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Research Article

A Comparison of Fishes and Invertebrates Living in the Vicinity of Energized and Unenergized Submarine Power Cables and Natural Sea Floor off Southern California, USA

Milton S. Love,[1] Mary M. Nishimoto,[1] Linda Snook,[1] Donna M. Schroeder,[2] and Ann Scarborough Bull[2]

[1] *Marine Science Institute, University of California, Santa Barbara, Santa Barbara, CA 93106, USA*
[2] *Bureau of Ocean Energy Management, 760 Paseo Camarillo, Camarillo, CA 93010, USA*

Correspondence should be addressed to Milton S. Love; love@lifesci.ucsb.edu

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Increasing reliance on deep-water renewable energy has increased concerns about the effects of the electromagnetic fields (EMFs) generated by submarine power cables on aquatic organisms. Off southern California, we conducted surveys of marine organisms living around energized and unenergized submarine power cables and nearby sea floor during 2012–2014 at depths between 76 and 213 m. In general, EMFs declined to background levels about one meter from the cable. We found no statistical difference in species composition between the fish assemblages along the energized and unenergized cables. The natural habitat community statistically differed from both energized and unenergized cable communities. Within species (or species groups), we found no differences in densities between energized and unenergized cables. Total fish densities were significantly higher around the cables than over the natural habitat. We found that invertebrate communities were structured by habitat type and depth and, similar to the fishes, there was no statistical difference between the energized and unenergized cables. Individually, the densities of four invertebrate species or species groups (*Metridium farcimen*, *Luidia* spp., unidentified black Crinoidea, and *Urticina* spp.) differed between energized and unenergized cables, but this difference was not significant across all depth strata. The invertebrate community inhabiting the natural habitat strongly differed from the energized and unenergized cable community exhibiting the fewest species and individuals.

1. Introduction

It is likely that, for the foreseeable future, renewable energy technologies will focus on the offshore generation of electricity (e.g., wind and wave). These technologies harness energy from an array of individual devices and send electricity to shore via submarine power cables. These cables will transmit either alternating current or direct current, and, if the cable uses alternating current, this current will generate both electric and magnetic fields. Armoring of cables suppresses the emission of electric fields; however, magnetic fields escape into the surrounding environment. As fishes and other organisms and water currents pass through this field, an induced electric field is generated. This combination of induced electric field and emitted magnetic field is termed as electromagnetic field (EMF) [1].

Research has shown that cartilaginous and some bony fishes, as well as at least some invertebrates, are sensitive to EMF and that these fields can alter the behavior of some organisms [2–5]. However, worldwide, very few studies have documented the effects of EMF on aquatic organisms in situ [6, 7].

Alternating current submarine power transmission cables that power offshore oil platforms in southern California provide a unique opportunity to assess behavior and reaction of marine organisms to power transmission. In particular, the occurrence of both energized and unenergized cables in a corridor on the sea floor in southern California allowed for an experiment testing the effects of EMF on these organisms. The identical cables, all of which are exposed along much of their lengths, stretch several miles from platforms Heritage, Harmony, and Hondo (at depths to about 326 m) to Las

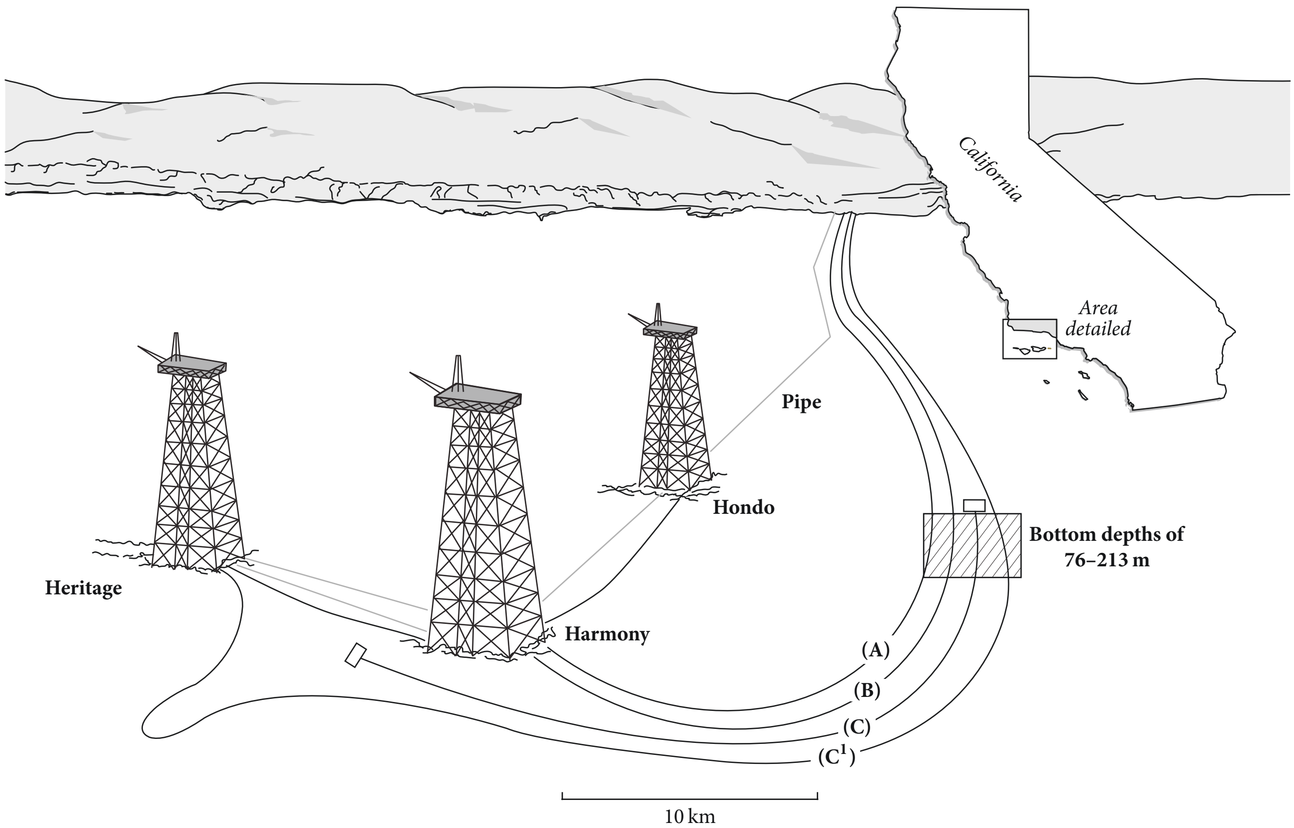

Figure 1: Location of the off-shore energized and unenergized submarine power cables surveyed in this study. Cable lengths, widths, and spatial relationships to each other are not to scale. 10 km scales refer to whole figure.

