-invertebrates, and density of sessile macro-invertebrates between control and trawled plots and within control and trawled plots over time using the R statistical package (R Development Core Team 2008). However, questions remained about the independence of ROV transects, the low statistical power resulting from the need to pair the trawled treatments adjacent to one another, and the high number of zeros in some metrics due to low organism counts. To address these concerns a second technique was used to assess potential differences between treatments. We randomly selected 100 photos from each pair of plots for both treatments (200 total photos per treatment), and then conducted t-tests for the density-based metrics and z-tests for proportions for the percent micro-topographic complexity coverage to further assess the significance of our results. This approach increased the statistical power of our analyses considerably (Appendix III) and minimized the extent to which spatial autocorrelation influenced the results.

Research Timeline

The primary sampling period for the project was from September 2009 to May 2012. During that time period, a total of 14 research cruises were conducted aboard five vessels, including NOAA's R/V *Fulmar* and four collaborative fisheries vessels, the *Rita G*, the *South Bay*, the *Donna Kathleen*, and the *Bonnie Marietta*. Table 1 summarizes the activities conducted during the research cruises .

Table 1. Summary of research cruises and a description of associated activities. ROV transects and benthic samples represent the number of unique samples, while trawl tows represents the total number of trawls necessary in each year to achieve the desired level of effort in each pair of trawled plots. Additional ROV transects (across the study plots) were added in May and September 2011 to investigate smoothing of the seafloor following an aperiodic event in the study area. In May 2012 we added transects in reference sites to the north and south of the study area to provide context for our study site along a broader extent of the coast.

Cruise	Vessel	Description	ROV transects	Benthic samples	Trawl tows	Notes
Sep '09	Fulmar	Pre-trawling baseline ROV survey	18			
Sep '09	Rita G	Pre-trawling baseline grab sampling		80		
Oct '09	South Bay	Directed trawling (low-intensity)			16	
Nov '10	Donna Kathleen	Immediate post-trawling (low-intensity) ROV survey	46			
Nov '10	Bonnie Marietta	Immediate post-trawling (low-intensity) grab sampling		80		
May '10	Donna Kathleen	6-months post-trawling ROV survey	48			
Sep '10	Fulmar	1-year post-trawling ROV survey	29			
Sep '10	Bonnie Marietta	1-year post-trawling grab sampling		80		
Oct '10	South Bay	Directed trawling (high-intensity)			40	
Nov '10	Donna Kathleen	Immediate post-trawling (high-intensity) ROV survey	48			
May '11	Donna Kathleen	6-months post-trawling (high-intensity) ROV survey	54			**48 transects + 6 cross plots*
Sep '11	Donna Kathleen	1-year post-trawling (high-intensity) ROV survey	60			**48 transects + 12 cross plots and 4 exploratory transects*
Sep '11	Bonnie Marietta	1-year post-trawling (high-intensity) grab sampling		24		
May '12	Donna Kathleen	1.5-year post-trawling (high-intensity) ROV survey	36	9		*24 transects in the primary study area + 6 each in references sites 12 km north and south of the study site

Below we include summary results of the project, both quantitative and non-quantitative observations resulting from our sampling.

Results

Temporal Variability in the Benthic Community

One of the dominant characteristics of the study site was variability in the benthic and demersal community of invertebrate species from one sampling period to the next. Though overall both species diversity and organismal densities were low (fractions of individuals per m^2) in the study plots, we observed marked changes across two years of sampling (Figure 4) including high densities of some rapidly colonizing organisms. In particular, the abundance of some organisms like polychaete worms and brittlestars exhibited very patchy distributions, varying widely among plots and at different times during the study.

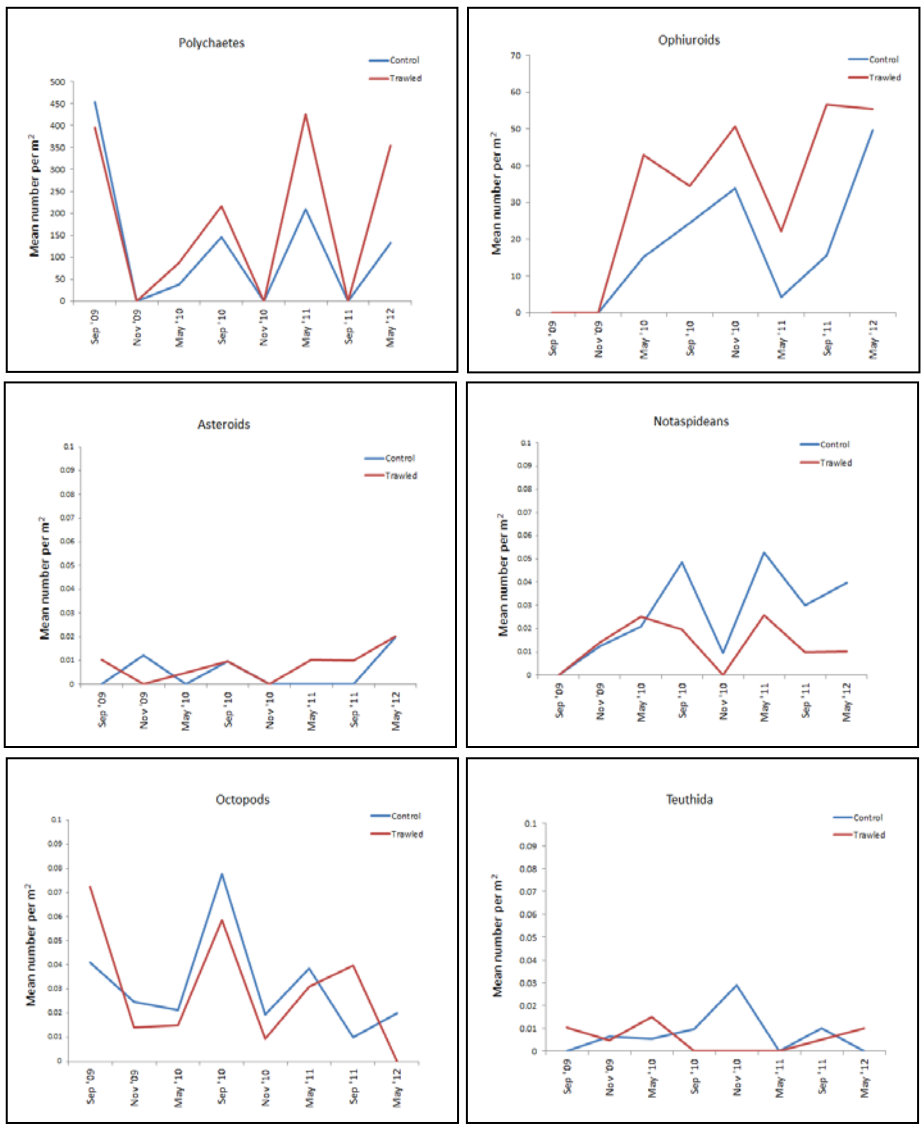


Figure 4. Temporal variability in the mean density (numbers per m^2) of six members of the invertebrate community in the study plots, including scale worms (Polychaetes), brittle stars (Ophiuroids), sea stars (Asteroids), sea slugs (Notaspideans), octopus (Octopods), and squid (Teuthida). Note the scale on the y-axis differs among plots.

Spatial Variability in the Benthic Community

Within one timer period (May 2012) we observed some variability across the eight study plots with respect to micro-topographic structure (Figure 5), while little variability was observed with respect to densities of sessile and mobile invertebrates. The north reference site had a similar assemblage of sessile invertebrates to the primary study area. The south reference site had more mobile invertebrates (primarily pink shrimp) that were not generally observed in the other areas. These results show the patchiness of invertebrate distributions on multiple scales in these unconsolidated shelf habitats. However, it should be noted that the amount of recent trawling effort in the north and south reference sites is unknown.

