Evaluation of a US west coast groundfish habitat conservation regulation via analysis of spatial and temporal patterns of trawl fishing effort

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Evaluation of a US west coast groundfish habitat conservation regulation via analysis of spatial and temporal patterns of trawl fishing effort

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Abstract: We examined the extent to which the 2000 Pacific Fishery Management Council footrope restriction shifted and reduced trawl fishing effort on Oregon fishing grounds, related these changes to the seafloor habitat type over which they occurred, and developed methods for enhancing spatial review of fishing effort. Density analysis of trawl start locations demonstrated how fishing efforts increased and decreased in relation to habitat distribution and fishery management actions between 1995 and 2002. Trawl effort patterns exhibited significant interannual variability and were patchy in distribution. Tow end-point locations from 1998 to 2001 were retrieved from manual logbooks for five reference sites located in proximity to rocky habitat. Trawl towlines were mapped and demonstrated a marked enhancement of fine-scale fishing effort resolution. Spatial shifts in fishing intensity (measured as kilometres towed) away from rock habitat were evident at all reference sites after the footrope restriction, with an average reduction of 86%. Some slight shifts into surrounding unconsolidated sediments also occurred. Our results indicate that the footrope restriction, in conjunction with associated landing limits, was effective in protecting rocky habitats from trawl fishing impacts. Continued spatial monitoring of trawl data would assist in fishery management assessment of conservation objectives for depleted groundfish and essential fish habitat protection.

Résumé : Nous examinons de quelle façon la restriction concernant les ralingues de fond imposée en 2000 par le Pacific Fishery Management Council a modifié et réduit l'effort de pêche au chalut sur les aires de pêche de l'Oregon; nous mettons ces changements en relation avec les types de fonds marins sur lesquels ils se sont produits; enfin, nous mettons au point des méthodes pour améliorer la surveillance spatiale de l'effort de pêche. Une analyse de densité des points de départ des chalutiers montre combien les efforts de pêche ont augmenté et diminué en fonction de la répartition des habitats et des activités d'aménagement de la pêche de 1995 à 2002. Les patrons d'effort de chalutage varient significativement d'une année à l'autre et suivent une répartition contagieuse. Nous avons obtenu les positions des points de départ et d'arrêt du chalutage des années 1998 à 2001 dans les livres de bord manuels pour cinq sites de référence situés près d'habitats rocheux. Nous avons transcrit sur des cartes géographiques les tracés de chalutage, ce qui se traduit par une amélioration marquée de la résolution de l'effort de pêche à petite échelle. Il y a des indications d'une réduction spatiale en moyenne d'environ 86 % de l'intensité de la pêche (évaluée en kilomètres de traits de chalutage) dans les habitats rocheux dans tous les sites de référence après la restriction des ralingues de fond. Il y a aussi des déplacements peu importants vers les sédiments meubles avoisinants. Nos données indiquent que la restriction des ralingues de fond, en conjonction avec les limites de débarquement associées, a protégé efficacement les habitats rocheux de l'impact de la pêche au chalut. La poursuite de la surveillance des données de chalutage pourrait être utile pour l'évaluation des objectifs de conservation en aménagement de la pêche pour la protection des populations décimées de poissons de fond et de l'habitat essentiel des poissons.

[Traduit par la Rédaction]

Introduction

There has been substantial concern over the effects of bottom trawling and other fishing activities on seafloor ecosystems and the sustainability of fish populations (Johnson 2002; National Research Council 2002; Dieter et al. 2003). Because bottom trawling alters essential fish habitat (EFH), it is important to understand fishing patterns both spatially and in the context of fishery management. Identifying both the distribution of seafloor habitat types and the spatial extent of

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fishing effort over these habitat types is critical for evaluating where fishing gear impacts take place (Meaden 2000; Johnson 2002). The severity of fishing impact is determined by the intensity of fishing effort and the habitat where impacts occur (Jennings and Kaiser 1998; Auster and Langton 1999). Therefore, by shifting fishing effort between habitat types or reducing fishing intensity within habitat types, regulatory measures can act to protect the long-term sustainability of groundfish through conservation of EFH. It is imperative that the performance of fishery management measures implemented to protect depleted groundfish species and their associated habitat be critically evaluated. Previous studies reviewing the effects of Pacific groundfish management have rarely assessed spatial or habitat specific implications (Pikitch 1987; Gillis et al. 1995; Babcock and Pikitch 2000).

The Pacific Fishery Management Council has implemented a combination of management measures for the US west coast groundfish trawl fishery to protect and rebuild depleted rockfish (*Sebastes* spp.) populations (65 FR 221, 67 FR 57973). Many rockfish species are associated with hard-bottom, high-relief rocky areas (Love et al. 2002; McCain 2003). These areas are thought to have the greatest sensitivity to fishing impacts from mobile trawl gear because they are normally relatively stable and have high habitat complexity (substrate surface topography) with a prominent degree of biogenic cover (Auster and Langton 1999; Kaiser et al. 2002, 2003). When the structural and biogenic components of this habitat are reduced and damaged by trawling, obligate rockfish associations are diminished. The reduction of bottom trawling over rocky habitat is therefore an important component of any management strategy designed to avoid impacts to rockfish EFH.

The primary objective of this study was to examine trawl effort shifts over seafloor habitats in response to regulatory changes in the US west coast groundfish fishery. In particular, this study focused on a Pacific Fishery Management Council mandated restriction in trawl footrope size for landing nearshore and shelf rockfish species as well as most flatfish species. This regulation, enacted in 2000 to shift fishing incentives, linked various groundfish trip limits to large (>20.5 cm in diameter) and small (≤20.5 cm in diameter) footrope configurations (65 FR 221). By inhibiting the large footrope gear necessary to pass over rough terrain and obstructions, this restriction was designed to redirect fishing effort off of high-relief rocky areas where depleted rockfish species are most abundant. Furthermore, the retention of most fish normally caught in these areas was prohibited if using large footrope gear. A previous study by Hannah (2003), based solely on catch information, indicated that a reduction in fishing effort had occurred after the trawl footrope restriction but did not determine any relationship to seafloor habitat.

Comprehensive maps of seafloor lithology along the west coast of the United States have recently been compiled. Goldfinger et al. (2003) assembled and interpreted existing geological and geophysical data for the Oregon continental margin. The system used to describe surficial geologic habitat types was a modification of the classification described by Greene et al. (1999). Seafloor habitat, as defined for this study, refers to the surficial lithologic units dictating substrate type as described by Romsos (2004). While broader definitions of habitat may encompass many other ecological and abiotic factors, this study uses the seafloor substrate component as a proxy for associated fish communities (Hixon et al. 1991; Stein et al. 1992; Yoklavich et al. 2000).

Our analysis utilized methods for obtaining an adequate spatial resolution of fishing effort to review the relationship between targeted, patchy fishing effort and seafloor habitat features. The spatial resolution of fishing effort is determined by information reported by the fishery, yet to address different management issues, the proper resolution is required. Data collection procedures for the US Pacific west coast groundfish fishery include a tristate trawl logbook program (Sampson and Crone 1997). Trawl logbooks contain fishing location information, but prior to 1997, spatial resolution was poor because many locations were reported as the center point of large (10 × 10 nautical miles; 1 nautical mile = 1.852 km) reporting blocks. Trawl fishing effort is known to be concentrated in particular areas with patchy distribution (Larcombe et al. 2001; Marrs et al. 2002; Ragnarsson and Steingrimsson 2003), and seafloor habitats occur on a finer, more detailed scale than that of traditional reporting blocks. This contributes to potential bias when applying data values over coarse-scale blocks or grids (Rijnsdorp et al. 1998; Piet et al. 2000; Pitcher et al. 2000). Spatial resolution of fishing effort has also been limited in Oregon and Washington because electronic conversion of paper logbooks results in only the trawl start location being entered into electronic databases. A single point can limit our ability to review spatial patterns at the scale of actual fishing practices (e.g., tows can cover large distances, overlap, and cross arbitrarily defined grid cells).

