Abstract.–An assessment of the population status of the eastern spinner dolphin (*Stenella longirostris orientalis*) in the eastern tropical Pacific is required by the U.S. Marine Mammal Protection Act (MMPA), because dolphin are killed in the tuna purse-seine fishery. A pooled estimate of abundance from recent (1986–90) research vessel surveys, in combination with estimates of fisheries kills from tuna vessel observer data, was used to estimate the historical (pre-exploitation) population size with a population dynamics model. Estimates of relative population size (current population size divided by historical population size) were calculated by using a range of values for the maximum net recruitment rate and the maximum net productivity level (MNPL). The resulting estimates of relative population size ranged from 0.32 to 0.58, with a best estimate of 0.44 based on available life history data. Estimates of relative population size were all below the value of MNPL used to calculate each estimate. Calculation of confidence limits for relative population size by Monte Carlo simulation showed that the precision of the estimates was sufficient to make a status determination. The results indicated that, as of 1988, the stock of eastern spinner dolphin was depleted as defined by the U.S. MMPA.

Estimation of historical population size of the eastern spinner dolphin (Stenella longirostris orientalis)

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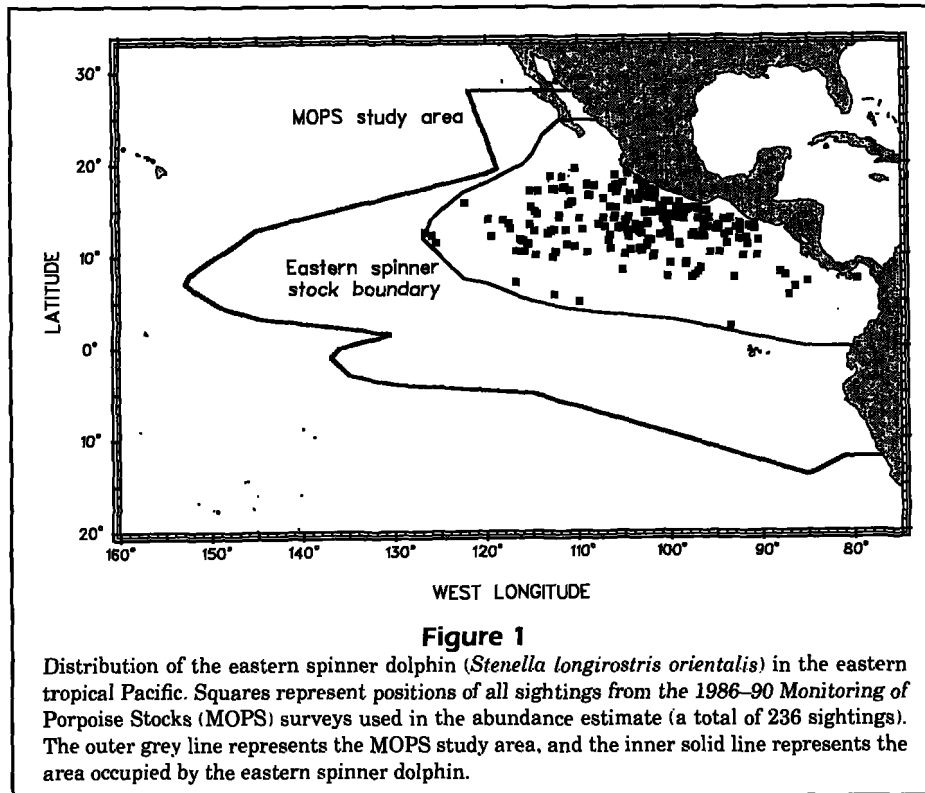La Jolla, CA 92093

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The range of the eastern spinner dolphin, *Stenella longirostris orientalis* (Perrin, 1990), is entirely contained within the eastern tropical Pacific (Fig. 1). An assessment of population condition or status of this stock is required under the U.S. Marine Mammal Protection Act (MMPA), because eastern spinner dolphins are killed in the tuna purse-seine fishery, which includes some U.S. vessels, that occurs in this region. The MMPA requires that each marine mammal population be maintained at an "optimum sustainable population" (OSP) level, which has been defined by the U.S. National Marine Fisheries Service as a population size between the maximum net productivity level (MNPL) and carrying capacity (Federal Register, 21 December 1976, 41FR55536). Therefore, assessing the status of a marine mammal stock involves, if possible, determining if it is above its MNPL. Populations shown to be below MNPL are considered depleted under the MMPA.

One method for determining a population's status relative to MNPL is to estimate historical abundance, meaning abundance prior to significant fisheries mortality, which is assumed equivalent to the equilibrium population size (i.e., carrying capacity). The current population size is then compared with what is thought to be the MNPL for the population, given the estimate of equilibrium population size (Gerrodette and DeMaster, 1990). The

historical abundance of several cetacean populations has been estimated by back-calculating from a current abundance estimate, with a population model and annual records of the number of animals harvested (Reilly, 1981; Breiwick et al., 1980, 1984; Lankester and Beddington, 1986). Smith (1983) described a method for back-calculating historical population size (N_h) for spinner and spotted dolphins (*Stenella* spp.) from estimates of the current population size (N_c), the historical kill in the tuna fishery, the maximum net recruitment rate (R_m), and the maximum net productivity level. He used this technique to estimate historical abundance for the eastern spinner dolphin, resulting in estimates of relative population size (N_c/N_h) for 1979 ranging from 0.17 to 0.25.

An estimate of N_h for a population of spinner or spotted dolphins, which have a relatively low R_m, can be very sensitive to the estimate of N_c, as long as the time period between N_c and N_h is not too great (Smith and Polacheck, 1979). Over a long time period (138 years), the estimate of N_h has been shown to be insensitive to the estimate of N_c for a baleen whale (*Balaena mysticetus*) population with a similarly low R_m (Breiwick and Braham, 1990). However, for a population that has experienced a relatively recent decline from known losses, the estimate of N_h should still be sensitive to the estimate of N_c (Gerrodette and DeMaster, 1990).