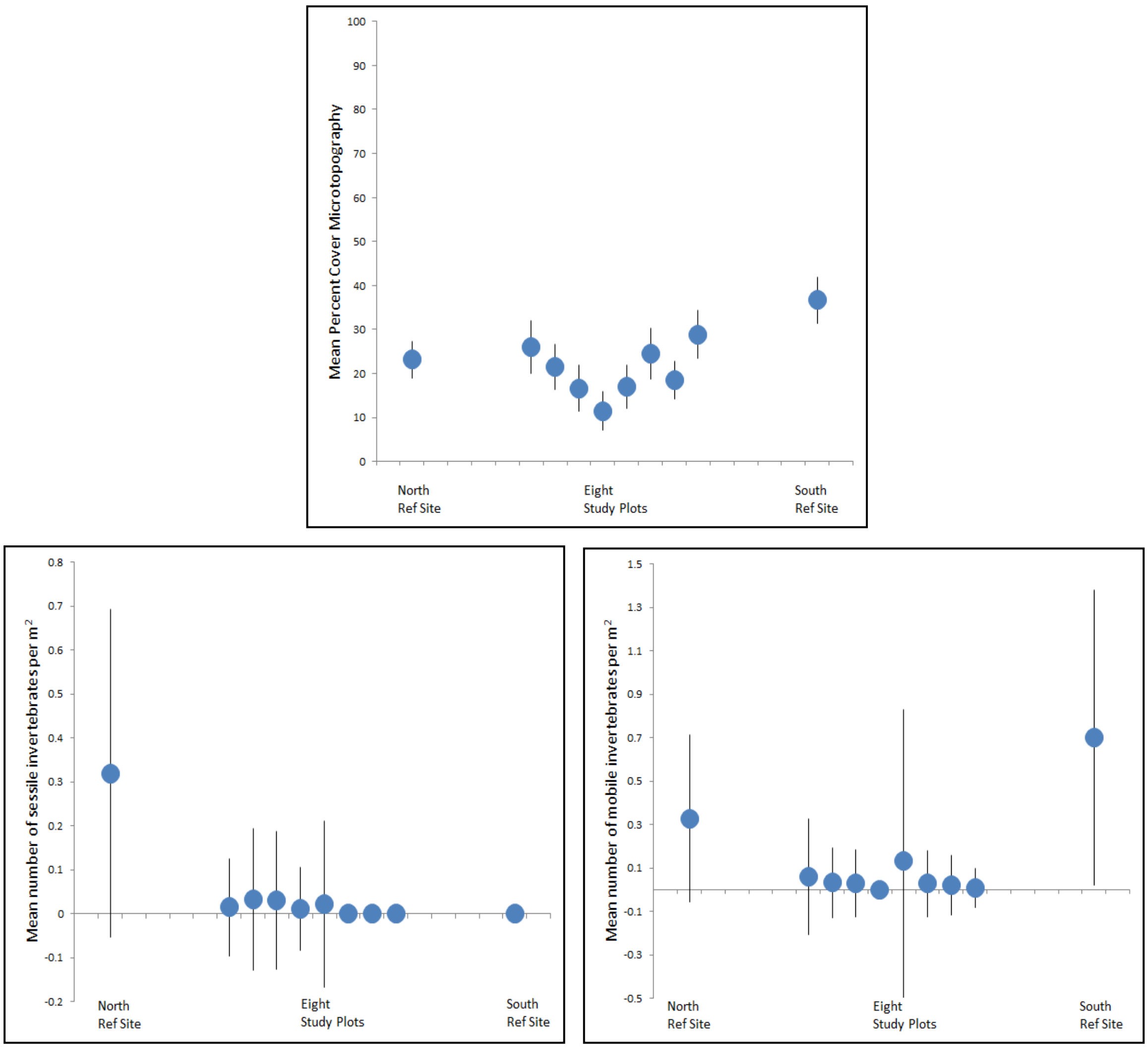


Figure 5. Mean percent cover of micro-topographic structure and mean density of mobile and sessile invertebrates (individuals per m^2) for eight primary study plots as well as the north and south reference sites from May 2012. Bars represent the standard error.

Persistence of Trawl Tracks

Figure 6. Trawl door scour in one of the trawled plots as depicted in an ROV still photograph (left) and ROV sonar (right) one year after low-intensity trawling.

In Year 1, trawl door scour marks from the low-intensity trawling effort were clearly evident in ROV surveys conducted immediately after the directed trawling and persisted a full year until September 2010 (Figure 6).

In Year 2, similar trawl tracks were observed in November 2010 immediately following the high-intensity trawling treatment; however, by the May 2011 surveys six months later, no trawl door scour marks were visible in the video or sonar images from the ROV surveys. To confirm the absence of trawl door scour marks we conducted multiple additional ROV transects perpendicular to the direction of trawling activities across the plots with the goal of increasing the chance of encountering door scour marks (Table 1). Though small-scale micro-topographic structure continued to be evident, the larger-scale door scour marks were completely absent. We hypothesize that this smoothing over of the study site may have been caused by an unidentified event sometime between November 2010 and May 2011.

Sediment Grain Size

Grab samples were collected across the eight study plots before the low-intensity trawling (September 2009) and one-year post low-intensity trawling (September 2010) to sample the sediment grain size and infauna (Table 1). Grain size analyses revealed that the bulk portion of all sediment samples could be categorized as coarse silt and/or fine sand. An overlay grain size distribution analysis was conducted using LS Coulter software to evaluate the average distribution of sediment per plot within a given sampling period. Analysis of pre-trawl samples indicated that all eight plots shared the same general curvature, including major peaks around 45 µm and 160 µm. Both the fine sand and silt fraction each account for 40-50% of the total volume, with about 5-10% of the sample consisting of clay (Kitaguchi 2011).

The post-trawl samples displayed the same major peaks as the pre-trawl samples at ~ 45 µm and 160 µm, although the post-trawl curves showed a slight increase in silt content, with an accompanying decrease of 2% in the fine sand fraction. The average mean grain size per plot (ranging from 27 to 43 µm) indicated no visible differences between the pre-trawl samples and the post-trawl samples. No quantifiably significant sedimentary differences were recorded between the trawled and control plots or between sample periods.

Micro-topographic Complexity of the Seafloor

Overall, the topographic relief in the study area was low, characterized by unconsolidated sediments in a depositional environment. However, a great deal of micro-topographic complexity (at the scale of centimeters) was evident in the down-looking still photographs collected by the ROV (Figure 7). Due to the water depth at the study site (170 m) and presence of fauna, we attribute these small-scale features to the result of bioturbation in the area, created by a variety of organisms as they interact with the upper-centimeters of the sediment, rather than to bedforms formed by physical processes.

Figure 7 – Micro-topographic complexity. The most prominent features in this photo is a trough in the sediment likely left by a burrowing mud urchin and numerous small holes created by burrowing organisms creating sediment complexity at the scale of centimeters. Also note the head of a partially-buried flatfish in the upper left-hand corner of the image. The two red dots in the lower half of the image are the paired-lasers paced 10 cm apart.

Micro-topographic complexity in control and trawled plots, measured by percent of the area bioturbated, were similar immediately prior to trawling in September 2009 (Figure 8). Post-trawl surveys indicated that control and trawled plots both showed reductions in micro-topographic complexity over time; the small differences between control and trawled plots over time were not statistically significant. Micro-topographic complexity in the same study plots was quantified post-high-intensity trawling (Figure 9). Immediately post-high-intensity trawling, micro-topographic cover in the control and trawled plots both declined precipitously, but did not differ from one another. At six-months post-trawl, the trawl and control plots had diverged significantly (* = $p < 0.05$). The amount of micro-topographic complexity in the trawl and control plots converged at 1-year post trawling.

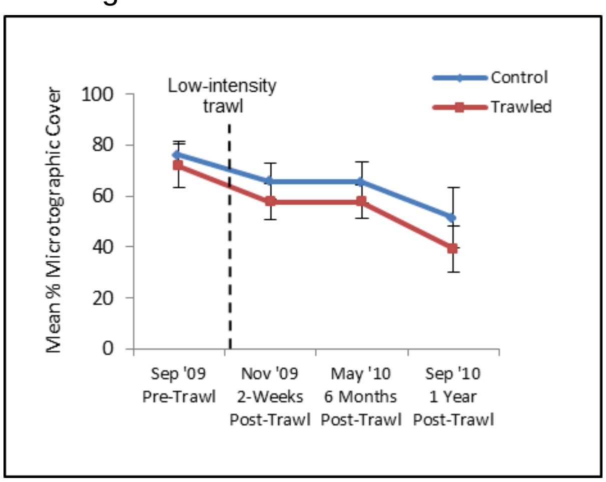


Figure 8. Micro-topographic complexity under low-intensity trawling.

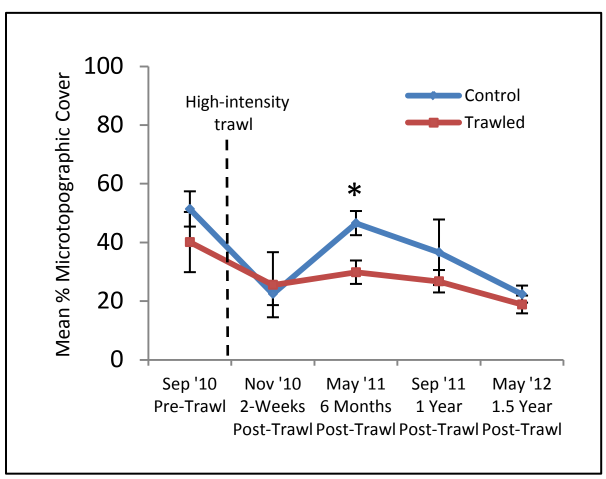


Figure 9. Micro-topographic complexity under high-intensity trawling.