This study was focused exclusively off the coast of Oregon and consisted of several components. First, an analysis of spatial and temporal shifts in trawl fishing effort over seafloor habitat was performed using available trawl start locations for the entire study period (1995–2002). This provided an initial spatial understanding of where increases and decreases in fishing effort occurred in relation to habitat distribution and fishery management measures. Second, tow end-point information from 1998 to 2001 was retrieved from manual logbooks for five reference sites located in proximity to rock habitat features. Trawl towlines were then mapped from start point to end point for finer scale resolution of fishing locations to enhance the examination of fishing effort shifts over seafloor habitat. Fishing intensity (measured as kilometres towed) was calculated to quantify fishing effort by habitat type. Finally, fine-scale spatial shifts in relation to the 2000 footrope restriction were then reviewed using trawl towlines.

Materials and methods

Commercial trawl logbook data were obtained for the limited entry groundfish fishery from state databases maintained by the Oregon Department of Fish and Wildlife (1995–2002), the Washington Department of Fish and Wildlife (1995–2001), and the California Department of Fish and Game (1995–2001). Washington and California data were filtered so that only trawls that occurred off the coast of Oregon were represented. Oregon data were not requested with

Table 1. Number and percentage of records filtered from raw logbook database records that were provided by each of the three states.

Filter applied	1995	1996	1997	1998	1999	2000	2001	2002	Total	% of total
Oregon										
Initial records	18 459	18 787	18 129	15 719	13 557	11 670	11 579	8 716	116 616	
Midwater gear	1 885	1 965	1 907	1 467	1 700	2 103	1 417	679	13 123	11.25
Center of block	1 520	1 678	665	27	19	0	0	0	3 909	3.35
Over landmass	39	53	74	33	85	53	2	4	343	0.29
Outside Oregon waters	5 500	4 939	4 520	4 694	4 011	3 215	3 235	3 096	33 200	28.47
Final records for analysis	9 515	10 152	10 963	9 498	7 742	6 299	6 935	4 941	32 845	
Washington										
Initial records	52	46	56	17	25	103	60	—	359	
Midwater gear	26	41	28	10	25	58	43	—	231	64.35
Center of block	16	7	0	0	0	0	0	—	23	6.41
Over landmass	0	0	0	0	0	0	0	—	0	0
Final records for analysis	10	5	28	7	0	45	17	—	112	
California										
Initial records	428	445	511	833	627	474	340	—	3 658	
Center of block	428	445	13	2	1	1	0	—	890	24.33
Over landmass	0	0	3	1	1	0	3	—	8	0.22
Final records for analysis	0	0	495	830	625	473	337	—	2 760	

Note: The resulting annual record totals were then used for analysis. Records were removed if the trawler used midwater gear, the set location was recorded as the center of a statistical reporting block, or the set location was accidentally noted over a landmass. California and Washington data were only requested for those logbook records that occurred in Oregon waters.

any geographical restriction and records extended into both Washington and California waters. These logbook records were removed from the analysis during the process of spatially joining annual fishing effort layers with a seafloor habitat layer exclusively off the Oregon coast. A single logbook record corresponds to an individual trawl tow and includes information pertaining to the vessel, date, time and location of tow, gear used, and catch. This study included only trawl tows using gear that contacts the seafloor. Unfortunately, it was impossible to review specific bottom trawl gear types used before and after the footrope restriction owing to the inconsistency of gear codes recorded by different states and the confounding use of a nonspecific groundfish trawl gear code before 2000. The application of data filters removed approximately 15% of Oregon logbook records, 25% of California logbook records, and 69% of Washington logbook records (Table 1).

Spatial analysis and mapping were conducted with ArcGIS desktop version 8.2 (Environmental Systems Research Institute, ESRI, Redlands, California). Data layers created and used in this study were all standardized using the same projected coordinate system (Universal Transverse Mercator Zone 10N) and datum (World Geodetic System of 1984) to minimize distortion of spatial properties in the study region and thus minimize spatial error in the analysis.

To begin reviewing trawl fishing effort, we mapped for each year and by state fishing fleet the locations where trawl fishing begins, referred to as the set of each tow. Fishermen are instructed to record the position where the brake is set, when all of the cable has been released for the appropriate depth in order for the net to be fishing on the seafloor. Trawl set locations from all three states' vessels were then combined into annual point (vector) layers of fishing effort in which each set location was represented by a single point. Oregon habitat polygons (rock, gravel, sand–gravel, sand, sand–mud, and mud) (Fig. 1), as described by Romsos (2004) and Goldfinger et al. (2003) were spatially joined to annual effort point layers to compute the geometric intersection between data layers to count the number of tows per year in each habitat type.

To observe the spatial shift in fishing effort between years, we converted each annual trawl set point layer to a continuous surface (raster) layer based on point density and then subtracted between years to observe areas of increased and decreased fishing effort. To identify patterns where trawl set points were concentrated, a density calculation measured the number of trawl set points contained within a given area and assigned this value to corresponding cells in a raster layer. We used a kernel density calculation per square kilometre with a 5-km search radius and an output cell size of 0.01 km^2. These parameters were selected to assure that the calculation and resulting patterns were a realistic representation of trawl fishing activities. Square kilometre area units have been previously used to represent trawl fishery-scale features (Kulka and Pitcher 2001). The search diameter used in this calculation was later verified to be within the average distance of trawl towline lengths (average = 11.86 km), which preserves the small-scale integrity of the data. Since each point is a representation of the set of a trawl tow, the calculation area should not extend beyond the area that could be covered during the average length of a trawl tow.

Five reference areas were selected by comparing spatial patterns of fishing effort with seafloor habitat type (Fig. 1). Four sites were selected that contained both rock habitat and significant fishing effort (sites 1–4). One additional site was selected, the Rogue River Canyon, with a greater proportion of soft sediment habitat and significant fishing effort (site 5). The ideal site area was determined and then used to select

Fig. 1. Location of reference sites (sites 1–5) in proximity to rock habitat and marine geomorphological features on the continental shelf off the west coast of Oregon, USA. Seafloor habitat data are represented in the lithologic units described by Goldfinger et al. (2003) and Romsos (2004). Reference site buffers (circles) indicate the area within which trawl start (set) locations were selected for further retrieval of trawl end (haul) locations in manual logbooks.

