Seabird-Prey-base Interaction
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Although it is obvious that there should be a correlation between the distribution, and perhaps the abundance, of seabirds and their prey this association is "noisy" for several reasons: Predators would not necessarily be expected to find all patches of prey, particularly when food is not limiting. Thus, while some aggregations of seabirds may be associated with concentrations of prey, other prey concentrations will remain "untouched." Prey patch size may also play a role in the tendency for seabirds to aggregate. Heinemann et. al. (1989) has suggested that krill predators may forego small patches of known location in favor of continued searching for large patches. Seabirds may distribute themselves according to other factors than food - gregarious species are often found in large rafts in the immediate vicinity of the breeding colony (Parrish pers. obs.). Thus, some aggregations of seabirds may not be associated with concentrations of prey. Taken together, this means that although seabirds and fish may co-occur, both predator and prey would also be expected to be found separately. Veit et. al. (1993) found just such a relationship between several species of Antarctic seabird and the principal prey item, krill: "...of the 962 data points on each graph in Figure 8, fewer than 10 represent the coincidence of large numbers of both predators and prey." (pg. 561).

Attempts to find correlations between seabird distribution and abundance, and that of their prey have been varied. Several studies have found that seabird density was an indicator of the presence of prey (Obst 1985, Safina and Burger 1985, Heinemann et. al. 1989), at least one study has found no relationship between seabird and prey density (Woodby 1984), while still others have found significant relationships between seabird and prey abundance (Veit et. al. 1993, Schneider and Piatt 1986, Piatt 1990). Several generalizations can be drawn from these studies. First, the amount of variance in predator abundance explained by prey abundance is usually small, albeit significant (see for instance Veit et. al. 1993). Second, there appears to be a "threshold" in prey density below which there is no apparent correlation between predators and prey (Piatt 1990, Veit et. al. 1993). Third, significant relationships were found at "coarse" scales, usually greater than one nautical mile, often tens of miles (see for instance "event" and "block" scale of Heinemann et. al. 1989; 8 and 16 minute frame size of Piatt 1990). Fourth, at larger scales elevated seabird densities are ultimately related to colony size. This last point brings one full circle: large, stable colonies are found in areas with predictable food supplies.

Few systematic studies of the distribution and abundance of seabirds off the Washington coast have been performed. Most studies have attempted to describe seabird diversity

along a broad swath of marine habitat, usually encompassing the entire outer coast from nearshore to offshore environments. Occasionally surveys have been run repeatedly, such that estimates of error could be made. Wahl (1984) and Briggs et. al. (1992) sampled the outer coast using both boat and aerial surveys, and Warheit (1995) used boat only. In general, all studies concluded that shearwaters, gulls, and alcids were the most abundant groups of seabirds in the nearshore and shelf environment during July and August. Wahl (1984) estimated these populations at: shearwaters - 740,000 (62% of total sample), larids - 150,000 (13%), and alcids - 195,000 (16%), respectively. Briggs et. al. (1992) estimated maximum seabird abundance in the shelf environment in July of each year sampled (1989 and 1990), and maximum abundance in July of 1990 for the slope environment. Warheit (1995), in a preliminary report of the NOAA ship *McArthur* (21-27 July 1995) presents data indicating the three most abundant species on-transect were Sooty Shearwaters (SOSH), *Puffinus griseus* (56% of total sample), Fork-tailed Storm-petrels, *Oceanodroma furcata* (21%), and Common Murres (COMU), *Uria aalge* (13%). Larids, in total, accounted for only 2% of the total sample. Vermeer et. al. (1989) surveyed the distribution and abundance of seabirds off the southwest coast of Vancouver Island during September and October 1986-87. The lower end of the survey area overlapped with the survey area for this pilot study. In contrast to the Washington coast surveys, Vermeer et. al. (1989) found that California Gulls (CAGU), *Larus californicus* were the most abundant species, followed in rank order by Sooty Shearwaters, Cassin's Auklets, Northern Fulmars, *Fulmar glacialis*; and Common Murres. Glaucous-winged Gulls (GWGU), *Larus glaucescens*; and Rhinoceros Auklets were not well represented in the data. Vermeer et. al. (1989) noted that CAGU abundance, specifically large feeding aggregations, were typically found in conjunction with fishing trawlers.

Although these surveys do provide a clear and consistent picture of seabird diversity along the outer coast of Washington, they are not detailed enough to provide information on seabird distribution and abundance around single known breeding colonies. Furthermore, none of these studies have concurrently sampled forage fish.

System Background

In 1991, the *Tenyo Maru* oil spill resulted in the recovery of 4,300 bird carcasses, and the death of an unknown additional number. Ten species representing 88% of this count breed on Tatoosh Island, the closest breeding colony to the spill and one of the largest seabird colonies on the outer coast of Washington State (Speich and Wahl 1989). The vast majority (73%) of the carcasses were Common Murres. Following the oil spill, murre

colony most probably affected by the *Tenyo Maru* oil spill - Tatoosh Island. The specific goals of the study were to:

1.) Describe the distribution and abundance of seabirds on the water around Tatoosh Island
   a.) during the same time of year as the original spill (22 July 1991), and
   b.) during the period when chicks were present on the colony (late July through August), thus maximizing the probability of observing seabird-preybase interactions.
2.) Concurrently sample forage fish using hydroacoustic surveys.
3.) Sample fish directly to groundtruth hydroacoustic data.
4.) Determine the degree to which seabird distribution and abundance was associated with forage fish densities versus other non-food factors.
5.) Determine the efficacy of survey techniques for potential future use in ongoing restoration efforts.

Methods

All data were collected during daylight cruises from 24 to 27 July 1995 (Table 1). Seabird and hydroacoustic data were collected aboard the 20m WDFW vessel *G. H. Corliss*. Vessel speed ranged from 7 to 10 knots. All transects were conducted along a rectilinear grid centered on Tatoosh Island (48° 24'N, 124° 44' W), ranging from 48° 18'N to 48° 32'N and 124° 37' W to 124° 59' W. Data were collected on latitudinal legs only. Transects were divided into "long" and "short," operationally defined by length, position relative to the island, and latitudinal separation (Figure 1). On long transects hydroacoustic data were collected continuously and seabird data were collected in 15 minute sampling periods spaced by intervals of 5 minutes. On short transects, all data were collected continuously. Vessel position was calculated by GPS and recorded at one minute intervals. Forage fish groundtruthing was attempted on the 15m Research Vessel *Kittiwake* (Biomarine Enterprises).

Data Collection

Seabirds: Seabird distribution and abundance were collected following strip transect methods outlined in Gould and Forsell (1989). One or two observers identified all seabirds south of the vessel within a 300 m wide strip defined by the axis of transit. Only birds lateral to and foreward of the observer were identified. All observations were immediately entered into a TurboBasic program using an HP palmtop computer, which stamped each entry with the date and time. The program prompted the data recorder to type in

standardized entries (see below) using a set of function keys to minimize time spent typing. Observations were recorded as:

1.) *date*; automatically recorded by the program

2.) *time*; automatically recorded by the program

3.) *species*

4.) *number* = number of birds counted per sighting

5.) *behavior* = flying; sitting; feeding; following boat; rafting (used for group sizes greater than 5 and all mixed species rafts - see comments below); feeding aggregation (used for group sizes greater than 5); flying with fish; sleeping; other (see comments below)

6.) *direction* = clock direction relative to the axis of transit, with the bow of the boat at 1200; only applicable if the behavior code was flying.

7.) *age* = juvenile or adult; only applicable if the species code was Common Murre

8.) *comments* = encoded miscellaneous information which could be typed in as text, and used to flag species observations where birds were part of a mixed species raft (MR), flock (MF), or feeding aggregation (MFAGG). The comment flag could be used at any point in the sequence of data entry.

Mistakes in data entry or observer identification which were caught during data collection were flagged in the comments column and corrected in the subsequent entry. In cases where boat presence altered bird behavior, as in a diving escape response (usually Alcids) or a seated raft which took flight (usually shearwaters), we noted the prior behavior. Occasionally seated birds avoided the boat by flying forward along the axis of transit and reseating within the strip transect. In these cases, birds were only recorded once and behavior was classified as the first (i.e. pre-boat) behavior observed. Data entries were stored as ASCII files where each column represented a standardized entry (see above) and each row an observation.

Hydroacoustic: Nekton was used as a surrogate for forage fish, and was assessed using the echo integration and target strength analyses techniques described by Johannesson et. al. (1983). Acoustic data were acquired with a 120Khz Simrad EK500 echosounding system coupled to a 7.4 degree split beam transducer. The transducer was suspended one meter below the surface and transmitted energy vertically through the water column at a one second ping rate.. As a consequence of the transducer position, the upper 5m were not adequately sampled. Acoustic data were collected and output at one minute time intervals directly to computer (ASCII format) as well as to hard copy color echogram. Data were displayed as density and number of acoustic targets, over ten continuous depth intervals of 15m each.

To calculate nekton density, the integration process quantified the amount of transmitted acoustic energy which was backscattered by targets (e.g. fish) to the transducer. This quantity was measured as 10log (Sv), where Sv is the volume backscattering measurement over a vertical layer r_1 to r_2. Averaged outputs were expressed as Sa (m^2/nm^2) according to the equation:

$$Sa = 4\pi r^2 \bullet mean\left[\int_{r_2}^{r_1} Svdr\right] \bullet (1852m/nm)^2$$

(Simrad Subsea 1993). Occasionally the equipment failed to detect the bottom, and/or produced Sa values which were obviously incorrect (always orders of magnitude too large). In these cases, values were first checked against the color echograms to verify authenticity, and then deleted if necessary.

Nekton Groundtruthing. Concentrations of nekton observed by the hydroacoustic equipment is normally identified by net sampling (Lemberg 1978). Attempts were made to groundtruth the acoustic data using a second vessel outfitted for trawl net sampling. The *RV Kittiwake* was chartered to tow a single wire, 3m wide x 7m deep x 15m long trawl net, modified with a removable fine meshed codend to enumerate larval and minnow size fishes, as well as invertebrates that may constitute nekton sign fed upon by seabirds. A 3m x 3m x 10m Kvichak trawl net was also deployed. Both nets were calibrated at the site for wire out to depth using a Bathykymograph.

Net sampling was hindered by a prodigous quantity of jellyfish: *Cyanea capillata* and *Aurelia aurita*, that encompassed the sampling region. All attemptes to sample aroundthese organisms by area, water depth and time of sampling resulted in the trawl nets plugged and coasted with jellyfish. Eventually, cod ends of both nets gave way. Identity of the nekton concentrations observed by the hydroacoustic equipment was therefore unobtainable at the time of this pilot study.

Data Analysis

All seabird observations were summed to produce a sighting index by species. Although 16 known species were sighted (Figure 2A & B; Table 2), a few species predominated the sightings (76%) as well as the overall count (72%): Sooty Shearwaters, Common Murres, Rhinoceros Auklets, and Glaucous-winged Gulls. In determining the relationship between spatial arrangement of seabirds and their prey, it is important to have an adequate sample of

non-zero cells distributed over the sampling area. Therefore, the remaining analysis was conducted on these four species.

Seabird and hydroacoustic data were stored as two separate Excel files, where each row of data contained a date and time stamp. Because hydroacoustic data were collected continuously and recorded every minute while seabird data were collected opportunistically (i.e. whenever birds appeared), data files were not initially integratable. Furthermore, we wished to analyze the data as a function of space, not time, such that data from repeated transects could be compared and/or averaged. To surmount these problems, all data were binned into minutes of latitudinal space. For example, all seabird observations occurring within the boundaries 124° 40' W and 124° 41' W on a given transect were summed to produce density per space minute, by species. Sa values were similarly treated. The resulting data sets were combined into a single file where each row represented binned data by space minute on a known transect. This data file was used to address the following questions: Where were the birds; and was there an association between the birds and the nekton?

Seabirds in Space: The average density of each of the four main species was calculated per unique space minute for the area covered by the short transects (48° 22' N to 48° 25' N, and 124° 41' W to 124° 47' W) and again for the long transects (see Figure 1 for transect position and sample size). Data are presented as density by space minute by species.

Seabirds as a Function of Nekton: Because the transects were centered on a known breeding island, and three of the four main species bred there (Common Murres, Rhinoceros Auklets, and Glaucous-winged Gulls), seabird densities should be influenced by distance from land as well as other factors such as food. Therefore, seabird-nekton associations were assessed after removing the effect of distance from the data, according to the following protocol.

Data were averaged within unique space minute (see Seabirds in Space), such that all space minutes were equally weighted regardless of original sample size (range 1 to 5; see Figure 1). All space minutes were then categorized as a function of distance from land, in kilometers, to the center of the space minute. Initially, two distance functions were explored, distance from the mainland (including Vancouver Island) and distance from Tatoosh. Results of the mainland analysis were not as clean as those relative to the island, so the former was dropped. Essentially the data were binned into a set of concentric

annuli, centered on Tatoosh (Figure 3). Annulus width was set at 2 km (except for the first and last categories, see Figure 3) for the initial analysis, but later reduced to 1 km to increase resolution.

Because annuli were of constant width but increasing radius, the number of space minutes encompassed by each ring should theoretically grow. This relationship is somewhat subverted by the U. S. mainland, which cuts off approximately 25% of each ring, as well as the boundaries of our survey (Figure 3; Table 3). Conversely, the percent of units we sampled should decrease, in part because of the hypersampling within the area bounded by the short transects, and in part because we are imposing a circular structure on data collected rectilinearly. This problem is largely unaddressed in this pilot project, as the number of times we were able to repeat any transect was small enough to make adequate measures of variance unreliable. However, we did attempt to take sampling differences into account: density as a function of distance analysis was cut off for annuli with fewer than four unique space minutes sampled for either seabird or hydroacoustic data as the limiting factor. Data are presented as the average seabird density (per space minute) by distance category, in km.

In order to factor out the effect of Tatoosh on the pattern of seabird density, by species, data were fit to the following simplistic diffusion function:

$$\text{Density} = \beta_0 + \beta_1(\text{Distance from Tatoosh})^{-2}$$

where "Density" refers to seabird density within each unique space minute categorized by annulus from 1 to 22 km distant from the island. The square of the distance was used because the birds could diffuse anywhere within the area of a circle of radius equal to "Distance from Tatoosh." For each of the four main species, residuals from these functions (observed density - expected density) were averaged within annulus (i.e. sample size becomes 22) and linearly regressed against average Sa within each annulus to test the association between nekton and seabird density unrelated to island effects.

