ON THE ESTIMATION OF NUMBERS OF NORTHERN FUR SEAL, *CALLORHINUS URSINUS*, PUPS BORN ON ST. PAUL ISLAND, 1980-86

ANNE E. YORK[1] AND PATRICK KOZLOFF[2]

ABSTRACT

Since 1962, the numbers of northern fur seal, *Callorhinus ursinus*, pups born on St. Paul Island have been determined using a mark-recapture procedure. We investigate the feasibility of determining estimates of the total pup population on the 14 rookeries of St. Paul Island from subsamples of rookeries. Estimates are derived from simple random sampling and stratified (by rookery size) random sampling using standard ("blow up") estimation procedure, and ratio and regression estimates (based on the same sampling procedure but taking advantage of a strong relationship between numbers of breeding males and live pups on the various rookeries). Evaluation of the sampling schemes and estimation methods is based on the performance of the estimators for 3 years (1965, 1970, 1975) of data for which the mark-recapture estimates from all 14 rookeries were available. Ratio estimates are preferred to estimates obtained from the standard procedure for both simple random sampling and stratified random sampling. Furthermore, estimates from sampling plans based on three strata proved more satisfactory than those based on either unstratified or two-strata sampling. The ratio methods are applied to data collected during 1980-86. The number of northern fur seal pups born on St. Paul Island decreased at approximately 7.5% per year during 1975-81. There was no statistically detectable trend in numbers born during 1981-86.

The number of northern fur seals, *Callorhinus ursinus*, born on St. Paul Island (approximately 80% of the total Pribilof Islands herd production) has been determined in a variety of ways since the United States assumed direct management of the fur seal herd in 1910 (Parker 1946). The history of northern fur seal population estimation during 1912-47 and analyses of the reliability of methods then proposed for estimating numbers of pups are presented in Kenyon et al. (1954). The evolution of the "shearing-sampling" method, a variant of the mark-recapture technique, is discussed in Chapman (1964) and Chapman and Johnson (1968).

Since 1962, the estimate of the size of the pup population has been obtained using the "shearing-sampling" method. The safety of the crew, the accuracy of the estimate, and the minimization of disturbance to rookeries are major concerns; hence, the work is done as the breeding structure breaks up, but before pups spend most of their time in the water. During early August, a large number of pups (approximately 10% of the population) are marked by shearing a small patch of hair from the top of their heads; this exposes the pale underfur and produces an easily identifiable mark. The marking effort is allocated throughout the rookery so that each pup has an approximately equal chance of being marked. A few days later, each rookery is sampled twice during different periods to estimate the proportion of marked animals on the rookery. Thus, estimates of the population size and its variance can be calculated for each rookery. The estimate of the population present at the time of shearing is the number of sheared animals divided by the proportion of sheared pups among all those resighted—the normal Petersen estimate. The variance of this estimate is one-fourth the squared difference of the two estimates.

The purpose of this paper is to demonstrate the feasibility of obtaining accurate estimates of the total pup population on St. Paul Island from "shearing-sampling" estimates on a few sample rookeries. The advantages of obtaining estimates of the population from a subsample of rookeries include 1) less disturbance on the total northern fur seal population (each season that pup production is estimated on a particular rookery, crews must traverse the rookery four times—once to do the marking, twice to estimate the proportion of marked pups among the population, and once to count the number of dead pups); and 2) considerable savings in time, energy, and funds.

[1]National Marine Mammal Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115.
[2]National Marine Mammal Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115; present address: Tanadgusik Cooperation, St. Paul, AK 99660.

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METHODS AND AVAILABLE DATA

The data (Table 1) used for evaluating procedures for estimating the size of the pup population on St. Paul Island were the counts of breeding males made in mid-July and the estimate of the size of the pup population made in early August.

We assumed that for any year, the sum of the estimated numbers of live pups from each of the 14 rookeries, T, was the known or "true" size of the population. Estimates of the variances of each rookery were available; we assumed that the counts from each rookery were independent and estimated the variance of the total population, σ^2, as the sum of the estimated variances on the 14 rookeries. An approximate 95% confidence interval for the total population was $T \pm t(0.975,14)\,\sigma$, where $t(0.975,14)$ is the 97.5 percentile of Student's t distribution with 14 degrees of freedom.