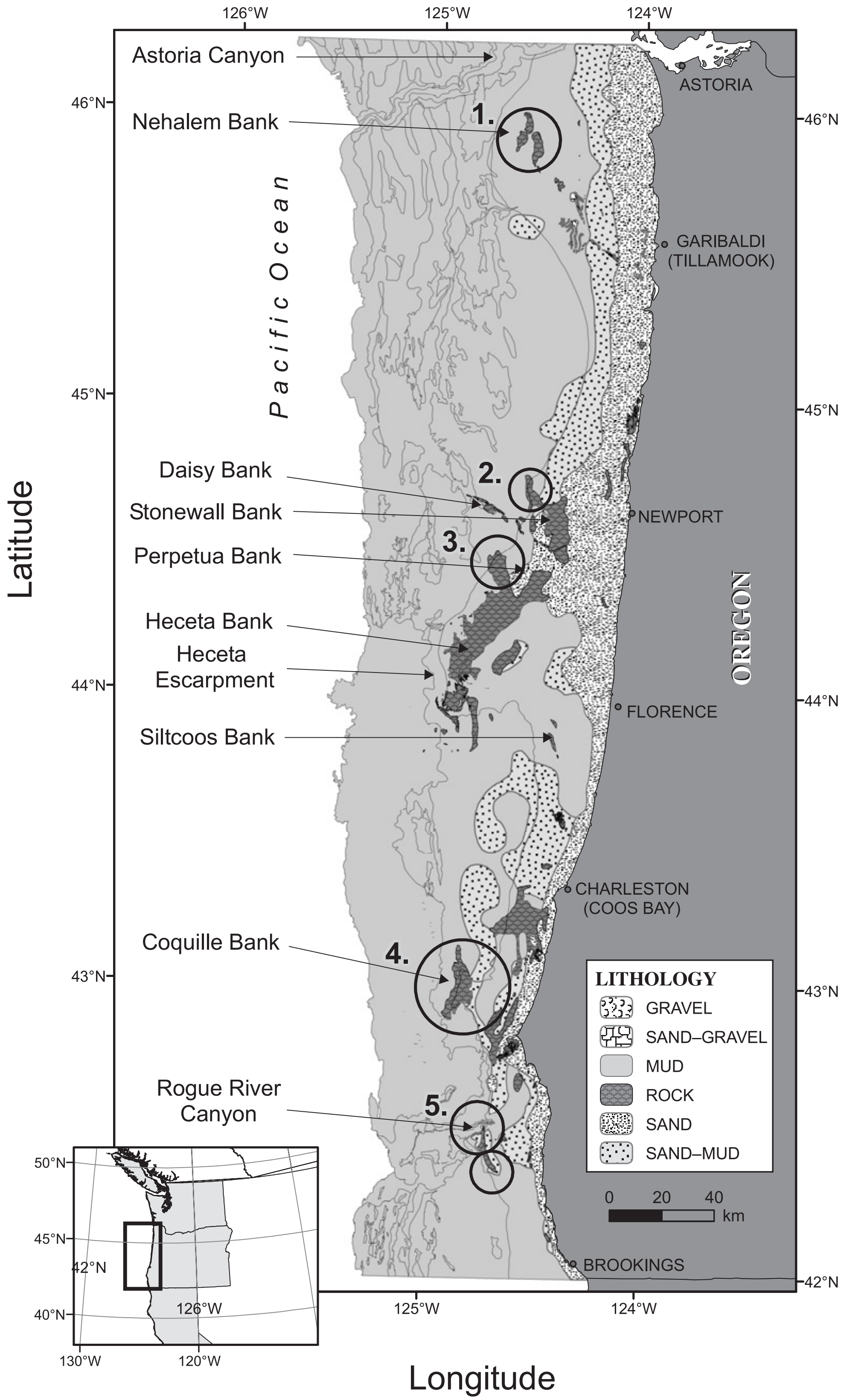


Table 2. Description of five selected reference sites and the logbook records from within these sites used to construct trawl towlines by retrieval of tow haul (end) locations.

	Site 1	Site 2	Site 3	Site 4	Site 5
Site description					
Site selection area diameter (km)	24	16	20	36	20 and 16
Mean reported site depth (fathoms)	102	94	101	160	166
Minimum reported site depth (fathoms)	51	53	60	39	50
Maximum reported site depth (fathoms)	250	185	320	650	600
Filtering process					
Initial selected Oregon logbook records	326	538	1442	1551	1350
Haul location missing	26	28	30	84	48
Haul location identical to set location	0	6	7	3	3
Haul location over landmass	0	0	1	5	1
Final records for analysis					
Oregon records	300	504	1404	1459	1298
Selected California records	—	—	—	71	429

Note: The filtering steps that were applied to identify and remove unsuitable records for this study are noted. 1 fathom = 1.8288 m.

trawl set points for further data retrieval. Two adjoining selection areas were used at the southern-most site (site 5) for optimal coverage of fishing effort patterns, which could not be adequately represented by a single selection. A subset of Oregon logbook records was created for each reference site (Table 2). Additionally, the data quality for habitat type (primarily rock) was assessed within each site area using ranked distributions of data density and quality, as developed by Romsos (2004). The order of rock habitat quality values ranked site 1 as the highest, followed closely by sites 2 and 4 with equal values, site 5 with a moderate value, and site 3 with the lowest value.

To improve the spatial resolution of fishing effort, we manually retrieved tow end locations, referred to as haul points, for each site's subset of records from paper logbooks held by the Oregon Department of Fisheries and Wildlife office in Newport, Oregon. A protocol was developed to assure data confidentiality and quality control. Logbook records that did not contain haul location information (4% of all reference site records) were removed from the analysis. Records with haul locations identical to the tow set location or for which trawling occurred over a landmass were also dropped from the analysis (<0.5%).

Trawl towlines were created using a Visual Basic script that drew a straight line from each set location to each corresponding haul location. The azimuth of each towline from true north (0°) was also calculated. The length of each towline was measured to estimate the distance that a vessel traveled. To determine if towline distances could have been traveled within a realistic range of towing speeds, we then used towline length to predict vessel speed based on the logbook-reported tow duration.

An overlay of trawl towlines across benthic habitat type subsequently split each towline into multiple segments at each habitat boundary and joined the attributes of the underlying habitat type to each towline segment. The length of each resulting towline–habitat type segment was measured and segment lengths were then summarized annually by habitat type. Patterns of trawl towlines were reviewed in both a spatial and a temporal context.

California logbook records were used for a comparison with the spatial and temporal patterns observed in towlines originating from Oregon logbook data. California state database logbook records from 1997 to the present contain the location for both tow set and tow haul. Subsets of California trawl towlines for the two southern reference sites (where Oregon and California fishing effort overlapped) were processed and mapped using the same methodology as for the Oregon reference site records noted above.

Swept area calculations, defined as the area of seafloor potentially contacted by trawl gear, were not made for the purposes of this study in part because of the absence of detailed trawl gear notation in logbooks and the variety of gear used in the fishery. Often, averaged gear parameters or those based on a fixed door spread are used in calculations for the purpose of swept area estimation (Ragnarsson and Steingrimsson 2003). The detailed spatial distribution of trawl towlines and towline distance measurements in this study provided similarly acceptable information to review fishing intensity. If detailed gear parameters and other influencing factors were adequately accounted for in the future, swept area estimates could be derived from our measurement of trawl towline distances.

A compilation of temporal management measures provided the basis by which corresponding fishing effort distributions were reviewed. Groundfish management measures for the limited entry trawl fishery were tabulated from the Federal Register for the time period 1995–2002. Acceptable biological catch, optimal yield, and annual allocation to the commercial trawl fishery were recorded by year for each managed species or fish assemblage (supplementary Table S1).[2] Cumulative trip limits were organized and recorded by month.

[2] Supplementary data for this article are available on the Web site or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Building M-55, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada. DUD 4035. For more information on obtaining material refer to http://cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml.

Table 3. Results of the geographic overlay of tow set point locations and corresponding seafloor habitat type.