For regressions in which the slope was a significant predictor of the relationship between birds and nekton, a Monte Carlo simulation was used to assess the probability that the significance level of the relationship was a non-random event: seabird residuals were re-shuffled and then linearly regressed against nekton 1000 times. For each regression, a significance level (p-value) was calculated. Thus, we created a "population" of significance levels given 1001 different combinations of the data, 1 actual and 1000 manufactured. A Z statistic was used to determine the probability that the actual significance value was part of

the generated population. In other words, we asked the question: what percentage of the generated p-values were equal to or less than our actual value?

Results

Density of each of the four main species (COMU, RHAU, SOSH, GWGL), averaged within each space minute sampled is shown in Figure 4 (data are from short transects and relevant long transect excerpts) and Figure 5A-D (data are from long transects only). Data are presented separately to minimize the visual concentration created by superimposing the short transect data on the long transect area. In general, it is apparent that island breeders occur much closer to Tatoosh and appear to concentrate immediately north of the island. Rhinoceros Auklets had the most restricted distribution. However, this species accounted for only 8.6% of all birds seen (compare to the three other species, Table 2) and is the smallest of the three, meaning we may have missed individuals and/or not had a sampling rate (in time or space) adequate to represent the distribution. Sooty Shearwaters, on the other hand, appeared to actively avoid the nearshore environment (Figure 4). Although Figure 5D appears to show a relationship between distance from shore and latitude, this may simply be an artifact of sampling (see Figure 1).

When the data are presented as a function of distance from Tatoosh, the breeder versus nonbreeder pattern is more strikingly apparent (Figure 6A-D; note unit differences on the ordinate axis). The densities of all three breeding species: COMU, RHAU, and GWGL drop off precipitously. Within the first 7km, 75%, 96%, and 78% of cumulative density of each species is accounted for, respectively. By contrast, only 13% of cumulative SOSH density is found within 7km of Tatoosh. Several additional elements are worth noting. First, murre density is highest within the first kilometer of the island, in contrast to the other two breeders. This may be the murre rafts to the north of the island, commonly found off North and Pole Islands (USF&WS rock #'s 022 and 023; Parrish unpub. obs.). Neither of the other two breeders aggregate to the same degree, although GWGL are regularly seen in feeding aggregations (Parrish unpub. obs.). Second, close to the island, RHAU and GWGL have similar patterns of density as a function of distance, a pattern mirrored by COMU lagged one kilometer. Nekton density (measured as average Sa per space minute within annulus) shared this pattern - densities were highest close to the island, showed the three-step pattern to a maximum at 3km, and decreased sharply thereafter (Figure 7).

The pattern of density of all three island breeders could be modeled with the nonlinear diffusion function; SOSH densities could not (Figure 6A-D). In essence, the island can be thought of as an attraction source for breeding species, while land per se is probably a repellant for shearwaters. Residual densities from the nonlinear model, averaged for each annulus, were regressed against average nekton density (Figure 8A-D). Murre densities were lagged one kilometer (that is, km 2 becomes km 1) to account for the hyperdensity created by rafts adjacent to the island. For the three breeders, nekton density was a significant predictor of residual seabird density (Table 4). In all cases higher nekton densities had higher seabird densities, although the relationships were driven by only a few points (Figure 8A-C). Thus, it is possible that the relationship is spurious.

To account for these results, we ran a Monte Carlo simulation, which holds nekton density constant and reshuffles seabird density iteratively. In each run of the simulation, a linear regression is performed and a T statistic and associated p-value calculated. At the end of the simulation, the actual p-value is compared to the generated population of p-values, to assess the probability that the actual regression reflects a chance occurrence. In all three cases, less than 1% of the generated p-values fell below the actual value, a highly significant result (Table 5).

A second line of evidence suggesting an association between seabirds and their prey is the relationship between type of multispecies aggregation and prey density (measured as Sa) in the localized area (Figure 9). In general, there is no apparent relationship between either raft size and Sa, or feeding aggregation size and Sa, as the highest prey densities are associated with smaller raft sizes. This pattern may be due to small sample sizes, the possibility that smaller aggregations would have become larger later, or the possibility that raft size is not determined by food alone. However, it is noteworthy that on average, feeding aggregations occurred in areas of higher prey density than rafts.

Discussion

Our data indicate that common seabirds using the nearshore and shelf environments (sensu Wahl 1984) in the area surrounding Tatoosh Island and the mouth of the Strait of Juan de Fuca are distributed according to both breeding location and food. In fact, the relationship between nekton and seabird density is strong enough that minimal pilot data (that is, without adequate sample sizes) binned into average values as a function of distance from the breeding island (despite the fact that there is no reason for densities of either seabirds or nekton to be uniform within annulus) is still significant. The similarities in pattern of

breeding seabird and nekton density (i.e. the three-step to a maximum followed by a precipitous drop; Figures 6A-C & 7) is striking. In short, it appears that these birds do not need to go far from their breeding grounds to obtain food, even though they may be physically able to do so (see distances in Schneider and Hunt 1984, Ainley and Boekelheide 1990). The fact that Sooty Shearwater distribution did not match nekton distribution may be explicable in terms of the nearshore distribution of maximum nekton density (i.e. within the repellant zone of land). Vermeer et. al. (1989) found a similar, albeit coarser pattern (distance from shore categories were lumped into 15km bins) of seabird occurrence off the west coast of Vancouver Island for Common Murres, adult Glaucous-winged Gulls and Sooty Shearwaters during the months of September and October (data from 1986 and 1987; Figure 10).

Schneider et. al. (1990) suggest that foraging seabirds should balance both the cost and expected gain to maximize net gain, where costs are proportional to distance traveled (Figure 11). Assuming the cost function is static, net gain is a function of the changing distribution of gross gain, as prey resources move within the range boundaries of the seabirds. Because seabird prey is mobile (i.e. schooling) and may also not be present within the foraging range of the colony throughout the breeding period (see Hay et. al. 1992), seabirds should adopt foraging strategies which maximize the likelihood of finding mobile food. Such strategies might include use of ephemeral physical oceanographic structures such as fronts and eddies (e.g. Woodby 1984, Schneider et. al. 1990) and forage-area copying resulting in both mono and heterospecific feeding aggregations (e.g. Piatt 1990, Veit 1994). Our finding that feeding aggregations occurred over higher prey densities than rafting birds supports this latter strategy.

At the level of the population as well as the colony (i.e. seabird community), persistent areas of positive net gain (e.g. Figure 11) should result in stable colonies the size of which may be regulated by total food availability (Kaiser and Forbes 1992). The mouth of the Strait of Juan de Fuca may be such an area. This area is subject to extremes of tidal flow in and out of the Strait. Seabird feeding aggregations are often observed along the slick created by the moving tidal front immediately south of Tatoosh Island (J. Parrish pers. obs.). The area also experiences localized upwelling associated with the Juan de Fuca canyon (Freeman 1992) which begins in the Strait and arcs west and south, curving around Tatoosh Island. The highest seabird densities observed in this study (i.e. Figures 4 and 5) were north and northwest of Tatoosh, close to the canyon. The preliminary report of the 1995 whiting, *Merluccius productus*, cruise on the NOAA ship *Miller Freeman* (in pilot

study area 16-17 August 1995) indicates a strong whiting signal in the area surveyed by our study (see Figure 4 in NMFS 1995). It is also apparent from these data that strong signals appear to be absent from the remainder of the Washington coast. One major caveat to these results is that the acoustic frequency used to detect adult whiting was 38Khz, well below the 120Khz used for forage fish in our study. However, it is also probably true that highly productive areas will sustain elevated levels of both seabird and fish predators.

Is food, or can food be, limiting in this system? Woodby (1984), studying associations between murres and their prey in the Bering Sea between the Pribilof Islands and the mainland, found no obvious relationships and suggested that in areas where food is abundant or superabundant predators need not necessarily forage only in areas of highest prey density (but see krill patch size arguments in Heinemann et. al. 1989, Veit et. al. 1993). If this hypothesis is true, one might expect to find seabird-prey associations in systems or years where/when food is limiting, or potentially in systems where food is superabundant extremely close to the breeding colony. If food was limiting in this system, we would expect breeding seabirds to experience lowered reproductive success (e.g. Monaghan et. al. 1989, Aebischer et. al. 1990). In 1995, murres breeding on monitored crevice subcolonies on Tatoosh had higher reproductive success than in previous years (1991-1994; Parrish 1996) suggesting that food was not limiting in that year. Given a relatively high level of reproductive success combined with indications from this pilot study as well as other fisheries surveys (e.g. NMFS 1995 whiting cruise), it seems likely that seabird-forage fish association in the mouth of the Strait of Juan de Fuca system is probably a response to persistent, nearshore, abundant sources of food.

Future Recommendations

Of the five study goals outlined in the Introduction, four were met. We were not able to groundtruth the hydroacoustic data (goal #3). We feel it is imperative to adequately groundtruth the hydroacoustic data as well as try to determine forage fish species occuring underneath feeding aggregations. We suggest that any future studies explore the use of larger vessels able to trawl with larger nets, as well as other gear types, potentially including purse seines. Groundtruthing would also allow accurate target strength analysis as a function of known forage fish species and length/frequency distribution. Although the hydroacoustic equipment was highly sensitive to acoustic targets, it did not provide a total picture of the water column, specifically underestimating surface-associated nekton (to 5m). As many seabirds feed within this depth range, future studies with increased effort might include sidescan sonar, albeit at increased cost. Basic oceanographic data, including

bathymetry, sea surface temperature, conductivity and sea state might also improve our ability to link seabird and forage fish density to underlying physical structuring processes. Finally, we strongly recommend all future data be collected relative to both direct output of clocktime and space (using DGPS).

Although the results of this pilot study shed light on the importance of the interaction between seabirds and fish, limited data collections, both in space and time, prevented an accurate portrayal of either seabird or nekton distribution and abundance, especially as regards variance estimation. As food limitation is a product of total food availability at any one time, as well as the variance inherent in the system, both types of data need to be collected. We recommend repeating transects to increase sample size within a sampling period, and more than one sampling period. Sampling periods should be relative to the breeding phenology on colonies of interest (e.g. Tatoosh Island): pre-egg/egg stage (mid-late June), chick stage (late July), fledging/migratory stage (late August).

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Figure Legends

Figure 1. Map of the pilot study area, with transects outlined by date. Hydroacoustic and seabird data were collected from the same vessel, WDFW vessel *G. H. Corliss*. See table 1 for relevant information.

Figure 2A & B. Number of (A) observations (sightings) and (B) individuals, by species. Data from all transects. PIGU - Pigeon Guillemot, TUPU - Tufted Puffin, CAGU - California Gull, PECO - Pelagic Cormorant, SOSH - Sooty Shearwater, THAU - Rhinoceros Auklet, COMU - Common Murre, GWGU - Glaucous-winged Gull (also included are Western Gulls and Glaucous-winged Western hybrids), HEGU - Hermann's Gull. See Table 2 for relevant statistics.

Figure 3. Graphic representation of distance categories, relative to all space minutes within the sample area. In the final analysis, distance categories were 1 km in width and ranged from 1 to 22, excluding 20 due to small sample sizes. See Table 3 for relevant statistics.

Figure 4. Average densities of the four main species within the short transect sample area. Data include both short and long transects. Sample size ranges from 2 to 5.

Figure 5A-D. Average densities of the four main species for the long transects only. Sample size ranges from 1 to 2.

Figure 6A-D. Average densities of the four main species as a function of distance from Tatoosh, in 1 km categories. Data were averaged within unique space minutes, and then within distance category (i.e. all unique space minutes were equally weighted regardless of initial sample size). Open bars are actual data, lines are modeled values using a simplistic diffusion function (see text for details). Dashed lines are 5 and 95% confidence about the expected value.

Figure 7. Average nekton density (measured as Sa) as a function of distance from Tatoosh, in 1 km categories. Data prepared as in Figure 6.

Figure 8A-D. Averaged residual densities of the four main species as a function of averaged nekton density (measured as Sa), one sample per distance category: 1 to 22 km, except for km 20. See Tables 4 and 5 for relevant statistics.

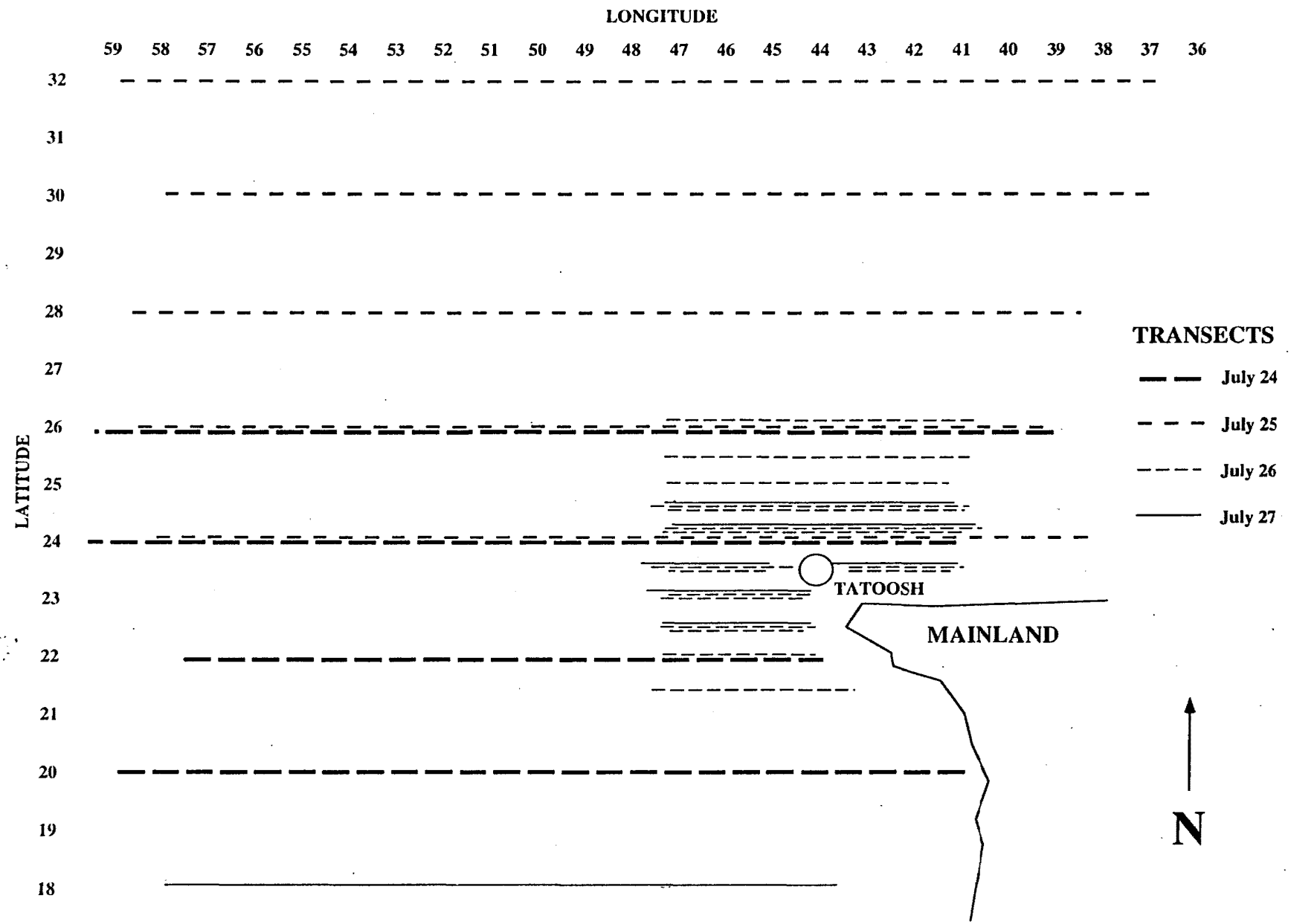
Figure 9A & B. Nekton density (measured as Sa) as a function of size of observed seabird rafts (A; indicated by large, sometimes multispecies aggregations of resting birds) and feeding aggregations (B). Nekton density within the same space minute (see Figure 1) as well as a 3 minute range surrounding the relevant "raft" minute are plotted. The dotted line in B represents the maximum value on the Y-axis of A.

