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RESEARCH VESSEL SURVEY DESIGN FOR MONITORING DOLPHIN ABUNDANCE IN THE EASTERN TROPICAL PACIFIC

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ABSTRACT

During 1986 the National Marine Fisheries Service began conducting long-term research ship surveys to determine status of spotted dolphin, *Stenella attenuata*, stocks in the eastern tropical Pacific. This is the main dolphin species taken incidentally by the yellowfin tuna, *Thunnus albacares*, purse seine fishery. We use research vessel survey data collected from 1977 to 1983 to investigate the annual changes in spotted dolphin population size that could be detected given various levels of research vessel survey effort during specified time periods for several levels of statistical error.

We find that two research vessels each operating for 120 days per year for 5 years (six surveys) could detect a 10% annual rate of decrease in dolphin abundance (a total 41% decrease over 5 years) with alpha and beta error levels of 10%. Adding a third vessel would provide better coverage of the dolphins' range, but would allow only a slightly lower rate of decrease to be detected (an 11% annual rate, for a total decrease of 44%). These numbers point out the difficulty of detecting even major changes in spotted dolphin population size with present survey methods. Alternatives are discussed, but all either cost more money, require a longer time to detect a decline, or accept higher levels of statistical error.

The National Marine Fisheries Service (NMFS) has the responsibility of determining the status of dolphin stocks which are taken incidentally by the yellowfin tuna, *Thunnus albacares*, purse seine fishery in the eastern tropical Pacific (ETP) (Richey 1976[4]). The status of spotted dolphins, *Stenella attenuata*, is of special concern since it is the major species taken by the fishery (Smith 1979[5]). Of the spotted dolphins, the northern offshore stock is of more concern since it has been fished more frequently than the southern offshore stock. The spinner dolphin, *S. longirostris*, and the common dolphin, *Delphinus delphis*, are also taken. In addition, the striped dolphin, *S. coeruleoalba*, and the Fraser's dolphin, *Lagenodelphis hosei*, are occasionally caught but are difficult to distinguish from the other three species at a distance (Holt and Powers 1982). These 5 species are herein termed target species.

The NMFS conducted assessments of population status in 1976 (SWFC 1976[6]) and again in 1979 (Smith fn. 5) based on estimates of *absolute* stock abundance. The validity of the absolute estimates depended on several assumptions being met. Unfortunately, some assumptions, such as not allowing systematic errors in data recording or the assumption that dolphin schools do not move prior to being detected by shipboard observers, may not have been met and thus the assessments were not entirely satisfactory. An alternative approach for assessing stock status, therefore, is to use *relative* population estimates to detect trends in stock sizes over a long time period. Relative estimates can provide an assessment of stock condition as long as the biases in the abundance estimates are consistent over the sampling period. Therefore, the NMFS is presently considering using annual estimates of population abundance as relative estimates to detect declines in population size of spotted dolphins during a sampling period of at least 5 years.

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[4]Richey, C. R. 1976. Memorandum of opinion. CA NO. 74-1465 and CA NO. 75-0227 U.S. District Court, District of Columbia, May 11, 1976.

[5]Smith, T. D. 1979. Report of the status of the porpoise stock workshop (August 27-31, 1979, La Jolla, California). Southwest Fish. Cent. Adm. Rep. No. LJ-79-41, 120 p. SWFC La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038

[6]SWFC (Southwest Fisheries Center). 1976. Report of the workshop on stock assessment of porpoises involved in the eastern tropical Pacific yellowfin tuna fishery. Southwest Fish. Cent. Adm. Rep. No. LJ-76-29, 60 p. SWFC La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

Manuscript accepted February 1987.
FISHERY BULLETIN: VOL. 85, NO. 3, 1987.

In this paper, we investigate the annual changes in the size of spotted dolphin populations that can be detected given various levels of research vessel survey effort within specified time periods. We investigate how many research vessels, assuming 120 days searching per vessel per year, would be required to survey the physical area inhabited by the major stocks. We also investigate how many vessels would be required to detect various levels of population declines in spotted dolphins during 5 years or, given fixed number of vessels, how many years of survey effort it would take to detect various population declines or, given fixed number of vessels for fixed number of years, the probability of detecting a decline (i.e., the power). We use historical data and current abundance techniques to predict variability of data which will be collected during the sampling period.

AREA INHABITED AND DATA SOURCES

For our analyses, the study area included the area described by Au et al. (1979)[7] as being inhabited by the target species (Fig. 1). The area north of lat. 20°N was excluded because spotted dolphins do not usually occur there. We partitioned the study area into four strata: the inside, middle, and west strata, which are located north of lat. 1°S, and a south stratum. The three northern strata were collectively termed the north area and all strata were termed the total area. In addition, a calibration area was defined as including part of the inside stratum (Fig. 1).

Data used in our analyses were collected from 1977 through 1983 by scientific observers aboard the NOAA ships *David Starr Jordan* and *Townsend Cromwell*. Survey coverage from the two ships for all years combined was thorough (Fig. 1). Data collected for each school included estimates of dolphin school size, species composition, and line transect observations, which we used to calculate density estimates.