Sessile Epifaunal Macroinvertebrates

Sessile, erect macrofaunal invertebrates, defined here as organisms that are attached to, and extend above the plane of the seafloor (i.e. sea whips, sea pens, anemones), provide important habitat structure for demersal fishes. In the study area, these organisms were neither diverse nor abundant (see the species list in Attachment A1). This was not unexpected as it is consistent with other research in similar habitats along the outer-continental shelf along the California coast that show a similar low-diversity and low abundance of macroinvertebrates.

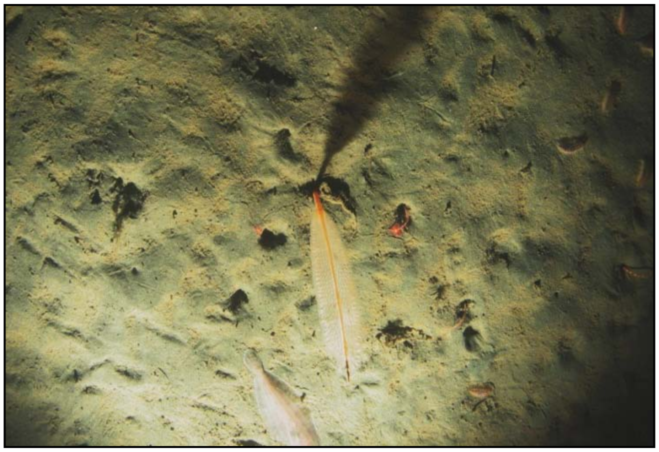


Figure 10 - Sessile invertebrates. The down-looking still photograph to the left shows a sea pen as well as brittle star arms extending from the sediment. Note the flatfish in the lower portion of the image, as well as the presence of small polychaete worms on the sediment surface.

The mean density per 100 m^2 for sessile epifaunal invertebrates was calculated for all trawled and control plots (Figure 11). Immediately prior to low-intensity trawling, the trawl and control plots were not significantly different from one another. Though the trajectories in trawl and control plots are slightly different , we found no statistically significant differences between control and trawled plots at two-weeks, six-months and one-year post-trawling.

Density of sessile invertebrates in control and trawled plots were nearly identical immediately prior to the high-intensity trawling, and they remained similar (no significant difference) at two-weeks, six-months, one-year, and 1.5 years post-trawling (Figure 12).

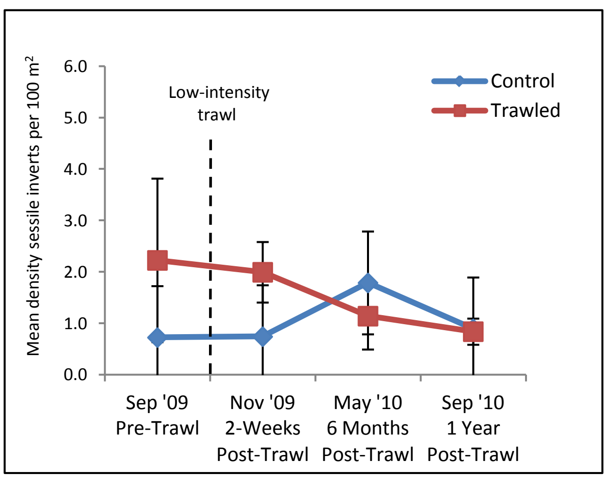


Figure 11. Mean density of sessile invertebrates at Low-Intensity Trawling.

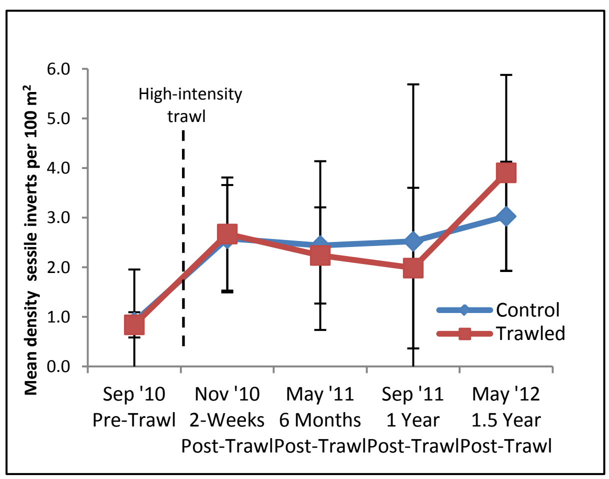


Figure 12. Sessile invertebrates at High-Intensity Trawling.

Mobile Macro-Invertebrates

Mobile invertebrates observed in the study area included a wide variety of echinoderms and molluscs, with smaller numbers of crustaceans and annelids (Figure 13; see species list in Appendix I). Generally, the density of these organisms in the study area was low; however, there were very high densities of selected organisms (especially polychaete worms and brittlestars) that were patchily distributed in space and time. This was consistent with our observations of similar or related fauna at other locations along California's continental shelf.

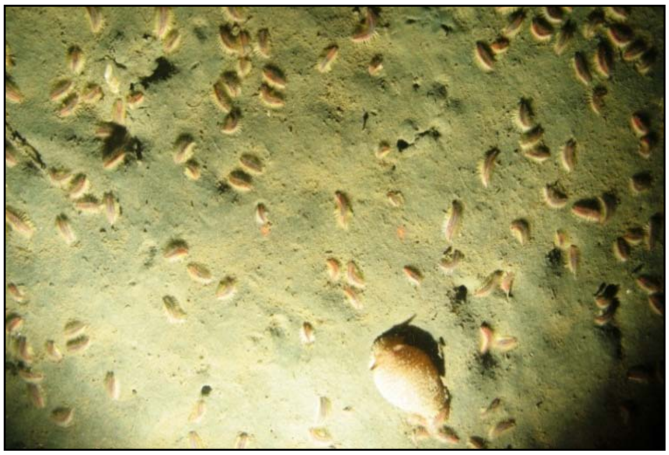


Figure 13 - Mobile invertebrates. Though sea slugs (pictured left) and many larger invertebrates were recorded in the ROV still photographs and video, the polychaete worms, *Chloeia pinnata* (also pictured) were abundant in the study plots on multiple occasions over the course of four years of ROV surveys.

Before the trawling treatment in September 2009, the density of mobile invertebrates was similar in control and trawled plots (Figure 14). In November 2009, immediately after low-intensity trawling, the mean density of mobile organisms increased dramatically, in both control and trawled plots, though there was no statistically significant difference between the two treatments. The trajectories continued to vary in overall density, but did not differ significantly between trawl and control treatments at six-months and one-year post-trawling.

Patterns in the density of mobile invertebrates were also similar between control and trawled plots following the high-intensity trawling treatment (Figure 15). Overall, the variability in density was less extreme in Year 2 following high-intensity trawling, with densities declining over time in both control and trawled plots (though not significantly different).

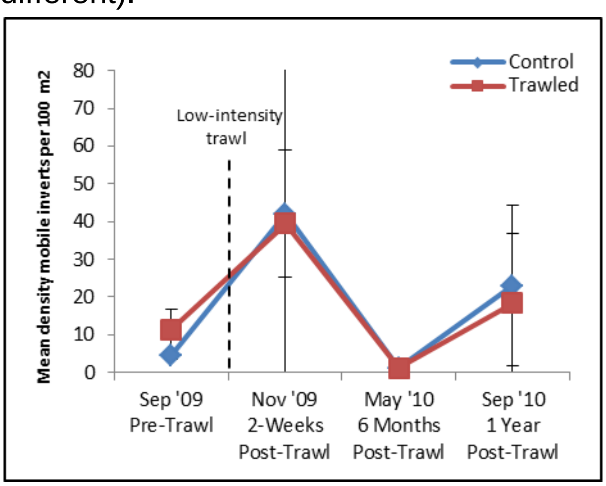


Figure 14. Mobile invertebrates at low-intensity trawling.

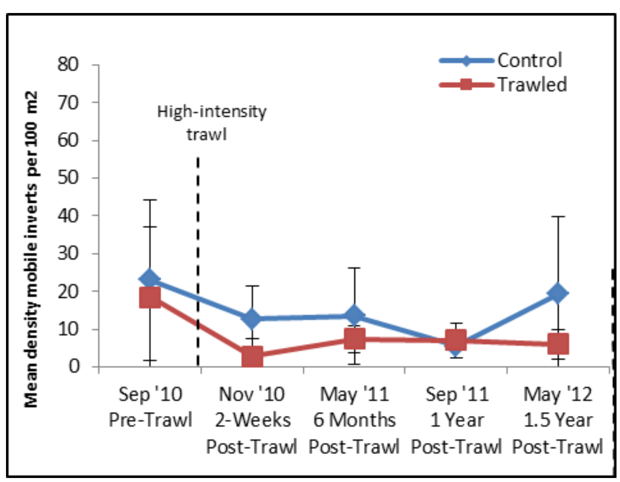


Figure 15. Mobile invertebrates at high-intensity trawling.