Figure 1

Distribution of the eastern spinner dolphin (*Stenella longirostris orientalis*) in the eastern tropical Pacific. Squares represent positions of all sightings from the 1986–90 Monitoring of Porpoise Stocks (MOPS) surveys used in the abundance estimate (a total of 236 sightings). The outer grey line represents the MOPS study area, and the inner solid line represents the area occupied by the eastern spinner dolphin.

For N_c, Smith (1983) used an estimated abundance of 293,000 animals for the eastern spinner dolphin, which was based on combined data from aerial and research vessel surveys conducted in 1979 (Holt and Powers, 1982). Recently, the U.S. National Marine Fisheries Service conducted large-scale research vessel surveys annually for five years (1986–90) as part of the Monitoring of Porpoise Stocks (MOPS) program, resulting in a revised estimate of abundance of 632,700 (Wade and Gerrodette, 1992b[1]). For a number of reasons, discussed below, this estimate should be more reliable (both more precise and less biased) than the 1979 estimate of abundance used by Smith (1983).

This revised abundance estimate was sufficiently different from the 1979 estimate to justify re-estimation of historical population size for the eastern spinner dolphin. Additionally, estimates of the historical kill have also been revised since Smith (1983), although they did not differ greatly from the previous estimates (Lo and Smith, 1986; Wahlen, 1986). Therefore, I estimated the historical population size for the eastern spinner dolphin using the same methods and the same ranges for the parameters R_m and MNPL as Smith (1983), but with revised abundance and fishery mor-

tality estimates. This resulted in new estimates of relative population size for this stock.

Confidence limits for the estimates of relative population size were calculated by using Monte Carlo simulation methods (Buckland, 1984). These confidence limits only incorporated uncertainty due to sampling error of the current population estimate and the mortality estimates. They did not incorporate uncertainty in the model parameters R_m and MNPL. Therefore, confidence intervals were calculated for all parameter combinations.

Population abundance estimate

The MOPS cruises (1986–90) had approximately five times more kilometers of survey effort in the region occupied by eastern spinner dolphins than the 1979 survey. About 75% of the 1979 survey was concentrated within 1,000 km of the coast, whereas the range of the eastern spinner dolphin is up to 2,000 km from the coast (Fig. 1, Perrin et al., 1985). Therefore, the 1979 survey provided little coverage of the western half of the area occupied by eastern spinner dolphin (Holt and Powers, 1982, fig. 1). Raw sample sizes show the large difference in the quantity of data: a total of 285 schools containing eastern spinner dolphins were recorded during the MOPS surveys; a total of only 41 schools, during the 1979 survey. The large increase in

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[1] Wade, P. R., and Gerrodette, T. 1992b. Estimates of cetacean abundance in the eastern tropical Pacific. Paper SC/44/018 presented at the annual meeting of the Int. Whal. Comm., June 1992.

the quantity of data made the MOPS estimates of abundance more precise for this stock, whereas the increased coverage of the stock range reduced the potential bias of geographical variation in abundance.

Both Holt and Powers (1982) and Wade and Gerrodette (1992b[1]) used line-transect analysis methods (Burnham et al., 1980) to estimate abundance. However, the relatively low number of sightings that resulted from the 1979 survey required an analysis technique that pooled sightings of different stocks and species of dolphin to estimate the abundance of each stock (Holt and Powers, 1982). Although the same technique was used initially to estimate annual abundance for the first four years of the MOPS data (Holt and Sexton, 1989, 1990, a and b; Gerrodette and Wade, 1991), the greater number of sightings in each year made this unnecessary. Therefore, to examine trends in abundance, a revised analysis of all five years of MOPS data was undertaken in which annual estimates of abundance for each stock were made only from sightings of that stock (Wade and Gerrodette, 1992a). These estimates were considered to be less biased estimates of abundance than earlier estimates available for eastern tropical Pacific dolphins (IWC, 1992). No significant trend in abundance for eastern spinner dolphins was observed over this short period, but the power of detecting a trend was low (Gerrodette, 1987; Wade and Gerrodette, 1992a). The five annual estimates of abundance for the eastern spinner dolphin ranged from 391,200 to 754,200, with a mean of 588,500.

Wade and Gerrodette (1992a) discussed in detail the differences between their analysis technique and the Holt and Powers (1982) technique, but I will briefly summarize the two major differences here. First, Holt and Powers (1982) calculated a single effective strip width (i.e., 2.0/f(0), Burnham et al., 1980) for all dolphin species, whereas Wade and Gerrodette (1992a) estimated a separate value for each stock. These effective strip widths varied substantially between the different dolphin stocks, ranging from a low of 2.5 km to a high of 11.9 km (Wade and Gerrodette, 1992a), indicating that the Holt and Powers (1982) technique may have introduced considerable bias by pooling across different stocks and species.

Second, Holt and Powers (1982) estimated the abundance of each stock by making a pooled estimate for each species, and then divided the species estimate between the stocks of that species according to the relative size of the area occupied by each stock. For example, an estimate of spinner dolphin abundance was made by pooling sightings of eastern spinner dolphins with sightings of whitebelly spinner dolphins, a different morphological form that is distributed farther offshore and partially overlaps the area occupied

by the eastern spinner dolphin (Perrin et al., 1985, 1991). The abundance estimate for the eastern spinner dolphin was then made by multiplying this pooled estimate by the ratio of the area occupied by the eastern spinner dolphin to the sum of that area plus the area also occupied by the whitebelly spinner dolphin. This approach would only be un-biased if the two stocks had exactly the same density (number of animals per unit area) within their respective stock areas. There is no reason to assume this is true; therefore, an analysis based solely on sightings of eastern spinner dolphin, as in Wade and Gerrodette (1992a), is likely to be less biased.