SURVEY COVERAGE

We investigated the physical coverage of the area that is possible when using 1, 2, or 3 ships for

[7]Au, D., W. L. Perryman, and W. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific. Southwest Fish. Cent. Adm. Rep. No. LJ-79-43, 59 p. SWFC La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

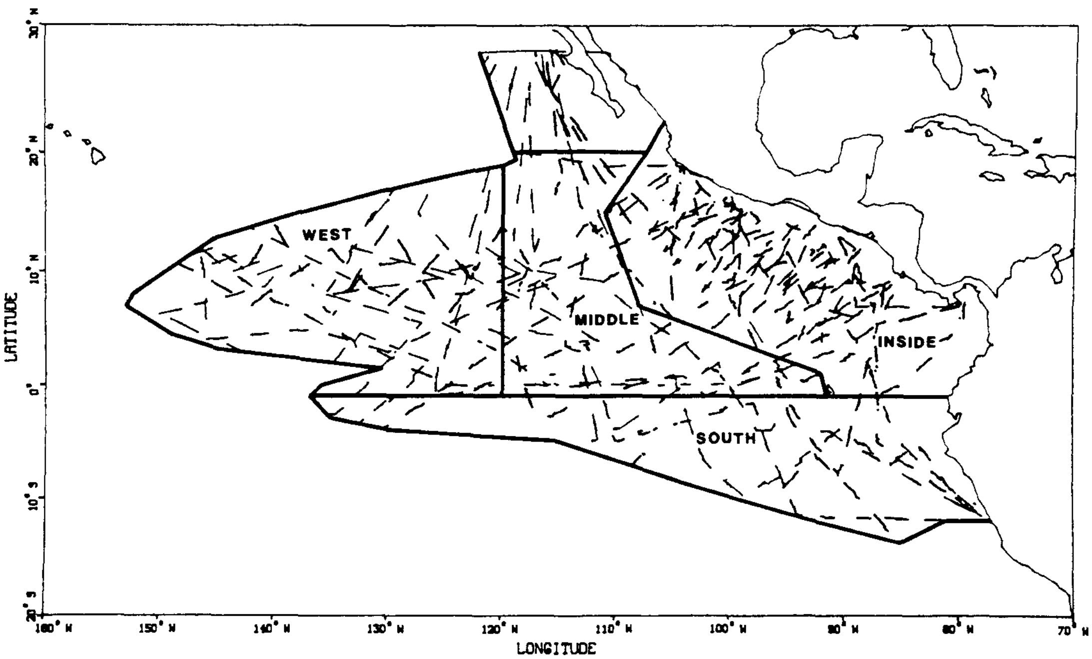


FIGURE 1.—Research vessel tracklines in each stratum during 1977 through 1983.

120 days each by plotting hypothetical tracklines. Approximately 370 km (200 nautical miles) of trackline could be covered in each survey day; with searching restricted to daylight hours, only about one-half of this distance would be searched. Approximately 40,700 km of trackline could be covered by each ship with less than 50% of this distance searched during daylight hours. Each ship's searching distance was allocated to each stratum by the square root of school density in the stratum. Effort of each ship was partitioned into 30-d segments between ports to meet logistical constraints of the vessels. We found that thorough coverage of the entire area was provided when three ships were used, two ships provided adequate coverage, and one ship provided very poor coverage with tracklines separated by large distances (Fig. 2).

DETECTION OF CHANGES IN POPULATION SIZE

Survey Design

The relationship among the number of samples, the rate of change, the precision of the population estimate, and the levels of alpha (type I) and beta (type II) statistical errors for several models of change and sample variability was investigated by Gerrodette (in press). We assumed that population size would change exponentially (constant rate per year). From Gerrodette's equation 15, using slightly different notation,

$$a(a+1)^2(a+2)[\ln(1-r)]^2 \geq 12(Z_\alpha + Z_\beta)^2 \sum_{i=0}^{a} \ln\left[\frac{CV_0^2}{(1-r)^i} + 1\right] \qquad (1)$$

where a = number of years in the survey period,
r = annual rate of decrease,
Z_α = percentile of standardized normal curve for one-tailed Type I error,
Z_β = percentile of standardized normal curve for Type II error, and
CV_0 = coefficient of variation of the population estimate at the present population size.

In this formulation, r is a positive number, and, since the first survey occurs at time 0, the total number of samples (i.e., number of annual surveys) is $a + 1$. Note that the null hypothesis is one-sided, namely, that spotted dolphin abundance is decreasing. In addition to the annual rate of decrease (r), the total population decrease which would occur over the entire survey period was calculated as

$$\text{Total decrease} = [1 - (1 - r)^a].$$

The survey design to detect changes in dolphin abundance was investigated in three ways. Using Equation (1), we computed 1) the minimum number of years (a), given one to three ships per year and 120 searching days per ship per year, required to detect various annual decreases in spotted dolphin abundance; 2) the minimum proportional annual change (r) that could be detected in 5 years given one to three ships per year at various levels of alpha and beta; and 3) power ($1 - \beta$) or the probability of detecting various decreases in population size in 5 years, given one to three ships per year.

To use Equation (1), the relationship of $CV(\hat{N})$, the coefficient of variation of the population estimate, and n, the number of schools detected must be determined. In addition, the rate per day at which dolphin schools are expected to be encountered must be known. We used the 1977–83 research vessel data to investigate these factors assuming these data would be representative of data that we will obtain during the proposed sampling period of 1986–91.