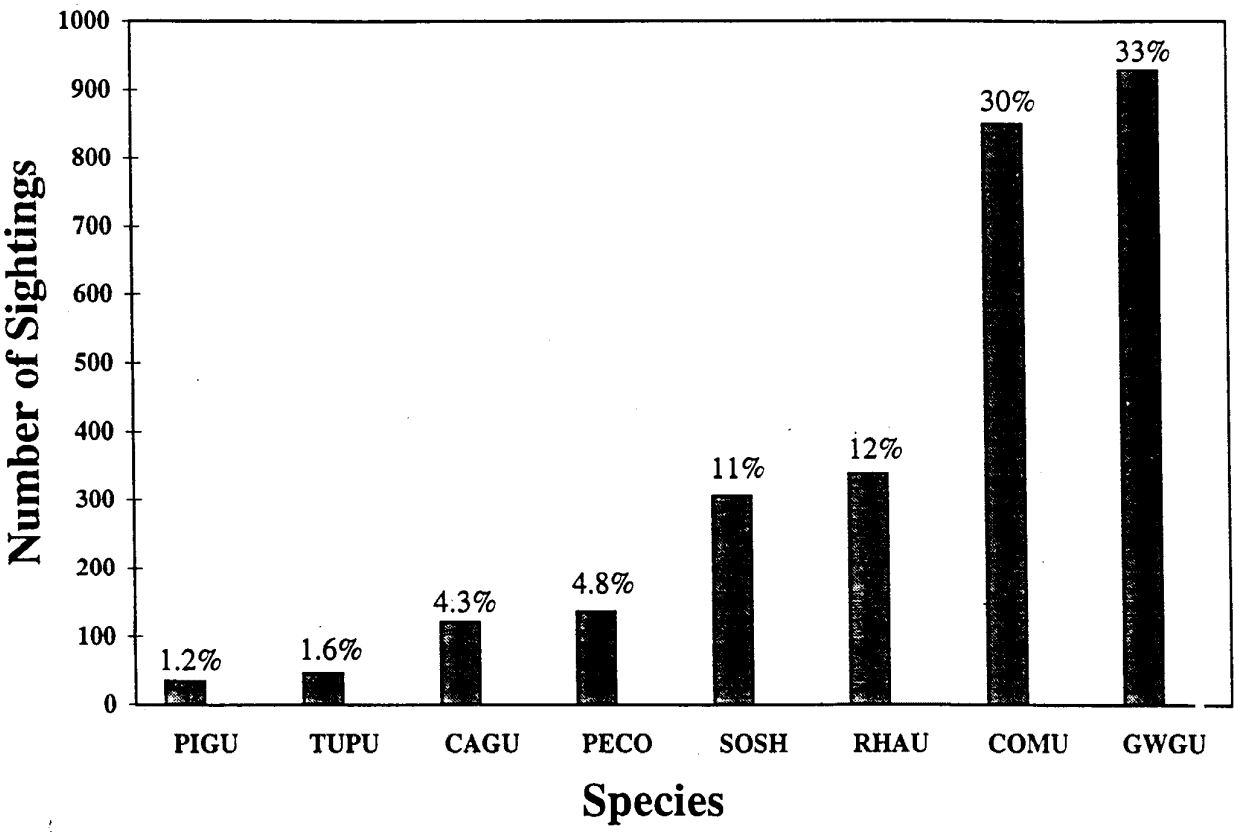
Figure 10. Seabirds per km of transect as a function of distance from shore from surveys off SW Vancouver Island (including the sample area in this study) in September and

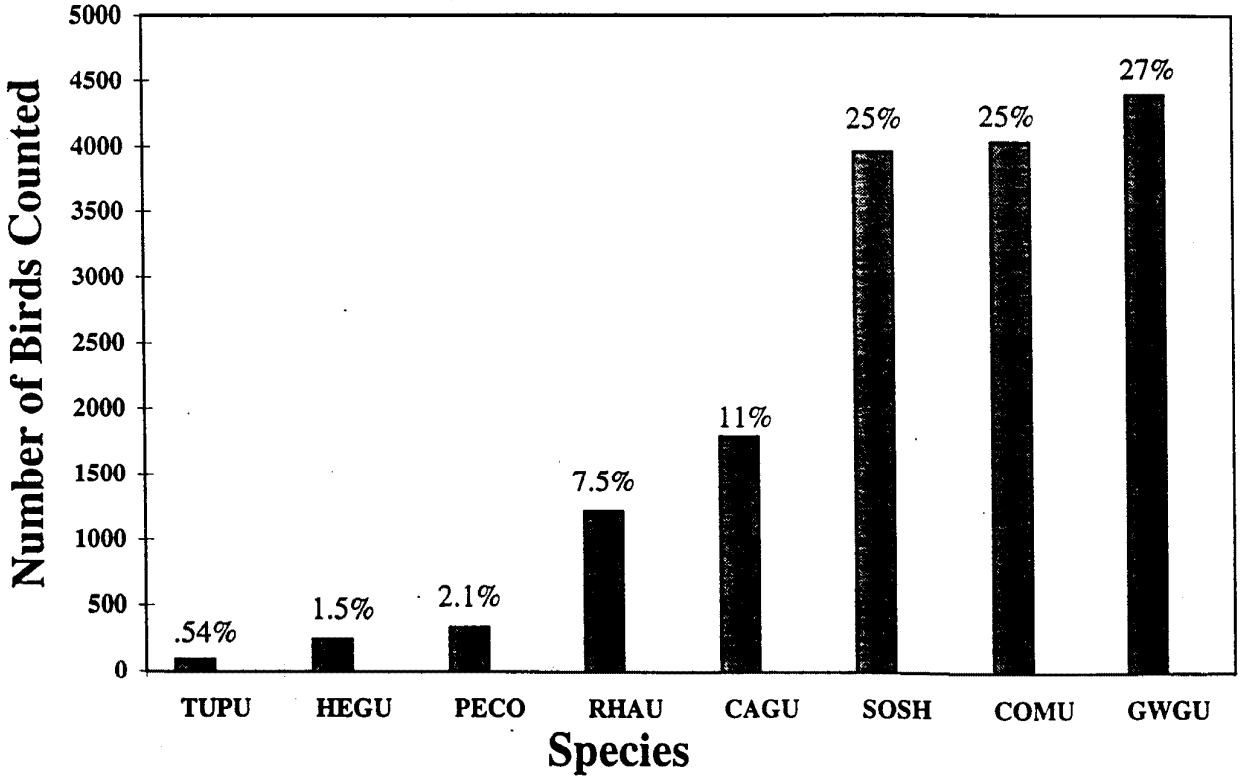
October 1986-87. NOFU - Northern Fulmar; A - adult; all other abbreviations as in Figure 2. Note that the most abundant species, CAGU, is not represented on this graph. Data originally from Table 3, Vermeer et. al. 1989.

Figure 11. Theoretical relationship between the cost of seabird foraging (a linear function of distance traveled) and the gain (a function of the quantity and quality of food). Because net gain decreases as distance increases, seabirds should forage close to their breeding colonies even if there are higher gross gains within their range. After Figure 5, Schneider et. al. 1990.

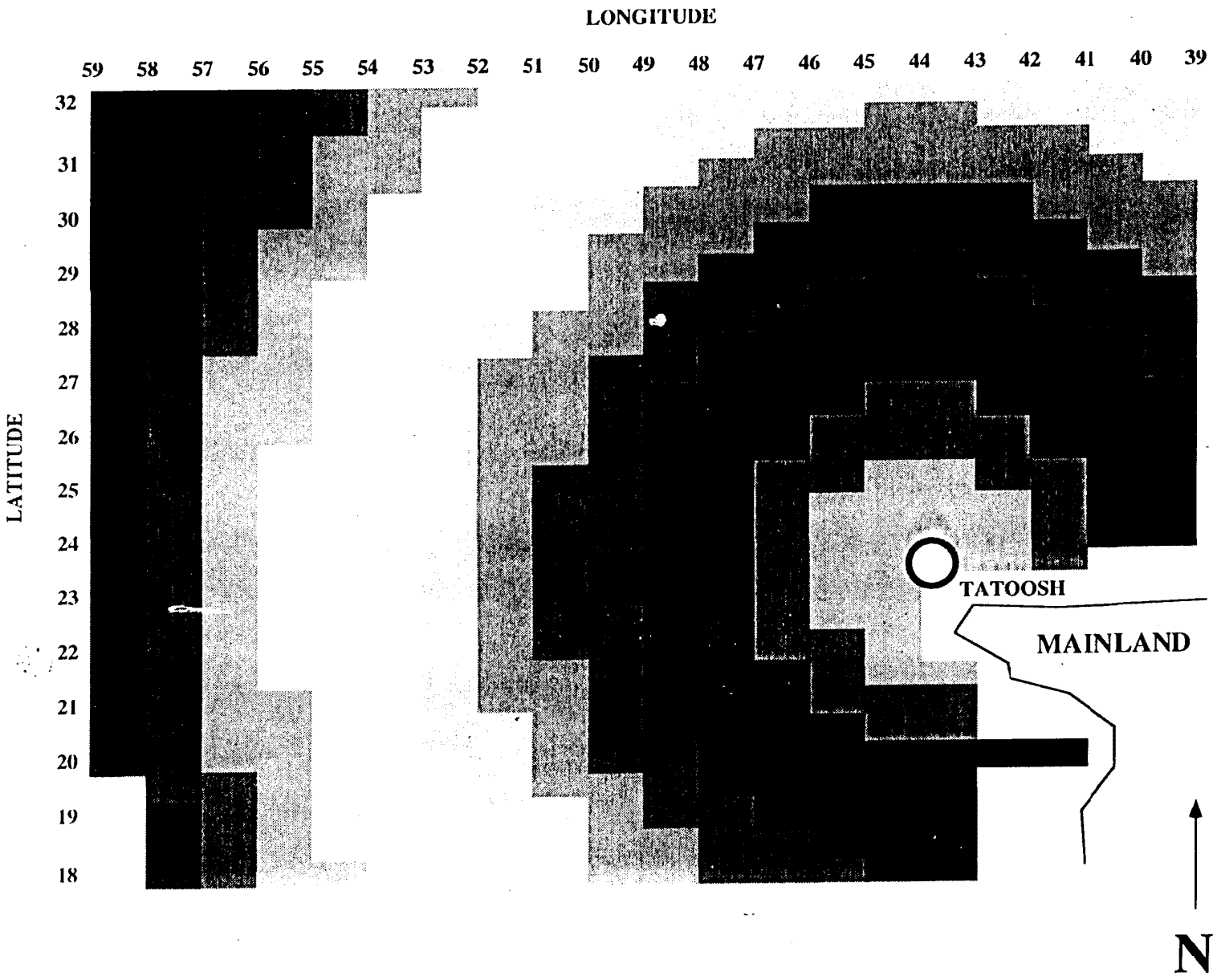
1995 SURVEY AREA




Number of Sightings
1000
900
800
700
600
500
400
300
200
100
0
1.2%
1.6%
4.3%
4.8%
11%
12%
30%
33%
PIGU
TUPU
CAGU
PECO
SOSH
RHAU
COMU
GWGU
Species


Number of Birds Counted
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
.54%
1.5%
2.1%
7.5%
11%
25%
25%
27%
TUPU
HEGU
PECO
RHAU
CAGU
SOSH
COMU
GWGU
Species

1995 SURVEY AREA

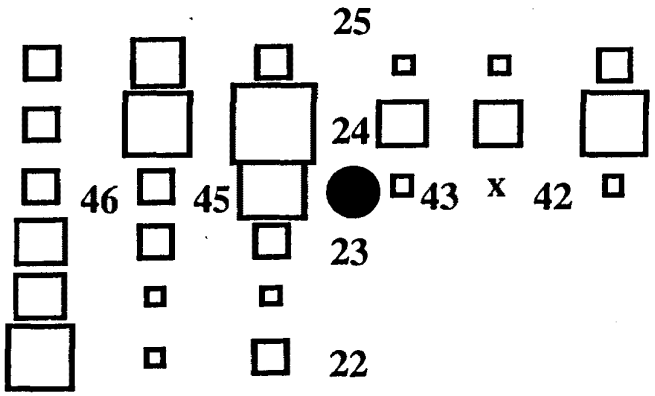


DISTANCE FROM TATOOSH (KM)

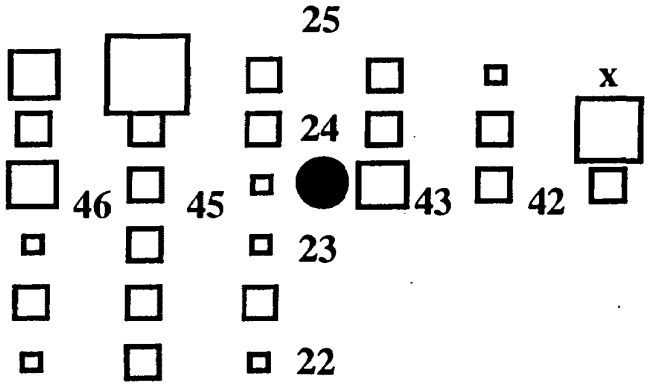
- 27 - 30
- 25 - 27
- 23 - 25
- 21 - 23
- 19 - 21
- 17 - 19
- 15 - 17
- 13 - 15
- 11 - 13
- 9 - 11
- 7 - 9
- 5 - 7
- 3 - 5
- 0 - 3