To obtain a best estimate of absolute abundance, the five years of MOPS data were pooled across years for a second analysis to estimate average abundance for the period for 25 stocks of cetaceans in the ETP, including the eastern spinner dolphin (Wade and Gerrodette, 1992b[1]). The analysis technique of Wade and Gerrodette (1992a) was used, supplemented by a technique for prorating sightings from unidentified categories. Abundance estimate from this analysis should represent the (least biased and most precise) abundance estimate currently available for eastern spinner dolphin, and was therefore used as the starting point for the back-calculations. A summary of the methods and results from that paper for the eastern spinner dolphin has been presented here.

Methods

Pooled (1986–90) abundance estimate

The methods of Wade and Gerrodette (1992a) were mostly repeated but were applied to all five years of data together rather than separately to each year by itself. Population abundance (N) of eastern spinner dolphins was computed by line-transect methods (Burnham et al., 1980) as:

$$N = \sum_{k=1}^{4} N_k,$$ (1)

where

$$N_k = \frac{n_k f_k(0)}{2 L_k} S_k A_k$$ (2)

and

N_k = abundance estimate for eastern spinner dolphins in stratum k,

n_k = number of eastern spinner dolphin schools in stratum k,

$f_k(0)$ = detection function in stratum k, evaluated at zero distance,

S_k = mean school size for eastern spinner dolphin schools in stratum k,

L_k = total effort in stratum k in kilometers,

A_k = total area in stratum k in square kilometers.

This represents a stratified analysis, where only sightings from a stratum were used to calculate the density and, therefore, abundance within the stratum. Abundance estimates for each stratum were summed across the four strata to get a total estimate for the stock. The only change in methodology from Wade and Gerrodette (1992a) involved the calculation of f(0). In that analysis, f(0) was estimated by pooling across strata because of inadequate sample sizes in each stratum in each year. With the larger sample sizes available from pooling the five years of data, there were enough sightings in the inshore and middle strata (Wade and Gerrodette, 1992a; fig. 1) to estimate f(0) independently in each stratum. A third stratum (west) on the edge of the stock area had only four sightings, so a single pooled estimate of f(0) was estimated for the middle and west strata. As expected, because it was outside of the range of eastern spinner dolphin (Perrin et al., 1985), there were no sightings in the fourth stratum (south). A hazard rate model (Buckland, 1985) was fit to the data to estimate f(0). The perpendicular distances were truncated at 5.5 km, because not all dolphin schools further than 5.5 km perpendicular distance were pursued for species identification and school size estimation.

Eastern and whitebelly spinner dolphins partially overlap in range, but can be distinguished from each other by their color pattern and morphology (Perrin, 1990; Perrin et al., 1991). Out of 134 sightings of spinner dolphins in the area of overlap between the two stocks, 16 were, for various reasons, unidentified to stock. Those sightings were prorated to the eastern stock of spinner dolphin by using the estimated proportion of spinner dolphin in the overlap area from the eastern stock (Wade and Gerrodette, 1992b[1]). Similarly, sightings of unidentified dolphins were prorated to the eastern stock, based on the estimated proportion of dolphins from the eastern stock in each stratum (Wade and Gerrodette, 1992b[1]). The prorated portions of unidentified spinner dolphin and unidentified dolphin were added to the original estimate to give a final estimate of abundance. The standard error of the abundance estimate was calculated by bootstrap methods (Efron, 1982), by using legs of effort as the resampling unit, with 1,000 iterations.

Fisheries kill estimates

Estimates of dolphin kill from the tuna fishery in the ETP have been revised since Smith (1983). Lo and Smith (1986) presented revised kill estimates for 1959–1972, and Wahlen (1986) presented revised kill estimates for 1973–1978, in each case with associated standard errors. Additionally, kill estimates for 1979–87, with associated standard errors, have been published (IATTC, 1989). However, Lo and Smith (1986) reported total dolphin kill and did not divide it into stock categories, while Wahlen (1986) reported kill estimates by stock, but only for the U. S. tuna vessel fleet. Therefore, I divided the estimates of Lo and Smith (1986) to stock by the same stock proportions used in Smith (1983). I adjusted the estimates of Wahlen (1986) using the estimated total number of sets, as reported in Punsly (1983). Wahlen (1986) reported the estimated number of sets by the U.S. fleet. I multiplied the kill estimate in each year from Wahlen (1986) by the ratio of the sets made by the entire fleet to the sets made by the U.S. fleet to produce an estimate of the total number of eastern spinner dolphins killed in each year. This assumes that the kill rates of the unobserved international fleet were the same as the U.S. fleet.

Population model

The methods of Smith (1983) were duplicated, by using the simple recursive relationship

$$N_{t+1} = N_t - K_t + R_t \left(N_t - \tfrac{1}{2} K_t \right), \qquad (3)$$

where

N_t = population abundance in year t

K_t = fisheries kill in year t

R_t = net recruitment rate in year t.

Density-dependence is incorporated into the equation through the net recruitment rate, which is defined as

$$R_t = R_m \left[1 - \left(\frac{N_t}{N_h} \right)^z \right], \qquad (4)$$

where

R_m = maximum net recruitment rate

z = shape parameter that sets the maximum net productivity level (MNPL)

N_h = historical population size (assumed to be the equilibrium population size).

For any value of R_m and MNPL, z can be calculated as in Polachek (1982). Equation 1 can be solved for N_t as a function of N_{t+1}, R_t, and K_t. Therefore, by specifying an initial population size, the number of animals killed in each year, the maximum net recruitment rate, and the maximum net productivity level, these two equations can be iteratively solved for N_h.

Estimates of R_m and MNPL

Values used by Smith (1983) for R_m were 0.0, 0.03, and 0.06, which he thought to encompass the range of possible values of R_m for spinner dolphins. No direct estimate of net reproductive rate (R) exists for eastern spinner dolphins because of the difficulty in estimating survival rates. The calving interval is approximately three years (Perrin and Reilly, 1984). The age of sexual maturity (ASM) has been reported as five years (Perrin and Henderson, 1984). However, a new study using a much larger data set estimated ASM for the eastern spinner dolphin to be approximately 10 years, by using data collected from 1974 to 1990[2]. This is similar to the estimate of approximately 11 years for the congener northern spotted dolphin, *Stenella attenuata* (Chivers and Myrick, 1991[3]; Myrick et al., 1986), which is found in the same region of the eastern tropical Pacific.

