Sidescan-sonar mapping of benthic trawl marks on the shelf and slope off Eureka, California

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Abstract.–The abundance and orientation of trawl marks was quantified over an extensive portion (>2700 km^2) of the Eureka, California, outer shelf and slope, an important commercial bottom trawling ground for such high-value species as rockfish, sole, and sablefish. Fishing logbook data indicate that the entire reporting area was trawled about one and a half times on an average annual basis and that some areas were trawled over three times annually. High-resolution sidescan-sonar images of the study area revealed deep gouges on the seafloor, caused by heavy steel trawl doors that act to weigh down and spread open the bottom trawls. These trawl marks are commonly oriented parallel to bathymetric contours and many could be traced for several kilometers. Trawl marks showed a quadratic relationship in relation to water depth, with the greatest number of trawl marks observed at ~400 m. There was a significant positive correlation between the number of trawl marks observed on the sidescan images and the number of annual trawl hours logged within reporting areas. This finding indicates that acoustic remote sensing is a promising independent approach to evaluate fishing effort on a scale consistent with commercial fishing activities. Bottom trawling gear is known to modify seafloor habitats by altering benthic habitat complexity and by removing or damaging infauna and sessile organisms. Identifying the extent of trawling in these areas may help determine the effects of this type of fishing gear on the benthos and develop indices of habitat disturbance caused by fishing activities.

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Concerns about trawl impacts on benthic fish habitats date back to the earliest use of this gear in the 13th and 14th centuries (de Groot, 1984), but the extent and longevity of these impacts have been difficult to quantify. The effects of trawling depend on the size and type of bottom trawl, footrope gear, bridles, doors, scope of main wires, trawling speed, duration, and repetition of trawling. Vulnerability of the sea floor to trawling impacts depends on the nature of the bottom type, benthic fauna, sedimentation rates, tidal velocity, and the degree of reworking of sediments caused by storms. Seabed disturbance can occur over the entire distance between the doors but is most pronounced in the region scoured by the trawl doors (Messieh et al., 1991), which have been shown to plough to depths greater than 15 cm (Caddy, 1973; Churchill, 1989).

In the short term, disturbance from bottom trawling can cause resuspension of sediments and make benthic infauna more available to scavenging predators (Kaiser and Spencer, 1994; Kaiser and Ramsay, 1997; Ramsay et al., 1997; Lindeboom and de Groot, 1998). Long-term shifts in abundance and diversity of benthic fauna have been noted in areas where trawling has been conducted for extended periods of time (Reise, 1982; de Groot, 1984; Sainsbury, 1987; Hutchings, 1990; Collie et al., 1997; Lindeboom and de Groot, 1998). Chronic, long-term disturbance can delay or prevent recovery of ecological communities (Collie et al., 1997) and large-scale removal of macrobenthos can lead to permanent changes in the community (Jones, 1992; Collie, 1998; Rogers et al., 1998). The removal of benthic organisms and sedimentary structures (e.g. sand waves, depressions) by trawls can lead to modifications of the physical complexity of benthic habitats (Reise, 1982; Jones 1992; Auster et al., 1996; Collie, 1998; Dorsey and Pederson, 1998). Schwinghamer et al. (1996, 1998) found that trawling homogenized sediments on the Grand Banks of Newfoundland to a depth of at least 4.5 cm, thus reducing fine-scale complexity of the substrate. Sediment mixing and frequent bottom disturbance from trawling activity may affect resuspension fluxes and produce changes in the successional organization of soft-sediment infaunal communities (Pilskaln et al., 1998). Reduction or removal of benthic structural complexity can lead to reduced recruitment of benthic organisms and often to reduced production (Botsford et al., 1997).

The degree of impact on benthic habitat is related to the timing, severity, and frequency of disturbance (Watling and Norse, 1998). The average annual area swept by trawls on Georges Bank from 1976 to 1991 was between 200% and 400% of the total area (Auster et al., 1996). Trawling does not occur evenly over this area but is concentrated in locations that produce better catches and fewer obstructions to towing (Dorsey and Pederson, 1998; Auster and Langton, 1999). As a result, some areas are subjected to trawling at a much higher rate than these reported averages and other areas may not be trawled at all. The effects of dredging on tidal flats in the Wadden Sea persisted for more than 15 years (van der Veer et al., 1985); by contrast, experimental trawl marks in a relatively dynamic intertidal zone in the Bay of Fundy persisted only 2–7 months (Brylinsky et al., 1994). The effects of mobile fishing gear on biodiversity are most severe where natural disturbance is least prevalent, such as at outer continental shelf and slope habitats (Watling and Norse, 1998). An experimental program to examine the impacts of mobile fishing gear on the benthic ecosystems in Atlantic Canada clearly indicated that trawling changed the physical habitat structure on sandy bottom at 120–146 m over a three-year period (Gordon et al., 1998). Biomass of epibenthic organisms in the trawl catch decreased with repeated trawling and the total biomass, as sampled by epibenthic sled, was lower in trawled areas compared with adjacent habitats. Fishing effort is spatially nonuniform, and thus techniques are needed that will allow analysis of trawling activity, and thus trawling impacts, on spatial scales appropriate to the large scales on which fisheries operate. In this study, we examine sidescan-sonar records as one approach to this analysis.

The continental shelf off Eureka (water depths less than ~120 m) is relatively flat (<0.5 degree) and topographically very smooth due to large inputs of fine terrigenous sediments from the Eel and Mad Rivers and reworking by storms (Fig. 1; Goff et al., 1999). Bottom photographs and samples from the shelf generally show smooth, mud-covered bottom with small-scale bottom roughness resulting from bioturbation and occasional wave ripples (Wiberg et al., 1996). The dominant morphological feature of the shelf is the Eel River delta, a sediment bulge in water depths of 20 to 60 m adjacent to the mouth of the Eel River and elongated to the north. Slope deposits are dominated by fine-grain sediments that show a transition from sandy silt in the south near the Eel Canyon to clayey silt in the northern portion of the study area (Syvitski et al., 1996).

Seafloor depressions 5 to 20 m in diameter and several meters deep, termed "pock marks," are common on both the outer shelf and slope throughout the region. These depressions are inferred to form by the removal of particles during expulsion of gas and fluid from subsurface deposits (Yun et al., 1999). The excavation is thought to occur both at slow rates, inducing particle-by-particle removal, and at rapid rates during sudden release of subsurface gas by earthquake shaking or other mechanisms (Field and Jennings, 1987).

In addition to natural processes that modify the seafloor, such as bottom currents, landslides, and fluid-expulsion features, the sidescan data and bottom photographs also show evidence (trawl marks) of fishing activities that modify these benthic habitats. The northern California outer continental shelf and slope off Eureka are important commercial fishing grounds. The trawl fleet that fishes the area off Eureka presently consists of 36 vessels from Eureka and 29 from Crescent City.[1] These vessels range in size from 18 to 24 m (60 to 80 ft), the larger vessels having entered the fleet in recent years in response to a shift of fishing effort into deeper water. Trawl designs vary but currently the most common trawl configuration is a Nor'eastern design with 114-mm (4 1/2 in) diamond stretched-mesh polyethylene netting equipped with roller gear. Trawls are currently

[1] Quirollo, L. F. 1998. California Department of Fish and Game, 619 Second Street, Eureka, CA 95501. Personal commun.

