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ACOUSTIC ASSESSMENT OF NORWEGIAN SPRING SPAWNING HERRING IN THE WINTERING AREA, DECEMBER 1994 AND JANUARY 1995

by

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ABSTRACT

The abundance of the mature component of the stock of Norwegian spring spawning herring has been estimated based on a series of echo integration surveys. These were performed in the wintering area of Ofotfjord, Tysfjord, and Vestfjord in December 1994 and January 1995 using the SIMRAD EK500/38 kHz echo sounder and Bergen Echo Integrator postprocessing system. Compensation has been made for extinction, assuming that the ratio of extinction and backscattering cross sections is 2.41. Three considerations have dictated the form of stratification of the wintering area: coastline compexity, presence of herring, and herring size distribution as determined by pelagic trawling. The variogram has been computed for each stratum to determine the characteristic scale size of aggregation. Geostatistical theory has been applied to estimate the variance associated with abundance estimates due to the degree of survey coverage in relation to observed aggregation properties and fjord geometry.

INTRODUCTION

The mature component of the stock of Norwegian spring spawning herring (Clupea harengus) has been wintering in the fjords of northern Norway since autumn 1987. Since autumn 1991 the spawning stock has been concentrated, apparently exclusively, in a single fjord system, that of Ofotfjord and Tysfjord, indicated in Fig. 1. Acoustic abundance estimation surveys have been conducted annually in these fjords, but with much greater impetus and effort from December 1992, following three developments. These were introduction of the SIMRAD EK500 echo sounder (Bodholt et al. 1989), with nominal 160-dB dynamic range, development of the Bergen Echo Integrator (Foote et al. 1991), and determination of methods to measure and compensate for extinction (Foote 1990, Foote et al. 1992). Acoustic measurements of herring have also been made in Vestfjord during the outward migration in early January.

Surveying the particular herring stock provides a textbook case for the echo integration method (Foote 1991, Gunderson 1993). The fish is pelagic, its geographical extent is essentially bounded and small, allowing a degree of over-sampling, and weather conditions seldom hinder the measurement process. At the same time, as is invariably the case, there are complicating factors or difficulties that render each survey a challenge.

This paper is, to the authors at least, something more than mere documentation of another acoustic assessment in a series (Foote 1993, Røttingen et al. 1994), albeit of a most important stock. Rather, it attempts to describe the exact conditions and peculiarities of herring spatial distribution that distinguish the present surveys. It also identifies shortcomings and suggests remedies for future surveys, assuming continued wintering of the herring in the Ofotfjord-Tysfjord system.

MATERIALS AND METHODS

Acoustic measurements

The basic measurement was that of the area backscattering coefficient s_A (Knudsen 1990). This was made with a calibrated scientific echo sounder system, the SIMRAD EK500 echo sounder (Bodholt et al. 1989) with ES38B transducer, operating at its resonant frequency of 38 kHz. The acoustic platform was R/V "Johan Hjort", a 2000-BRT research vessel with stern-trawling capability, with particular transducer mounted on a retractable keel at 5-m depth under ordinary sailing conditions in the fjords.

According to the fundamental equation of echo integration, s_A is proportional to area fish density ρ_A:

$$s_A = \rho_A \bar{\sigma}_b \quad , \tag{1}$$

where $\bar{\sigma}_b$ is the average backscattering cross section. This quantity is determined from a standard target strength - length relationship (Foote 1987), namely

$$TS = 10 \log \frac{\bar{\sigma}_b}{4\pi r_o^2} = 20 \log \ell - 71.9 \quad . \tag{2}$$

In this equation r_o is a reference distance of 1 m, and ℓ is the root-mean-square (rms) measure of applicable length distribution in units of centimeters.

Calibration of the echo sounder was performed according to the standard-sphere method recommended by ICES (Foote et al. 1987). The 60-mm-diameter copper sphere was used.

The pulse repetition frequency was typically about 50 pings per minute, although this was influenced both by bottom depth and the number of transducers in simultaneous use, typically four. At a nominal vessel speed of 8 knots, the distance sailed between successive pings was 4 m.

Survey design

The survey design was determined by a number of factors: total area to be covered, time available for this, characteristic times for large-scale movements of herring, geometrical and navigational complexity of local regions, and herring distribution patterns. Since it was desired to put survey effort in areas of greatest herring concentration, a two-stage design was adopted for Ofotfjord. This was not necessary in Tysfjord, because of the smaller quantity of fish, but it was not especially feasible either, because of the complex coastline and navigational hazards.