There are no estimates of survival rates for eastern spinner dolphin. Therefore, estimating the net reproductive rate for eastern spinner dolphin required using estimates of survival rates from another species. Among the best estimates of survival rates for a delphinid come from a long-term study of known individuals of a coastal population of *Tursiops truncatus*, with estimates of adult and calf survival of 0.96 and 0.80, respectively (Wells and Scott, 1992). From Reilly and Barlow (1986), those survival rates in combination with a calving interval of three years and an ASM of nine years resulted in an R of 0.03, which could be considered the best estimate of R for the eastern spinner dolphin. Those survival rates may be low, however, because the Wells and Scott (1992) study was of a population that was thought to be at equilibrium, as it had been relatively constant in abundance for many years. Using the maximum survival rates considered by Reilly and Barlow (1986) with the same calving interval (3 yr) and ASM (9 yr) results in an R of 0.05. If the eastern spinner dolphin was well below half its equilibrium population size in 1979 (Smith, 1983), then its net reproductive rate should have been very close to its maximum, R_m. For this paper I therefore considered 0.04 as the best estimate of R_m currently available for the eastern spinner dolphin, with 0.06 the greatest value of R_m possible. Therefore, the same range of values as in Smith (1983) was used for R_m, ranging

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[2]Susan Chivers, Southwest Fish. Sci. Cent., La Jolla, CA. Pers. commun.

[3]Chivers, S. J., and A. C. Jr. Myrick. 1991. Comparison of age at sexual maturity for two stocks of offshore spotted dolphins subjected to different rates of exploitation. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038. Admin. Rep. LJ-91-31, 19 p.

from 0.00 to 0.06 by increments of 0.002, for a total of 31 values.

Values used by Smith (1983) for MNPL were 0.50, 0.65, and 0.80 (MNPL is expressed as a fraction of equilibrium population size in this paper), corresponding to z values (see Eq. 4) of 1.0, 3.482, and 11.216, respectively. These encompassed the range of actual values of MNPL for long-lived marine mammals, such as dolphins, based on work by Fowler (1981). No direct estimate of MNPL exists for the eastern spinner dolphin. Fowler (1984) gave evidence that MNPL was greater than 0.50 for cetaceans. A value of 0.60 is currently being used for management of cetaceans under the U.S. MMPA (Federal Register, 31 October, 1980, 45FR64548), and for this paper, will be considered the best working value of MNPL currently available for the eastern spinner dolphin. Values of z were used so that MNPL ranged from 0.50 to 0.80 (the same range as in Smith, 1983), by using increments of 0.01, for a total of 31 values. The exact value of z necessary to give the specified MNPL for any value of R_m was calculated as in Polachek (1982).

The 31 values used for both R_m and MNPL produced a total of 961 parameter combinations for which relative population size was estimated. This large number of parameter combinations allowed the calculation of contours for the estimate of relative population size as a function of the 2 parameters of the model.

Confidence limits for N_h

For every combination of the parameters R_m and MNPL, confidence limits for relative population size were calculated by a Monte Carlo simulation (Buckland, 1984) which incorporated the sampling error of the current abundance and kill estimates. On each of 1,000 iterations, an artificial data set was randomly generated by sampling values for the current abundance and for the fisheries kill in each year. These values were each drawn from Gaussian distributions with means and variances equal to the appropriate point estimates. Relative population size was then estimated for each of these artificial data sets, and 95% confidence limits for relative population size were calculated using the percentile method (Efron, 1982).

The kill estimates for 1959–1972 were not independent from each other, as Lo and Smith (1986) estimated the kill in each year by multiplying an average mortality-per-set for 1959–1972 by the number of fishing sets in each year. Therefore, on each simulation iteration the kill values for 1959–1972 were randomly generated with the same random deviate. This resulted in the kill values for those years being perfectly correlated amongst themselves from simulation

trial to trial, which correctly reflected the lack of independence in the actual estimates. The kill values for all other years were sampled independently.

Results

Estimates of abundance and kill

The five years of the MOPS surveys resulted in 236 sightings of eastern spinner dolphins used in the abundance estimate. The abundance estimate based solely on these sightings was 568,100. Adding prorated numbers of unidentified spinner and unidentified dolphin sightings resulted in a final estimate of 632,700, with a CV of 0.167 (Table 1). The fisheries kill estimates ranged from a high in 1961 of 138,000 to a low in 1983 of 700 (Table 2).

Contours of relative population size (N_c/N_h) as a function of R_m and MNPL ranged from 0.35 to 0.55 (Fig. 2). Relative population size increased with both R_m (growth rate) and MNPL (the amount of non-linearity in the density-dependence response). The lowest relative population size was 0.32, for the case of R_m=0.00, (i.e., no net growth in the population before fisheries kill was included). The highest relative population size was 0.58 for the case of the highest growth rate and MNPL (0.06 and 0.80, respectively). These low and high estimates of relative population size correspond to estimates of pre-exploitation abundance of 1,956,000 and 1,100,000, respectively. Relative population size increased by approximately 0.03 for every increase of 0.01 in R_m. The influence of MNPL was greater at higher growth rates, as relative population size increased by approximately 0.02 for every increase of 0.10 in MNPL at R_m=0.02, but increased by approxi-

mately 0.05 for every increase of 0.10 in MNPL at R_m=0.06. There were no combinations of parameter values such that relative population size was estimated to be above MNPL.

The upper 95% confidence limit for relative population size as a function of R_m and MNPL, based on the sampling error of the abundance and kill estimates, ranged from 0.45 to 0.91 (Fig. 3). The upper confidence limit was always above MNPL when R_m was greater than 0.046 (Fig. 3, shaded region). The lower 95% confidence limit for relative population size as a function of R_m and MNPL, ranged from 0.22 to 0.36 (Fig. 4).