Two sampling schemes and three estimation procedures were investigated. In particular, estimates based on the standard procedure or the "blow-up" estimate, were compared with ratio and regression estimates, which take advantage of a strong correlation between the numbers of breeding bulls and numbers of pups on the rookeries (Figs. 1, 2); these estimation procedures were compared under both simple random sampling and stratified random sampling schemes. For each sampling scheme, all possible subsamples of the 14 rookeries were generated, and the distributions of estimates for each of the 3 years of data were constructed. To determine how well the estimates predict the "true" population, we computed the fraction of (nominal) 95% confidence intervals about the estimate which contained the "true" value (the actual confidence level of the 95% confidence region). In addition, we computed the variance, bias, and the average half-width of the nominal 95% confidence interval of each estimator under the given sampling design.

"Blow-up" estimates of the total numbers of pups on the rookeries under simple random sampling, T_{BU}, were calculated in the following way (Cochran 1977): Let (P_1, P_2, ... P_n) be estimates of pup numbers on n sample rookeries. The total on all rookeries was approximated by multiplying the average number of pups on the sample rookeries by the total number of rookeries:

$$T_{BU} = \frac{14}{n} \sum_{i=1}^{n} P_i = 14\,\bar{P}. \quad (1)$$

The estimate of the variance of this estimate is

$$\mathrm{Var}(T_{BU}) = \frac{14 - n}{n} \frac{14}{n(n-1)} \sum_{i=1}^{n} (P_i - \bar{P})^2 + \frac{14}{n} \sum_{i=1}^{n} \mathrm{Var}(P_i). \quad (2)$$

When sampling was stratified, the above procedure was applied to each stratum. The total number of pups on all rookeries was estimated as the sum of the estimates on all strata; the variance was approximated by applying Equation (2) to each stratum and then summing over the strata.

Other methods of estimating the total number of pups on all rookeries, when a total count of breeding males was available, were suggested through an examination of the regression equations of numbers

TABLE 1.—Numbers of northern fur seal pups counted and their standard deviations, numbers of breeding bulls, and ratio of pups counted to breeding males for the rookeries of St. Paul Island, AK for 1965, 1970, and 1975.

	1965				1970				1975			
Rookery	Pups	SD	Bulls	Ratio	Pups	SD	Bulls	Ratio	Pups	SD	Bulls	Ratio
Vostochni	34,208.0	2,091.6	1,434	23.9	33,808.5	4,797.7	791	42.7	41,356.0	2,300.9	799	51.8
Tolstoi	25,122.0	294.2	876	28.7	22,194.0	1,759.3	570	38.9	31,107.5	1,375.3	621	50.1
Zapadni	25,066.0	4,228.5	978	25.6	33,665.5	1,112.3	664	50.7	36,815.5	4,413.1	610	60.4
Reef	29,032.5	488.6	1,179	24.6	24,907.0	4,464.7	716	34.8	27,561.0	1,050.8	622	44.3
Morjori	15,434.5	204.4	739	20.9	14,894.0	3,624.6	352	42.3	21,284.5	3,926.6	376	56.6
Polovina Cl.	18,547.5	491.4	650	28.5	17,092.5	1,880.2	390	43.8	24,869.5	4,017.1	461	53.9
L. Zapadni	14,306.0	1,937.5	551	26.0	15,240.0	739.6	325	46.9	21,168.0	2,115.7	363	58.3
Kitovi	11,361.0	244.7	486	23.4	12,713.0	1,678.7	241	52.8	12,965.0	2,511.0	267	48.6
Gorbatch	16,929.0	1,347.7	674	25.1	15,027.5	1,248.0	385	39.0	17,038.5	761.6	387	44.0
Ardiguen	2,680.5	997.7	105	25.5	3,106.5	77.1	108	28.8	2,774.0	297.0	85	32.6
Lukanin	5,290.0	895.2	204	25.9	5,508.5	1,608.7	107	51.5	5,704.0	868.3	112	50.9
Zapadni Reef	5,259.0	58.0	221	23.8	4,191.5	560.7	106	39.5	7,223.0	657.6	139	52.0
Polovina	5,291.0	2,426.8	220	24.1	3,707.5	222.7	87	42.6	4,354.5	1,130.7	88	49.5
L. Polovina	6,117.5	236.9	236	25.9	3,848.0	257.4	103	37.4	3,415.0	43.8	88	38.8
	214,644.5	6,019.9	8,553	25.1	209,904.0	8,479.6	4,945	42.4	257,636.0	8,558.0	5,018	51.3