Densities of All Species in Multiply Sampled Transects

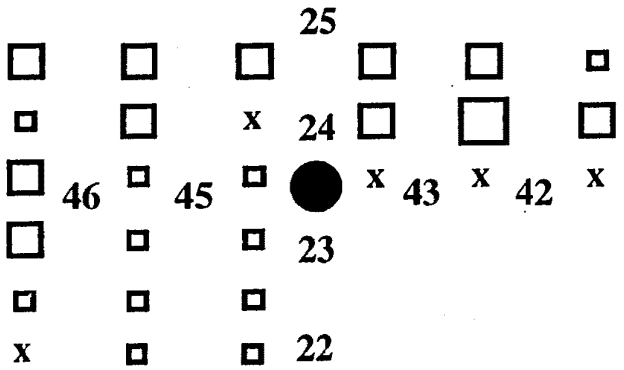
Common Murre Densities



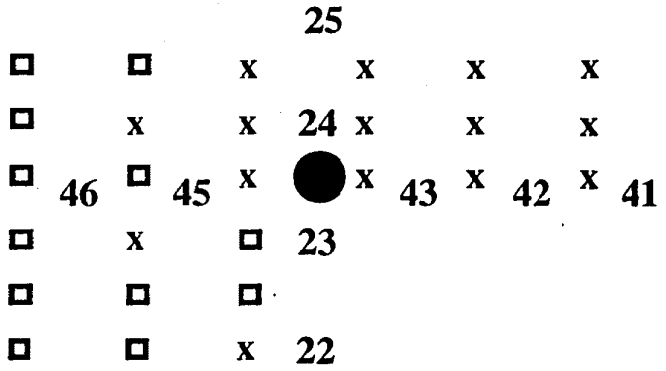
Glaucous Winged Gull Densities

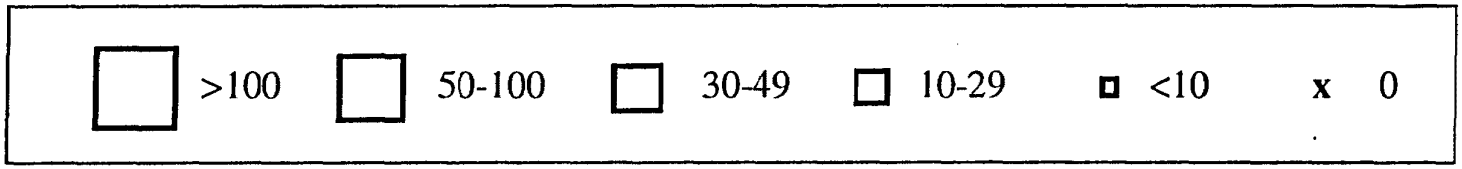


Rhinoceros Auklet Densities

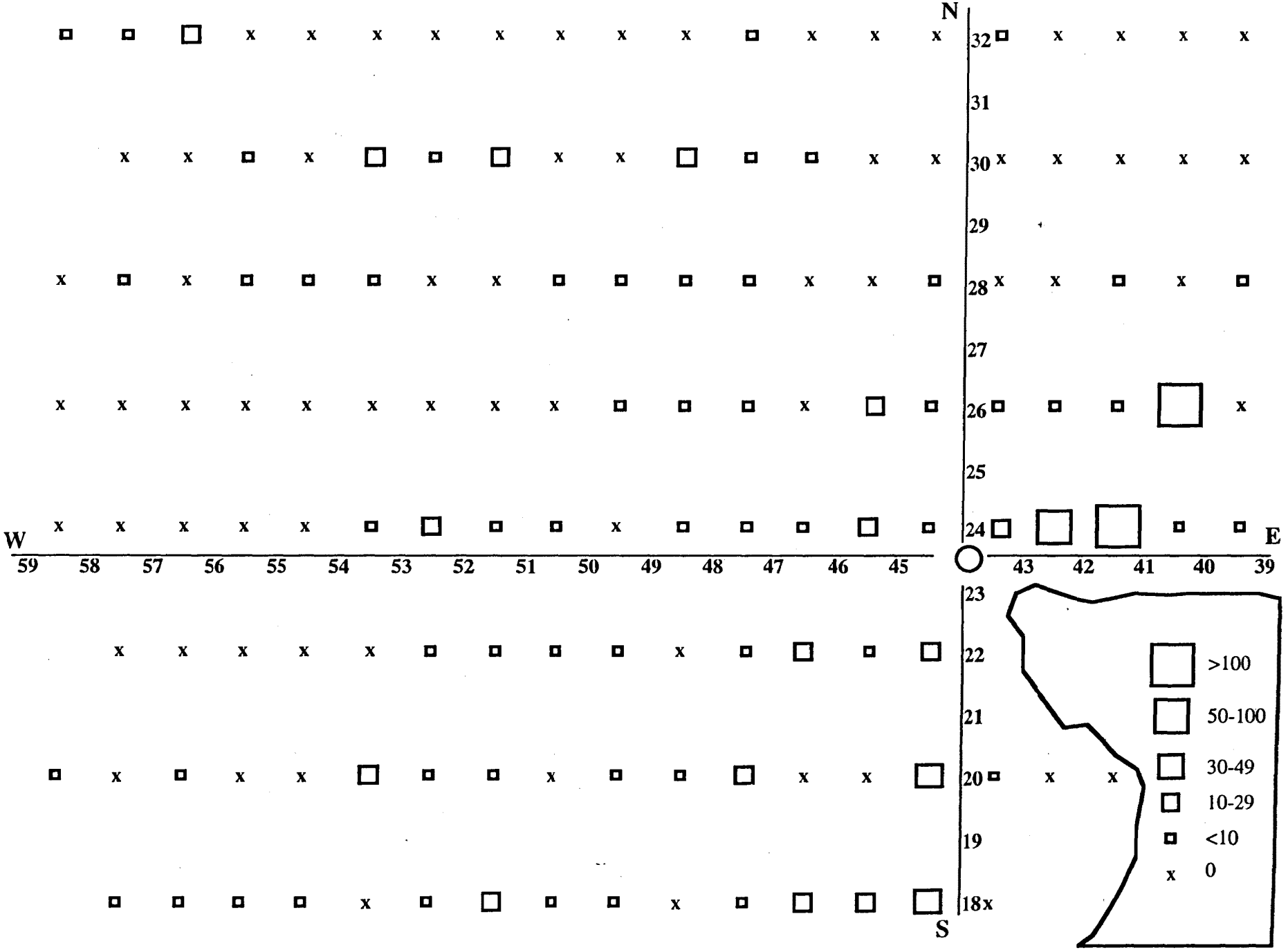


Sooty Shearwater Densities

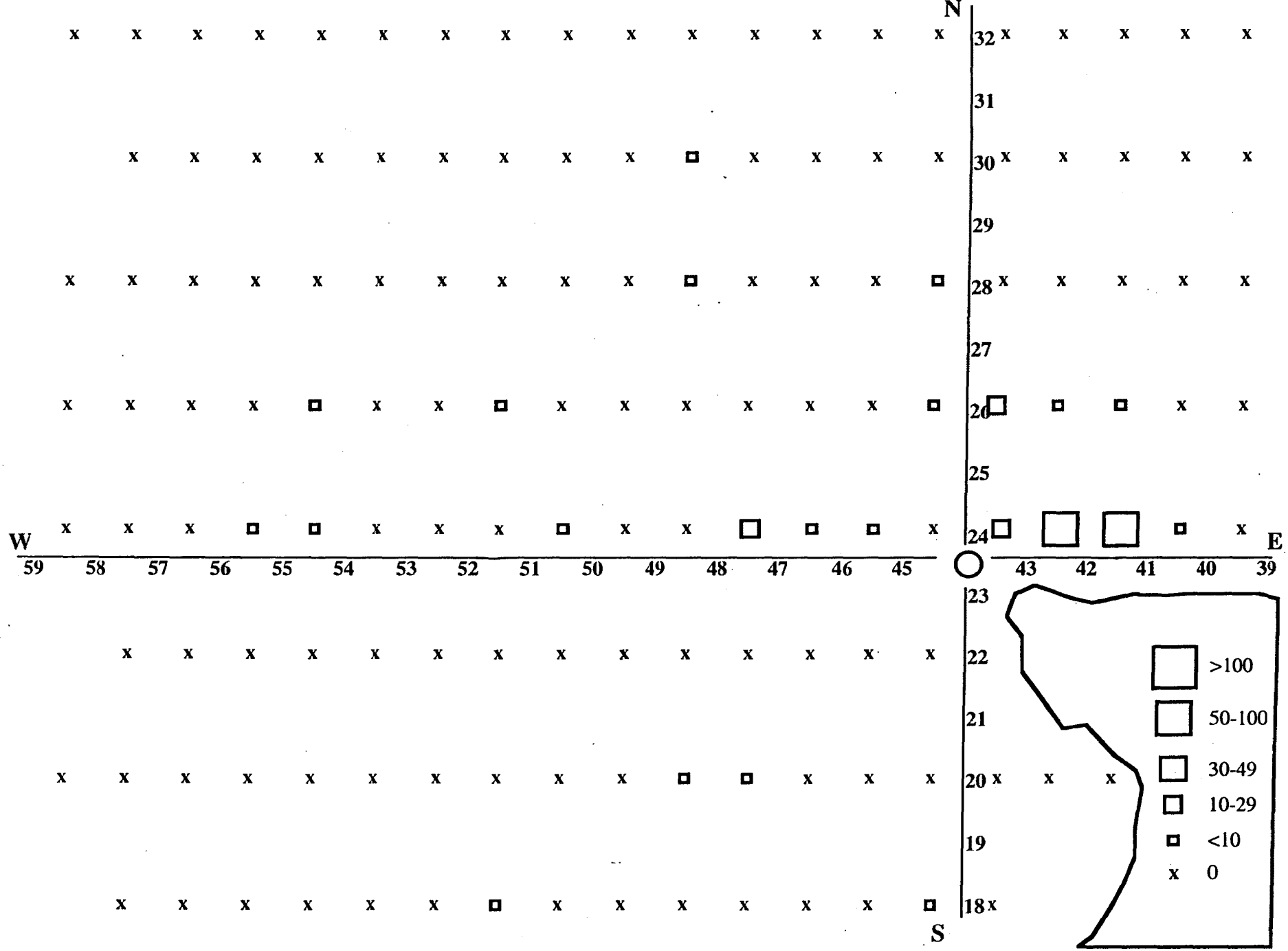




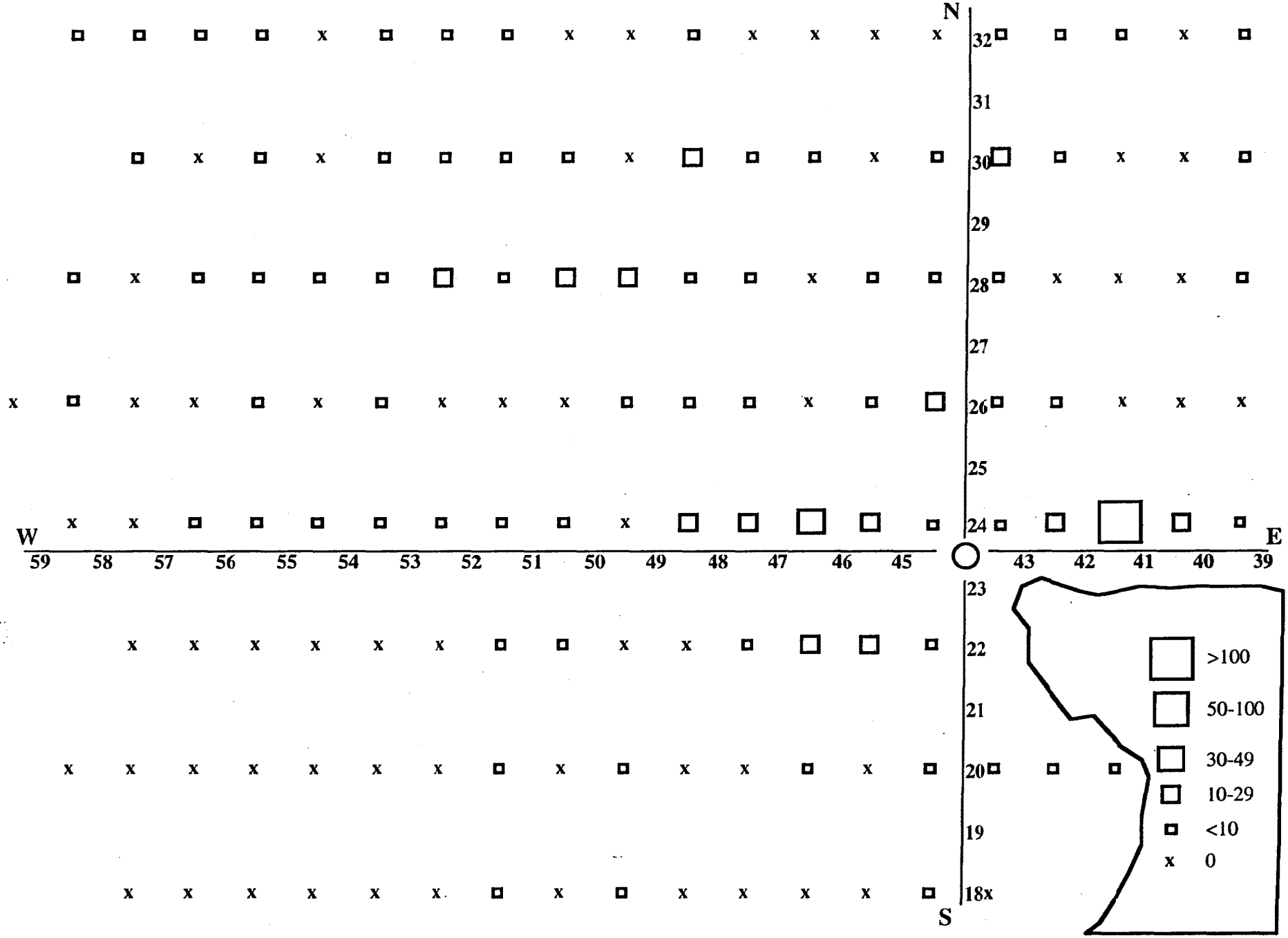
Distribution and abundance of Common Murres around Tatoosh Island During Long Transects Only (24-27 July 1995)



