Effects of Sounds from a Geophysical Survey Device on Catch-per-Unit-Effort in a Hook-and-Line Fishery for Rockfish (*Sebastes* spp.)

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We examined the concern of commercial fishermen that the sounds generated by acoustic geophysical survey devices result in decreased commercial catches. In blind experimental trials, a test of effects was performed on the rockfish (*Sebastes* spp.) hook-and-line fishery located along the central California coast. A single 1639-cm^3 air gun with a source level of 223 dB re 1 μPa was used to produce peak pressures above 186 dB re 1 μPa at the base of rockfish aggregations. There was an average decline in catch-per-unit-effort of −52.4% (90% confidence interval −27.9%, −76.9%) under emission conditions relative to control trials. This overall decline was also reflected in the individual catches of chilipepper (*S. goodei* (α = 0.046)), bocaccio (*S. paucispinis* (α = 0.007)), and greenspotted rockfish (*S. chlorostictus* (α = 0.021)). The overall reduction in catch translated to an average economic loss of 49.8% (90% confidence interval −21.7%, −77.9%) under the test conditions of this experiment. Fathometer recordings during the study showed no significant change in an index of aggregation size as the result of air-gun emissions (α = 0.374). However, aggregation height appeared to change as the result of emission (α = 0.094) after adjustment for species composition of the catch.

Nous avons étudié les plaintes formulées par les pêcheurs commerciaux et selon lesquelles les sons produits par les appareils acoustiques utilisés au cours des levés géophysiques donnaient lieu à une baisse des prises. Des essais à l'aveugle ont été réalisés. Ces essais ont porté sur la pêche à la ligne du sébaste (*Sebastes* spp.) le long de la côte du centre de la Californie. Un canon à air comprimé de 1 639 cm^3 et d'une puissance sonore à la source de 223 dB à 1 μPa a été utilisé pour produire des pressions de pointe de plus de 186 dB à 1 μPa à la base des concentrations de poisson. Il y a eu baisse moyenne de 52,4 % (intervalle de confiance à 90 % de 27,9 à 76,9 %) des prises par unité d'effort de pêche par rapport aux essais témoins. Cette baisse générale s'est aussi reflétée sur les prises de sébaste de Goode (*S. goodei*, α = 0,046), de bocaccio (*S. paucispinis*, α = 0,007) et de sébaste à tache verte (*S. chlorostictus*, α = 0,021). La réduction totale des prises, dans les conditions des essais, a donné lieu à une perte économique moyenne de 49,8 % (intervalle de confiance à 90 % de 21,7 à 77,9 %). Des enregistrements à l'échosondeur n'ont pas permis de noter de modification significative d'un indice des tailles de concentration pendant les essais (α = 0,374). Il semble cependant que la hauteur des concentrations, après correction pour la composition spécifique des prises, ait été modifiée par les émissions sonores (α = 0,094).

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There has been concern that sounds generated by air guns and other acoustic devices used in offshore oil and gas exploration have been affecting the commercial hook-and-line fishery for rockfish (*Sebastes* spp.) along the California coast. Fish are known to show behavioral responses to a variety of sounds (for review, see Tavolga et al. 1981). Air-gun discharges have been reported to change the depth distribution of whiting (Chapman and Hawkins 1969). A Norwegian study suggested that fish distribution can be changed along transects made by a survey vessel using an array of air guns (Dalen and Raknes 1985). Also, a previous study in California (Greene 1985) suggested that the behavior and catchability of rockfish were affected by sounds from an air-gun array. The purpose of this study was to examine the proposition that geophysical seismic devices can reduce the catch-per-unit-effect (CPUE) of a fishery.

A test of effects on CPUE was the primary focus of the fishing experiment reported here. An ancillary objective of this experiment was to assess the effects of acoustic emissions on the size and configuration of the rockfish aggregations. Any changes in the spatial pattern would indicate possible effects on the fishery uncluttered by the complications of fishing success.

The study was structured to deal with two problems. The first problem was the difficulty of detecting differences in fishing success when the parameter that measures success (CPUE) was known to have a high variation. A preliminary survey gathered information on the variability of CPUE in the hook-and-

TABLE 1. Power ($1 - \beta$) of the proposed field experiment to detect a 30 or 50% reduction in CPUE at a statistical significance level of $\alpha = 0.10$ as a function of the number of control (n_C) and emission (n_E) trials.

Number of trials ($n_C = n_E$)	Power	
	$\Delta = 30\%$	$\Delta = 50\%$
14	0.39	0.74
20	0.46	0.84
26	0.52	0.90

line fishery in order to calculate the necessary sample size for the fishing experiment. The second problem was the difficulty of attributing any observed effects to sounds from seismic survey activity. Because an experimental approach permits designs that actively control for confounding factors, systematic errors, and alternative explanations (Cox 1958), an experimental approach was adopted.

Preceding the fishing experiment discussed here, a behavioral experiment (companion paper, Pearson et al. 1992) determined the threshold at which sounds from an air gun produced a startle response or other behavioral changes in captured rockfish. Output from this behavioral experiment was used to establish test parameters of this fishing experiment. Specifically, the behavioral data were used to examine the appropriate magnitude of the experimental sound treatment and the minimum distance to be traveled between trials to assure statistical independence of the trials.

Experimental Design and Methods

Preliminary Survey

A preliminary survey was conducted May 6–10, 1986, to select a standard unit of effort and estimate associated variance components for sample size calculations. A total of 17 fishing trials was performed on separate rockfish aggregations. Each setline consisted of 80 hooks spaced 0.305 m apart and baited with salted mackerel. We deployed one to four setlines per trial, each with a bottom time of either 15 or 20 min. Based on industry procedures and statistical performance, a standard unit of effort consisting of a fishing trial with three setline deployments and bottom times of 20 min was ultimately selected for the field experiment. The preliminary survey produced a mean CPUE of 62.5 fish per trial and a between-trials coefficient of variation (CV) of 95.7%.