Flores Canyon on the mainland (Figure 1). The cables run from the platforms toward the mainland to a near-shore sea floor depth of 10 m and from there are buried to the shore. One severed (and thus unenergized) cable runs from a platform to the border of federal and state waters at a bottom depth of about 150 m. All of these cables use the industry standards of the power cables which will be used for connecting devices (35 KV) within future renewable energy installations. These cables were emplaced concurrently by the manufacturer. Thus, the cables form a natural experiment, allowing for a comparison of energized power cables with unenergized ones to determine the potential impacts from electromagnetic fields while controlling for the habitat effect contributed by the structure of the cables themselves.

The goal of this study was to more fully understand the potential effects of energized, seabed deployed, power cables on marine organisms. Specific objectives were to determine the following:

(1) The differences, if any, among fish and invertebrate communities associated with (a) energized cable habitat, (b) unenergized cable habitat, and (c) sea floor habitats lacking cables

(2) The strength, spatial extent, and variability of EMFs along both energized and unenergized cables

2. Materials and Methods

Our surveys were conducted off the coast of Las Flores Canyon, southern California (34°27.6′N, 120°02.7′W) (Figure 1). At this site, there are four, variously energized and unenergized, 20.3 cm (8 inches) in diameter submarine power transmission cables providing power to three offshore oil platforms. Cables carrying energy are kept energized throughout the year. Surveys were conducted aboard the research submersibles *Dual DeepWorker* (2012 and 2014) and *DeepWorker* (2013). These submarines are 7.2 m in length and have a maximum operating depth of 610 m. *DeepWorker* accommodates a pilot and *Dual DeepWorker* accommodates both a pilot and an observer. Dives were made in September and October during daylight hours.

We conducted belt transects along cables and on the nearby sea floor with the submarines traveling at 1–1.5 knots. These were documented with an externally mounted high-definition video camera positioned on the starboard bow of the submersible. A green laser and a red laser were set at an angle such that they intersected one another at a distance 2 m away from the submersible. All transects were 2 m wide and a set of lasers was used to measure transect width. While the cameras were able to film fishes several meters above the bottom, only those no more than one meter above the bottom were counted. The submersible followed a path parallel to the cable such that the intersection of the lasers landed on the cable. For off-cable (natural sea floor) transects, the crossing lasers were used to delineate the outside edge of each transect with the submarine continuing along a straight path along a compass heading for the duration of that transect. During the transects, water visibility had to be a minimum of 2 m. All transects were 15 minutes long. Transect lengths varied and are given in [8].

The distance between the natural habitat surveys and the nearest cable varied between 100 and 400 m.

During 2012 and 2014 and while in the submersible, the observer recorded into the microphone of a video recorder the species (to lowest possible taxon) of every fish observed within the transect boundary. The observer also estimated the total length (cm) of these fishes using reference light points from two parallel lasers installed 20 cm apart on either side of the external video camera. Comments were also made regarding general habitat and notable invertebrates. These videos were also reviewed in the laboratory. In 2013, when there was only a pilot aboard the submersible, we took data on fishes from the high definition video after returning to the laboratory.

In the laboratory, each video-recorded transect (from each of the three years) was reviewed and each fish again identified to the lowest possible taxa and its total length (estimated to the nearest 5 cm) recorded in an Access database. In a separate viewing of these videos, large invertebrates within the dimensions of the transects were surveyed. Any bottom-dwelling individual invertebrate with at least one dimension of ≥5 cm was included. The minimum dimension of 5 cm was selected because it was the size that could reliably be seen and identified. A few invertebrates, such as brittle stars, which were mostly buried could not be distinguished as individuals and were not counted. Invertebrates were identified to the lowest possible taxon. We estimated their maximum width and maximum height and recorded their color. We also signified in the database the distance of each fish and invertebrate from the cable using the following categories: within 0 m, 0.5 m, 1 m, 1.5 m, or 2 m of the cable.

Transect lengths for the cable surveys were measured using an existing map of the cables and positions from a USBL tracking system on the submersible. Navigation fixes were received from a Thales GeoPacific Winfrog ORE Trackpoint 2 USBL system at two-second intervals. Using the start and end points and general path of the submarine from the USBL tracking system, the length of the submersible's path along the cable was measured using a straight-line ruler tool in ArcGIS. For the off-cable (natural sea floor) sites, the tracking system points were smoothed using a 9-point moving boxcar average and then plotted. Then the end-to-end straight-line distance was measured using a ruler tool in ArcGIS for each straight segment of a transect and segment lengths were totaled to obtain transect length. Most transects were only one straight segment. This method was found to be more accurate than calculating the distance between smoothed points, as the two methods were compared using the data from the cable surveys along a known path.

2.1. Measuring the Electromagnetic Field. We measured the EMF emitted by the cables and the natural sea floor sites using a calibrated 3-Axis ELF AC Milligauss Meter built and tested to IEEE specifications. In 2012, EMF readings were taken at distances of 1 m, 0.5 m, and 0 m from each cable. A Y-shaped measuring stick was attached to the EMF reader on the submersible's mechanical arm in order to ensure a perpendicular measurement from the cable. For each reading, the device was held in position until the readings stabilized (within approximately 1% of one another) and then the next three readings were taken and averaged. For natural habitat sites, readings were taken in a similar manner but in a single position with the device touching the bottom. In 2013 and 2014, readings were taken on all cables and on mud but only at the 0 m distance.

2.2. Analyses. We used Primer v6.1.13 [9] to examine the biological assemblage data in relation to the type of habitat (energized cable, unenergized cable, and sea floor without cable) and bottom depth. Density was transformed to $\log[(\text{number per } 100\,\text{m}^3) + 1]$ for the multivariate analyses. Bray-Curtis similarity coefficients were calculated to quantify the resemblance between transect samples, and similarity matrices were generated for fish and invertebrates, separately. Natural groupings of samples were examined using hierarchical clustering with the group average linkage option and multidimensional scaling (MDS) ordination.

To test the null hypothesis that there are no assemblage differences among the two cable states and natural habitats (factor A) and depth (factor B), we used a two-way crossed analysis of similarity (ANOSIM), a nonparametric permutation procedure that operates on the resemblance matrix [9, 10]. Transects were divided into four depth stratum groups based on the clustering and MDS representations. The ANOSIM test statistic R ranges between 0 (approximately) and 1 and is very close to 0 if the null hypothesis is true with similarities between and within groups the same on average. The R statistic is a useful comparative measure of the degree of separation between groups. R values close to 1 are indicative of complete separation between groups. The global ANOSIM test indicates an overall difference among groups, and pairwise comparison test using ANOSIM identifies the groups that differ from one another ($p < 0.05$).