Lithologic unit habitat type	Total area of habitat (km^2)	1995	1996	1997	1998	1999	2000	2001	2002	Total
Tow set locations										
Sand–mud	4 236 922	1170	1398	1493	1520	1240	986	990	949	7 178
Sand	5 922 956	610	664	912	653	582	350	625	968	4 090
Mud	32 555 575	7081	7217	8343	7423	6219	5428	5560	2927	35 900
Rock	1 756 087	599	849	725	733	313	52	105	93	2 021
Gravel	7 489	0	0	0	0	0	0	0	0	0
Sand–gravel	37 606	65	24	13	6	13	2	0	0	34
Porportion of tow set locations										
Sand–mud		0.123	0.138	0.130	0.147	0.148	0.145	0.136	0.192	0.146
Sand		0.064	0.065	0.079	0.063	0.070	0.051	0.086	0.196	0.083
Mud		0.743	0.711	0.726	0.718	0.743	0.796	0.764	0.593	0.729
Rock		0.063	0.084	0.063	0.071	0.037	0.008	0.014	0.019	0.041
Gravel		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sand–gravel		0.007	0.002	0.001	0.001	0.002	0.000	0.000	0.000	0.001

Note: Results are noted as both the number and the proportion of tow set locations over each habitat type. The total mapped area of each habitat type is also noted.

In-season changes to trip limits were added to these tables for each management change that took effect during the course of a year (supplementary Table S2).[2]

Results

A decreasing trend in annual trawl fishing effort off the Oregon coast was observed across all years from 1997 to 2002 (Table 1). Directed fishing effort in Oregon waters by Washington vessels was concentrated along the Oregon–Washington border and diffused in a southerly direction. California trawl effort was concentrated at the Oregon–California border and diffused gradually in a northerly direction.

Trawl fishing effort differed by location and intensity in proximity to major rocky bank features on the Oregon continental shelf (Fig. 1). Trawl set points over Nehalem Bank occurred predominantly over western portions of the bank. On Stonewall Bank, there was a concentration of set points along the north to northwest slope edge of the bank but very few over the main bank. Perpetua Bank had a similar concentration of set points around the northwest slope edge portion of the bank but again, very few points over the main bank. Trawl set points were located throughout the Heceta Escarpment, the slope edge just offshore of Heceta Bank, with only a few points appearing over the southern tip of the actual bank itself. Siltcoos Bank did not have any associated trawling activity. Coquille Bank displayed set point patterns to the north, south, and west of the bank, with a lesser density of set points directly over the main bank.

In addition to an overall decline in effort, there were shifts in the number of trawl sets between years and between habitat types (Table 3). Trawl set points for the entire study period were within mapped seafloor lithology, which extended to approximately the 3000-m depth contour. The number of trawl sets per habitat type was positively correlated with the total area of habitat type available (i.e., the majority of trawl sets took place in the largest geographically mapped habitat type: mud). The smallest extent of mapped habitat, gravel habitat, did not contain any trawl set locations, although it is still possible that actual trawl tows may cross into this habitat designation.

Broad-scale spatial shifts in trawl fishing effort distribution were apparent between years, as visualized by density maps (Fig. 2). The location of areas experiencing increases and decreases in fishing effort are summarized in Table 4. Areas of increased fishing effort were still evident in each between-year calculation, despite the overall decline in trawl tows each year. This provided clear evidence that trends or shifts in effort are occurring that were not attributed solely to the decrease in annual tow numbers. The continuous decrease in fishing effort along the outer continental shelf in 2002 relative to fishing effort in 2001 is attributed to the first depth-related spatial closure of the fishery from approximately 100 to 250 fathoms (1 fathom = 1.8288 m) in September of 2002 (67 FR 57973). A large portion of the continental shelf was closed to trawling through establishment of the Darkblotched Rockfish Conservation Area to protect overfished darkblotched rockfish (*Sebastes crameri*). Even though this closure was only reflected in the study data for 4 months at the end of the fishing year, it nevertheless was revealed as a marked decrease in fishing effort throughout the closure boundaries.

The use of trawl towlines created for each reference site demonstrates a substantial improvement in the resolution of fishing effort data relative to the use of start-point locations alone. Towlines provide an enhanced visual representation of spatial fishing patterns to detect changes or shifts in trawl towing behavior relative to habitat, bathymetry, and tow direction. Based on an azimuth calculation from true north (0°) for each towline, the majority of towlines are positioned within northern (315–45°) or southern (135–225°) directional quadrants (Table 5). The straight-line towline model is a conservative estimate of actual distances trawled owing to the many factors that prevent towing in exactly straight lines. Predicted vessel speeds derived from towline length and logbook duration fell within a realistic range of towing speeds (1.8–3.0 knots) established from interviews conducted with

Fig. 2. Density maps of the extent and degree of increase or decrease in trawl fishing efforts calculated by subtracting an annual set location density layer from the density layer of the previous year (calculated for each year pair between 1997 and 2002). Fishing effort change is represented by a spectrum from areas of decrease (blue) to no change (yellow), to areas of increase (red).

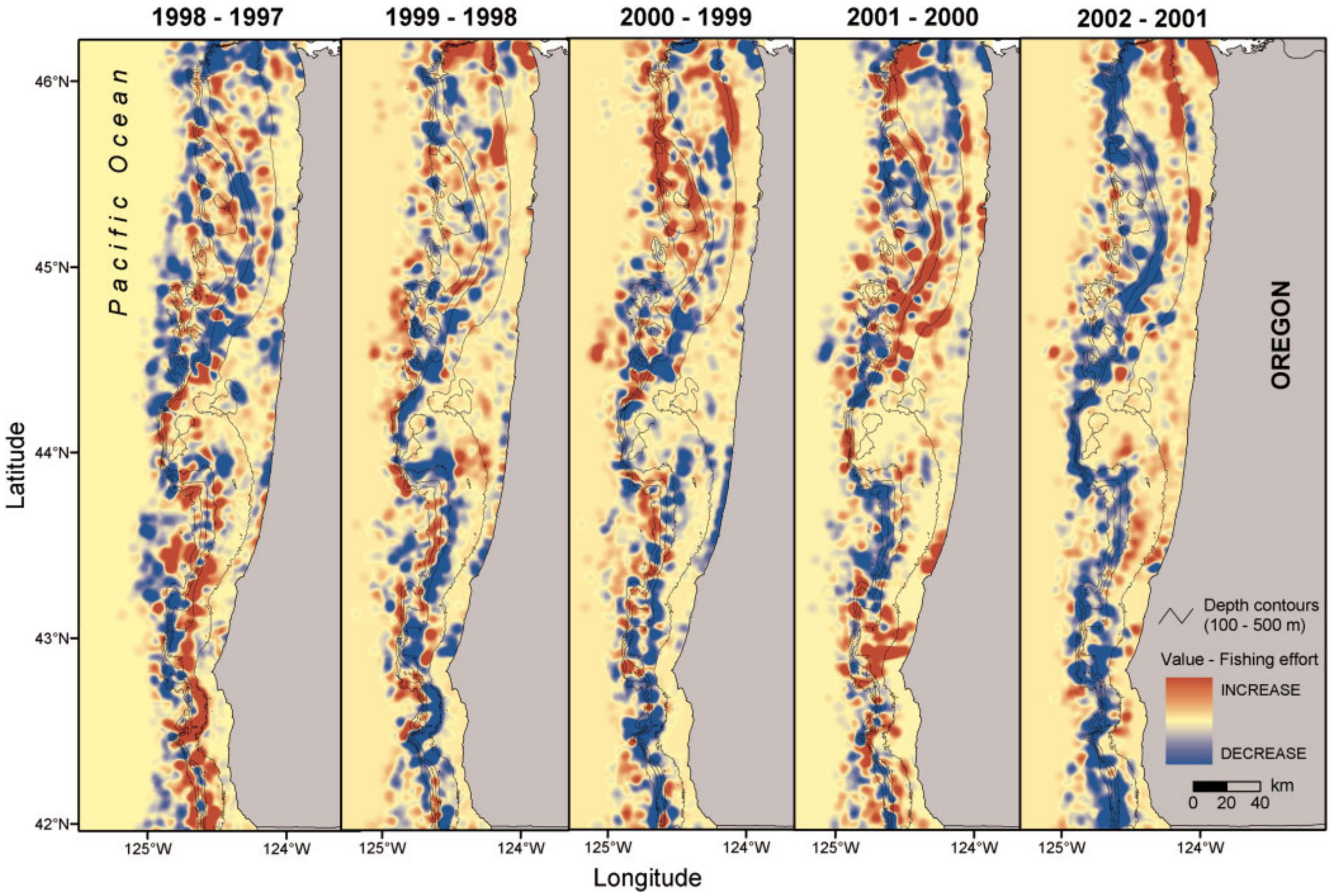


Table 4. Summary of major locations off the Oregon coast experiencing increasing and decreasing trawl fishing effort calculated by subtracting an annual set location density layer from the density layer of the previous year.