To establish the level of replication required to detect a significant effect during the fishing experiment, sample size (n) calculations were performed using noncentral F-distributions (Tiku 1967, 1972). Ideally, in a situation where the consequences of falsely identifying an acoustic effect are equal to missing an appreciable effect (e.g. 50% reduction in CPUE, $\Delta = 0.50$) on the fisheries, the Type I (α) and Type II (β) error rates should be equal. The magnitude of the treatment effect (Δ) was expressed as a function of the control (μ_C) and emission (μ_E) means where $\Delta = |\mu_E - \mu_C|/\mu_C$. An α-level of 0.10 for a one-tailed test of the null hypothesis of no effect under acoustic emissions was chosen for this study to bring about a closer equality of these error rates. With $n = 20$ replicate trials per treatment (Table 1), the fishing experiment had a projected power of $1 - \beta = 0.84$ in detecting a 50% decline in CPUE at a statistical significance level of $\alpha = 0.10$. This level of fishing effort ($n = 20$) and set of quantitative objectives ($\alpha = 0.10$, $\beta = 0.16$, and $\Delta = 0.50$) were selected for the fishing experiment. As it turned out, the preliminary estimates and stipulations ($\Delta = 0.50$, CV = 95.7%) used in the power calculations closely approximated the actual parameters observed during the field experiment (i.e. $\Delta = 0.524$ and CV = 72.4% for controls, CV = 92.5% for emission trials).

Fishing Experiment

Study area

The fishing experiment was conducted from July 19 to August 3, 1986, off the California coast (Fig. 1) north of Morro Bay between Pt. Piedras Blancas and Pt. Sur where there is a productive commercial hook-and-line fishery for rockfish. All fishing trials were restricted to fish aggregations on rock pinnacles occurring at depths between 82.3 and 182.9 m. The minimum distance between successive trials was 10 km apart. A distance of 10 km was selected to assure that fish aggregations were not exposed to a sound level greater than 170 dB re 1 μPa radiating from a previous test location (hereafter, dB will be expressed as relative to a reference level of 1 μPa). Based on preliminary results from a behavioral experiment (Pearson et al. 1992), sound levels below 170 dB were not expected to influence fish behavior. A minimum of 3 d was allowed before a repeat control or emission trial in the same area. For statistical independence, a unique rock pinnacle was used for each trial of the fishing experiment.

Experimental design

The field experiment used a completely randomized design with individual fish aggregations being the experimental units. The treatments, which were randomized to the trial sequence, consisted of two acoustic emission levels, zero or mock emission, and acoustic emission above 180 dB at the base of the rock pinnacle. The 180-dB level was selected because the behavioral experiment (Pearson et al. 1992) indicated that levels above 180 dB elicit behavioral responses in rockfish. Knowledge of the treatment regime was limited to the project biometrician with the acoustic crew being informed only after all sound production equipment had been deployed. With only a single air gun, it was also possible to keep the fishing crew blind to the treatments during the study.

A source of high-pressure air was used during the control trials to simulate the bubbles released during air-gun operation. This mock or control emission was done to eliminate possible bias from visual cuing of the fishing vessel operators when the air gun was operating. A solenoid valve air control system enabled selection of either air gun or bubble source from the control panel. It was found that a 1-s burst of high-pressure air through a perforated tube located near the air gun provided a bubble at the surface that was similar in size to the bubble produced by the air-gun operation. This system was operated at the same rate of six pulses per minute as the firing of an air gun during acoustic trials. Acoustic monitoring during the trials showed that the pulsing of the bubble source had no acoustic influence on the control trials.

Fishing trials were performed using a 11.6-m fishing vessel, the F/V *BONNIE MARIETTA*. A fishing trial began with three echosounder transects using a Si-Tex model HE-351 echosounder to measure the size and configuration of the fish aggregation selected. The aggregations recorded on the chart recordings were analyzed with a Planix 6 digital planimeter to measure the area of each aggregation in square centimetres. The height of the aggregation on the chart recording was measured