Infaunal Invertebrates

Benthic grab sampling for infaunal invertebrates was conducted before and after low-intensity trawling only. There were no quantifiable differences with respect to infaunal organisms between trawled and control plots or between sampling periods following low-intensity trawling.

Most crustaceans were identified to species level, and on average contributed to about 17-35% of the total number of individuals per infauna sample (Appendix I). Polychaete worms were identified to family, genus, or species level as able, accounting for 50-70% of the total number of individuals per sample. Molluscs were identified to species level, and represented roughly 5-15% of the total number of individuals per sample. Echinoderms, Cnidarians, Sipunculids, Nemerteans, and other minority groups accounted for less than 5% of the total number of individuals, and were only identified to their major class or phylum in most cases. Polychaetes, crustaceans and molluscs together accounted for 97% of the total number of individuals collected from all samples, with crustaceans responsible for 22% of that total, polychaetes 65%, and mollusks 10%. The mean number of individuals per sample was ~237, with the most abundant sample containing 568 individuals, and the least abundant less than 93 individuals.

The most prolific polychaete species found throughout the samples included *Spiophanes berkeleyorum, Paraprionospio alata, Levinsenia gracilis, Cossura candida*, and *Chloeia pinnata*. The most abundant crustaceans included species such as *Protomedeia articulata, Photis* sp., *Euphilomedes producta, Diastylis* sp., *Eudorella pacifica, Gammaropsis ociosa, Metaphoxus frequens,* and *Pinnixa occidentalis* . The most frequently encountered mollusks in samples included the species *Tellina carpenteri, Rhabdus rectius, Gadila aberrans,* and *Yoldia seminuda*. One of the largest organisms found in this sample set was *Brisaster latifrons*, a burrowing heart urchin seen in all plots and on both grab sampling cruises. There were also a number of different holothuroid and ophiuroid species. Even though the abundance of echinoderms was relatively low, their contribution to the total biomass of the sample was over 50% when present.

Demersal Fishes

To-date we have observed with the ROV or caught (with the trawl) a variety of fishes (primarily demersal) in the study area (Table 2). These data indicate that the ROV was able to observe a very similar assemblage of fish as caught in the trawl nets, with more species observed with the ROV. Data analyses on demersal fishes observed in the ROV surveys is part of active on-going research and will be included in other publications.

Table 2. List of fishes encountered to-date in the study area either by ROV observation or trawl catch during directed trawling of the experimental study plots.

Taxonomic group	Common name	*Genus species*	ROV	Trawl
Chondrichthyans				
	Spotted ratfish	*Hydrolagus colliei*	X	X
	Torpedo ray	*Torpedo californica*	X	X
	Longnose skate	*Raja rhina*	X	X
	Big skate	*Raja binoculata*		X
	Soupfin shark	*Galeorhinus galeus*	X	X
	Spiny dogfish	*Squalus acanthias*	X	X
Flatfish				
	Dover sole	*Microstomous pacificus*	X	
	Petrale sole	*Eopsetta jordani*	X	X
	Slender sole	*Eopsetta exilis*	X	X
	English sole	*Parophrys vetulus*	X	X
	Rex sole	*Glyptocephalus zachirus*	X	X
	Pacific Sanddab	*Citharichthys sordidus*	X	X
	Curlfin sole (turbot)	*Pleuronichthys decurrens*	X	X
	Rock sole	*Lepidopsetta bilineatus*		X
	Unk. Flatfish		X	
Rockfish				
	Striped tail rockfish	*Sebastes saxicola*	X	X
	Greenstriped rockfish	*Sebastes elongatus*	X	
	Splitnose rockfish	*Sebastes diploproa*	X	X
	Shortbelly rockfish	*Sebastes jordani*	X	X
	Chilipepper rockfish	*Sebastes goodei*	X	X
	Halfbanded rockfish	*Sebastes semicinctus*	X	X
	Blackgill rockfish	*Sebastes melanostomous*	X	
Other fishes				
	Northern anchovy	*Engraulis mordax*	X	X
	Pacific hake	*Merluccius productus*	X	X
	Pacific hagfish	*Eptatretus stouti*	X	
	Sablefish	*Anoplopoma fimbria*	X	X
	Sculpin	*Icelinus sp.*	X	
	Bigfin eelpout	*Lycodes cortezianus*	X	
	Blackbelly eelpout	*Lycodes pacificus*	X	X
	Black eelpout	*Lycodes diapterus*	X	
	Bearded eelpout	*Lyconema barbatum*	X	
	Poacher	*Xeneretmus sp.*	X	
	Lingcod	*Ophiodon elongatus*	X	X
	Juv Lingcod	*Ophiodon elongatus*	X	X
	Prickleback, bluebarred	*Plectobranchus evides*	X	
	Plainfin midshipman	*Porichthys notatus*	X	X
	Cusk-eel, spotted	*Chilara taylori*	X	X
	Unk. Fish		X	

Trawl Caught Fishes

Overall, the majority of the trawl catch from low-intensity trawling in October 2009 and high-intensity trawling in October 2010 consisted primarily of flatfishes both in terms of total number of organisms and percentage of weight caught (Figures 15 and 16 below). Roundfishes, elasmobranchs (skates and rays, sharks, and ratfish), and invertebrates also contributed substantially to the overall catch in terms of both numbers caught and weight. Other miscellaneous fish groups and rockfishes made up a minor portion of the catch. Flatfishes were most numerous, making up 43.5% of the overall catch, followed by roundfishes (lingcod and sablefish) at 20%, and all invertebrate groups combined at around 11%. The remainder of the other taxonomic groups made up <10% of total catch in terms of numbers caught. In terms of total weight, flatfishes dominated at 25.7%, followed by sharks, skates and rays, and invertebrates at 20%, 17.7%, and 15.4% respectively.

In 2009 flatfishes, ratfish, and other miscellaneous fish groups made up most of the low-intensity trawl catch in terms of numbers caught (Figure 16). Northern anchovy (*Engraulis mordax*) was the species that contributed the highest number of fish in the miscellaneous fish group category at 118 caught. As in 2009, flatfishes were the most important taxonomic group caught in the high-intensity directed trawling in October 2010 (Figure 17). Flatfish accounted for 44.7% of the total catch and 33% of the total weight. There were more roundfishes caught in 2010 in terms of both number of fish and weight, primarily due to a high percentage of juvenile sablefish. Ratfish and invertebrates were still important components of the catch, although fewer ratfish were caught in 2010. There were also three different species of rockfish in 2010 that were not caught in 2009, including bocaccio (*Sebastes paucispinis*), chilipepper (*S. goodei*), and shortbelly rockfish (*S. jordani*). All of these rockfishes were caught in small numbers.

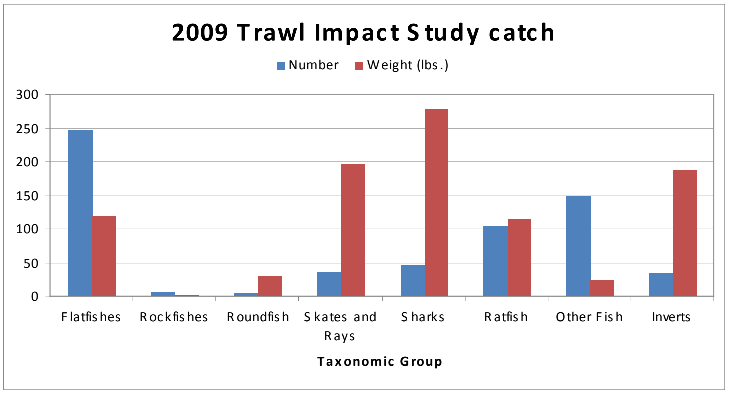


Figure 16 –Trawl catch in Low-Intensity Trawling.

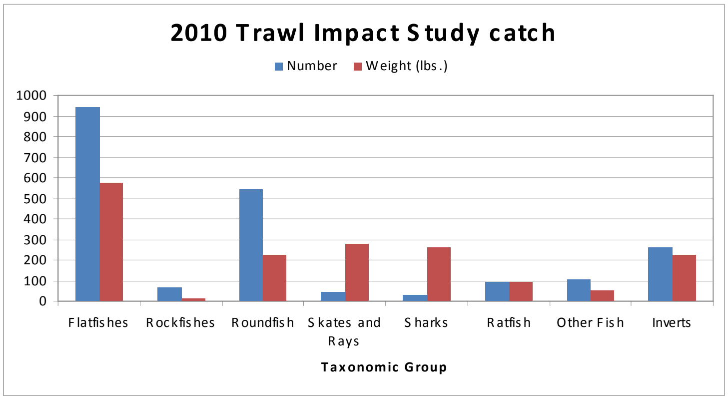


Figure 17 – Trawl catch in High-Intensity Trawling.