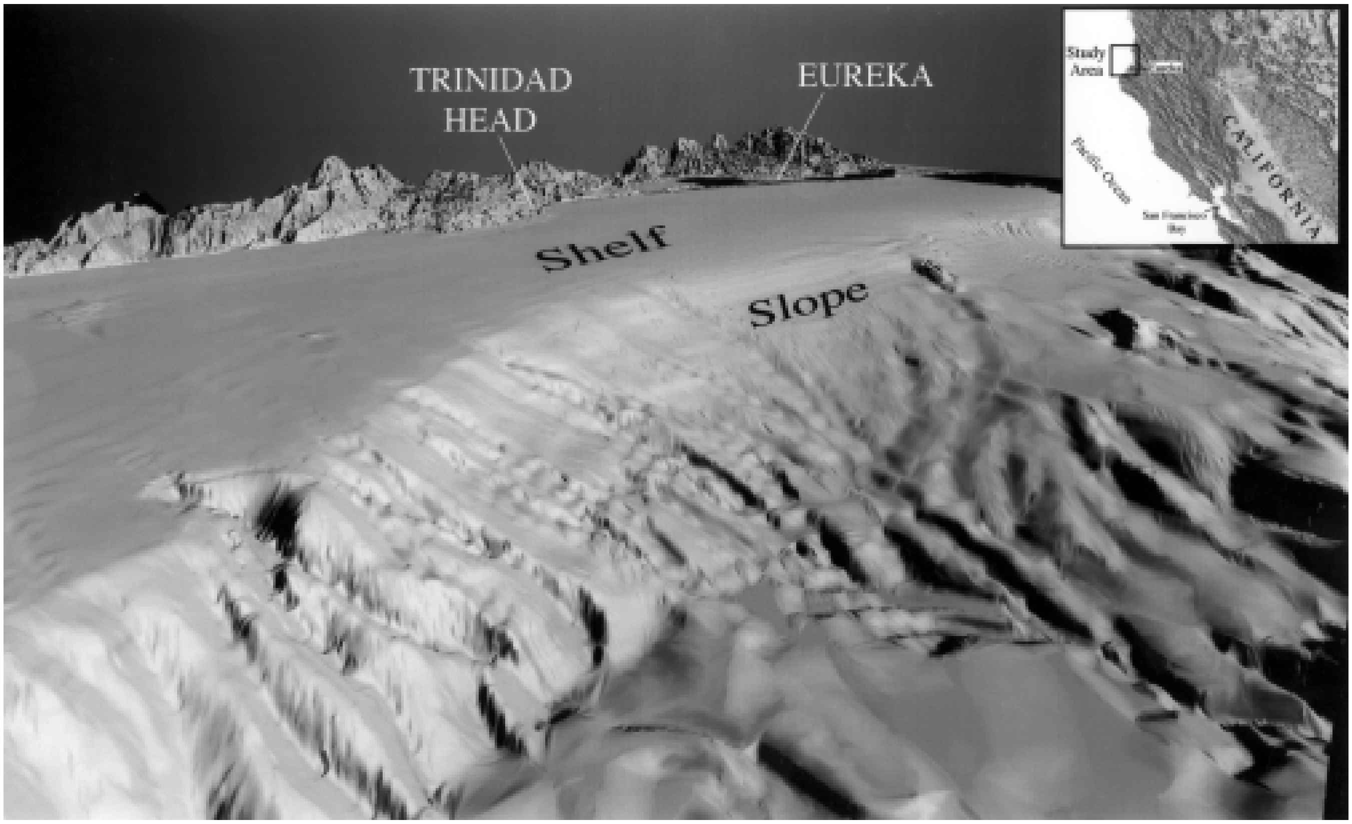

Figure 1

Perspective, shaded-relief view of the study area based on high-resolution multibeam bathymetry. Vertical exaggeration is 20×. The continental shelf (<120 m water depth) is bathymetrically smooth owing to large input of fine terrigenous sediments from the Eel and Mad Rivers and to reworking by storms. The southern portion of the shelf is dominated by the Humboldt slide. The northern portion of the slope is ~60 m deeper and ~7 km farther from shore than in the Humboldt slide area.

rigged with a 33.5-m (110-ft) net opening with trawl doors hung ~76–91 m (250–300 ft) apart.

The trawl fishery on the shelf primarily occurs over soft-sediment habitat and mainly targets flatfishes. The important species in this assemblage include English sole (*Pleuronectes vetulus*), Petrale sole (*Eopsetta jordani*), and sanddabs (*Citharichthys* spp.). The slope fishery occurs over rougher and more heterogeneous habitats that begin at the shelf break (~120 m) and continue to depths >900 m. The catch in this assemblage is dominated by Dover sole (*Microstomus pacificus*), sablefish (*Anoplopoma fimbria*), thornyheads (*Sebastolobus* spp.), and several rockfish species (*Sebastes* spp.). A midwater trawl fishery also exists in waters above the slope for Pacific whiting (*Merluccius productus*) and widow rockfish (*Sebastes entomelas*). The assemblages in this region are similar to those found along other portions of the U.S. west coast by the National Marine Fisheries Service triennial trawl surveys (Jay, 1996).

Groundfish are among the most diverse and economically valuable fishery resources along the west coast of the United States (NOAA, 1996). Diversity, quality, and extent of habitat are among the most important environmental determinants of distribution, abundance, and species diversity for groundfish (Carlson and Straty, 1981; Matthews and Richards, 1991). The broad spatial extent of these fisheries generally precludes careful examination of the nature of the exploited habitats, the relationship among species and habitats, and the degree to which fishing activities have affected these habitats. Conservation of fisheries habitat is an important consideration for sustaining fisheries production. The reauthorization of the Magnuson-Stevens Fisheries Conservation and Management Act requires incorporating the concept of “essential fish habitat” in Fishery Management Plans (Schmitten, 1996). Because fishing, particularly with bottom trawls, can alter essential fish habitat, it is important to quantify fishing activity and its effects on the associated habitat. The goals of this study are to evaluate the extent of marks from bottom trawls off Eureka, California, at a scale consistent with commercial fishing activities and to compare these results with fishing-effort data from commercial fishery logbook data.

Materials and methods

Geological setting

The study area is the upper continental margin of northern California, north of Cape Mendocino. The shelf and slope in this region are within the Eel River Basin, a forearc basin filled with sediment derived from high sediment loads during the late Neogene (Clarke, 1992). The entire basin is highly faulted and folded from multiple episodes of deformation. Shearing and compression of the margin related to underthrusting of the Gorda plate beneath the North American plate has resulted in thrust faulting, uplift, and an overall youthful geologic setting, and this has produced varied relief and structure of the seafloor (Carver, 1987; Clarke and Field, 1989).

Studies of seafloor structure and sediment history of this area (Field et al., 1999; Gardner et al., 1999; Goff et al., 1999) have identified many features related to submarine landslides and to downslope sediment transport through channels and gulleys. Sidescan-sonar images of the seafloor along the shelf and slope, as well as multibeam maps, high-resolution seismic reflection data, and instrumented tripods from complementary investigations, all show abundant evidence of modern processes at work on the seafloor (Field and Jennings, 1987; Alexander and Simoneau, 1999; Field et al., 1999; Gardner et al., 1999; Goff et al., 1999; Yun et al., 1999).

There are three main types of relief on the seafloor in this region. Along the slope, in the center of the study area, a large growth fold (anticline) has uplifted through the modern seafloor, exhibiting 100 m of steep relief. South of the anticline, the slope between 120 and 600 m depths is dominated by the Humboldt slide, an area where slope deposits have undergone deformation and limited downslope movement (Field and Barber, 1993; Gardner et al., 1999). North of the anticline, the slope is crossed by a series of shallow gullies that are 100 to 200 m wide and 1 to 2 m deep (Field et al., 1999). Gullies are spaced about 200 to 300 m apart. Gullies also occur south of the anticline where they are generally fewer in number and somewhat deeper (~20 m). The gullies are thought to represent sediment pathways during earlier periods when sea level was at a lower position.