of pups as a function of numbers of breeding males (Figs. 1, 2). The analyses of variance of these regressions indicated that the quality of the fits was excellent and that the relationship might be used for predictive purposes. No intercepts, except that for 1916 data, were significantly ($P > 0.95$) different from 0. We were interested in subsampling the rookeries (possibly conducting the estimation on as few as four rookeries) and therefore, if a regression estimator were to be used, it was desirable to reduce the number of parameters as much as possible. Inasmuch as the intercepts were not different from 0, the simpler model with no intercept was considered appropriate. Since the variance of the pup estimates was not constant for each rookery, weighting appeared necessary. The variance of the estimates of pup numbers was roughly proportional to the number of bulls, and in such cases (Draper and Smith 1966), the best estimate of the slope of regression line is the average number of pups divided by the average number of bulls (equivalent to the ratio of the total number of pups to the total number of bulls). In this case, the total number of pups on all rookeries was estimated in the following manner: Let $P_1, \ldots, P_n$ and $B_1, \ldots, B_n$ be as above, and B a count of the total number of bulls on all rookeries. Then the total number of pups on all rookeries may be estimated as

$$T_R = \frac{B \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} B_i} = r\,B. \tag{3}$$

One estimate of the variance of this ratio estimator is

$$\mathrm{Var}\,(T_R) = \frac{B^2}{\left(\sum_{i=1}^{n} B_i\right)^2} \sum_{i=1}^{n} \mathrm{Var}(P_i) \quad \text{(Cochran 1977).} \tag{4}$$

When stratified random sampling was used instead of simple random sampling, we calculated the estimator in the same way since the ratio of pups to breeding males did not vary significantly between strata. The difference was due to the evaluation procedures; the number of logical sampling combinations differed and the analysis was restricted to those combinations of sample rookeries that were consistent with the sampling design (e.g., one small rookery, one medium-sized rookery, and two large rookeries).

Another way to estimate the ratio and its variance is with jackknife methods (Mosteller and Tukey 1977). Let r_{-i} be the ratio of pups to breeding males on all but the i^{th} rookery, and r the ratio of pups to breeding males on all the sample rookeries (as in Equation (5)):

$$r_{-1} = \frac{\sum_{i=1}^{n} (n\bar{P} - P_i)}{\sum_{i=1}^{n} (n\bar{B} - B_i)}. \tag{5}$$

Then, the i^{th} pseudovalue is $r_i^* = nr - (n-1)\,r_{-i}$. The jackknife estimate of the ratio, r^*, is the mean of the r_i^*'s and the variance of r^* is (Mosteller and Tukey 1977):

$$\mathrm{Var}(r^*) = \frac{\sum_{i=1}^{n} (r_i^* - r^*)^2}{n\,(n-1)}.$$

Thus, the jackknife estimate of the total numbers of pups on all rookeries, T_j, is

$$T_j = r^* B, \text{ and } \mathrm{Var}(T_j) = B^2\,\mathrm{Var}(r^*).$$

The advantage of the jackknife estimate over the ordinary ratio estimate is the reduction of bias and a simple method of calculating the variance.

The ordinary regression estimate (assuming that the intercept is 0) of the ratio of pups to bulls is

$$s = \frac{\sum_{i=1}^{n} P_i B_i}{\sum_{i=1}^{n} (B_i)^2}.$$

Thus, the regression estimator of total numbers of pups is

$$T_{Rg} = sB \text{ and } \mathrm{Var}(T_{Rg}) = B^2\,\mathrm{Var}(s).$$

The estimate of the variance of s is calculated from the mean square residual of the regression equation.

