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POPULATION DYNAMICS OF THE HARD CLAM: A STATISTICAL ANALYSIS BASED ON EXISTING TOWN OF BROOKHAVEN SURVEY DATA

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Introduction

Since 1985, the Town of Brookhaven has been undertaking an annual census of the hard clam (*Mercenaria mercenaria*) population in that portion of Great South Bay lying within its jurisdiction. An initial examination of this census data suggests that the baywide distribution of hard clams is heterogeneous, with several areas of consistently (over time) high hard clam abundance interspersed within regions of low clam abundance. This pattern suggests that environmental factors on a regional scale may be very important in determining the distribution and abundance of hard clams within Brookhaven's waters.

The goals of this project were to: 1) analyze the available census data to determine if areas of high and low abundance can be statistically defined and persist in time, 2) compare hard clam population characteristics (i.e., recruitment, age structure, ontogenetic growth, and mortality) between a selected high and low density area, and 3) compare the distribution and abundance of hard clams to relevant environmental factors. This study forms part of a larger shellfish management project which is being undertaken and administered by the Town of Brookhaven's Division of Environmental Protection. The purpose of the overall project is to enhance shellfish populations and to develop effective shellfish management programs within the Town's waters.

Methods

1. Review of Sampling Methods

Census data for 1986 through 1988 were analyzed. The 1985 census was not considered in this study since only a small portion of the Town's waters was sampled in that year. The Town of Brookhaven's census is carried out by dividing Great South Bay between Blue Point and Howells Point into a grid of 412m X 409m quadrats. Within each quadrat, two replicate samples are taken with a 1.0 square meter clamshell bucket. Station locations within each quadrat are chosen randomly and vary from year to year. Samples have been sieved using either a 12 mm (1986 and part of the 1987 census) or a 6 mm (part of the 1987 and the entire 1988 census) screen. The larger sieve efficiently retains only those clams which are greater than or equal to 20 mm in length. Shell length and width (and height in 1988 only) are measured on all hard clams using vernier calipers. Animals collected from selected stations during the 1988 census and a few stations from 1987 were retained for shell growth analysis. Further details of the Town's survey methods may be found in Kassner (1988).

2. Abundance Maps

Plots of hard clam abundance and contour maps of abundance were prepared using several commercially available software packages. A base map of the shoreline was created with Freelance Plus (Lotus Development Corporation, 55 Cambridge Parkway, Cambridge, MA 02142) and saved as a file of pen plotter commands. This file was later converted to sets of Cartesian coordinates using a program written in BASIC. Station locations were digitized with Sigma-Scan (Jandel Scientific, 2656 Bridgeway, Sausalito, CA 94965) from the station charts for each census prepared by the Town of Brookhaven. Charts were aligned such that the north-south borders of the quadrats were vertical on the digitizing tablet. All additional work was done in SURFER (Golden Software, Inc., PO Box 281, Golden, CO 80402).

Preparation of contour maps in SURFER is a multistep process. The first step is to create a regularly spaced grid array from the original set of irregularly spaced station locations. Abundance at each regularly spaced grid node is calculated by interpolation based on the abundances at the original station locations in the neighborhood of that node. As a result of experience using this program, an average of the abundances of the three nearest neighbors, weighted by the inverse of the squared distance between the node and each station location, produces a satisfactory grid array. The distance between grid nodes was chosen to match the Town's original quadrat size (400 m X 400 m), and the nodes were located approximately in the center of each quadrat. This initial grid array consisted of 25 rows and 26 columns of interpolated abundance values.

The next step in the contouring process is to modify the grid array in two ways: to smooth the array by applying a cubic spline and to blank out those nodes lying outside of the survey area. The purpose of splining is to produce smooth, less angular appearing contours. The size of the grid array is increased by inserting new nodes between the existing ones. Values assigned to the new nodes are obtained by fitting a cubic polynomial to the original nodes. Abundances at the original nodes are not altered by this procedure. Based on experience, the default expansion factor of 2 (i.e., 2 new nodes inserted between existing ones) produces smooth contours. By applying this procedure to the original grid array, the array size was increased to 73 rows and 76 columns. The blanking procedure was applied to this new grid array. This procedure assigns a blanking code to selected nodes which lay outside of the survey area (e.g., portions of the Bay not sampled, land areas, etc.). This prevents contours from being drawn in these regions.

The final step is to create the contour plot from the grid array. It is at this stage that the contour intervals are chosen, the size of the final plot is determined, and a caption is added. Also, during this final step, the shoreline map and the original station data are overlaid on the contour plot.

3. Sampling Theory

The sampling scheme adopted by the Town of Brookhaven is a form of stratified random sampling with each quadrat regarded as a stratum. A simple random sample is collected within each quadrat, and all quadrats are sampled. With stratified random sampling, the equations for estimates of the population mean density ($\bar{y}_{st}$), its variance ($v(\bar{y}_{st})$), and standard error ($s_e=\sqrt{v}$) are quite different than those for simple random sampling (Cochran, 1977). Let L be represent the number of quadrats in the census, and let h be used to index each quadrat (h=1,...,L). Further, define

n_h = the number of replicates taken in stratum h,

$n = \sum_{h=1}^{L} n_h$ = total sample size,

N_h = the number of sampling units in stratum h,

$N = \sum_{h=1}^{L} N_h$ = the total number of sampling units in the census area, and

$W_h = N_h/N$ = stratum weight (i.e., the proportion of sampling units within stratum h). For the Town census, n_h=2 and n=2L. Given that the size of the clamshell bucket is 1 m^2, then N_h is 412x409 m^2/1 m^2 = 1.685×10^5 and $N = 1.685 \times 10^5 L$.

Given these definitions, the general formula for estimating the population mean with stratified random sampling is (Cochran, 1977)

$$\bar{y}_{st} = \sum_{h=1}^{L} W_h \bar{y}_h = \sum_{h=1}^{L} N_h \bar{y}_h / N \quad ,$$

where $\bar{y}_h$ is the sample mean density for stratum h. It should be noted that this estimate will differ in general from the sample mean. The sample mean is

$$\bar{y} = \sum_{h=1}^{L} n_h \bar{y}_h / n \quad ,$$

and the difference is that the contribution of each $\bar{y}_h$ in $\bar{y}_{st}$ is weighted in proportion to the size of each stratum. However, for the Town census, two replicates were collected in each quadrat, and each quadrat is the same size (ignoring the slightly reduced areas in a few quadrats bordering the shoreline in Patchogue Bay). In this particular case,

$$n_h/n = N_h/N = W_h$$

for all stratum. This condition specifies a particular form of stratification called proportional allocation. When stratified sampling is proportional, $\bar{y}_{st} = \bar{y}$.

In the Town census, the sampling fraction (n_h/N_h) in each quadrat (i.e., the fraction of the area sampled) is negligible. Given this, the general form for the unbiased estimate of the variance in $\bar{y}_{st}$ is (Cochran, 1977)

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} W_h^2 s_h^2 / n_h \quad ,$$

where s_h^2 is the estimated variance of the simple random sample taken within stratum h, i.e.,

$$s_h^2 = \frac{1}{n_h-1} \sum_{i=1}^{n_h} (y_{hi}-\bar{y}_h)^2 \quad .$$

Here y_{hi} is the clam abundance in the ith replicate of quadrat h. With proportional allocation, $n_h=nW_h$, and the above formula can be reduced to the following simpler form

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} W_h s_h^2/n \quad .$$

As in the case for the population mean, $v(\bar{y}_{st})$ will in general differ from the variance of the mean one would have obtained had a single, large, simple random sample been taken for the census (Cochran, 1977). The advantage of stratification is that, if carried out properly, it almost always results in a smaller variance in the estimated mean than would result for a comparable sized, simple random sample. The exception primarily occurs when the strata are chosen incorrectly such that the variations in clam abundance within the strata are greater than the variations in mean abundance among strata. As long as the distribution of clams within quadrats is more homogeneous than the variations in mean abundance among quadrats, stratification will generally yield a lower variance.

Cochran (1977) derives a general equation for calculating an unbiased estimate of the variance of the mean of a single, simple random sample using the data collected by stratified random sampling. First, define the sample variance in the usual way

$$s^2 = \sum_{h=1}^{L} \sum_{i=1}^{n_h} (y_{hi}-\bar{y})^2/(n-1) \quad .$$

For stratified sampling with proportional allocation and a negligible sampling fraction ($n/N<<1$), the estimated variance of the mean for a single, simple random sample is

$$v_{ran} = \frac{1}{n}\left(\frac{n-1}{n}s^2+v(\bar{y}_{st})\right) \quad .$$

The difference between $v(\bar{y}_{st})$ and v_{ran} (or more appropriately the corresponding standard errors) provides a means of assessing the gain in precision due to stratification relative to simple random sampling.

4. Statistical Analysis of the Abundance Data

Census data for 1986 through 1988 were analyzed to determine if areas of high and low hard clam abundance can be statistically defined. The data were examined using the sampling theory outline in the last section to determine the gain in precision in the estimate of population mean density that results if eastern Great South Bay is stratified not on the basis of quadrats but on the basis of clam abundance into a set of bed (i.e., high abundance) and non-bed (i.e., low abundance) areas. A gain in precision over simple random sampling was used to determine whether the bed concept was valid. Also, persistence of the bed and non-bed areas over time was assessed by applying the results of one census to define strata for the following year's survey. If the census data between two successive surveys are correlated (i.e., the bed and non-bed areas persist in time), a gain in precision in estimating population mean density will occur. A gain in precision over simple random sampling was also used as a measure to quantify these results.

Given that the gains in precision can be quantified, a benchmark is needed to assess whether the resulting values are large enough to justify the bed concept. Cochran (1977) states that the gains in precision from geographic stratification are generally "modest". He discusses one example in detail which helps to clarify this term. In an analysis of farm economic items in Iowa (Jessen, 1942), he compares the relative precision of geographic stratification on the basis of 5 farming areas, 100 counties, and 1600 townships to simple random sampling of the entire state. Gains in precision over simple random sampling, expressed as reductions in standard errors, were 3%, 5%, and 15%, respectively, for the three stratification schemes. Given these as benchmarks for different numbers of strata, gains in precision which exceed these values by several times will be considered "large" in the present study.

Two questions that needed to be addressed as part of this analysis were how should the boundaries between geographic strata be defined and how many strata should there be? Three approaches were tried to define criteria for the construction of geographic strata: 1) use of simple properties of the distribution such as mean, median, and quantiles, 2) minimization of $v(\bar{y}_{st})$ with respect to the stratum boundaries, and 3) cluster analysis with a combined distance measure based on both clam abundance and geographic location.

a. Geographic Stratification Based on Simple Distributional Properties

In the first approach, simple characteristics of the frequency distribution of abundances were used to define geographic stratum boundaries and the number of strata. Stratification based on mean abundance will be described in detail to illustrate this approach.

A contour map with mean abundance as the single contour level was prepared from the census data for each survey year. From the contouring results, contiguous groups of two or more quadrats with abundances above the mean were designated as bed areas. The remaining quadrats were grouped into a single stratum of low abundance (i.e., a non-bed area). Separate estimates of v_{ran} for each bed and the single non-bed stratum were computed from the census data. These variances were then combined to produce an estimate of $v(\bar{y}_{st})$ with stratum weights defined as the fraction of the study area within each bed or non-bed area. This final value represented an estimate of the variance of the population mean density that would have been obtained by geographically stratifying the study area into bed and non-bed areas assuming simple random sampling within each geographic stratum. The standard error $\sqrt{v}$ calculated in this way was compared to the estimate obtained assuming simple random sampling for the entire study area in order to assess the gain in precision due to geographic stratification.

To assess the persistence in bed areas over time, the geographic strata (i.e., bed and non-bed areas) defined by one census were applied to the following year's survey. Estimates of v_{ran} within each geographic strata and the overall $v(\bar{y}_{st})$ were obtained as described above. The results were again compared to simple random sampling.

Stratification based on the median or quantiles of the abundance distribution followed a similar scheme. For quantiles, two or more contour levels were used. The geographic strata then represented a non-bed (low abundance) area, one or more intermediate abundance regions, and bed (high abundance) areas.

b. Geographic Stratification Based on Minimization of $v(\bar{y}_{st})$

The second approach to defining geographic strata was to choose stratum boundaries in a way which minimizes $v(\bar{y}_{st})$. This method, was developed by Dalenius and Hodges (1959) and is outlined in Cochran (1977).

Without going into the details of the derivation, given the frequency distribution of hard clam abundances, f(y), and assuming proportional allocation, this method leads to the following stratification rule. First, choose the number of intermediate stratum boundaries desired (this is arbitrary). Then form the cumulative of $\sqrt[3]{f(y)}$ and choose the actual stratum boundaries so that they result in equal intervals on the cum $\sqrt[3]{f(y)}$ scale.

If one intermediate stratum boundary is chosen, the rule leads to a single abundance level which, when contoured, subdivides the bay into geographic bed and non-bed areas. When two or more stratum boundaries are chosen, application of this rule leads to two or more contour levels. Calculation of $v(\bar{y}_{st})$ for the geographic strata then proceeds as described earlier.

c. Geographic Stratification Based on Cluster Analysis

This approach is an implementation of a geographic grouping method proposed by Wartenberg (1984). As in ordinary cluster analysis, a distance matrix is formed quantifying the degree of difference between all pairs of sampling stations. Wartenberg suggests that this distance matrix should be calculated as a combination of both phenetic (i.e., in our case abundance) and geographic information. The simplest form of his combined distance measure is

$$D^* = aD_G + (1-a)D_P$$

where a is a weighting parameter, D_G is a matrix of geographic distances among stations, and D_P is a matrix of phenetic (abundance) distances. In the present application, the metric used to calculate elements in D_G was ordinary Euclidean distance, and the Bray-Curtis index was used for D_P.

Before combining, each component matrix was standardized to range from 0 to 1 by dividing elements in the matrix by the maximum element. Several clustering algorithms (single linkage, UPGMA, and complete linkage) and a range of a values ($0<a<1$) were tried. Resulting clusters were then defined as geographic strata, and the $v(\bar{y}_{st})$ calculations proceeded as described earlier.

5. Population Characteristics at Selected High and Low Density Areas

Based on the approach which yielded the most reasonable geographic stratification of eastern Great South Bay, population characteristics (i.e., recruitment, age structure, ontogenetic growth, and mortality) were estimated and compared for a selected high and low density area. To select the areas for this analysis, contour plots for each census year were initially overlaid to identify quadrats falling into bed and non-bed areas. Individual quadrats were retained if they were classified as part of a bed or non-bed area during at least one census. The final choice of the two areas to include in this analysis and the quadrats to include within each area was constrained by the following:

- Shell samples from quadrats within each area were available for sectioning.
- The high and low density areas needed to contain a reasonably large number of quadrats and be roughly equal in size.
- The qualitative sediment type recorded by the Town at individual quadrats could not vary from one census to the next.

a. Growth and Age of Individuals

For the selected high and low density areas, a subsample of valves obtained from the 1987 and 1988 surveys were analyzed. Length, width, height, and the axis of maximum growth were measured for each clam using vernier calipers. Left valves were marked along the axis of maximum growth and were embedded using a mixture of ten parts Epon 815 resin and one part DTA curing agent (Miller-Stephenson Chemical Co., PO Box 950, Danbury, CT 06810). With a lapidary saw equipped with a diamond blade, the embedded valves were sectioned along the axis of maximum growth. The cross-sections were wet ground using 240, 400, and 600 grit sandpaper. Next, the sections were rinsed and polished with a levigated aluminum compound. All sections were examined under a low powered dissecting microscope. Winter and summer growth breaks were marked and measured on each section. Age was determined by counting the number of seasonal growth breaks.

b. Age Structure

Using the Town's survey measurements, length-frequency distributions for selected high and low density regions and for the surveys in 1987 and 1988 were converted to age distributions using a modification of an iterative maximum likelihood technique developed by Hosmer (1973). The method, as developed by Hosmer, estimates the parameters (mean sizes, variances, and proportions) of a mixture of two normal distributions given known information about a subsample taken from the total sample. The modification of Hosmer's method entailed extending it to cover more than two overlapping normal distributions.

Within a population, individual clams of the same age will not generally be the same size. When size data from a bivalve cohort is plotted as a length-frequency histogram, it will generally appear as a normal or slightly positively skewed distribution (Craig and Hallam, 1963). Because recruitment is seasonal, a length-frequency histogram for a population will be polymodal, with each peak or mode representing one or more cohorts. Hosmer's technique, extended for multiple cohorts, attempts to distinguish age classes in a length-frequency distribution by producing a maximum likelihood estimate of a series of overlapping normal distributions fitted to the distribution. This fit is constrained by known length-age relationships of a random subsample taken from the total sample. In the present study, clams sectioned for the growth analysis represent the aged subsample. Since shell samples were available only for 1987 and 1988, the 1986 survey was not considered in this analysis.

The following is a brief outline of the extension of Hosmer's technique. It is assumed that the length-frequency distributions for each of k age classes can be approximated by a normal density function with a mean length μ_i and variance σ_i^2 $(i=1,2,\ldots,k)$. Also, assume that a randomly chosen subsample of size n is taken from the overall sample of clams, and the length and age (by sectioning) of each clam in the subsample is measured. Let $x_{i1}, x_{i2}, \ldots, x_{in_i}$ $(i=1,2,\ldots,k)$ represent the length observations for this aged subsample. Here, n_1 is the number of one year olds, n_2 is the number of two year olds, etc. in the subsample and

$$n = \sum_{i=1}^{k} n_i \quad .$$

Since this aged subsample was chosen randomly from the overall sample, the x_{ij} are random variables with probability density function

$$f_i(x_{ij}) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(x_{ij}-\mu_i)^2/2\sigma_i^2} \quad .$$

Let the remainder of the sample (i.e., the non-aged individuals) consist of n_M clams, and let x_{Mj}, $j=1,2,\ldots,n_M$, represent the length observations for this subsample. Each x_{Mj} is assumed to be a random variable taken from a mixed probability density function (i.e., a set of overlapping normal distributions) defined as

$$f_M(x_{Mj}) = \sum_{i=1}^{k} p_i f_i(x_{Mj}) \quad ,$$

where the p_i are the unknown proportions of each age class in the overall sample and

$$\sum_{i=1}^{k} p_i = 1 \quad .$$

Note that one of these proportions, say p_k, is not independent but may be calculated from the others using the above constraint, i.e.,

$$p_k = 1 - \sum_{i=1}^{k-1} p_i \quad .$$

Taking the aged and the non-aged subsamples together, the overall sample size is

$$N = \sum_{i=1}^{k} n_i + n_M \quad .$$

Based on these definitions, the ln of the likelihood function of the overall sample can be written (as a modification of Hosmer, 1973) as

$$L = \sum_{j=1}^{n_M} \ln(f_M(x_{Mj})) + \sum_{i=1}^{k} \sum_{j=1}^{n_i} \ln(f_i(x_{ij})) + \ln\left(\frac{n!}{n_1! n_2! \ldots n_k!} p_1^{n_1} p_2^{n_2} \ldots p_k^{n_k} \right)$$

The first term on the right is the ln-likelihood function for the non-aged subsample. The second term is the ln-likelihood function for the aged subsample. And, the last term is the ln-likelihood function of a multinomial probability density function of the proportions of each age class in the overall sample.

Separating the length-frequency distribution of the sample into component age classes consists of estimating the set of unknown parameters

$$\mu_1, \mu_2, \ldots, \mu_k, \sigma_1, \sigma_2, \ldots \sigma_k, P_1, P_2, \ldots P_{k-1}$$

based on the observations of length from the aged (the x_{ij}) and non-aged (the x_{Mj}) subsamples. This is done by maximizing L with respect to the unknown parameters (i.e., finding the maximum likelihood estimates of the parameters). In the present study, a program in BASIC was written to maximize L using an iterative, direct search algorithm. In the program, initial parameter estimates come from the aged subsample. Maximum likelihood estimates of the parameters are obtained by a procedure suggested by Hasselblad (1966). A steepest descent iteration is carried out until L is close to converging on its maximum. At that point, the program switches over to Newton's method for the final iterations and for calculating standard errors of the parameter estimates.

c. Mortality Rates

From the age distributions obtained above, age-specific annual mortality rates were estimated as the difference in density of each age class from 1987 to 1988. Details of this method can be found in Buckner (1984).

d. Recruitment

In this study recruitment was defined in two ways: 1) the number of one year olds in the population and 2) the number added to the harvestable population. The estimated length-frequency distributions for the 1984 and 1985 year classes were used to estimate the fraction of individuals reaching harvestable size in the time interval between 1987 and 1988. These fractions were multiplied by the estimated abundances of the two and three year olds from the 1987 survey.

6. Relationship of Clam Abundance to Environmental Factors

The most complete set of environmental data for eastern Great South Bay was collected in 1978 by Wapora, Inc. Contour plots of depth, percent silt-clay, organic content, grass cover, and shell cover were prepared from the Wapora study data (Greene, 1981). Because of time constraints for completing this project and because these environmental data are over ten years old, only qualitative comparisons between the 1986-88 abundance data and the Wapora results were carried out. Hard clam abundances obtained by Wapora, Inc. using modified clam tongs (which retained clams > 15 mm in width) were also compared to the 1986-88 Town of Brookhaven survey results.

Results

1. Abundance Maps

Station locations for the surveys in 1986 through 1988 are presented in Figures 1-3. Total hard clam abundance (>= 20 mm in length) and the distribution of sublegal (20-48 mm in length) and legal (> 48 mm in length) size clams are posted in Figures 4-12. Average abundances for each survey year are listed in Table 1. Total population mean abundance declined slightly over the three survey years, and the change was due to a decrease in the average abundance of sublegal size clams.

The frequency distributions of total hard clam abundance for each survey year are plotted in Figures 13-15. These frequency distributions are positively skewed, and they are typical in form to that found for most benthic species. Median abundances for the 1986-88 surveys were 4.5, 3.5, and 3 clams per square meter, respectively. Like total mean abundance, a decline in median abundance was evident during the three survey years.

2. Statistical Analysis of the Abundance Data

a. Geographic Stratification Based on Simple Distributional Properties

Using mean hard clam abundances from Table 1 as a single contour level, contour maps of total, sublegal, and legal size clams are presented in Figures 16-24. For each census year, the contour maps for total and sublegal size clams are fairly similar in appearance. In contrast, areas of high abundances of legal size clams are more patchily distributed, and the spatial pattern does not closely resemble the total or the sublegal size contour plots. The effect of legal size clams on the total distribution appears to be minimal. This is consistent with the fact that legal size clams represent less than one-third of the population in the study area.

A cursory examination of the total contour maps (Figures 16-18) for the three surveys suggests that there are several areas within the bay with consistently high hard clam abundances. In Figures 25-27, strata are defined based on the survey data and mean abundance as the single contour level. In these figures, strata A represents areas within the bay with station abundances less than the population mean (i.e., non-beds). All other strata (B-H) are high abundance areas (i.e., beds). Note that the same letter is assigned to roughly the same geographic locality for all three surveys.

In 1986, four beds (B, E, F, and H) are apparent (Figure 25). The largest is area (B) which runs in a northeast direction starting in the southwest corner of the study area. Two other beds (E and F) lie along the same line to the east of B. The final bed (H) is just east of the mouth of the Patchogue River and is within the area closed to shellfishing.

In 1987 (Figure 26) and 1988 (Figure 27), seven bed areas are apparent. In addition to beds B, E, F, and H, three small areas along the north shore of the study area are present. One is a site just off of Blue Point (C). The others are located near the mouth of Corey (D) and Mud (G) Creeks, within the area closed to shellfishing.

Listed in Table 2 are estimated standard errors in total mean abundance calculated on the basis of different sampling schemes. When each quadrat is regarded as a separate strata, standard errors are from 32 to 56% lower than had the surveys been conducted with simple random sampling. This is a substantial gain in precision, and clearly demonstrates one of the strengths of the Town survey design. When the bed and the single non-bed areas in Figures 25-27 are used to stratify the bay, gains in precision range from 23 to almost 30%. Thus, roughly half of the gain in precision can be attained by subdividing the study area into only 5 (1986) or 8 (1987-88) discrete areas rather than several hundred quadrats.

Table 3 lists the gain in precision obtained using the results of a prior census as a basis for geographic stratification. When bed and non-bed areas from the 1986 census are used, the standard error of the mean for the 1987 census was 8.4% lower and the value for the 1988 census was 14.8% lower than the corresponding standard errors from simple random sampling. A larger gain in precision resulted when the stations from the 1988 census were stratified based on the bed and non-bed areas from the 1987 survey. In this case, the standard error of the mean was 20.7% lower than the estimated standard error for simple random sampling. The resulting standard error (0.384) and the gain in precision (20.7%) were almost identical to the values for 1988 listed in

Table 2 (SE=0.378 and a 21.9% gain in precision). This suggests a high correspondence in hard clam distribution for the two survey years (1987 and 1988).

Attempts at geographic stratification based on other simple distributional properties were not successful. Stratification based on the sample median as the single contour level is illustrated in Figures 28-30. Rather than subdividing the bay into discrete bed areas, this approach outlined, for the most part, a single, connected, high abundance area running from the southwest to the northeast corners of the study area and including the closed areas in Patchogue Bay. The only non-connected portion was a small, high abundance area of Blue Point. Geographic stratification based on these areas yielded higher standard errors than those obtained using mean abundance. This, coupled with the fact that sample median varied considerably between survey years, led to abandoning median as a viable stratification criterion.

The results of stratifying the study area into low (non-bed), intermediate, and high (bed) abundance areas using 33% quantiles are presented in Figures 31-33. In general, this approach fragments the bay into too many small areas which show no real consistency from one survey year to the next. In addition, rather than appearing to be distinct regions, the intermediate abundance areas almost always occur as transition zones between beds and non-beds. Very often the width of these zones was less than the distance between sampling stations (especially in Figures 32 and 33). As a result, use of quantiles as stratification criteria was not considered further.

b. Geographic Stratification Based on Minimization of $v(\bar{y}_{st})$

Application of the $v(\bar{y}_{st})$ minimization rule, assuming one intermediate stratum boundary, led to the choice of 8 clams per square meter as the single contour level. Contour maps using this value are presented in Figures 34-36. While defining somewhat smaller bed areas, these plots outline regions which still closely resemble those generated from mean abundance (Figures 16-18). Standard errors and the gains in precision due to geographic stratification based on these contour maps are listed in Tables 4 and 5. In all cases, standard errors were less than values for simple random sampling. Overall, however, results were comparable to those obtained using mean abundance as the stratification criterion (Tables 2 and 3). Since there were no distinct differences in standard errors, and because application of the $v(\bar{y}_{st})$ minimization rule is more complex, use of mean abundance is preferable.

Application of the $v(\bar{y}_{st})$ minimization rule, assuming two or more intermediate stratum boundaries was unsuccessful. The contour maps generated resembled those produced for quantiles (i.e., like Figures 34-36). Again, intermediate abundance regions were not distinct areas but thin, transition zones between non-bed and bed areas. This approach was not pursued further.

c. Geographic Stratification Based on Cluster Analysis

The attempt to implement Wartenberg's (1984) geographic clustering method was also unsuccessful. None of the trials using different clustering algorithms and a range of weighting parameter values resulted in contiguous groups of stations which could be considered beds. Several trials had dendrograms which were characterized by excessive chaining, such that no clear partitioning of quadrats into groups was possible. The remaining trials clustered quadrats which were scattered throughout the bay, so no discrete geographic regions could be defined. Based on these results, this approach was abandoned.

3. Population Characteristics at Selected High and Low Density Areas

From the analysis in the last section, using mean abundance as a single contour level produced the most reasonable geographic stratification of eastern Great South Bay. In the present section, population characteristics at a selected bed and non-bed area are compared. The areas chosen for this aspect of the study are shown in Figure 37. Each represents about 16-17% of the Town's census area. These two areas will be referred to as the "high density area" and the "low density area" throughout the remainder of this report. The high density area outlined corresponds to the largest bed within the bay and was, therefore, a logical choice. The low density area was the only contiguous non-bed area in the bay which satisfied the constraints listed in the methods section.

a. Growth and Age of Individuals

A total of 165 valves were sectioned and analyzed for age and growth. These represent samples collected from stations 44, 57, 70, 93, and 181 during the 1987 census and stations 52, 95, 108, 164, 289, and 302 from the 1988 census. About half of the specimens analyzed were difficult to age. Beginning after the second winter break (1.5 years), the summer and winter seasons in these specimens were often characterized by multiple breaks, making interpretation of the growth record very difficult. Overall, individuals 1-4 years old in the high density and from ages 1 through 5 in the low density area were found in the samples.

Mean shell height vs. age results backcalculated from the growth break measurements are shown in Figures 38 and 39. Little difference in growth is evident between areas or years, with the possible exception of slightly slower growth in the specimens from the high density area taken during the 1988 survey.

b. Age Structure

Shell length-frequency histograms for stations lying within the selected high and low density areas are presented in Figures 40-45. Length data were taken directly from the Town's survey logs. While these distributions are clearly multimodal, the presence of 4 or 5 modes (as suggested by the sectioned specimens) is not evident from a visual examination of the shape of these distributions.

The results of converting the length-frequency data to age-distributions, based on the maximum likelihood technique, are listed in Tables 6 and 7. Given in these tables are estimates of age-specific mean lengths and standard deviations, as well as, the proportions of each age class and the age structure expressed as the number of clams per square meter. Also listed are standard errors of each estimate.

Shell length vs. age plots generated from the maximum likelihood estimates are presented in Figures 46 and 47. With the exception of the low density area for 1987, little differences in growth are evident between areas and years. Estimates for the 1987 low density area, especially for ages 2, 4, and 5, are felt to be inaccurate. The aged subsample for this data set consisted of only five shell specimens: three of age 3, one 4 year old, and one 5 year old. This was much too small a subsample to adequately constrain the estimates. The anomalous estimated length at age 2 is a direct result of the absence of 2 year olds in the aged subsample. In contrast, the estimated length at age 1 is probably accurate because of the presence of a distinct mode in the length distribution corresponding to this age class.

Estimated age structure for each area and year, presented as the average abundance of each age class, is shown in Figures 48 and 49. Three years olds dominate the distributions in all samples except for the 1988 low density area. The high density area has considerably greater abundances of younger clams (1-3 years old) relative to the low density area for both survey years. In most cases, this difference exceeds an order of magnitude in abundance. In contrast, abundances of older clams (>= age 4) were comparable between high and low density areas for both survey years.

c. Mortality Rates

Maximum likelihood estimates for age structure (Tables 6 and 7) were used to calculate mortality rates in both areas. The results are given in Table 8. Cases where the estimated abundance of a year class in 1988 exceeded the value for 1987 are indicated with a "?". This occurred in both areas for the 1985 year class and in the low density area for the 1986 year class. Potential explanations for this problem will be discussed later. Mortality rates which could be calculated are primarily for the 1984 and earlier year classes. These rates are fairly high and reflect both natural and fishery mortality.

d. Recruitment

Because of the large sieve sizes used during the surveys, recruitment to the population cannot be examined. However, the relative abundances of one year olds in the two areas can be compared to assess differences in the combined effects of recruitment and survival to age one. Maximum likelihood estimates in Tables 6 and 7 indicate that one year old hard clams are more than an order of magnitude more abundant in the high density area during both the 1987 and 1988 surveys.

Maximum likelihood estimates were also used to calculate recruitment to the fishery between 1987 and 1988. Calculations leading to recruitment estimates are given in Table 9. No correction for natural mortality was made, so these figures may slightly overestimate recruitment rates. Results indicate that recruitment to the fishery is about seven times greater in the high density area (6.01 individuals per square meter) when compared to the low density area (0.86 individuals per square meter).

4. Relationship of Clam Abundance to Environmental Factors

Contour plots of environmental data collected during the the 1978 Wapora study are presented in Figures 50-53. A comparison of these plots with the distribution of hard clams suggests that bed areas (Figures 25-27) correspond roughly to areas within the bay with silt-clay (mud) contents <20% and also with the presence of shell or gravel cover. This correspondence includes not only the bed areas running from the southwest to northeast corners of the study area (B, E, and F), but also the small bed off Blue Point (C) and the areas within the closed portion of Patchogue Bay (D, H, and G).

The abundance of hard clams based on the tong data from the Wapora study is contoured in Figure 54. High abundance regions in 1978 correspond roughly to the bed areas defined by the Town's 1986-88 surveys, suggesting a long term persistence in these areas. Excluding portions of the bay not sampled by the Town's survey (i.e., primarily along Fire Island and an area along the eastern border), abundances in 1978 averaged 7.46 clams per square meter. This is only about one individual per square meter higher than the mean abundances for the 1986-88 surveys (Table 1).