Sidescan survey

Through a collaborative effort of the U.S. Geological Survey (USGS) and the National Marine Fisheries Service (NMFS), we examined sidescan-sonar data off Eureka, California, collected by the USGS during the STRATA FORMation on Margins (STRATAFORM) program sponsored by the Office of Naval Research (Nittrouer and Kravitz, 1996; Nittrouer, 1999). A grid of 1600 line kilometers of high-resolution, digital, deep-towed (95 kHz) sidescan-sonar data was obtained during 1995 and 1996 (Fig. 2). The sidescan-sonar images were obtained by using the USGS Datasonics SIS-1000 chirp sonar system and an ISIS data-acquisition system. The sidescan sonar operates as a swept FM signal with a frequency band from 90 to 110 kHz (port channel sweeps from low to high, starboard channel sweeps high to low). Usual swath width during the cruises was 0.5 s (750-m swath). Sidescan data were recorded on magneto-optical disks and downloaded to a DEC ALPHA workstation. The digital sidescan-sonar data were all processed with USGS MIPS image-processing software (Chavez, 1984; 1986). The raw data were geometrically corrected (slant range) by using the position, heading, speed, and nadir depth of the ship. Each of the 8-bit image pixels was geometrically located by assuming a flat seafloor which introduces a certain amount of uncertainty into the actual location of any given pixel. Our estimated location accuracy was about 100 m. After the geometric corrections were made, anamorphic corrections were applied to account for the aspect ratio between along- and across-track directions. Radiometric corrections had to be applied to the 8-bit digital number (DN) that represents backscatter. Each sidescan line was subdivided into segments and, for each segment, the average DN for each binned range was normalized to the mean of all the binned ranges within that segment. Each segment was several hours long, and this correction produced tone-matched adjacent segments.

Trawl marks

Trawl marks appear on the sidescan sonographs as long, narrow, linear depressions (Fig. 3). Trawl marks were traced on mylar overlaid on the sidescan records. Each sidescan track line was divided into 10-min time intervals. Vessel speeds during the surveys varied between 3 and 4 knots, and therefore each 10-minute interval covered from 0.9 to 1.2 km along the ship's course. The sidescan record covered a 750-m swath so that 10-min segments represent from 675,000 m^2 to 900,000 m^2 of area. To quantify the number of trawl marks per time interval, lines were drawn perpendicular to the course of the sidescan track line, and trawl marks that bisected these lines were counted. Mean trawl mark length was 0.77 km (SD=0.26) for 20 randomly selected 10-min

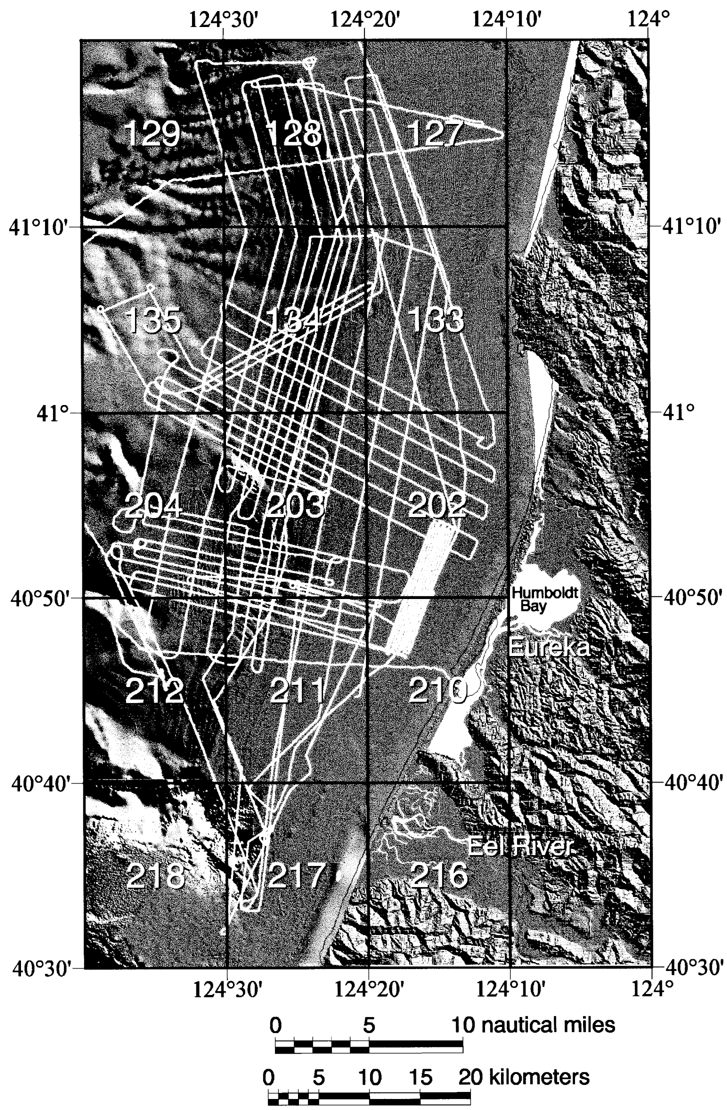

Figure 2

Track lines for high-resolution sidescan-sonar surveys. The reporting blocks from California Department of Fish and Game that are used for logbook data entry are superimposed on the survey area. Blocks are 10 minutes of longitude and 10 minutes of latitude on a side with block number in the center.

intervals from 10 different sidescan track lines (Fig. 4). From these results, it was determined that two random perpendicular lines were needed to properly sample each 10-min interval and minimize double-counting of trawl marks. Using a sample of 50 randomly selected 10-min time intervals from 10 sidescan track lines, we counted the actual number of trawl marks and compared this number with the mean number counted with the perpendicular line intercept method described above. The mean proportion of trawl marks counted with this sampling method to actual number of marks was 0.84 (SD=0.11). Trawl mark density in km^2 was calculated from each time interval and incorporated into a Geographical Information System (GIS) for analysis and contouring.

The angle of each trawl mark was measured in relation to the two perpendicular lines used to quantify trawl marks in all 10-min intervals. These angles were adjusted for the course of the sidescan track and computed in relation to magnetic north. Mean angles for each time interval were then calculated and plotted on a polar plot in an $r = f(\theta)$ format, where r is the number of trawl marks and theta (θ) is the angle relative to 0°. The grand mean angle and 95% CI were computed with the mean values from each time interval (Zar, 1984).

Fishing effort

Trawlers provide information on catch and effort of individual trawl hauls to the California Department of Fish and Game (CDF&G). Hauls are spatially recorded in blocks that are 10 minutes of latitude by 10 minutes of longitude (Fig. 2). Blocks within the Eureka STRATAFORM survey area were extracted from the NMFS Tiburon Laboratory groundfish database and used in these analyses. Trawling is prohibited by state law within 5.6 km (3 nm) of the coast. All reporting blocks adjacent to the coast were truncated for all estimates and comparisons.

Pacific whiting form extensive midwater aggregations during the day, and the fishery is conducted almost exclusively with midwater trawls (Dorn and Saunders, 1997). Because fishermen did not report whether their trawl hauls were bottom trawls or midwater trawls, all trawl hauls with catches of Pacific whiting greater than 454 kg (~1000 lb) were eliminated from these analyses. Mean annual fishing effort (trawl hours) was calculated for each reporting block within the Eureka area for the years 1990 to 1994. Depths from the logbook data were used to obtain mean fishing depths for each reporting block for comparisons with fishing effort.