We used a generalized linear model (GLM) approach to test if cable state (energized versus unenergized), controlling for other factors, affected the abundance of individual taxa of fishes and invertebrates. The GLM, with a normal distribution response and identity link function, included four factors: cable state, side of cable (west and east nested in cable state), bottom depth (stratum groups 1, 2, 3, and 4), and year (2012, 2013, and 2014). The model, analogous to a multiple linear regression, was fit to transformed density data, $\log[(\text{number per } 100\,\text{m}^3) + 1]$, by Firth's bias-adjusted maximum likelihood estimation method. A likelihood-ratio Chi-square test evaluated the hypothesis that all the model parameters in the whole model were zero. If the whole model was statistically different from the intercept model ($p < 0.05$), then effect tests were used to identify which of the four factors

Table 1: Electromagnetic field (EMF) level measurements (in microtesla (μT)) at three habitats during 2012–2014.

	Mean (SD)	Range
EMF levels at the energized cables at 0 m ($n = 18$)	107.6 (36.6)	51–205
EMF levels at the unenergized cables at 0 m ($n = 14$)	0.5 (0.6)	0.0–1.5
EMF levels at the natural habitat	0.8 (0.3)	0.3–1.0
Attenuation of EMF levels with distance from a cable. EMF levels in microtesla (μT) measured at cable A in 2012. Measurements were taken at three distances from the cable (0 m, on cable; 0.5 m; and 1 m) and at four locations along cable ($n = 4$).		
0 m	93.1 (18.6)	67.6–106.0
0.5 m	30.1 (7.4)	22.6–39.8
1.0 m	7.5 (8.4)	3.2–20.1

had a significant effect on a taxon's abundance ($p < 0.05$). Analyses were performed in JMP [11, 12].

The same GLM approach was used to test if habitat type (cable versus natural) affected the abundance of individual taxa controlling for the effects of bottom depth and year. In order to avoid including transects from both the west side and east side of the cable within any given depth level and year in a single model, we used transects on the east side of the cable or on the west side if the east side was not surveyed. If side of cable had a significant effect on abundance, then we would evaluate models using transects from each side of the cable separately.

We conducted surveys of energized and unenergized cables and of the nearby sea floor during 2012 (6–9 October), 2013 (3–5 October), and 2014 (23–25 October) at depths between 76 and 213 m. During 2012, only the east side of each cable was surveyed. However, out of concern that there might be differences in species assemblages between the sides of cables, in 2013 and 2014 we surveyed both sides of the cables at similar depths. On average, cables were about 30 m apart. All natural habitat surveys were conducted between 100 and about 400 m from the nearest cable.

Note that for some analyses we divided the transect depths into four strata based on species groupings determined by MDS analyses of fish and invertebrate communities. These are defined as the following nominal depth strata: stratum 1 (transect categories 1–8 = 76–107 m), stratum 2 (transect categories 9-10 = 108–144 m), stratum 3 (transect categories 11–13 = 145–180 m), and stratum 4 (transect categories 14–17 = 181–213 m).

3. Results

3.1. EMF Levels. On 6 October 2012, we measured the EMF levels along the sea floor at three distances perpendicular from energized cable A. Cable A was the westernmost of the cables and had been energized continually for many years. These measurements were taken at four locations along the cable (at bottom depths of 108, 112, 135, and 158 m). At all four locations, EMF levels dropped off precipitously with distance from the cable and, at one meter from the cable, approached background levels at three of the four locations (Table 1). This sharp drop-off was similar to that found in the nearshore part of this cable [13].

With one exception (cable C^1 was not measured in 2013), in each year we measured the EMF levels at each cable (A, B, C, and C^1) and at the sea floor away from these cables. In all years, cable A was energized and this cable formed the basis of our energized cable surveys. In all years, cable C was unenergized and cable B was energized in 2012 and 2014 but unenergized in 2013. Cable C^1 was unenergized in 2012 and energized in 2014. In general, field strengths on the energized cables were around 100 μT, while those on the unenergized cables were very low and near background (sea floor) levels. We note that the values of EMF that we measured are those typical of a 35 KV AC industrial cable, as modeled in [6].

3.2. Fishes. Over all habitats, we observed 9,675 individuals of at least 41 fish species [8]. Dominant species included *Sebastes semicinctus* (Gilbert, 1897), *Sebastes saxicola* (Gilbert, 1890), *Sebastes elongatus* (Ayres, 1859), *Ophiodon elongatus* (Girard, 1859), unidentified flatfishes (Pleuronectidae), Agonidae, and *Zaniolepis* spp. For energized cables, in the vicinity of the energized cables, we observed at least 33 species of fishes, comprising 4,455 individuals [8]. *Sebastes semicinctus* dominated this habitat, comprising 56% of all fishes observed and present in 82.3% of the transects. Other important species or species groups included unidentified flatfishes and Agonidae, *S. saxicola*, and *Zaniolepis frenata* (Eigenmann & Eigenmann, 1889). For unenergized cables, similar to the fish assemblage found around energized cables, there were at least 35 fish species in proximity to the unenergized cables [8] and 3,691 individuals. As with the energized cables, *S. semicinctus* were by far the most abundant species, comprising 37.4% of all fishes observed. Other important species included *S. saxicola* and *S. elongatus*, unidentified flatfishes, Agonidae, and *Zaniolepis* spp. Fewest species (at least 23) and fishes (1,529) were observed on the natural habitats [8]. Here, unidentified flatfishes, Zoarcidae and Agonidae, *Zaniolepis* spp., *Citharichthys* spp., and *S. semicinctus* dominated.

We found that fish species communities were structured by depth (global $R = 0.553$; $p = 0.001$) more so than by habitat type (global $R = 0.176$; $p = 0.001$) (Figure 2). There was no statistical difference between the fish assemblages along the energized and unenergized cables ($R = -0.055$;

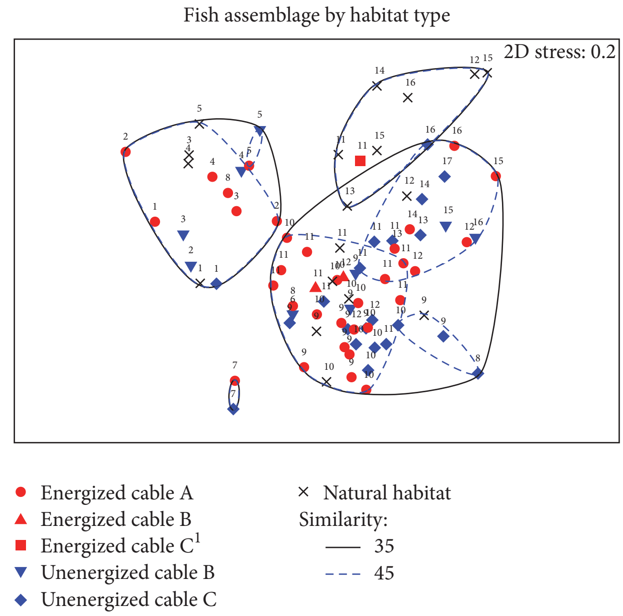

FIGURE 2: A 2D multiple dimensional scaling model comparing the fish assemblages observed over energized and unenergized cables and natural habitats surveyed during 2012–2014. Numbers near symbols refer to the depth category of that transect. The higher the number the deeper the transect. Depth ranges of the depth categories are given in [8].