Abundance Estimation

Relative estimates of population abundance of spotted dolphins in the north and total areas were calculated using two methods, methods A and B. In method A, density and mean school size estimates were calculated in each stratum and abundance was determined (Holt and Powers 1982) as

$$\hat{N} = \hat{P}_t \sum_{k=1}^{m} \hat{D}_k \hat{S}_{tk} \hat{P}_k A_k. \qquad (2)$$

In method B, density and mean school size estimates were calculated for data pooled for the entire area (north area or total area) and abundance was determined as

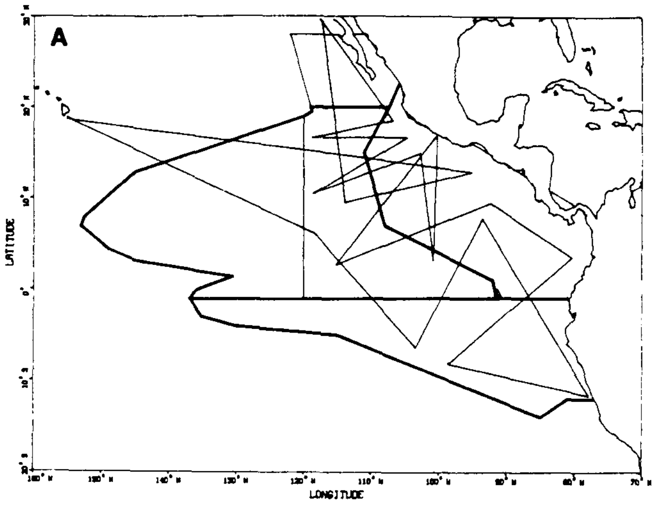


FIGURE 2.—Plot of hypothetical tracklines expected from use of one (A), two (B), or three (C) ships for 120 days each.

$$\hat{N} = \hat{P}_t \hat{D} \hat{S} \sum_{k=1}^{m} \hat{P}_k A_k. \qquad (3)$$

where m = number of strata (3 for the north area and 4 for the total area),

k = 1, 2, 3, or 4 denotes the inside, middle, west, or south stratum, respectively,

$\hat{N}$ = estimated number of spotted dolphins in the survey area,

$\hat{D}$ = density estimate of number of schools of all dolphin species in the survey area (schools/1,000 km^2),

$\hat{D}_k$ = density estimate of number of schools of all dolphin species in the kth stratum (schools/1,000 km^2),

$\hat{S}$ = mean school size estimate for target species in the survey area (number of animals),

$\hat{S}_{tk}$ = mean school size estimate for target species in the kth stratum (number of animals),

$\hat{P}_t$ = proportion of all dolphins that were target species in the survey area,

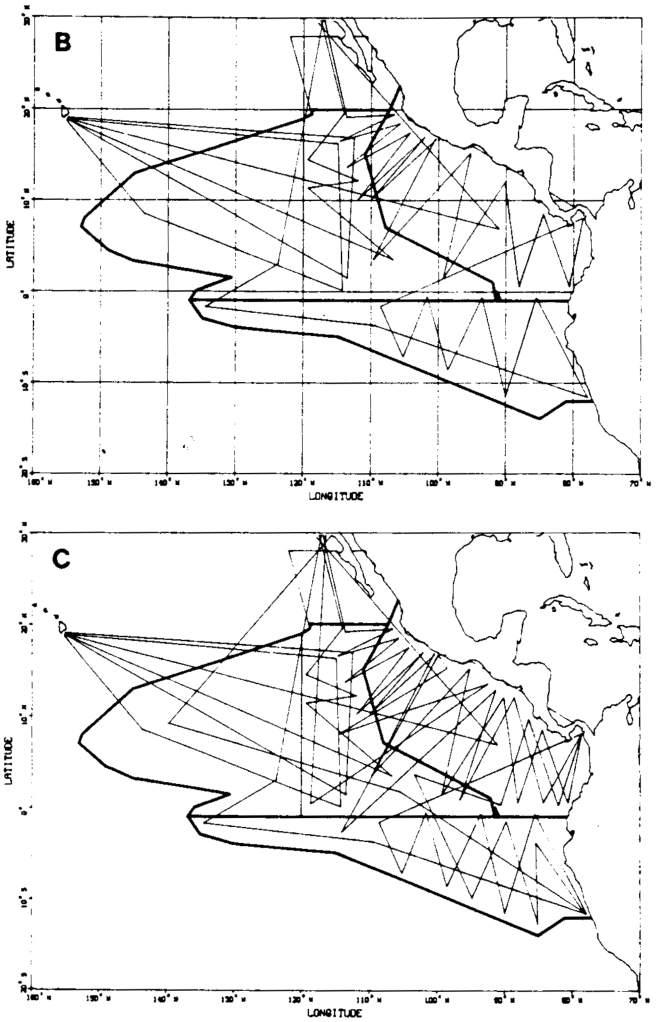
$\hat{P}_k$ = proportion of spotted dolphins in the target schools in the kth stratum, and

A_k = area inhabited by all dolphins in the kth stratum.