Discussion

1. Abundance Maps

From the posted abundance data (Figures 4-12) and the contour plots based on mean abundance (Figures 16-24), it is clear that the hard clam population is distributed heterogeneously in eastern Great South Bay. Total hard clam abundances (>= 20 mm in length) averaged from 6.27 to 6.79 individuals per square meter, and a slight decline in abundance was apparent over the three census years. These census abundances are quite similar to the mean abundance (>= 15mm in length) of 7.46 individuals per square meter from the 1978 Wapora study. This latter abundance estimate is based only on those stations in the Wapora study which are located within the Town's 1987-88 census area. There is, therefore, no evidence that hard clam abundances have declined, as harvests did (1978 Brookhaven Great South Bay landings = 203,375 bushels and 1987 landings = 34,258 bushels based on NMFS unpublished data), over the past decade.

In contrast, there is evidence that the size distribution of clams may have shifted considerably over the past decade. From the 1986-88 census data, only about 31-32% of the hard clams sampled were of harvestable size (>= 48 mm in length). Buckner (1984), using a similar sampling procedure to the Brookhaven census, found that 54% of the clams in Islip Town waters were of harvestable size during 1978-79. And, about 69% of the individuals were legal size in the Wapora study of the Brookhaven waters shown in Figure 54.

It should be noted that the value of 31-32% legal size is an overestimate of what is actually available to clammers. This estimate was calculated from all sampling stations and includes the closed area which has a fairly high abundance of legal size clams (Figures 22-24).

2. Statistical Analysis of the Abundance Data

A number of approaches were tried to define criteria appropriate for geographic stratification of Brookhaven waters. Of these, average abundance as a single contour level was found to have the best balance between simplicity and gain in precision. Cluster analysis was the least successful. Perhaps, however, a more extensive analysis, trying out other metrics and more combinations of weighting parameters, would have yielded satisfactory results. The one marked advantage of cluster analysis is that it can handle multivariate data. So, for example, it would have been possible to define D_P on the combined 1986-88 data, and D_G could have been calculated using both geographic locality and environmental parameters (e.g., sediment type, shell cover, etc.). For this reason alone, it should still be considered in future studies as a possible stratification approach.

Analysis of the standard errors generated for stratified random sampling led to two interesting results. The first is that the Town census design is efficient from a statistical perspective. Stratified random sampling at the quadrat level yielded standard errors which were 32 to 56% lower than estimates for simple random sampling. These gains are considerably higher than the 5% and 15% values in the Iowa farm example given by Cochran (1977) for 100 and 1600 strata, respectively (see the methods section). Additionally, estimated standard errors are only 2.6 to 4.4% of the mean abundances, so approximate 95% confidence intervals (±2 SE) are equivalent to about ±0.5 individuals per square meter. This interval is sufficiently small to allow meaningful tests of hypotheses concerning differences in mean abundance.

Sufficient census data now exists should the Town wish to alter their survey design to reduce standard errors still further. The most logical change would be to adopt an optimal allocation strategy as discussed by Cochran (1977). Assume for now that the overall sample size is fixed at current levels, and there is no difference in the cost (or time) to process a sample in any particular quadrat (This may not be true since sediment type varies). Under these assumptions, an optimal allocation strategy would attempt to reduce the standard error by concentrating greater sampling effort in areas within the bay where the hard clam population is most variable. For example, in regions where within quadrat variances are low, quadrat sizes could be increased by joining together say 2 or 4 contiguous quadrats into one larger one. The extra samples (remember the total sample size is fixed) could then be used to either increase the number of replicates or decrease the quadrat size in areas of the bay where within quadrat variances are high. If the cost (or time) needed to collect a sample varies from one quadrat to the next, this could also be incorporated into the sample allocation scheme if estimates of the cost (or time) differences are available (see Cochran, 1977). Existing data are sufficient to both design and test the feasibility of such a reallocation scheme.

Different allocation strategies (either optimal or otherwise) could also be examined if for some reason the sample size that can be taken during the annual census must be changed. For example, suppose that sample size must be reduced. One obvious way to do this would be to cut out the least critical areas of the bay (e.g., the area closed to shellfishing, the low abundance areas along Fire Island, or the far eastern part of the study area). Alternatively, the number of samples could be reduced without decreasing the size of the study area by enlarging quadrat sizes in areas of the bay where the hard clam population is least variable. The opposite is also possible; if the sample size is increased, the extra sampling could be concentrated in areas of the bay where the hard clam population is most variable. Again, changes in precision associated with the different allocation strategies can be estimated from available data.

Any expected gains in precision associated with these different allocation schemes must be balanced against several disadvantages of changing the Town's current proportional stratification design. If sampling effort is altered as suggested above, the natural weighting of proportional stratification would be lost, so the sample mean and the estimated population mean would differ. There may also be a loss of some geographic detail in sparsely sampled areas, and the survey would become more complex to design and execute. Additionally, if the distribution of hard clams happened to change substantially, the allocation scheme could become inefficient and result in a loss in precision. Finally, it should be noted that total abundance is only one relevant statistic. Optimizing the sampling design to reduce its standard error could result in a loss of precision for other important variables which are not closely correlated to it. For example, since the distribution of legal size clams did not closely resemble total abundance, the allocation scheme could actually increase the standard error for the mean abundance of legal size clams. Given these disadvantages, our overall recommendation is that unless explicit, quantitative values for the standard errors are required, the current census design is sufficient and should be retained.

The second interesting result of the statistical analysis was that high abundance or bed areas can be identified in Brookhaven waters. These persist as discrete areas over short term (the 3 census years), and perhaps even longer term (decade), time periods. Graphically, evidence for the occurrence and persistence of beds was obtained from an examination of Figures 25-27 and 54. The most compelling statistical evidence was a gain in precision ranging from 8.4 to 20.7% when the results of a prior census were used to stratify the bay into 5 to 8 bed areas. This gain is several times higher than the 3% gain in the Iowa farm example given by Cochran (1977) for 5 strata (see the methods section).

It is important to note that the quadrat locations were originally set up arbitrarily, and the physical environment within a quadrat is not always uniform. This is especially true for quadrats along the boundary of bed areas. Town census records show instances where the samples within a quadrat were, for example, characterized as muddy one year and sandy in another. Sediment type and other variables do affect hard clam abundance. And, abundance results in environmentally nonuniform quadrats may vary widely from year to year not because the population is varying considerably in time, but because sampling locations happen to be in different sediment patches. This would have an effect on the standard error and tend to reduce the gain in precision when a prior census is used for geographic stratification. It is likely that had stratification been based not only on the prior census results, but also had incorporated detailed environmental information, gains in precision would have been greater. Therefore, preparation of a sediment map, detailed enough to identify transitions in sediment type within individual quadrats, should be considered by the Town as a future project.

3. Population Characteristics at Selected High and Low Density Areas

Application of the maximum likelihood technique to convert length distributions to age distributions was in general quite successful. For most data sets, however, the aged subsample was only about 5% of the total number of clams collected at the stations within the areas. As a result, convergence on the maximum likelihood estimate was very slow. Based on tests of this technique, aged subsamples representing at least 10% of the total sample are recommended. This subsample should be collected during the census in one of two ways: 1) randomly choose 10% of the clams from each clamshell dredge sample or 2) randomly choose 10% of the clamshell dredge samples and retain all clams collected.

Population characteristics at the selected high and low density areas shown in Figure 37 revealed several interesting similarities and differences. Based on both the shell sectioning results and the maximum likelihood estimates, ontogenetic growth was similar among areas. There was also no difference in the abundances of older clams (>= age 4) in the high and low density areas. This is consistent with the lack of correspondence between the contour plots for legal size clams and those for total abundance. One year olds were, however, more than an order of magnitude more abundant in the high density area. This large difference in abundance was maintained through all of the younger age classes (ages 1-3) and resulted in recruitment to the fishery being a factor of seven times greater in the high density area. This result suggests that differential settlement and/or survival to age 1 can account for much of the differences in abundance between the two areas. Further research into those factors controlling hard clam abundance in the bay should, therefore, concentrate on the early life history stages.

The most problematic aspect of this study was the difficulty encountered in calculating mortality rate estimates for the 1985 and 1986 year classes. The failure to obtain a mortality rate estimate for the 1986 year class in the low density area is not particularly worrisome. During the 1987 census, a 12 mm sieve was used at most stations, and 1 year olds (i.e., 1986 year class) may have been undersampled. Additionally, the difference in abundance between years (0.11 in 1987 and 0.17 in 1988) is not large and is about the same as the standard error of the individual means. Thus sampling error (i.e., the SE's of the abundance estimates) could also account for some of the problem. Neither of these two explanations, however, resolve the problem with the 1985 year class. For both the high and low density areas, estimated abundances of two year olds in 1987 were far lower than the abundances of three year olds in 1988.

Three additional explanations for the mortality rate estimate problem were considered. First, the growth patterns in the sectioned shells were often difficult to interpret, and the shells may have been aged incorrectly. This would obviously influence the age structure since the proportions in the aged subsample constrain the maximum likelihood estimates. However, a comparison of growth curves from the current study to backcalculated height vs. age estimates in Buckner (1984) and length vs. age estimates in Greene (1978) did not reveal any substantial differences. We feel, therefore, that our age estimates were reasonably accurate.

A second possible explanation was that the maximum likelihood estimation technique yielded inaccurate results. To test this, a size-age key from Buckner (1984) was applied to the length distributions. The resulting age structures using the key were fairly similar to the maximum likelihood estimates. Using this approach, mortality rates still could not be calculated for the 1986 year class in the low density area and for the 1985 year class in both areas. Estimated abundances for two year olds in 1987 were still far lower than values for three year olds in 1988.

The third possibility examined was that two year olds were undersampled during the 1987 census. For this to account for the differences, sampling efficiency for two year olds needed to be as low as 20 to 25%. Even with the larger 12 mm sieve used at most stations during 1987, a sampling efficiency this low is unlikely since two year olds are quite large (~28-32 mm in average length). This possibility was tested anyway by repeating the maximum likelihood analysis for the high density area using only those samples which were sieved through a 6 mm sieve. The abundance of two year olds was estimated to be 1.86 individuals per square meter. This was essentially the same value as that obtained in the original analysis (1.92 clams per square meter). At present, therefore, the problem with the mortality rate estimates still remains unresolved.

4. Relationship of Clam Abundance to Environmental Factors

A qualitative comparison of the 1986-88 census results to environmental data collected during the 1978 Wapora study suggests that there is a rough correspondence between the distribution of hard clams and the occurrence of shell/gravel and low silt-clay sediments. This is consistent with the observed long term presence of bed areas in the bay. Unfortunately, time did not permit further analysis of these data.

To quantify the apparent relationships between hard clam abundance and environmental conditions, two approaches are recommended. First, the 1986-88 census data should be abridged by selecting out only those stations which correspond closely to the sampling locations in the Wapora study. Sampling stations in the Wapora study were relatively far apart, and it would be inappropriate to interpolate environmental data over the distances between stations. A Mantel test (Mantel, 1967) could then be used to test the significance of geographic patterns. The other, better but substantially more expensive, approach would be to collect and analyze environmental data from each of the current sampling stations. A Mantel test could be used here as well.

Summary

In this study, hard clam census data and shell samples collected in eastern Great South Bay by the Town of Brookhaven's Division of Environmental Protection were analyzed in detail. The goals of this project were to: 1) analyze the available census data to determine if areas of high and low density can be statistically defined and persist in time, 2) compare hard clam population characteristics between a selected high and low density area, and

3) compare the distribution and abundance of hard clams to relevant environmental factors. The principal results of this study were:

1) Over the three census years, total hard clam abundances (>= 20 mm in length) ranged from 6.27 to 6.79 individuals per square meter, and a slight decline was apparent. However, mean abundances were similar to the 1978 Wapora study estimate of 7.46 clams per square meter for the same area.

2) During 1986-88, about 31-32% of the hard clams were legal size (> 48 mm in length). In contrast, 69% were legal size in 1978 for the same study area, suggesting that a shift in the size distribution has occurred.

3) The Town's survey design is efficient from a statistical point of view, resulting in standard errors which are satisfactory for biological sampling.

4) The distribution of hard clams in the study area can be characterized as having several high abundance or bed areas which persist in time.

5) A comparison of population characteristics at a selected high and low density area revealed:

a) no differences in ontogenetic growth;

b) no differences in the abundances of older clams (>= 4 years old);

c) abundances of younger clams (ages 1-3) which were often more than an order of magnitude greater in the high density area; and

d) recruitment to the fishery which was seven times greater in the high density area.

6) Based on environmental data collected in 1978, high abundance or bed areas correspond to regions in the bay characterized by low silt-clay sediments and the presence of shell/gravel cover.

References

Buckner, S.C. 1984. Aspects of the Population Dynamics of the Hard Clam, Mercenaria mercenaria, in Great South Bay. Ph.D. Thesis. Marine Sciences Research Center, State University of New York, Stony Brook, NY. 217 pp.

Cochran, W.G. 1977. Sampling Techniques. Wiley and Sons, New York. 428 pp.

Craig, G.Y., and A. Hallam. 1963. Size-frequency and growth ring analysis of Mytilus edulis and Cardium edule and their paleoecological significance. Paleontology 6: 731-750.

Dalenius, T. and J.L. Hodges, Jr. 1959. Minimum variance stratification. J. Amer. Stat. Assoc. 54: 88-101.

Greene, G.T. 1978. Population Structure, Growth and Mortality of Hard Clams at Selected Locations in Great South Bay, New York. M.S. Thesis. Marine Sciences Research Center, State University of New York, Stony Brook, NY. 199 pp.

Greene, G.T. 1981. Hard Clams, Competitors, Predators, and Physical Parameters in Great South Bay. First Impressions, New York Sea Grant Institute, Stony Brook, New York. 157 pp.

Hasselblad, V. 1966. Estimation of parameters for a mixture of normal distributions. Technometrics 8: 431-444.

Hosmer, Jr. D.W. 1973. A comparison of iterative maximum likelihood estimates of the parameters of a mixture of two normal distributions under three different types of sample. Biometrics 29: 761-770.

Jessen, R.J. 1942. Statistical investigation of a sample survey for obtaining farm facts. Iowa Agr. Exp. Sta. Res. Bull. 304.

Kassner, J. 1988. Hard Clam Population Survey Data for the Eastern Great South Bay. Unpublished ms. Town of Brookhaven, Division of Environmental Protection, Medford, New York.

Mantel, N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Res. 27: 209-220.

Wartenberg, D.E. 1984. The Statistical Analysis of Spatial Pattern in Biological Systems. Ph. D. Thesis. Department of Ecology and Evolution, State University of New York, Stony Brook, NY.

Table 1. Mean hard clam abundances in eastern Great South Bay. Abundances expressed as the number of individuals per square meter.

Census Year	Number of Quadrats	Total (>=20 mm)	Sublegal (20-48 mm)	Legal (> 48 mm)
1986	181	6.79	4.71	2.08
1987	233	6.67	4.51	2.16
1988	232	6.27	4.25	2.03

Table 2. Gain in precision over simple random sampling due to stratifying the study area on the basis of quadrats and beds. Bed strata based on average abundance contour. SE is standard error.

Census Year	Quadrats as Strata			Beds as Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	Number of Strata	SE	% Gain	SE
1986	181	0.285	32.0	5	0.322	23.2	0.419
1987	233	0.173	55.8	8	0.275	29.7	0.391
1988	232	0.276	43.0	8	0.378	21.9	0.484

Table 3. Gain in precision over simple random sampling due to stratifying the study area on the basis of a prior census. Strata based on average abundance contour. SE is standard error.

Census Year	1986 Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	SE
1987	5	0.403	8.4	0.440
1988	5	0.462	14.8	0.542

Note: All quadrats lying outside of the 1986 census area were omitted from the above calculations

Census Year	1987 Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	Se
1988	8	0.384	20.7	0.484

Table 4. Gain in precision over simple random sampling due to stratifying the study area on the basis of the minimum variance rule. Bed strata based on a contour level of 8 individuals per square meter. SE is standard error.

Census Year	Beds as Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	SE
1986	5	0.320	23.6	0.419
1987	8	0.280	28.4	0.391
1988	6	0.373	22.9	0.484

Table 5. Gain in precision over simple random sampling due to stratifying the study area on the basis of a prior census. Strata based on the minimum variance rule leading to a single contour level of 8 individuals per square meter. SE is standard error.

Census Year	1986 Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	SE
1987	5	0.398	9.5	0.440
1988	5	0.464	14.4	0.542

Note: All quadrats lying outside of the 1986 census area were omitted from the above calculations

Census Year	1987 Strata			Simple Random Sampling
	Number of Strata	SE	% Gain	Se
1988	8	0.390	19.4	0.484

Table 6. Maximum likelihood estimates for the high and low density area for 1987. Based on size-age data, the length distribution was truncated, to remove some of the largest clams, prior to estimation. These individuals were grouped into the last age class. SD is standard deviation and SE is standard error.

<u>High Density Area</u>

Size of Aged Subsample = 60
Size of Non-Aged Subsample = 1370

Age	Mean Size (mm)	SD (mm)	Proportion	Age Structure (# per sq. m)
1	15.03	3.56	0.309	5.58
2	32.25	4.62	0.106	1.92
3	43.39	5.56	0.578	10.47
4	51.18	0.88	0.007	0.13
>=5	-	-	-	0.14

Age	SE Mean (mm)	SE SD (mm)	SE Proportion	SE Age Struct. (# per sq. m)
1	0.19	0.14	0.013	0.23
2	0.76	0.66	0.017	0.30
3	0.31	0.20	0.020	0.37
4	1.02	0.47	0.006	0.10
>=5	-	-	-	-

<u>Low Density Area</u>

Size of Aged Subsample = 5
Size of Non-Aged Subsample = 184

Age	Mean Size (mm)	SD (mm)	Proportion	Age Structure (# per sq. m)
1	17.18	1.38	0.043	0.11
2	23.39	3.82	0.065	0.16
3	46.66	6.28	0.669	1.66
4	56.78	1.05	0.109	0.28
5	62.24	2.33	0.114	0.29
>=6	-	-	-	0.11

Age	SE Mean (mm)	SE SD (mm)	SE Proportion	SE Age Struct. (# per sq. m)
1	0.69	0.48	0.020	0.05
2	2.25	1.12	0.028	0.07
3	0.80	0.61	0.047	0.12
4	0.38	0.36	0.033	0.08
5	0.76	0.52	0.029	0.07
>=6	-	-	-	-

Table 7. Maximum likelihood estimates for the high and low density area for 1988. Based on size-age data, the length distribution was truncated, to remove some of the largest clams, prior to estimation. These individuals were grouped into the last age class. SD is standard deviation and SE is standard error.

High Density Area

Size of Aged Subsample = 82
Size of Non-Aged Subsample = 1190

Age	Mean Size (mm)	SD (mm)	Proportion	Age Structure (# per sq. m)
1	15.88	3.57	0.202	3.25
2	32.21	3.90	0.148	2.39
3	42.75	3.78	0.567	9.13
4	50.77	4.20	0.083	1.34
>=5	-	-	-	0.14

Age	SE Mean (mm)	SE SD (mm)	SE Proportion	SE Age Struct. (# per sq. m)
1	0.25	0.19	0.012	0.19
2	0.47	0.36	0.015	0.24
3	0.25	0.17	0.023	0.37
4	0.69	0.49	0.013	0.21
>=5	-	-	-	-

Low Density Area

Size of Aged Subsample = 32
Size of Non-Aged Subsample = 122

Age	Mean Size (mm)	SD (mm)	Proportion	Age Structure (# per sq. m)
1	15.48	3.97	0.136	0.28
2	34.07	3.19	0.084	0.17
3	43.57	4.66	0.323	0.66
4	52.32	3.23	0.381	0.78
5	61.27	3.55	0.076	0.16
>=6	-	-	-	0.07

Age	SE Mean (mm)	SE SD (mm)	SE Proportion	SE Age Struct. (# per sq. m)
1	0.87	0.63	0.028	0.06
2	1.16	0.79	0.035	0.07
3	1.41	0.75	0.068	0.14
4	0.57	0.42	0.056	0.11
5	1.45	0.95	0.025	0.05
>=6	-	-	-	-

Table 8. Mortality rates calculated from age-specific abundance estimates. Mortality rate was calculated as $(N_{87}-N_{88})/N_{87}$, where N_{87} and N_{88} represent the age-specific abundances of each year class for 1987 and 1988, respectively.

High Density Area						
	Year Class					
	1987	1986	1985	1984	<=1983	
Abundance in 1987	–	5.58	1.92	10.47	0.27	
Abundance in 1988	3.25	2.39	9.13	1.34	0.14	
Age Interval		1-2	2-3	3-4	4 +	
Mortality Rate		0.57	?	0.87	0.48	

Low Density Area						
	Year Class					
	1987	1986	1985	1984	1983	<=1982
Abundance in 1987	–	0.11	0.16	1.66	0.28	0.40
Abundance in 1988	0.28	0.17	0.66	0.78	0.16	0.07
Age Interval		1-2	2-3	3-4	4-5	5 +
Mortality Rate		?	?	0.53	0.43	0.83

Table 9. Estimated recruitment to the fishery between 1987 and 1988. Recruitment was calculated as the change in the fraction of legal size clams in each year class multiplied to the age-specific abundances for 1987. Fraction of legal size assumes that size data for a cohort are normally distributed and uses maximum likelihood estimates for mean size and standard deviation.

High Density Area					
	Fraction Legal Size				
Year Class	1987	1986	1985	1984	<=1983
1988 Census	0	0	0.08	0.76	1.00
1987 Census	-	0	0	0.20	1.00
Change in Fraction Legal Size		0	0.08	0.56	0
1987 Abundance (# per sq. m)	-	5.58	1.92	10.47	0.27
Age-specific Recruitment to fishery (# per sq. m)		0	0.15	5.86	0
Total Recruitment to Fishery (# per sq. m)			6.01		

Table 9 (continued)

Low Density Area						
	Fraction Legal Size					
Year Class	1987	1986	1985	1984	1983	<=1982
1988 Census	0	0	0.17	0.91	1.00	1.00
1987 Census	–	0	0	0.41	1.00	1.00
Change in Fraction Legal Size		0	0.17	0.50	0	0
1987 Abundance (# per sq. m)	–	0.11	0.16	1.66	0.28	0.40
Age-specific Recruitment to fishery (# per sq. m)		0	0.03	0.83	0	0
Total Recruitment to Fishery (# per sq. m)			0.86			

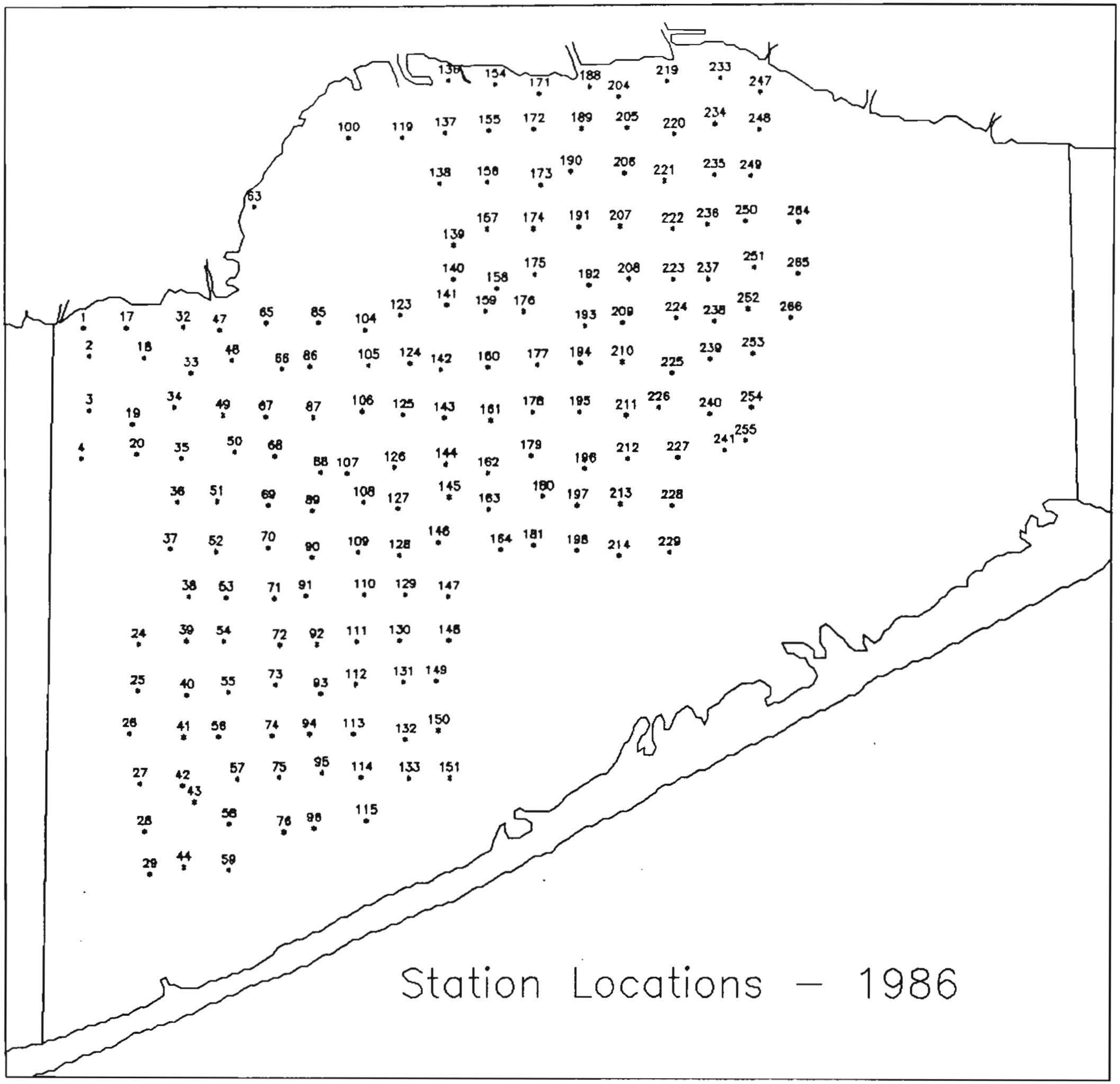


Figure 1. Station locations for the 1986 census.

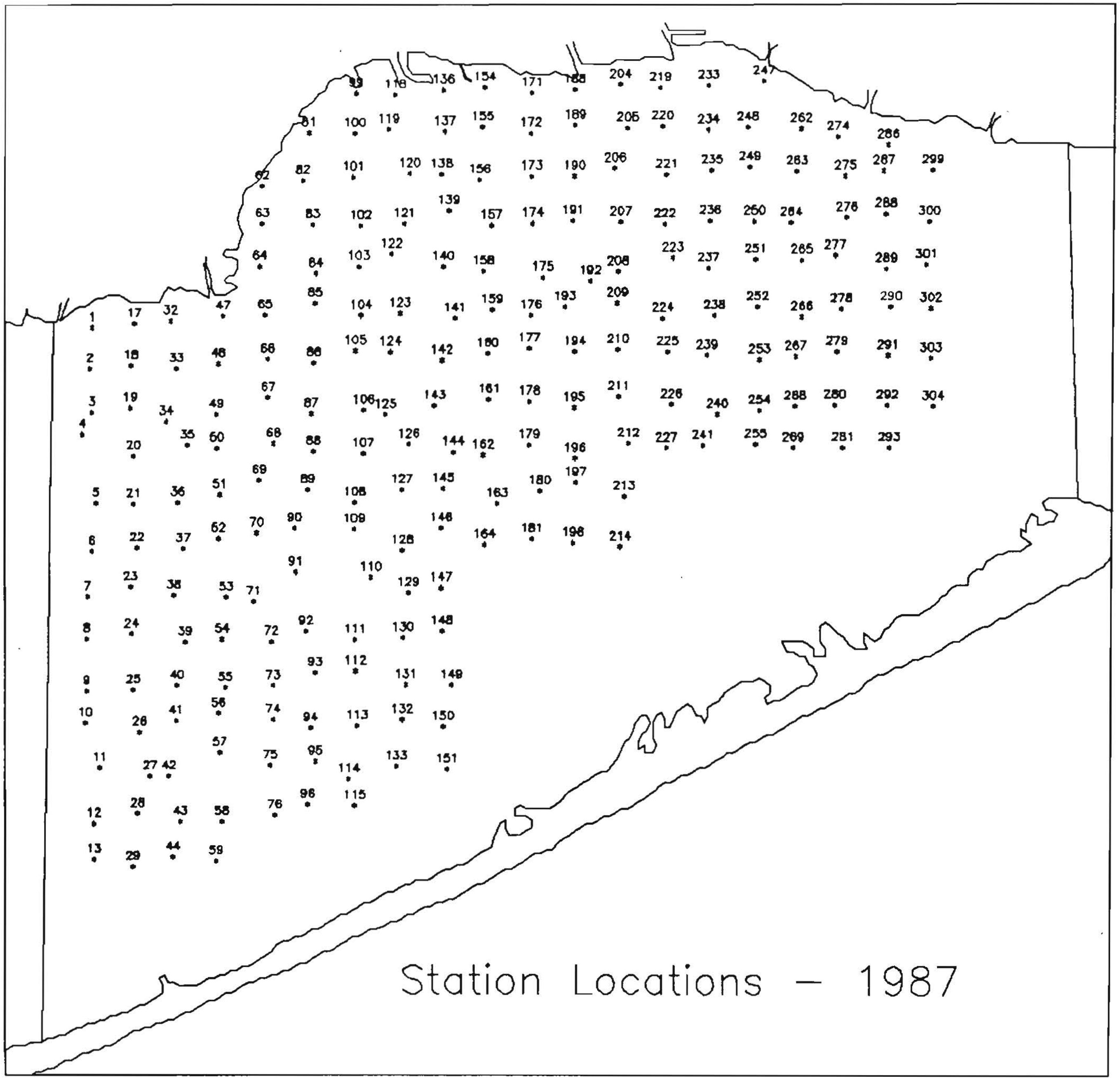


Figure 2. Station locations for the 1987 census.

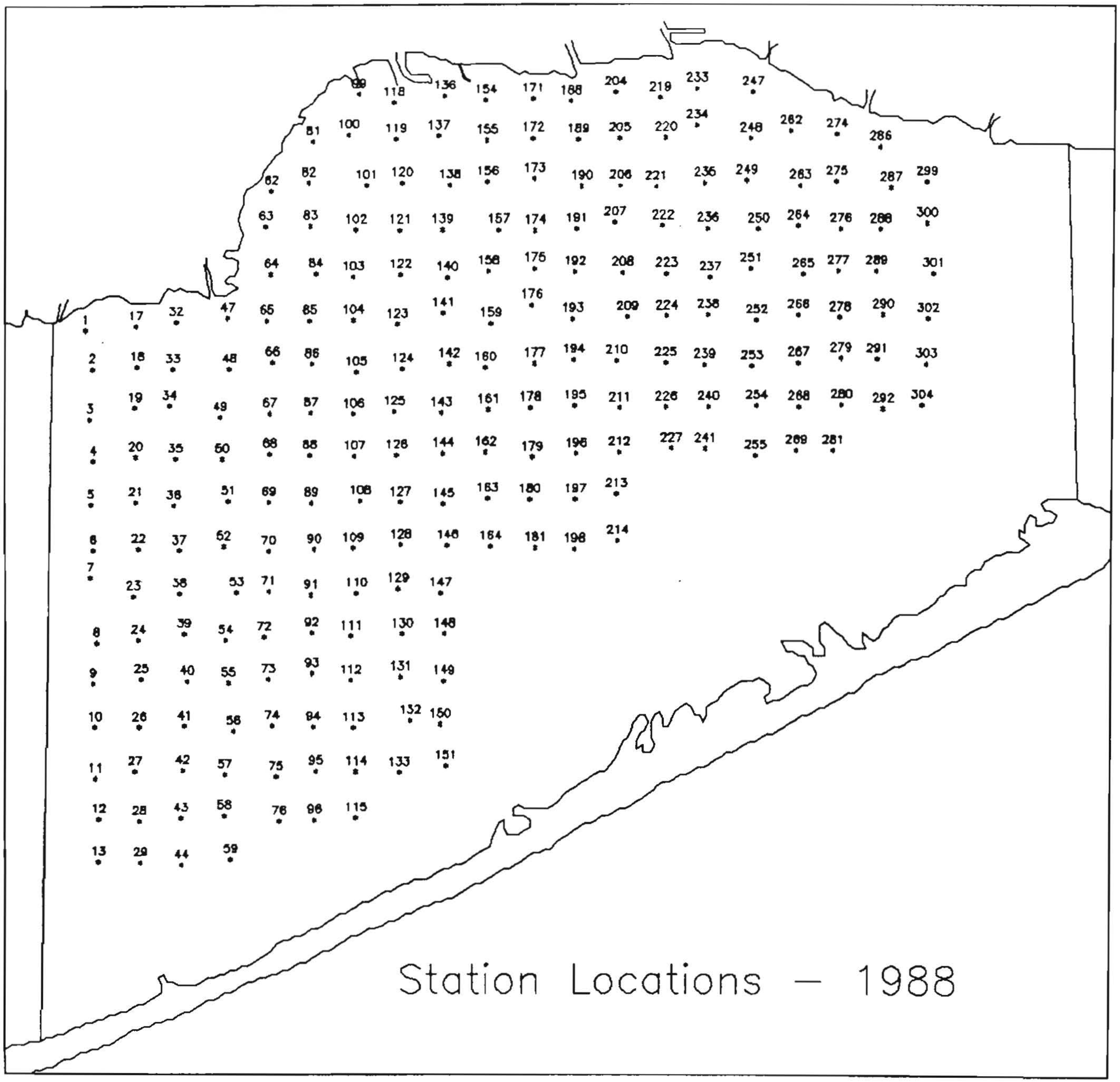


Figure 3. Station locations for the 1988 census.