The reporting block grid was incorporated into a GIS and the mean density of trawl marks was calculated for each block (Table 1). Water depths from a high-resolution multibeam mapping survey (Goff et al., 1999**)** were binned to obtain mean bottom depth in each block for comparison with mean number of trawl marks. Effort, expressed as mean annual trawl hours per block, was compared to the mean number of trawl marks in each reporting block with a Spearman rank order correlation. Two reporting blocks (129 and 218) were excluded from this analysis owing to a lack of adequate sidescan coverage. To estimate the total area swept by bottom trawls on an annual basis, the total annual number of fishing hours per reporting block was multiplied by a typical vessel speed (5.5 km/h) and a typical door to door width of 85 m.

Detrended correspondence analysis (DCA) was used to identify clusters of similar reporting blocks in ordination space on the basis of fish assemblage structure from CDF&G logbook data (Ludwig and Reynolds, 1988). A matrix of reporting blocks by catch was created for use in this analysis. Habitat types were defined *a priori* by depth and physical characteristics of the habitat from previous geological surveys and then overlaid on the station clusters created by DCA. A Kruskal-Wallis rank sum test (Hollander and Wolfe, 1973) was used to compare the density of trawl marks and total fishing hours per reporting block in each habitat type discerned by DCA. Pairwise comparisons of trawl marks and fishing effort between habitats was conducted by using Dunn's multiple comparison procedure at $\alpha = 0.05$ (Hollander and Wolfe, 1973).

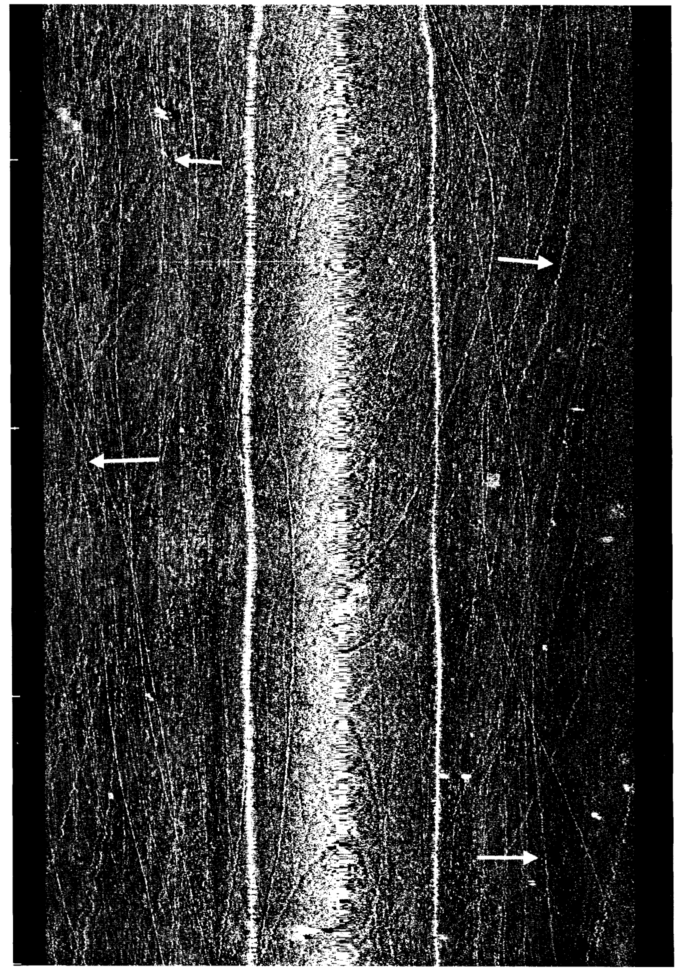

Figure 3

Sidescan-sonar image (white is shadow; dark is reflection) of trawl marks on the seafloor at a water depth of ~150 m. Sidescan swath width is 750 m. Tick marks are 5-min time intervals (~0.55 km). Arrows point to examples of trawl marks. Shallow circular depressions on the sonograph are gas pockmarks. Ship's course for this sonogram is 345°.

Results

We measured the range, density, and orientation of marks on the seafloor caused by trawling activity as resolved by the sidescan-sonar records. Of the 1246 10-min intervals examined, ~10% were washed out and could not be analyzed. Densities of trawl marks/km^2 per 10-min interval ranged from 0.00 to 98.55 and mean density per block ranged from 0.94 to 38.3 with a grand mean of 20.0 marks/km^2 (Table 1). Trawl marks were most abundant on the slope, particularly the northern portion and least abundant on the continental shelf (Fig. 5).

Trawl marks commonly were oriented parallel to isobaths and some could be traced for several km (Fig. 6). The overall mean trawl direction was 352.6° (95% CI +/–5°) (Fig. 7) which agrees with the general orientation of isobaths in this area. Because trawl marks were generally orientated in the north–south direction along isobaths, sidescan tracks orientated in the east–west direction (>45° and <135°) might not distinguish as many trawl marks in relation to those orientated in the north–south direction. Using 25 randomly selected time intervals from five east-west sidescan track lines and 25 from five north–south track lines, we found that the proportion of trawl marks sampled with the perpendicular line intercept method was not significantly different from the actual number of trawl marks for the two track line orientations (Mann-Whitney rank sum test=759.5, P=0.775).

We compared the orientation of trawl mark angles between east–west and north–south orientations by selecting seven locations where east–west and north–south sidescan-sonar track lines intersected during the 1996 survey. The intersecting time interval, along with one time interval to either side were pooled for each orientation (21 time intervals for each orientation) and compared by using a Watson-Williams two-sample test for mean angles (Zar, 1984). There was a significant difference (F=44.7, P<0.001) in the mean angle of trawl marks detected along north–south orientated track lines (mean=357.9) compared with east–west orientated track lines (mean=294.5) at these intersection points.

Table 1

Summary statistics for density estimates of trawl marks in each California Department of Fish and Game (CDF&G) reporting block. Block numbers with asterisks are excluded from comparative analysis with fishing effort owing to small sample size and lack of adequate block coverage.

CDF&G block	Mean (no/km^2)	SD (no/km^2)	Max (no/km^2)	Min (no/km^2)	*n*
127	25.22	16.77	52.92	0.00	34
128	35.07	18.56	98.55	2.09	132
129*	31.19	7.94	45.08	21.59	13
133	11.80	13.20	49.13	0.00	81
134	38.26	11.82	63.49	0.00	144
135	22.02	10.69	52.11	1.39	34
202	4.13	6.44	26.67	0.00	169
203	18.01	12.65	43.87	0.00	159
204	22.82	15.71	64.09	0.00	115
210	0.94	2.25	14.03	0.00	69
211	10.99	16.89	76.75	0.00	102
212	28.98	13.56	66.42	8.25	39
217	27.39	27.23	75.55	0.00	25
218*	28.68	15.58	39.69	17.66	2
Mean	19.99	18.34	98.55	0.00	Σ = 1118

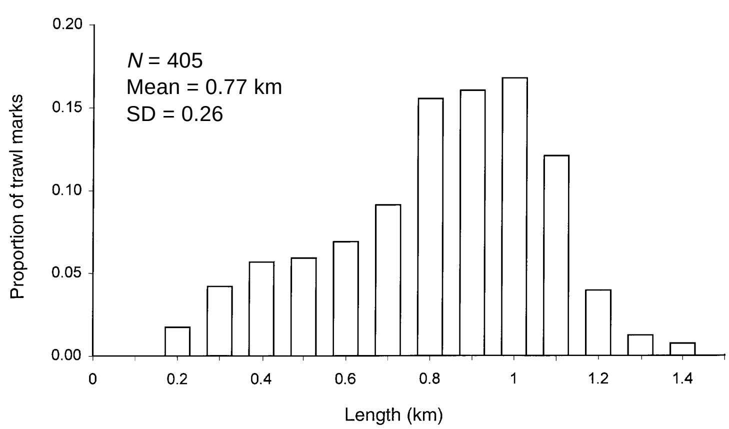

Figure 4

Frequency distribution of trawl-mark length per 10-min interval. Ten minute time intervals ranged from 0.77 to 1.2 km in length (mean=0.91). Data are from 20 randomly selected 10-min intervals from 10 different sidescan tracks.