Conclusions

Though the scientific literature on the ecological effects of bottom trawling has grown over the past twenty years, important questions remain, particularly with respect to the impacts of trawling on the structural attributes of seafloor habitat in unconsolidated sediments. On the one hand, there is a perception that low-relief sand and mud environments will recover more quickly following the cessation of trawling than harder substrates and the fauna associated them (NRC 2002). However, the existing data are less clear in this regard. In the North Sea, a study of soft sediment infauna found a measurable impact from a single pass of a beam trawl, even in an environment that had been trawled for decades (Reiss et al. 2009), while a project in South Africa found no measurable impacts to a chronically trawled area (Atkinson et al. 2011). There is also a growing recognition that not all unconsolidated habitats are alike. On Georges Bank, Lindholm et al. (2004) found evidence of trawling impacts to sand habitats below the 60 m isobath, but no impact was evident shallower than 60 m in similar grain size, where regular storm and tidal currents re-sorted the sediment. In California, Hallenbeck et al. (2012) found higher densities of small fish and invertebrate fauna inside of naturally occurring rippled scour depressions (RSDs) when compared to low relief habitats outside the RSD's. These features are now known to occur across California's continental shelf in sandy substrates and demonstrate the importance of micro-topographic structure.

Insight into the ecological effects of bottom trawling in unconsolidated sediments is particularly important for California, where greater than 80% of the continental shelf is comprised of soft substrates (Allen et al. 2006). However, a common and significant challenge across the few existing studies of trawling impacts along the west coast of the US (Engel and Kvitek 1998; McConnaghey et al. 2000; Hixon and Tissot 2007; de Marignac et al. 2009) was the fact that trawling effort was not controlled as part of these studies. Historical data on the distribution of trawling are rarely available, especially with the level of precision in geo-referenced track lines that are critical for the accurate quantification of impacts to the seafloor; most historical data occur as broad or average estimates across fishing blocks or large areas (Mason et al. 2012).

The primary effect of trawling that we observed was the persistent trawl door scour marks in the sediment. Some smoothing out of the seafloor, as measured by reductions in bioturbation, were observed in the trawled plots compared to controls; however, these minimal differences with respect to micro-topographic structure on the seafloor were statistically significant only at one time period. Small-scale benthic features such as these have been shown to provide habitat to demersal fishes of a variety of species, creating the potential for larger, population-scale impacts from bottom trawling. However, no impact from bottom trawling was discernible in this study with respect to the densities of structure-forming sessile invertebrates, a common indicator of trawling impacts to fish habitat in other studies worldwide (Auster & Langton 1999). Further, despite considerable variability in the densities of mobile macro-invertebrates in the study area, there were no significant difference between trawled and control plots attributable to trawling. These results, discussed in more detail below, provide important context for on-going efforts to manage the distribution of bottom trawling effort in the waters along the west coast.

Limited effects observed from bottom trawling in unconsolidated shelf sediments

We predicted that impacts to the structural attributes of fish habitat, including physical (micro-topographic structure) and biological (epifaunal invertebrates) would be discernible between control and trawled plots following low-intensity bottom trawling and that the difference would increase following high-intensity. These predictions were based on our understanding of seafloor impacts from other studies in which we have participated directly (de Marignac et al. 2009; Tamsett et al. 2010) as well from other studies on the west coast (e.g., Engel and Kvitek 1998; Hixon and Tissot 2007) and global reviews (e.g., Auster and Langton 1999; NRC 2001).

These predictions were largely not borne out by the results of this study. Following low-intensity trawling, the small, but persistent, difference between control and trawled plots (Figure 8) was suggestive of an impact from trawling on micro-topographic complexity. We attributed this difference to the smoothing of habitat features by the trawl foot rope as it passed over the bottom, as well as to the removal of the mobile organisms responsible for bioturbating the sediment. However, the difference was not statistically significant in our analyses, despite fairly high statistical power (see Appendix III). Following high-intensity trawling (Figure 9), the trajectories of the control and trawled plots were less clear, converging at two weeks post-trawling, diverging significantly at six months (*$p < 0.05$), and then converging again at one-year post-trawling.

In addition to the small reduction in micro-topographic structure observed in the trawled plots, we also observed larger-scale alteration of the seafloor in the form of trawl door scour marks that were visible immediately after low- and high-intensity trawling at both intensities and persisted for up to a year after low-intensity trawling. The ecological effects of these trawl door scour marks, which we estimated to be up to 20 cm wide and 10 cm deep, and extend for many meters, are not known; however, they do represent an alteration of the seafloor that could positively or negatively affect organisms depending on the nature and extent of their association with the seafloor.

Interestingly, the persistence of the trawl door scour marks following the high-intensity trawling was cut short by an ‘event’ of indeterminate nature. During the cruise to the study area in May 2011, no trawl door scour marks were evident within any of the four plots that had been extensively trawled the previous October. This was in stark contrast to the previous year when low-intensity trawling resulted in door scour marks that were visible and persistent for a full year. To confirm the disappearance of the marks we conducted additional transects oriented perpendicular to the axis of the trawling effort and no marks were observed. Potential explanations for the smoothing of the seafloor in the study area include the Japanese tsunami of March 2011, incursion of the southern California Countercurrent onto the outer edge of the shelf, as well as oceanographic conditions extant at the site off the coast of Pt. Buchon. We were not able to determine which of these potential explanations may have been responsible for the change in the study area.

Impacts to, and/or alteration of, these seafloor features are important because in the relatively low-relief, sedimentary environments that characterize the majority of California's continental shelf, much of the complexity in the seafloor is the result of bioturbation. Bioturbated sediment (micro-topography), created as animals move around on the seafloor, is important for fishes and mobile epifaunal invertebrates in these low-relief environments as refugia from predators and bottom currents. Therefore, diminishment of micro-topography in the sediment or the addition of trawl door scour marks, could ultimately contribute to population-level impacts on species, including some commercially-exploited fishes.

Our predictions were also not borne out with respect to macro-invertebrates, both epifuanal and infaunal. There were no significant differences between control and trawled plots with respect to densities of sessile (attached) macro-invertebrates and infaunal invertebrates, both of which were already at relatively low densities at the start of the study. Biogenic structures on the seafloor have been shown to be important for demersal and benthic fishes at multiple life histories (Auster and Langton 1999). Further, the densities of mobile invertebrates varied considerably over the course of the study, but did not differ significantly between control and trawled plots at either low- or high-intensity trawling intensities. Most of the invertebrate groups we assessed had relatively low densities, but showed high spatial and temporal variability; polychaete worms and ophiuroids were especially patchy and variable in their distributions.

Our collective knowledge of the dynamics of organisms in and on the unconsolidated sediments of the outer continental shelf continues to be very limited, despite the fact that unconsolidated sediments characterize upwards of approximately 80% of the continental shelf in California. Indeed the dominant characterization of soft sediment communities world-wide is one of patchiness at multiple scales (Morrisey et al.1992; Oliver et al. 2010), where the distributions of organisms are frequently more diffuse than shallower, reef-associated species where habitats are more discrete. In this regard, we expect the time series data on invertebrate communities (both sessile and mobile) collected as part of this project will ultimately enhance our understanding of the ecology of organisms in unconsolidated sediments, including seasonal and inter-annual variability in the distribution of mobile and epibenthic invertebrates, the patchiness of opportunistic organisms, and inter-annual variability in invertebrate community structure.

Contextualizing the Results of this Project

The results of any field research project, as well as the implications of those results, must ultimately be contextualized by a variety of factors. The conservative statistical analyses that we employed (described in Appendix III) provided fairly high statistical power for identification of moderate to large effects of trawling on the metrics we analyzed. This relatively high statistical power is strongly suggestive that moderate to large impacts to metrics we analyzed would have been detected if they occurred. However, the very limited impacts of bottom trawling to the seafloor that we observed must be considered in light of two primary factors; the small foot-rope bottom trawl that we used for the study and the unconsolidated sediments in which we located the study. The small footrope trawl gear (with ≤8 inch footrope) has been required to be used shoreward of the trawl Rockfish Conservation Area since 2000 (Bellman et al. 2005). The directed trawling employed two distinct trawling intensities (2x and 5x per trawled plot) that were designed to be reflective of historic trawling intensity in the region (Mason et al. 2012). However, much of that historic effort was persecuted using a variety of bottom trawls, most of them likely employing larger foot-ropes and heavier trawl doors than the gear we used in this study. As such, small footrope trawl gear may cause less impact than heavier gear and the extent to which the lack of impacts that we observed can be extrapolated to other gear types is potentially limited. An additional study is currently in the planning stages to investigate the relative impact of large footrope bottom trawls to other gear also designed to have limited contact with the seafloor. We anticipate that the results from the new study will help further contextualize the results of this study.