All population trajectories declined until 1973 (Fig. 5), after which the estimated fisheries kill declined substantially (Table 2). For the highest growth rate, the population trajectory showed an increasing trend from 1976 to 1988 (Fig. 5, line C), whereas for the lowest growth rate the model resulted in a relatively stable population level between 1976 and 1988 (Fig. 5, line A).

The confidence limits around relative population size broadened with increasing R_m. For example, for a MNPL of 0.60, the confidence limits ranged from 0.23 to 0.44 for R_m=0.00, whereas they ranged from 0.33 to 0.72 for R_m=0.06 (Fig. 6). As in Smith (1983), relative population size was a linear function of R_m.

Discussion

For all parameter values of R_m and MNPL equal to those in Smith (1983), estimates of relative population size were higher in this analysis. For example, for R_m=0.03 and MNPL=0.65, Smith (1983) reported a relative population size of 0.20 versus a result of 0.42

Table 1

Estimate of abundance (in thousands of animals) of the eastern spinner dolphin (*Stenella longirostris orientalis*) from the Monitoring of Porpoise Stocks surveys (1986–90). Strata are identified in Figure 1.

	Abundance estimates			
	Total	Inshore	Middle	West
From eastern spinner dolphin schools	568.0	364.8	160.2	43.1
Prorated from unidentified spinner dolphins	15.4	9.0	6.0	0.4
Prorated from unidentified dolphins	49.2	37.5	10.9	0.8
Final estimate	632.7			
Standard error	105.7			
Coefficient of variation	0.167			
Upper 95% confidence limit	778.9			
Lower 95% confidence limit	403.2			

Table 2

Estimates of fisheries kill in thousands by year for the eastern spinner dolphin (*Stenella longirostris orientalis*). CV is the coefficient of variation of the kill estimate. Sources for the estimates are 1) 1959–72 from Lo and Smith (1986), using the stock proportions of Smith (1983); 2) 1973–78 from Wahlen (1986), adjusted for number of sets of total fleet in Punsly (1983); 3) 1979–87 from IATTC (1989). See text for explanation.

| Year	Mortality	CV
1959	14.3	0.32
1960	124.3	0.31
1961	138.8	0.28
1962	56.2	0.25
1963	62.4	0.22
1964	101.4	0.20
1965	119.6	0.20
1966	97.2	0.15
1967	66.8	0.16
1968	59.5	0.15
1969	106.0	0.15
1970	107.4	0.15
1971	58.4	0.17
1972	87.4	0.16
1973	18.4	0.16
1974	17.8	0.11
1975	17.1	0.11
1976	14.7	0.12
1977	1.8	0.12
1978	1.1	0.11
1979	1.5	0.24
1980	1.1	0.20
1981	2.3	0.28
1982	2.6	0.33
1983	0.7	0.38
1984	6.0	0.52
1985	8.9	0.16

here. The different results must be due to either the use of revised estimates of abundance and kill or the use of 1988 as a starting point rather than 1979; these were the only differences between the analyses. As will be shown, most of the difference resulted from the higher estimate of current population size, although the lower revised kill estimates also contributed to a higher estimate of relative population size. Repeating the back-calculation of Smith (1983) from 1979, but using revised population and kill estimates, resulted in nearly the same estimate of relative population size as reported here. For example, for R_m=0.03 and MNPL=0.65, back-calculating from 1979 as opposed to 1988 resulted in an

estimate of relative population size of 0.41 versus 0.42, whereas Smith (1983) reported a value of 0.20. An inspection of the population trajectories (Fig. 5) confirms that the difference was not due to the different starting year, as the model trajectories, except at the highest growth rates, indicated little change in the population size between 1979 and 1988. This also agrees with the independent results of Buckland et al. (1992), which indicated little difference in relative population size between those two years. Therefore, the difference in the results reported here and those of Smith (1983) should not be interpreted as a recovery in the population between 1979 and 1988. These new, higher estimates of status should instead be interpreted as a revision of the estimate of relative population size, due mostly to the improved abundance estimate available from the MOPS surveys.

The new estimates of relative population size, although higher than Smith (1983), are still below MNPL for all parameter combinations. Because the parameter values used encompassed those values possible for a spinner dolphin (Reilly and Barlow, 1986), this result indicated that, as of 1988, the eastern spinner dolphin was still well below its 1959 population size. With R_m=0.04 and MNPL=0.60, the population was estimated to be at 44% of its historical size. Even with the maximum value of R_m of 0.06, the population in 1988 was estimated to be 43% (MNPL=0.50) to 58% (MNPL=0.80) of its size in 1959. However, careful consideration must be given to several issues before accepting these results as valid. These issues include the precision (reflecting the precision of the abundance and kill estimates) and potential biases (reflecting either biased abundance and kill estimates or mis-specification of the model) of the result, and the quality of pre-1972 fisheries kill data.

Precision

The precision of the estimates of relative population size was investigated by simulation to explore the uncertainty of the results due to sampling error, under the assumptions that the population model and parameter values were true. This addresses the question of how likely the estimates of relative population size were below MNPL if the true relative population size was above MNPL, solely because of variability associated with sampling the current abundance and fisheries kill estimates. The upper 95% confidence limit of relative population size was below MNPL for the majority of the parameter combinations, moving above MNPL only for values of R_m greater than 0.018 (Fig. 3). If MNPL was assumed to be 0.60, then the upper 95% confidence limit of relative population size was only above MNPL for values of R_m greater than 0.034 (Fig. 3). The upper confidence limit was always above MNPL if R_m was at least 0.046. Viewed in a hypothesis testing context, this result indicated that the null hypothesis that relative population size was greater than MNPL in 1988 could be rejected for most of the parameter combinations. Only at higher growth rates could this hypothesis not be rejected. From sampling error alone, it was equally possible that the population was actually worse off than estimated, as the lower 95% confidence limits go as low as 0.22, and were as low as 0.28 even at the highest growth rate of R_m=0.06.
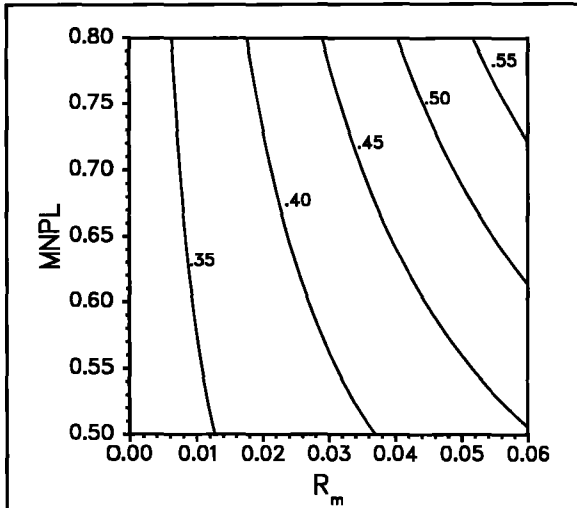
Figure 2