The mean density of trawl marks in each CDF&G reporting block fitted a quadratic relationship with water depth (y=–0.0002x^2 + 0.1374x + 2.9353, R^2=0.501, P=0.04). The lowest density of trawl marks was observed in the shallowest water with maximum number of trawl marks observed at ~400m depth (Fig. 8). Mean annual trawl hours (1990–94) also fitted a quadratic model with water depth for each reporting block (y=–0.0082x^2 + 8.7015x – 960.57, R^2=0.723, P<0.001) (Fig. 8). There was a significant positive correlation between the density of trawl marks and the mean annual number of trawl hours per reporting block (r_s=0.573, P=0.048).

The fishing blocks off Eureka can be separated into three depth zones on the basis of fish assemblages analyzed by DCA (Fig. 9). The upper and mid slope blocks are relatively close in DCA ordination space, whereas the shelf blocks showed a distinct assemblage structure. The shelf blocks nearest the coastline have effective fishing depths of ≤102 m (Table 2). From logbook data, the dominant species at these depths are flatfishes (e.g. sanddabs, Petrale sole, and English sole) and rockfishes. Dominant species from trawling on the upper slope (175 to 437 m) primarily consisted of Dover sole and rockfishes. Thornyheads, Dover sole, and sablefish are the dominant species on the mid slope (effective fishing depth from ~595 to 837 m).

The mean density of trawl marks was significantly different (Kruskal-Wallis H=287.4, P<0.001) among the three depth zones recognized by DCA (Fig. 10A). Upper and mid slope depths were not significantly different from one another (P>0.05) but both had significantly greater numbers of observable trawl marks than the shelf depth zone (P<0.05). Mean annual fishing effort per block also showed significant differences among depths (Kruskal-Wallis H=9.5, P=0.009, Fig. 10B). Fishing effort was lowest in the shelf habitat and highest in the upper slope, although the upper slope and deep slope depth zones were not significantly different from one another (P>0.05).

The cumulative annual area swept by commercial bottom trawls, as calculated from logbook data, was compared to the total area in each reporting block (Fig. 11). The entire study area was trawled ~1.5 times on an average annual basis. The area trawled exceeded the total block area in the majority of the blocks. This was particularly true in the deeper blocks where the ratio of area trawled to block areas ranged from 127% to 339%.

The mean trawl depth and mean duration of hauls for bottom trawls off Eureka has increased steadily since the early 1980s (Fig. 12A). Along with this change in fishing depth has come a shift in the composition of species landed. Thornyheads are deeper-water species and their catch contribution has increased from ~4% of the total catch in the late 1970s to ~14% in the 1990s. Conversely, the English sole is a shallow-water flatfish whose landings have declined from nearly 7% of the total catch in the late 1970s to 2–3% in the 1990s.

Discussion

Utility of sidescan sonar

Acoustics are useful in fisheries for stock assessment (Karp, 1990), for remotely sensing characteristics of bottom habitat (Able et al., 1987; Greenstreet et al., 1997; Mayer et al., 1997; Yoklavich et al., 1997; Auster et al., 1998a, 1998b), and for assessing impacts to fisheries habitat (Auster et al., 1996; Collie et al., 1997). Our results demonstrate that the use of acoustic remote sensing also presents a promising independent approach for evaluating fishing effort on a spatial scale consistent with commercial fishing activities. Sidescan-sonar data are useful for identifying the location of trawling activity, as well as for evaluating the amount of disturbance to the seabed, and may be used in developing indices of habitat disturbance caused by fishing activities. Despite minimal sidescan coverage in some reporting blocks and biases in the logbook data associated with misreporting, there was a significant positive correlation between the density of trawl marks per reporting block from sidescan-sonar data and the mean annual number of trawl hours. A quadratic relationship with depth was observed for the number of trawl marks and fishing effort per reporting block with maximum values at ~400 m and ~500 m, respectively. This relationship, together with the density contour plot of trawl marks and the vector plot of trawl orientation, shows that fishing effort was concentrated on the upper to mid slope and along bathymetric contours.

The entire study area off Eureka is trawled ~1.5 times its total area on an annual basis. Because of narrow bands of rocky outcrops and anticlines,

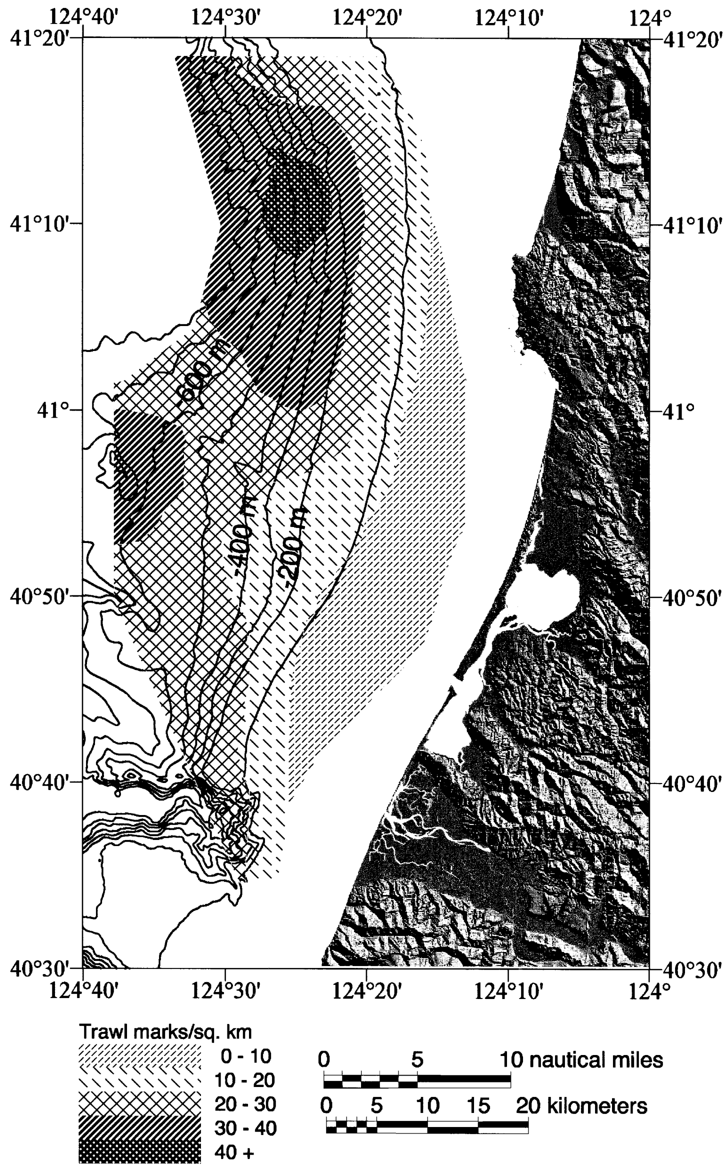

Figure 5

Contour plot of trawl mark densities (number/km^2) derived from 10-minute intervals along sidescan survey track lines. Actual locations of data points are in Fig. 6.

trawlable fishing area within the mid slope reporting blocks is less than the total area of the blocks. The area swept by trawls is therefore an under-estimate of the effective fishing area that is impacted by trawl gear in these blocks. Gislason (1994) estimated that trawling swept the entire area of the North Sea annually, with some fishing grounds in the southern North Sea likely being swept more than three times a year by beam trawls. This type of chronic impact on the seafloor can have a long-term effect on the local benthic epifauna (Rogers et al., 1998). For example, there is abundant evidence of rich ecological communities associated with cold-seeps and extensive bioturbation off Eureka (Syvitski et al., 1996). Released gases and fluids from cold seeps are rich in methane and sulfide and support unique productive cold-seep biological communities (Syvitski et al., 1996). The magnitude of trawling activity in this area has the potential to modify these communities by direct physical damage or by smothering from resuspended sedimention.