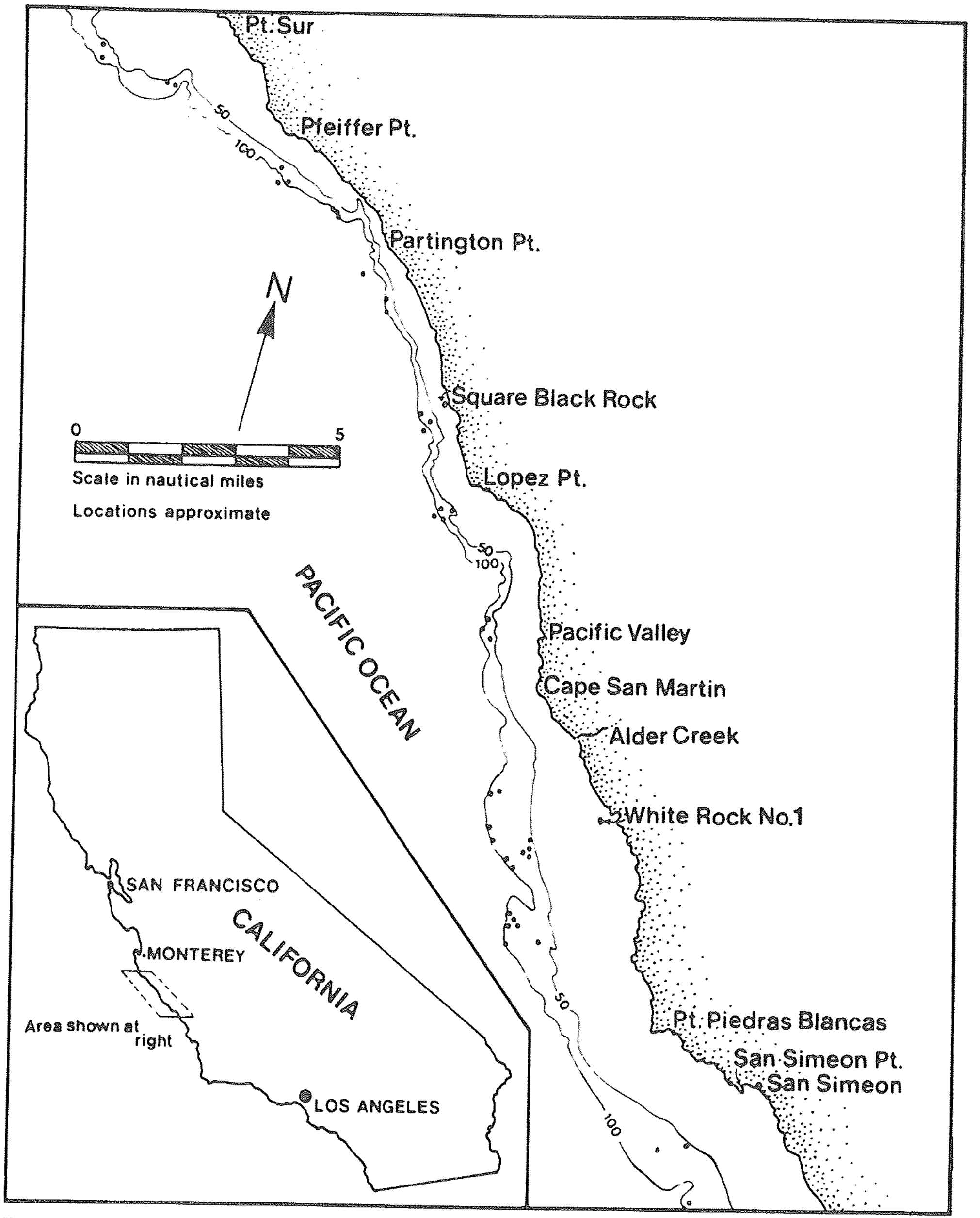

FIG. 1. Locations of the fishing trials (dots) along the California coast used in the fishing experiment.

in millimetres. A mean was calculated from two replicate measurements of aggregation area and height for each record.

After completion of the three preoperational transects, the 33.5-m industrial vessel M/V *NAUTILUS* was instructed to commence the scheduled treatment. The M/V *NAUTILUS* began its treatment maneuvers by traversing over the top of the rockfish aggregation and then proceeding to a standoff distance of approximately 165 m where it continued circling the pinnacle throughout the course of the trial to provide sound exposure during fishing. The passage over the aggregation was perfomed to provide an initial sound exposure of at least 180 dB. During the fishing experiment, sound levels at the sea bottom were always above 180 dB and often above 190 dB, so that the treatment applied to the aggregation was within the range that produced alarm responses in the behavioral experiment. The aggregations were exposed to a lesser extent to sound levels above 200 dB, the level at which startle responses were observed. The standoff distance was chosen to be the minimum distance that could be accommodated without the sound vessel (i.e. the M/V *NAUTILUS*) interfering with the fishing vessel F/V *BONNIE MARIETTA*. After the passage of the sound boat over the aggregation, the fishing vessel deployed the first setline and repeated the three echosounder transects. A sequence of three setlines was deployed with one setline soaked at a time. A trial ended with the retrieval of the third setline.

The standard unit of fishing effort used in the trials of the fishing experiment was three setlines deployed for 20 min each. Each setline had 80 hooks spaced 0.305 m apart and baited with salted mackerel as used in the preliminary survey. Variously colored rubber balloons were added to the hooks as an additional lure to the rockfish and to hide the hook's shank. The hooks on the setline were numbered individually from 1 to 80 to record fish placement along the line. All trials consisted of three setlines regardless of the fishing success on earlier lines.

On recovery of the setlines, the catch was examined and the species and size category recorded by hook location. Fish caught during a fishing trial but detached from the setlines during recovery (i.e. "floaters") were also recorded by species and size category for assignment to the proper setline. Floaters were included in the data analyses. Fish were sorted according to market value (i.e. whole fish or fillet fish species), placed in fish baskets, and weighed on a deck scale after completion of each trial. The CPUE for a trial was calculated as the number of fish caught during the three setlines.

Species composition of a rockfish catch, as well as the catch weight, was used to determine the economic value of a particular catch to the fishermen. For each trial, the total weight of fillet fish (e.g., chilipepper (*S. goodei*), bocaccio (*S. paucispinis*), and yellowtail rockfish (*S. flavidus*)) and of fish sold whole in the marketplace (e.g. vermilion (*S. miniatus*) and greenspotted (*S. chlorostictus*) rockfish) was measured. Prices paid to the fishermen at the time of this study were \$1.98/kg for whole fish and \$.99/kg for fillet fish. Using these prices, cash value of the catch for each trial was computed. It is important to note that results of the data analysis on the cash value of catch is invariant to the actual prices received by fishermen so long as the ratio of the wholesale price of whole to fillet species remains 2:1.

Sound production and monitoring

The same sound production system was used in this fishing experiment as was used in the behavioral experiment (Pearson et al. 1992). A single 1639-cm^3 air gun operated at 4500 psi (1 psi = 6.895 kPa) was chosen in order to provide a simple, well-defined sound source for the field trials. Air guns are the type of device most frequently used in geophysical surveys off California (Malme et al. 1986). During experimental fishing, the air gun was towed at a depth of 6.1 m and a speed of about 1.8 km/h. The towing depth was typical of industry practice. The towing speed was slower than industry practice so that the sound boat had sufficient maneuverability at the pinnacle to deliver the experimental treatment levels desired. A diesel-driven air compressor on the M/V *NAUTILUS* provided high-pressure air in sufficient volume to operate the air gun at a firing rate of six pulses per minute during the fishing trials. The compressor was mounted on vibration isolation supports to reduce sound radiation into the water.

The sound monitoring and analysis systems were installed on the M/V *NAUTILUS*. A hydrophone towed 12 m behind the air gun provided data for determining the acoustic source level of the gun and monitoring its output during the course of each trial. The signals from the hydrophones were amplified and recorded on a multichannel analog tape recorder, a storage oscilloscope, and a strip chart recorder. A real-time narrowband spectrum analyzer was also used to obtain records of pressure wave forms and pressure level spectra. All equipment were calibrated to give pressure sensitivity with a reference of 1 V/μPa. Spectrum analysis records were calibrated to obtain the sound pressure levels in a specified analysis bandwidth (termed band level (BL)) or in a 1-Hz bandwidth (termed spectrum level (SL)) relative to 1 μPa. Details of the acoustic measurement technique can be found in Pearson et al. (1987).

Statistical analysis

The analyses of CPUE, cash value of the catch, and spatial configuration of the rockfish aggregations are not wholly independent (e.g. cash value is a function of catch) but were deemed important either in exploring alternative response variables for measuring the effects on the fishery or in assessing the economic consequences of any observed effects. Throughout, statistical significance will imply an α-level of 0.10 or less. Exact α-levels are also reported for each statistical test performed.