TABLE 2: Effects of cable state (energized or unenergized), side of cable surveyed (west or east) nested in cable state, stratum groups (1–4), and year (2012–2014) on fish density tested using a generalized linear model (normal distribution, identity link) ($p < 0.05$). Densities were $\log(x+1)$-transformed. Cable state is energized or unenergized. Stratum groups are discussed under Results. ∗ indicates statistical significance.

Taxon	DF	Whole-model difference	Cable state	Cable side	Stratum groups	Year
		8	1	2	3	2
Sebastes semicinctus	X^2	26.133	1.116	0.210	6.707	13.735
	p	0.0010*	0.2908	0.9003	0.0819	0.0010*
Sebastes saxicola	X^2	54.474	3.344	0.549	51.093	9.687
	p	<0.0001*	0.0674	0.7599	<0.0001*	0.0079*
Unident. Agonidae	X^2	57.808	2.761	0.142	49.148	6.836
	p	<0.0001*	0.0966	0.9314	<0.0001*	0.0328
Zaniolepis frenata	X^2	46.427	0.793	10.287	22.828	5.225
	p	<0.0001*	0.3731	0.0058*	<0.0001*	0.0733
Sebastes elongatus	X^2	36.740	3.583	1.320	18.111	5.222
	p	<0.0001*	0.0584	0.5168	0.0004*	0.0735
Ophiodon elongatus	X^2	25.439	2.178	0.867	10.116	20.052
	p	0.0013*	0.1400	0.6484	0.0176*	<0.0001*
Citharichthys spp.	X^2	12.909	0.331	0.993	7.405	4.965
	p	0.1150	0.5649	0.6088	0.0601	0.0835
Unident. Zoarcidae	X^2	51.044	0.103	0.191	45.158	2.645
	p	<0.0001*	0.7484	0.9091	<0.0001*	0.2665
Total fishes	X^2	8.7853	2.1205	1.0314	1.4355	3.2553
	p	0.3607	0.1453	0.5971	0.6972	0.1964

$p = 0.87$). The natural habitat community statistically differed from both the energized cable ($R = 0.304$; $p = 0.003$) and unenergized cable ($R = 0.341$; $p = 0.001$) communities.

We used a GLM approach to test for the effects on fish density of (1) cable state (energized or unenergized), (2) side of cable (nested in cable type), (3) depth strata, and (4) year (Table 2). Within species (or in several cases species groups) that formed at least 1% of the fishes observed, we found no differences in densities between energized and unenergized cables. We did find differences based on cable side (*Z. frenata* densities were higher on the west side of cables, two-tail t-test: $t = 2{,}582$, df = 61, and $p = 0.012$), depth strata (*S. saxicola*,

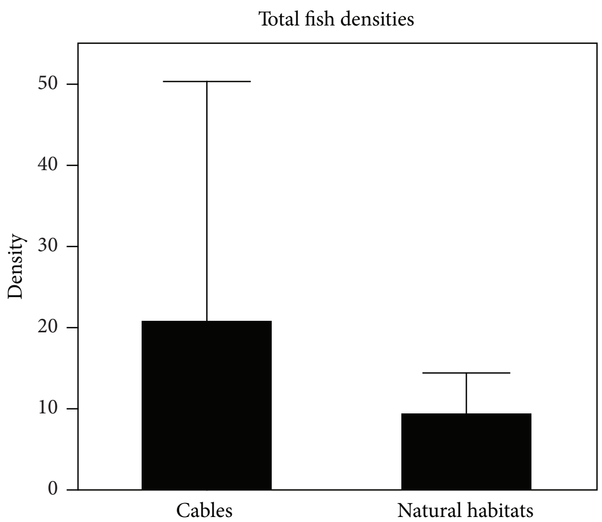

Figure 3: Densities of all fishes between all cables (energized and unenergized) combined and natural habitats of major species or species groups. Densities are in fishes per 100 m^3 and means and standard deviations are provided.

S. elongatus, unidentified Agonidae, unidentified Zoarcidae, *O. elongatus*, and *Z. frenata*), and year (*S. semicinctus*, *S. saxicola*, and *O. elongatus*).

Total fish densities were significantly higher around the cables than over the natural habitat ($X^2 = 10.2876$, df = 1, and $p = 0.0013$) (Figure 3). Among the more important species, densities of *S. semicinctus*, *S. saxicola*, *S. elongatus*, *Z. frenata*, and *O. elongatus* were higher at the cables and unidentified Zoarcidae were found at higher densities over natural habitat (Figure 4). There were no significant differences in the densities of *Citharichthys* spp. and unidentified Agonidae. There were very slight, but statistically significant, differences in both mean lengths and size distributions of fishes among the three study habitats as fishes at the unenergized cables tended to be slightly larger (mean = 14.8 cm) than those at both natural habitats (mean = 13.7 cm) and energized cables (mean = 13.0 cm) [Welch's test: energized versus unenergized: $F = 260.36$, df = 1, and $p < 0.0001$; energized versus natural habitat: $F = 18.37$, df = 1, and $p < 0.0001$; unenergized versus natural habitat: $F = 36.51$, df = 1, and $p < 0.0001$].

3.3. Invertebrates. Over all habitats, we observed a total of 30,523 invertebrates of at least 43 species [8]. *Metridium farcimen* (Brandt, 1835) was by far the most abundant species and comprised 43.4% of all invertebrates recorded. *Pandalus platyceros* (Brandt, 1851), unidentified "thin" Pennatulacea, *Apostichopus californicus* (Stimpson, 1857), *Luidia* spp., and *Octopus rubescens* (Berry, 1953) were also found at relatively high densities [8]. For energized cables, we observed 13,388 individuals, of at least 36 species, living on or near the energized cables [8]. *Metridium farcimen*, unidentified "thin" Pennatulacea, and *P. platyceros* were the species found in highest densities, forming on aggregate 79.7% of all invertebrates observed. *Apostichopus californicus*, *Luidia* spp., *O. rubescens*, an unidentified black Crinoidea, and *Urticina* spp. were also common. Along the unenergized cables, at least 35 species and 14,619 individuals were observed [8]. Three species, *M. farcimen*, *P. platyceros*, and unidentified "thin" Pennatulacea, were by far the densest (on aggregate forming 79.2% of all invertebrates surveyed). *Apostichopus californicus*, *Luidia* spp., *O. rubescens*, *Urticina* spp., and *Serpula* spp. were also characteristic of this habitat. Over the natural habitats, we observed the fewest number of species (a minimum of 27) and individuals (2,516) [8]. The unidentified "thin" Pennatulacea, *O. rubescens*, *Lytechinus pictus* (Verrill, 1867), and *Luidia* spp. dominated this habitat, along with smaller numbers of *M. farcimen*, *Strongylocentrotus fragilis* (Jackson, 1913), *A. californicus*, and California sea cucumber.