The variance of $\hat{N}$ for Equation (2) was estimated using Taylor series expansion (Seber 1973) as

$$\begin{aligned}\hat{\mathrm{Var}}(\hat{N}) = \sum_{k=1}^{m} [&(\hat{S}_{tk} \hat{P}_t \hat{P}_k A_k)^2 \hat{\mathrm{Var}}(\hat{D}_k) \\ &+ (\hat{D}_k \hat{P}_t \hat{P}_k A_k)^2 \hat{\mathrm{Var}}(\hat{S}_{tk}) \\ &+ (\hat{D}_k \hat{S}_{tk} \hat{P}_k A_k)^2 \hat{\mathrm{Var}}(\hat{P}_t) \\ &+ (\hat{D}_k \hat{S}_{tk} \hat{P}_t A_k)^2 \hat{\mathrm{Var}}(\hat{P}_k)] \qquad (4)\end{aligned}$$

The variance of $\hat{N}$ in Equation (3) was determined using Equation (4), but density and school size estimates that were calculated for the entire area



were substituted for the respective stratified estimates.

Specific formulae to estimate variables and associated theoretical variances in Equations (2) through (4) are from Burnham et al. (1980), Holt (1985,[8] in press) and Barlow and Holt (1986). Variances for estimates of school sizes and school densities were calculated using jackknife techniques (Miller 1974).

Since serial correlation among sampling units (days of effort) will yield biased estimates of standard errors using the jackknife method, we analyzed serial correlation of dolphin school detection rates among various combinations of successive days of effort. Analyses indicated that correlation was significant among successive single days but was not significant for periods of 2 or more days. Therefore, the data were grouped by 2-d increments for the jackknife analyses.

Estimates of spotted dolphin population abundance and values used in Equations (2) and (3) to calculate the estimates are presented in Table 1. CV ($\hat{N}$)s were smaller for estimates calculated using method B than for estimates using method A.

[8]Holt, R. S. 1985. Estimates of abundance of dolphin stocks taken incidentally in the eastern tropical Pacific yellowfin tuna fishery. Southwest Fish. Cent. Adm. Rep. No. LJ-85-20, 32 p. SWFC La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

TABLE 1.—School density of all dolphin schools, proportion of all schools which were target schools, mean school size of target schools, proportion of target animals which were spotted dolphins, area of each stratum, abundance and K values for spotted dolphins. SE and CV denote standard error and coefficient of variation, respectively. Methods A and B refer to different ways of pooling data on school size and density (see text).

	Stratum				Area	
Variable	Inside	Middle	West	South	North	Total
School density ($\hat{D}$)						
(Schools/1,000 km^2)	5.33	3.42	0.82	1.93	3.20	3.03
SE ($\hat{D}$)	0.87	1.13	0.30	0.39	0.54	0.51
CV($\hat{D}$)	16.3	33.1	37.2	20.2	17.0	16.8
Prop. target (P_t)[1]	—	—	—	—	0.775	0.775
Mean school size (S_t)						
(Number animals)	108.59	113.89	121.06	157.65	111.62	118.21
SE (S_t)	9.82	11.24	23.28	29.84	7.44	7.92
CV (S_t)	8.6	9.9	19.2	18.9	6.7	6.7
Area (km^2 · 10^6)	4.602	3.764	5.298	4.359	13.664	18.024
Prop. spotted (P_k)[2]	0.38	0.51	0.51	0.26	—	—
SE (P_k)[2]	0.039	0.048	0.048	0.085	—	—
Abundance and K Values						
Method A						
$\hat{N}$ (Animals · 10^6)					1.571	1.839
SE ($\hat{N}$)					0.283	0.294
CV ($\hat{N}$)					0.18	0.16
Sample size (n)					507	602
K					4.05	3.93
Method B						
$\hat{N}$ (Animals · 10^6)					1.761	2.081
SE ($\hat{N}$)					0.240	0.250
CV ($\hat{N}$)					0.14	0.12
Sample size (n)					507	602
K					3.06	2.94

[1]Source Holt (in press).
[2]Source Barlow and Holt (1986).

Relationship Between Var ($\hat{N}$) and Number of Schools Detected

In order to minimize the number of years required to detect a specific trend, Var ($\hat{N}$) should be as small as possible (Gerrodette in press). Var ($\hat{N}$) depends on the variance of the estimates of school size, school density, and proportions of the various dolphin species, as shown in Equation (4). Each of the variances of these estimates, in turn, depends on n, the number of sighted schools. Therefore, the dependence of Var ($\hat{N}$) on n must be known to calculate the number of sightings needed to attain a given level of precision (Var ($\hat{N}$)). We investigated the dependence of each of the individual variance terms on n.

Dependence of Var (S_{tk}), Var ($\hat{P}_t$), and Var ($\hat{P}_k$) on n

Because $\hat{S}_{tk}$ is the mean of n individual school size estimates, its variance is Var ($\hat{S}_{tk}$) = Var (S_{tk})/n where Var (S_{tk}) is the variance of school size. The Var ($\hat{P}_t$) = $P_t(1 - P_t)/n$ where P_t is the true proportion of target schools among all dolphins. Var (S_{tk}) and $P_t(1 - P_t)$ are both constant with respect to n, so Var ($\hat{S}_t$) = $O(1/n)$ and Var ($\hat{P}_t$) = $O(1/n)$, where $O(1/n)$ means "of the same order as $1/n$" and implies that as $1/n$ approaches zero, the variance approaches zero at the same rate. Similarly, Var ($\hat{P}_{ik}$), which is also a proportion, is equal to $O(1/n)$.