Covariance analysis was used to analyze the total catch of all rockfish and the catches of the five most abundant species: chilipepper, vermilion rockfish, bocaccio yellowtail rockfish, and greenspotted rockfish. The variable ln (catch + 1) was used as the dependent variable with catch being the number of fish. The logarithmic transformation was performed to stabilize the within-treatment variances and was appropriate because (1) the CV was constant across treatments (Snedecor and Cochran 1980, 291–292; Sokal and Rohlf 1981; Bliss 1967, p. 232), (2) proportional rather than additive effects were expected (Snedecor and Cochran 1980, p. 291–292), and (3) the catch showed positive skewness (Sokal and Rohlf 1981, p. 419–421). The addition of 1 to all data enabled analysis of trials with zero catch. Polynomial response equations to degree 3 (i.e. linear, quadratic, or cubic) were fitted to the catch data as a function of depth for all individual species, as well as total catch. Stepwise regression procedures were used to determine the degree of the polynomial equations. In addition, the height and area of the rockfish aggregation were used in the covariance analysis. One-tailed tests of the null hypotheses of no difference in mean CPUE or cash value against the alternative of a decline in response were performed.

The relative change (RC) in CPUE and the cash value of the catch as the result of the acoustic emissions of the air gun were estimated by the equation

$$(1)\quad \hat{RC} = \frac{\bar{x}_E - \bar{x}_C}{\bar{x}_C}$$

with associated estimate of variance

$$(2)\quad \hat{Var}(\hat{RC}) = \left(\frac{\bar{x}_E}{\bar{x}_C}\right)^2 \left[\frac{S^2_{\bar{x}_E}}{\bar{x}_E^2} + \frac{S^2_{\bar{x}_C}}{\bar{x}_C^2}\right]$$

where $\bar{x}$ and s^2 are the sample mean and variance among replicate trials for control (C) and emission (E) conditions, respectively. Construction of 90% confidence interval estimates for RC was based on the formula $\hat{RC} \pm 1.645\sqrt{\hat{Var}(\hat{RC})}$.

Regression diagnostics were performed as part of the data analysis to identify influential data and outliers. Studentized residuals were calculated to identify influential data points with high leverage (Belsley et al. 1980, p. 17–20), but in no instance was the α-level for a residual test less than α = 0.348. Additionally, leverage points were analyzed by data-point deletion techniques (Belsley et al. 1980, p. 11–26). In no instance was the significance of the conclusions altered.

To determine whether area or height of the fish aggregations had changed the result of acoustic trials, analyses of variance and covariance were performed using the response variable

$$(3)\quad y_{ij} = \ln\left[\frac{\dfrac{\left(\sum_{k=1}^{3}\sum_{l=1}^{2} X'_{ijkl}\right)}{6}}{\dfrac{\left(\sum_{k=1}^{3}\sum_{l=1}^{2} X_{ijkl}\right)}{6}}\right]$$

where y_{ij} = ln − relative change in aggregation size for the jth trial ($j = 1, \ldots, 20$) of the ith treatment ($i = 0, 1$), X'_{ijkl} = Nth duplicate measurement ($N = 1, 2$) of the kth replicate operational transect ($k = 1, \ldots, 3$) for the jth trial ($j = 1, \ldots,$

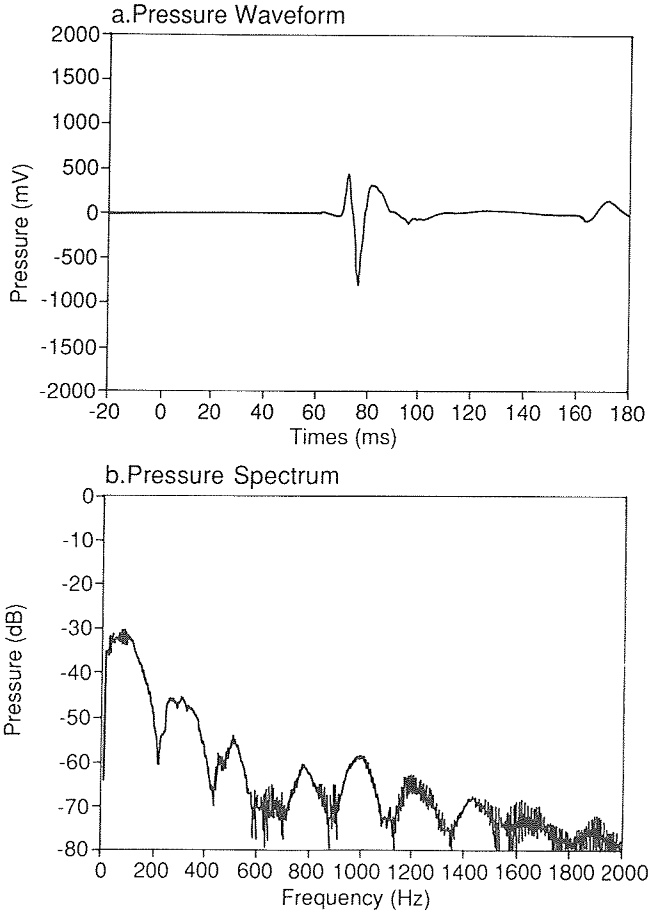

FIG. 2. Representative (a) air-gun signature and (b) pressure level spectrum measured by the spar buoy hydrophone at a depth of 60 m and at a range of 100 m. The single air gun used had a volume of 1639 cm^3. Calibration: (a) 1 V = 5.6 kPa; (b) 0 dBV = 188 dB re 1 μPa; band width = 5 Hz.