RESULTS

Regressions of numbers of northern fur seal pups

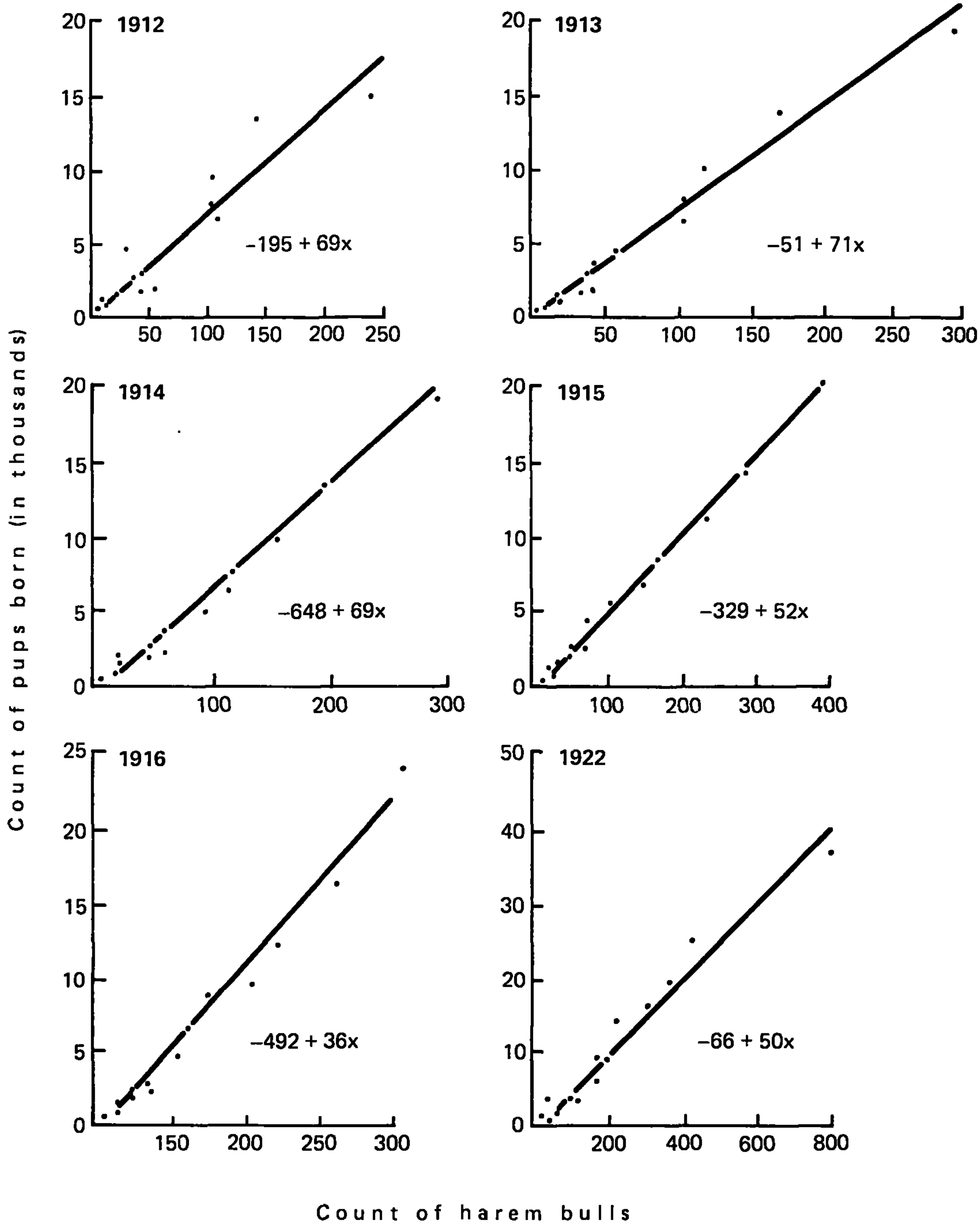

FIGURE 1.—Relationship of counts of northern fur seal pups born to counts of harem bulls for the various rookeries of St. Paul Island, AK, during 1912-22 (data from Lander 1980).