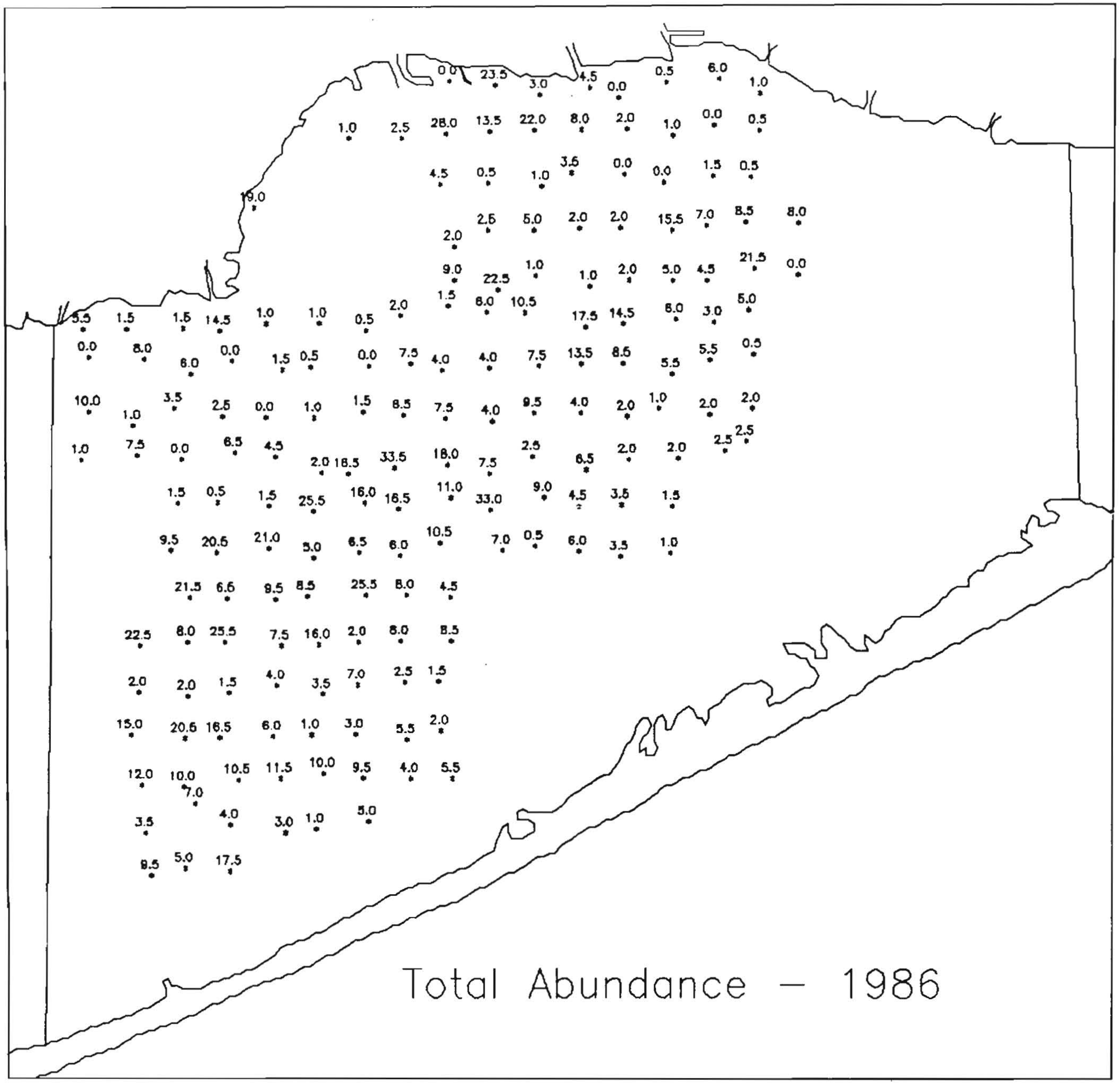


Figure 4. Total abundance (per sq. m.) of hard clams >= 20 mm in shell length for 1986.

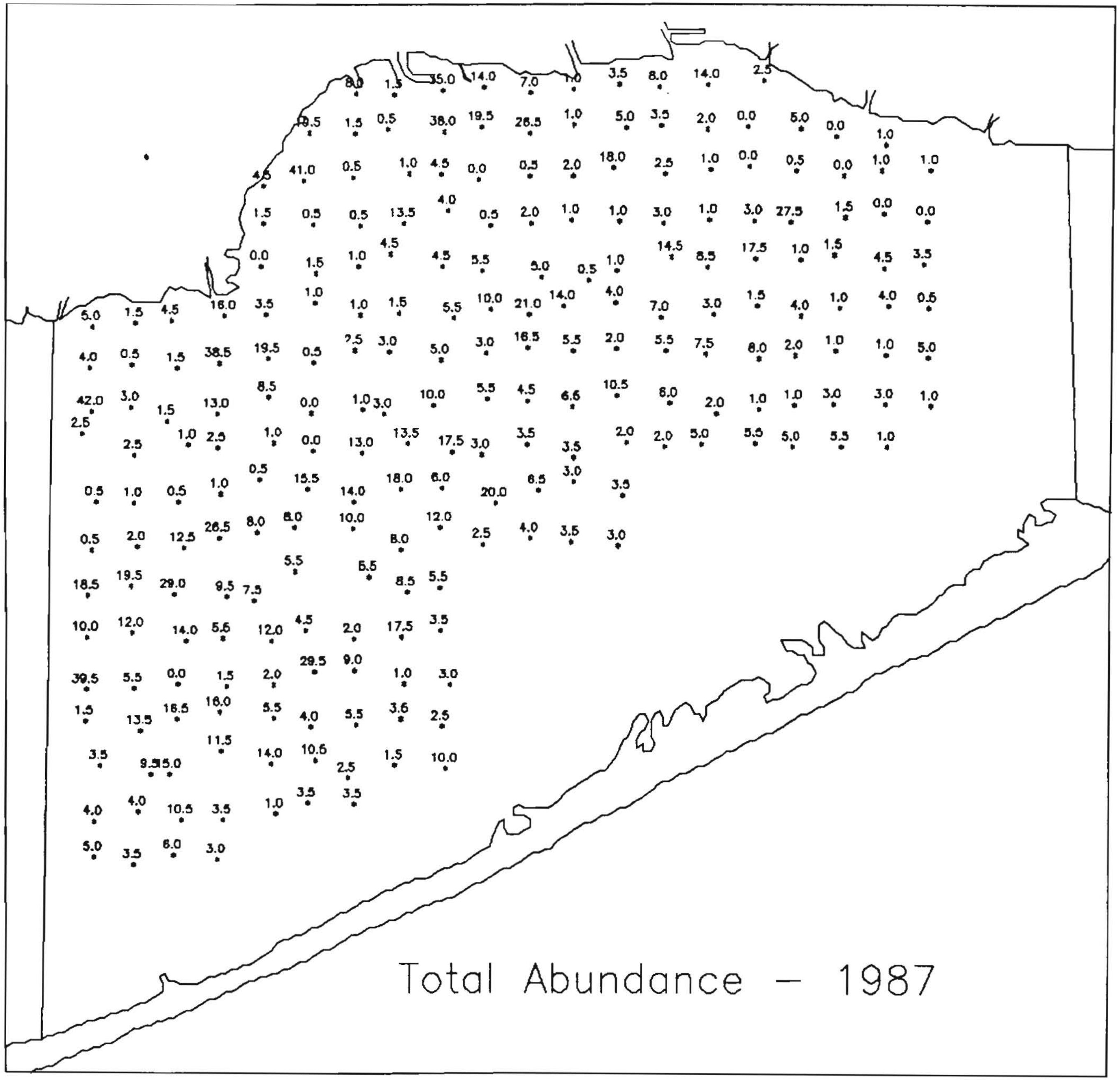


Figure 5. Total abundance (per sq. m.) of hard clams >= 20 mm in shell length for 1987.

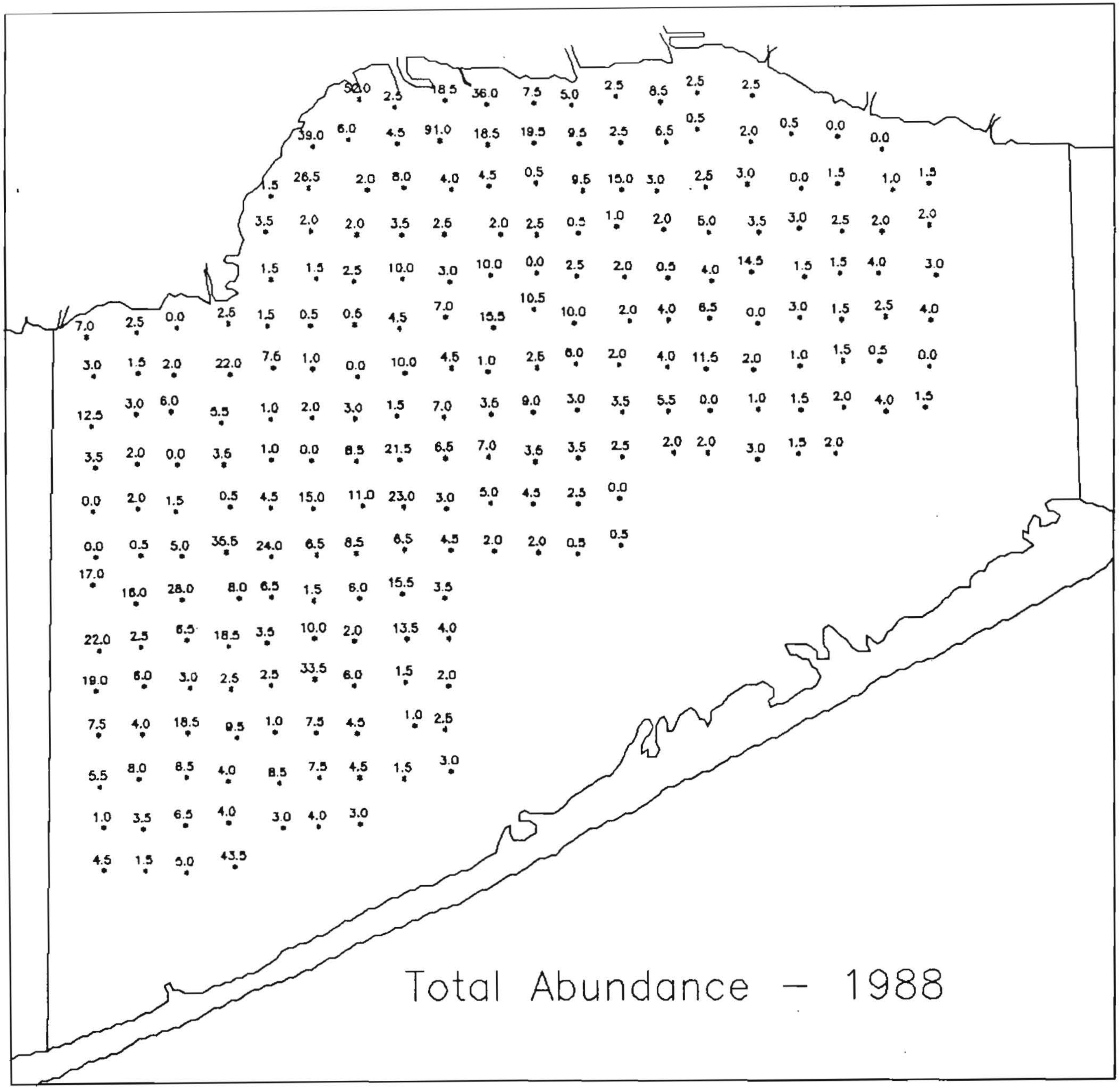


Figure 6. Total abundance (per sq. m.) of hard clams >= 20 mm in shell length for 1988.

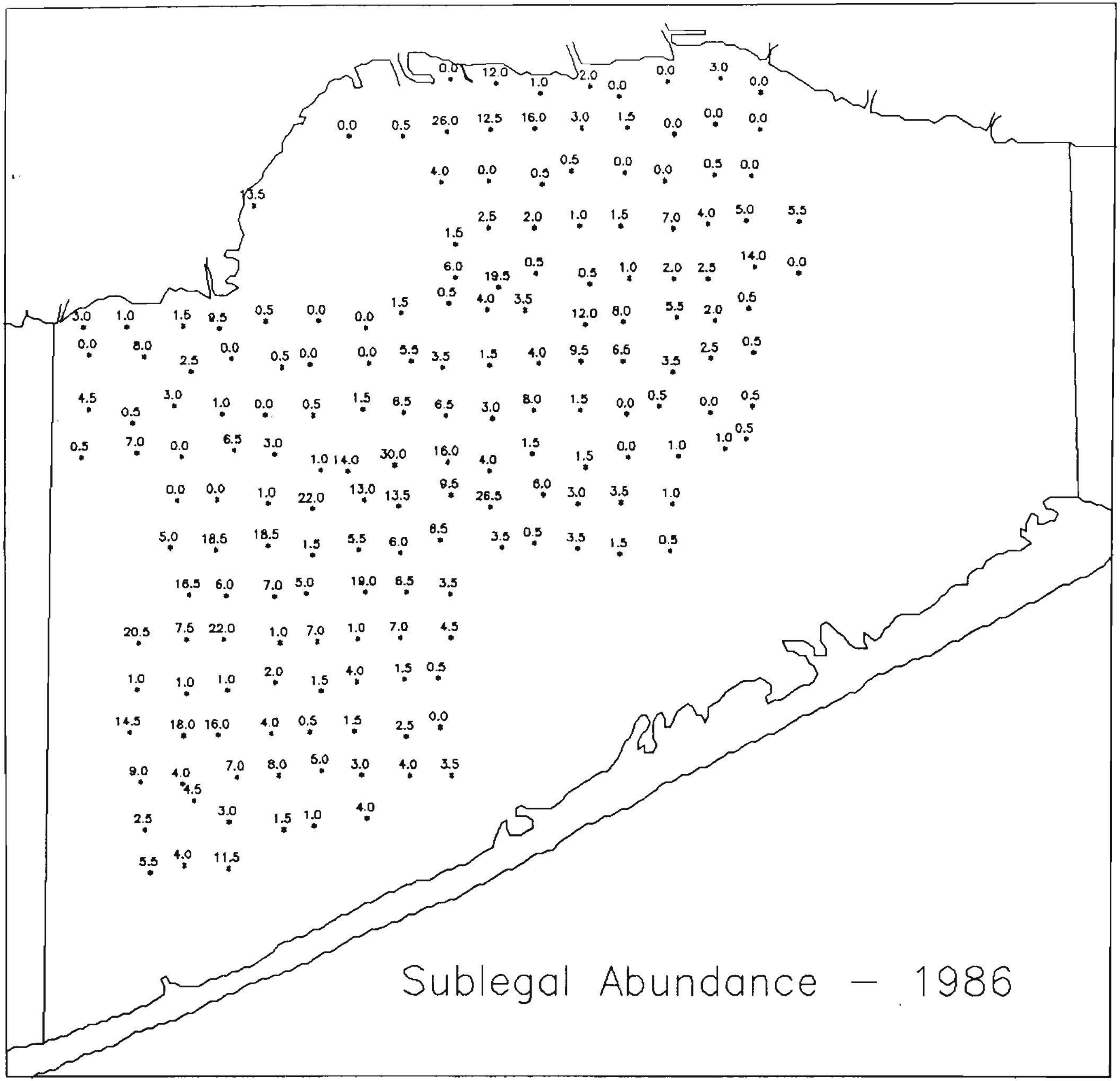


Figure 7. Abundance (per sq. m.) of sublegal size hard clams (20-48 mm in shell length) for 1986.

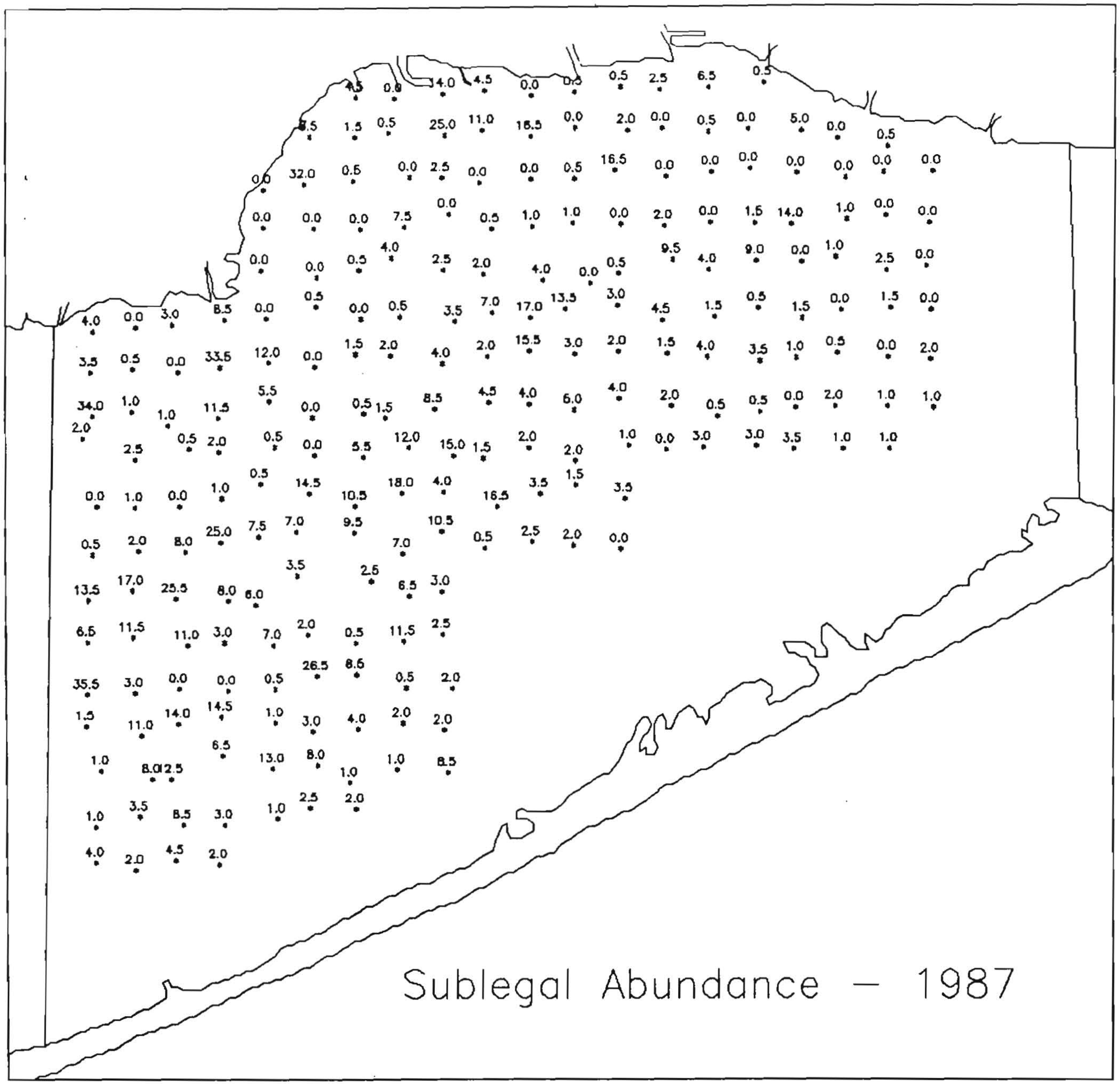


Figure 8. Abundance (per sq. m.) of sublegal size hard clams (20-48 mm in shell length) for 1987.

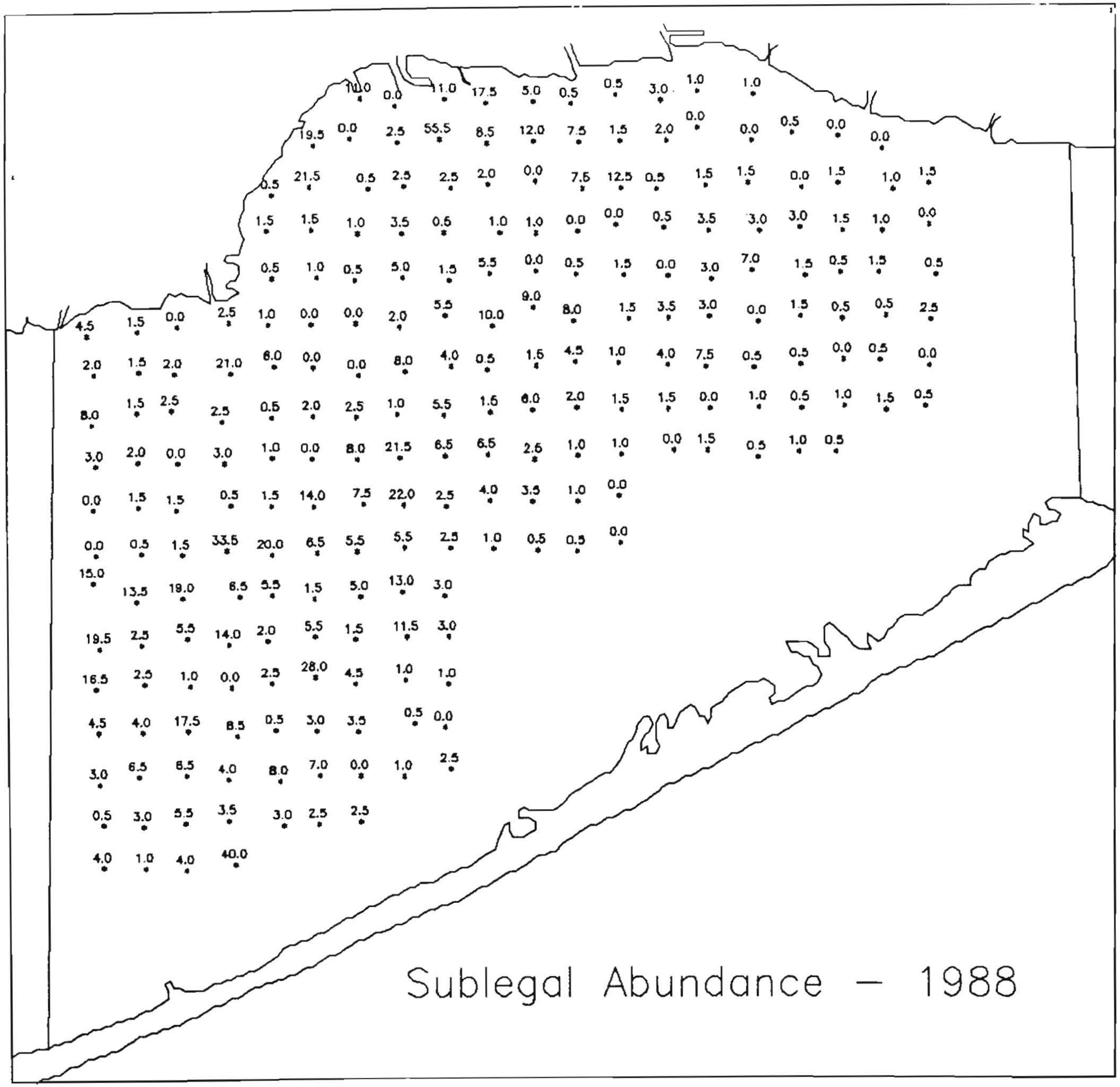


Figure 9. Abundance (per sq. m.) of sublegal size hard clams (20-48 mm in shell length) for 1988.

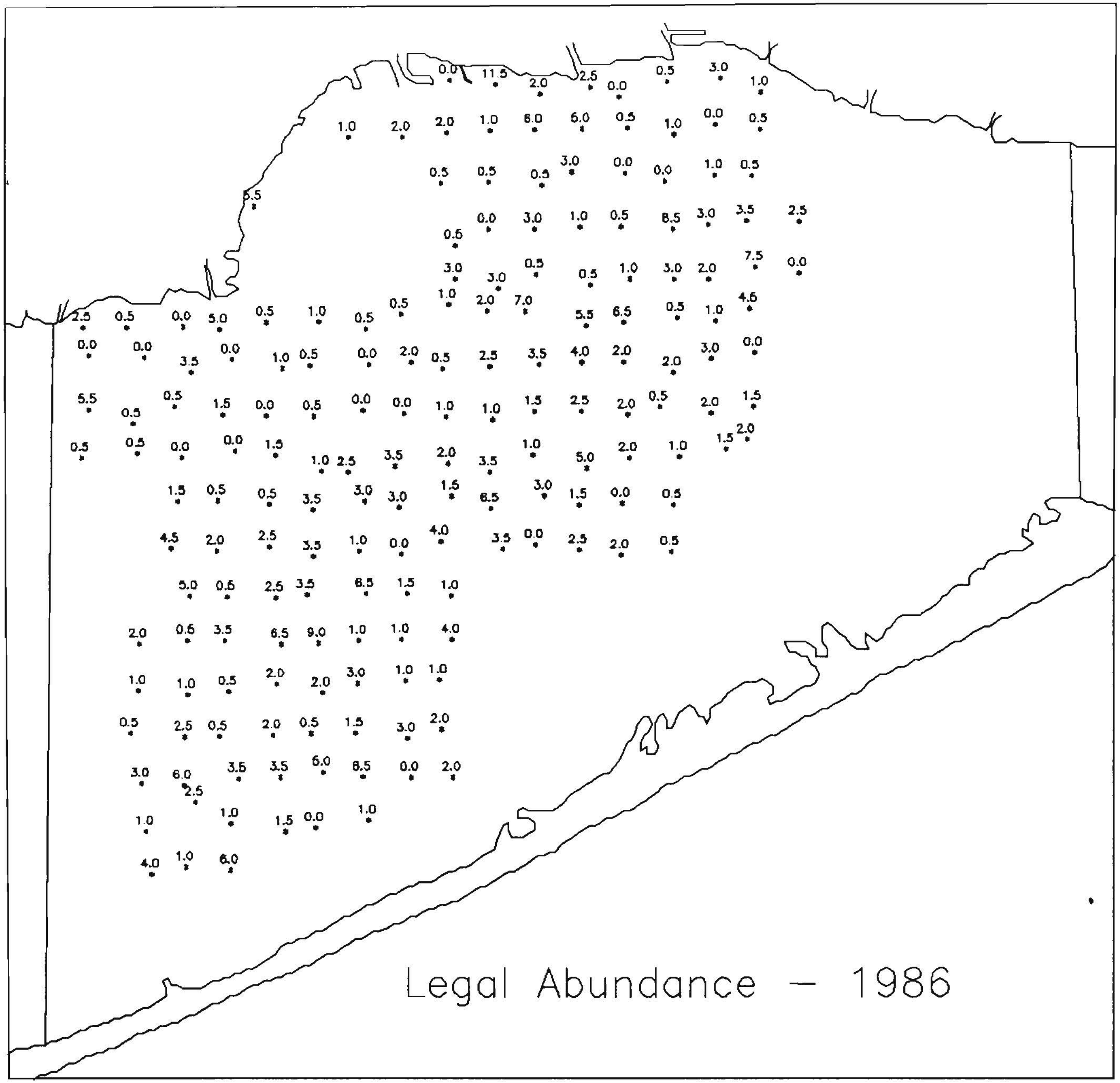
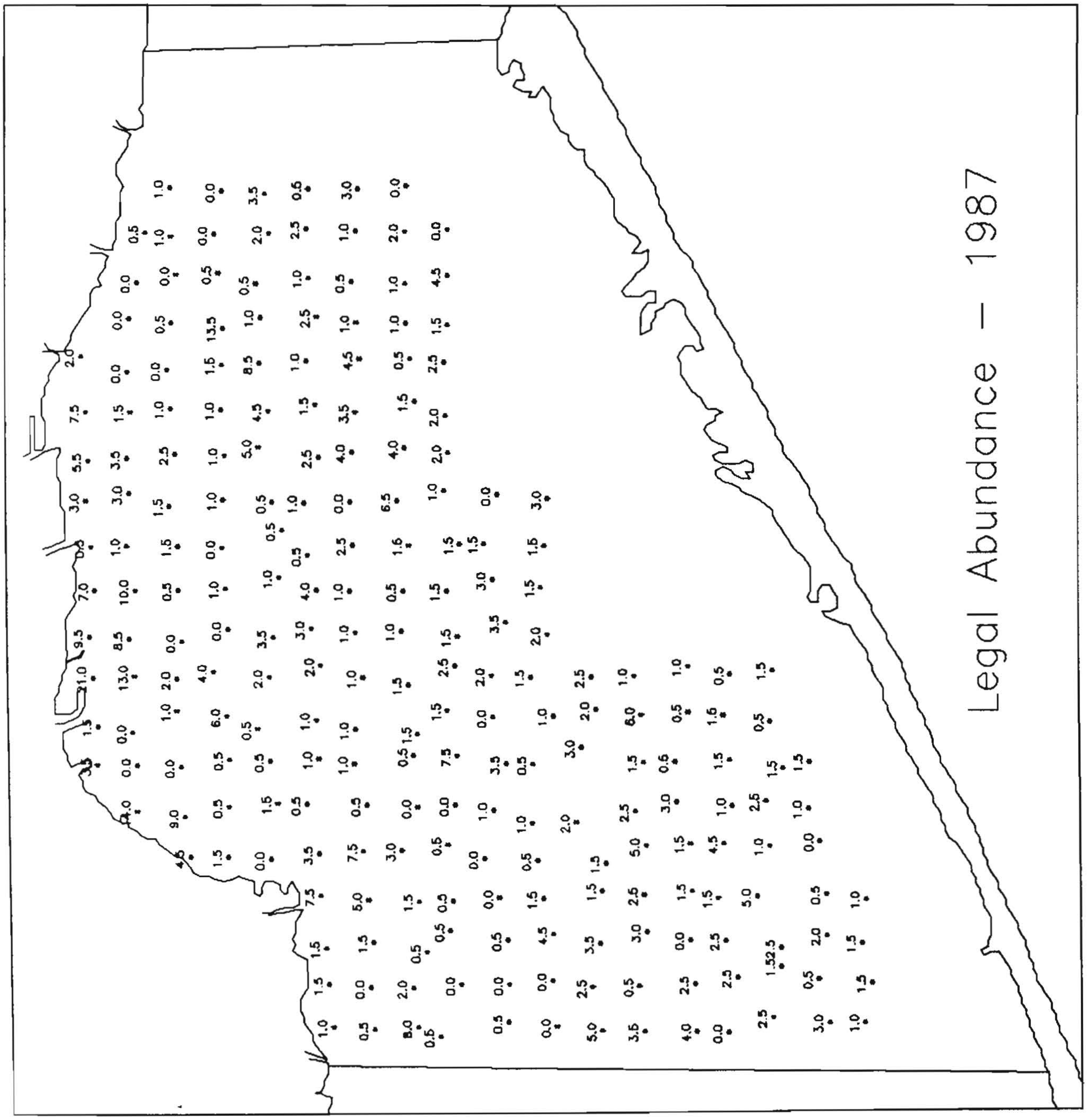


Figure 10. Abundance (per sq. m.) of legal size hard clams (>48 mm in shell length) for 1986.

Figure 11. Abundance (per sq. m.) of legal size hard clams (>48 mm in shell length) for 1987.