The substrate type in the study is also an important factor that must be considered in any extrapolation of the results. The study was strategically located on the outer continental shelf in an area characterized by low-relief unconsolidated sediments of relatively low diversity. We considered the area to be broadly representative of the shelf to the north and south of the study area based on preliminary exploratory surveys done prior to this study being initiated and additional research we've completed elsewhere along the coast. As described above, the additional reference sites that we sampled in May 2012 appeared to be similar to the study area with respect to each of the three metrics of analysis. While our results should not be extrapolated to other habitats, gear types, or to parameters not measured in this study, they do add to the body of knowledge about the effects of trawling in other soft-bottom habitats to provide a fuller picture of the range of effects across soft and hard-bottom habitats (NRC 2002).

Results inform management of bottom trawling impacts in California

California has a long history of bottom trawling and many ports have relied on landings of trawl-caught groundfishes; however, due to various regulatory and socioeconomic factors, trawling effort has shifted spatially and diminished in recent years. Regulations on bottom trawl gear design have resulted in much of the effort shifting away from rocky habitats. The area open to trawling off California has been reduced through regulatory measures including a state ban on most trawling in state waters (through SB 1459) and federal trawl closures such as the Rockfish Conservation Area and Essential Fish Habitat closures); these closures have resulted in shifts in effort (Bellman et al. 2005; Mason et al. 2012). The level of trawling effort (number of active trawl permits) has also been reduced over the last decade through attrition, a federal trawl buy back, and private purchase of trawl permits in the Central Coast (Gleason et al. *in press*). Through fishery reform projects and the transition of the trawl fishery to an Individual Transferable Quota system, there is also a recent focus on use of non-trawl gear (fixed-gear) to target other higher value species and to reduce bycatch through spatial fishing plans for both trawl and fixed-gear.

Trawling is still the primary way to catch flatfish and remains an important component of California's fisheries. It is important to reconcile our need for local seafood, fish landings, and fishermen's livelihoods with environmental impacts of trawling in different habitats, as well as bycatch and discard rates associated with the gear. The types of management measures this study could inform include:

- Type of trawl gear employed – this study demonstrated relatively small impacts of small footrope trawl gear in unconsolidated shelf sediments. Similar studies could be conducted with large footrope gear or other modified gear types to better inform gear design and use in different habitats.

- Level of trawl effort and trawl footprint – this study demonstrated relatively small impacts of 2x and 5x effort applied in 1km x 0.3km plots; the reduction in topographic complexity in trawl plots did not differ between the two intensities applied. Depending on the amount of available trawl effort in a fishing region, concentrating trawl effort in a smaller area (higher intensity but smaller trawl footprint) may have less overall impact relative to spreading that effort out over a larger area.
- Spatial management of trawling – this study demonstrated relatively few impacts of trawling on metrics related to fish habitat in low diversity unconsolidated sediments on the shelf. Spatial management of trawl effort may be warranted to avoid hard substrate, areas with high diversity or density of epibenthic organisms that have been shown in other studies to be more vulnerable to effects of trawling, and areas with high bycatch of overfished species.

Collaborative fisheries research partnerships advance the science and discourse on fisheries issues

One of the great benefits of this project has been the collaborative partnership that has evolved among diverse stakeholders interested in moving beyond rhetoric to a more quantitative evaluation of the impacts of bottom trawling on seafloor communities and a greater understanding of ecosystem dynamics and resilience. Collaborative fisheries research projects that involve fishermen in the design and implementation of field studies engages the fishing community in advancing the science needed to support management decisions and best management practices. We have also conducted considerable outreach on this project to expand its reach (see Appendix IV) and aim to use the results to inform the ongoing dialog in the California on the role and contribution of bottom trawling to the fishery and appropriate management measures.

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Appendix I: List of Species Encountered

ROV Surveys

Invertebrates		*Genus species*
Anthozoans		
	Metridium	*Metridium farcimen*
	Burrowing anemone	*Family Halcampidae, unk sp.*
	Sandrose anemone	*Uticina sp.*
	Tube anemone	*Pachycerianthus fimbriatus*
	Fleshy sea pen	*Ptilosarcus gurneyi*
	Sea whip debris	*Possibly Disthoptilum gracilis*
	Red gorgonian	*Possibly Swiftia or Lophogorgia*
	Sea whip, live	*Halipteris sp?*
	White sea pen	*Stylatula or Virgularia sp.*
	Red sea pen	*Pennatula sp.?*
	Thin orange seapen	*Virgularia or Pennatula sp.*
Echinoderms		
	Mediaster	*Mediaster aequalis*
	Cucumber	*Parastichopus californicus*
	Purple sea potato	*Mopadia intermedia*
	Sun star	*Rathbunaster californica*
	Other cucumber	*Infaunal, proboscis extending*
	Crinoid	*Fluorometra seratissima*
	Luidia	*Luidia foliolata*
	Brittlestar	Ophiuroidea, multiple species
	Mud urchin	*Brisaster latifrons*
	Other star	Asteroidea
	Ophiuroids on surface	Ophiuroidea
Molluscs		
	Octopus	*Octopus californicus*
	Gastropod	Gastropoda
	Red octopus	*Octopus rubescens*
	Pleurobrachia (sea slug)	*Pleurobranchia californica*
	Long white gastropod	Gastropoda
	Squid, Market	*Doryteuthis opalescens*
	Stubby squid	*Rossia pacifica*
	Humboldt squid	*Dosidicus gigas*
	Turban snail	Gastropoda
	Bivalve, small pink	Bivalvia
	Scaphopod	Gastropoda
Crustaceans		
	Crab	*Metacarcinus magister*
	Red rock crab	*Cancer productus*
	Spot Prawn	*Pandalus platyceros*
Annelids		
	Polychaetes, surface	*Harmathoe sp. (*Polynoidae*)*
	Fan worms	Serpulidae
	Red polychaete	Opiuroidea

Fishes

Chontrichthyans		
	Spotted ratfish	*Hydrolagus colliei*
	Torpedo ray	*Torpedo californica*
	Longnose skate	*Raja rhina*
	Big skate	*Raja binoculata*
	Soupfin shark	*Galeorhinus galeus*
	Spiny dogfish	*Squalus acanthias*
Flatfishes		
	Dover sole	*Microstomous pacificus*
	Petrale sole	*Eopsetta jordani*
	Slender sole	*Eopsetta exilis*
	English sole	*Parophrys vetulus*
	Rex sole	*Glyptocephalus zachirus*
	Pacific Sanddab	*Citharichthys sordidus*
	Curlfin sole (turbot)	*Pleuronichthys decurrens*
	Rock sole	*Lepidopsetta bilineatus*
	Unk. Flatfish	
Rockfishes		
	Striped tail rockfish	*Sebastes saxicola*
	Greenstriped rockfish	*Sebastes elongatus*
	Splitnose rockfish	*Sebastes diploproa*
	Shortbelly rockfish	*Sebastes jordani*
	Chilipepper rockfish	*Sebastes goodei*
	Halfbanded rockfish	*Sebastes semicinctus*
	Blackgill rockfish	*Sebastes melanostomous*
Other fishes		
	Northern anchovy	*Engraulis mordax*
	Pacific hake	*Merluccius productus*
	Pacific hagfish	*Eptatretus stouti*
	Sablefish	*Anoplopoma fimbria*
	Sculpin	*Icelinus sp.?*
	Bigfin eelpout	*Lycodes cortezianus*
	Blackbelly eelpout	*Lycodes pacificus*
	Black eelpout	*Lycodes diapterus*
	Bearded eelpout	*Lyconema barbatum*
	Poacher	*Xeneretmus sp.*
	Lingcod	*Ophiodon elongatus*
	Juv Lingcod	*Ophiodon elongatus*
	Prickleback, bluebarred	*Plectobranchus evides*
	Plainfin midshipman	*Porichthys notatus*
	Cusk-eel, spotted	*Chilara taylori*
	Pacific sunfish	*Mola mola*
	Unk. Fish	

Van Veen Grab Samples – Infauna

Polychaete (50 spp)
Amaeana
Ampharetid
Amphinoid
Aphrodita spp.
Aricidea
Aricidea long
Capitella
Capitelid/Oligochaete
Chaetopterid
Cirratulid
Cossura
Eumida
Eteone
Exogone
Flabelligerid
Flabelligerid-like
Glycera
Glycinde
Goniadidae (Glycera-like)
Harmothoe
Hesione
Lumbrineris
Maldanid
Nephtys
Nereis
Nerinides-like
Onuphid
Ophelia
Paraonidae
Paraonidae long
Pectinaria
Pilargidae
Pista
P. Pista
Prionospio cirrifera
Prionospio malgrammi
Prionospio pinnata
Phyllodoce
Polydorid
Scoloplos
Spiophanes
Spionids
Spio-like
Sternaspis
Sternaspis-like
Syllidae
Turbonilla spp.
Yoldia seminude
Terebellidae
Thelenessa
Travisia
Unknown

Echinodermata (13 spp)
Amphiodia spp.
Amphiura arcystata
Amphiura diomedeae
Brisaster latrifrons
Crinoidea spp. 1
Crinoidea spp. 2
Dougaloplus amphacanthus
Holothuroid spp. 1
Holothuroid spp. 2
Holothuroid spp. 3
Holothuroid spp. 4
(archival Sp #20)
Juvenile ophiuroids
Molpadia spp.