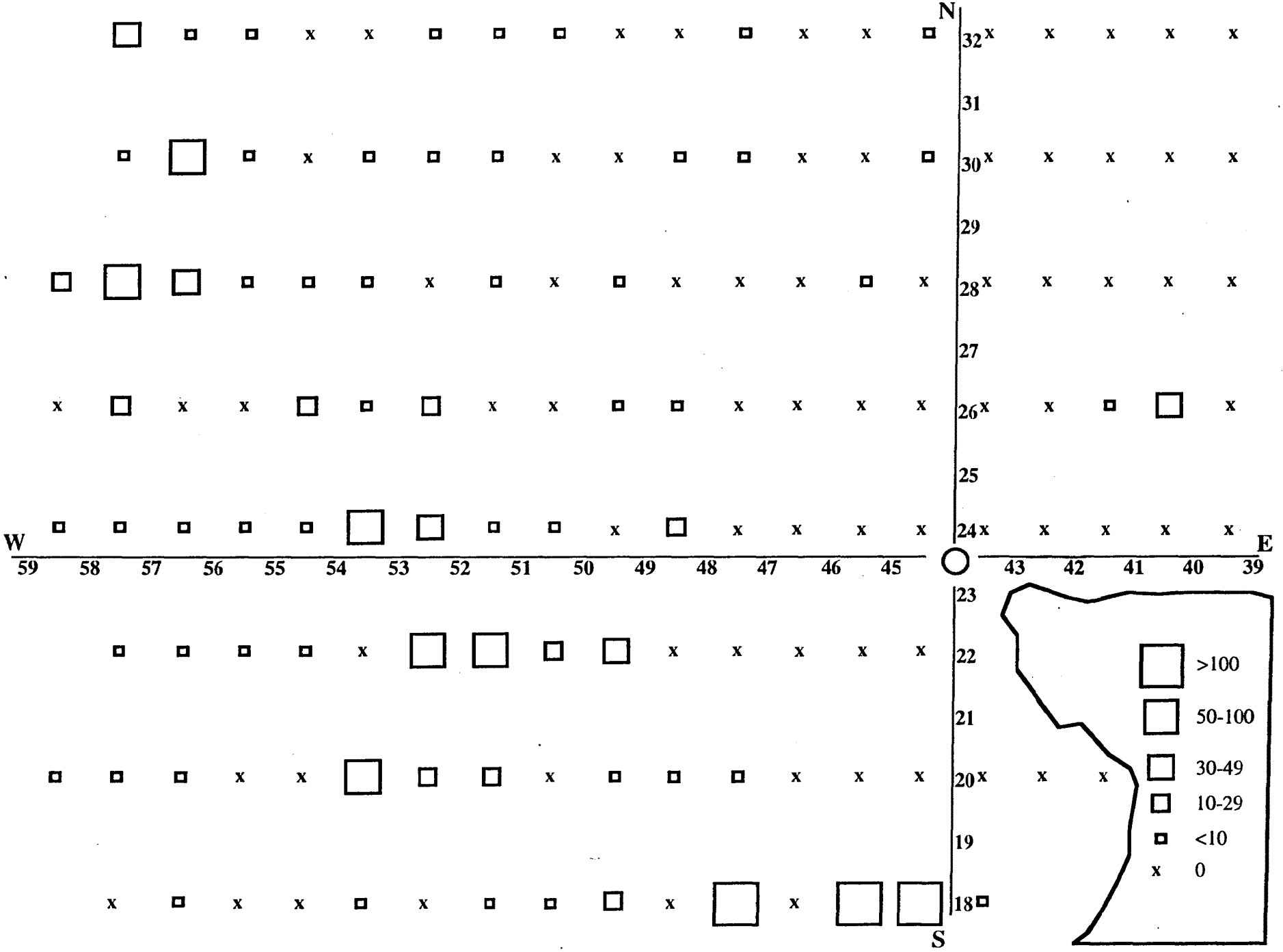
Distribution and abundance of Rhinoceros Auklets around Tatoosh Island Long Transects Only (24-27 July 1995)

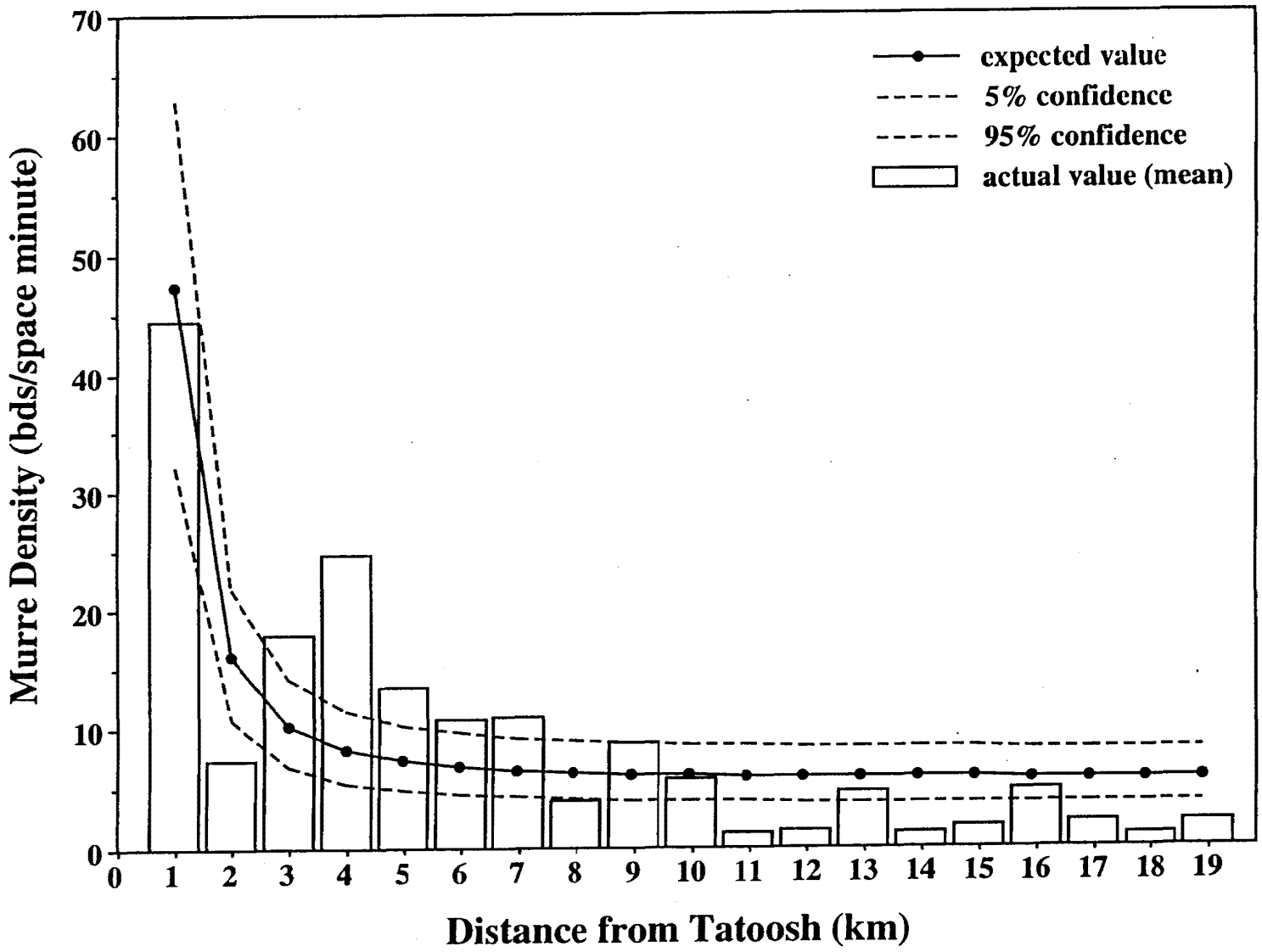


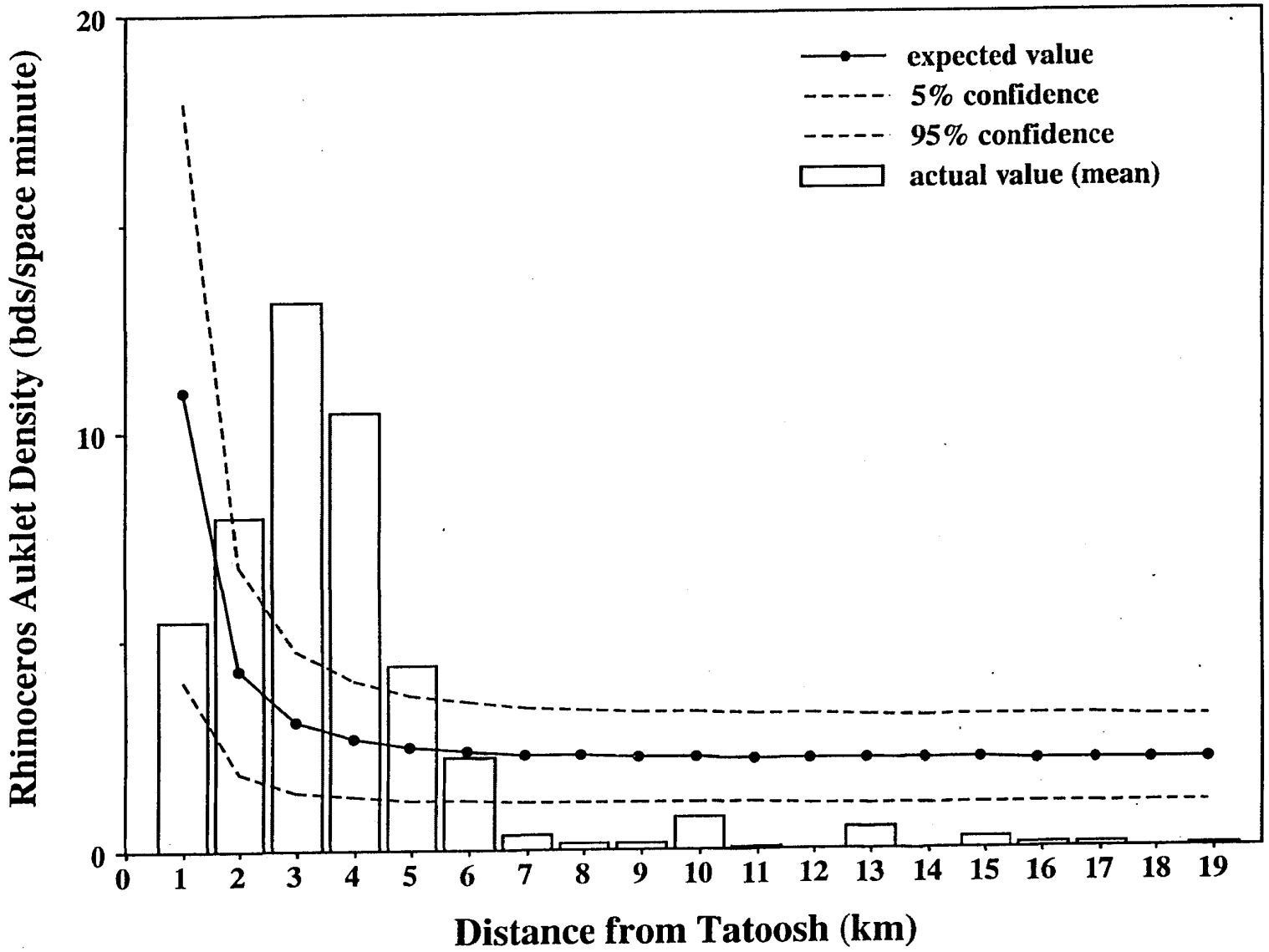
Distribution and abundance of Glaucous Winged Gulls around Tatoosh Island Long Transects Only (24-27 July 1995)