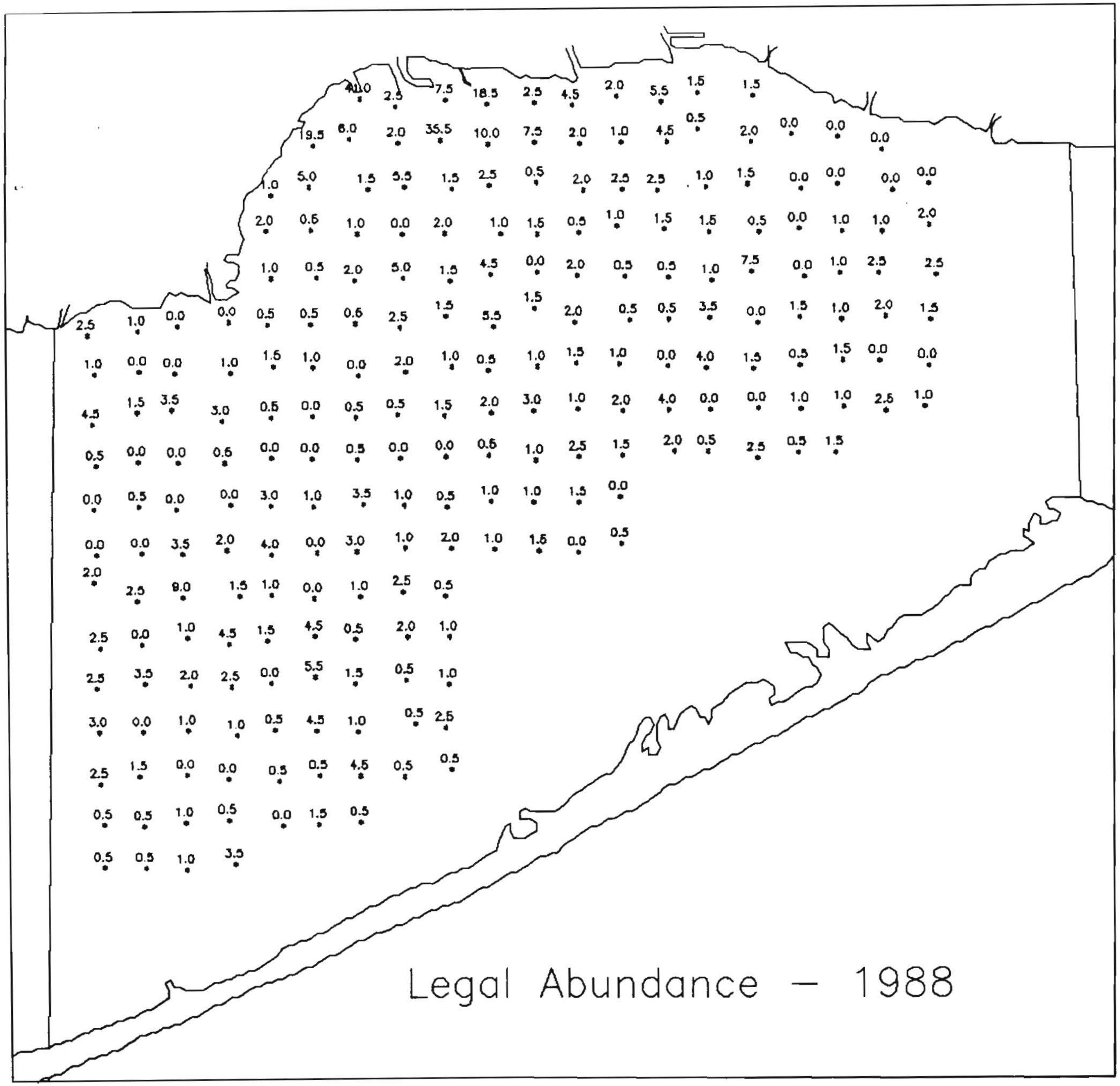


Figure 12. Abundance (per sq. m.) of legal size hard clams (>48 mm in shell length) for 1988.

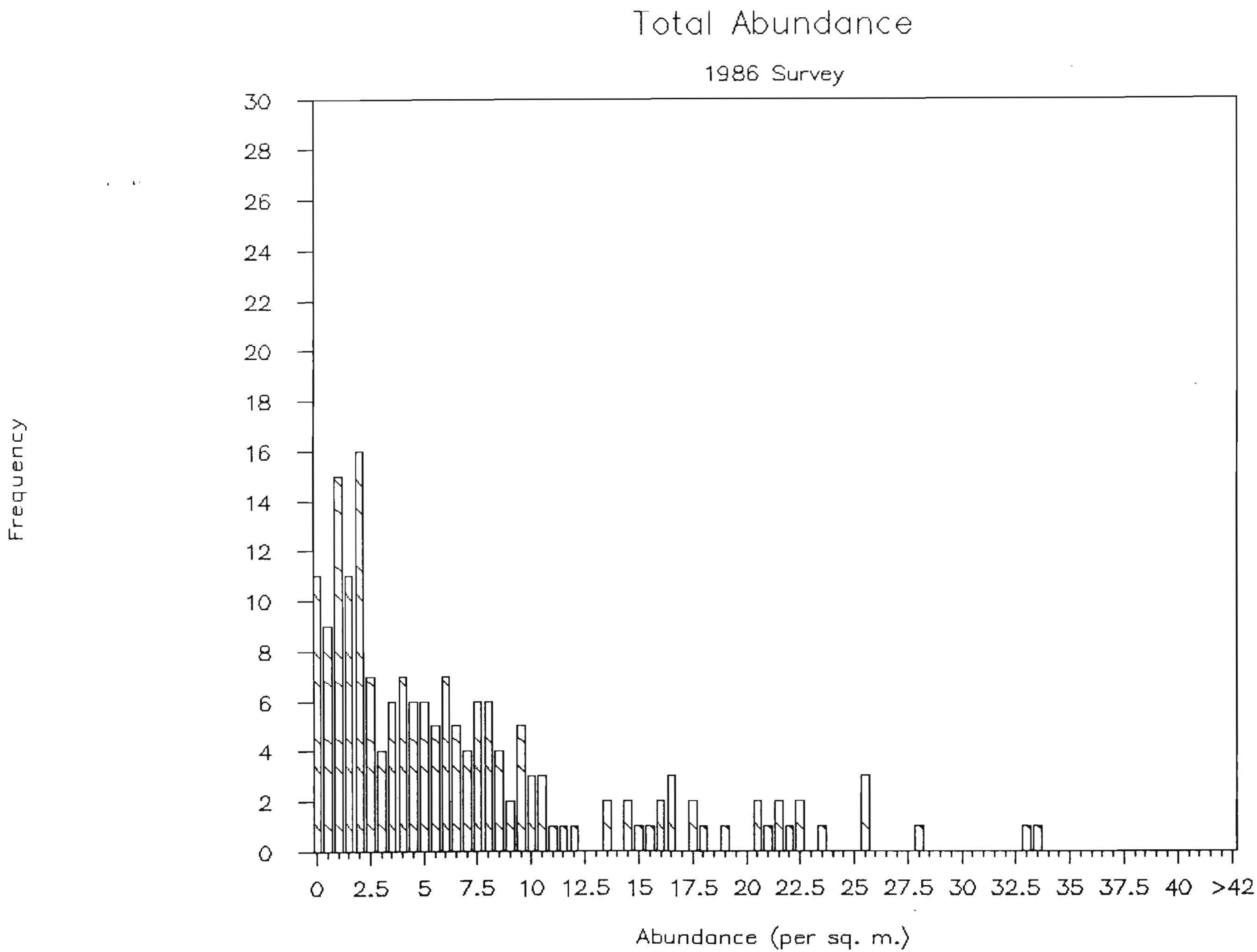


Figure 13. Total abundance-frequency distribution for 1986.

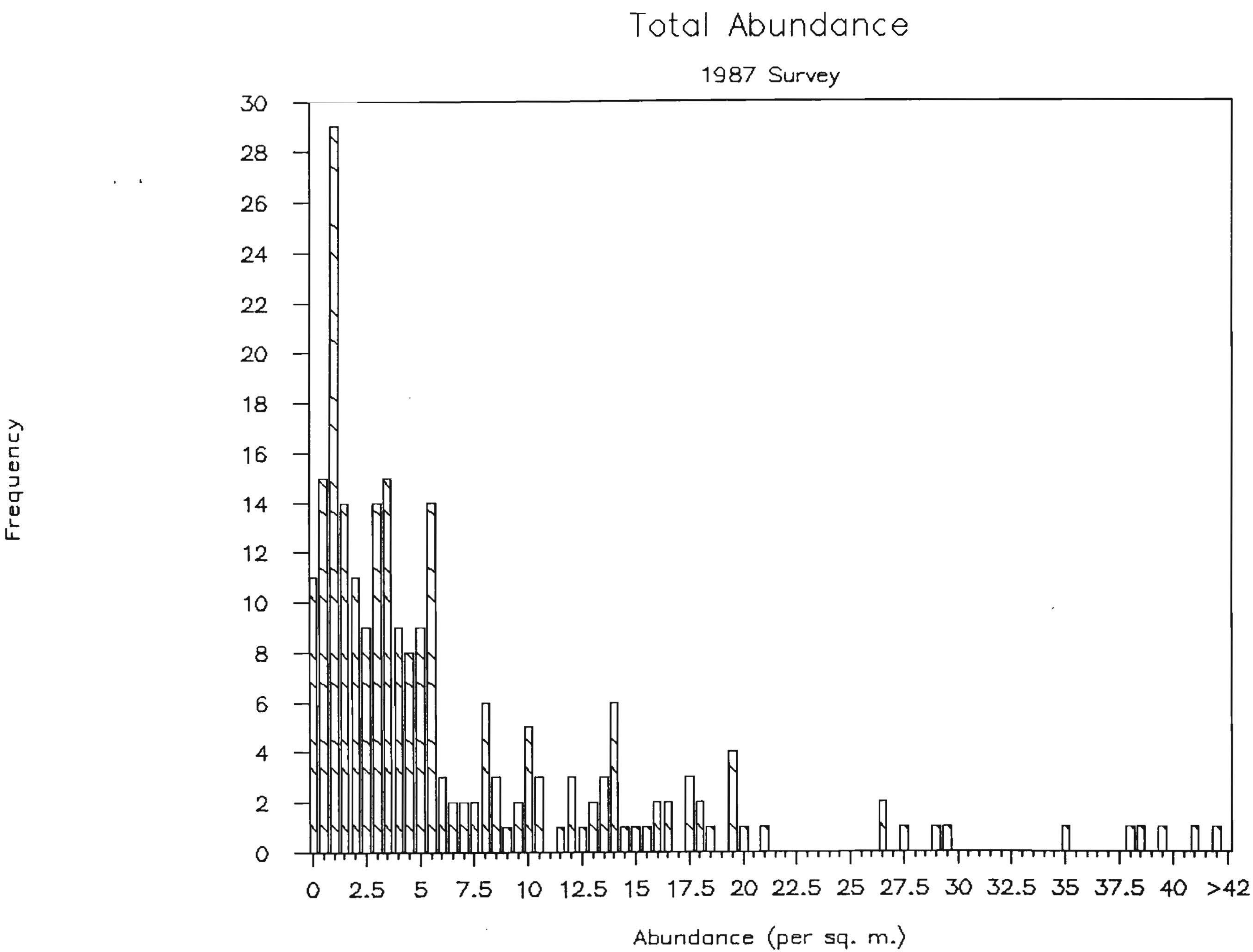


Figure 14. Total abundance-frequency distribution for 1987.

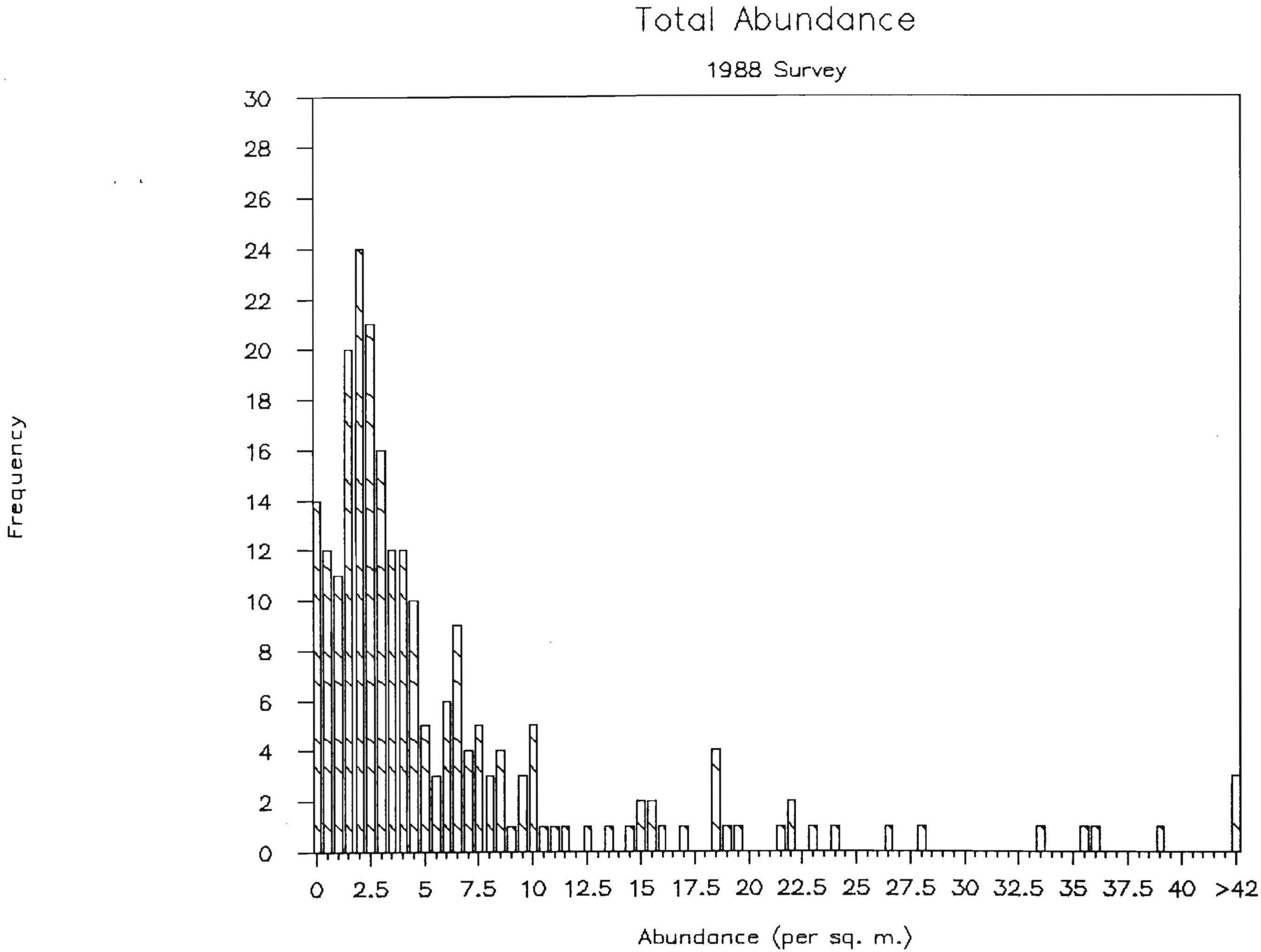


Figure 15. Total abundance-frequency distribution for 1988.

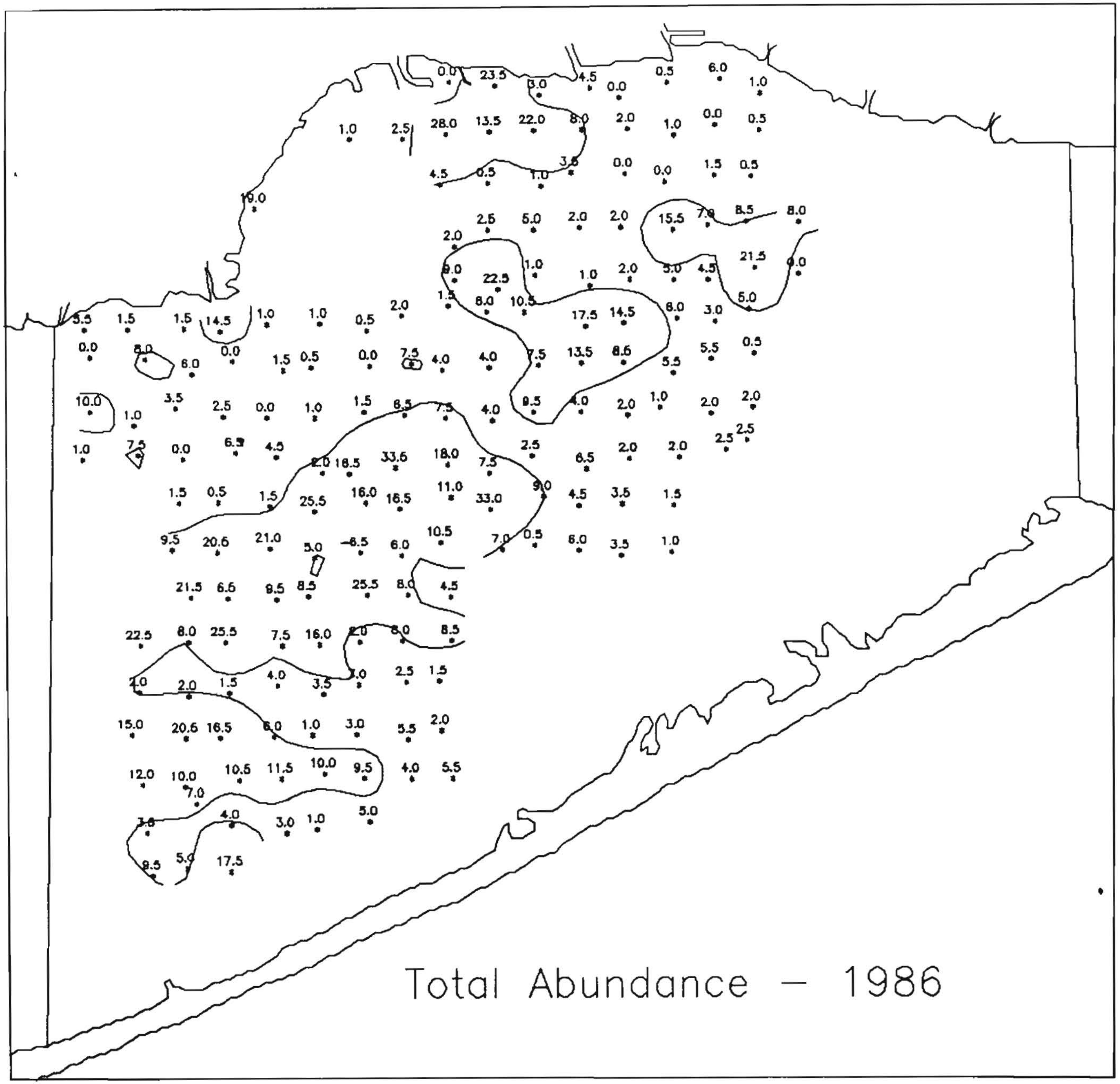
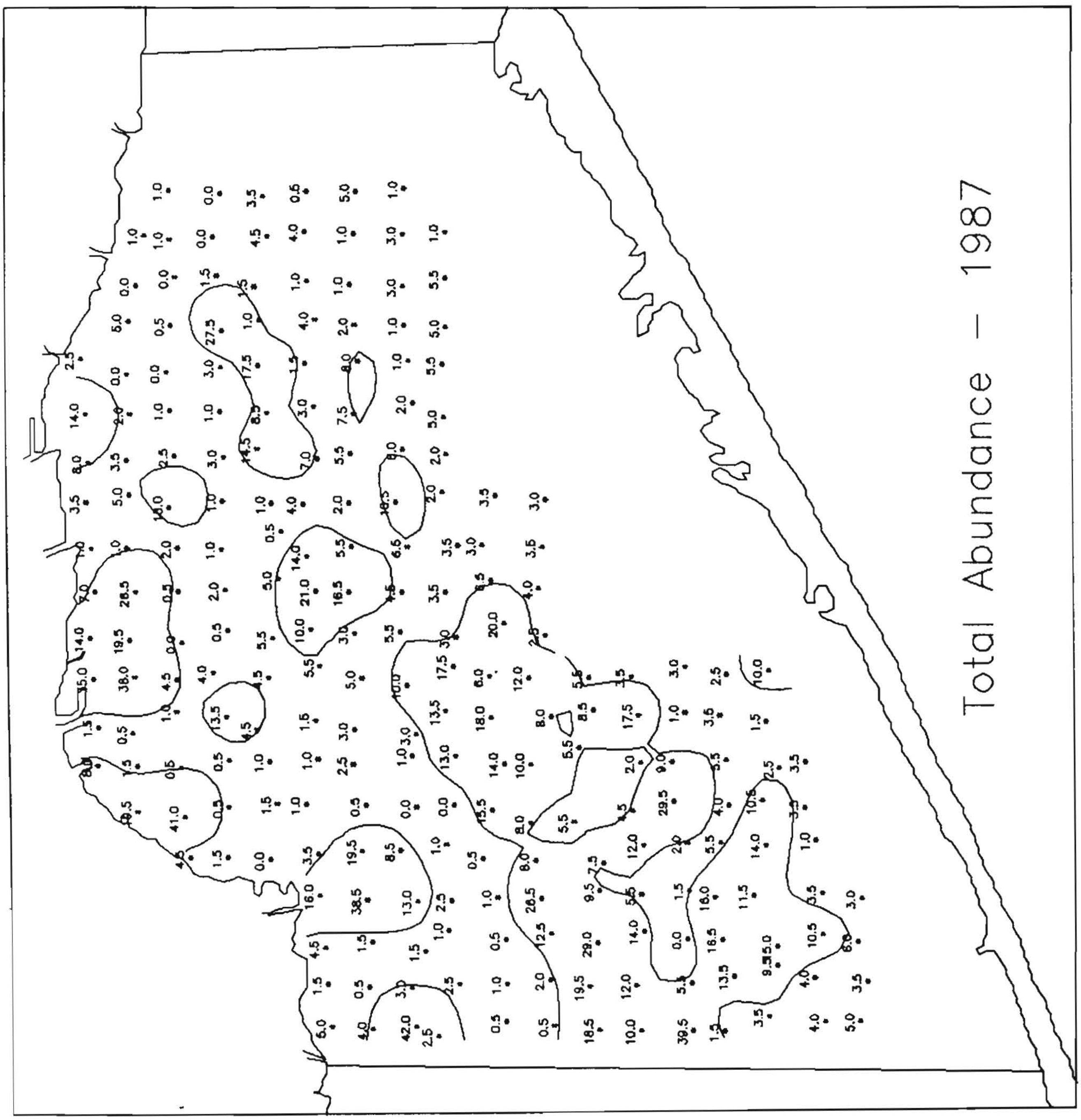


Figure 16. Contour map of total abundance for 1986. Contour level is mean abundance.

Figure 17. Contour map of total abundance for 1987. Contour level is mean abundance.



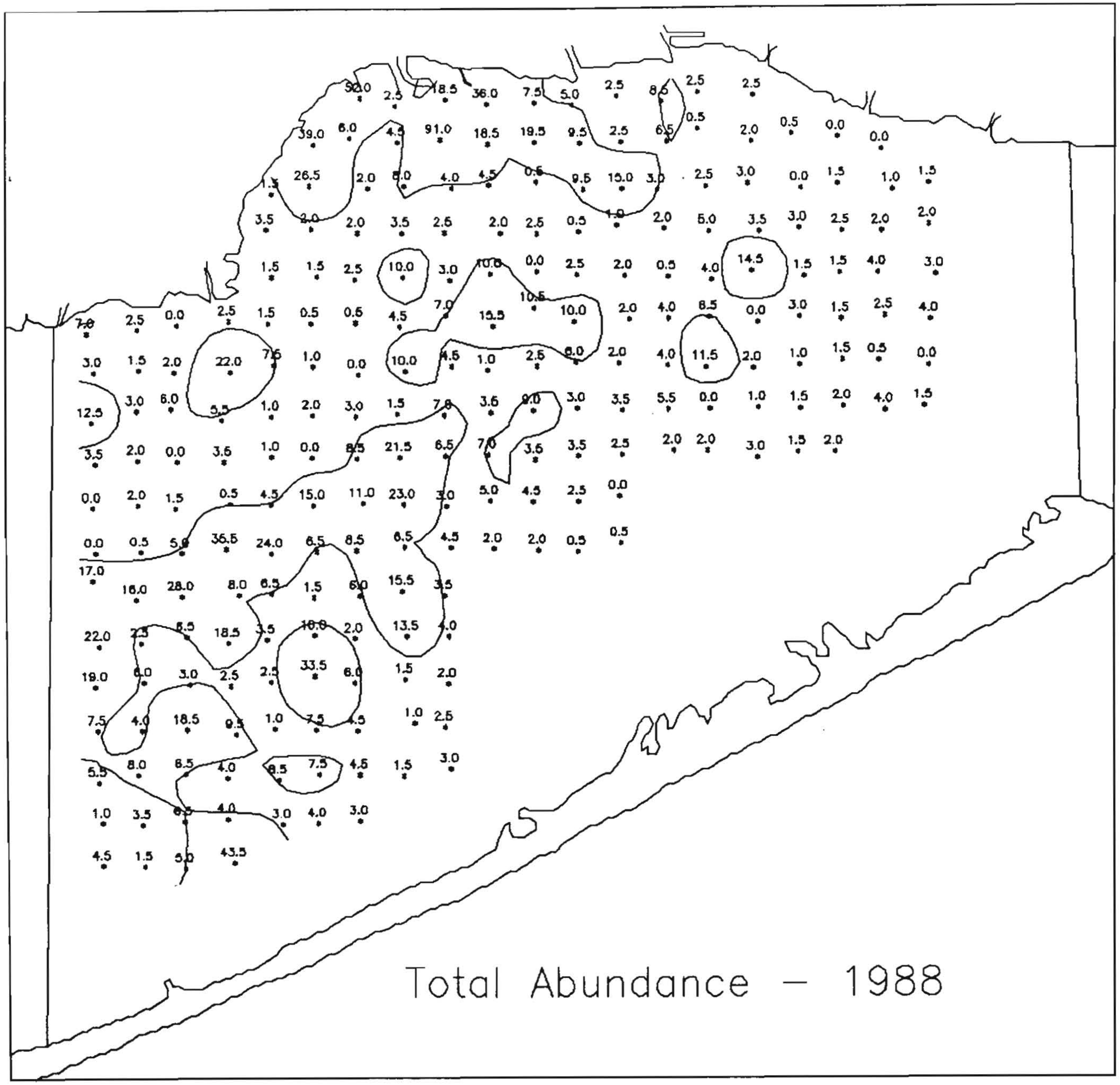


Figure 18. Contour map of total abundance for 1988. Contour level is mean abundance.

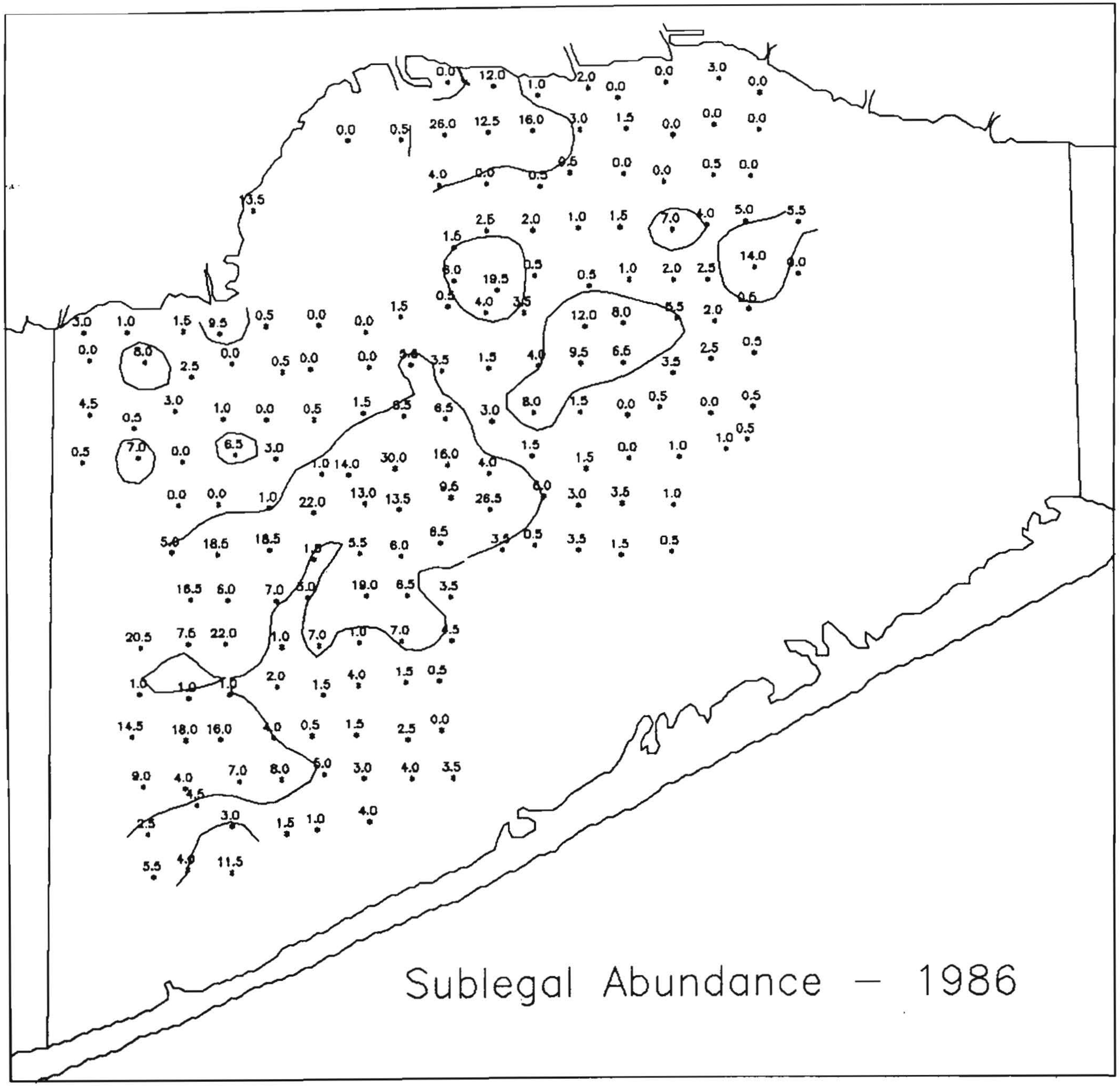


Figure 19. Contour map of sublegal abundance for 1986. Contour level is mean abundance of sublegal size clams.

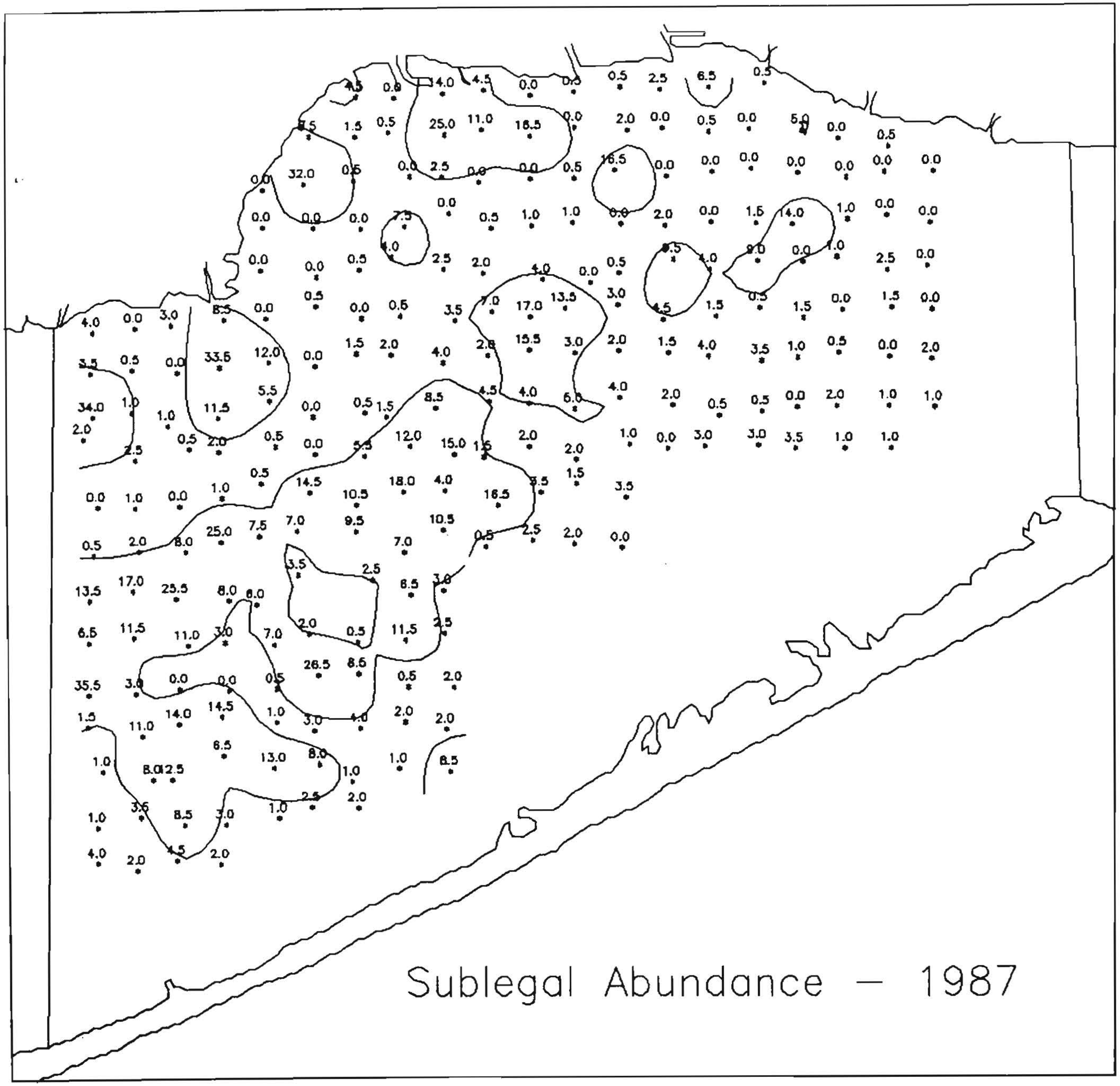


Figure 20. Contour map of sublegal abundance for 1987. Contour level is mean abundance of sublegal size clams.