Contours of relative population size (current abundance divided by historical abundance) for the eastern spinner dolphin (*Stenella longirostris orientalis*), as a function of maximum net recruitment rate (R_m) and maximum net productivity level (MNPL).
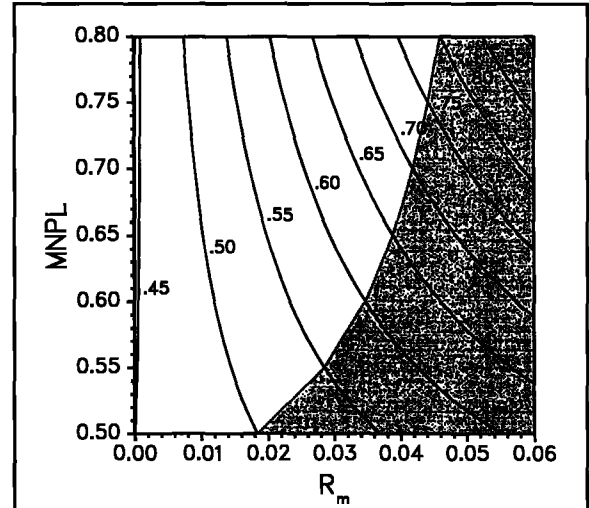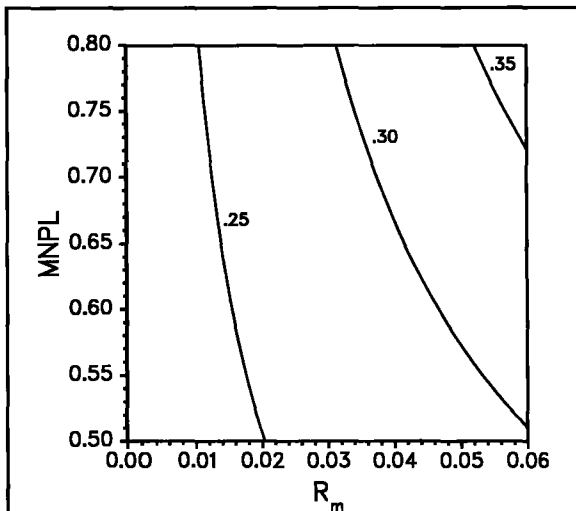

Figure 3

Contours of the upper 95% confidence limit for relative population size for the eastern spinner dolphin (*Stenella longirostris orientalis*), as a function of maximum net recruitment rate (R_m) and maximum net productivity level (MNPL). The shaded region represents the area where the confidence limit was above MNPL.

The confidence limits around relative population size were not much greater proportionally than the confidence limits around N_c (Fig. 6). For example, from the simulation the confidence limits for relative population size with values of 0.04 for R_m and 0.60 for MNPL were 0.29–0.62, representing a coefficient of variation

(CV) of 19%, whereas the CV of N_c was 17% (Table 1). Although one might have expected the precision of the estimate of relative population size to be much less than the precision of N_c, this was not the case because of the independence of most of the kill estimates. Sampling variance in the kill estimates would therefore
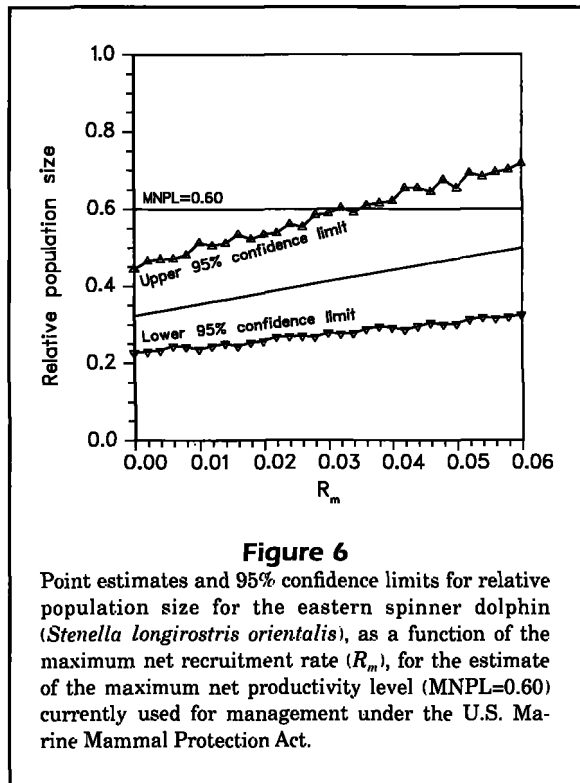