Annual difference	Increased effort	Decreased effort
1998–1997	Largely located from central to southern Oregon on the continental margin between the 100- and 200-m contours, with patchy distribution along the entire margin	Patchy decreases observed from nearshore to deep offshore regions but concentrated mostly along the northern border west of Astoria and extending into central Oregon along the 200-m contour
1999–1998	Concentrated along the northern border west of Astoria with additional light increases in deeper water offshore along the entire margin	Concentrated in a semisolid band from Depoe Bay to the southern Oregon border along and just inshore of the 200-m contour
2000–1999	Primarily located in the northern region both along the 100-m contour and in deeper offshore waters past 300 m	Several concentrated areas are west of Astoria and Newport and also in the southern region from Bandon to Brookings between the 100- and 300-m contours
2001–2000	From the northern border to central Oregon between the 200- and 300-m contours with several patches centrally located along the 100-m contour; additional patches are located between Bandon and Port Orford	Noted in the northern region along the 100-m contour and also offshore in deeper waters both north and south of Heceta Bank
2002–2001	Only several small patches are noted in the northern region, two west of Astoria (at <50 and 100 m) and one between Netarts and Pacific City from the 50- to the 100-m contour	Observed in a large band along the entire continental margin focused at the 200- to 300-m contours

Note: Effort shifts were calculated for each year pair between 1997 and 2002, with effort in the previous year subtracted from effort in the most recent year in the pair.

Table 5. Percentage of reference site trawl towlines that lie within each directional quadrant based on their azimuth (calculated from true north (0°)).

	Site 1	Site 2	Site 3	Site 4	Site 5
North–south quadrants (315°–45° and 135°–225°)	90	77	84	89	65
East–west quadrants (45°–135° and 225°–315°)	10	23	16	11	35

fishermen. This evidence supports the assertion that the trawl towline model is a close approximation of reality, although the model cannot determine the exact path that a vessel trawled.

Spatial shifts in fishing effort away from rock habitat were strikingly evident for all reference sites after the 2000 footrope restriction (Fig. 3). Fishing intensity was calculated as the kilometres towed per year for a given habitat type. Total distance trawled over each habitat type was pooled for the 2 years prior to the footrope restriction (1998–1999) and the 2 years after its implementation (2000–2001) (Table 6). There is a distinct difference between just counting the number of total trawl tows over each habitat type (number of towline segments) and getting an estimate of actual fishing distances covered over each habitat. Decreasing fishing intensity and a decreasing number of towlines segments over rock habitat are demonstrated for all five reference sites after the footrope restriction. Fishing intensity decreases were greatest after the footrope restriction at site 2 (93.7% reduction) and site 1 (93.6% reduction). Site 5 demonstrated a 90% reduction followed by reductions of 84.8% at site 3 and 69% at site 4. Increasing fishing intensity is shown over mud habitat at sites 1 and 4, although the number of towline segments decreases slightly. Smaller increases occur over sand habitat at sites 1, 3, and 4. Site 3 demonstrates a small increase in towing distance over sand habitat, despite a decrease in the number of towline segments represented.

In general, spatial towline patterns of Oregon and California vessels at site 5 are consistent, but Oregon towlines demonstrate two additional fishing patterns. Oregon vessels also trawl within and along the length of the canyon and over an area just south of the canyon at depths of approximately 150–200 m. These trawl patterns are closely associated with the bathymetric features of the Rogue River canyon. The canyon's east–west orientation reflects the higher percentage of towlines positioned within east and west directional quadrants at site 5 (Table 5). The majority of California tows began north of the canyon and trawling occurred in a northerly direction. A second group of tows by California vessels began in the southwestern section of the upper site 5 selection area and towed south along the 400-m contour. The third group of tows by California vessels began in the southwestern section of the lower site 5 selection area at depths greater than 150 m and trawled in a southeasterly direction. California vessel towlines in site 4 were consistent with Oregon towline spatial patterns. Most of the California set points were located in the southern half of the site 4 selection area and trawling occurred in a southerly direction.

Discussion

There is significant interannual variability in bottom trawl fishing effort off the Oregon coast. These interannual shifts are affected by factors such as changes in target species, trip limit regulations, and fishing strategies (Babcock and Pikitch 2000; Sampson 2001). Overall, Oregon bottom trawl fishing effort exhibited patchy distribution and maintained similar statewide patterns over the entire study period. This consistency is common when fishermen return to areas previously known to harbor high abundances of target species and suitable seafloor for trawling.

The evaluation and continuous monitoring of spatial fishing effort distributions within various habitats will be a critical component in executing management decisions for habitat conservation objectives. Patchy distribution of trawl effort typically disturbs the same areas of seabed frequently but in turn leaves large areas unaffected by the impacts of mobile fishing gear. From a conservation standpoint, patchy fishing distribution may be acceptable because those areas have already been altered by repeated disturbance, as long as fishing efforts do not expand into previously unaffected areas of high-quality habitat. However, conservation objectives may also choose to review which habitats or nontarget species are located within already targeted fishing grounds to reduce impacts on those habitat types or species particularly sensitive to fishing pressure. Spatial management measures, such as closed areas, can have the potentially undesirable effect of shifting fishing activity to areas that were previously lightly fished or very rarely fished (Rijnsdorp et al. 2001; Holland 2003). Therefore, the mitigation of a closed area should be carefully weighed against the potential for redistribution of fishing effort. Larcombe et al. (2001) demonstrated that a redistribution of trawl fishing effort unrelated to closed areas tended to concentrate in relatively small, high-effort areas rather than expanding into new fishing grounds. Using finer-scale spatial analysis, such as the trawl towline model, it is possible to identify whether fishing effort is localized to a small area or the same amount of fishing effort is spread out over a larger area. These two different spatial patterns of fishing effort have not been clearly addressed by fishing impact and recovery studies.

Density mapping creates views of aggregated fishing effort that closely reflect habitat-related patterns usually undetected by grid methods, unless the grids are perhaps set at very fine scales (i.e., ≤1 km × 1 km cells). A grid method splits geographical space into a pattern of arbitrarily sized cells and assigns fishing effort homogeneously within each cell. Grid cell size has a large influence on the results of such work. Grid cell size can either be too small and fishing practices overlap into multiple cells or too large and assigned fishing effort is too broadly distributed. Another concern is that grid cells are often unable to reflect the spatial complexity of geographic features, such as habitat boundaries, an issue addressed by this work. Density mapping greatly facilitated the identification and extent of particular habitat areas that were experiencing changes in fishing pressure, which aided in the selection of study sites. Another brief consideration is that density mapping provides an eas-

Fig. 3. Spatial shifts in trawl effort away from rock habitat at five selected reference sites before (1998–1999) and after (2000–2001) the footrope restriction. See Fig. 1 for reference site locations. Note the scale changes between sites. (*a*) site 1; (*b*) site 2; (*c*) site 3, (*d*) site 4; (*e*) site 5.