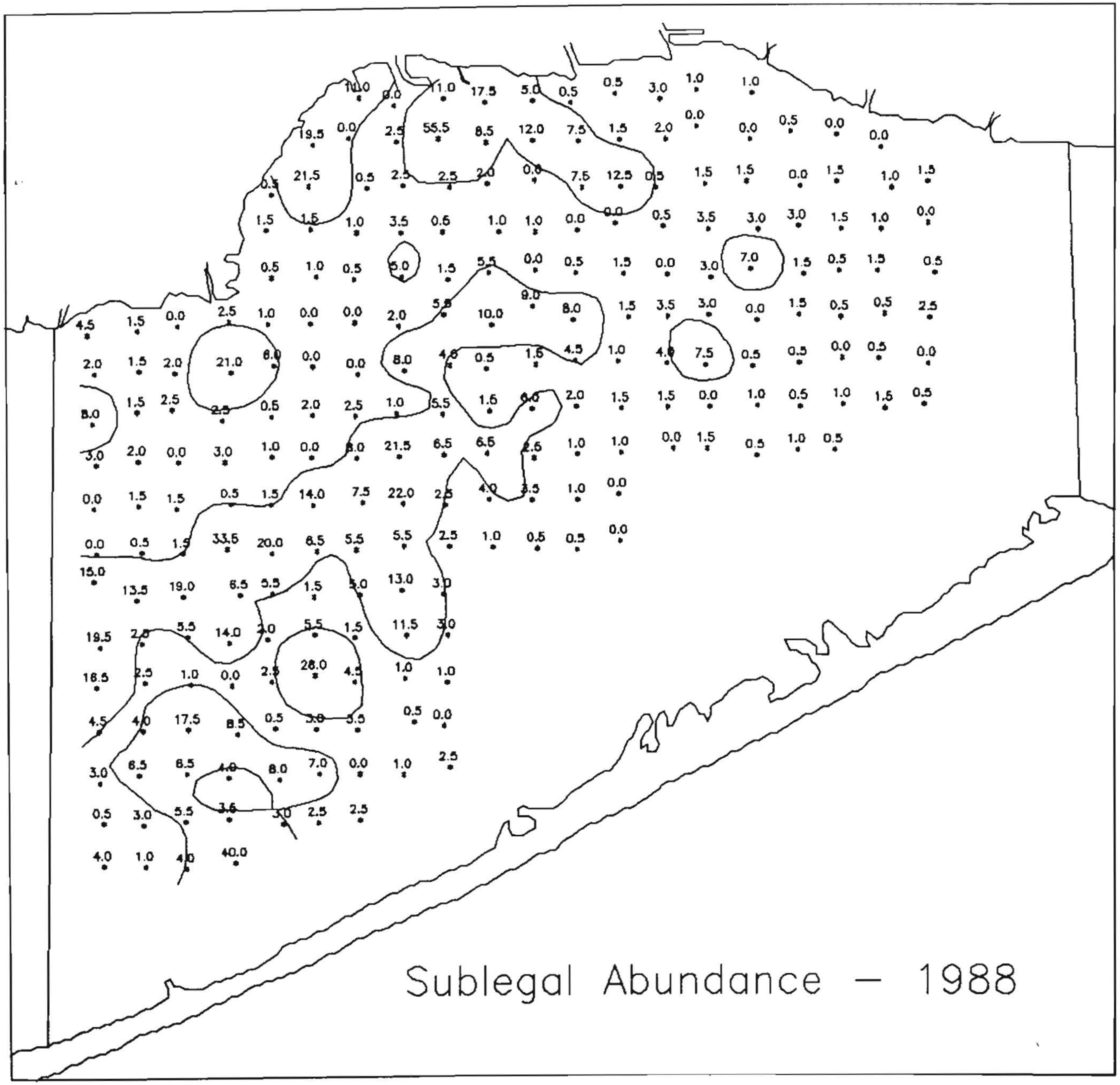


Figure 21. Contour map of sublegal abundance for 1988. Contour level is mean abundance of sublegal size clams.

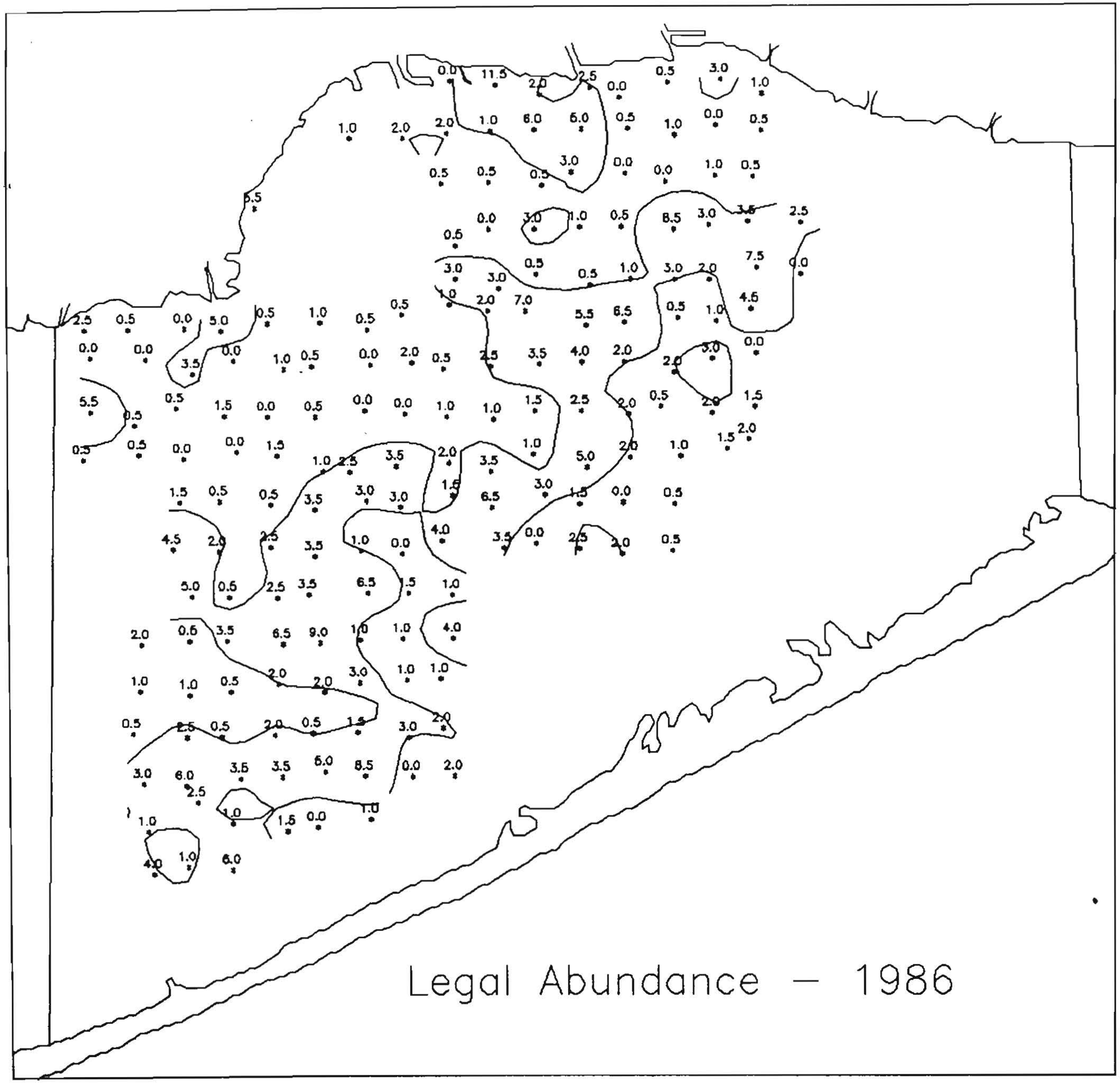


Figure 22. Contour map of legal abundance for 1986. Contour level is mean abundance of legal size clams.

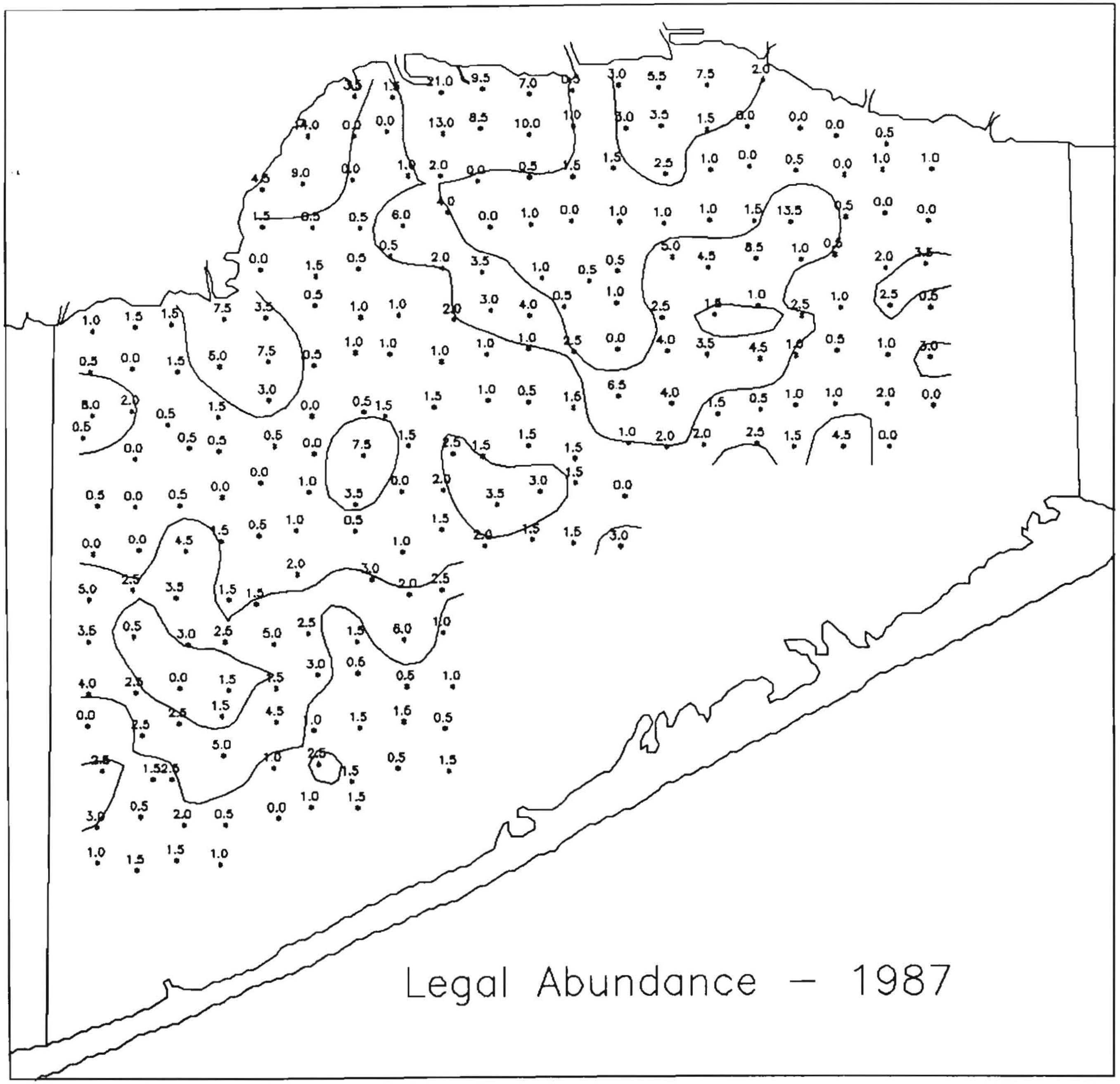


Figure 23. Contour map of legal abundance for 1987. Contour level is mean abundance of legal size clams.

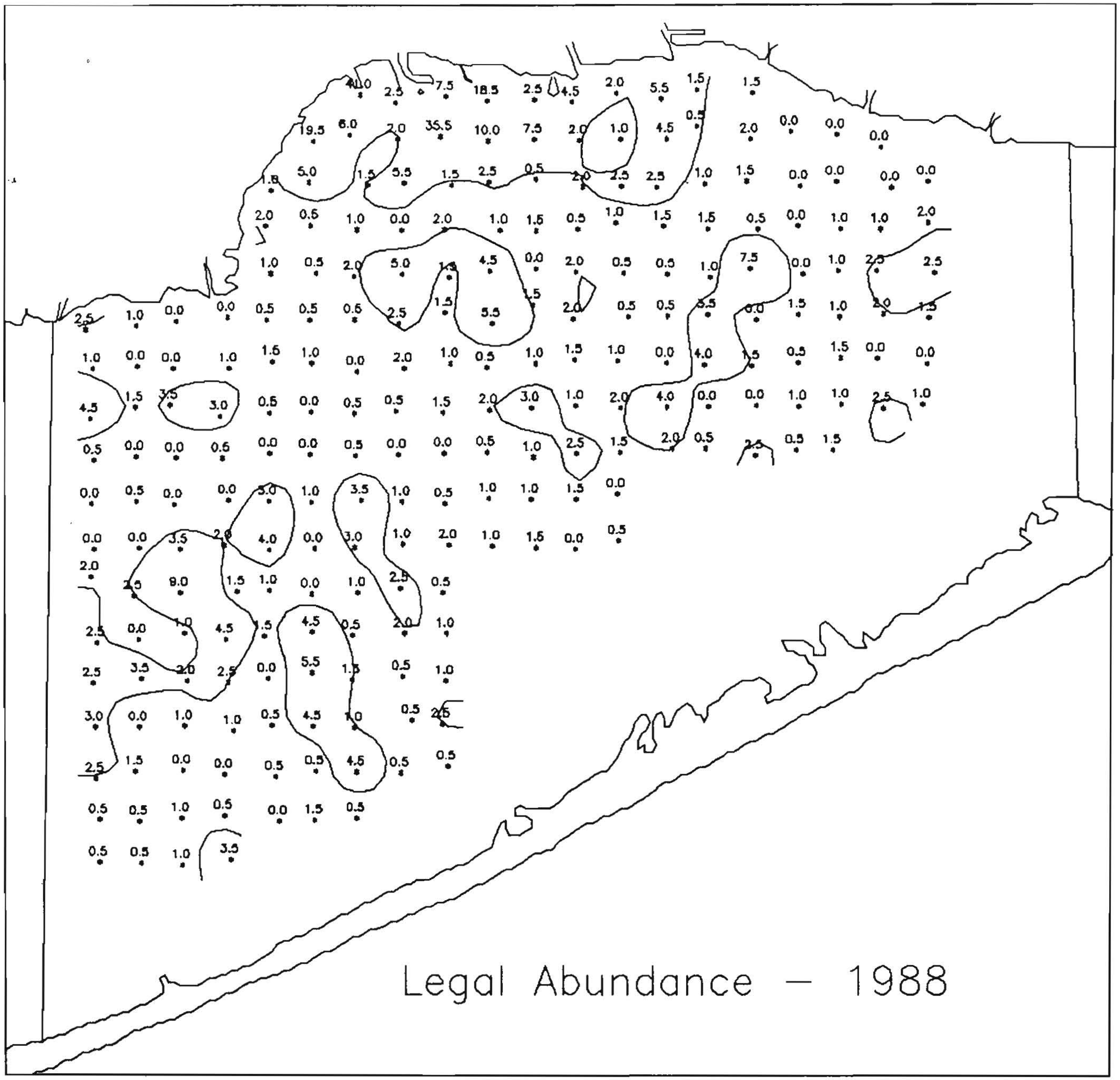


Figure 24. Contour map of legal abundance for 1988. Contour level is mean abundance of legal size clams.

Figure 25. Strata for 1986 based on total abundance. Contour level is mean abundance. See text for details.

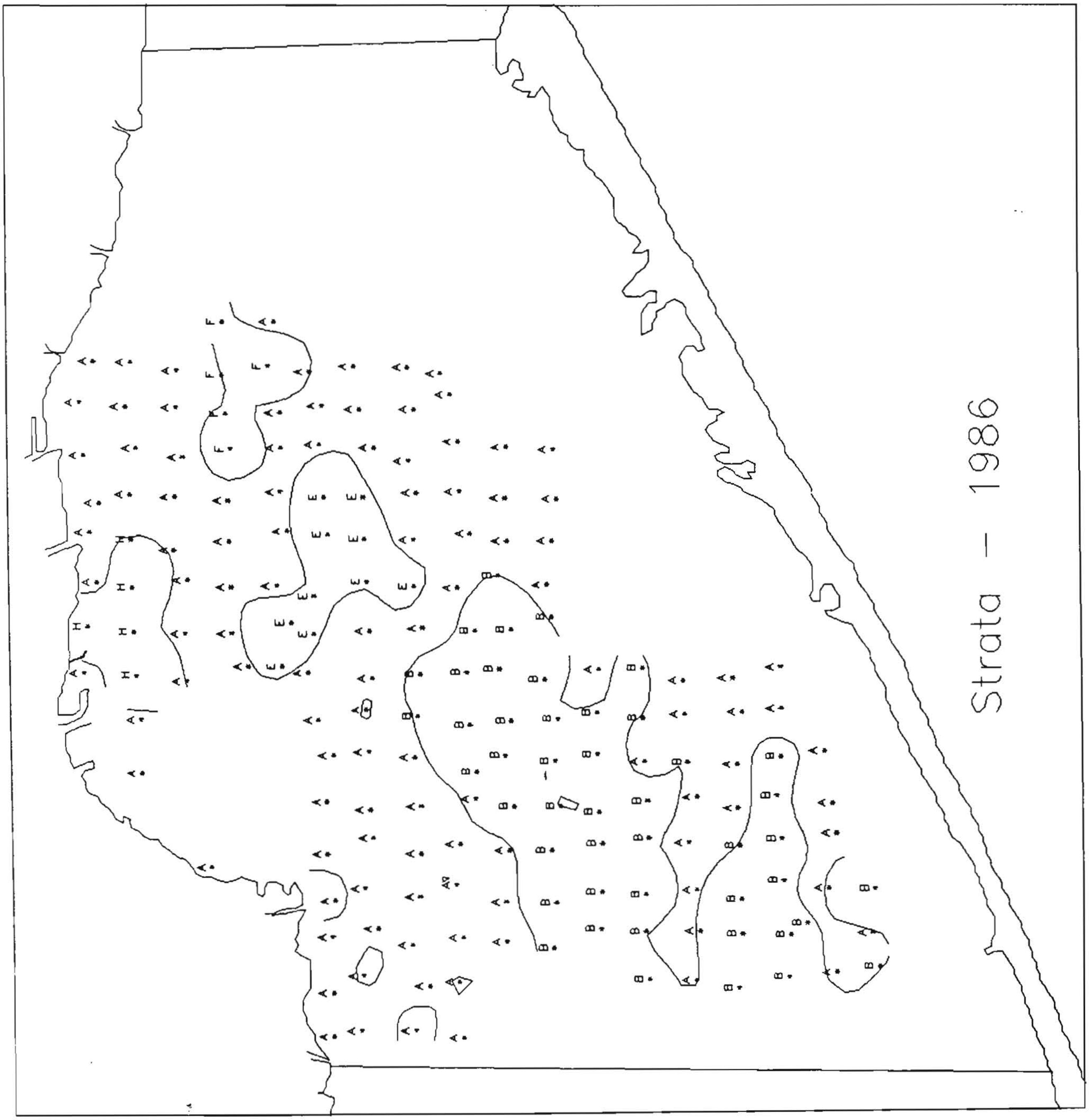


Figure 26. Strata for 1987 based on total abundance. Contour level is mean abundance. See text for details.

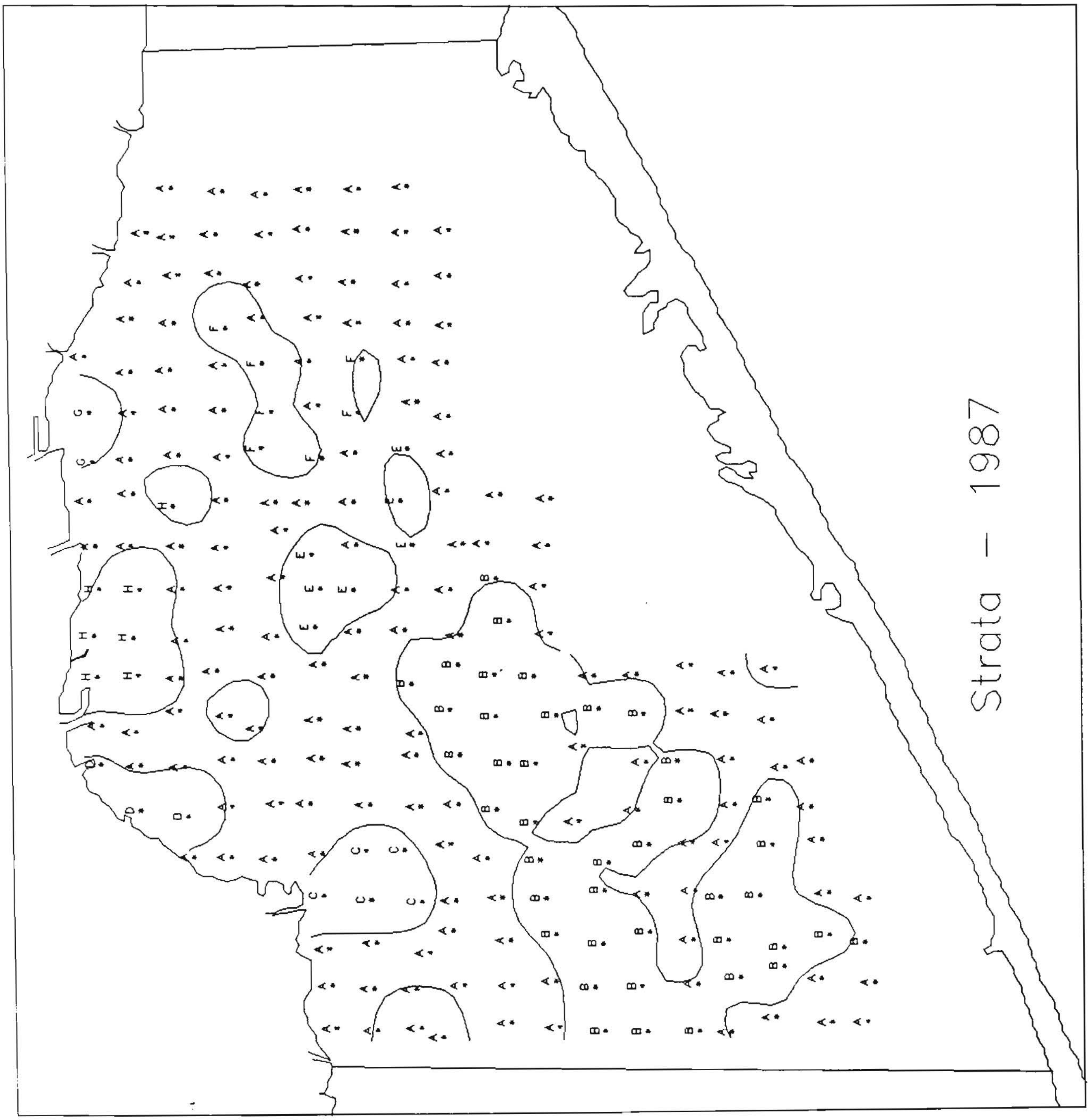


Figure 27. Strata for 1988 based on total abundance. Contour level is mean abundance. See text for details.

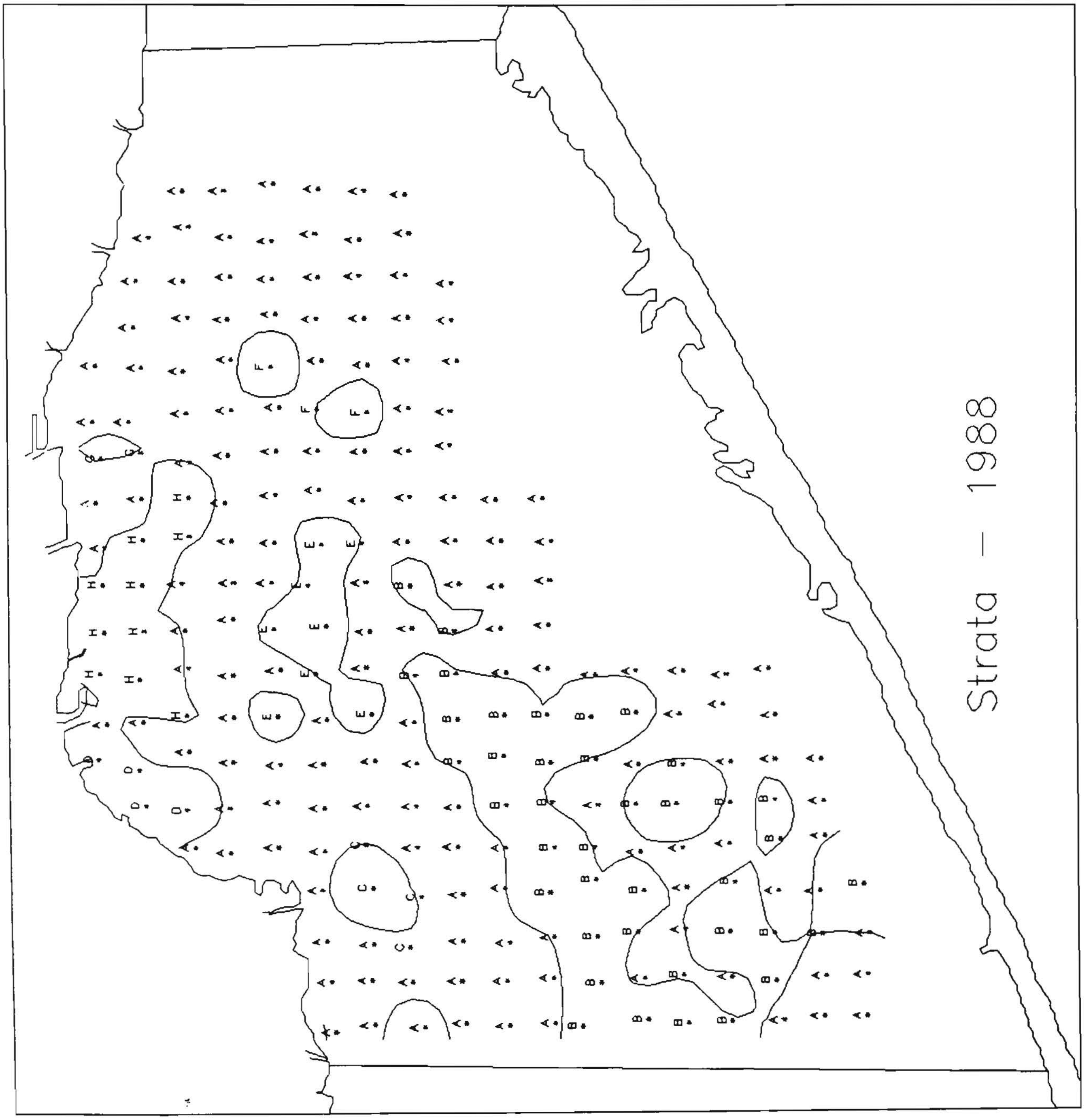
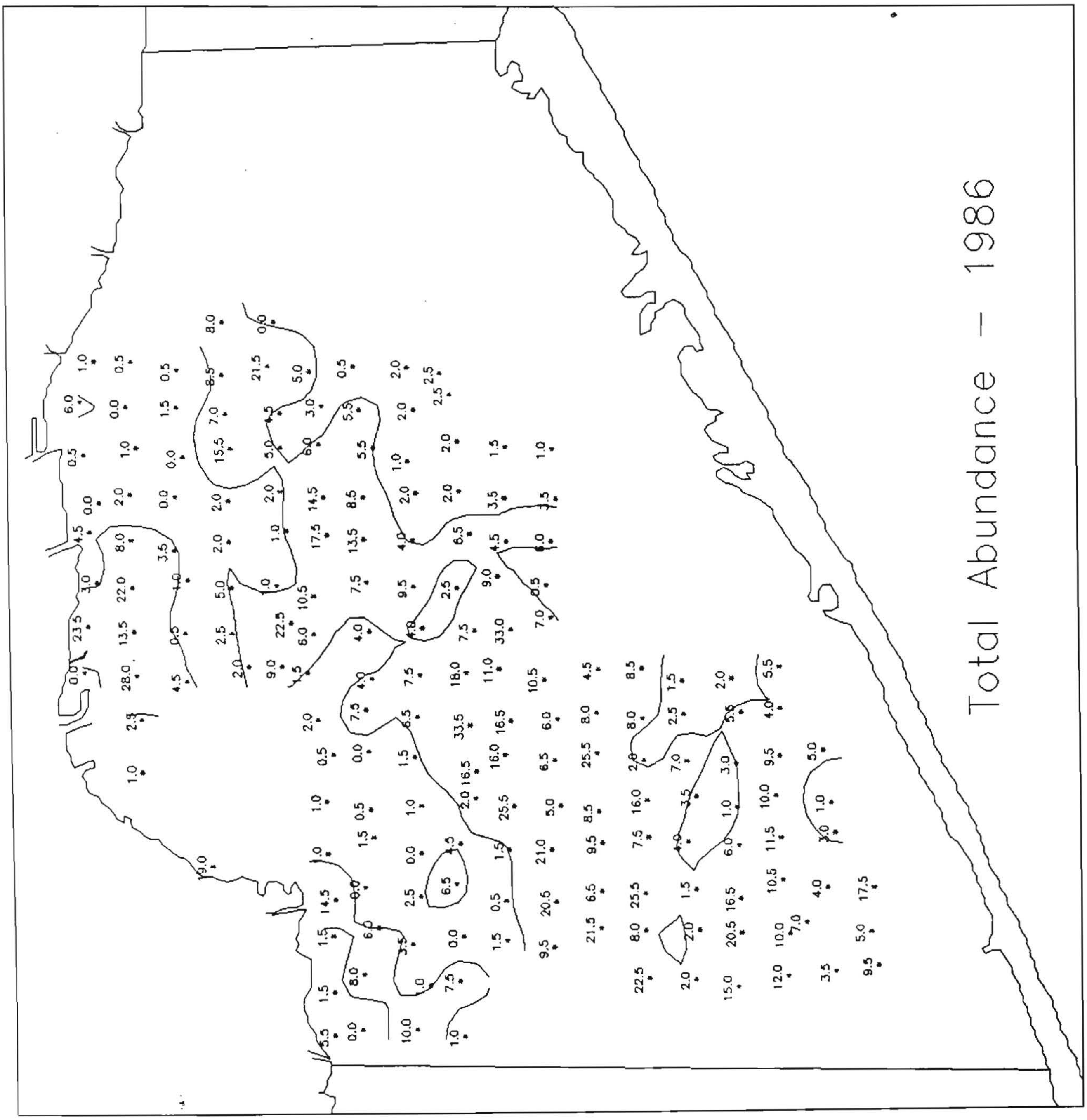


Figure 28. Contour map of total abundance for 1986. Contour level is median abundance.