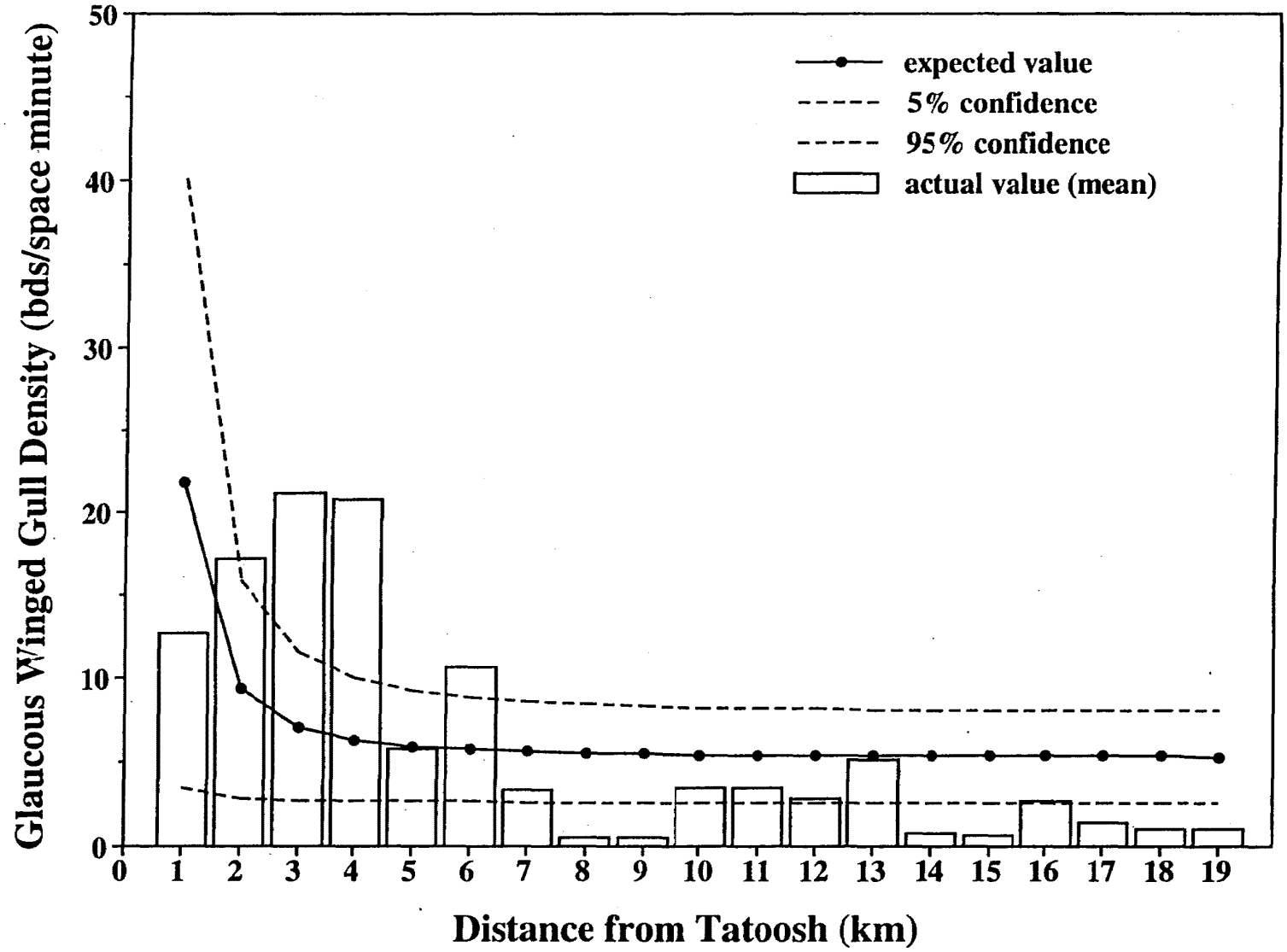


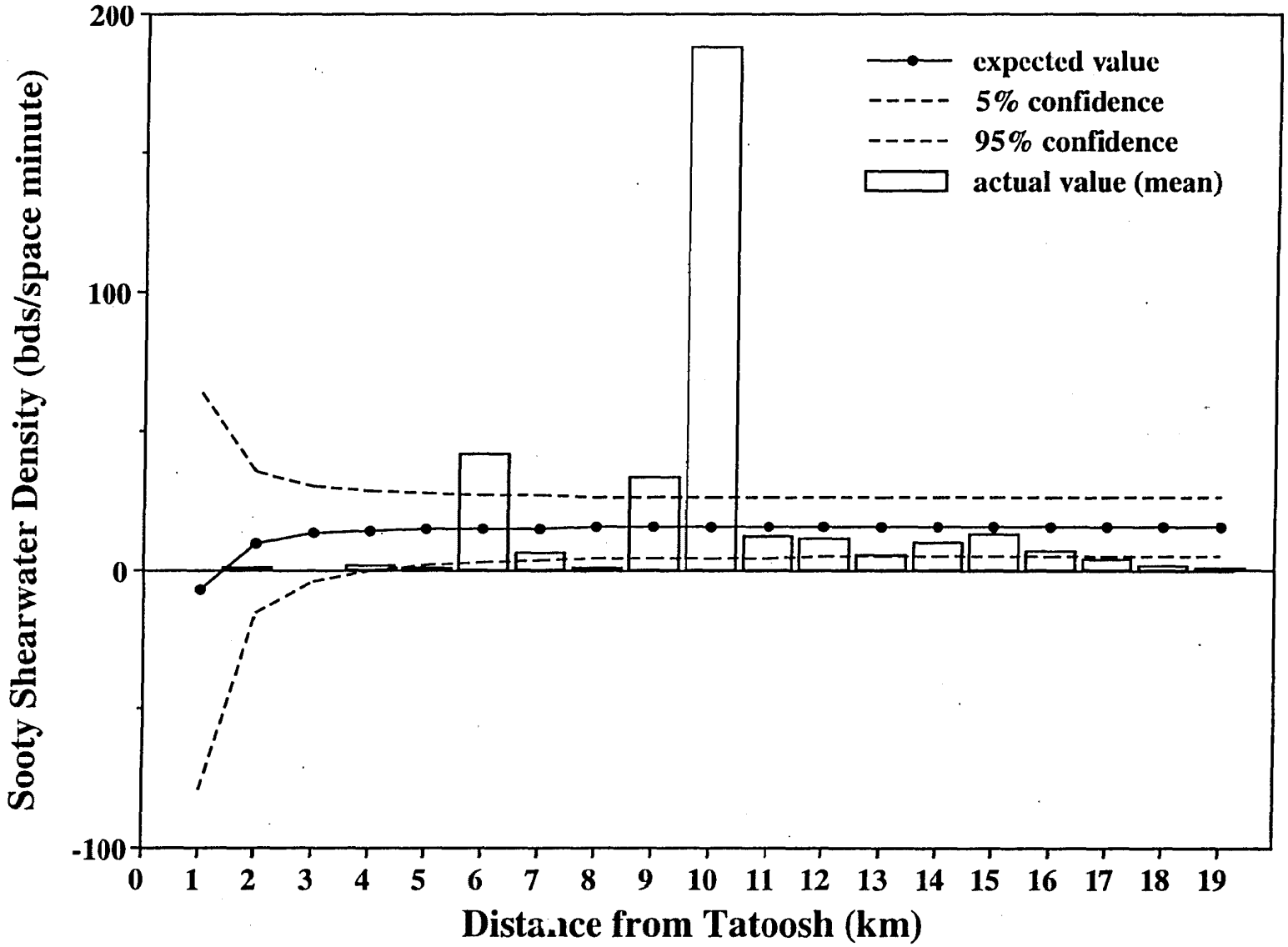
Distribution and abundance of Sooty Shearwaters around Tatoosh Island Long Transects Only (24-27 July 1995)

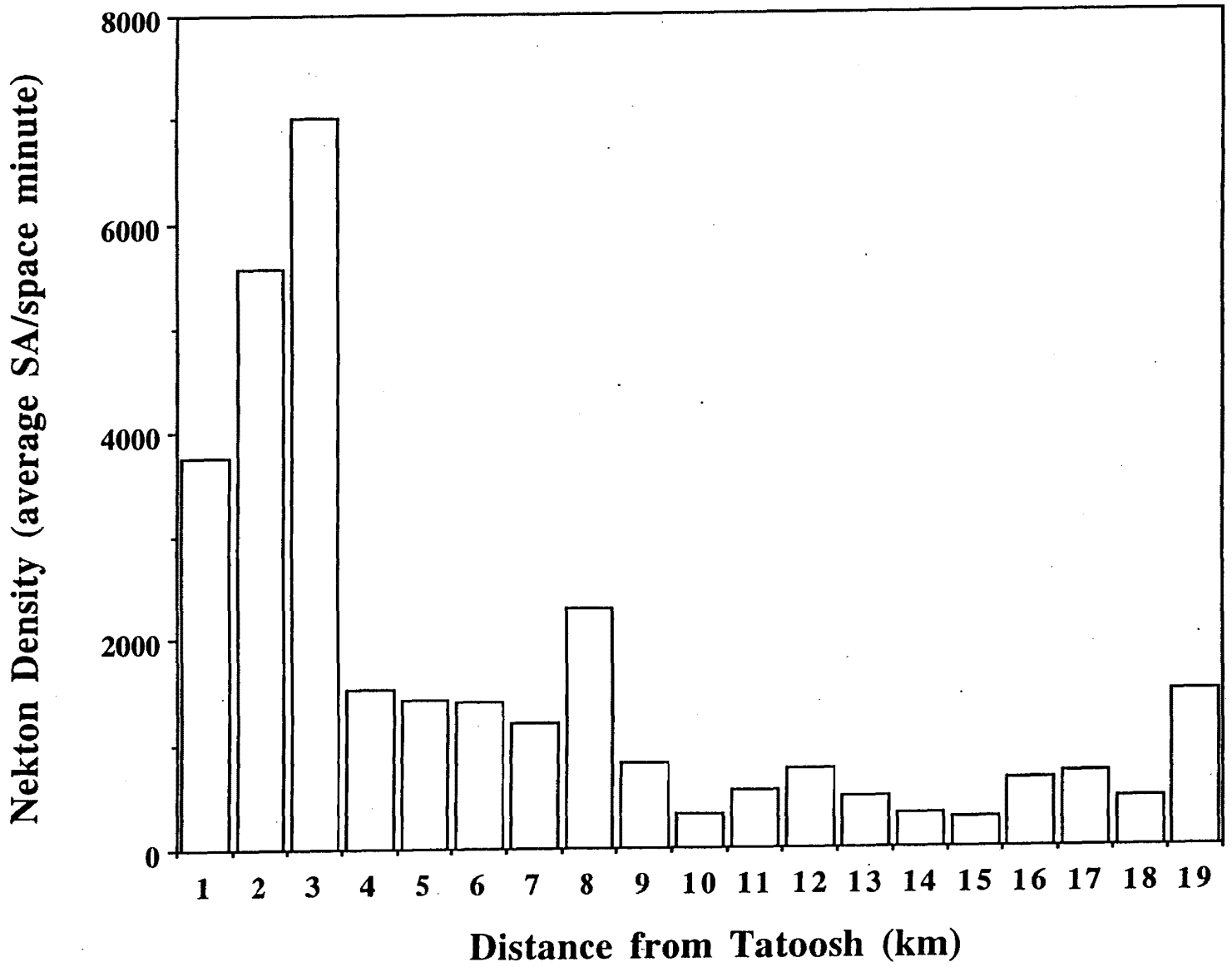


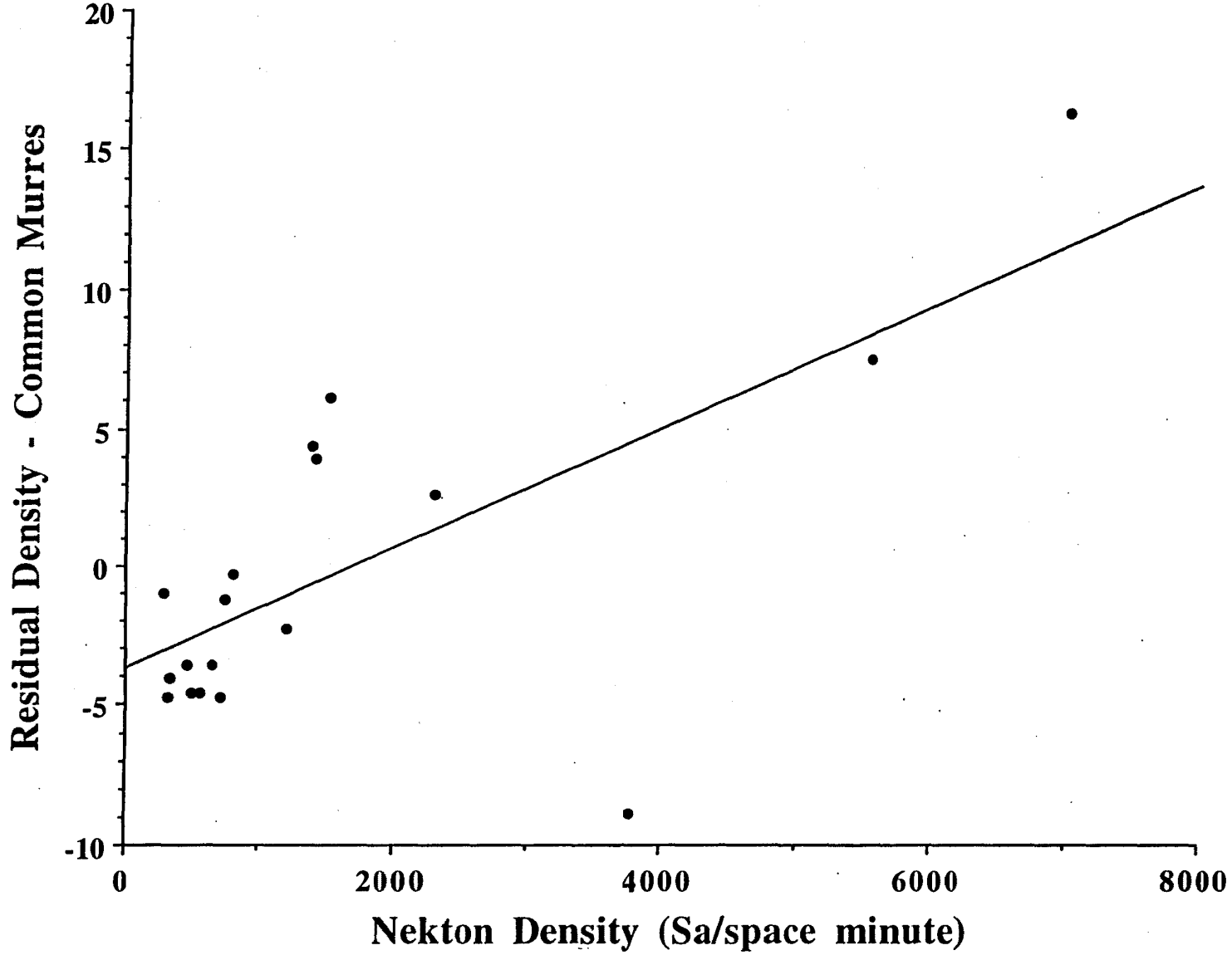

expected value
5% confidence
95% confidence
actual value (mean)
Murre Density (bds/space minute)
0
10
20
30
40
50
60
70
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Distance from Tatoosh (km)

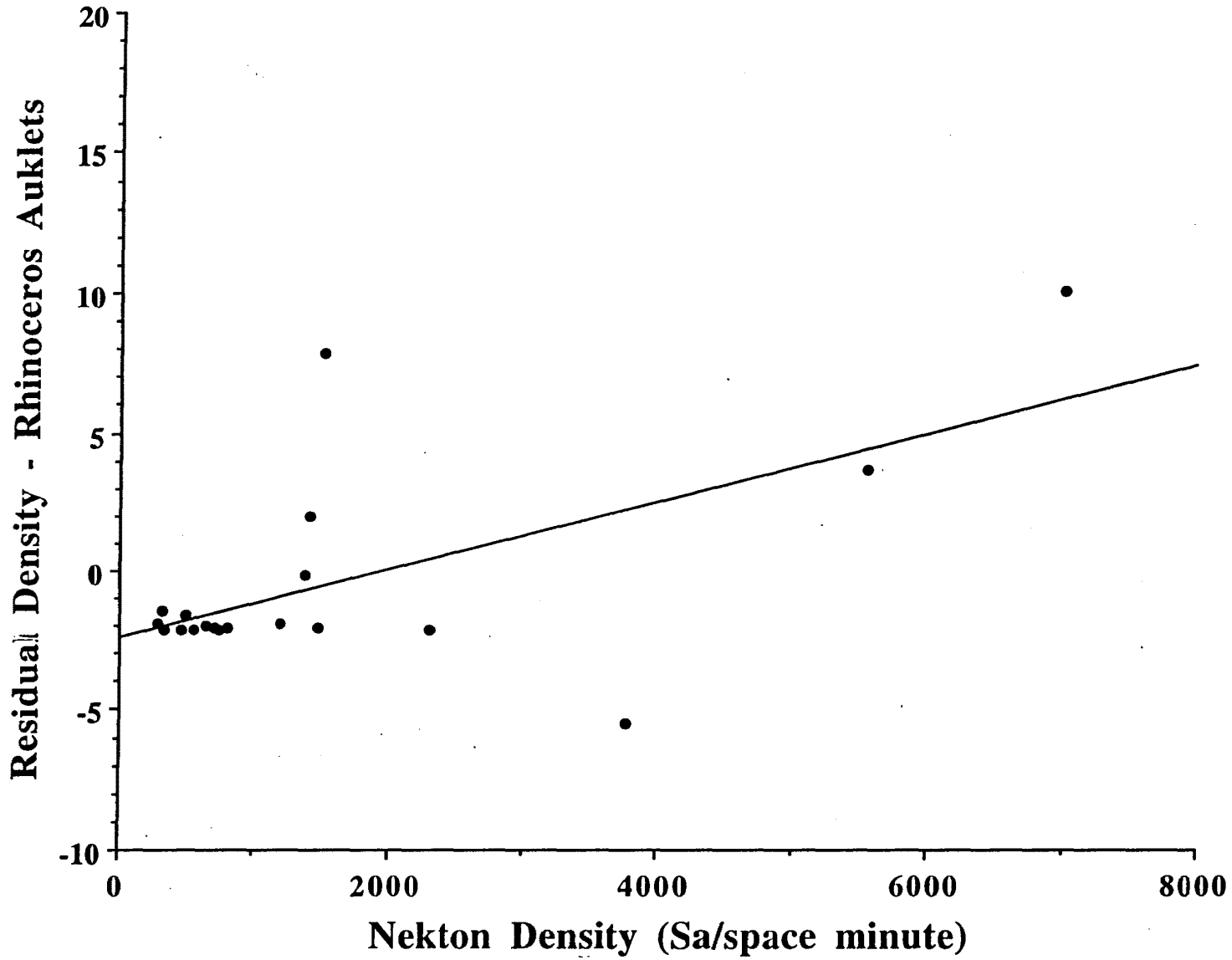

Rhinoceros Auklet Density (bds/space minute)
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Distance from Tatoosh (km)
expected value
5% confidence
95% confidence
actual value (mean)