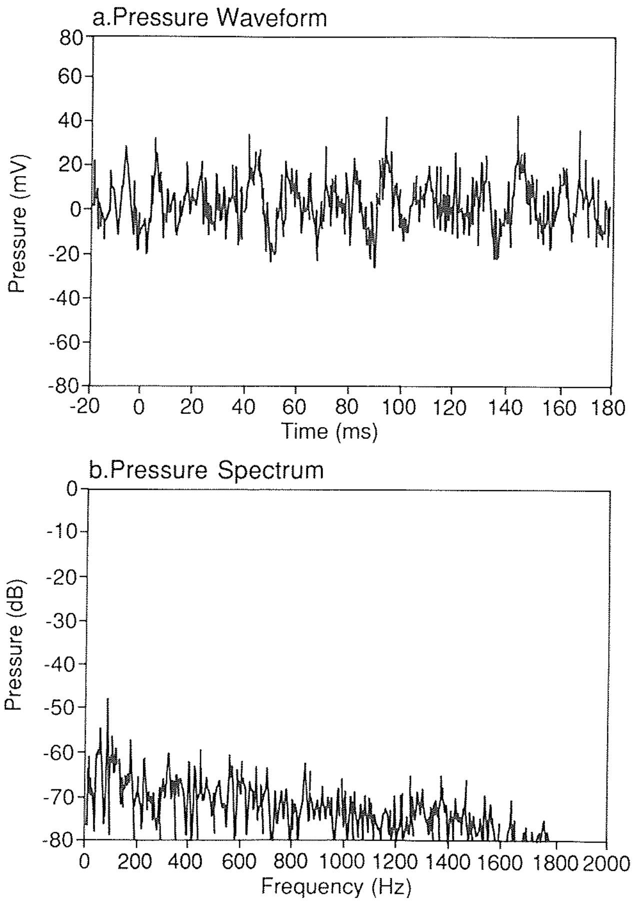

FIG. 3. (a) Acoustic signature and (b) pressure spectrum measured by the spar buoy during bubble source operation at close range (primarily dominated by radiated noise from the M/V *NAUTILUS*). Calibration: (a) 1 V = 178 Pa, (b) 0 dBV = 158 dB re 1 μPa; band width = 5 Hz.

20) of the ith treatment ($i = 0, 1$), and X_{ijkl} = the Nth duplicate measurement ($N = 1, 2$) of the kth replicate preoperational transect ($k = 1, \ldots, 3$) for the jth trial ($j = 1, \ldots, 20$) of the ith treatment ($i = 0, 1$). Because rockfish aggregations have been reported by fishermen to either expand or contract in the presence of an acoustic disturbance, two-tailed tests of effects were performed. To interpret the nonrejection of a null hypothesis, post hoc power analysis was performed.

Results

Sound Characterization during the Fishing Experiment

Measurements showed that sound propagation from the air gun followed spherical spreading laws (Malme et al. 1986) and was not significantly changed by fluctuations in near-surface temperature structure during the trials. Pressure signature and pressure level spectrum that would be experienced by a fish aggregation at a depth of 60 m and at a range of 100 m from the sound source are shown in Fig. 2.

The bubble source used to simulate the surface effects of air-gun operation during mock or control emission was not impulsive but operated in 1-s bursts at a rate of six bursts per minute. The sound produced by its operation contained primarily high-frequency energy. The pressure signature and pressure level spectrum observed by the spar buoy hydrophone during the bubble source operation at a distance of about 80 m are shown in Fig. 3. This record has been processed to retain sound energy at frequencies below 1.5 kHz to make it comparable with the air-gun records. Sounds recorded during bubble source operation were a combination of ambient noise and radiated noise from the M/V *NAUTILUS*. Because no change was observed in this frequency range whether or not the bubble source was operating, no acoustic influence on the fishing tests was expected from the pulsing of the bubble source.

Effects on Catch-per-Unit-Effort (CPUE)

The CPUE based on the catch of all species showed (Fig. 4) a significant curvilinear relationship as a function of trial depth ($r^2 = 0.534$) with the maximum predicted catch at approximately 146 m. Control trials had a mean depth of 124 m, and emission trials were conducted at a mean depth of 107 m. Analysis of covariance indicated a significant decline ($\alpha = 0.016$) in the mean total catch of rockfish per trial under emission conditions after adjustment to a common depth (Table 2). At a depth of approximately 109.7 m, control trials had a predicted mean catch of 34.0 ($\mathrm{CI}(23.5 \leqslant \mu_C \leqslant 49.0) = 0.90$) fish, while emission trials had a mean catch at the same depth of 16.2 fish ($\mathrm{CI}(11.0 \leqslant \mu_E \leqslant 23.6) = 0.90$). This difference represents an RC in mean catch of -52.4% ($\mathrm{CI}(-27.9\% \leqslant \mathrm{RC} \leqslant -76.9\%) = 0.90$) as a result of the acoustic emissions under the fishing conditions of this study.

To provide a second analysis of the catch that also takes into account differences in mean trial depth, only those trials conducted at depths ≤118.9 m were analyzed. Eight control trials (mean depth 99.2 m) and 15 emission trials (mean depth 100.5 m) were conducted within that depth class. Covariance analysis indicated no significant relationship ($P(F_{1,20} > 0.1860) = 0.671$) between catch and depth within this subclass of trials. A subsequent two-sample *t*-test [$P(t_{21} \leqslant -2.0808) = 0.025$) nevertheless indicated a significant difference in mean catch between control and emission trials. For trials at ≤118.9 m, the relative change in catch was −47.0% as a result of acoustic emissions ($\mathrm{CI}(-17.8\% \leqslant \mathrm{RC} \leqslant -76.1\%) = 0.90$).

For the five most abundantly caught rockfish species, three species showed significant declines in catch associated with acoustic emissions after adjustment of the mean catches to a common depth (Table 2) (chilipepper, $P(t_{35} \leqslant -1.7341) = 0.046$; bocaccio P, $(t_{37} \leqslant -2.6057) = 0.007$; and greenspotted rockfish, $P(t_{38} \leqslant = 2.1109) = 0.021$)).

The catch of chilipepper showed a cubic response with depth ($P(F_{3,35} > 35.9500) \approx 0$) and bocaccio a linear response ($P(F_{1,35} > 13.5627) = 0.00007$), while no relationship was found between the catch of greenspotted rockfish and trial depth ($P(F_{1,35} > 2.3030) = 0.138$). The decline in CPUE across species strengthens the conclusion that the observed differences are real and are not the result of chance.