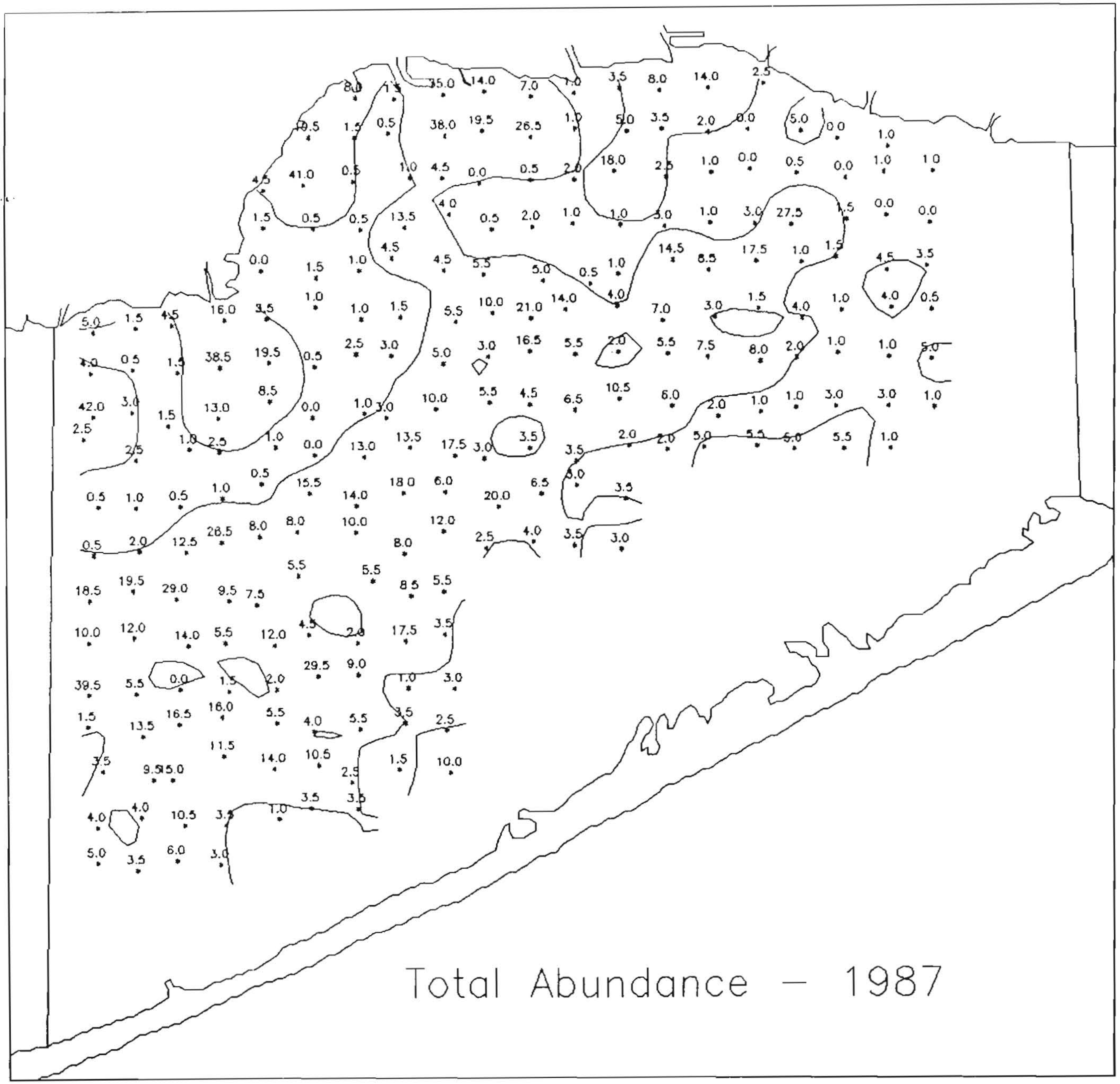


Figure 29. Contour map of total abundance for 1987. Contour level is median abundance.

Figure 30. Contour map of total abundance for 1988. Contour level is median abundance.

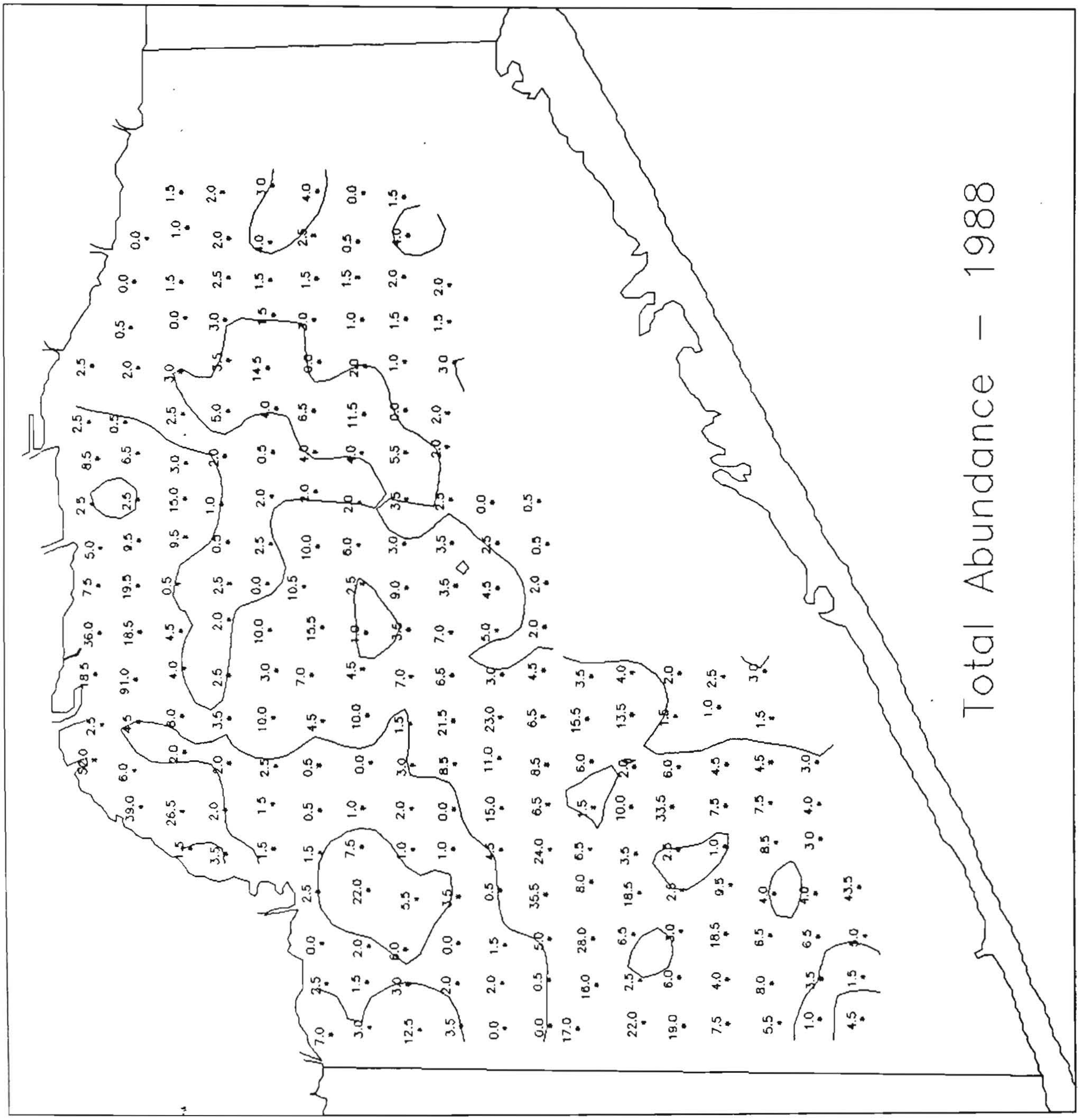
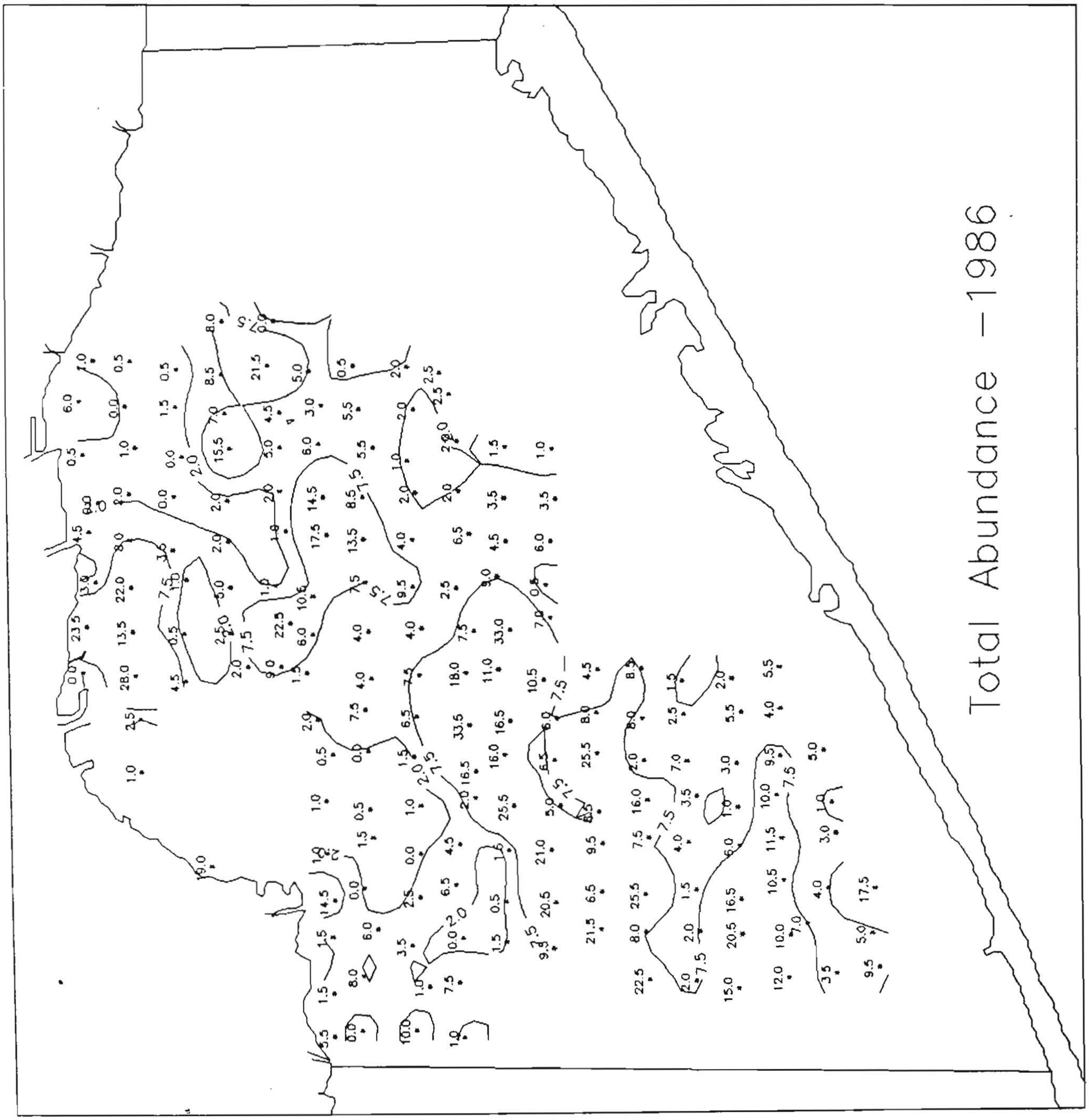


Figure 31. Contour map of total abundance for 1986. Contour levels are 33% quantiles.



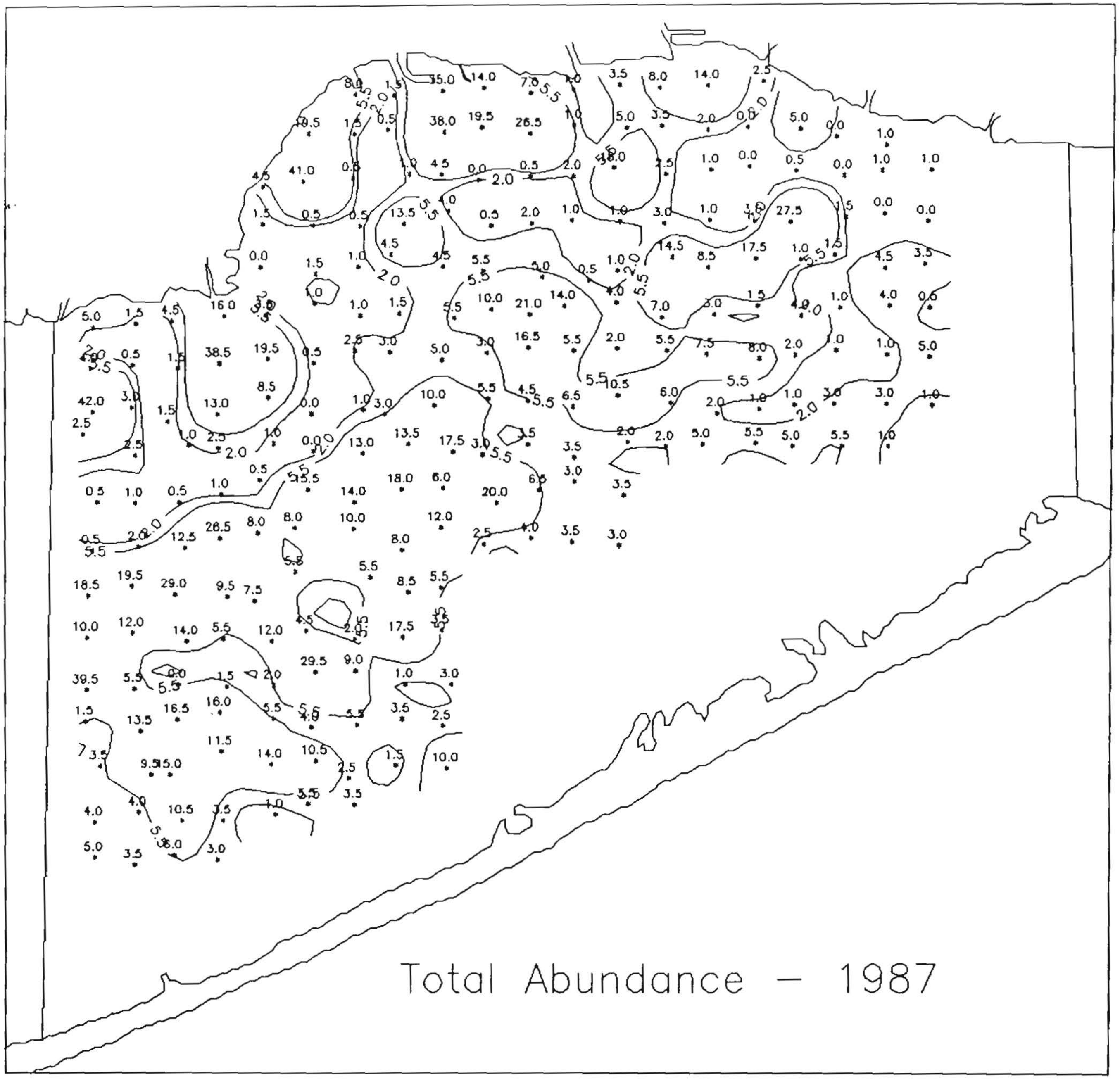


Figure 32. Contour map of total abundance for 1987. Contour levels are 33% quantiles.

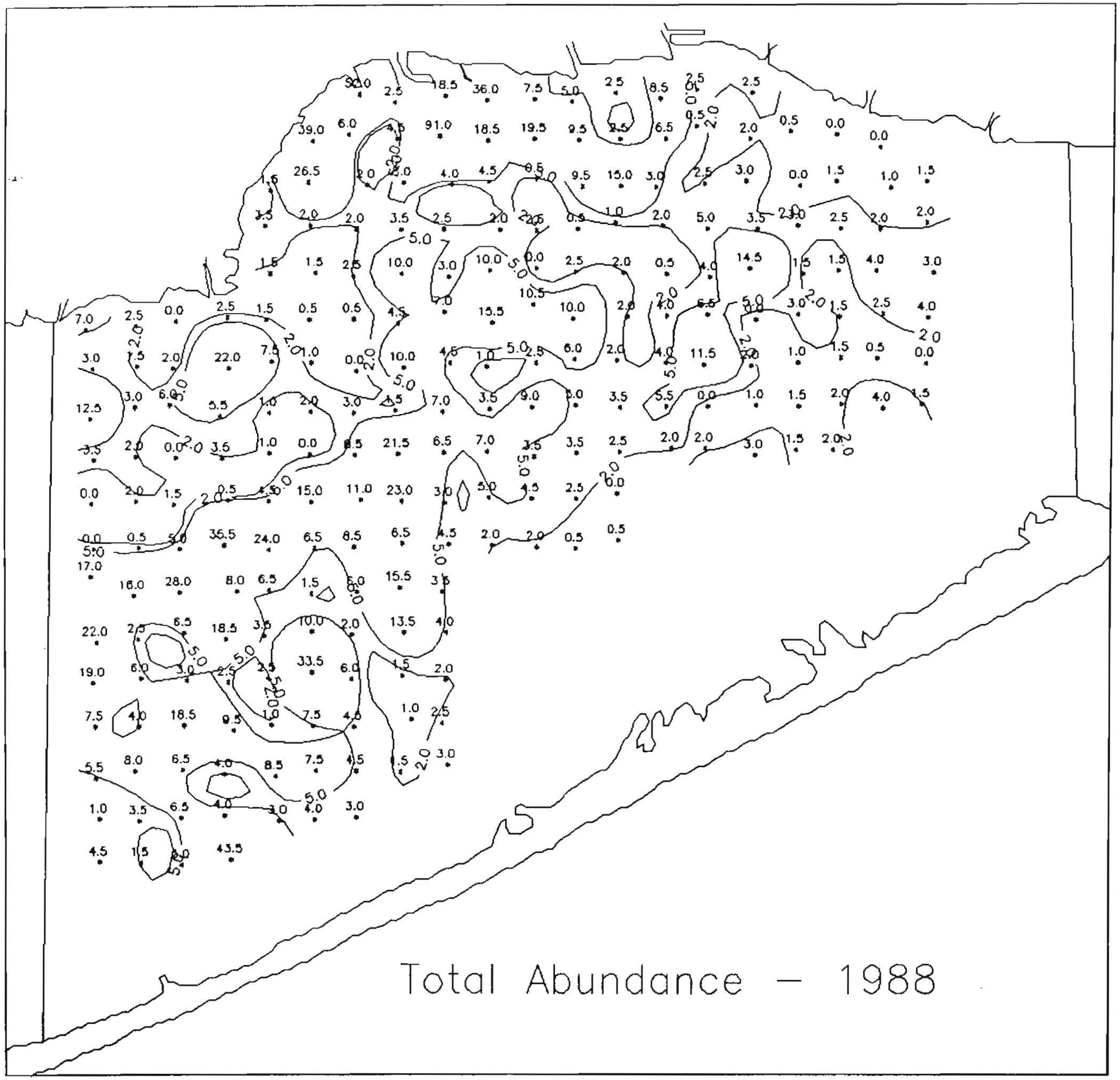
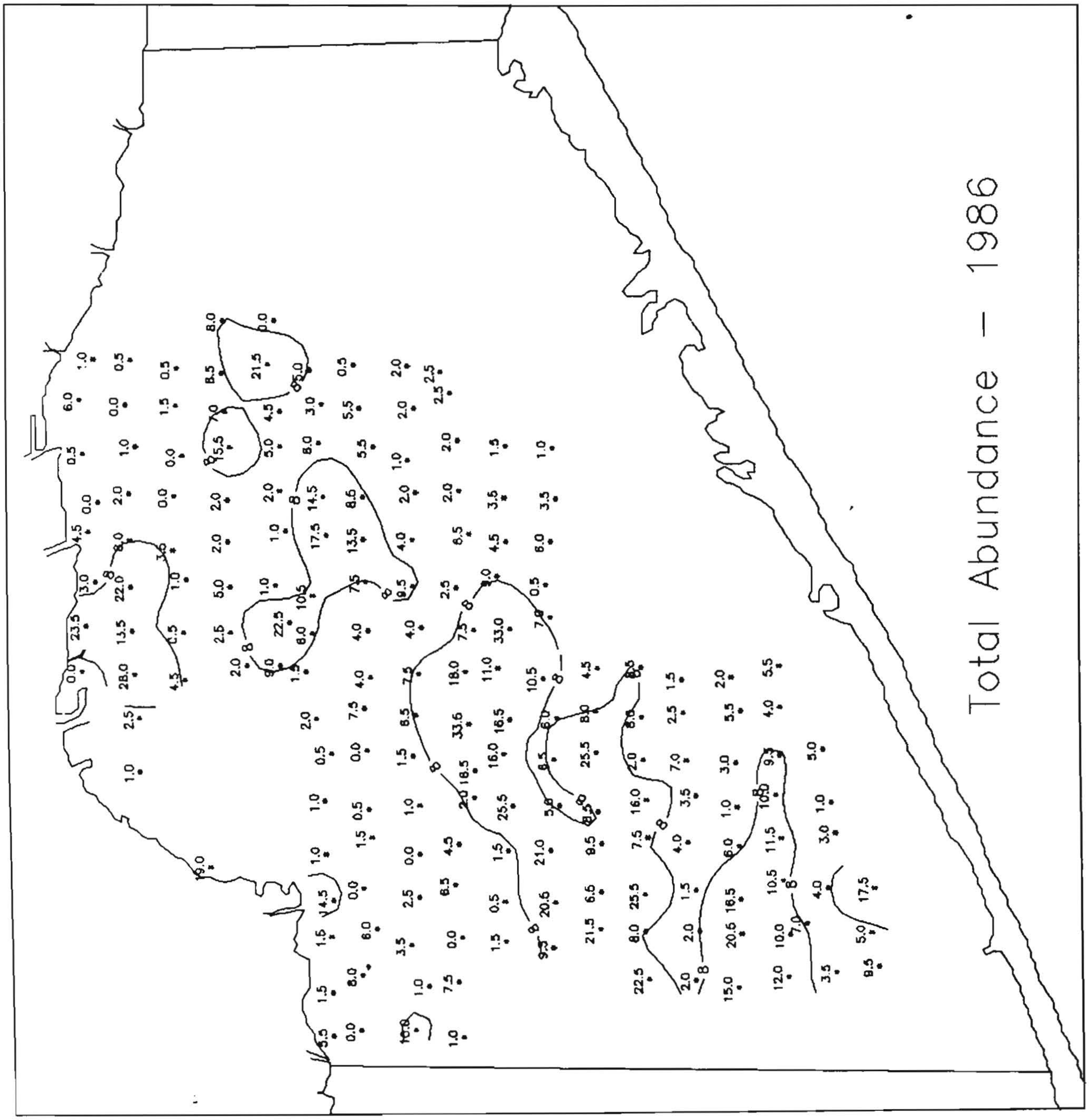


Figure 33. Contour map of total abundance for 1988. Contour levels are 33% quantiles.

Figure 34. Contour map of total abundance for 1986. Contour level based on minimum variance rule.



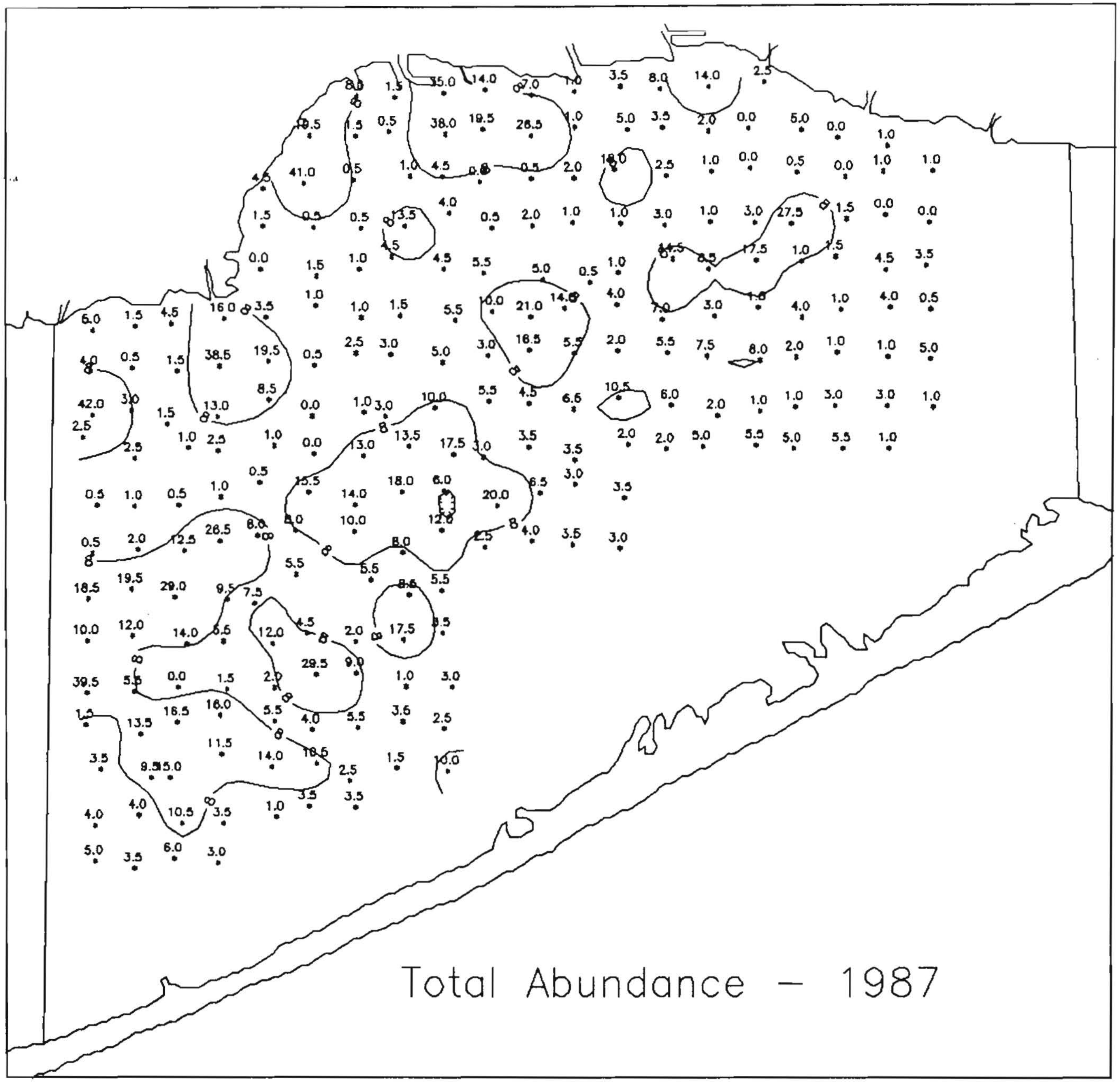


Figure 35. Contour map of total abundance for 1987. Contour level based on minimum variance rule.

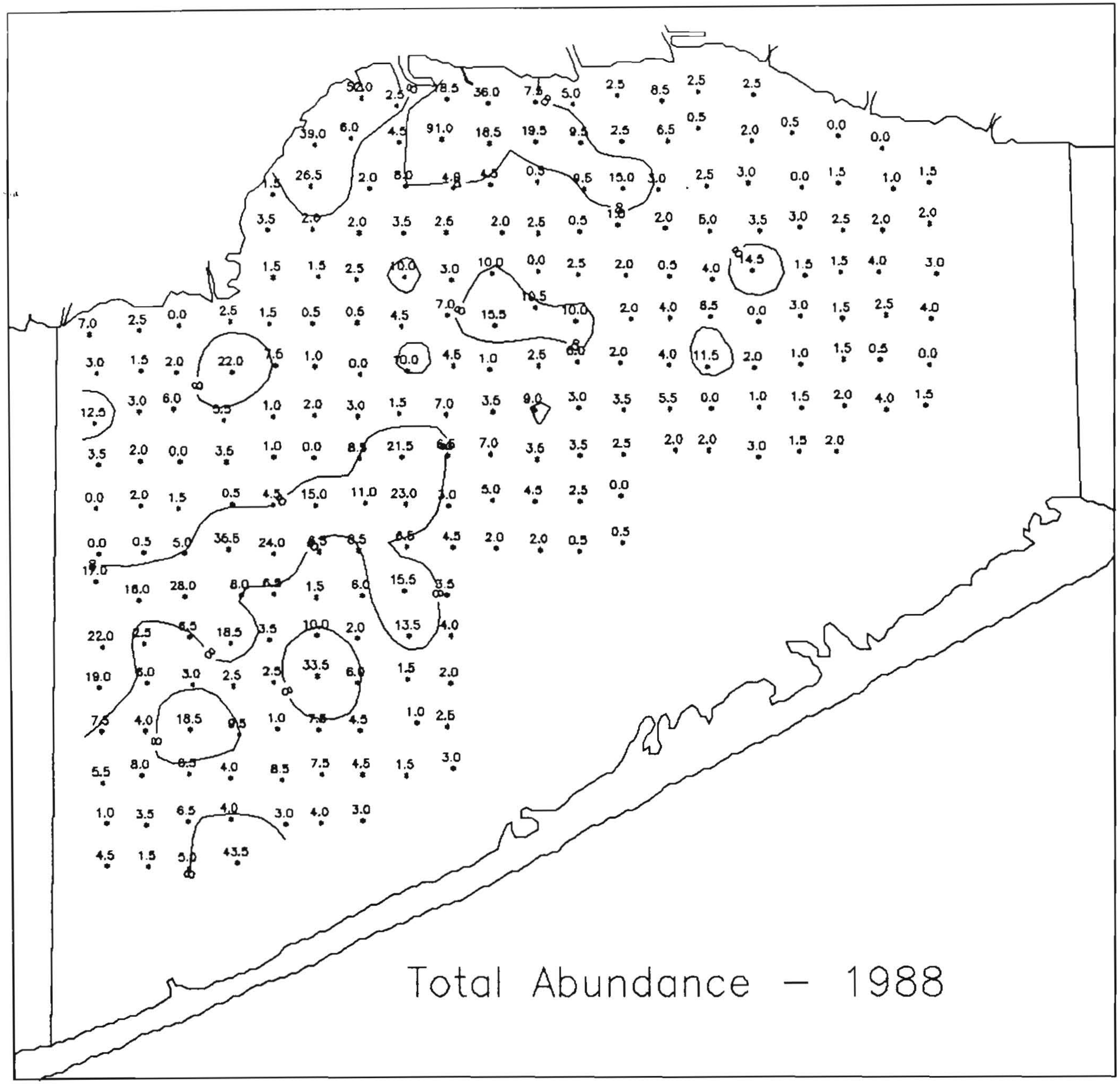
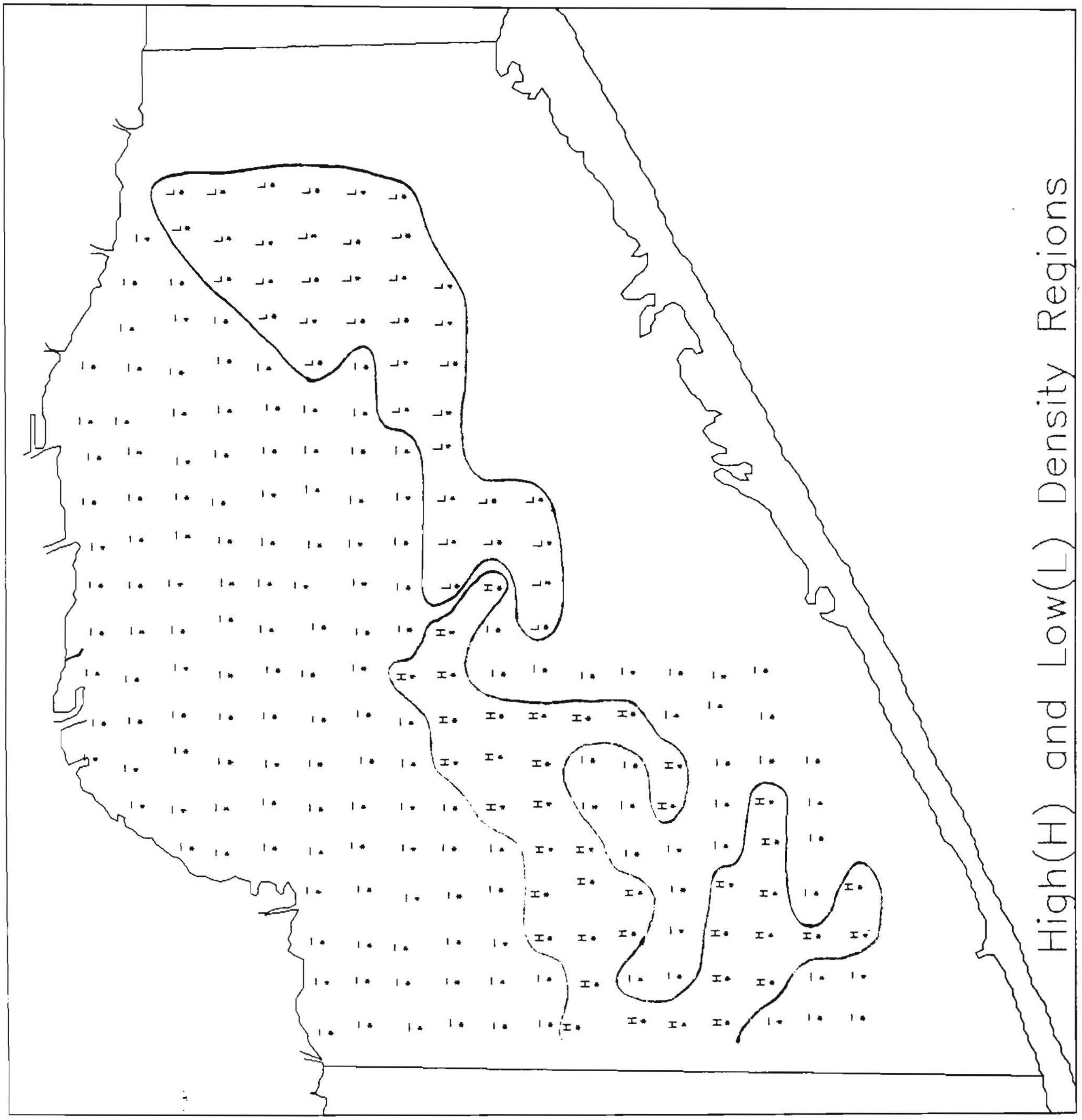


Figure 36. Contour map of total abundance for 1988. Contour level based on minimum variance rule.