Dependence of Vâr ($\hat{D}$) on n

The Vâr ($\hat{D}$), based on replicate tracklines (Burnham et al. 1980), is

$$\widehat{\mathrm{Var}}(\hat{D}) = \hat{D}^2 \left[\frac{\widehat{\mathrm{Var}}(n)}{n^2} + \frac{\widehat{\mathrm{Var}}[\hat{f}(0)]}{[\hat{f}(0)]^2}\right] \tag{5}$$

where n is the number of sightings and $\hat{f}(0)$ is the estimate of the probability density function of perpendicular distances extrapolated to the trackline. First,

$$\hat{\mathrm{Var}}\,(n) = \frac{R \sum_{i=1}^{R} (n_i - \bar{n})^2}{R-1}$$

where R is the number of replicate lines of equal length (l). For R of moderate size, $R \cong (R-1)$. Thus

$$\hat{\mathrm{Var}}\,(n) = \sum_{i=1}^{R} (n_i - \bar{n})^2 = O(\mathrm{R}).$$

This is because $\hat{\mathrm{Var}}\,(n)$ is the sum of the variances of R independent values (n_i, $i = 1, 2, ..., R$) each having the same expected variance. But $R = n/E(n_1)$, the total number of sightings divided by the expected number of sightings for a line of length l. Thus, $R = O(n)$, and

$$\frac{\hat{\mathrm{Var}}\,(n)}{n^2} = \frac{O(n)}{n^2} = O(1/n). \qquad (6)$$

Second, $\hat{f}\,(0)$ was estimated using a Fourier series (FS) model (Burnham et al. 1980); therefore,

$$\hat{\mathrm{Var}}\,[\hat{f}\,(0)] = \sum_{j=1}^{m} \sum_{k=1}^{m} \mathrm{Cov}\,(\hat{a}_j, \hat{a}_k)$$

$$k = 1, 2, 3, ..., \textit{and } k > j > 1$$

where the a's are the coefficients in the series

$$\hat{a}_k = \frac{2}{nw}\left[\sum_{i=1}^{n} \cos\left(\frac{k\pi x_i}{w}\right)\right] = O\,(1)$$

with x_i equal the perpendicular distance to the ith sighting and w equal the truncation point for the perpendicular distance. Therefore, we only need to know the dependence of $\mathrm{cov}(a_j, a_k)$ on n. If n is much larger than one, $(n-1) \cong n$ and

$$\hat{\mathrm{Cov}}\,(\hat{a}_j, \hat{a}_k) = \frac{1}{n-1}\left[\frac{1}{w}\,(\hat{a}_{k+j} + \hat{a}_{k-j}) - \hat{a}_j\,\hat{a}_k\right]$$

$$= O\,(1/n).$$

Since $\hat{f}\,(0)$ estimates a quantity which is constant with respect to n,

$$\frac{\hat{\mathrm{Var}}\,[\hat{f}\,(0)]}{[\hat{f}\,(0)]^2} = O\,(1/n). \qquad (7)$$

Combining Equations (6) and (7) with Equation (5), $[\mathrm{CV}\,(\hat{D})]^2 = O(1/n)$. This confirms discussions presented by Burnham et al. (1980).

In addition to investigating the theoretical dependence of $[\mathrm{CV}\,(\hat{D})]^2$ on n, we tested its empirical dependence on n using the research vessel data which included 479 days of survey effort. Data were truncated at 3.70 km perpendicular distance from the ship. Paired days of shipboard searching effort were randomly selected using a uniform random number generator until the number of associated sightings (n) equaled or exceeded a previously selected sample size. Sample sizes selected were 20, 30, 40, 50, 60, 80, 100, 200, 500, and 1,000. The resultant perpendicular distance distributions were smeared (a data smoothing technique described by Butterworth 1982, Hammond 1984, and Holt fn.8), and density, variance, and coefficient of variation estimates were calculated for each data set. The simulation was completed three times for each value of n.

The relationship between CV ($\hat{D}$) and $1/\sqrt{n}$ (Fig. 3) was linear ($F_{\text{lack-of-fit}} = 0.83$; $P = 0.59$) with intercept not significantly greater than zero ($t = 1.56$; $P > 0.10$). This confirms the analytical result above, that $\mathrm{CV}\,(\hat{D}) = O(1/\sqrt{n})$; however, as n increased, the probability of randomly selecting data from each of the 240 pairs of days (479 survey days) multiple times increased which may

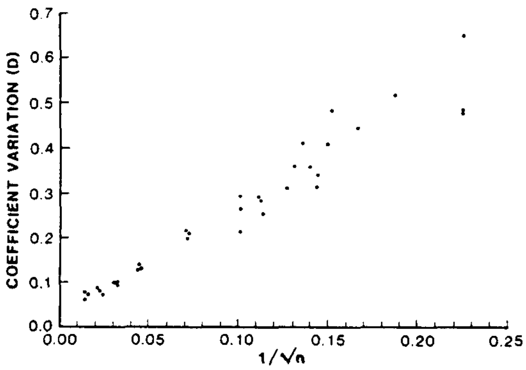


FIGURE 3.—Comparison of number of dolphin sightings ($1/\sqrt{n}$) and precision of the population estimate (CV(D)).

have biased CV ($\hat{D}$) if the distribution of sightings for the days were biased due to the effects of season or area. If we had included more large samples in our simulation, the linear relationship may not have been evident.