Cnidaria (8 spp)
Anthozoan spp. 1
Anthozoan spp. 2
Anthozoal spp. 3
Edwardsia spp.
Pennatulacea spp. 1
Pennatulacea spp. 2
Pennatulacea spp. 3
Hydrozoans pp. 1

Echiura
Echiura spp. 1

Nematoda
Nemertean spp.

Nemertea
Nemertean spp.

Sipunculida (3 spp)
Sipunculid spp. 1
Sipunculid spp. 2
Sipunculid spp. 3

Oligochaete
Oligochaete spp.

Mollusca (28 spp)
Amphissa bicolor
Aplacophoran spp. 1
Aplacophoran spp. 2
Astyris spp.
Balcis
Cadulus tolmiei
Compsomyax subdiaphana
Cylichna diegensis
Eulimid
Eunucula tenuis

Mollusca (cont)
Gadila aberrans
Kellia spp.
Lyonsia californica
Macoma carlottensis
Muricidae
Neptunea tabulate
Parvilucina tenuisculpta
Philine spp.
Rhabdus rectius
Rochefortia tumida
Saxicavella pacifica
Siphonodentalium quadrifissatum

Crustaceans (86 spp)
Acidostoma hancocki
Americhelidium rectipalmum
Americhelidium shoemakeri
Ampelisca hancocki
Ampelisca pacifica
Ampelisca romigi
Ampelisca spp.
Ampelisca unsocalae
Anonyx liljeborgi
Aoroides inermis
Aoroides spp.
Bathymedon spp.
Bathymedon tone
Byblis spp.
Byblis veleronis
Bruzelia tuberculata
Campylaspis biplicata
Campylaspis spp.
Caprella mendax
Cirripedia
Conchoecinae
Cylindro leberididae
Diastylis crenellata
Diastylis glabra
Diastylis quadriplicata
Diastylis santamariensis
Diastylis sentosa
Diastylis spp.
Dyopedos spp.
Eudorella pacifica
Eudorellopsis longirostris
Euphausid
Euphilomedes productis
Flabellifera (suborder)
Foxiphalus cognatus
Foxiphalus similis
Gammaropsis ociosa
Gnathia spp.

Crustaceans (cont)

Haliophasma geminatum
Harbansus mayeri
Harpiniopsis fulgens
Heterophoxus oculatus
Idarcturus allelomorphus
Idoteidae (Family)
Ilyarachna acarina
Isochyrocerus pelagops
Leptochelia dubia
Leptostylis calva
Leucon falcicosta
Leucon pacifica
Listriella diffusa
Listriella spp.
Maera simile
Melphisana bola
Metaphoxus frequens
Microjassa barnardi
Munnogonium tillerae
Neocrangon communis
Nicippe tumida
Opisa tridentata
Pachynus barnardi
Photis brevipes
Photis lacia
Photis macrotica
Photis spp.
Pinnixa occidentalis
Pleurogonium californiense
Pleurophoxus
Podocopid
Prochelator spp.
Protomedeia articulata
Rhachotropis spp.
Rutiderma lomae
Rutiderma sarsielloidea
Scleroconcha trituberculata
Siphonolabrum californiensis
Stenothoidae
Guernea reduncans
Tanaella propinquus
Tanaopsis cadieni
Tritella laevis
Typhlotanais williamsae
Westwoodilla tone

Appendix II: Trawl Gear Design and Measurements

TNC, with our fisherman partners, have used a modified (small footrope) trawl gear described in these specifications on the F/V South Bay, based in Morro Bay, California. Measurements were made with local fishing partners in 2008.

Overview*:*

A basic trawl design consists of two panels of netting that are laced together to form an elongated funnel shaped bag (Figure 1). The funnel tapers down to the cod-end where the fish are collected while the net is hauled. The mouth, or opening, of the net is held open on the top by floats along the headline rope and weighted down on the bottom by groundgear that is attached to the footrope. The net is held open on the side by wires (bridles and mudgear, aka sweeps) running from the net to the trawl doors.

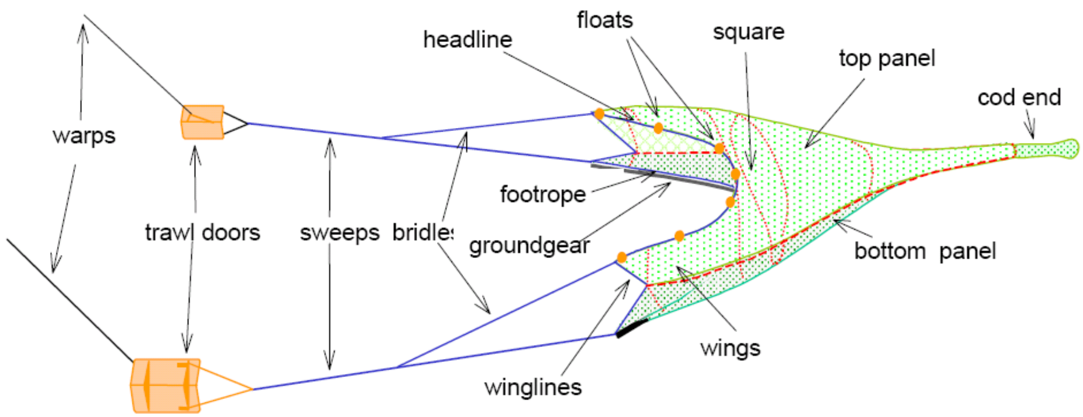


Figure 1. Diagram showing the basic design of bottom trawl gear.
(**Source: http://www.seafish.org/upload/b2b/file/r__d/BOTTOM%20TRAWL_5a.pdf**)

The modified trawl design consists of a two bridle trawl and the opening has a fishing circle of 300 meshes with a mesh size of 4 9/16 in. The funnel tapers down to the codend at a 2:1 cutting ratio and the mesh size at the codend is 4 ½ in.

Headrope and Footrope Design:

The length of the headrope for the trawl is 61 ft long while the footrope is 60 ft (Figure 2). Groundgear is attached below the footrope and runs along the entire length. The groundgear keeps the net from dragging directly along bottom substrate. The footrope is attached to the groundgear, which is constructed of both 8-inch and 4-inch discs that are evenly spaced along the groundgear (Figure 3).

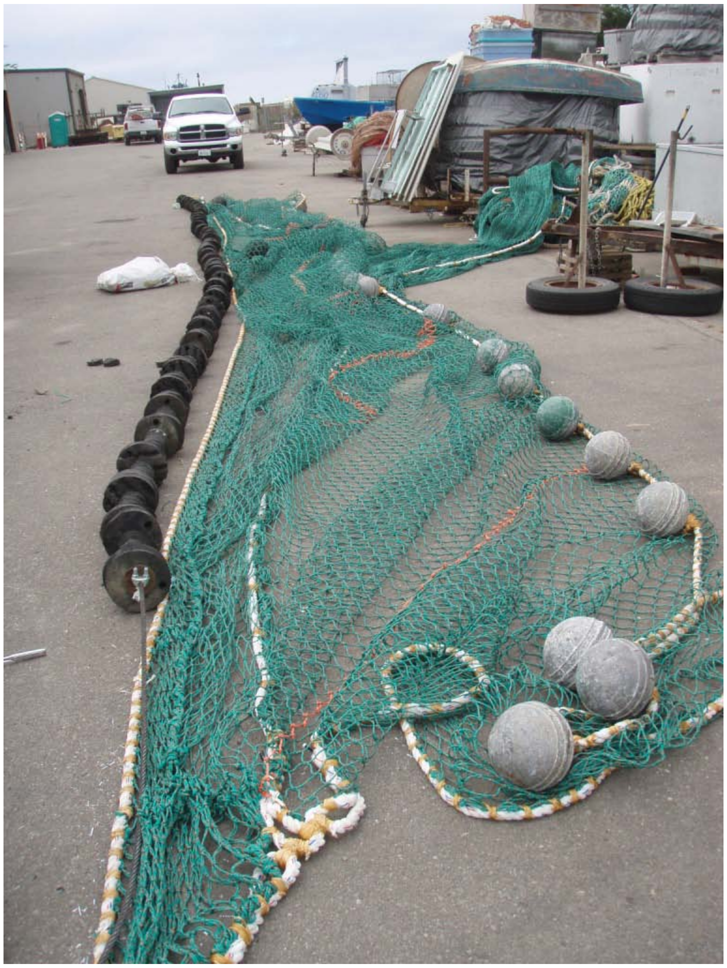


Figure 2. Picture showing the footrope and groundgear (left) and the headrope with attached floats (right).