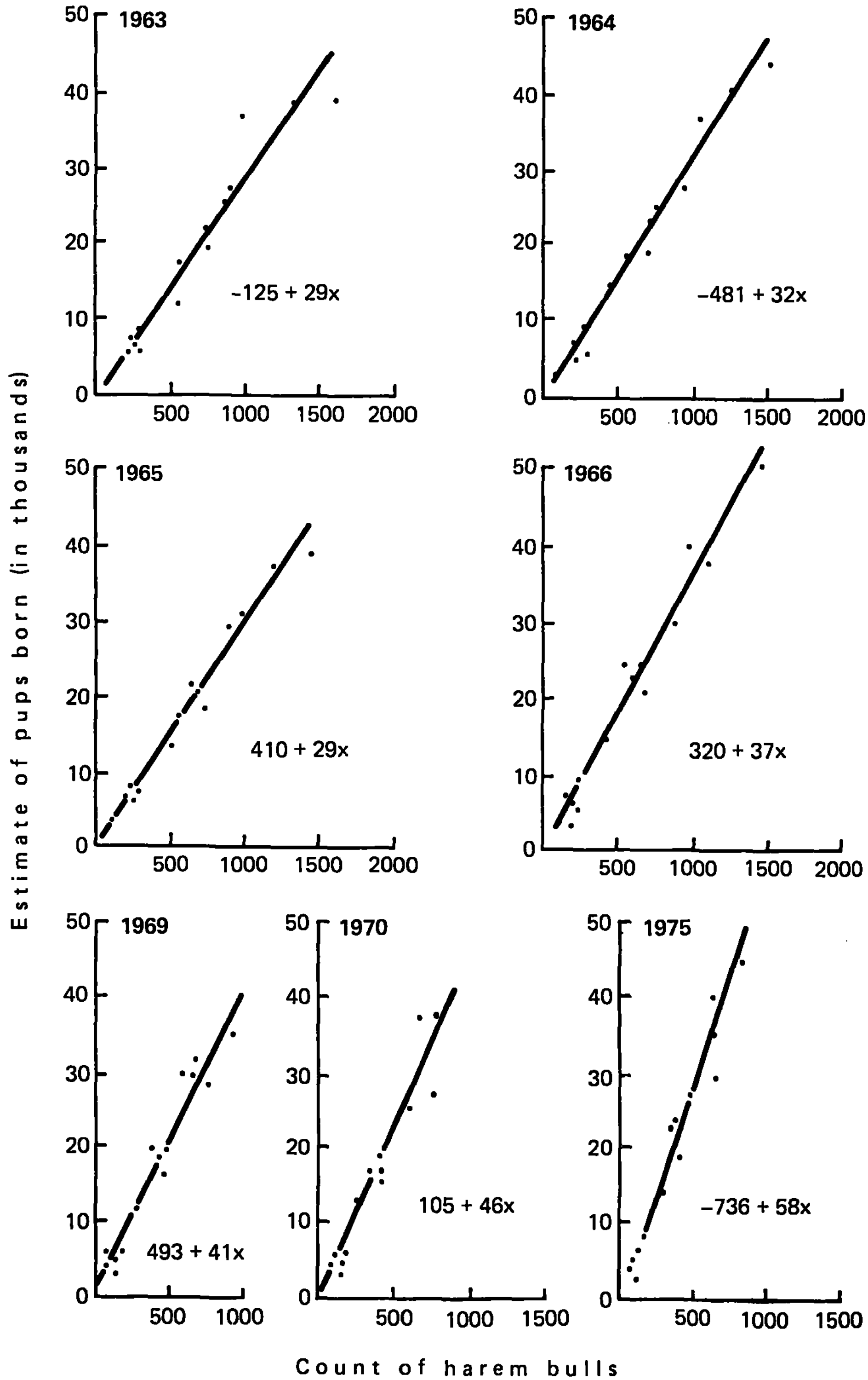

FIGURE 2.—Relationship of estimates of northern fur seal pups born and counts of harem bulls for the various rookeries of St. Paul Island, AK, during 1963-75 (data from Lander 1980).

versus numbers of breeding males for those years in which data were collected on all rookies indicated a strong relationship that could be used for prediction of total pup production if only subsamples of rookeries were censused. The relationship held for those years when censuses of pups were conducted by counting (Fig. 1), and for later years when the shearing-sampling method was used (Fig. 2). Although the slopes varied substantially from year to year (they ranged from 71 in 1913 to 29 in 1963), the variance about the regression line within any particular year was very small.

We compared the various estimators and sampling plans by analyzing the bias and variance of the estimates and the half-width and coverage properties of nominal 95% confidence intervals for 3 years (1965, 1970, 1975) of data when all rookies were sampled. Detailed statistics on the performance of the estimators under all sampling plans appear in a manuscript report available from the authors[3].