Calculation of *K* Values

Because all terms used to calculate Var ($\hat{N}$) equal $O(1/n)$ and Var ($\hat{N}$) is a linear sum of the terms, Var ($\hat{N}$) = $O(1/n)$ or CV ($\hat{N}$) = $O(1/\sqrt{n})$. Therefore, the relationship

$$CV(\hat{N}) = K/\sqrt{n} \tag{8}$$

can be used to determine the change in CV ($\hat{N}$) for various values of n, where K is a constant. This relationship is true if the number of schools sighted is proportional to population size. This seems to be a reasonable assumption, although a more complicated relationship between density and school size, based on dolphin social structure and its interaction with the fishery process, is possible. K values for spotted dolphins in the north and total areas were calculated for methods A and B using the 1977–83 data (Table 1). These K values were then used to determine CV ($\hat{N}$)s for specified values of n which would be expected assuming from one to three annual ship surveys.

Detection Rates

The number of expected sightings with use of one to three ships was calculated by computing detection rates as the average number of dolphin sightings per searching day. A day's searching effort generally consisted of searching from sunrise to sundown; therefore, we assumed most survey days covered approximately the same trackline distance. However, distance searched may vary inversely with rates of detecting dolphin schools because effort is halted so that observers can identify schools and make school size estimates. The number of survey days, and hence number of ships, required to obtain a specified CV ($\hat{N}$) was determined by dividing the number of required sightings by the rate of detecting schools.

Detection rates were caculated separately for data from the *Jordan* cruise and from the *Cromwell* cruise because of the wide disparity in detection rates of dolphins from the two vessels when operating simultaneously in the calibration area (Table 2). The *Jordan* has a much better platform from which to detect dolphins because its observation station was higher relative to the water and because the *Jordan* rode much smoother than the *Cromwell*. Pooled *Jordan* and *Cromwell* detection rates were calculated by standardizing the *Cromwell* rates to *Jordan* rates (Table 2) as

$$DR = \frac{R_j T_j + R_c T_c C}{T_j + T_c} \tag{9}$$

where DR = pooled standardized detection rate for all dolphin schools,

R_j = dolphin schools detected per day by observers aboard the *Jordan*,

R_c = dolphin schools detected per day by observers aboard the *Cromwell*,

T_j = days searched aboard the *Jordan*,

TABLE 2.—Detection rates of all dolphin schools from the *Jordan* and *Cromwell* in the calibration area and pooled standardized detection rates for both vessels combined calculated in each stratum. Standardized detection rates were calculated using the ratio of *Jordan* to *Cromwell* detection rates in the calibration area.

Stratum/area	*Jordan* (*J*) Number of schools (*n*)	Days searched (*D*)	*n*/*D*	*Cromwell* (*C*) Number of schools (*n*)	Days searched (*D*)	*n*/*D*	*J*/*C* ratio of detection rates
Calibration area	102	28	3.643	49	31	1.581	2.304
							Pooled standardized *n*/*D*
1. Inside	237	106	2.24	87	56	1.55	2.70
2. Middle	108	80	1.35	18	22	0.82	1.47
3. West	43	54	0.80	14	56	0.25	0.69
4. South	91	60	1.52	4	5	0.80	1.54
North area (Pooled strata 1-3)	388	226	1.72	119	128	0.93	1.87
Total area (Pooled strata 1-4)	479	282	1.70	123	132	0.93	1.84

T_c = days searched aboard the *Cromwell*, and

C = ratio of schools detected per day by observers aboard the *Jordan* in the calibration area during 1979 to schools detected per day by observers aboard the *Cromwell* in the calibration area during 1979.

The percent of searching days when one to three ships were used was allocated to each stratum (Table 3) by the square root of school density. The number of schools which would be expected to be detected based on the standardized detection rates then was calculated (Table 4).

TABLE 3.—Percent of searching days allocated by square root of density to each stratum in the north and total areas.

Stratum	North area	Total area
Inside	45.6	35.8
Middle	36.5	28.7
West	17.9	14.0
South	—	21.5

TABLE 4.—Number of days searched and number of schools detected per year of effort with use of 1, 2, or 3 ships allocated to the various strata by square root of density.

	North		Total	
Stratum	Number days	Number schools	Number days	Number schools
1 ship = 120 days				
Inside	55	149	43	116
Middle	44	65	34	50
West	21	14	17	12
South	—	—	26	40
Total	120	228	120	218
2 ships = 240 days				
Inside	110	298	86	232
Middle	88	130	68	100
West	42	28	34	24
South	—	—	52	80
Total	240	456	240	436
3 ships = 360 days				
Inside	165	447	129	348
Middle	132	195	102	150
West	63	42	51	36
South	—	—	78	120
Total	360	684	360	654

RESULTS

For either the north or total area, the same decrease in spotted dolphin populations can be detected 2 to 4 years earlier using method B, which uses pooled density and school size estimates, than when using method A, which uses estimates calculated for each stratum (Table 5). This is because large variances associated with the method A population size estimates occur due to small sample sizes in some strata. Therefore, method B was used in subsequent calculations.

The same number of years is required to detect a specific trend if the north or total areas are surveyed (Table 5). This result is true only if the 1977–83 data, which contain small sample sizes in the south stratum, are representative of future data. However, the northern offshore spotted dolphin stock occurs only in the north area and elimination of the south stratum will ensure better coverage of this north area, especially in the west stratum where sample sizes are minimal for applying the Fourier series model (Table 4). Therefore, subsequent calculations were made only for the north area. Annual population estimates for the northern stock would be biased only if substantial variation in the amount of dolphin migration between the north area and south stratum occurred during survey years.