There has been increased interest in recent years on the impacts of fisheries on the marine environment (Dayton et al., 1995; Boehlert, 1996; Lindeboom and de Groot, 1998; Watling and Norse, 1998), and an important component is the relationship between exploited fish species and their associated habitats (Schmitten, 1996). With a greater understanding of these associations, concerns have been raised about the adverse impacts that mobile fishing gear may have on the entire ecosystem. The severity and duration of disturbance are both factors that affect ecological communities (Gislason, 1994; Connell et al., 1997; Tuck et al, 1998; Auster and Langton, 1999). Mobile fishing gear, such as trawls, is the most widespread form of direct disturbance to marine systems below depths affected by storms (Watling and Norse, 1998). Natural disturbances to the benthic community off Eureka probably occur from high-energy wave events, floods, and even tectonic activity. The first two processes likely have a greater impact in the shallower water on the shelf, and the latter process is likely too infrequent to play a major role in impacting the benthos. Thus, in the habitat covered by this study, trawls represent the greatest form of direct disturbance to the benthic habitat—a finding that is consistent with the conclusions of Watling and Norse (1998) for depths below the influence of storms. The extent and location of fishing activity, noted in this study from logbook data and sidescan-sonar records, can potentially have a large impact on the local ecological communities, particularly on the slope where the frequency and magnitude of natural disturbance is less than that on the shelf.

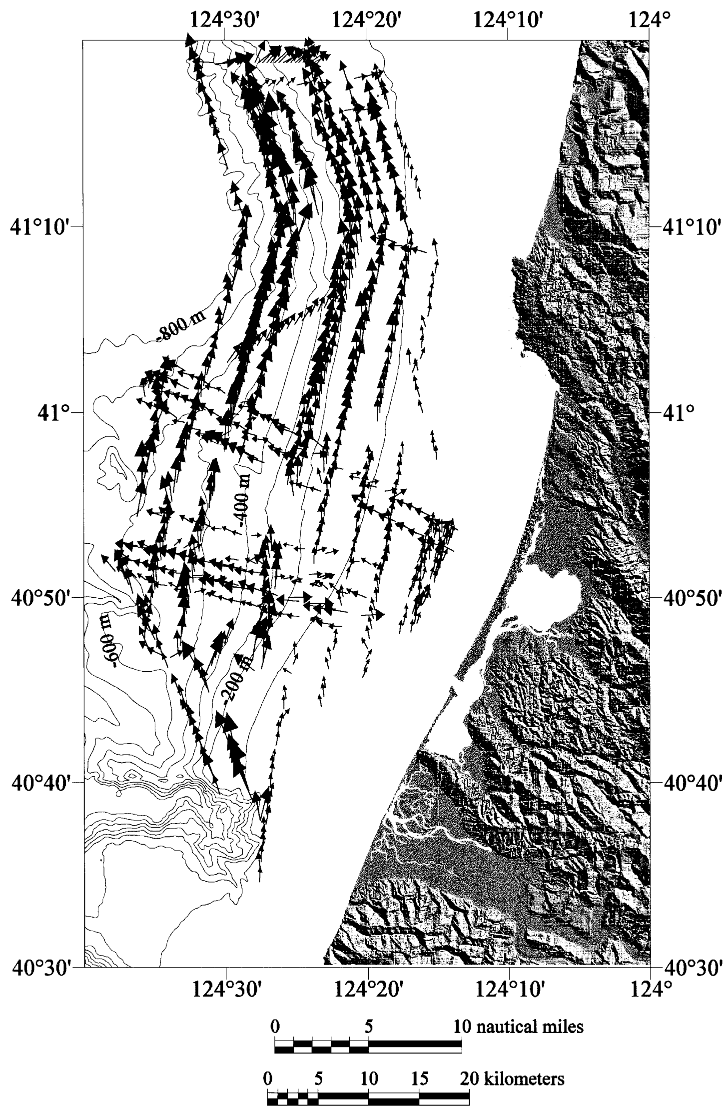

Figure 6

Vector plot showing orientation and magnitude of trawl marks along sidescan track lines. Length of arrow is proportional to the density of trawl marks in each 10-min interval, and direction is the mean angle of all trawl marks in each time interval. Note that angles are plotted in relation to north so that trawls towed north or south resulted in the same orientation.

Examination of trawl marks was not the primary goal of the sidescan-sonar survey conducted off Eureka (Syvitski et al., 1996). Consequently, there are aspects of the survey method that could have been conducted differently to improve the quality of these data. Because fishing activities in this area are generally conducted along the north–south bathymetric contours, sidescan-sonar tracks oriented east–west tended to resolve slightly fewer trawl marks. Any future study of trawl marks using sidescan sonar should concentrate tracks to orientations subparalleling trawling directions in order to maximize the resolution of the survey.

There are biases associated with this method, particularly in a dynamic physical location like the northern California continental margin. Estimates of the actual number of trawl marks are minimal because of variability in resolution of the sidescan records, obliteration of older trawl marks by more recent trawling, burial by sedimentation or reworking of the seafloor by

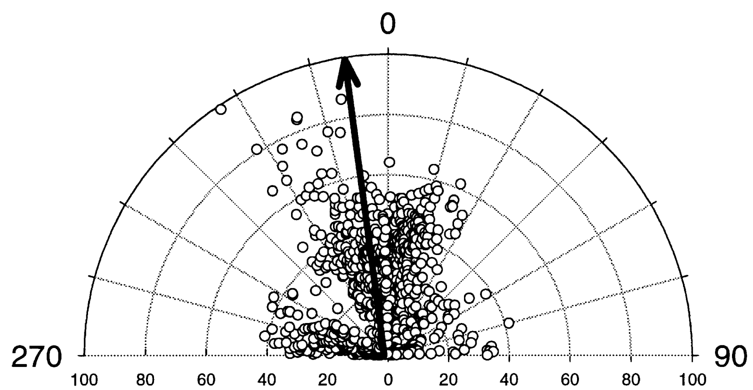

Figure 7

Polar plot of mean angle and density of trawl marks for each time interval. Polar plot in an $r = f(\theta)$ format where r is the density of trawl marks and theta (θ) is the angle relative to 0°. The grand mean trawl direction was 352.6° (95% CI +/–5°).

large waves, particularly at shallower depths. Trawl marks may persist for longer duration in deeper water where sedimentation rates are lower and storm waves have a lessened or negligible effect. Shelf sediment presently accumulates 2 to 10 times faster on the shelf than on the slope (1–3 mm/yr on the slope; 6–10 mm/yr on the shelf based on ^{210}PB activities; Alexander and Simoneau, 1999; Sommerfield and Nittrouer, 1999). At present rates, and assuming trawl track depths of ~15 cm, it would take 50–75 years to fill in a typical trawl mark, but evidence shows that small natural gullies on the slope are being draped and are infilled at present and thus maintain their shape and relief even though they are in the process of being buried (Field et al., 1999). The sedimentation rates on the shelf are higher than on the slope (the flood deposits from the 1964 Eel River flood now lies ~45 cm below the seafloor) (Sommerfield and Nittrouer, 1999), and annual storm waves resuspend sediments at depths up to 100 m. Resuspension and redeposition of silt particles may lead to draping of trawl gouges and thus preserve their shape and relief on the seafloor. In the presence of bottom currents, which usually are present from tides, storm waves, or boundary flows, the resuspended particles may fill in the trawl gouges and thus slowly erase them over time. Since fishing effort in the study area was shown to be concentrated in water deeper than 100 m, these effects are possibly compounded by the longevity of trawl marks in this habitat. Research is needed to address the longevity of trawl marks in various environments as well as to determine the impacts on (and recovery of) diversity and production in benthic communities.