Effects on the Cash Value of the Catch

A covariance analysis using a quadratic regression between the cash value of the catch and trial depth was performed (Fig. 5). The adjusted mean of the ln(cash value + 1) for emission trials was significantly lower ($P(t_{36} \leqslant -1.8503) = 0.036$) than the mean value for control trials (Table 2). After adjustment to a mean depth of 109.7 m, control trials had an average cash value of \$51.33 ($\mathrm{CI}(34.27 \leqslant \mu_C \leqslant 76.62) = 0.90$), while emission trials yielded a mean cash value of \$25.78 ($\mathrm{CI}(17.05 < \mu_r < 38.72) = 0.90$). This difference in economic return represents a relative change of −49.8% ($\mathrm{CI}(-21.7\% \leqslant \mathrm{RC} \leqslant -77.9\%) = 0.90$) in the dollar value of fish caught per trial under emission and fishing conditions of this study. This average decline in economic value of the catch takes into account all species caught. For both CPUE and cash value, the estimated declines do not take into account any alternate fishing strategies which might mitigate such losses.

Effects on the Rockfish Aggregations

Two possible covariants used in the analysis of aggregation area were the trial depth and the fraction of pelagic fish in the aggregation as characterized by the catch composition (i.e. chilipepper, bocaccio, and greenstriped (*S. elongatus*), yellowtail, olive (*S. serranoides*), and widow (*S. entomelas*), rockfish) versus primarily demersal fish (i.e., cowcod (*S. levis*) and vermilion, greenspotted, yelloweye (*S. ruberrimus*), flag (*S. rubrivinctus*), canary (*S. pinniger*), starry (*S. constellatus*), rosy (*S. rosaceus*), copper (*S. caurinus*), greenblotched (*S. rosenblatti*), and rosethorn (*S. helvomaculatus*) rockfish). Bank rockfish (*S. rufus*) constituted only 1% of total number of rockfish caught and were not used in the analyses. Because pelagic species were found higher in the water column and were more mobile, it was suspected that this group of fish might respond differently to an acoustic disturbance. However, neither depth ($P(F_{1,37} > 0.6180) = 0.437$) nor fraction of fish which were pelagic ($P(F_{1,37} > 1.630) = 0.210$) was significantly correlated with the change in areal size of the aggregations (Equation 3) between preoperational and operational phases of the fishing trials. Further, the subsequent one-way analysis of variance indicated that no significant treatment effect was associated with any observed changes in the aggregation areal size ($P(F_{1,38} > 0.8084) = 0.374$) between phases of the fishing trials.

One of the more important observations obtained from the chart records is the fact that the aggregation area has tremendous temporal variation. The set of 20 control fishing trials exhibited substantial decreases, as well as large increases, in aggregation area size between preoperational and operational phases. The same observation pertains to emission trials. Under control and emission conditions, the response variable (Equation 3) for areal size had means of 0.1706 and 0.3127, respectively. In other words, an 83% change in the observed response occurred under emission conditions. However, with an error variance of 0.2496, the field study had a power of only $1 - \beta = 0.206$ of detecting a significant effect at $\alpha = 0.10$ with a change as large as the 83% shift observed. Indeed, as many as $n = 260$ replicate trials would be required per treatment to have a power of $1 - \beta = 0.90$ to detect the observed difference of 0.1421 (= 0.3127 − 0.1706, significant at $\alpha = 0.10$). Consequently, a few scattered observations lacking experimental control as in the report by Greene (1985) may result in conclusions which are misleading about the amplitude and direction of the response. This post hoc power analysis indicates that a shift in the areal size of aggregations is an extremely insensitive response variable for detecting the effects of air-gun sounds.

The mean change in aggregation height between trial phases (Equation 3) proved significantly different ($P(F_{1,37} > 2.9501)$

TABLE 2. Unadjusted and adjusted (to a common depth) means of ln(x + 1) based on covariance analysis of the total catch and catch of five rockfish species and cash value with corresponding 90% confidence intervals (CI) and tests of significance.

Response variable	Control			Emission			Test of adjusted means (α)
	Unadjusted mean	Adjusted mean	Adjusted mean 90% CI	Unadjusted mean	Adjusted mean	Adjusted mean 90% CI	
Total catch	3.8300	3.5554	$3.198 \leqslant \mu_C \leqslant 3.913$	2.5694	2.8440	$2.487 \leqslant \mu_E \leqslant 3.201$	0.016[a]
Species catch							
Chilipepper	2.4812	1.8913	$1.509 \leqslant \mu_C \leqslant 2.273$	0.7125	1.3025	$0.921 \leqslant \mu_E \leqslant 3.201$	0.046[a]
Vermilion rockfish	1.3015	1.0759	$0.662 \leqslant \mu_C \leqslant 1.490$	1.2059	1.4315	$1.018 \leqslant \mu_E \leqslant 1.846$	0.835
Bocaccio	1.4019	1.2736	$0.889 \leqslant \mu_C \leqslant 1.660$	1.2736	0.5467	$0.162 \leqslant \mu_E \leqslant 0.931$	0.007[a]
Yellowtail rockfish	0.7432	0.9480	$0.512 \leqslant \mu_C \leqslant 1.384$	0.8890	0.6842	$0.248 \leqslant \mu_E \leqslant 1.120$	0.205
Greenspotted rockfish	1.0461	—[b]	$0.766 \leqslant \mu_C \leqslant 1.326$	0.5505	—[b]	$0.271 \leqslant \mu_E \leqslant 0.830$	0.029[a]
Cash value	4.2328	3.9576	$3.563 \leqslant \mu_C \leqslant 4.352$	3.0122	3.2875	$2.893 \leqslant \mu_E \leqslant 3.682$	0.036[a]

[a] Significant decline ($\alpha \leqslant 0.10$) attributed to acoustic emission.

[b] Unadjusted means used because no significant relationship was found between catch and depth of trial ($\alpha = 0.138$).