The structure of the invertebrate communities living around energized and unenergized cables and natural habitats was similar to that of fishes (Figure 5). We found that invertebrate communities were structured by habitat type (global $R = 0.596$; $p = 0.001$) and depth (global $R = 0.481$; $p = 0.001$). Similar to the fishes, there was no statistical difference between the invertebrate assemblages along the energized and unenergized cables ($R = 0.039$; $p = 0.218$). The natural habitat community of invertebrates strongly differed from both the energized cable ($R = 0.846$; $p = 0.001$) and unenergized cable ($R = 0.751$; $p = 0.001$) communities.

To determine if there were significant differences in species densities between energized and unenergized cables, we compared the densities of those important species that comprised at least 1% of individuals observed in this study in the same way as for fishes. Comparing taxa living on energized and unenergized cables, we did note slight but statistically significant differences in the densities of four of nine species or species complexes: *M. farcimen*, *Luidia* spp., *Urticina* spp., and unidentified black Crinoidea (Table 3). In addition, three species (unidentified "thin" Pennatulacea, *O. rubescens*, and *L. pictus*) differed between cable sides. Seven species (*M. farcimen*, *P. platyceros*, unidentified "thin" Pennatulacea, *A. californicus*, *O. rubescens*, *Urticina* spp., and unidentified black Crinoidea) exhibited differences among bottom depths. Lastly, densities of five species (*M. farcimen*, *P. platyceros*, unidentified "thin" Pennatulacea, *Luidia* spp., and unidentified black Crinoidea) varied among years.

A number of these important species were more abundant around the cables than over the natural habitats: these included *M. farcimen*, *P. platyceros*, unidentified "thin" Pennatulacea, *A. californicus*, *Luidia* spp., and *Urticina* spp. By comparison, *Octopus rubescens* and *L. pictus* were denser over natural habitats (Figure 6). Lastly, we did not observe a statistically significant difference in interhabitat abundances of the unidentified black Crinoidea.

4. Discussion

The fish communities living around the cables and adjacent natural habitats in this study are typical of those found throughout central and southern California on (1) soft substrata, (2) cobble-strewn edges of rocky reefs, (3) the low-relief shell mounds around oil and gas platforms, and (4) adjacent to the low-relief oil and gas pipelines [14–16]. A

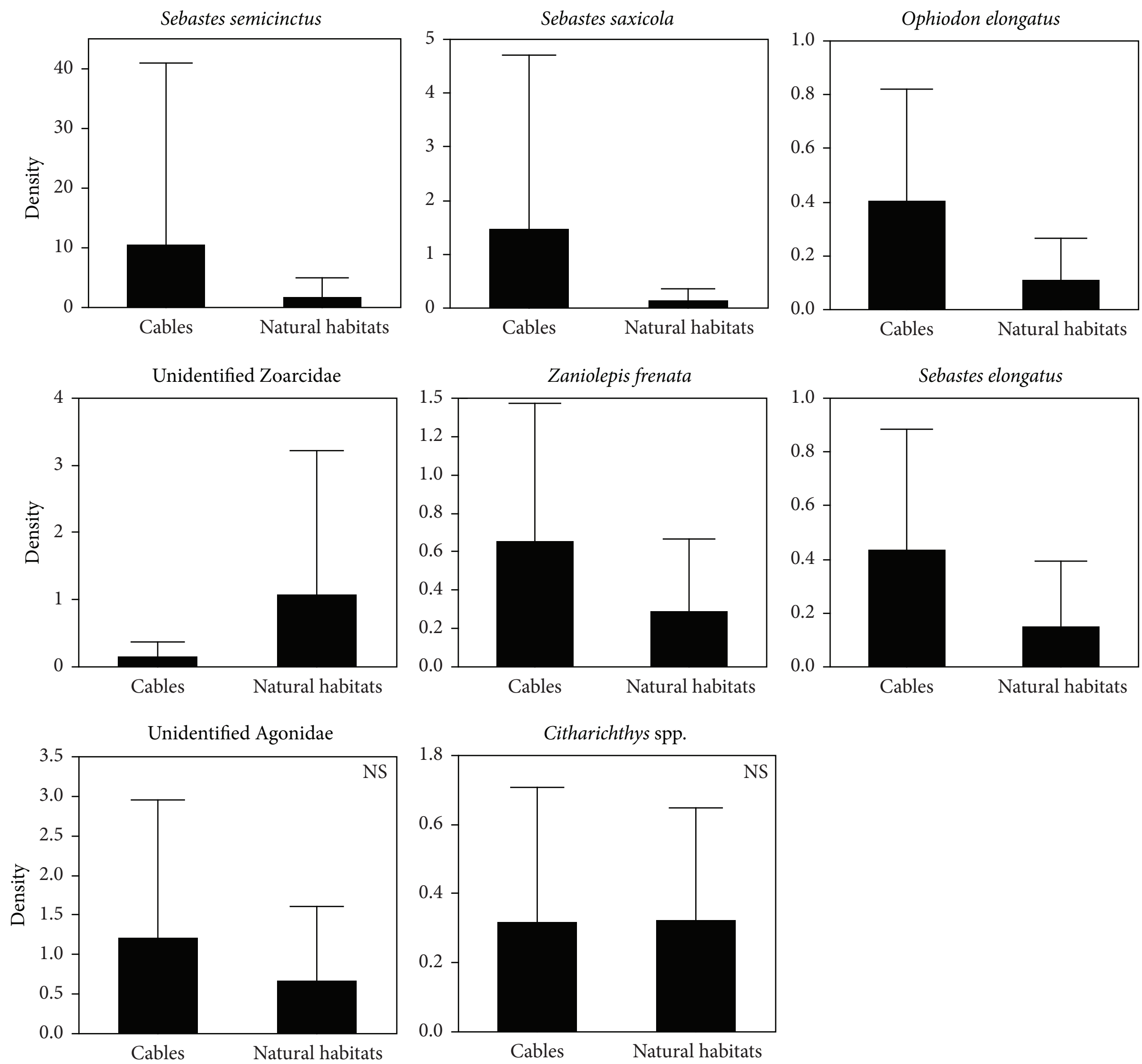

Figure 4: Densities of important fish species (defined as comprising at least 1% of all fishes observed), comparing (1) energized and unenergized cables and (2) natural habitats. Densities are in fish per 100 m^3 and means and standard deviations are provided. NS: not significant.

number of species of not only rockfishes, in particular, but also flatfishes, combfishes, and eelpouts are representative of these habitats. These fishes tend to be solitary rather than schooling (*S. semicinctus* are an exception) and benthic rather than water-column dwelling. They also tend to reach relatively small maximum size. All of these characteristics reflect living in an environment that has no large structures that would allow for refuges or points of orientation.