Figure 37. High and low density areas selected for detailed analysis of population characteristics.



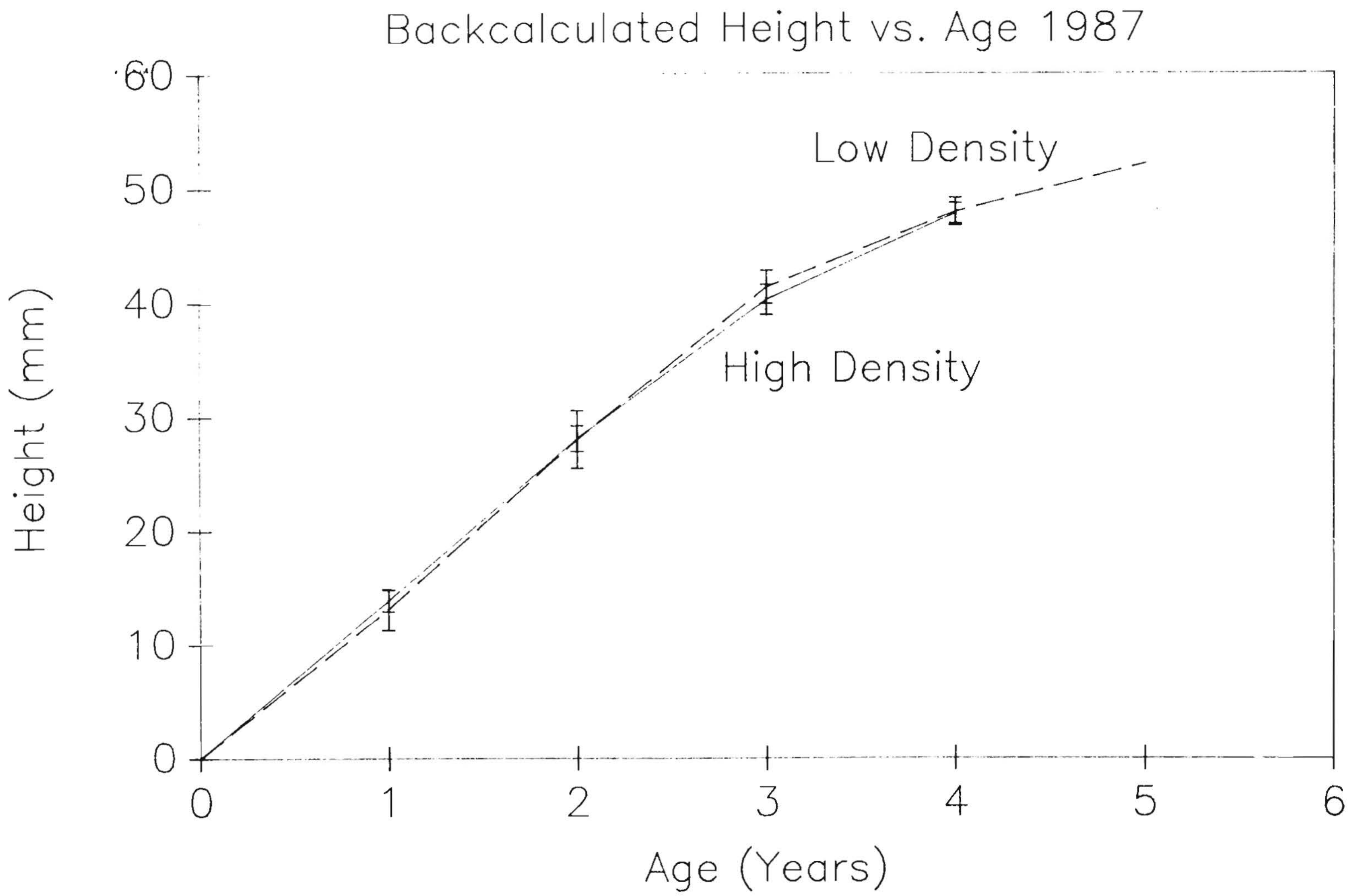


Figure 38. Shell height vs. age from shell sectioning analysis. Shell samples from the 1987 census. Error bars are +2 SE

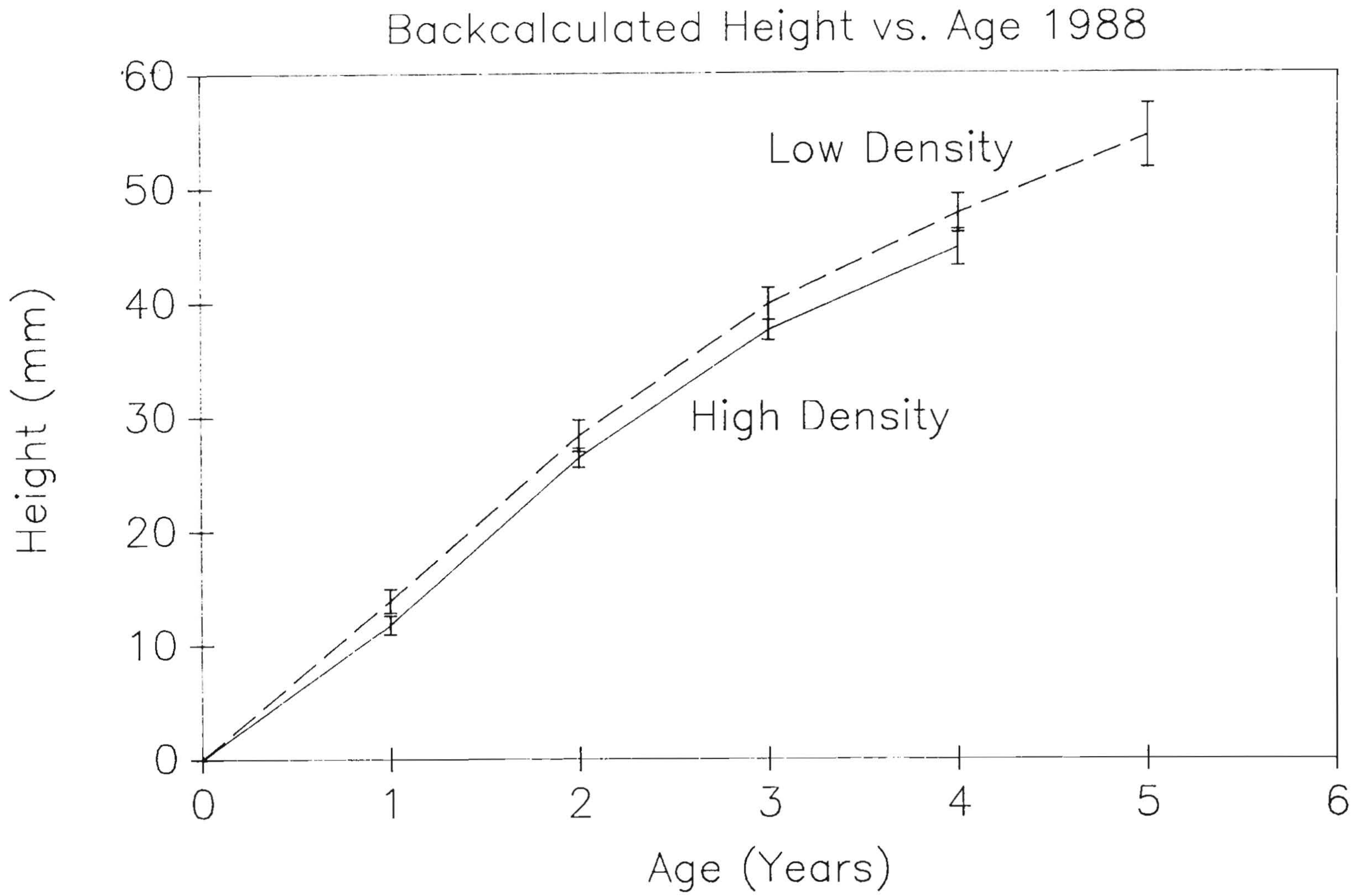


Figure 39. Shell height vs. age from shell sectioning analysis. Shell samples from the 1988 census. Error bars are +2 SE

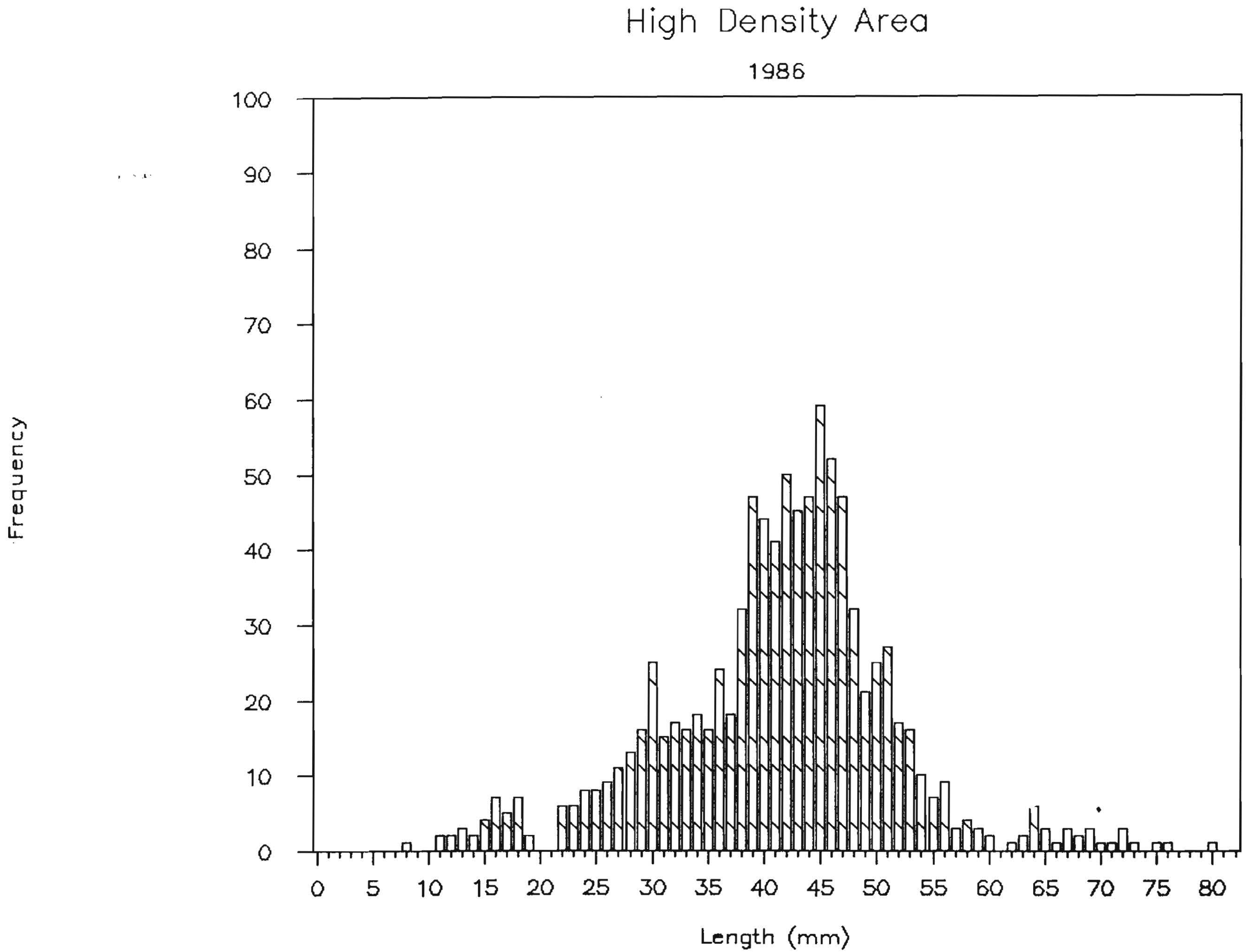


Figure 40. Shell length-frequency distribution for the high density area in 1986.

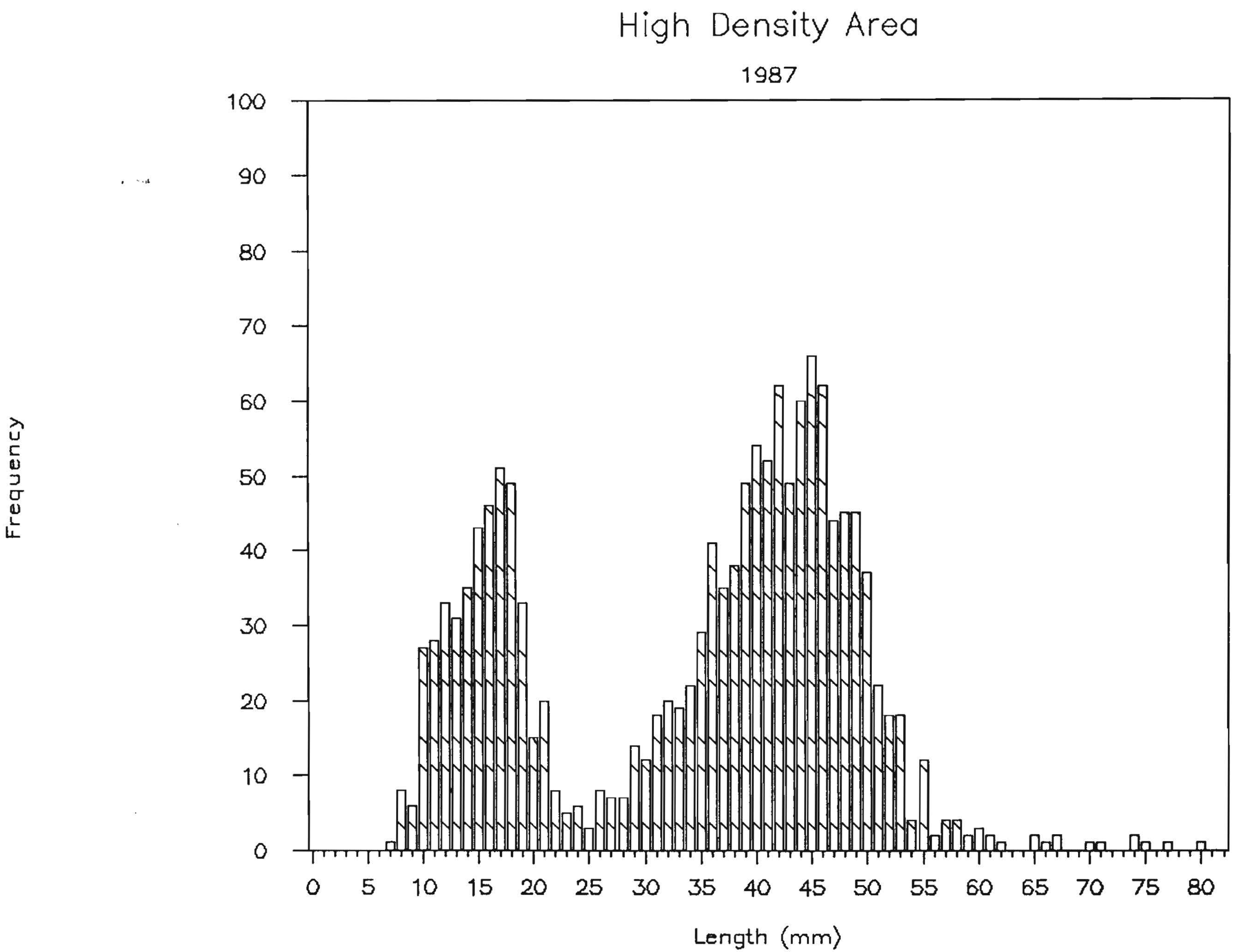


Figure 41. Shell length-frequency distribution for the low density area in 1986.

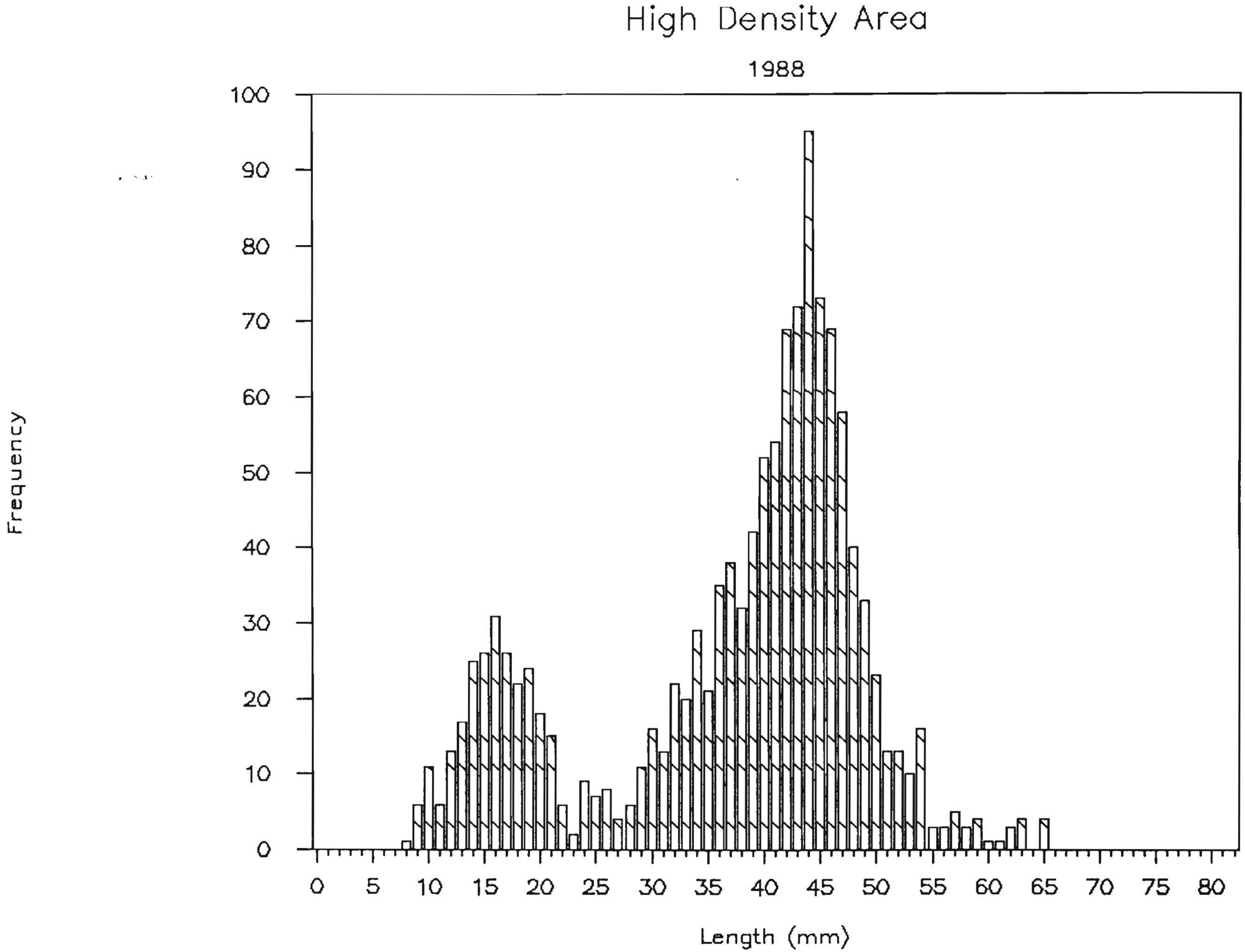


Figure 42. Shell length-frequency distribution for the high density area in 1987.

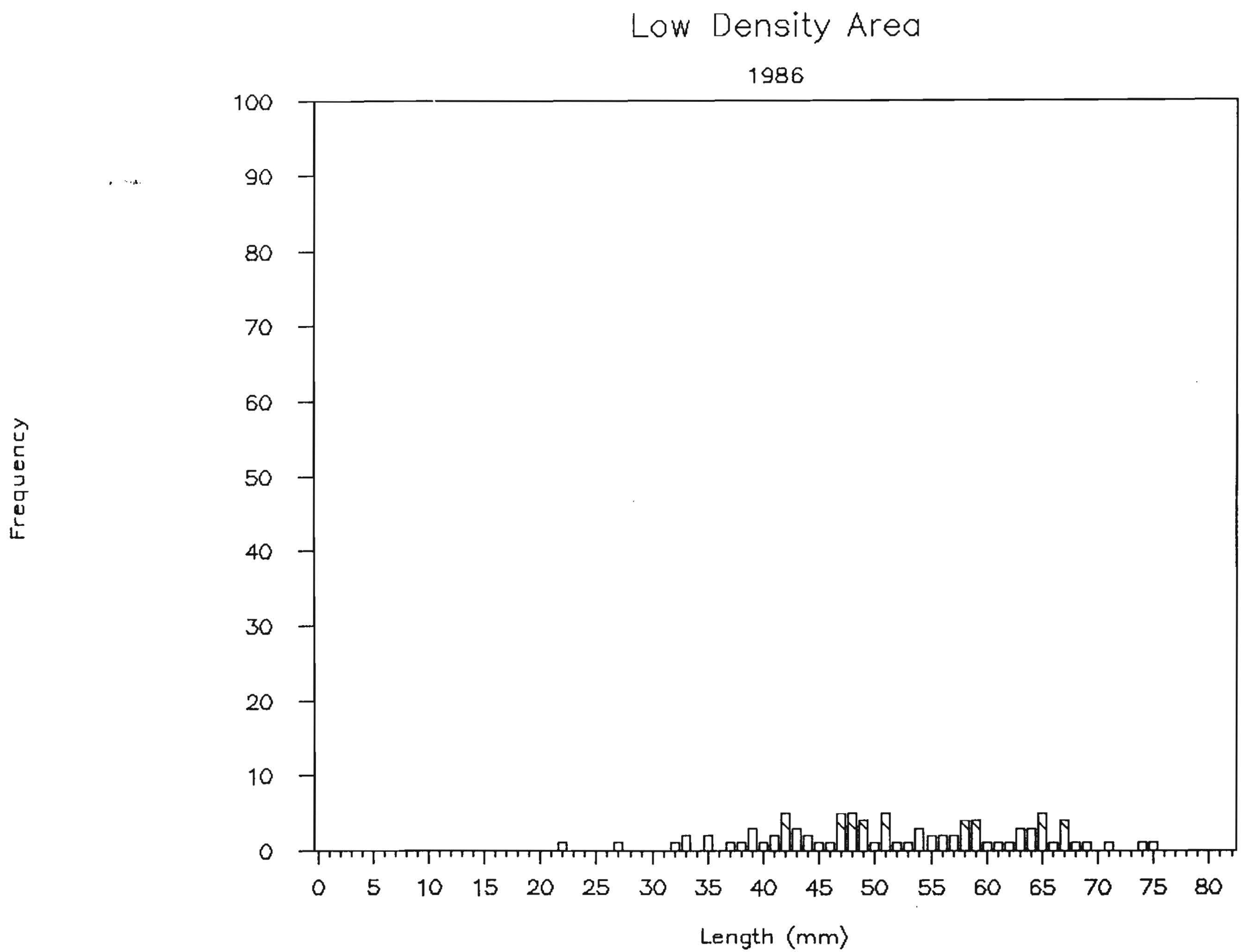


Figure 43. Shell length-frequency distribution for the low density area in 1987.

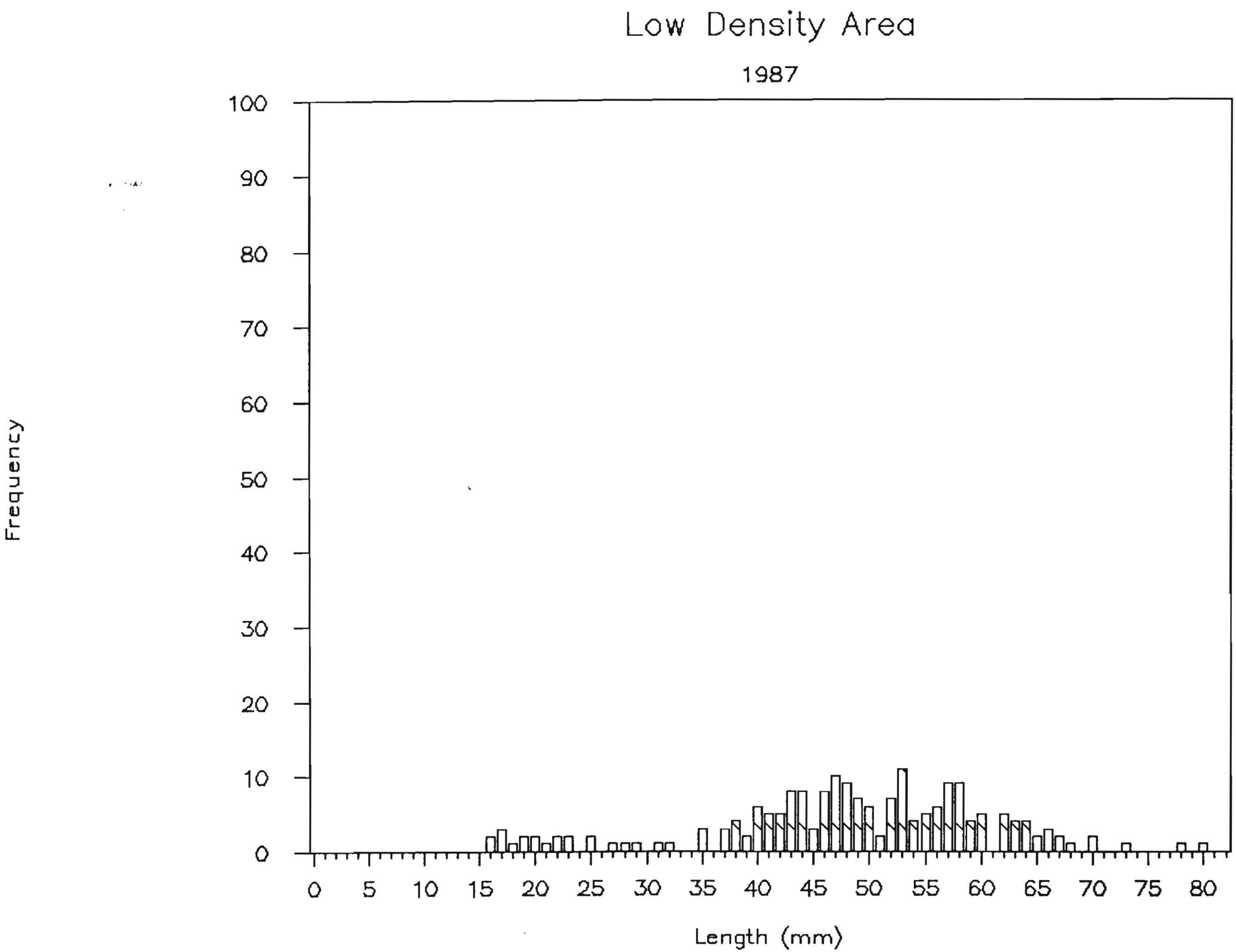


Figure 44. Shell length-frequency distribution for the high density area in 1988.

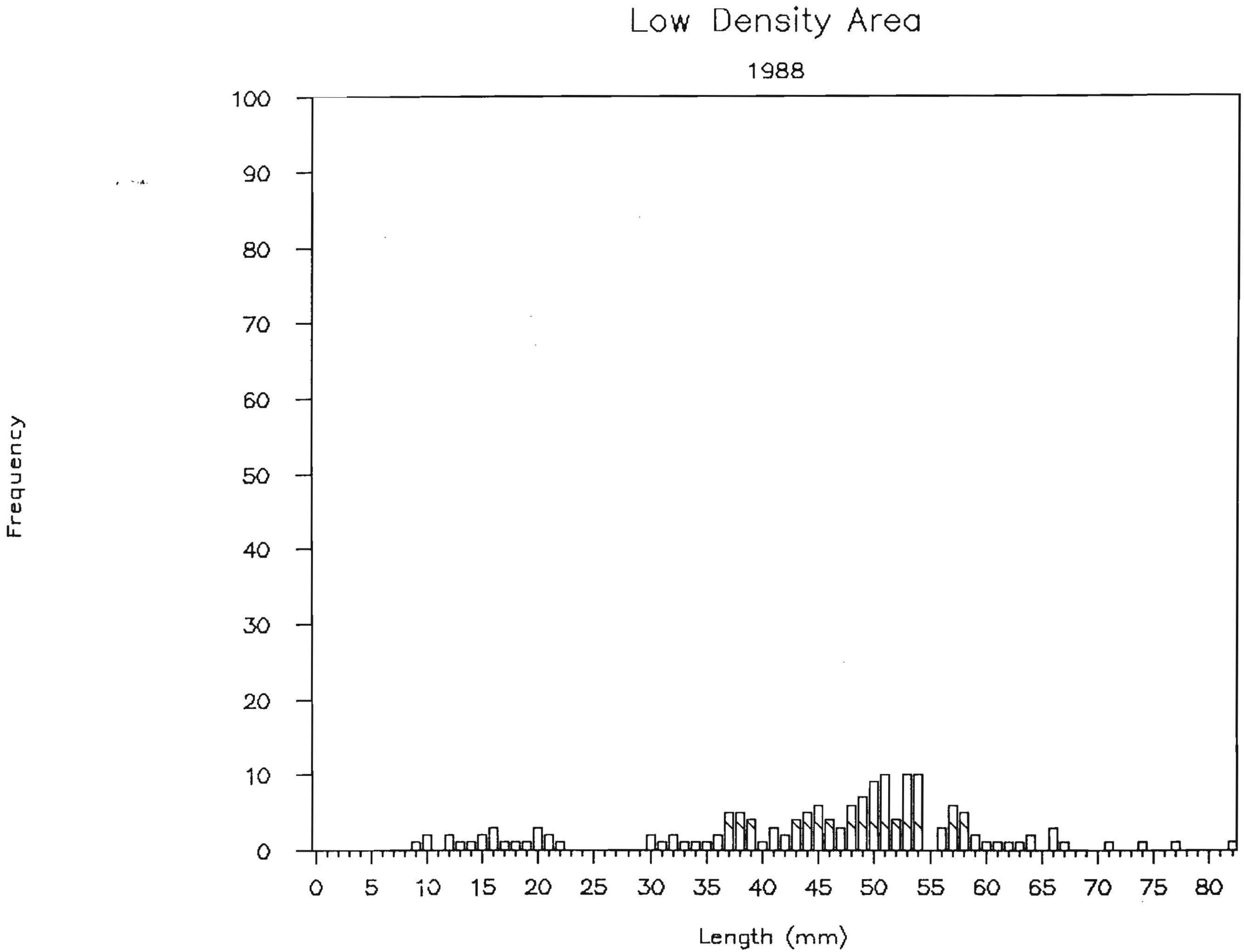


Figure 45. Shell length-frequency distribution for the low density area in 1988.