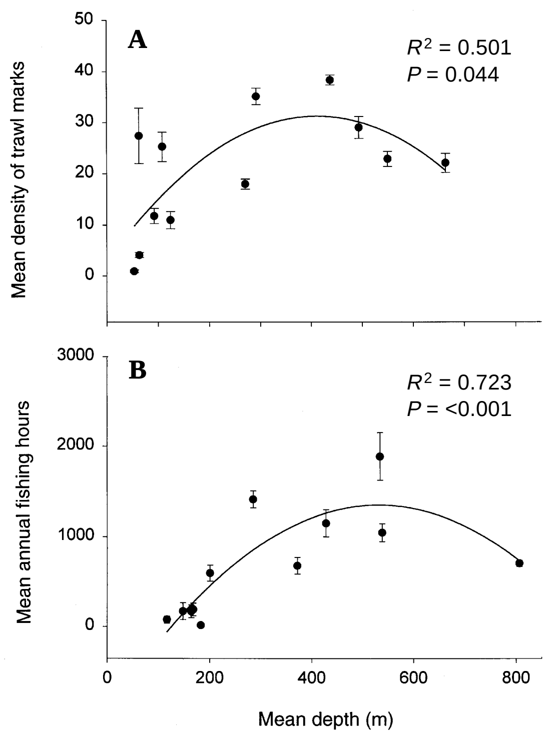

Figure 8

(**A**) The nonlinear relationship between mean density of trawl marks per 10-min interval by CDF&G reporting block depth (m). Mean trawl mark block depth is calculated from the mean depth of 10-min intervals along the sidescan track in each reporting block. (**B**) Mean annual fishing hours per reporting block and block depth (m). Mean fishing hour block depth is calculated from the depths reported from logbooks in each reporting block. Error bars are standard error of the mean.

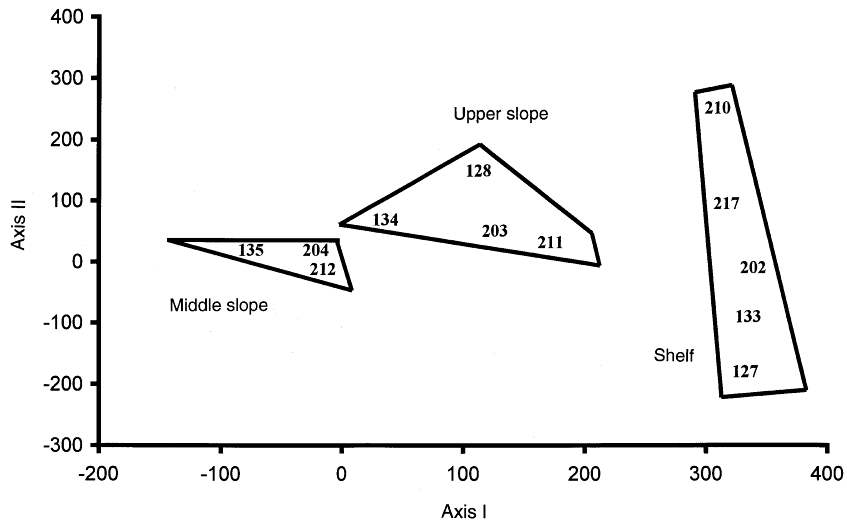

Figure 9

Results of a detrended correspondence analysis of mean annual species catch composition (1990–94) in CDF&G reporting blocks off Eureka. Three clusters are recognized as unique depth zones. Numbers are CDF&G reporting block numbers.

Table 2

Characteristics of California Department of Fish and Game (CDF&G) reporting blocks by habitat zone. Values for fishing depth are mean depth per trawl in each reporting block from logbook data (1990–94). Block depth and area are calculated from Geographical Information System (GIS) data and exclude areas within the 5.6-km (3-nmi) no trawl zone. Values for dominant species are percentages of mean total annual catch (1990–94).

Habitat zone	Block	Fishing depth (m)	Block depth (m)	Block area (km^2)	Fishing effort	Dominant species caught					
Shelf											
	127	68	83	251	191	Sanddab	30.31	English sole	27.59	Petrale sole	14.82
	133	102	83	207	16	Sanddab	33.31	English sole	14.35	Widow rockfish	9.87
	202	67	69	202	169	Sanddab	48.46	English sole	12.80	Petrale sole	11.88
	210	93	52	55	78	Rockfish	29.46	Sanddab	25.85	Petrale sole	14.25
	217	101	96	147	170	Widow rockfish	52.36	Rockfish	12.64	Sanddab	11.29
Zone mean		86	77	Σ = 862	Σ = 623	Sanddab	29.84	Rockfish	13.80	English sole	13.15
Upper slope											
	128	359	347	259	691	Dover sole	40.10	Rockfish	22.78	Sablefish	13.92
	134	437	425	259	1156	Dover sole	60.50	Sablefish	16.48	Thornyhead	7.76
	203	265	260	260	1425	Dover sole	34.07	Rockfish	21.41	Petrale sole	10.29
	211	175	118	256	599	Dover sole	22.68	Rockfish	22.52	Sanddab	13.49
Zone mean		309	288	Σ = 1034	Σ = 3871	Dover sole	39.34	Rockfish	10.18	Sablefish	10.95
Mid slope											
	135	837	873	259	707	Thornyhead	45.75	Dover sole	33.11	Sablefish	16.21
	204	539	583	260	1054	Dover sole	57.06	Sablefish	15.45	Thornyhead	12.13
	212	525	570	260	1900	Dover sole	51.92	Thornyhead	16.80	Sablefish	15.63
Zone mean		634	675	Σ = 779	Σ = 3661	Dover sole	47.36	Thornyhead	24.89	Sablefish	15.76

The general temporal trend in fisheries development begins with localized fisheries that then expand geographically and to less accessible habitats, such as the deep sea (Deimling and Liss, 1994). In the present study, mean trawl depths have increased over the years as a result of changes in management strategies, changes in market demands, and overfishing of nearshore resources. Shortspine thornyheads (*Sebastolobus alascanus*) and longspine thornyheads (*S. altivelis*) are slope rockfish species whose landings have increased along the West Coast in recent years (Ianelli et al., 1994) whereas English sole has decreased. An export market for thornyheads developed during the 1980s because a similar and highly valued species (*S. macrochir*) was depleted off Japan (Rogers et al., 1997). As the Japanese market developed, the trawl fishery moved into deeper water following a typical pattern (Deimling and Liss, 1994) where longspine thornyheads and larger shortspine thornyheads are most common. Several of the most important species in the trawl catch (e.g. Dover sole and sablefish) segregate at depth by sex, size, and maturity stage. These biological characteristics as well as size and harvest restrictions makes interpretation of changes in the catch of these species difficult to interpret.