Under simple random sampling, the "blow-up" estimate is unbiased. The various ratio estimates are all slightly biased (in most cases less than 1%) with the regression estimate exhibiting the largest degree of bias. In Figure 3 the percentage of bias of the three ratio estimates for the 1975 data is shown as a function of sample size (under simple random sampling). Estimates based on 1975 data were the most biased among the 3 years analyzed, and these biases are exhibited as a worst case. The regression estimate was the most biased, and for these data the bias increased as the sample size increased; however, the bias was only about 1% and is not serious.

Confidence intervals were constructed for each subsample and a count was made of the number of nominal 95% confidence intervals containing the "true" population. The observed coverage was near 95% for most procedures. Confidence intervals for the regression estimate tended to be conservative, i.e., a higher than 95% coverage rate, while the coverage rate for the ordinary ratio estimate tended to be less than 95%. Coverage rates for the jackknife and blow-up estimates were near 95% or a bit higher. This indicates that the estimate of the variance of the regression estimate tended to be too large, that of the ordinary ratio estimate was too small, and that the estimates of the variance of the blow-up and jackknife estimates tended to be unbiased. The half-widths of confidence intervals for the ratio estimates were nearly equal. All were less than one-half the length of the half-width of the confidence interval of the blow-up estimate.

The rookeries were stratified by population size. Two methods for stratifying the rookeries were investigated: one using two strata (small and large rookeries) and the other using three strata (small, medium, and large rookeries). As in the case of simple random sampling, the ratio estimators were superior to the blow-up estimates. The estimators under the three-strata sampling plans were less variable than under the two-strata sampling plans. In addition, the computed levels of the nominal 95% confidence intervals were higher and the size of the confidence intervals smaller. Under the three-strata sampling plans, the standard deviations of the estimates were about 10% smaller than under simple random sampling with the same size sample. This resulted in a similar reduction in the size of the confidence intervals. These results indicated that reasonable estimates of the size of the pup population can be made using any of the ratio estimators under various sampling plans. The superior plans use three strata: two small, one medium, and one large rookery; one small, two medium, and one large

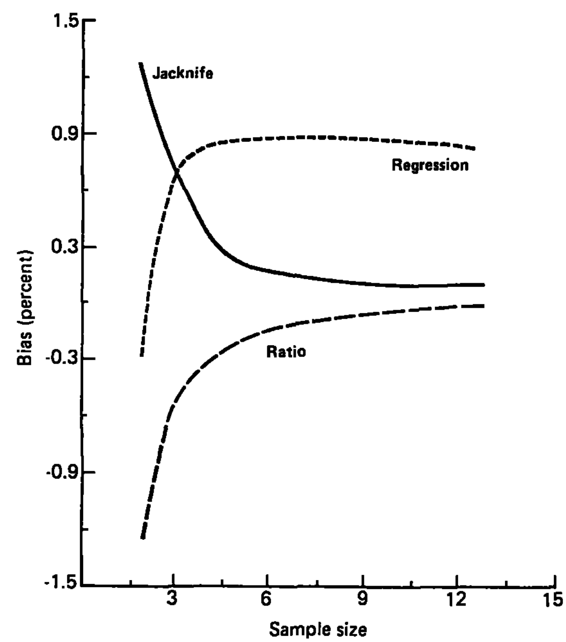

FIGURE 3.—Percent bias of the jackknife estimates (——), ordinary ratio estimates (· · ·), and regression estimates (– – –) based on simple random sampling of 1975 northern fur seal data.

[3]York, A. E., and P. Kozloff. 1985. Estimation of numbers of fur seal pups born on St. Paul Island, 1980-84. Unpubl. manuscr. Available National Marine Mammal Laboratory; 7600 Sand Point Way N.E., Seattle, WA 98115. (Background paper submitted to the 28th Annual Meeting of the Standing Scientific Subcommittee of the North Pacific Fur Seal Commission, March-April 1985, Tokyo, Japan.)

rookery; and, one small, one medium, and two large rookeries.

A subsampling estimation procedure was developed for 1980-84: rookeries were grouped into three strata—large, medium, and small rookeries; one small, one medium, and two large rookeries were sampled each year. Furthermore, in order that some rookeries were not disturbed inordinately more than others, each rookery was sampled at least once, but no more than twice during the 5-yr period. We had intended to census all rookeries in 1985, but logistic difficulties permitted a sampling of only seven rookeries.