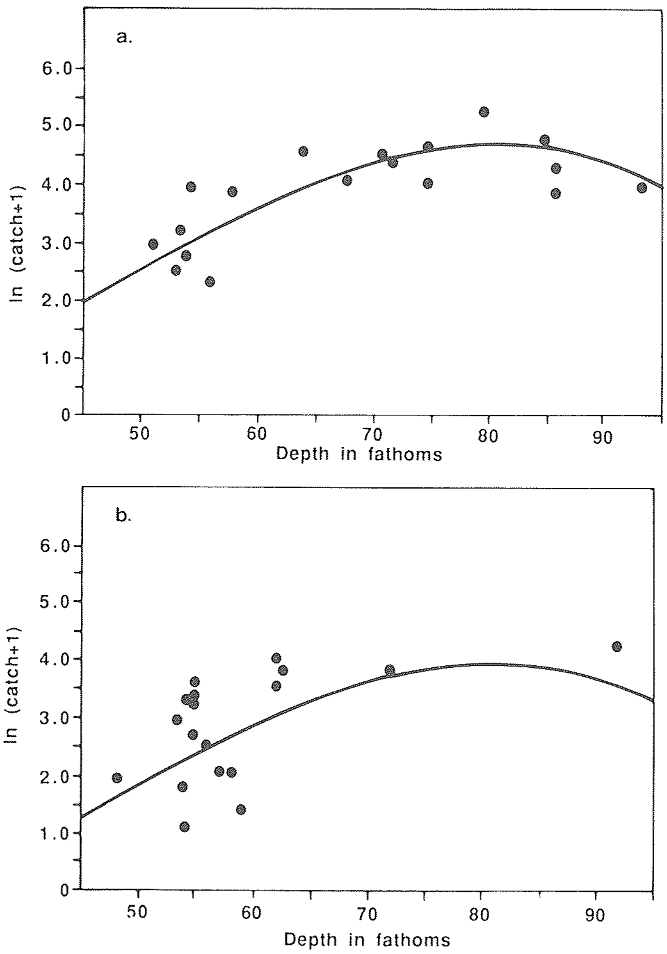

FIG. 4. Regression curves for ln(catch + 1) as a cubic function of the trial depth for (a) control and (b) emission trials. The multiple regression coefficient was $r^2 = 0.534$ for the fitted covariance model.

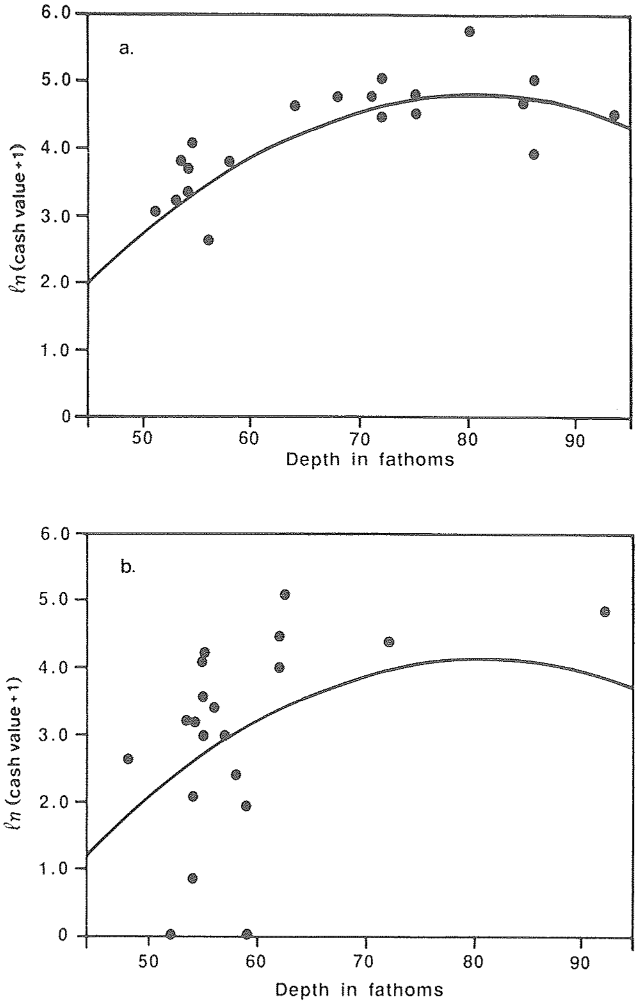

FIG. 5. Regression curves for ln(cash value + 1) as a quadratic function of the trial depth for (a) control and (b) emission trials. The multiple regression coefficient was $r^2 = 0.468$ for the fitted covariance model.

= 0.094) between control and emission trials after adjustment for species composition (i.e. portion of fish which were pelagic). Plots of the relative change in aggregation height (Fig. 6) indicated that under control conditions, there was a tendency for no change in height when the aggregations were composed entirely of demersal species. Alternatively, as the aggregations became more and more composed of pelagic species (e.g. chilipepper), the aggregation height increased by 24% between preoperational and operational phases of the setline fishing (right side of Fig. 6a). In other words, pelagic species like the chilipepper had a tendency to ''flare'' up the setline during fishing, while demersal species tended to be vertically stationary under control conditions (Fig. 6a). Under acoustic emission conditions (Fig. 6b), there was an across-the-board decrease in aggregation height regardless of species composition. As the species composition became entirely composed of demersal species, the height of the aggregations decreased by 26% between phases (left side of Fig. 6b). As the catch became entirely composed of pelagic species, aggregation height decreased by 8% between trial phases (right side of Fig. 6b). This phenomenon could have been masked had there not been rigorous use of control trials during the field experiment.

Discussion

In this study, the simple treatment design of a control and the worst-case scenario (within the limitations of a single air gun), in which the geophysical survey vessel traverses over the fish aggregation, was tested.) The purpose of this treatment design was to verify or refute allegations that sounds from an air gun affect fish catchability. The results substantiate an effect on CPUE under certain circumstances. Under emission conditions, the fishing experiment revealed a substantial ($\hat{RC} = -52.4\%$) and statistically significant ($\alpha = 0.016$) decrease in the catch of rockfish. Significant declines in catch were also observed for three of the five most abundant rockfish species. Further, the results held regardless of whether all fishing trials or only those ≤ 118.9 m were analyzed. The observation of significant decline in several species as well as total catch strengthens the credibility of the findings.