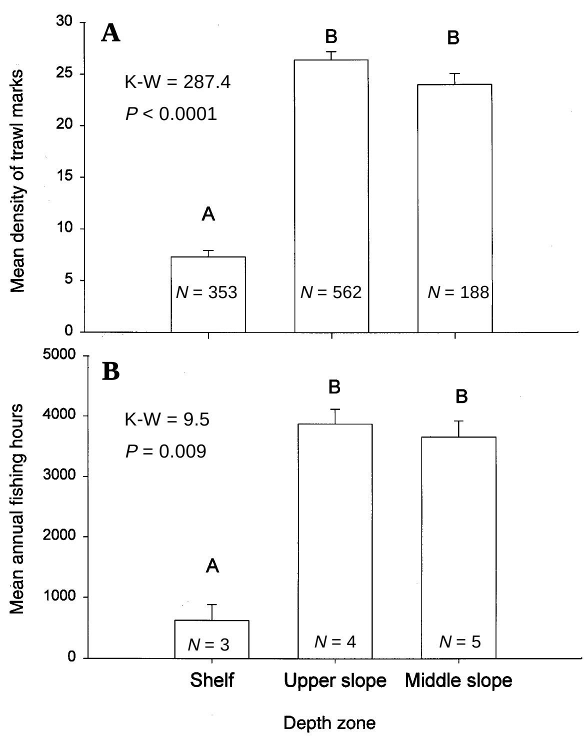

Figure 10

(**A**) Mean density of trawl marks per 10-min interval for the three habitat zones recognized by DCA. N = the number of time intervals in each habitat zone. (**B**) Mean annual fishing hours per CDF&G reporting block for the three habitat zones recognized by DCA. N = the number of reporting blocks in each habitat zone. Error bars are standard error of the mean. Statistical results from Kruskal-Wallis rank sum test. Dunn's multiple comparison procedure, $\alpha = 0.05$. Habitats with the same letter designation are not significantly different from one another.

Implications for management

The groundfish trawl fishery has experienced declining catches and increasing regulation in recent years. Current management strategies are imposed primarily on individual species or among small groups of congeneric species. These strategies do not address the impact to essential fish habitat from fishing activities and therefore may not be appropriate for the long-term sustainability of these resources. Marine reserves or harvest refugia are an effective management strategy that can help protect and maintain the complexity and quality of fish habitat as well as mitigate the direct effects of fishing (Bohnsack, 1996; Bohnsack and Ault, 1996; Auster and Shackell, 1997; Yoklavich, 1998). A number of studies have noted reduced diversity and abundance of emergent epifauna in trawled areas compared with adjacent areas closed to fishing (Bradstock and Gordon, 1983; Auster et al., 1996). The demersal trawl fishery off northwest Australia was thought to be responsible for a significant loss of emergent epifauna and decreased fish productivity (Sainsbury, 1987, 1988), both of which recovered in an area closed to fishing. The establishment of harvest refugia may be the most effective method of reducing the impact of trawls to benthic habitat and subsequently may help to improve the sustainability of the associated fish assemblages.

Detailed analysis of sidescan-sonar data has allowed us to map and quantify trawl marks in relation to fishery and habitat distributions. The combination of geophysical data with fisheries dependent and independent data in a GIS provides the ability to examine the impact of trawling at a scale appropriate for fisheries management. Evaluation of benthic habitat disturbance caused by fishing activities is important for meeting the mandate of the Sustainable Fisheries Act. Developing indices of benthic habitat disturbance can be valuable in comparing the impact of fishing activities among different areas and in establishing baselines for evaluating future management strategies such as closed areas.

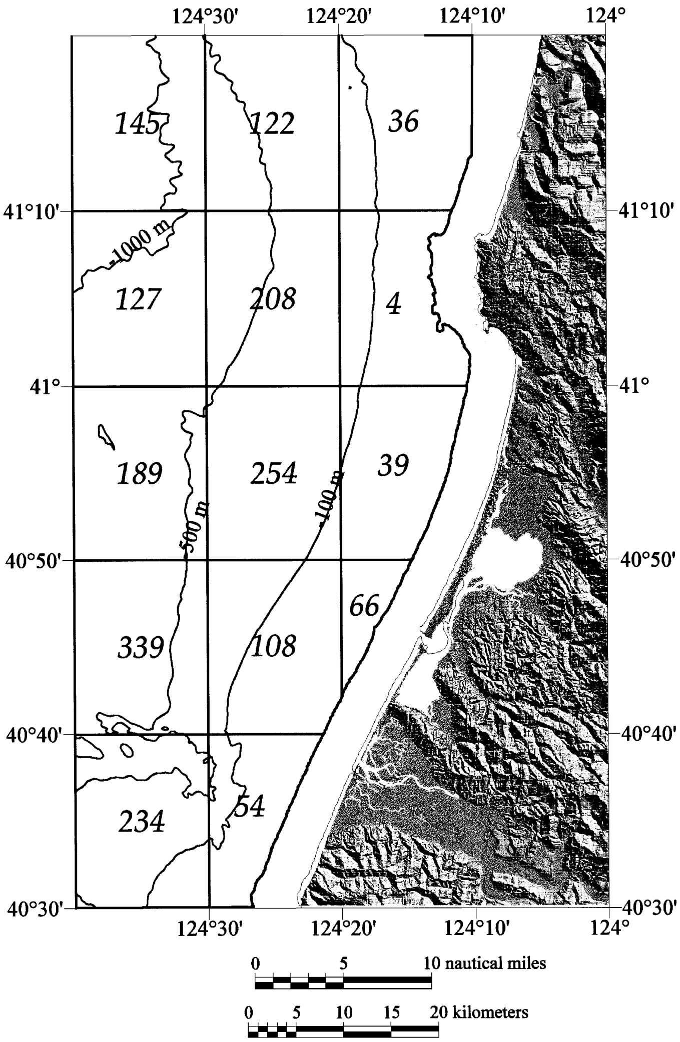

Figure 11

Total area trawled within each reporting block as a percentage of the total block area. Area trawled was calculated from the product of mean annual fishing effort (1990–94) from logbook data, typical vessel speed (5.5 km/h), and a typical trawl door to trawl door width of 85 m. "No trawl" areas within 5.6 km (3 nmi) of shore are not included in the total area calculations.

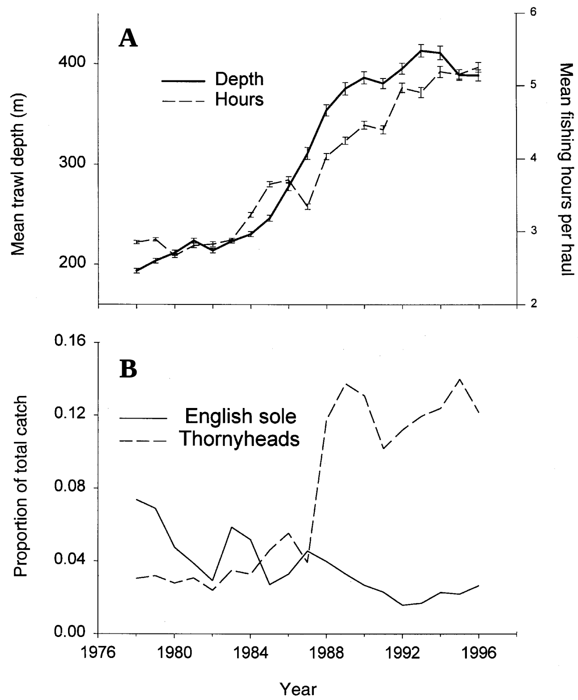

Figure 12

(**A**) Mean annual trawl depth and mean fishing hours per trawl haul off Eureka from 1978 to 1992. Error bars are standard error of the mean. (**B**) Proportion of total groundfish trawl catch of thornyheads and English sole from 1978 to 1994.

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