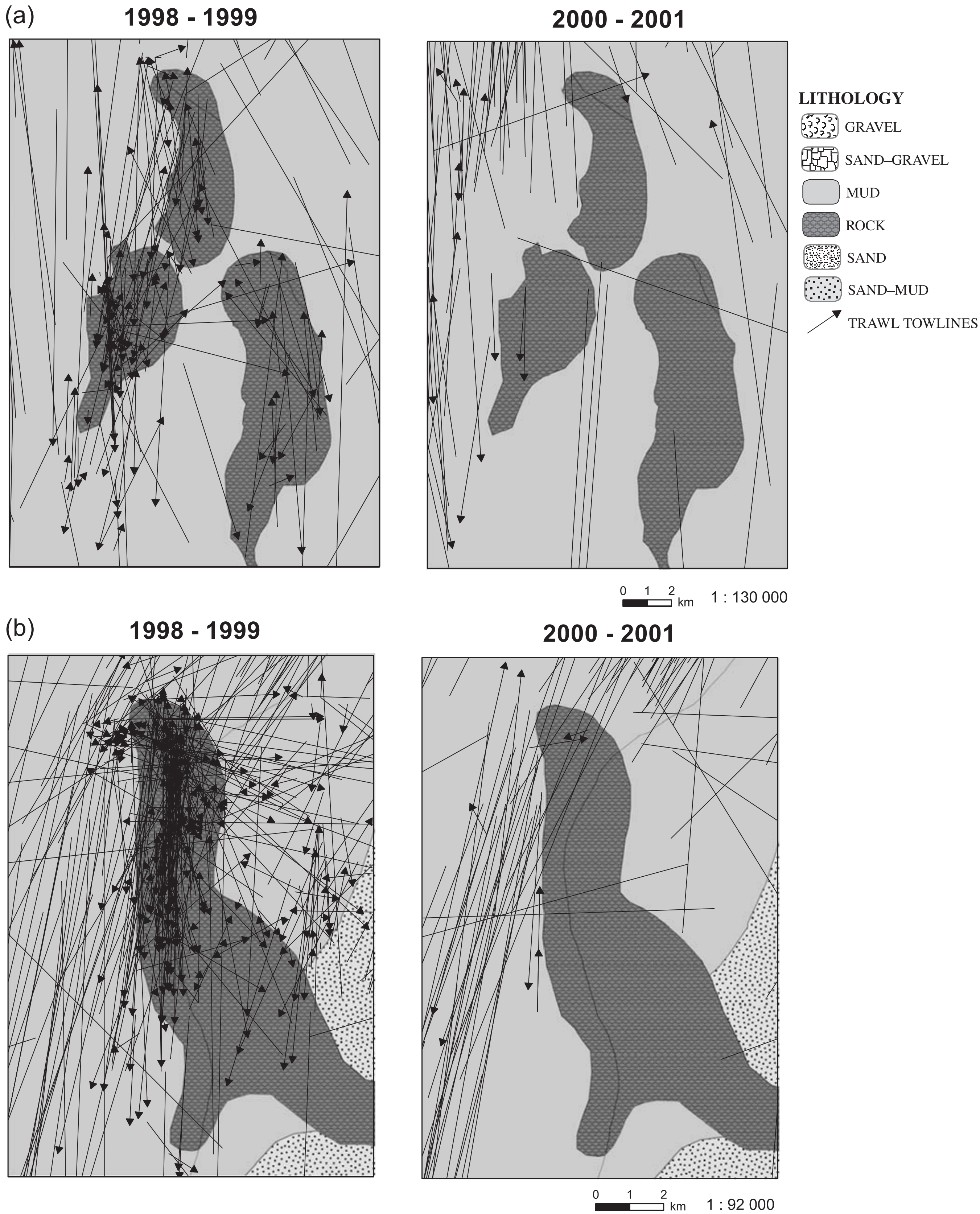


Fig. 3 (*continued*).

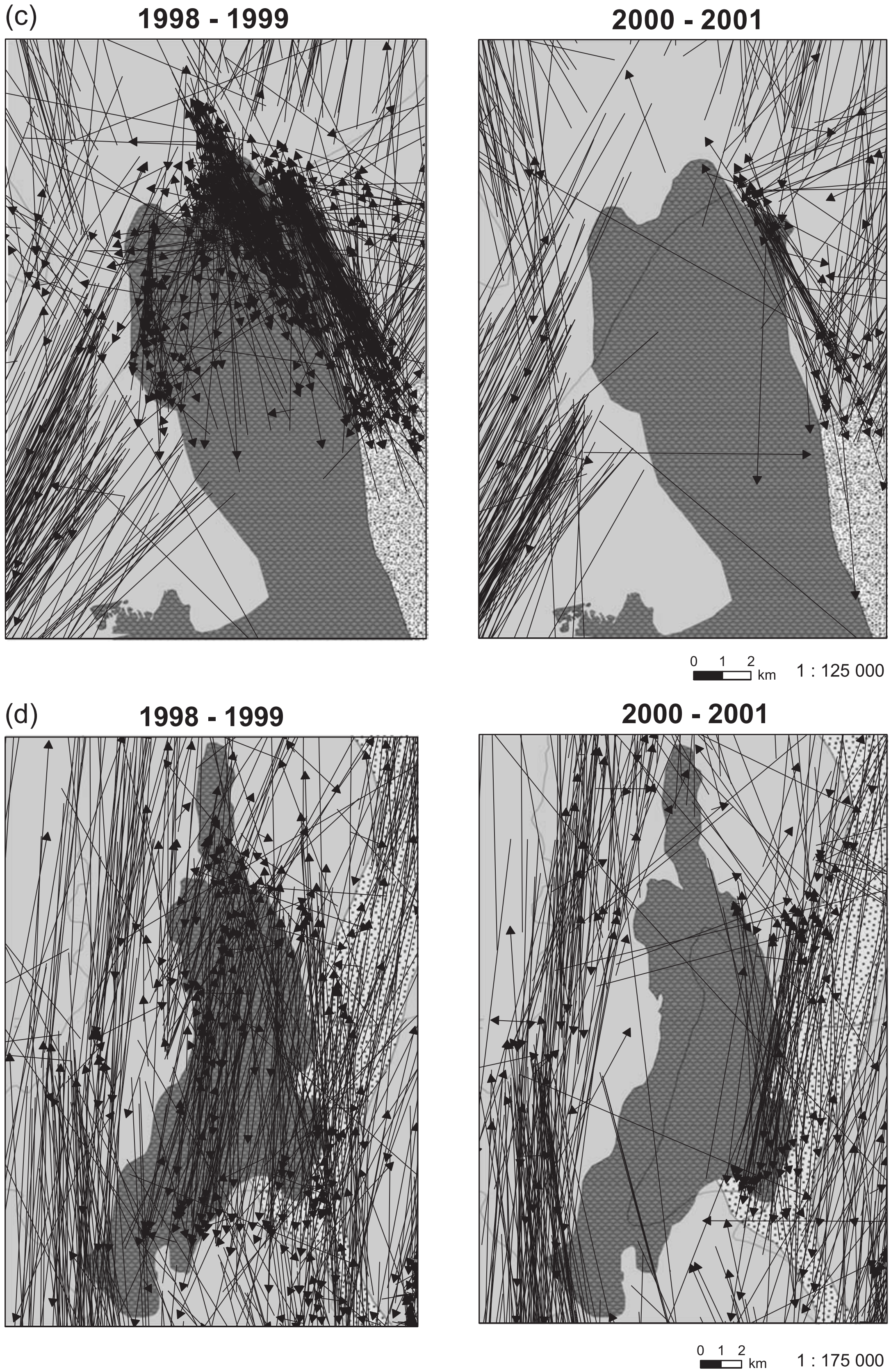
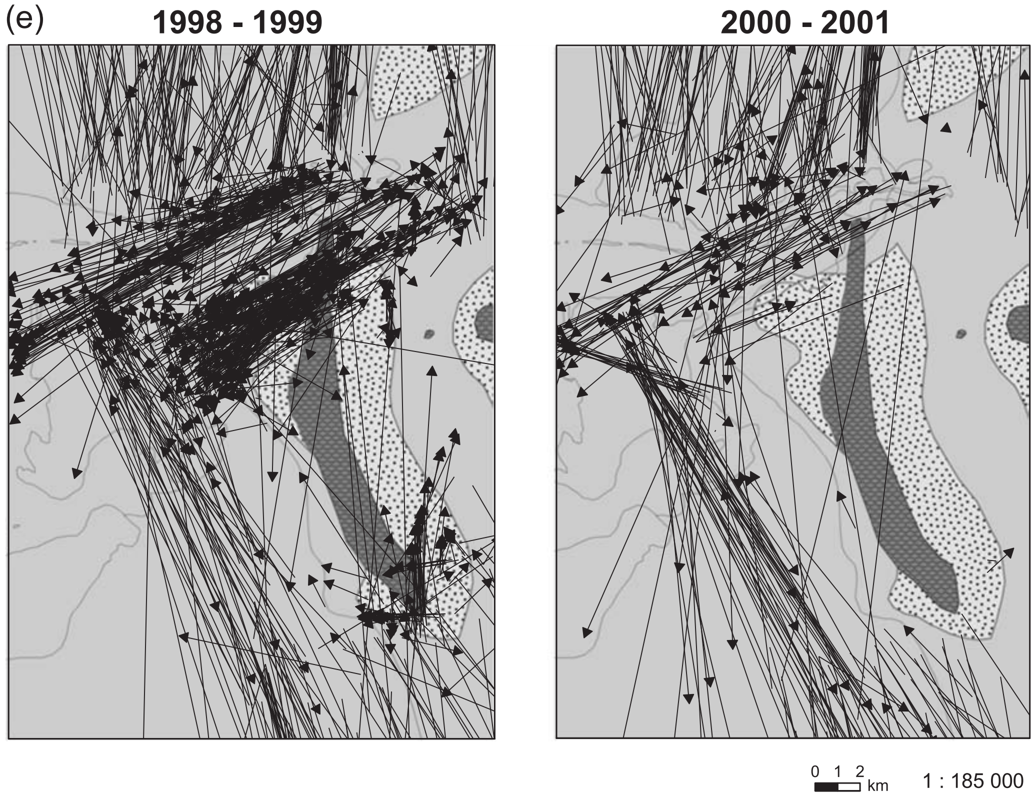