Figure 4

Contours of the lower 95% confidence limit for relative population size for the eastern spinner dolphin (*Stenella longirostris orientalis*), as a function of maximum net recruitment rate (R_m) and maximum net productivity level (MNPL).
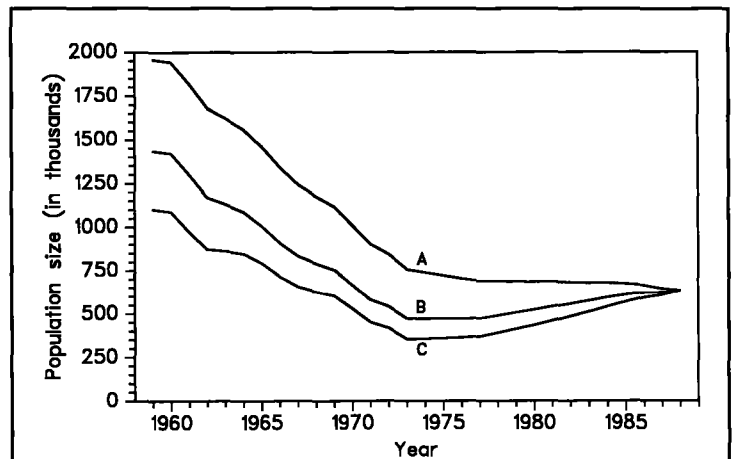
Figure 5

Population model trajectories for the eastern spinner dolphin (*Stenella longirostris orientalis*) for three different parameter combinations of maximum net recruitment rate (R_m) and maximum net productivity level (MNPL): (A) R_m=0.00 and MNPL=0.50, (B) R_m=0.04 and MNPL=0.60, and (C) R_m=0.06 and MNPL=0.80. A and C represent the lowest and highest estimates of relative population size, respectively. B represents the combination of the best estimates for the parameters based on available life history data.

Figure 6
Point estimates and 95% confidence limits for relative population size for the eastern spinner dolphin (*Stenella longirostris orientalis*), as a function of the maximum net recruitment rate (R_m), for the estimate of the maximum net productivity level (MNPL=0.60) currently used for management under the U.S. Marine Mammal Protection Act.

1979–1986 data from Mexico (Edwards, 1989), a major component of the fishery whose kill rates may have been higher than average during that time period. These biases would lead to under-estimates of kill and thus over-estimates of relative population size.

Additional sources of bias existed in the pre-1972 kill estimates, because of both a lack of observations of mortality-per-set (MPS) in many years and because the MPS data prior to 1971 were not collected as part of a systematic observer program. Data on the number and types of sets were collected in every year, starting in 1959 (Punsly, 1983), but an observer program for collecting MPS data was not started until 1971 and random placement of observers until 1972 (Edwards, 1989). The moderate amount of MPS data collected in 1971 was potentially biased because most of the boats with observers were smaller and older, and may have had a higher MPS (Edwards, 1989; Lo and Smith, 1986, table 1). Most of the pre-1971 data were from scientists who were on the tuna boats for the purpose of collecting dolphin specimens, but who also recorded MPS data on their own initiative (Smith and Lo, 1983). There is no obvious reason why tuna vessels that agreed to allow scientists to collect specimens during their fishing operations would tend to have different mortality rates, but in a strict sense these were not random samples of fishing trips. Data from one fishing trip in 1964 were recorded and reported by a fisherman, who may have done so because of the magnitude of the kill, making those data potentially biased (Smith and Lo, 1983). However, the MPS data did not differ greatly in those years from the data collected in 1972 (Lo and Smith, 1986, table 1). Because of this and the greater quantity of MPS data available from 1972, estimates of 1959–1972 fisheries kill made by multiplying the average 1972 MPS rate by the number of sets in each year would not differ greatly from the estimates used here from Lo and Smith (1986), which were made by using the pooled 1964–1972 MPS rate.

Therefore, the fisheries kill would only have been over-estimated if the MPS in the pre-1971 unobserved years was lower than in 1972. However, MPS has consistently declined over time, declining most rapidly following the passage of the Marine Mammal Protection Act in 1972 (Smith 1983). No evidence exists that MPS could have been lower from 1959 to 1970 than it was in 1971–72. MPS may have been higher, especially before use of the back-down procedure had become widespread and well practiced (Perrin, 1969; Edwards, 1989). If it is assumed that MPS has only declined since the beginning of the fishery, the 1959–1970 kill estimates of Lo and Smith (1986) were likely under-estimates of the true kill. Thus, the major sources of bias in fisheries kill estimates all suggest that kill estimates were negatively biased.

Bias in the estimate of abundance could also bias the estimate of relative population size. Wade and Gerrodette

tend to cancel itself, as over-estimates of kill in some years would be balanced by under-estimates in other years. However, systematic bias in the kill estimates would lead to a poor estimate of relative population size, creating a relatively precise yet inaccurate estimate. The same would be true for bias due to the use of an inappropriate model, or in the estimate of N_c. Potential biases in these three areas must therefore be considered.

Bias

Two major sources of bias may have existed in the fisheries kill estimates from 1972 to the present. One source of bias, that of observer effects, has been demonstrated and implies that less dolphin kill occurred on observed trips due to modifications in fishing behavior in response to the observer's presence (Wahlen and Smith, 1985). Unfortunately, there is no way to estimate the magnitude of the effect. The second potential source of bias was the lack of participation in data collection by some countries during some years, especially if significant differences in kill rates existed between countries. Most important may have been the lack of

(1992a) discuss a number of sources of potential bias when applying line-transect theory to the MOPS survey data. Several potential sources of bias do not appear to have a major effect. Independent observer experiments indicate that few schools (and no large schools) were missed on the trackline (Wade and Gerrodette, 1992a). Aerial photographs have confirmed that little bias has been introduced by the observer's estimate of school size (Gerrodette and Perrin, 1991[4]). One partially unresolved issue is that of vessel avoidance by dolphin schools, which would bias the estimate downwards, although this may not have been a major problem (Au and Perryman, 1982; Hewitt, 1985). Additionally, mean school size is likely over-estimated owing to the decreased probability of detection of small schools at larger perpendicular distances (Drummer and McDonald, 1987). Although some stocks in the MOPS surveys appeared to be biased by as much as 20% by this problem, the eastern spinner and other stocks were not (Wade and Gerrodette, 1992a). Finally, the distribution of the eastern spinner dolphin is well known (Perrin et al., 1985) and is well within the MOPS study area (Fig. 1), so it can be concluded that the abundance estimate applies to the entire population. Therefore, the estimate of abundance did not contribute any major bias to the estimate of relative population size.