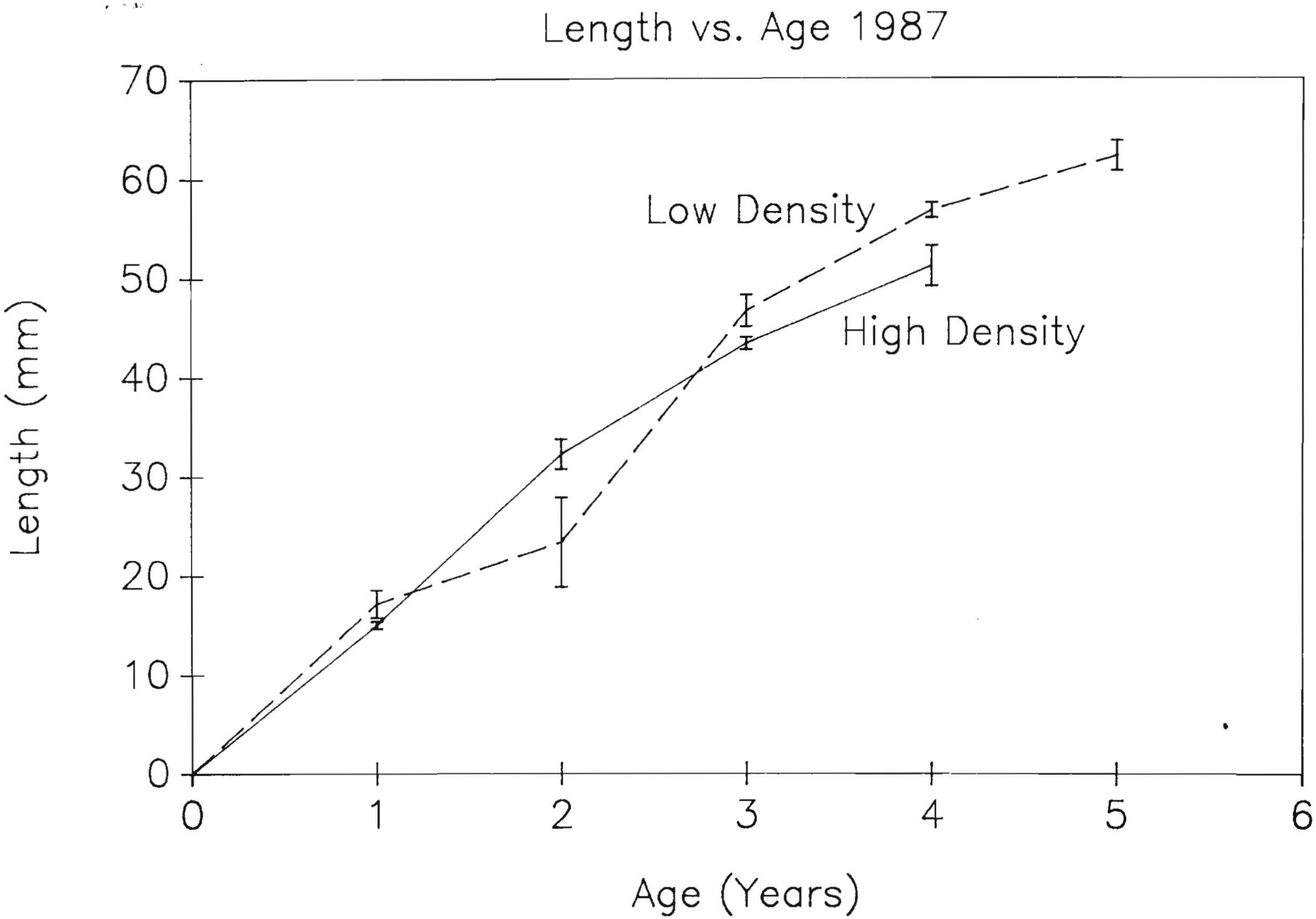


Figure 46. Shell length vs. age estimates for 1987 from the maximum likelihood analysis. Error bars are +2 SE

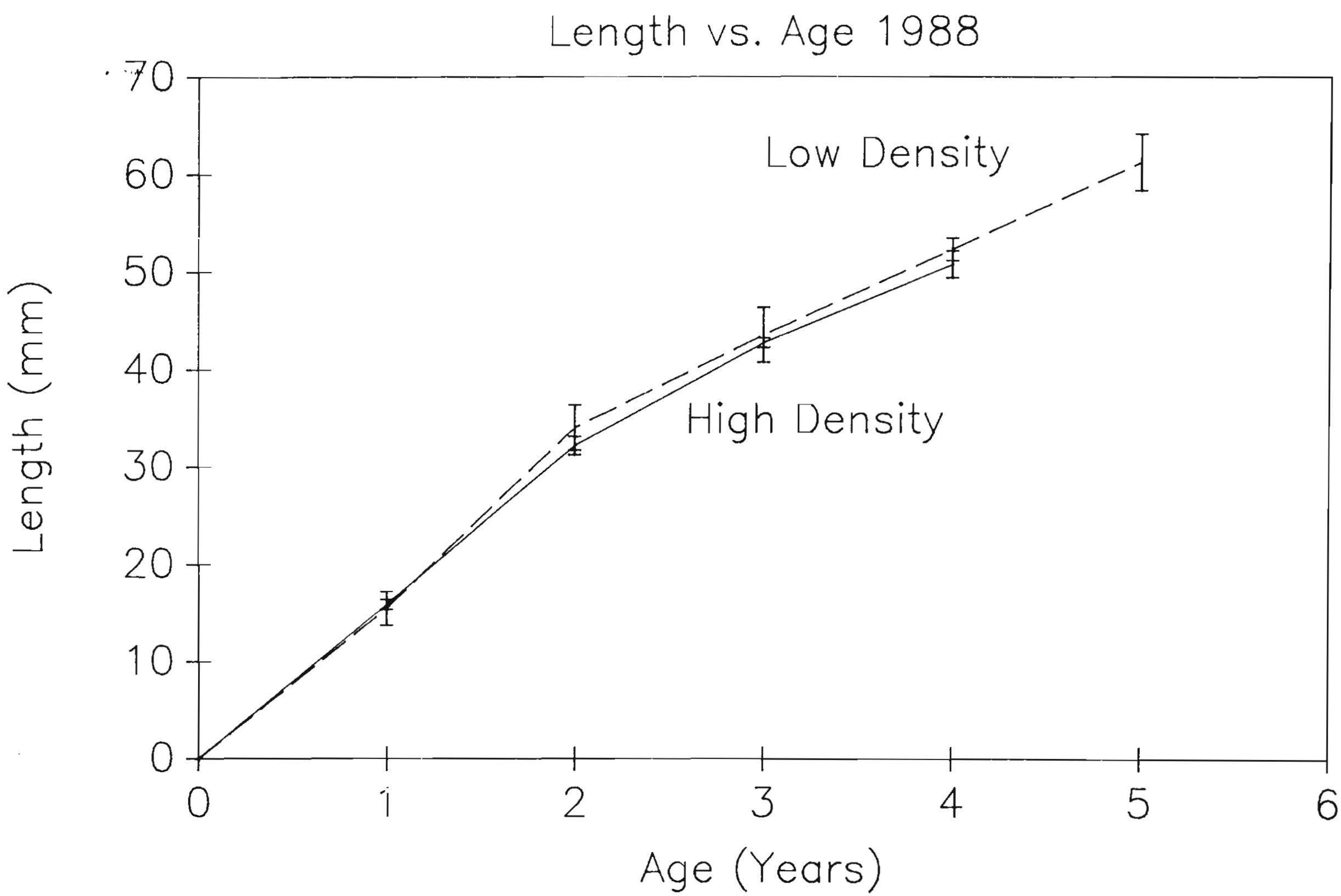


Figure 47. Shell length vs. age estimates for 1988 from the maximum likelihood analysis. Error bars are +2 SE

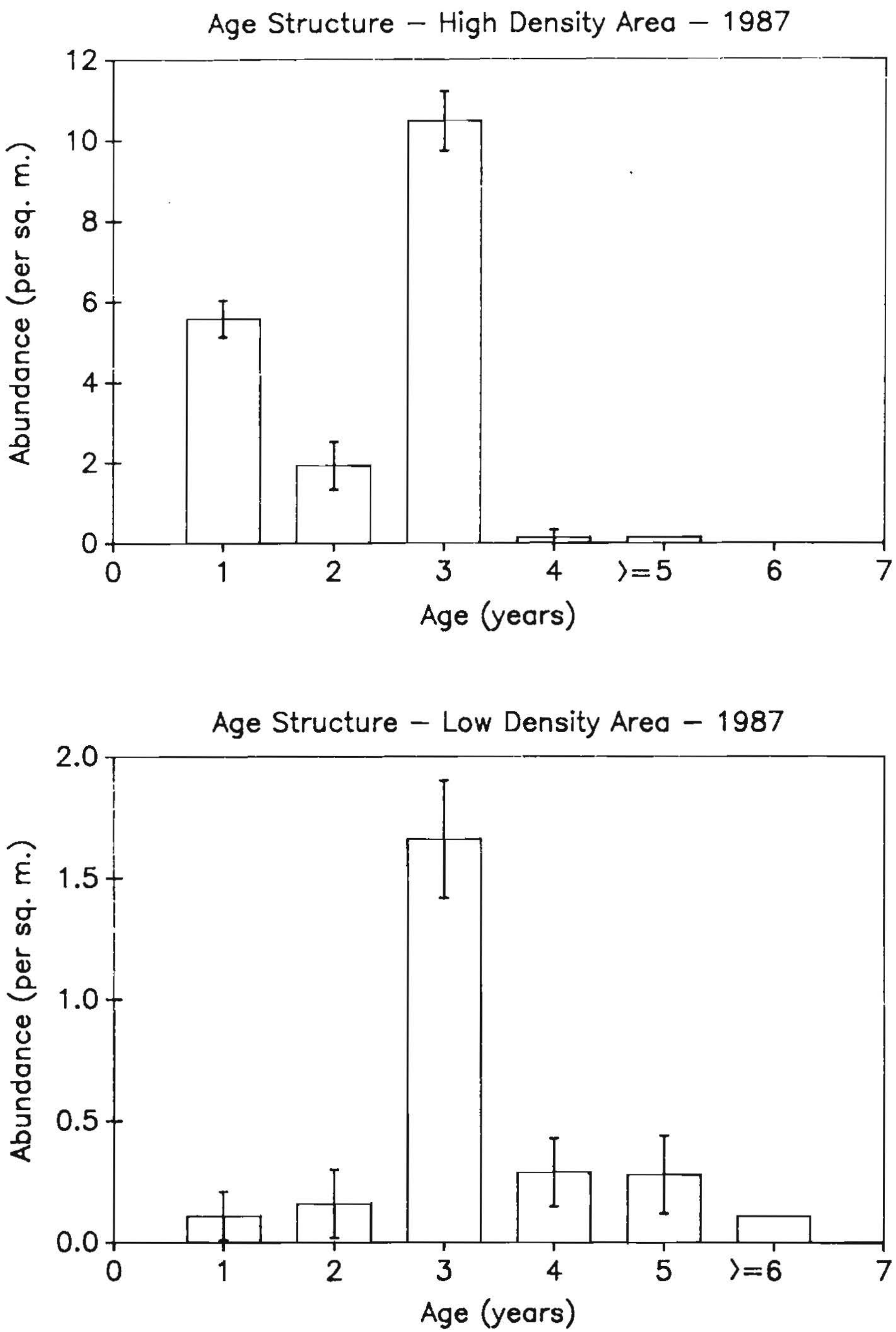


Figure 48. Estimated age structure for 1987 from the maximum likelihood analysis. Error bars are +2 SE.

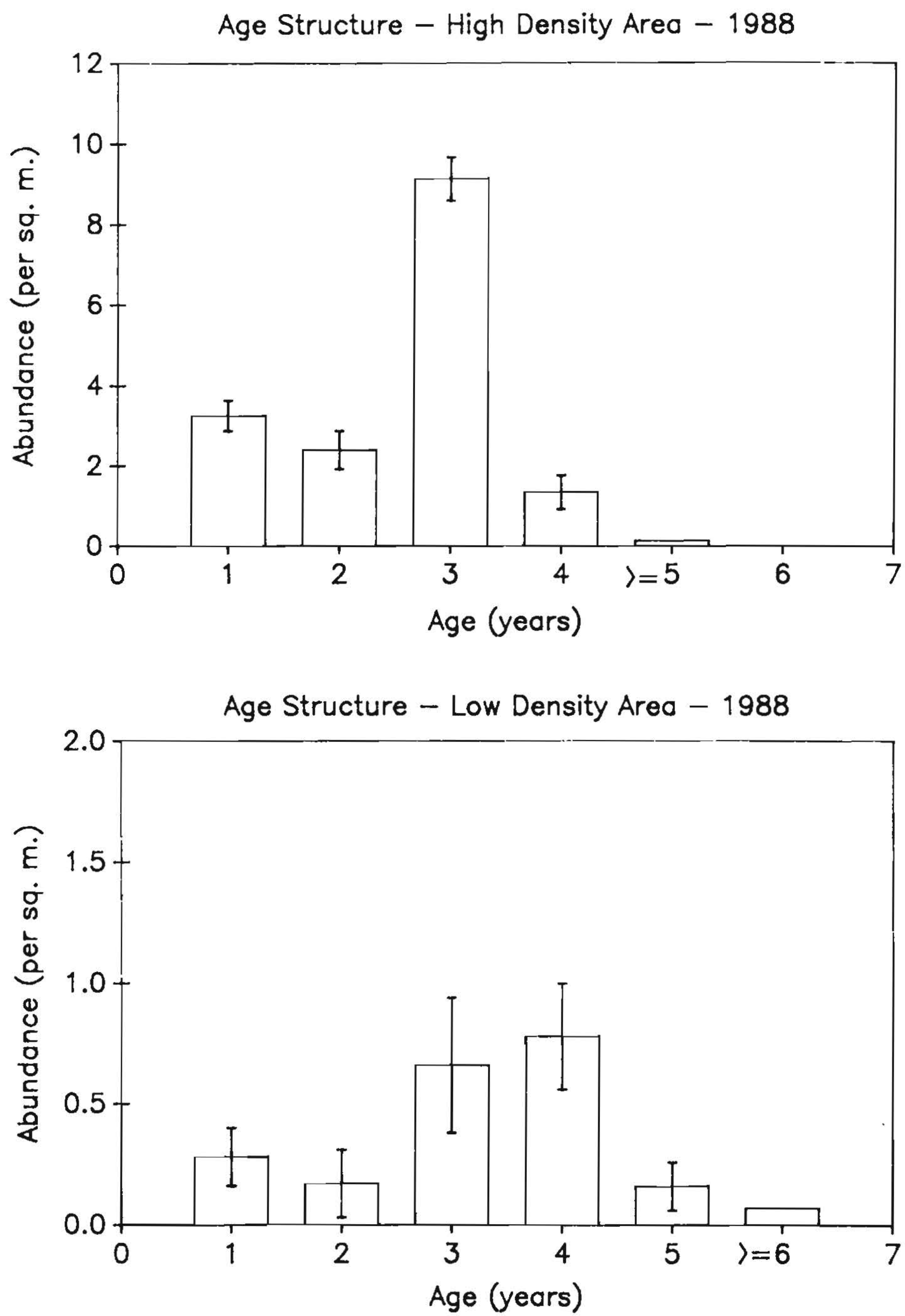


Figure 49. Estimated age structure for 1988 from the maximum likelihood analysis. Error bars are +2 SE.

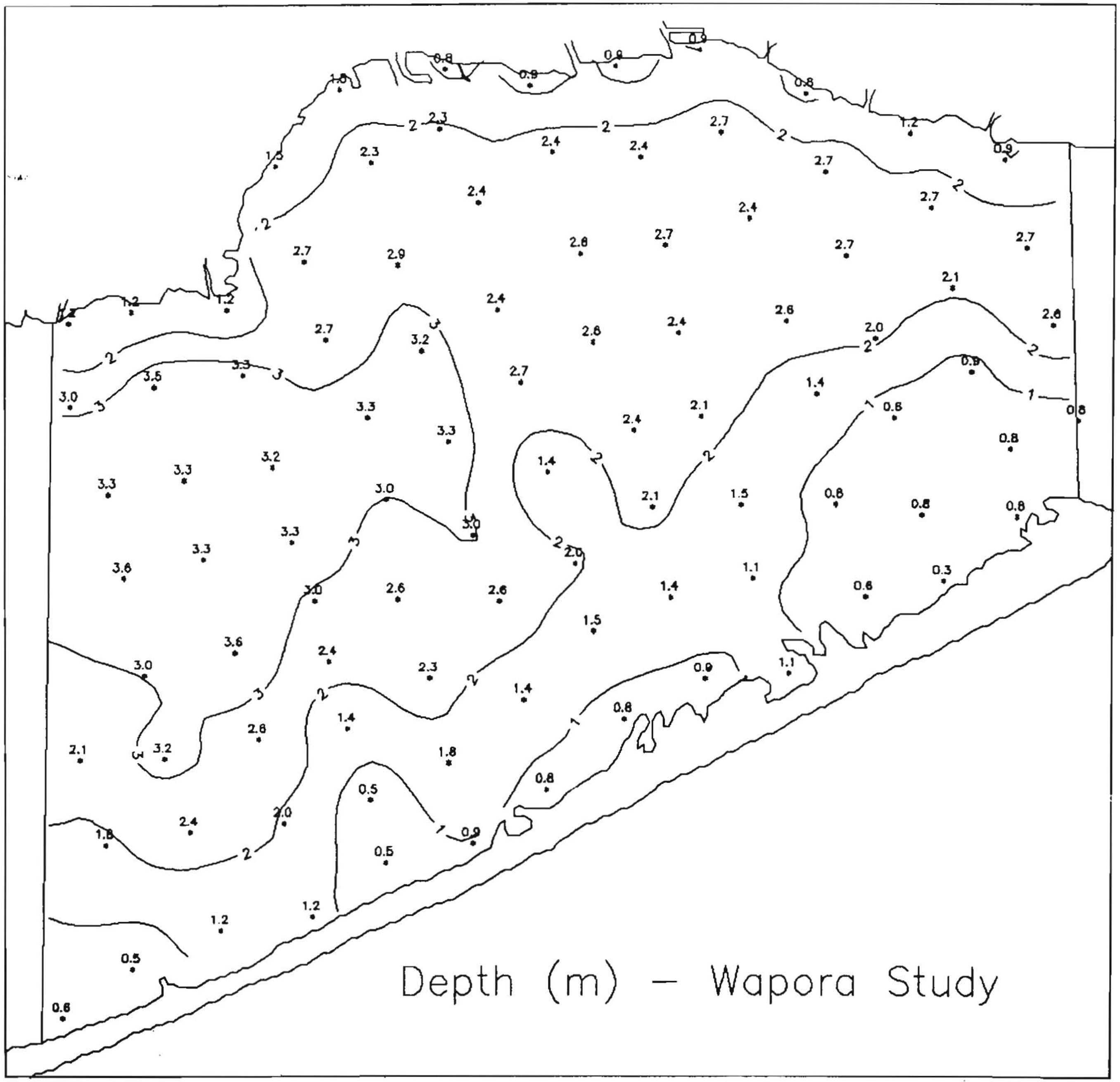


Figure 50. Station depths from the 1978 Wapora study. Data from Greene (1981).

Figure 51. Seagrass cover from the 1978 Wapora study. Station codes: (0) no seagrass, (1) heavy eelgrass, (2) patchy eelgrass, (3) Ruppia. Data from Greene (1981).

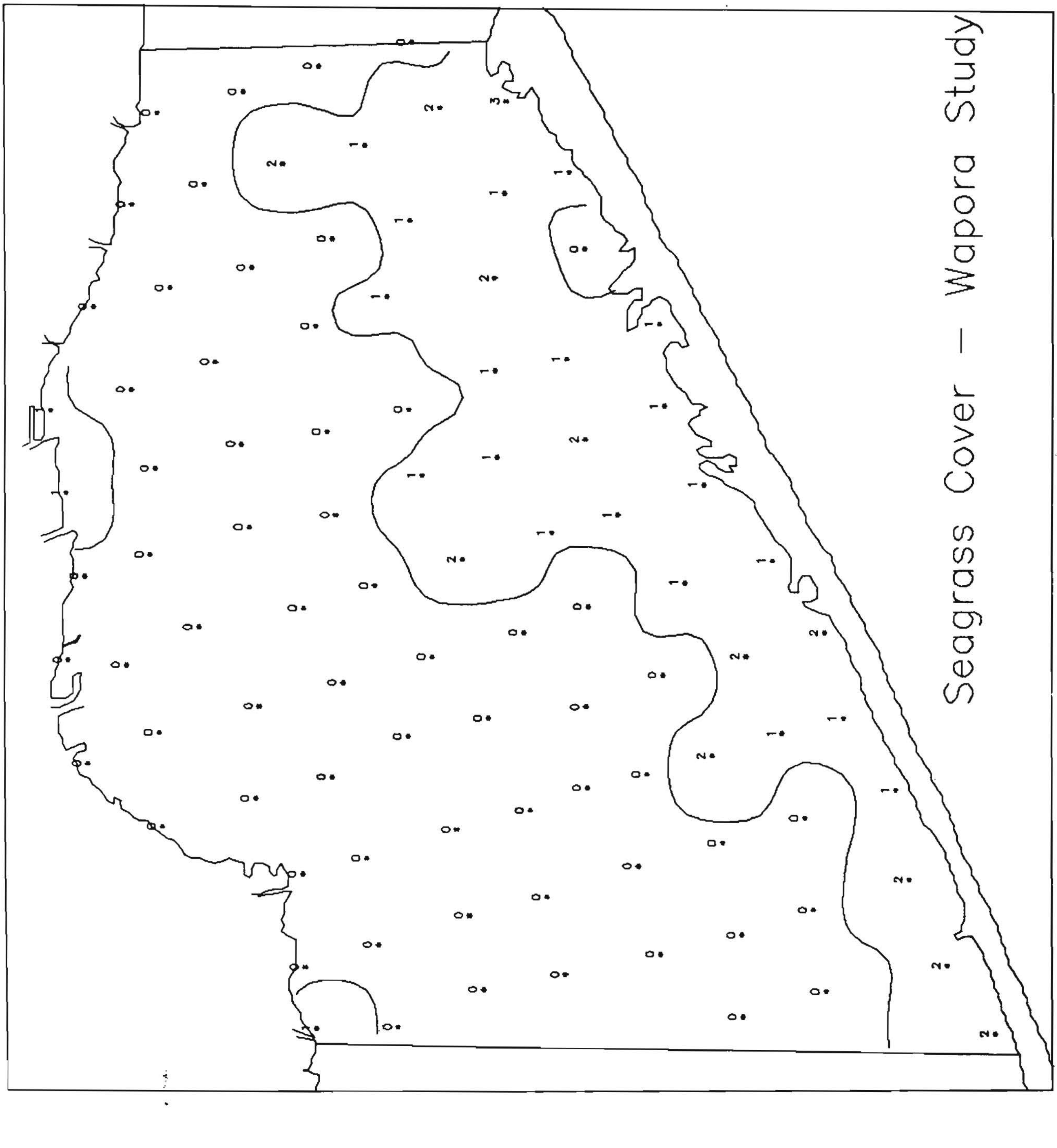


Figure 52. Percent silt-clay (mud) in the surficial sediments from the 1978 Wapora study. Data from Greene (1981).

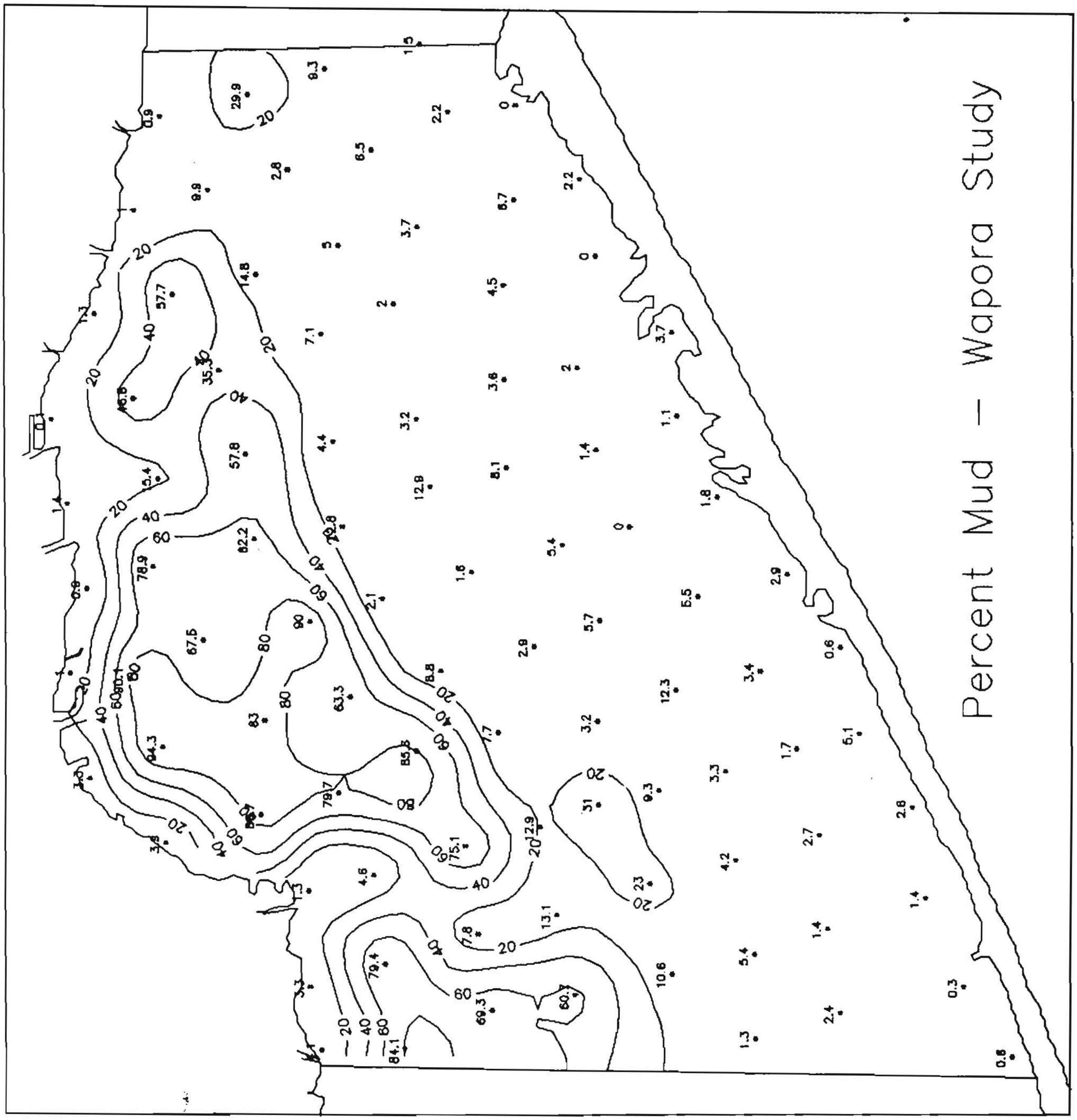
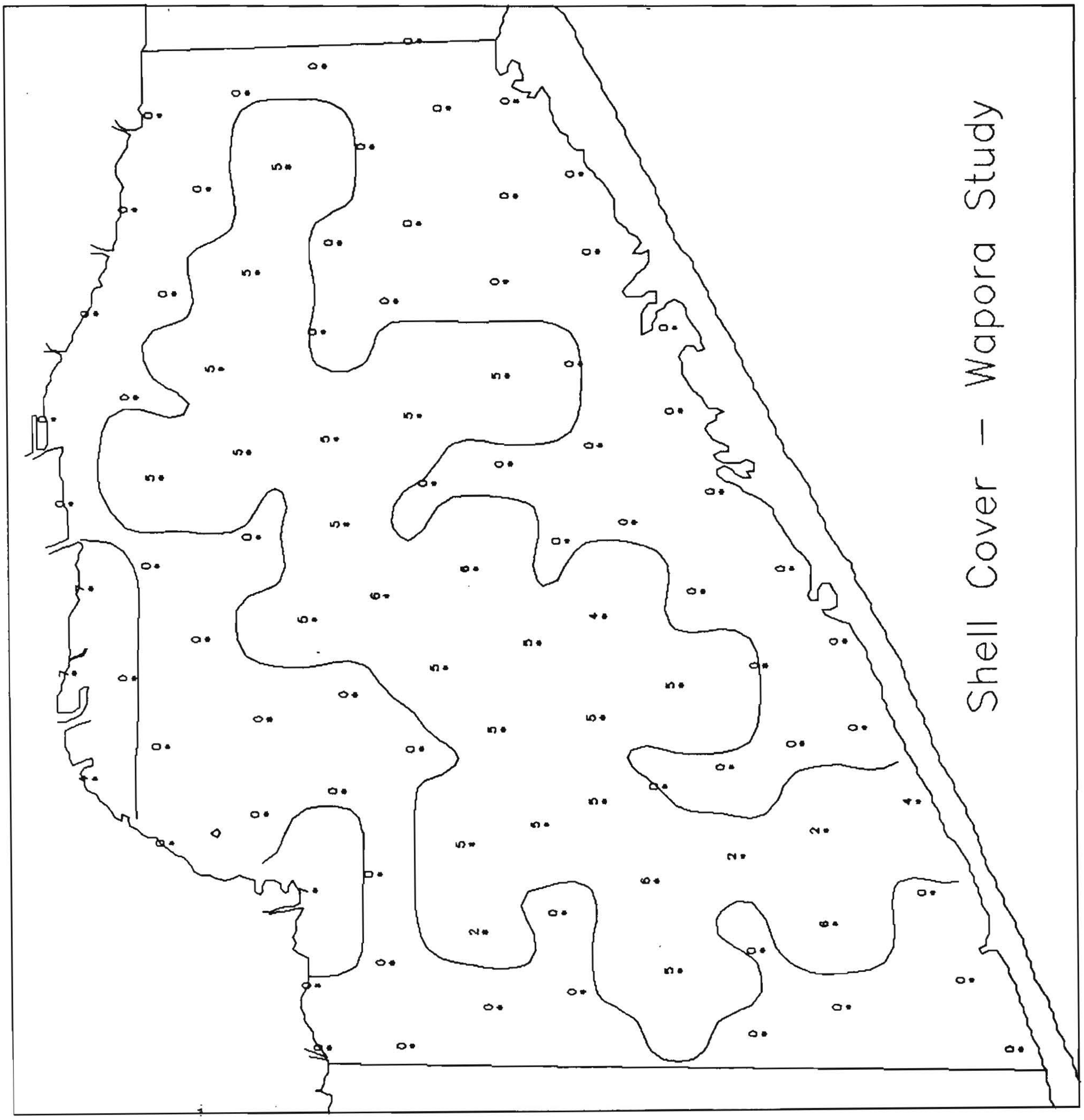


Figure 53. Shell and gravel cover from the 1978 Wapora study. Station codes: (0) no cover, (2) Crepidula shells, (4) scattered oyster and clam beds, (5) old oyster beds, (6) assorted shells and fragments, (7) gravel. Data from Greene (1981).



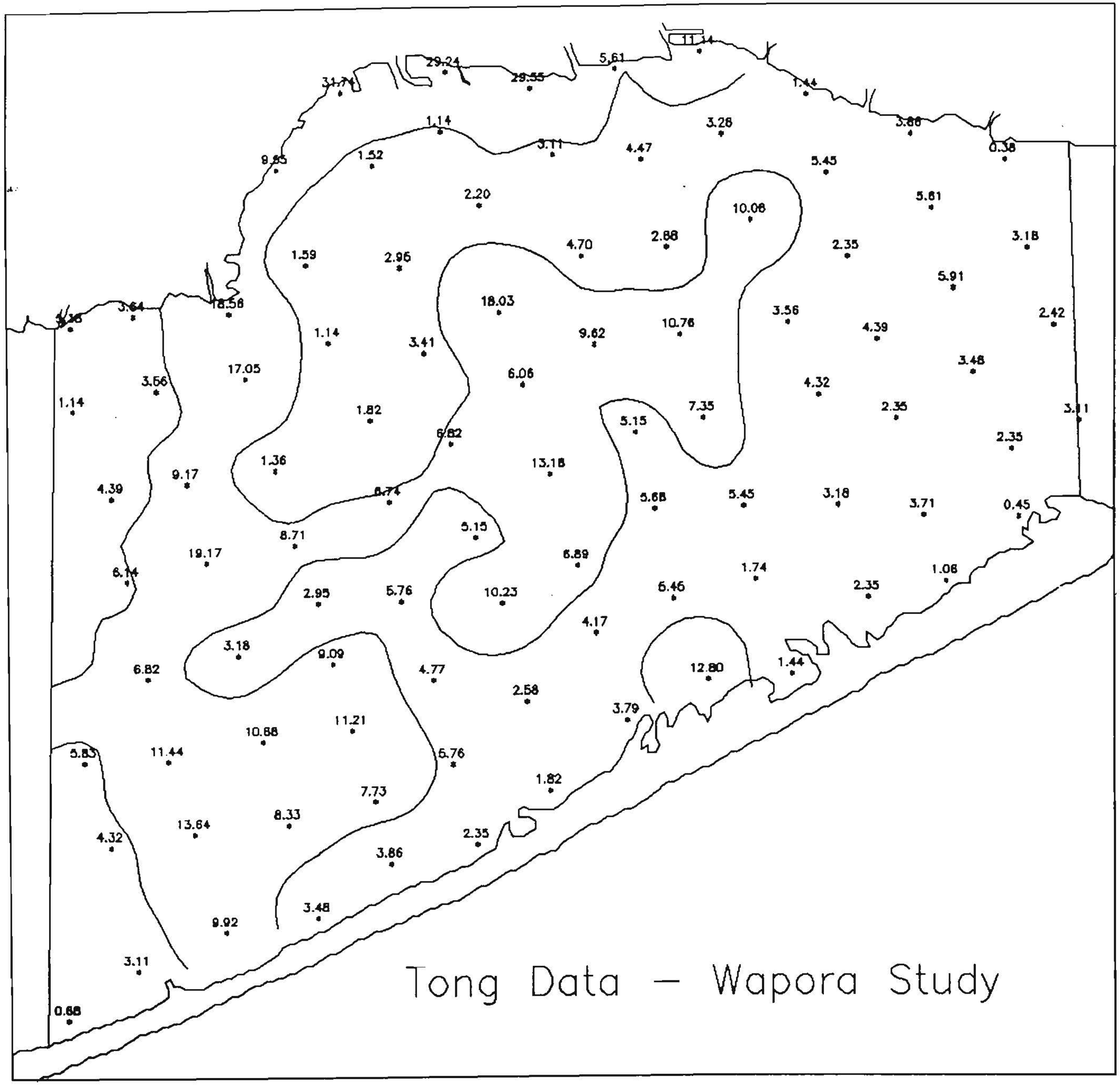


Figure 54. Abundance (per sq. m) of hard clams >= 15 mm in shell length from the 1978 Wapora study. Estimates from tong samples. Data from Greene (1978).

3 1794 02299066 8