Fig. 3 (*concluded*).



ily aggregated view of trawl start locations, which is often necessary when working with any confidential fishery-dependent data. Confidentiality concerns can still be addressed by this method and yet the spatial resolution of fishing effort patterns is improved.

The use of complete trawl towlines rather than only set points resulted in the analysis of fleet responses to management measures at a scale appropriate to evaluate the linkages between fishing effort and particular seafloor habitats. Trawl towlines can more accurately represent the distribution of fishing effort and intensity in geographic space as well as provide a basis by which to observe patterns of fine-scale yet realistic fishing effort. Based on this analysis, it is crucial that in the future all haul location data be entered into electronic databases maintained by fishery-dependent collection programs. Because haul locations have been and are currently provided by fishermen in paper logbooks, it would require only a minimal cost to include this field in the data entry process. The annual review and processing of spatial data would not only provide an additional quality control step by verifying realistic reporting of fishing location but also allow evaluation of current spatial management measures. Although this study focused on five reference sites off the Oregon coast, this work could easily be expanded to examine all trawl logbook data for the US west coast.

The spatial shift of tow patterns away from rock habitat was distinctly evident from visualization of trawl towlines after the 2000 Pacific Fishery Management Council footrope restriction. Towline analysis also provided a measurement of trawling intensity by habitat type. The reduction in towing over rocky habitat at our reference sites was both visibly evident and clearly measured by intensity with an average –86% change. The reduction in effort over rocky habitat did not simply result in overall reduced fishing effort, as some fishing effort shifted from rock habitat to surrounding areas of unconsolidated sediments. The outcome of management measures should be considered and reviewed as to the extent of such trade-offs between fishing impact on hard- versus soft-bottom habitats and possible effects on other groundfish species EFH.

We observed a majority of north–south tow directions, with the exception of east–west towing related to the Rogue River canyon bathymetry in southern Oregon. This supports previous observations by Friedlander et al. (1999) that trawl marks on the California seafloor are commonly oriented parallel to bathymetric contours and by Marrs et al. (2002) that trawl vessels followed depth contours parallel to the shoreline. Models of US west coast trawl fishing effort based on set locations could be fine-tuned by incorporating spatial parameters related to depth contour tow direction (National Marine Fisheries Commission 2005; Scholz et al. 2005).

Trawl gear disturbance on the seafloor can be examined through the use of high-resolution side-scan sonar (Krost et al. 1990; Friedlander et al. 1999), but the towline model can more efficiently quantify fishing effort. The path covered by a trawl, or trawl track, is often visible on sonographs as a long, narrow, linear depression. Side-scan sonar is costly and the detectability of trawl tracks is heavily dependent on timing of the side-scan survey and the time at which fishing occurred, while trawl towlines display fishing activity at the scale of the fishery and provide an enduring (if indirect) record of potential trawl tracks. Furthermore, side-scan sonar

Table 6. Total trawl towline distances and the number of towline segments over seafloor habitat type before (1998–1999) and after (2000–2001) the footrope restriction.

Reference site	Rock 1998–1999	Rock 2000–2001	Rock % change	Mud 1998–1999	Mud 2000–2001	Mud % change	Sand 1998–1999	Sand 2000–2001	Sand % change	Sand–mud 1998–1999	Sand–mud 2000–2001	Sand–mud % change
Towline distances (km)												
Site 1	403	25	–93.6	1340	2071	54.6	0	10	>100.0	39	51	29.7
Site 2	764	49	–93.7	1977	1402	–29.1	70	7	–89.4	518	300	–42.0
Site 3	1670	253	–84.8	6487	5731	–11.6	116	124	6.9	17	2	–88.4
Site 4	2049	636	–69.0	6924	7243	4.6	7	15	94.3	1929	1807	–6.3
Site 5	232	22	–90.4	7763	4913	–36.7	40	18	–54.5	1057	150	–85.8
Towline segments (no.)												
Site 1	450	37	–91.8	224	205	–8.5	0	1	100.0	8	9	12.5
Site 2	166	16	–90.4	402	133	–66.9	12	3	–75.0	90	54	–40.0
Site 3	906	135	–85.1	1329	760	–42.8	102	62	–39.2	2	1	–50.0
Site 4	579	257	–55.6	1436	1340	–6.7	2	5	>100.0	469	483	3.0
Site 5	203	12	–94.1	2638	1163	–55.9	18	6	–66.7	553	41	–92.6

Note: A towline segment represents one section of a towline after it was split at each habitat polygon boundary (i.e., multiple towline segments can be created by splitting an individual towline).

may not detect trawl tracks in hard-bottom habitats. However, these two methods may prove to be complementary. Reviewing trawl towlines may provide the first step for identifying areas where high fishing impact disturbance occurs and trawl marks could then be examined closely with the use of side-scan sonar to verify effort patterns from logbook data and which habitats have been impacted.