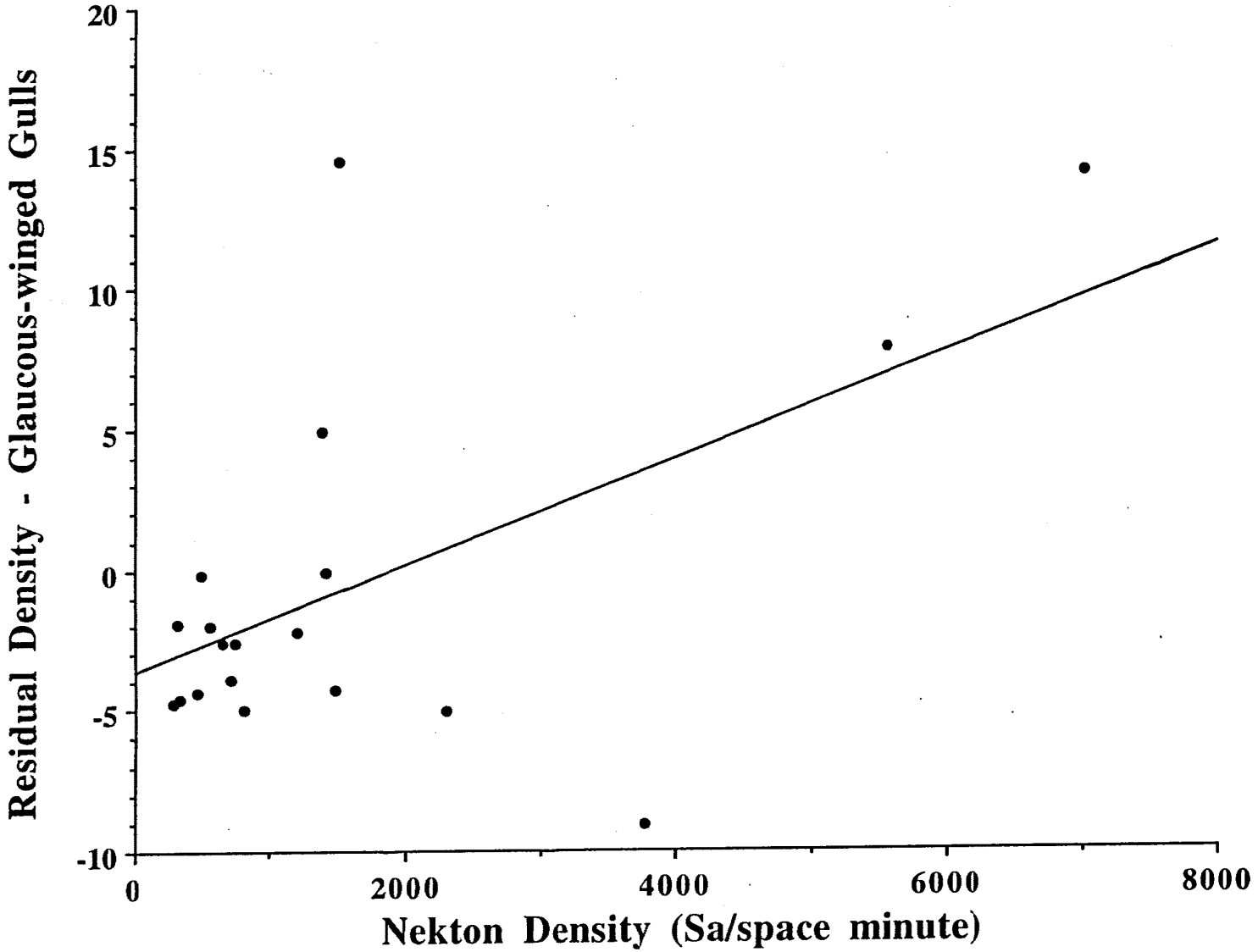

Glaucous Winged Gull Density (bds/space minute)
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Distance from Tatoosh (km)
expected value
5% confidence
95% confidence
actual value (mean)

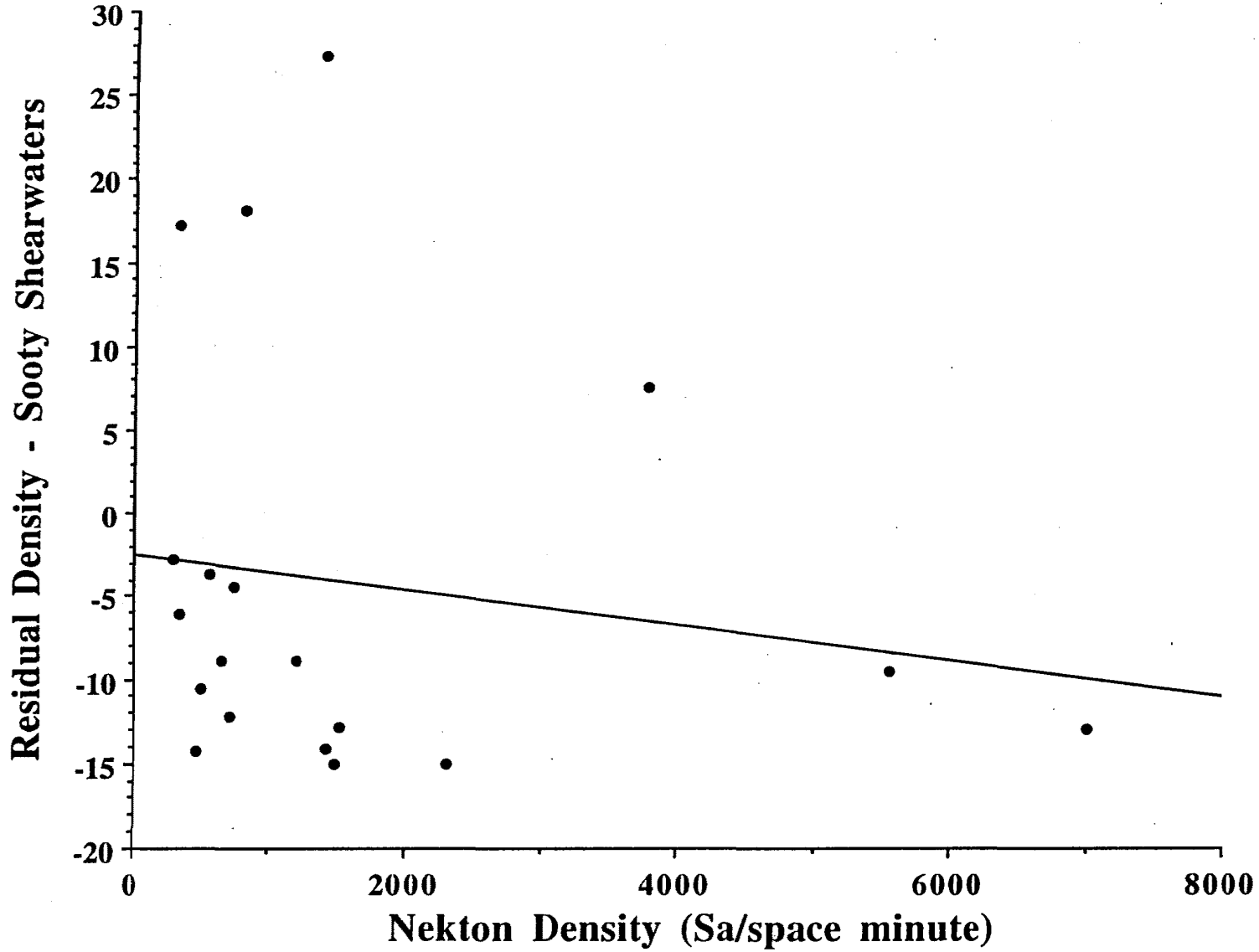

200
100
0
-100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Sooty Shearwater Density (bds/space minute)
Distance from Tatoosh (km)
expected value
5% confidence
95% confidence
actual value (mean)

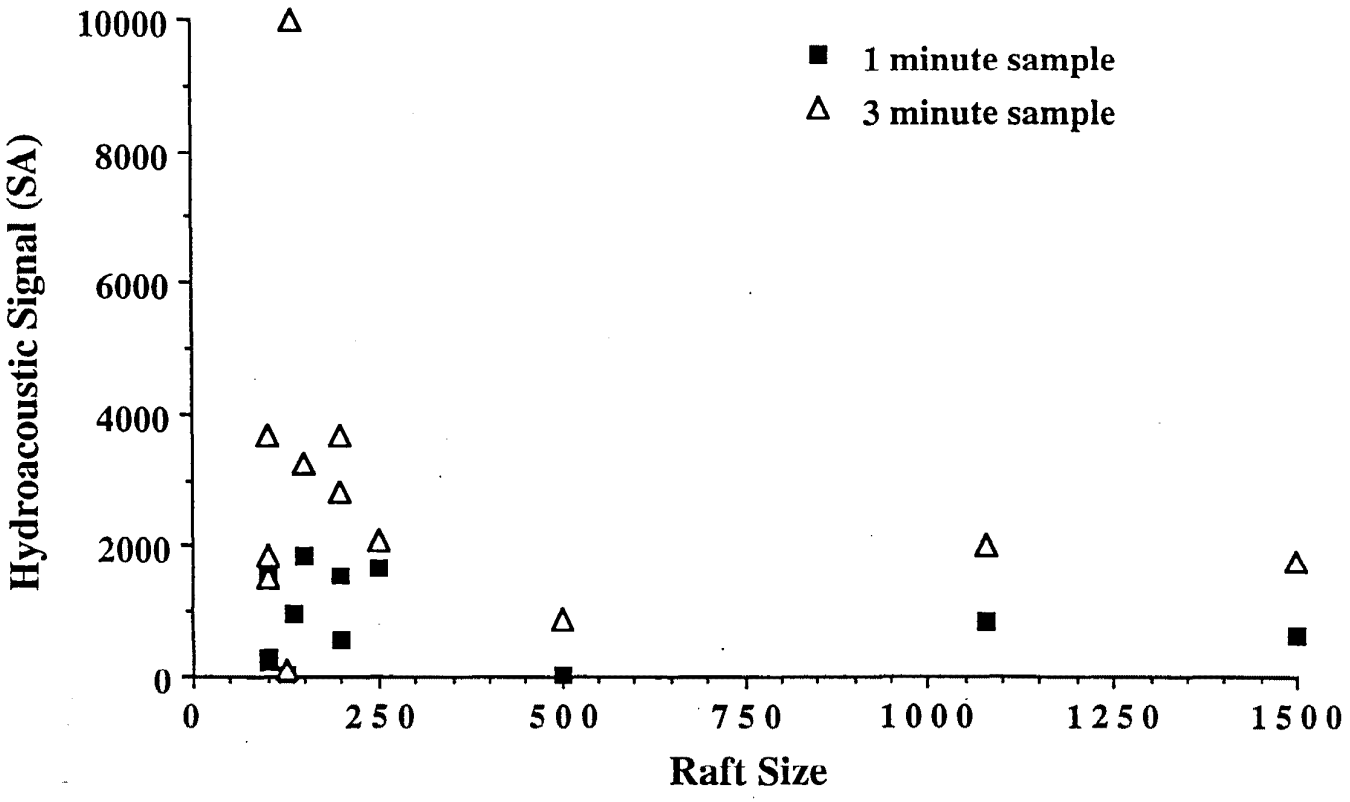

Nekton Density (average SA/space minute)
8000
6000
4000
2000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Distance from Tatoosh (km)

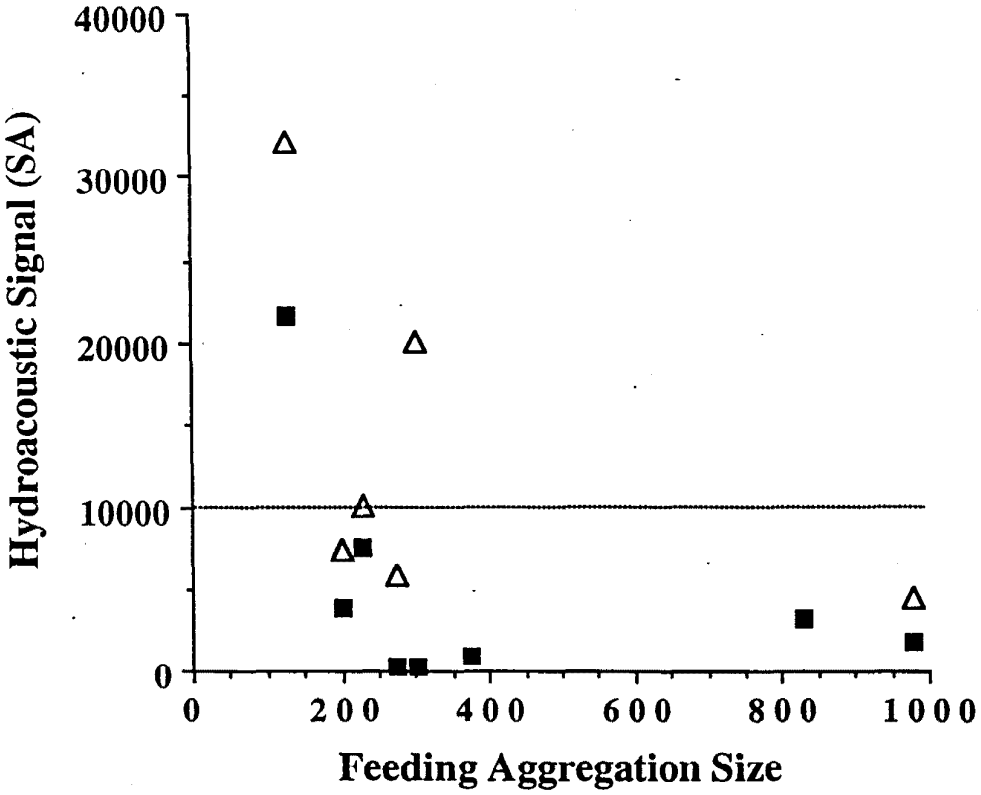

Residual Density - Common Murres
20
15
10
5
0
-5
-10
0
2000
4000
6000
8000
Nekton Density (Sa/space minute)