Although we found no evidence that there were differences in fish communities between energized and unenergized cables, the abundances of some fishes did vary (a) between cable sides (regardless of whether they were energized or not), (b) with depth, and (c) among years. It might be expected that abundances would vary with depth, reflective of depth preferences among species, and year, reflecting the patchiness of small-scale distributions. However, the greater abundance of *Z. frenata* on the west side of cables was unexpected and we have no definitive explanation for it. We have noted that, at times, mud will pile up on one side of the cable compared to the other, reflective of bottom current patterns. When this occurs, it could be argued that sediment grain size differs between the two sides and that *Z. frenata* is responding to this (perhaps finding higher densities of benthic invertebrate prey on one side over the other). However, when we examined those patches (using the video transects), where *Z. frenata* were most abundant, we did not observe any obvious differences between the sides. In addition, we noted that fishes around the unenergized cable were slightly larger than those at the natural habitat or the energized cable. However, the differences in mean lengths were small (a range of 1.8 cm among habitats). It is unlikely that this difference is biologically meaningful.

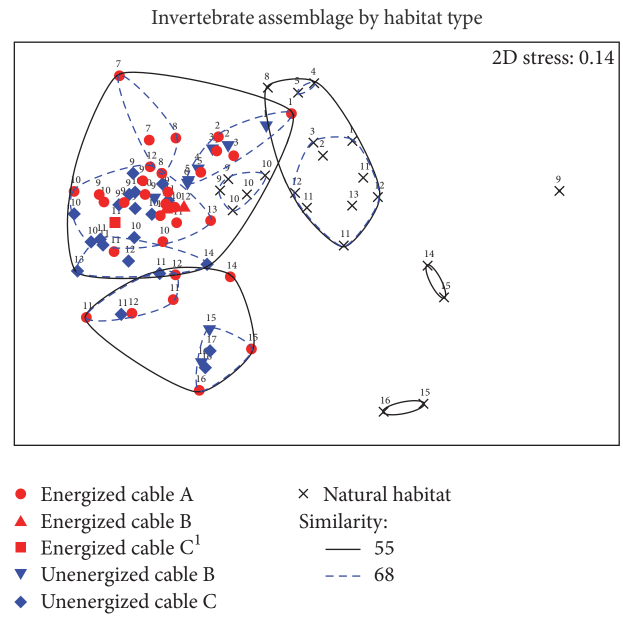

FIGURE 5: A 2D multiple dimensional scaling model comparing the invertebrate assemblages observed over energized and unenergized cables and natural habitats surveyed during 2012–2014. Numbers near symbols refer to the depth category of that transect. The higher the number the deeper the transect. Depth ranges of the depth categories are given in [8].

TABLE 3: Effects of cable state (energized or unenergized), side of cable surveyed (W or E) nested in cable state, stratum groups (1–4), and year (2012–2014) on invertebrate density tested using a generalized linear model (normal distribution, identity link) ($p < 0.05$). Densities were $\log(x+1)$-transformed. Cable state is energized or unenergized. Stratum groups are discussed under Results. $*$ indicates statistical significance.

Taxon	Source	Whole-model difference	Cable state	Cable side	Stratum groups	Year
	DF	8	1	2	3	2
Metridium farcimen	X^2	77.190	5.485	1.564	57.817	7.843
	p	<0.0001*	0.019*	0.458	<0.0001*	0.020*
Pandalus platyceros	X^2	73.407	0.911	0.271	56.182	37.781
	p	<0.0001*	0.340	0.873	<0.0001*	<0.0001*
Unident. thin Pennatulacea	X^2	93.957	0.009	66.213	46.116	9.299
	p	<0.0001*	0.925	<0.0001*	<0.0001*	0.010*
Apostichopus californicus	X^2	80.209	1.141	2.368	75.479	5.471
	p	<0.0001*	0.285	0.306	<0.0001*	0.065
Luidia spp.	X^2	45.971	12.983	0.960	4.591	24.452
	p	<0.0001*	0.0003*	0.619	0.204	<0.0001*
Octopus rubescens	X^2	27.199	0.019	14.847	10.446	0.003
	p	0.001*	0.889	0.001*	0.015*	0.999
Urticina spp.	X^2	75.522	5.480	1.954	58.734	4.900
	p	<0.0001*	0.019*	0.376	<0.0001*	0.086
Unident. black Crinoidea	X^2	42.274	7.728	6.192	27.052	12.625
	p	<0.0001*	0.005*	0.045	<0.0001*	0.002*
Lytechinus pictus	X^2	11.896	1.430	7.024	2.203	3.951
	p	0.156	0.232	0.030*	0.531	0.139
Total invertebrates	X^2	53.719	5.147	2.146	48.160	11.601
	p	<0.0001*	0.023*	0.342	<0.0001*	0.003*