Bias may also have been introduced by assuming that the simple model specified in Equation 3 correctly models eastern spinner population dynamics, although a simulation study has shown that a simple model can perform as well as a more complex model for this type of analysis (Lankester and Cooke, 1987). The most important feature of eastern spinner population dynamics for this analysis is their inability to undergo large increases in population size from one year to the next. Their relatively low maximum population growth rate, which is due to the biological constraints of their life history discussed above, was incorporated into Equation 3 by using only biologically plausible values of R_m. The only way in which the actual population could have substantially differed from the model would be if the population had a much lower growth rate than expected in some years. For example, large interannual variations in oceanographic conditions related to El Niño events in the eastern tropical Pacific (Fiedler et al., 1992) may lead to large changes in the quantity of prey available for the dolphins. This could lead to lower growth rates in some years, which would cause

the specified model to over-estimate relative population size.

Of more concern is the lack of age-structure in the model (Goodman, 1984[5]). The age-distribution of the northern spotted dolphin (S. attenuata) kill of 1974 to 1983 was heavily biased towards mature animals (Barlow and Hohn, 1984). If the kill of eastern spinner dolphin was similar for all years, then the simple model used would have over-estimated relative population size. Removing proportionally more mature animals, whose reproductive value was highest, would have temporarily reduced the growth rate of the population and caused the population to decline for a longer period than predicted by the simple model.

In fact, an independent abundance index derived from data on sightings of dolphin schools from tuna vessels estimated that the population experienced a statistically significant decline from 1975, the first year the index was available, until 1982 (Buckland et al., 1992). This is different from the population trajectory I estimated here, which declined only until about 1977 (Fig. 5). Additionally, Buckland et al.'s (1992) trajectory indicated that the population level in 1988 was not substantially different from that of 1979, which conflicts with the model trajectories presented here with higher growth rates (Fig. 6), in which substantial growth occurs over 1979–1988. If Buckland et al.'s (1992) estimated population trajectory was an accurate assessment of the true population trend, then the results presented here suggest either 1) that the population growth rate was less than R_m=0.04; or 2) that kill was under-estimated during the 1980's for reasons discussed above; or 3) that a skewed age-structure led to a lagged response to the large decrease in kill during the 1970's; or 4) some combination of these possibilities.

Current status

Estimated kill from the fishery in recent years has been as high as 19,526, with an average kill of 13,900 from 1986 to 1990 (DeMaster et al., 1992), which represented a kill rate of 2.1% of the population estimate of 632,700. As indicated by Equation 3, the estimates of historical population size presented here, which are back-calculated from 1988, were based only on kill data through 1987. Estimated kill was 18,793 in 1988 (IATTC, 1989) and 15,245 in 1989 (Hall and Boyer, 1991), representing 3.0% and 2.4% of the abundance

[4]Gerrodette, T., and C. Perrin. 1991. Calibration of shipboard estimates of dolphin school size from aerial photographs. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038. Admin. Rep. LJ-91-36, 24 p.

[5]Goodman, D. 1984. Consideration of age structure in back projection calculations for the northern offshore spotted dolphin population. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038. Admin. Rep. LJ-84-26C, 25 p.

estimate, respectively. These recent kill estimates were the highest since 1976 (Table 2), and may have been high enough to prevent recent recovery of the population. The most recent estimates of the abundance index from tuna vessel sighting data indicated the population was declining from 1986 to 1991 (Anganuzzi et al., 1992[6]). However, the most recent kill information indicated a substantial reduction in kill to less than 1% of the population in both 1990 (5,378, Hall and Boyer, 1992) and 1991 (5,879, Hall and Lennert, in press), which resulted in an average kill per year for 1988–91 of 11,324, or 1.8% of the population estimate of 632,700. Therefore, the current status of the population is unlikely to be substantially different from what it was in 1988. Managing kill levels so that they do not exceed some fraction of the expected maximum net recruitment rate may be the most reasonable management strategy for promoting recovery of the population (DeMaster et al., 1992). The U.S. National Marine Fisheries Service has recently proposed listing the eastern spinner dolphin as depleted under the U.S. MMPA (Federal Register, 17 June 1992, 57FR27010). A separate proposal to list the eastern spinner dolphin as "threatened" under the Endangered Species Act was not warranted at this time, as the population is in no immediate danger of extinction (Federal Register, 19 October 1992, 57FR47620). Proposed international quotas on fisheries kill for each dolphin stock in the eastern tropical Pacific (IATTC, in press; MMC, 1993), if implemented, would ensure that mortality levels stayed low enough to allow recovery of the population to the OSP level.

Conclusions

Based on the best data available on abundance, kill, and population dynamics, the population size in 1988 of the eastern spinner dolphin was estimated to be below MNPL, within the range of 32% to 58% of pre-exploitation population size. Based on available life history data, the population size was estimated at 44% of pre-exploitation population size. Relative population size was estimated to be higher than Smith's (1983) estimate for 1979, but this difference was due mostly to the use of a new, better estimate of abundance, rather than to a recovery of the population between 1979 and 1988. Although there are uncertainties associated with this analysis, especially with the early kill data, the results indicated that the eastern spinner

dolphin population was well below historical abundance levels in 1988. Most uncertainties appear to lead to over-estimates of relative population size, indicating the population may be at a lower level than indicated here. Calculation of confidence limits for relative population size showed that the precision of the estimates was sufficient to make a status determination except for higher values of R_m. However, higher growth rates ($R_m > 0.04$) were not supported by independent evidence available about the population trend since 1975. The results indicated that, as of 1988, the stock of eastern spinner dolphins was depleted as defined by the U.S. MMPA. The substantial fisheries kill that occurred after 1988 makes it unlikely that the population has experienced any significant recovery since then.

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