A summary of data collected during 1980-86 with the ordinary ratio, jackknife ratio, and regression estimates of the ratio of pups to breeding males appears in Table 2. The estimates based on the three methods are approximately equal within each year; in most cases, the jackknife estimate lies between the ordinary ratio and regression estimates. Estimates of the total number of pups born were obtained by adding counts of dead pups to number of pups alive at the time of census (based on jackknife ratios); approximate 95% confidence intervals were calculated (Table 2).

In Figure 4, estimated 95% confidence intervals

TABLE 2.—Summary of the total number of breeding northern fur seal males, ratios of the number of pups alive at the time of sampling to the number of breeding males counted, estimated number of pups alive at the time of sampling, counted number of dead pups, and estimated number of pups born, and approximate 95% confidence interval based on the jackknife standard errors, St. Paul Island, 1980-84.

Year	Total no. of breeding males	Ratios of pups to breeding males			Number of pups		
		Jackknife ratio	Ordinary ratio	Regression	Live	Dead	Born
1980	5,490	35.695	35.896	35.580	195,966	7,859	203,825 ± 36,838
1981	5,120	33.720	33.821	33.563	172,646	6,798	179,444 ± 20,054
1982	5,767	34.035	33.896	34.147	196,280	7,301	203,581 ± 9,665
1983	4,827	33.135	32.766	33.448	159,944	5,997	165,941 ± 19,216
1984	4,803	34.803	33.861	34.167	167,159	6,115	173,274 ± 22,531
1985	4,372	40.482	40.292	41.071	176,992	5,226	182,258 ± 18,887
1986	4,603	34.735	34.936	34.498	167,656	7,771	167,656 ± 16,272

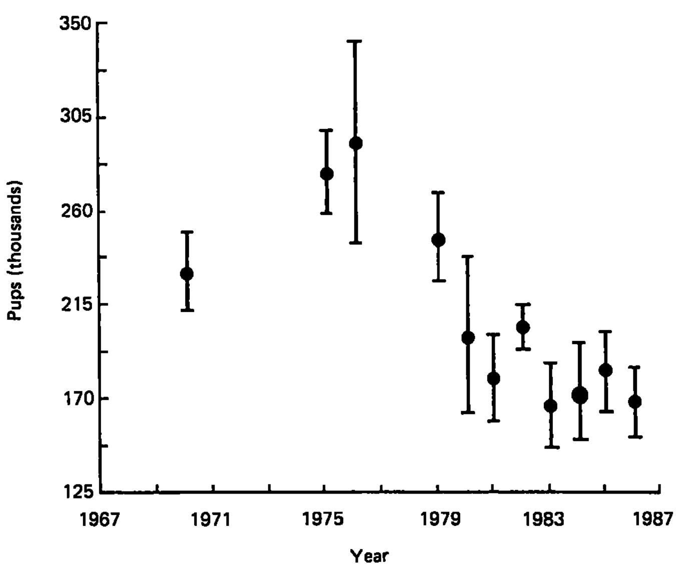

FIGURE 4.—Approximate 95% confidence intervals and estimates of numbers of northern fur seal pups born on St. Paul Island, AK, 1970-86. (We include only those years for which data were available to compute estimates according to the methods developed in this paper.)

of numbers of northern fur seal pups born on St. Paul Island since 1970 are presented; estimates for 1970-79 are based on data from Lander (1980). We computed estimates for those years in which censuses were made on all rookeries or for which data were available to compute estimates according to the methods developed in this paper. Regressions of logarithms of numbers of pups born versus time indicated a statistically significant decrease during 1975-81—a decrease of 7.5% per year with a standard error of 2%. During 1981-86, there is no statistically significant decreasing or increasing trend; the estimate of the slope is −1.8% with a standard error of 1.8%. This slope is statistically different from the −7.5% slope calculated for 1975-81 ($P > 0.90$).

DISCUSSION

Our study indicates that we can obtain reasonable estimates of the total number of northern fur seal pups born from subsampling as few as four rookeries of St. Paul Island if estimates of numbers of pups and breeding males are available for the sample rookeries and if a total bull count is available for the island. Subsampling is successful because within a given year, pup production is predictably proportional to numbers of breeding males. Some refinements in the reduction of bias and variance can be made by restricting the subsamples to stratified designs over large, medium, and small rookeries.