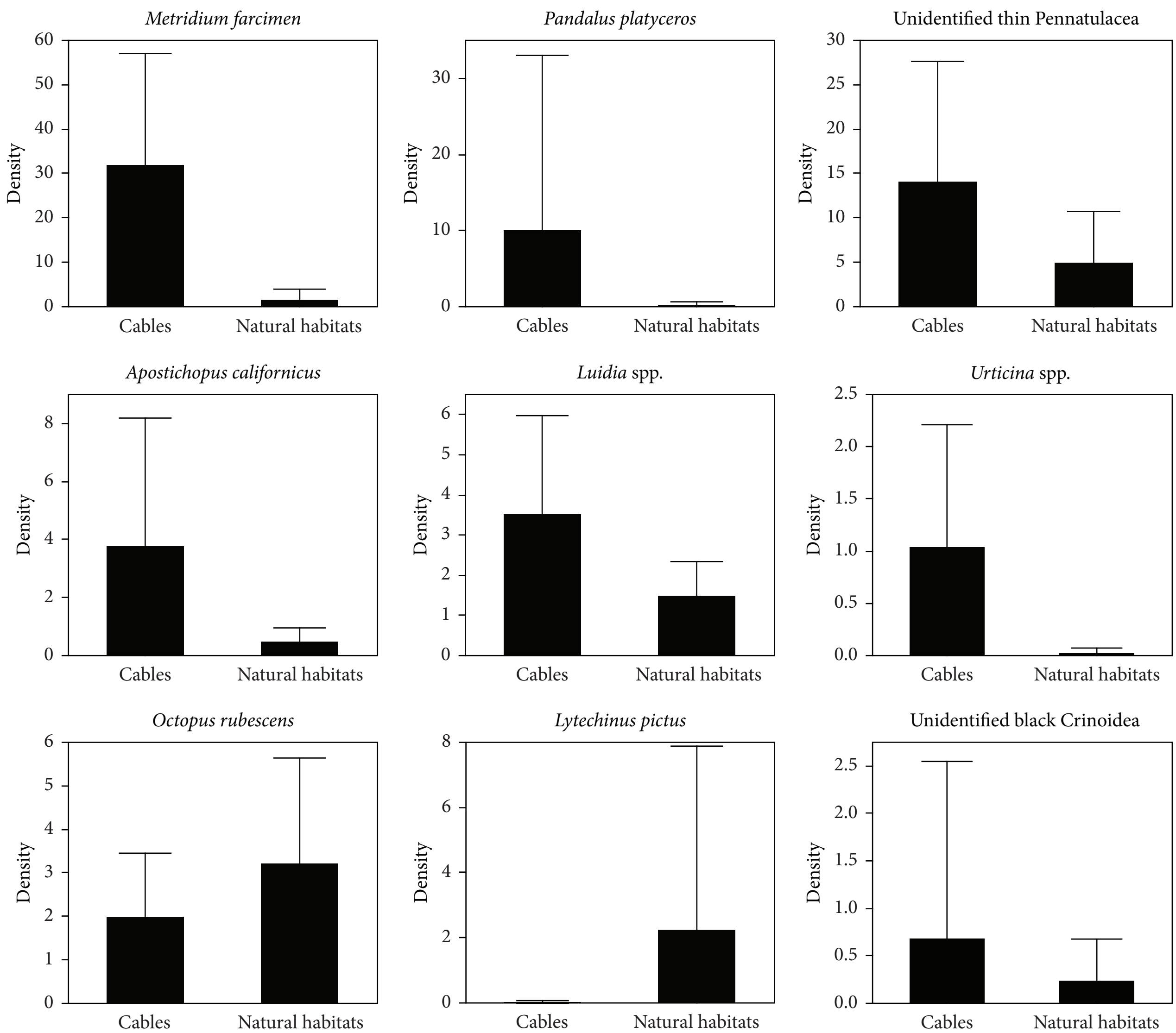

Figure 6: Densities of important invertebrate species (defined as comprising at least 1% of all invertebrates observed) between all cables (energized and unenergized) combined and natural habitats of major species or species groups. Densities are in invertebrates per 100 m^3 and means and standard deviations are provided.

Electrosensitive fishes were not commonly encountered on any of the three habitats. Only five *H. colliei* (three at the energized cables and two on the unenergized ones) and one *R. inornata* (at the unenergized cable) were observed. It is important to note that, in the depth ranges we surveyed, both benthic elasmobranchs (sharks, skates, and rays) and chimaerids (ratfishes) are common in southern California waters [17, 18]. However, with the exception of the schooling *Squalus suckleyi* and *Galeorhinus galeus*, most of these species are usually solitary and thus it would be unlikely that we would have observed large numbers of any of these taxa unless these habitats were somehow attracting these fishes. It is likely that too few electrosensitive individuals were observed to make statements concerning attraction or repulsion.

Regarding invertebrates, the species or species complexes that we observed were typical of both low-relief and soft substrata sea floors in southern and central California [19, 20]. Of the nine most important invertebrate species or species complexes, four (*M. farcimen*, *Luidia* spp., *Urticina* spp., and unidentified Crinoidea) exhibited slight, but significant, differences in densities between energized and unenergized cables. However, for each of these taxa or taxa groups, the differences were *not* statistically different across *all* depth strata (Figure 7) and thus no generalization can be made regarding the relationships of these organisms with cable energized state. Again, as with the fish communities, bottom depth was a major driver of invertebrate density variability as the abundances of seven of the nine most important species in the invertebrate communities varied with depth.

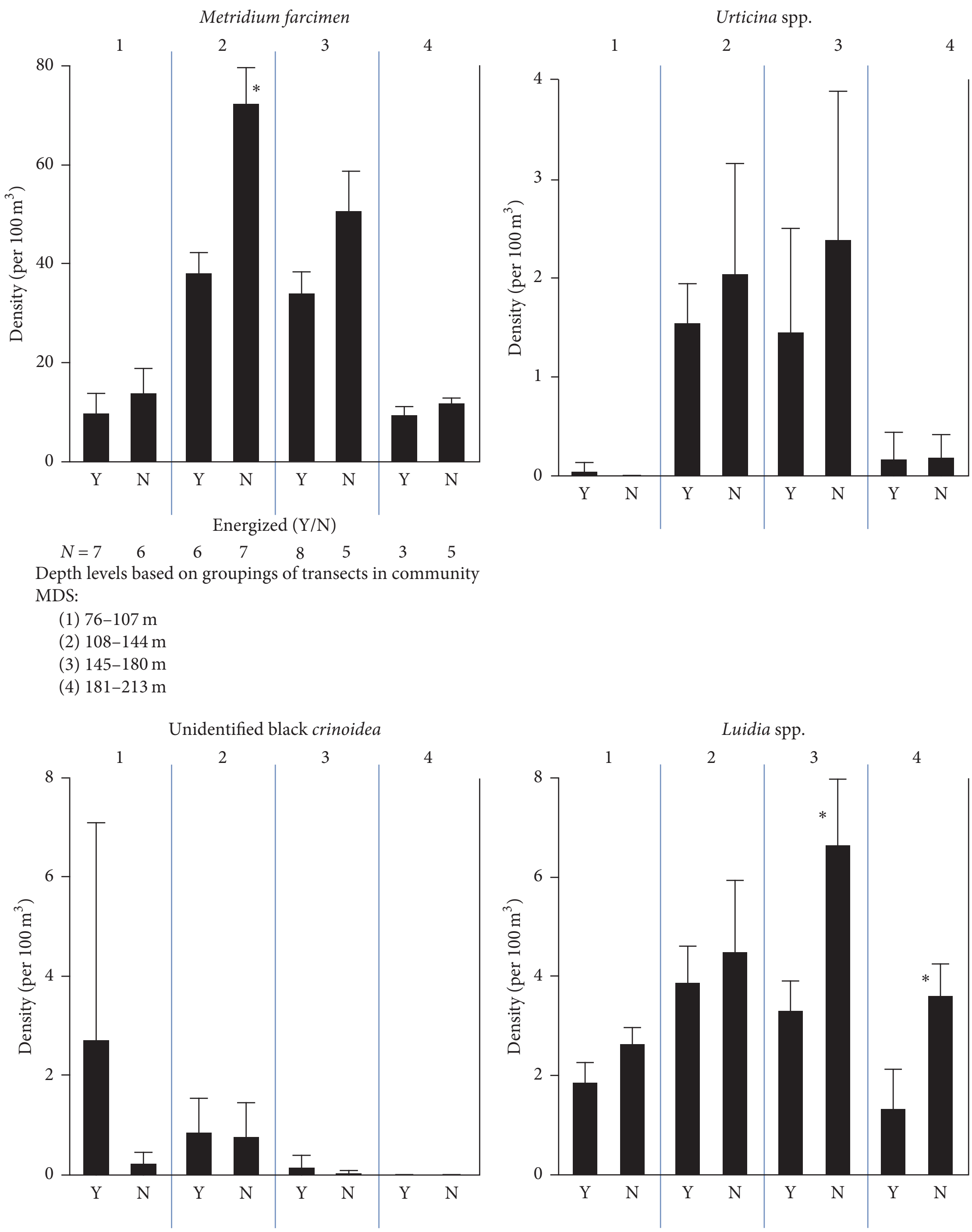

FIGURE 7: Densities of four invertebrate species or species complexes along energized and unenergized cables within four depth strata. Energized cables are labeled with Y and unenergized ones are labeled with N. *indicates statistically significant density differences.