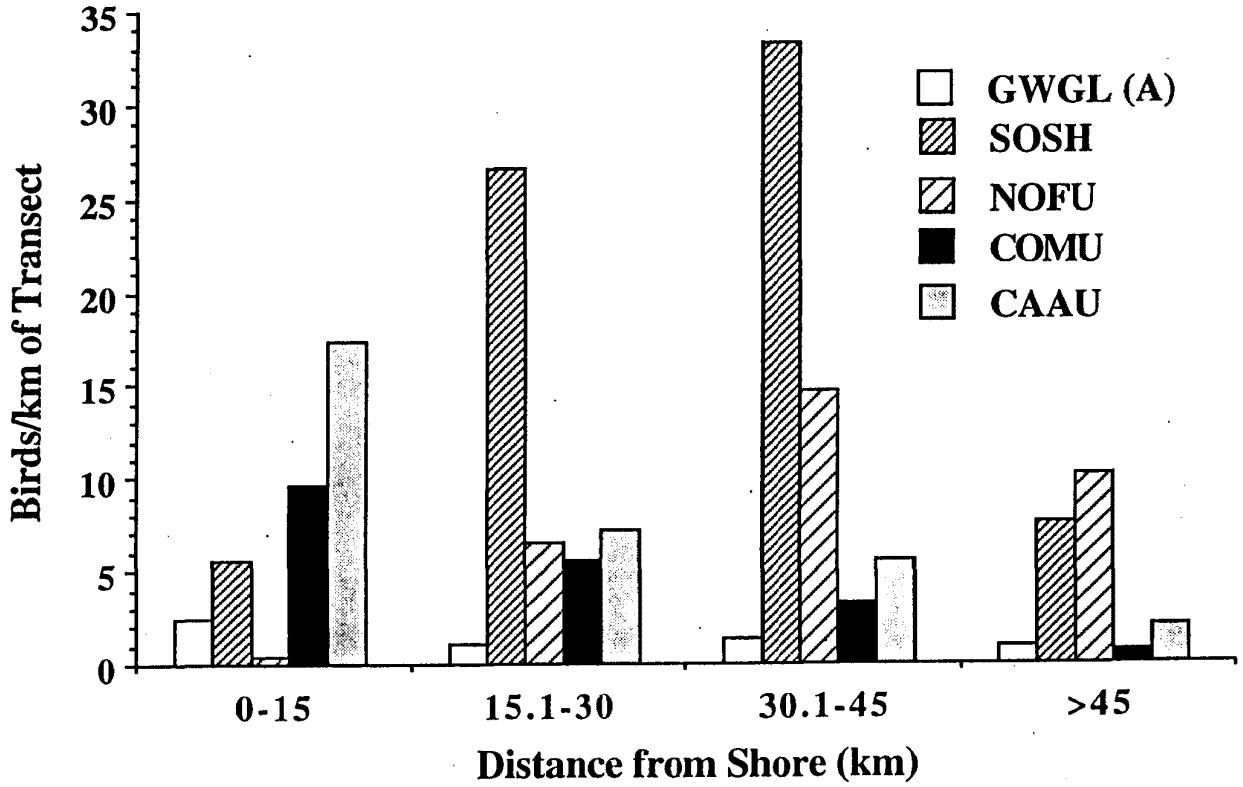

Residual Density - Rhinoceros Auklets
20
15
10
5
0
-5
-10
0
2000
4000
6000
8000
Nekton Density (Sa/space minute)


Residual Density - Glaucous-winged Gulls
20
15
10
5
0
-5
-10
0
2000
4000
6000
8000
Nekton Density (Sa/space minute)


Residual Density - Sooty Shearwaters
30
25
20
15
10
5
0
-5
-10
-15
-20
0
2000
4000
6000
8000
Nekton Density (Sa/space minute)


10000
8000
6000
4000
2000
0
Hydroacoustic Signal (SA)
1 minute sample
3 minute sample
0
250
500
750
1000
1250
1500
Raft Size


40000
30000
20000
10000
0
Hydroacoustic Signal (SA)
0
200
400
600
800
1000
Feeding Aggregation Size


35
30
25
20
15
10
5
0
Birds/km of Transect
GWGL (A)
SOSH
NOFU
COMU
CAAU
0-15
15.1-30
30.1-45
>45
Distance from Shore (km)

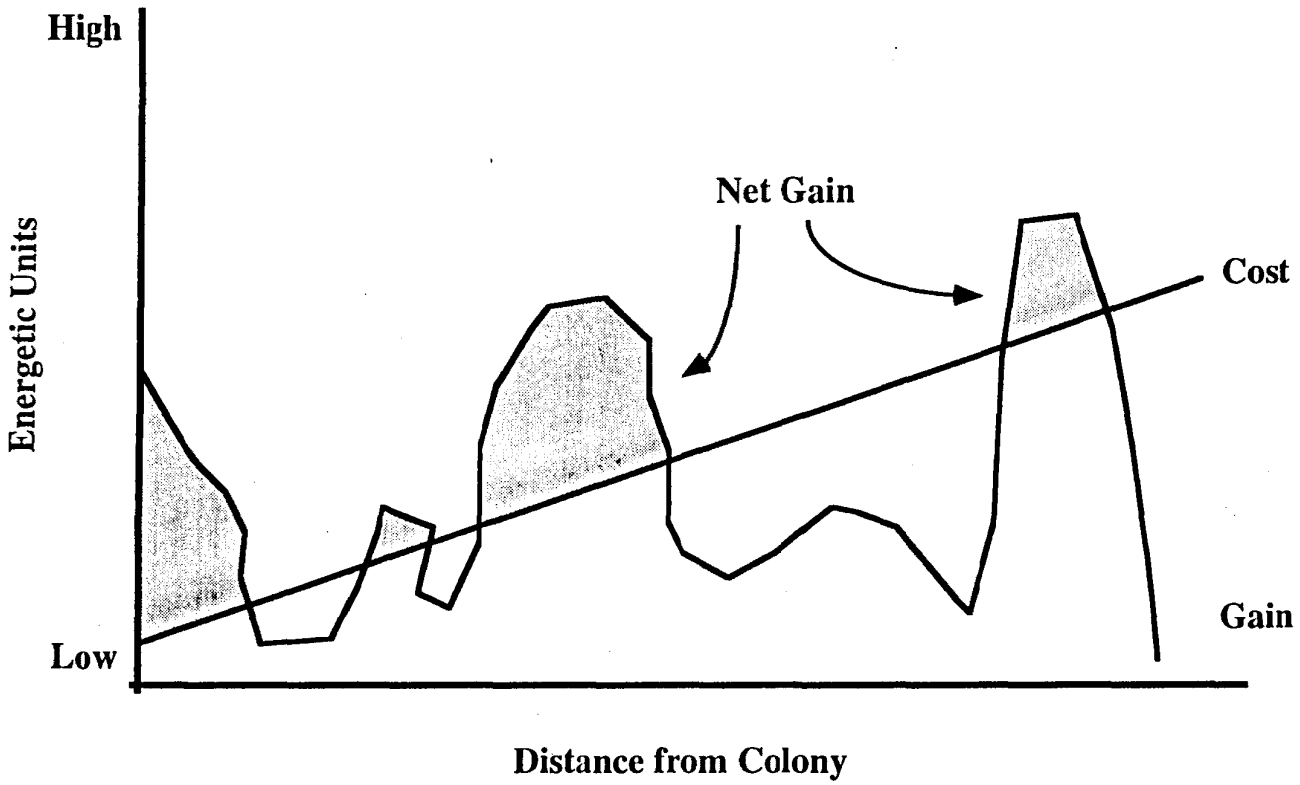

High
Low
Energetic Units
Net Gain
Cost
Gain
Distance from Colony

Table 1. Timing and placement of seabird/hydroacoustic surveys

TRANSECT ID	TYPE	DATE	START TIME	LATITUDE (minutes)	Start LONGITUDE (minutes)	End LONGITUDE (minutes)	#BIRDS SEEN	# SEABIRD WATCHES	SEABIRD WATCH LENGTH	SPACE MINUTES SAMPLED
724.1	LONG	7/24/95	1419.6	26.00	39	60	2614	5	15	21
724.2	LONG	7/24/95	1557.9	24.00	59	40	750	4	15	19
724.3	LONG	7/24/95	1805.3	22.00	44	57	799	3	15	13
724.4	LONG	7/24/95	1922.0	20.00	59	41	1461	4	15	18
725.1	LONG	7/25/95	843.0	24.00	39	58	1571	4	15	19
725.2	LONG	7/25/95	1017.0	26.00	58	39	285	5	15	19
725.3	LONG	7/25/95	1206.0	28.00	38	58	270	5	15	20
725.4	LONG	7/25/95	1402.5	30.00	58	37	238	5	15	21
725.5	LONG	7/25/95	1555.0	32.00	37	59	225	5	15	22
726.01	SHORT	7/26/95	935.5	23.50	44	41	139	1	CONTINUOUS	3
726.02	SHORT	7/26/95	948.7	24.00	41	47	1261	1	CONTINUOUS	6
726.03	SHORT	7/26/95	1025.5	24.50	47	41	1269	1	CONTINUOUS	6
726.04	SHORT	7/26/95	1120.6	25.00	41	47	234	1	CONTINUOUS	6
726.05	SHORT	7/26/95	1152.0	25.50	48	41	428	1	CONTINUOUS	7
726.06	SHORT	7/26/95	1229.5	26.00	41	47	606	1	CONTINUOUS	6
726.07	SHORT	7/26/95	1318.3	23.50	48	45	74	1	CONTINUOUS	3
726.08	SHORT	7/26/95	1339.9	23.00	44	47	178	1	CONTINUOUS	3
726.09	SHORT	7/26/95	1408.1	22.50	47	45	114	1	CONTINUOUS	2
726.10	SHORT	7/26/95	1429.8	22.00	44	47	161	1	CONTINUOUS	3
726.11	SHORT	7/26/95	1452.0	21.50	48	44	132	1	CONTINUOUS	4
726.12	SHORT	7/26/95	1534.2	23.50	44	41	204	1	CONTINUOUS	3
726.13	SHORT	7/26/95	1552.4	24.00	40	47	417	1	CONTINUOUS	7
726.14	SHORT	7/26/95	1635.1	24.50	48	41	369	1	CONTINUOUS	7
726.15	SHORT	7/26/95	1726.9	23.50	41	47	408	1	CONTINUOUS	3
726.16	SHORT	7/26/95	1749.3	23.00	48	45	206	1	CONTINUOUS	3
726.17	SHORT	7/26/95	1811.5	22.50	44	47	148	1	CONTINUOUS	3
727.1	SHORT	7/27/95	945.4	23.50	44	41	103	1	CONTINUOUS	3
727.2	SHORT	7/27/95	1002.8	24.00	40	47	415	1	CONTINUOUS	7
727.3	SHORT	7/27/95	1039.2	24.50	47	42	207	1	CONTINUOUS	5
727.4	SHORT	7/27/95	1217.0	23.50	45	47	135	1	CONTINUOUS	2
727.5	SHORT	7/27/95	1234.3	23.00	48	44	156	1	CONTINUOUS	4
727.6	SHORT	7/27/95	1256.7	22.50	44	47	82	1	CONTINUOUS	3
727.7	LONG	7/27/95	1350.0	18.00	58	43	474	3	15	15

Table 2. Numbers of sightings and birds counted

Species	#Sightings	#Birds Counted	% of Sightings	% of Count
BRCO	10	13	0.36%	0.08%
CAAU	10	10	0.36%	0.06%
CAGU	121	1786	4.31%	11.04%
COMU	850	4034	30.30%	24.94%
DCCO	6	7	0.21%	0.04%
GWGU	929	4394	33.12%	27.16%
HEGU	9	238	0.32%	1.47%
MAMU	4	3	0.14%	0.02%
PECO	135	332	4.81%	2.05%
PIGU	33	38	1.18%	0.23%
RHAU	338	1211	12.05%	7.49%
SOSH	306	3962	10.91%	24.49%
STSH	5	55	0.18%	0.34%
TUPU	45	87	1.60%	0.54%
OTHER	4	7	0.14%	0.04%
TOTALS	**2805**	**16177**		

Table 3. Actual and potential space minutes sampled at different distances from Tatoosh Island

Distance from Tatoosh (km)	Space Minutes Sampled	Potential Space Minutes/Distance	% Coverage
0-3	31	10	310.00%
3-5	69	31	222.58%
5-7	33	26	126.92%
7-9	24	44	54.55%
9-11	13	35	37.14%
11-13	22	46	47.83%
13-15	22	42	52.38%
15-17	20	37	54.05%
17-19	12	26	46.15%
19-21	16	32	50.00%
21-23	14	27	51.85%
23-25	12	24	50.00%
25-28	4	7	57.14%
Totals	**292**	**387**	**75.45%**

Table 4. Linear regression statistics
Model: Seabird density = Constant + β_1(Nekton Density)

Species	β_1	F	P (2 Tail)	R^2
COMU*	0.002	14.991	0.001	0.454
RHAU	0.001	10.945	0.004	0.366
GWGL	0.002	8.401	0.009	0.307
SOSH	-0.004	0.549	0.468	0.028

Table 5. Results of Monte Carlo analysis

Statistic	COMU*	GWGL	RHAU
Mean	0.503	0.497	0.503
Standard Error	0.009	0.009	0.009
Median	0.507	0.485	0.508
Standard Deviation	0.292	0.278	0.272
Sample Variance	0.085	0.078	0.074
Kurtosis	-1.213	-1.086	-0.995
Skewness	-0.018	0.042	-0.03
Range	0.999	0.999	0.999
Minimum	0.000002	0.000002	0.00003
Maximum	0.999	0.999	0.999
Sum	503.229	496.691	503.037
Count	1000.000	1000.000	1000.000
Confidence Level (95.0%)	0.018	0.017	0.017
Actual P Value	0.001	0.009	0.004
% of Values Less than the Actual Value	0.70%	0.80%	0.70%
Z-statistic	-1.725	-1.775	-1.845
Significance Level (P value) on the Actual P Value in this Distribution	0.0427	0.0384	0.0329

*Residuals lagged one kilometer.