The advantages of subsampling rookeries for censusing northern fur seal numbers are considerable. Most important is the reduction of total disturbance on the northern fur seal population on the island. Our sampling schedule over several years attempts to apportion disturbance approximately equally so that rookeries are neither under- or oversampled through time. This is an important aspect of the sampling design, since it is not known how great the long-term impact of disturbance is. In addition, subsampling requires a smaller crew for the shearing and less time for resampling, resulting in considerable savings of resources.

Ratios of numbers of males to pups, and consequently breeding females, vary considerably over time, even in successive years. It is difficult to interpret the meaning of these changes. During the period covered by Figure 1 (1912-22), numbers of pups born on St. Paul Island were increasing rather rapidly. Since males begin to breed at an older age than females, part of the increase in the ratio of breeding males to pups may be explained by the number of breeding males lagging a few years behind the number of breeding females. Significantly different ratios from one year to the next could also be due to differences in counting methods or abilities among individual counters, or to different survival rates among separate cohorts (e.g., harvest rates). Figures 1 and 2 also imply a certain consistency and a rather uniform rate of usage of rookeries by breeding males and females, in that, if a rookery accounts for 10% of breeding males within a year, it will account for approximately 10% of the total pup production within the same year. A rookery's relative contribution to both these populations may change but the correlation between them does not appear to change.

The recent history of the population of numbers of pups on St. Paul Island in Figure 4 shows a decrease of about 7.5% per year during 1975-81. No significant trend is detectable after 1981, although the number born in 1982 was significantly higher than in 1981 or 1983-86. The causes of the decline are unknown. There is no evidence that pregnancy rates have changed significantly since the 1950's (Goebel and Gentry 1984[4]). Thus, considerable attention has centered on potential causes of increased mortality of northern fur seals: entanglement in debris (e.g., Fowler 1985), effects of weather (Trites 1984; York 1985[5]), and direct effects on food availability from competition with fisheries in the North Pacific Ocean (York and Hartley 1981; Swartzman and Harr 1983; Kajimura 1984; Loughlin and Livingston 1985[6]). One may also speculate that the pattern of decline and possible stabilization in numbers of pups born resulted from a new disease which abated or was controlled by an immune response of the population (c.f., Geraci et al. 1982).

Of the aforementioned explanations for the decline, only entanglement has been cited as a major contributing factor with an attributed mortality of

[4]Goebel, M. E., and R. L. Gentry. 1984. The use of longitudinal records of tagged females to estimate fur seals survival and pregnancy rates. Unpubl. manuscr. National Marine Mammal Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115. (Background paper submitted to the 27th Annual Meeting of the Standing Scientific Committee of the North Pacific Fur Seal Commission, March-April 1984. Moscow, U.S.S.R.)

[5]York, A. E. 1985. Forecast of the 1985 harvest on St. Paul Island. Unpubl. manuscr. National Marine Mammal Laboratory, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115. (Background paper submitted to the 28th Annual Meeting of the Standing Scientific Subcommittee of the North Pacific Fur Seal Commission, March-April 1985, Tokyo, Japan.)

[6]Loughlin, T. R., and P. A. Livingston (editors). 1986. Summary of joint research on the diets of northern fur seals and fish in the Bering Sea during 1985. NWAFC Processed Report 86-19, 92 p. Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way N.E., Seattle, WA 98115.

about 5.5% per year (Fowler 1985). It is possible that entanglement in debris was indeed responsible for the decline during 1975-81, however, the data in Figure 4 do not seem to support this hypothesis. If entanglement were the principal cause of this decline, we would have expected the population to have continued to decrease at the pre-1981 rate since the observed entanglement rates have remained stable since 1976.

We may never know the cause of the 1975-81 decline in northern fur seal production. In general, estimates of population size are highly variable so several censuses are required to detect a statistically significant decrease in a population; thus, the fact of a decline, unless it is sudden and dramatic, is not usually known for several years following its initiation. Post facto studies are invariably subject to criticism for flaws in experimental design; thus, careful continual monitoring of the many aspects of the biology of a population is the best hope for ascribing a particular cause to a population change. Comparisons of the population dynamics, food habits, incidence of diseases, and entanglement rates of northern fur seals with other pinniped species which share their habitat in the North Pacific Ocean might shed additional light on the various hypotheses.

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