The cable habitat harbored many more invertebrate species, at higher densities, than did the natural habitat. It is likely that this was due to the cables creating a more complex environment (hard, although relatively low) than that of the mud that formed most of the natural sea floor. In our cable surveys, we included not only the cable but also the sea floor within 2 m of the cable. This methodology allowed us to include not only organisms that might preferentially live on hard structure, such as *M. farcimen*, but also those dwelling on soft sea floor, such as Pennatulacea.

As with the fishes, there were invertebrate taxa whose densities were greater on one side of the cable: densities of both "thin" Pennatulacea (mean = 15.6 versus 1.8 per 100 m^3) and *O. rubescens* (mean = 2.2 versus 1.0 per 100 m^3) were higher on the east side, while that of black Crinoidea was higher on the west side (mean = 1.7 versus 0.7 per 100^3).

While we do not know why these patterns occurred, in the case of sea pens, it is known that at least some species are highly sensitive to substratum grain size. For instance, several species of sea pens in Scottish marine waters are abundant in mud and become rare or, ultimately, absent as the amount of gravel increases [21]. As noted before, it is possible that currents, playing over the cables, can distribute sediments based on grain size, thus leading to coarser sediments on one side and finer ones on the other. Asymmetry in octopus densities may also reflect greater prey densities on one side of the cable compared to the other.

Data from the few field studies on the behavior of fishes in the presence of human-induced EMF in submarine power cables are, at best, equivocal. The swimming speed of European eel, *Anguilla anguilla*, passing over a 130 kV AC power cable in the Baltic Sea was observed [22] and a small effect was found with eels slowing their swimming speed when both approaching and exiting from the cable region. However, there was no statistically significant relationship between the amperage in various parts of the cable and swimming speed. The movements of three species of electrosensitive elasmobranchs (thornback ray *(Raja clavata)*, spurdog *(Squalus acanthias)*, and small-spotted catshark *(Scyliorhinus canicula)*) in enclosed mesocosms off Scotland containing either energized or unenergized cables were characterized [23]. In this study, one of the three species (spotted catshark) tended to be attracted to the energized cable compared to the unenergized one, while the other two species did not show any differences in their responses. Lastly, the distribution of fishes in a nearshore area of the North Sea before and after the energizing of a submarine power cable transmitting energy from an offshore wind farm was characterized [24]. This study found evidence that the migrations of four species, Baltic herring *(Clupea harengus)*, European eel, Atlantic cod *(Gadus morhua)*, and flounder *(Platichthys flesus)*, appeared to be somewhat hindered by an energized cable.

The most apt comparisons between our findings and those of others are the surveys of fishes and invertebrates conducted in Monterey Bay, central California, on and near a power cable extending from land to the Pioneer Seamount, located about 51 km offshore. Note that this cable was smaller than the cables we studied (3.2 cm versus 20 cm in diameter) and carried lower voltages (10 Kv versus 35 Kv) and the EMF emitted by the Monterey Bay Aquarium Research Institute (MBARI) cable was not measured.

Using an ROV, MBARI researchers compared the organisms living on, over (in areas where the cable is buried), or near cables with those living on natural habitat control sites 50–100 m away. The major findings of these studies [20, 25, 26] were the following:

(1) The abundances of most animals observed did not differ between the area over the cable route and in natural habitat.
(2) The overall faunal communities did not differ between the cable and control site. Thus, the cable had little or no detectable effect on the distribution and abundance of either faunal assemblage.
(3) The faunal communities did not differ between sampling years.
(4) Faunal assemblages did vary with depth.
(5) The abundance and distribution of fauna appear to be most closely linked to natural variation rather than to either the presence of the cable or whether it is energized.
(6) Although electroreceptive species such as skates and ratfishes were observed, the densities of these animals were not higher near the energized cable than at the control site.

In several ways, our findings mirror those of the MBARI studies (i.e., [20]). First, and most importantly, we also found little evidence that energized cables either attract or repel the marine organisms living in their vicinity. This is particularly striking as the cables in our study were physically larger in diameter and carried more voltage (and thus likely also created greater EMF). In addition, the same group of fishes and invertebrates that were characteristic of Kuhnz et al.'s study also dominated the habitats in ours.

5. Conclusions

Regarding the specific objectives of this study, we conclude the following.

As for *the differences, if any, of fish and invertebrate communities associated with energized and unenergized cable habitat and those communities in sea floor habitats lacking cables*, we did not observe any significant differences in the fish communities living around energized and unenergized cables and natural habitats. A very slight, and likely biologically insignificant, difference in mean sizes was observed as fishes at unenergized cables were marginally larger than those around energized ones. Overall species diversity and the densities of the most important fish species (defined as comprising at least 1% of all fishes observed) were higher at the cables than at the natural habitats. This is likely reflective of the more complex habitats afforded by the cables than the primarily soft substrata of natural habitats.

Similar to the fish communities, the invertebrate assemblages living around energized and unenergized cables and natural habitats were similar to one another and variability between these communities was primarily driven by sea floor depth.

Among the three habitat types, there were some statistically significant differences in densities for all nine of the most abundant species. These differences included (1) two species, sand star and black crinoid, whose densities differed between energized and unenergized cables, (2) three species, thin sea pen, red octopus, and white sea urchin, which differed between cable sides, (3) seven species, white-plumed anemone, spot prawn, thin sea pen, California sea cucumber, red octopus, *Urticina* spp., and black crinoid, which exhibited bottom depth differences, and (4) two species, thin sea pen and sand star, whose densities varied among years. Sand star densities were slightly greater at unenergized cables and black crinoid densities were greater at energized cables.

Regarding *the strength, spatial extent, and variability of EMFs along both energized and unenergized cables*, the EMFs produced by the energized cables were similar both over the three years of the study and along the cables. EMF strength dissipated relatively quickly with distance from the cable and approached background levels at about one meter from the cable. The EMFs at unenergized cables were similar to those found at the natural habitats.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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