Our results indicate that the footrope restriction, in conjunction with associated landing limits, was effective in protecting rocky habitats from trawl fishing impacts. This supports previous demonstrations that gear changes or modifications can achieve some purposeful level of habitat conservation (Van Marlen 2000; Valdemarsen and Suuronen 2003). Fishery managers often only manage for direct habitat conservation if forced by legislation or if it is demonstrated that a loss of habitat would directly lead to a loss of yield in the fishery. Similarly, in this case, although the footrope regulation was only indirectly aimed at habitat conservation, it ultimately served this purpose.

Future extensions of this research will need to incorporate analysis of catch data to clarify the effects of gear restriction versus trip limits. One possible method described by Larcombe et al. (2001) apportions catch equally along the length of a towline and then summarizes catch within a fine-scale grid of 1-km^2 cells. Branch et al. (2005) utilizes a clustering method related to trawl towline locations and associated catch data, which could then be used to delineate groups of tows in specific areas and their associated target species. This method would be useful for understanding various patterns of targeting fishing at or near the rocky banks examined in this study.

This study directly evaluated the effects of a specific preceding management action, which is not often done in the context of fishery management today. Substantial regulatory changes have occurred in the last decade that have ultimately resulted in a reduction in trawl fishing effort off the Oregon coast. Tracking of regulatory change by species provides the foundation to spatially examine individual management measures in a multispecies groundfish fishery. Effort shifts can be studied on any time step, from arbitrary (i.e., 1 year) to more natural steps, like regulatory regime shifts. Fishery management compilation tables created for this study have been valuable tools in both research and outreach but to our knowledge do not exist outside of our work. It is recommended that this type of systematic tracking be instituted formally as a required exercise for management purposes and that these materials be made readily available to all stakeholders.

It will be necessary to continue monitoring spatial responses in fishing effort to evaluate sustained habitat protection. Based on this monitoring information, an adaptive management process could learn from and adapt to changing circumstances in the fishery to influence habitat conservation (Cicin-Sain and Knecht 1998). Through the existing management process, trip limits and gear restrictions associated with the original 2000 footrope regulation have since been adjusted. Depth-based spatial management closures were implemented in September 2002 and related closures continued into 2003. Rock habitats within reference sites were not protected by these depth-based closures until May 2003. Therefore, the observed patterns in fishing effort reviewed here were based solely on previous management strategies. Potential rock habitat recovery from trawl impacts at our study sites began prior to the full spatial closure.

Reference site areas have been identified where EFH recovery is likely occurring off the coast of Oregon. These reference sites should be studied in situ as soon as possible to begin answering fundamental questions regarding recovery rates of habitat in the absence of trawling. A limited number of studies have been published that were designed to determine the recovery of rocky habitats upon removal of fishing impacts (Freese et al. 1999; Freese 2001). Research gaps still exist in the determination of event–response relationships as a function of gear, recovery time, and habitat type, especially in naturally stable, structurally complex habitats such as rocky reef habitat (Collie et al. 2000; Kaiser et al. 2002). For benthic communities that have experienced chronic fishing disturbance, it is not known whether eventual recovery to a former (often unknown) state will occur if fishing is halted or if the system might have reached an alternative stable state from which it cannot simply return following removal of fishing disturbances (Holling 1973; Holling et al. 1995). It is generally thought that at high fishing effort levels, initial reductions would decrease impacts marginally but that benefits would be more apparent as effort declined even further (National Research Council 2002). The reference sites identified in this study can be used for future research to provide additional insight in understanding such concepts.

By integrating new information on seafloor substrate at finer scales or by including ecological habitat factors, examining the effects of fishing effort distribution and intensity in the context of EFH would be enhanced. Habitat as defined in this study is fairly limited in the framework of groundfish EFH. Numerous studies have shown correlations between demersal fish and various classifications of seafloor substrate (Matthews 1989; McRea et al. 1999; Nasby-Lucas et al. 2002). New information on aspects of fish–habitat associations such as depth, temperature, salinity, biogenic structure, and nutrient or prey availability could be incorporated into the research methods of this study.

Results also demonstrate the necessity of improving the spatial resolution of fishery data to address current fishery management concerns. Limitations on spatial precision are ultimately tied to the accuracy of the original positions recorded in logbooks. The precision of fishing location using the global position system (GPS) is an improvement over Loran A and C, which were the shore-based navigation systems used prior to the implementation of GPS. Spatial precision works to the fishermen's advantage because they can place their gear more accurately with the aid of GPS chart plotters and supplementary acoustic equipment. Since the mid-1990s, the spatial precision of logbook data has also benefited from required recording of actual tow location in trawl logbooks and from observers' independent monitoring of fishing activities. Implementation of electronic vessel logbook systems to monitor fisheries would be effective in providing accurate and timely spatial data to improve fisheries management (Meaden 2000; National Research Council 2000). These systems would shorten the lag time that presently exists in the availability of data and facilitate utilization of spatial data on fishing catch and effort as a means to directly evaluate management of the fishery. Vessel monitoring systems may assist in verifying spatial location and patterns of fishing from individual tows, but this would require linkage to detailed fishing logbooks that host all of the other data fields associated with an individual tow during a particular fishing trip (Rijnsdorp et al. 1998; Kemp and Meaden 2002; Marrs et al. 2002). At this point in time, vessel monitoring systems in the US west coast groundfish fishery may not be useful for management purposes other than basic enforcement of spatial area violations. If the frequency of vessel location transmissions were increased or detailed trawl track data from position loggers were available, other fishing patterns, such as lifting trawl doors and resetting the same tow in a different direction, could be addressed. Until then, trawl towlines are one method by which we can improve fishing effort resolution.

Although extensive information is contained in logbooks, these data have been underutilized in fisheries management (Starr and Fox 1996; National Research Council 2000). This study's use of fishery-dependent logbook data demonstrates the extensive geographic and temporal coverage that these data contain relative to fishery-independent data sources. Research survey tows originating from reference sites were less than 1% of the fishing intensity by commercial tows selected from the same sites. Observer coverage and increases in collaborative research are incorporating more fishery-dependent data sources into the management arena (National Research Council 2004). Examining previous years' fishing effort data before considering future regulation changes may work to alleviate concerns by fishermen that fishery managers do not value the information that they provide (Kaplan 1998; Gilden and Conway 2002). With the recent shift to a 2-year groundfish management cycle (68 FR 52519) and improvements in earlier availability of fishery-dependent data, this can now be a realistic expectation when considering future policies and regulations.

In summary, this study demonstrated that the 2000 Pacific Fishery Management Council footrope restriction and associated landing limits shifted trawl fishing effort away from the rocky habitat of depleted rockfish (*Sebastes* spp.) off the Oregon coast. Methodologies developed in this study highlight the benefits of increasing the spatial resolution of fishery data collection. New information on relationships between groundfish and habitat type, advances in seafloor mapping and habitat classification, and ongoing changes in fishery management will each contribute valuable information to future analyses of this type. Careful review and monitoring of spatial data from the US west coast groundfish trawl fishery can assist in evaluating the extent and type of habitat affected by fishing disturbances and which management measures influence habitat conservation.

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