TABLE 5.— Number of years required to detect an annual 5% decrease in spotted dolphin population size using 1, 2, or 3 ships and 2 different methods of pooling data. Method A utilized Equation (2) in text while method B utilized Equation (3). Alpha and beta levels equal 0.05, and effort was allocated to the various strata by square root of density. Number of schools expected to be detected each year determined using detection rates from Equation (9). K determined using Equation (8). CV ($\hat{N}$) denotes coefficient of variation of population abundance estimate.

Stratum	Number ships	Number schools	K	CV ($\hat{N}$)	Years required
North area					
Method A	1	228	4.05	0.27	17
	2	456		0.19	12
	3	684		0.15	11
Method B	1	228	3.06	0.20	13
	2	456		0.14	10
	3	684		0.12	9
Total area					
Method A	1	218	3.93	0.27	17
	2	436		0.19	12
	3	654		0.15	11
Method B	1	218	2.94	0.20	13
	2	436		0.14	10
	3	654		0.11	8

At the 5% error level, only rates of change of 11% per year or greater can be detected in a 5-yr survey period, even using three ships per year (Table 6). This is a rather high rate of decrease,

TABLE 6.—Minimum rates of annual decrease and minimum total decreases in spotted dolphin population size which could be detected in 5 years under different conditions. Changes were calculated for several alpha and beta levels, with a one-tailed test, using 1, 2, and 3 ships, for CV (*N*) determined using jackknife formulae, and data in the north area pooled over all strata (method B).

Number ships	CV (*N*)	Decrease per year	Total decrease
$\alpha = \beta = 0.05$			
1	0.20	0.19	0.65
2	0.14	0.13	0.50
3	0.12	0.11	0.44
$\alpha = \beta = 0.10$			
1	0.20	0.14	0.53
2	0.14	0.10	0.41
3	0.12	0.08	0.34
$\alpha = \beta = 0.20$			
1	0.20	0.09	0.38
2	0.14	0.06	0.27
3	0.12	0.05	0.23

and would lead to a 44% reduction in population size over the 5-yr period. If two or one ship is used, however, the minimum detectable rates of decrease are higher still, 13% and 19%, respectively. When the power of the survey design is considered, the same dilemma is evident (Table 7). Even when three ships are used, the power is acceptably high only if the rate of decrease is at least 10% per year. The probability of detecting a 5% per annum decrease at a 5% alpha level, for example, is only 0.51. This means that with a probability of 0.49 we would conclude that no decrease had taken place, when in fact it had. Power is even less if only one or two ships are used.

Alternatively, we may have either to conduct the surveys for more than 5 years and/or relax the acceptable alpha and beta error level (Table 8). With three ships and 5% error levels, 5 years is sufficient to detect a 10% per annum decline, but 9 years are required to detect a 5% per annum decline and 13 years are required to detect a 3% per annum decline. For alpha and beta levels equal 0.10 or 0.20 and use of three ships, a 5% decrease can be detected in 7 or 5 years, respectively.

TABLE 7.—Power, or the probability of detecting a decrease in spotted dolphin population size during a 5-yr period. Power was calculated for surveys using 1, 2, or 3 ships, for various rates of annual and total population decrease, and for testing the regression of population size against time at various significance levels (α).

Number of ships	CV (*N*)	Rate of decrease per year	Total decrease	Power when α = 0.05	0.10	0.20
1	0.20	0.01	0.05	0.08	0.14	0.26
		0.03	0.14	0.15	0.25	0.41
		0.05	0.23	0.26	0.40	0.57
		0.10	0.41	0.62	0.75	0.86
2	0.14	0.01	0.05	0.09	0.16	0.29
		0.03	0.14	0.22	0.34	0.52
		0.05	0.23	0.42	0.56	0.73
		0.10	0.41	0.87	0.93	0.97
3	0.12	0.01	0.05	0.10	0.18	0.31
		0.03	0.14	0.27	0.40	0.57
		0.05	0.23	0.51	0.66	0.80
		0.10	0.41	0.94	0.97	0.99

TABLE 8.—Number of years required to detect various annual decreases and total declines of spotted dolphins calculated for several alpha and beta levels using 1, 2, and 3 ships. CV (*N*)s were calculated using jackknife formulae and using data in the north area pooled over all strata (method B).

Number ships	CV (*N*)	Decrease per year	Number years required	Total decrease
$\alpha = \beta = 0.05$				
1	0.20	0.01	39	0.32
		0.03	19	0.44
		0.05	13	0.49
		0.10	8	0.57
2	0.14	0.01	30	0.26
		0.03	14	0.35
		0.05	10	0.40
		0.10	6	0.47
3	0.12	0.01	27	0.24
		0.03	13	0.33
		0.05	9	0.37
		0.10	5	0.41
$\alpha = \beta = 0.10$				
1	0.20	0.01	32	0.28
		0.03	15	0.37
		0.05	11	0.43
		0.10	7	0.52
2	0.14	0.01	25	0.22
		0.03	12	0.31
		0.05	8	0.34
		0.10	5	0.41
3	0.12	0.01	23	0.21
		0.03	11	0.29
		0.05	7	0.30
		0.10	5	0.41
$\alpha = \beta = 0.20$				
1	0.20	0.01	24	0.21
		0.03	11	0.29
		0.05	8	0.34
		0.10	4	0.34
2	0.14	0.01	19	0.17
		0.03	8	0.22
		0.05	6	0.26
		0.10	3	0.27
3	0.12	0.01	17	0.16
		0.03	8	0.22
		0.05	5	0.23
		0.10	3	0.27