The available evidence suggests that the reduced catchability derived from behavioral changes. Results of the behavioral experiment (Pearson et al. 1992) suggest changes in swimming behavior of rockfish from directed movement to milling or undirected movement (i.e. eddying behavior) at sound levels as low as 168 and 154 dB, respectively. Alarm behavior was exhibited during the behavioral experiment at sound exposure levels over the range of 178–207 dB, with a threshold for startle responses between 200 and 205 dB. Mean peak pressures of 186–191 dB at the base of the rockfish aggregations during fishing trials therefore appear to have been sufficient to elicit changes in swimming and schooling behavior but not sufficient to consistently elicit startle responses. In the fishing experi-

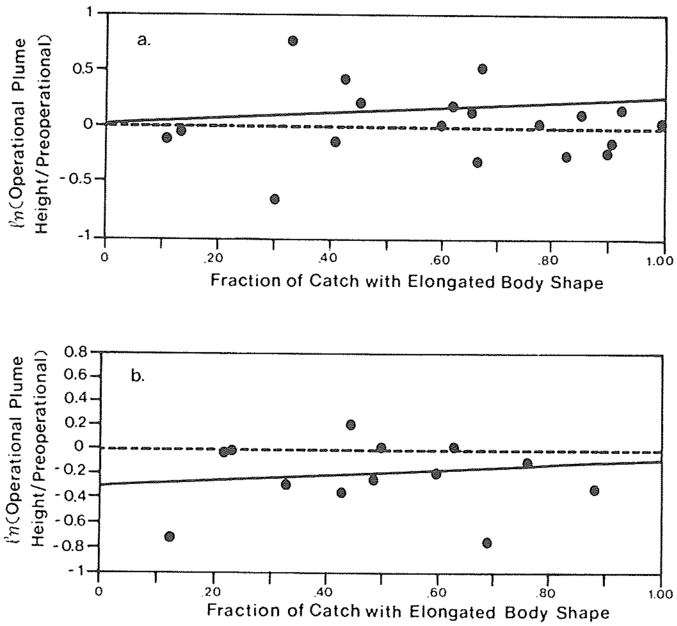

FIG. 6. Regression curves during (a) control and (b) emission trials for ln (operational phase height/preoperational phase height) as a linear function of the proportion of the catch composed of pelagic species (e.g. chilipepper). The multiple regression coefficient was $r^2 = 0.146$ for the fitted covariance model.

ment, height but not the areal size of the aggregations decreased under sound emission, suggesting that fish schools in the water column collapsed toward the bottom but did not disperse from the pinnacles to an observable degree. Had trials been conducted on fish aggregations located along shale banks (fish aggregations at pinnacles tend to be more stationary), dispersal as a response to acoustic emissions might have had a greater contribution to CPUE changes. Under the conditions of the fishing experiment, we suggest that the mechanism underlying the CPUE decline was not primarily dispersal but rather decreased responsiveness to baited hooks.

The length of time after sound exposure that CPUE effects persist is not known. The return of fish to preexposure behavioral patterns occurred within minutes after sound exposures ceased in the behavioral experiment (Pearson et al. 1992), suggesting the effects on fishing may be transitory, primarily occurring during the sound exposure itself. Persistent effects on CPUE would likely occur if the intensity or duration of sound exposure was great enough to elicit dispersal of the fish from the area. The extent or pattern of sound exposure that would elicit dispersal effects has to be determined in future investigations.

Extrapolation of the results of this study to geophysical surveys has some uncertainties because the exposure regime used in this study differs in several aspects from that likely during a typical survey with an air-gun array. Seismic survey vessels conduct operations along tracklines so that the sound level at any given location increases as the vessel approaches, peaks when the vessel is closest, and then decreases as the vessel moves away. This regime of increase, peak, and decrease in sound pressure is repeated as each trackline is performed, and the sound levels at approach, peak, and departure increase or decrease depending on whether the trackline is conducted closer or farther from the location of interest. The fact that the source level for arrays (240–250 dB; Malme et al. 1986) is substantially higher than that for the single air gun used here (223 dB) argues for a greater extent of effects from an array. Although single air guns have the same abrupt signature in all directions, large arrays show the abrupt signature that presumably elicits startle responses (Pearson et al. 1987) only in certain directions from the array (directly ahead, directly behind, directly underneath, and on each side, directly perpendicular to the array center; Malme et al. 1986). The limitation of the abrupt signature in certain directions around the array argues for lesser or more intermittent effects from an array's more intense sounds.

Despite these uncertainties, calculation of the sphere of influence about a typical survey trackline with a larger array suggests that the exposure regime of such a trackline would be similar to that of this study. In this study, during the deployment of the first setline, the rockfish aggregation received sounds above 180 dB from 120 discharges (20 min × 6 discharges/min) within 20 min. Examination of the trends in catch among the setlines indicated that the majority of the observed effect occurred within the deployment of the first setline (Pearson et al. 1987). For a typical array of 65 550 cm^3 with 32 guns and a source level of 255 dB, the sound exposure from a trackline passing directly over a point at a depth of 100 m can be calculated from the sonar equation $S = \mathrm{SL} - 20 \log R$, where S = sound level at the point, SL = source level at 255 dB, R = range in metres, and $20 \log R$ is the transmission loss. For a single tracking passing directly overhead and assuming typical vessel speed 11 km/h) and array discharge rate (6 discharges/min), at 100-m depth, an aggregation would receive sounds from approximately 89 discharges with abrupt signatures and levels above 180 dB within a 15-min period. With the array directly overhead, maximum sound level would be 200 dB at 100-m dpeth, substantially above the maximum of 193 dB produced at the same depth by the single air gun used here. This analysis indicates that sound exposures from a single trackline are sufficiently similar to those of this study to expect changes in rockfish behavior and catchability. Both the fishing experiment discussed here and the behavioral experiment of Pearson et al. (1992) indicate that the decreased responsiveness would derive from the fish exhibiting alarm responses and other behavioral changes under sound exposure.

For surveys with multiple tracklines, sound exposure at a single rockfish aggregation will vary as a function of trackline spacing. For a reconnaissance survey with a trackline spacing of 1.85 km, two to four tracklines would produce sounds above 180 dB at a point 100 m deep. For surveys requiring detailed information on the geological structure, trackline spacing can be as close as 25 or 50 m. For 50-m trackline spacing, about 37 tracklines would contribute sounds above 180 dB to a pinnacle at 100-m depth. Because of the several hours taken to conduct a single trackline, these sounds would occur as 15-min exposures scattered over 4–5 d. The prospects for effects on rockfish catchability from detailed surveys with close tracklines warrant concern.

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