Figure 3. Picture showing the groundgear with both 8 in. and 4 in. discs.

Trawl Door Size:

The door size of the trawl doors, or otter boards, is 3.5 ft by 4.5 ft and each individual door weighs approximately 700 lbs.

Opening and Dimensions:

Trawling operations on the F/V *South Bay* are usually conducted at a speed of 2.1 knots. Speeds slower than 2.0 knots can cause the net to dig into the bottom and results in large amounts of mud, urchins, and sea stars to become caught in the net. When the otter boards are spread open the net width is 33ft (Figure 4) and the height is 8 ft (Figure 5). The distance between the headrope and the footrope bridles is 5 ft.

Figure 4. Picture showing the estimated spread of the net while trawling.

Figure 5. Diagram showing estimated net height while trawling.

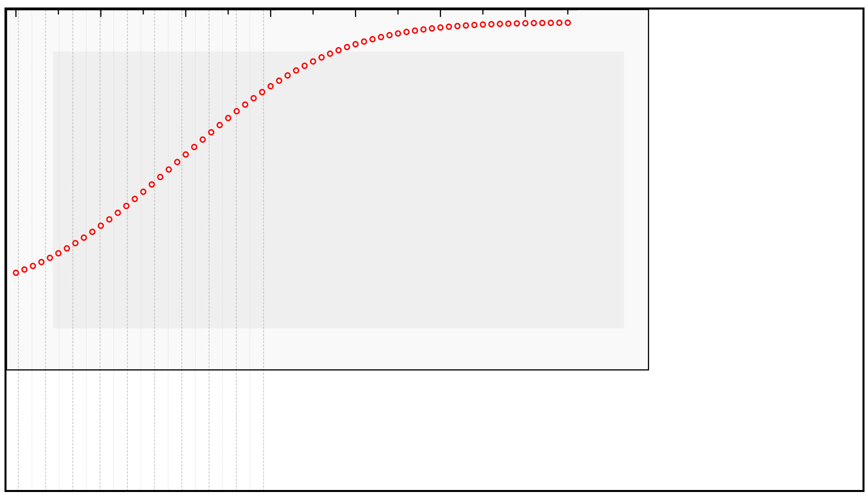
Wire attachments:

The wings along each side to the opening of the trawl net are attached to the trawl doors by a series of two types of wires called wires and mudgear (aka sweeps). A bridle runs from the headrope and footrope along each end of the net and connects to the mud gear which is then attached to the trawl doors or otter boards. The diameter of the wire for both the bridles and the mud gear is ½ in. The length of each of the bridles is 7 fathoms and the length of the mudgear is 70-75 fathoms long. The mudgear consists of tightly packed discs, similar to the footrope materials, which are 2.5 to 3 inches in diameter.

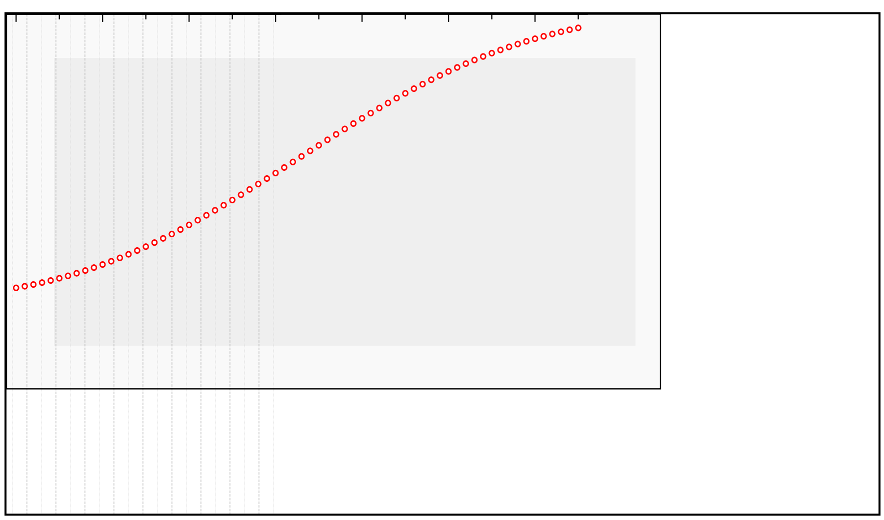
Appendix III: Power Analyses and Statistical Design

We conducted post-hoc power analyses on the sampling design using the program GPower (Faul et al. 2007) to evaluate the power to detect significant differences given the variability in the data and the low sample size. The preliminary assessment of our sampling design coupled with the use of ANOVA techniques for primary analyses suggested that the power of our approach was high for large effects but relatively low for small effects depending on how many transects we completed. While we sought to conduct as many as six transects per sample plot per time period, weather conditions at the study area frequently limited us to fewer transects, though we were able to obtain the minimum of three per plot across all time periods. The figures below indicate that our power to detect treatment effects increased measurably from three transects (a) to six transects (b).

a) Based on a 2X4 design (2 treatments, 4 plots per treatment) and 6 samples per plot.



b) Based on a 2X4 design (2 treatments, 4 plots per treatment) and 3 samples per plot.



To increase our ability to detect statistical differences, and reduce the probability of a type II error, we randomly selected 100 photos from each pair of plots for each treatment so that samples would be distributed across the entire study area. Though this effectively reduced the number of replicates for each treatment from four independent plots to two pairs of adjacent plots, the total sample size increased substantially for each treatment. The revised approach allowed for a greatly improved N by randomly selecting photos and treating each subdivision in the photo as a sample for the proportion tests. Importantly it also reduced the effect of spatial auto-correlation in data collected along sequential transects, and eliminated any inflated statistical significance due to psuedo-replication (Hurlbert 1984).

The revised approach greatly improved the statistical power of the analyses.

We then used the two-proportion z-test to determine whether the hypothesized difference between population proportions differed significantly.

Micro-topographic complexity coverage
Z-test for differences between independent proportions by treatments by date: N = 4800 (200 photos/treatment), Z-critical = 1.64485.

	Percent Micro-topographic Cover					
Date	Control	Trawl	df	Z-Statistic	Probability	
Sep 2009	76.18	71.87	198	0.0431	0.48400	
Nov 2009	65.98	55.12	198	0.1086	0.46017	
May 2010	67.79	58.20	198	0.0959	0.46414	
Sep 2010	54.42	38.86	198	0.1556	0.44038	
Nov 2010	23.06	24.60	198	0.0154	0.49601	
May 2011	49.17	29.80	198	2.8020	<0.001	***
Sep 2011	35.81	22.11	198	0.6754	0.25143	
May 2012	22.22	19.44	198	0.1531	0.44038	

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Appendix IV: Project Outreach

Oral Presentations

Lindholm, James, Mary Gleason, Donna Kline. The ecological effects of bottom trawling in unconsolidated sediments: a collaborative approach to resolving pressing management questions. North American Congress for Conservation Biology, Oakland, CA, July 2012.

Lindholm, James, Mary Gleason, Donna Kline. The ecological effects of bottom trawling in unconsolidated sediments. California Ocean Science Trust. San Francisco, CA, April 2012.

Lindholm, James, Mary Gleason, Donna Kline, Dirk Rosen and Andrew De Vogelaere. Penetrating the Depths: A collaborative research effort to quantify the ecological effects of trawling activities on California's continental shelf. Second International Marine Conservation Congress, Victoria, British Columbia, Canada, May 2011.

Lindholm, James. Behind the Green Curtain: Applied Research at the Interface of Science and Policy. Monterey Bay Aquarium Research Institute, Moss Landing, California. April 2011.

Lindholm, James. The Ecological Effects of Trawling: A Collaborative Fisheries Approach. COAST Legislative Briefing in Sacramento, California. September 2010.

Lindholm, James. Recovery in Seafloor Communities Impacted by Trawling in Central California. California and the World Ocean Conference. San Francisco, California. September 2010.

Lindholm, James. The Central Coast Trawl Impact and Recovery Project. Sanctuary Advisory Council of the Monterey Bay National Marine Sanctuary. Watsonville, California. August 2010.

Lindholm, James. Habitat recovery following the cessation of trawling activities in Morro Bay. Marine Interest Group Meeting. Morro Bay, California. January 2010.

Poster Presentations

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