DISCUSSION

Our analyses indicate that our ability to detect changes in the size of spotted dolphin populations in the eastern tropical Pacific is not very great without substantial long-term ship time. This is not surprising given the vast area of ocean inhabited by the dolphins and the low sighting rate from ships. We feel our results represent a generally accurate picture based on available data. However, the analyses must be qualified by noting that the data used to generate these results were accumulated during all seasons over 5 years. Data collected in the future will come from surveys conducted at the same time each year and may be less variable. In addition, more precise data gathering techniques or data fitting models may become available. If so, these factors would yield greater ability to detect lower rates of decrease, greater power, and lower required number of years. On the other hand, the estimates of expected variance have dealt with survey precision (measurement error) only. If environmental variability is important, data collected in future surveys may be more variable than we have calculated. In long-lived animals with many year classes contributing to reproduction, however, environmental variability will tend to be less important than survey imprecision (Gerrodette in press).

The selection of appropriate alpha and beta errors levels depends on one's perspective. An alpha error would occur if we concluded that a decrease in dolphin abundance was occurring when in fact it was not. It is therefore of interest to the tuna industry to minimize this type of error. A beta error would occur if we concluded that no decrease in dolphin abundance was occurring when in fact it was. It is in the interest of conservation groups to minimize this type of error. As is well known in statistical theory, however, there is a trade off between the two types of error, a decrease in one leads to an increase in the other. In our analyses we have balanced the two types of error by making alpha and beta equal. We have also used a range of equal alpha and beta levels (0.05, 0.10, and 0.20) to illustrate how choice of error level can affect sampling design. Higher tolerance of error leads to lower rates of decrease which could be detected in shorter times, but, of course, one is less sure of the conclusions reached. Thus the choice of acceptable alpha and beta levels to use in detecting changes in spotted dolphin population size is a management decision based primarily on social rather than statistical criteria.

At least two ships are required to provide representative coverage of the survey area. Although use of a third ship provides better coverage, it does not substantially improve detection of population decreases. For alpha and beta levels of 0.05, a 5% per year decrease can be detected in 9 years with use of three ships or 10 years with use of two ships (Table 8). For other alpha and beta levels, use of the third ship only increases our ability to detect specific decreases by about 1 year. Given the annual cost of each ship, it would be more cost-effective to conduct the surveys for an additional year using only two ships. Another strategy is to conduct surveys less frequently than annually. Gerrodette (in press) provides a numerical example of this approach. For parameter values appropriate to spotted dolphins, conducting surveys less frequently than annually (every second or third year, for example) could save substantial ship time, but more years would elapse before a trend was detected.

If a 5% annual decrease in population size occurred, the number of spotted dolphins killed would have to be large. Assuming a spotted dolphin population of 2.5 million animals (Table 1) and disregarding natural mortality and reproduction, approximately 125,000 animals would be killed each year. The estimates of all dolphins taken by the fishery during each of the last few years are only about 40,000 animals per year (Hammond and Tsai 1983). It may be unreasonable to expect annual decreases at the 5% annual level; rather decreases of 3% or 1% per year would be more reasonable. If so, two ships would require at least 14 years to detect the decline (Table 8).

Nonetheless, the number of dolphins actually killed may exceed 40,000 animals per year because dolphin mortality aboard the unsampled trips of U.S. and non-U.S. registered vessels, which is assumed to be similar to that on the sampled trips, may in fact be substantially higher. In addition, the effects of chasing and capturing dolphins several times per year are not estimated in our analyses.

Techniques and data are presented in our paper to determine the optimal number of ships and number of years required to detect decreases in spotted dolphin populations in the eastern tropical Pacific. However, these techniques are applicable to investigate the amount of effort and time required to monitor changes in any appropriate population index for any species where sufficient data exists or can be collected to determine reasonable estimates of coefficient of variation.

SUMMARY

Use of three ships provides excellent physical coverage of the eastern tropical Pacific dolphin area. Coverage using two ships appears adequate while use of one ship yields very sparse coverage.

Assuming alpha and beta levels of 0.05, use of two ships for each of 5 years will only allow us to detect a 13% annual decrease in spotted dolphin abundance. This means that the population could decline by 50% during the survey period before it could be detected. If three ships are used for 9 years, a 5% decrease per year could be detected.

Use of two ships instead of three only decreases our ability to detect specific trends by about 1 year. For alpha and beta levels of 0.05, use of two ships will allow detection of a 5% annual decrease in 10 years, instead of 9 with three ships.

The sampling period may be shortened if larger alpha and beta levels and larger annual decreases are acceptable. For alpha and beta levels of 0.10, use of two ships will allow detection of a 10% annual decrease after 5 years during which a 41% decrease in the population could occur.

ACKNOWLEDGMENTS

We thank J. Barlow, J. Michalski, W. Parks, S. Reilly, G. Sakagawa, S. Sexton, and T. Smith for their constructive reviews of the manuscript. The experimental design benefited greatly from discussions with members of the SWFC PreSOPS panel members including G. Broadhead, K. Burnham, D. Chapman, D. Goodman, and P. Patterson. J. Joy, S. Sexton, and K. Wallace provided computer support, and B. Whalen contributed statistical support.

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