The basic survey types are listed in Table 1. The initial survey of Ofotfjord used a zigzag design to achieve broad coverage in a relatively short time period. Subsequent surveys of the same fjord used parallel north-south transects spaced at 0.5-nautical-mile (NM) intervals. The design types in Tysfjord involved zigzags in some local areas, parallel transects in others, but also quite different designs which attempted to achieve uniform coverage while respecting navigational hazards in irregularly shaped fjord regions.

Detailed information on the survey designs is given in Figs. 2-4. These show the particular survey tracks, after stratification and elimination of some redundant or other biasing segments. In the case of Ofotfjord, the second, third, fourth, and fifth survey designs are essentially the same, differing only in western extent, which was determined by the encountered distribution or weather in the case of the fourth survey. The actual transects differ in small respects, as because of maneuvers required to avoid fishing vessels and other fjord traffic.

Trawl sampling and biological measurements

Physical capture of the acoustically observed herring distribution was accomplished with standard commercial pelagic trawl. This was typically towed at a speed of 4 knots. The quantity of fish swept into the trawl opening was monitored by the SCANMAR Trawleye System in order to secure moderate catches. The locations of the pelagic trawl stations are indicated in Fig. 5. The described catches were supplemented by samples obtained from commercial fishing vessels.

The usual suite of laboratory measurements was performed. For present purposes of determining abundance and length distribution, it was sufficient to measure the total length according to ICES standards. Additional measurements were made of weight, sex, maturity stage, and age. In addition to these conventional measurements, a special investigation was undertaken during the December 1994 cruise of *Ichthyophonus*. These measurements are extraneous to the assessment *per se*, so are not mentioned further here.

Postprocessing of acoustic data

Postprocessing was performed in the now familiar manner. The Bergen Echo Integrator (Foote et al. 1991) was used to redisplay the data on an electronic screen in the form of echograms. These could then be interpreted, a process by which particular acoustic registrations are allocated to species or other scatterer classes, for example, herring and non-herring.

By choice, results of this interpretation process were stored in the attached database with maximum resolution, namely 10 m in depth, from transducer to 500-m depth, and 0.1 nautical miles in sailed distance.

At this stage, owing to the high density and large vertical extent of the aggregation in many places, an adjustment for extinction was made (Foote 1990). The extinction cross section was assumed to vary with rms fish length ℓ as the backscattering cross section does, with proportionality constant of 2.41:

$$\sigma_e = 2.41\,\sigma_b \quad , \qquad (3)$$

as determined the previous year for herring in Ofotfjord (Foote 1994).

Summation of the extinction-corrected values over all 10-m layers determined a single value of s_A for each 0.1-nautical-mile interval. Attached to each such s_A-value was the geographical location as determined by the Global Positioning System (GPS) with some filtering, although less accurate than that of Differential GPS. The paired values of s_A and position were processed further, but after stratification, as described below.

Stratification

Acoustic data from fjord regions where herring were found were stratified according to two distinct criteria. The first criterion was based on the degree of local coverage. Clearly, by inspection of Fig. 3, the degree of coverage should vary with locality in Tysfjord. Given local differences in concentration, for example, extremely dense concentrations in some inner fjord arms and scarcity of herring near the mouth of Tysfjord in early December 1994, merely attempting to maintain similarity in degree of coverage would be highly inefficient.

The second criterion applied in stratification was that of biology. This was determined by trawl sampling or, in the case of distinct vertical differences, by echogram appearance supported by trawl sampling. Geographical and vertical differences in age and size structure during both cruises followed the pattern observed earlier by Røttingen et al. (1994). The consequence of this is a second level of stratification to be superimposed on the first level.

Strata for the several acoustic surveys of Ofotfjord, Tysfjord, and Vestfjord are indicated in Figs. 2-4. Corresponding areas are described in Tables 2 and 3. The tabulated number of acoustic samples n_s is the number of blocks, or statistical squares with 0.2-nautical-mile side length, containing at least one echo integrator value, as characterized by the start position of the corresponding interval. The block-averaged data themselves are presented in Figs. 2-4. Circles are used to represent s_A-values, with centers at the start of the respective 0.1-nautical-mile integration interval and diameters proportional to the square root of s_A-values above a minimum threshold size for position-registration.

The ensemble of plotted s_A-values represents either the totality of measurements made in each stratum or a large subset of these. The only criterion for deleting data to form a subset has been avoidance of conspicuous instances of non-uniform sampling. Surveyed fjord regions without herring have been ignored.

Computation of abundance and geostatistical variance

Integration of the data over 0.1-nautical-mile intervals and uncertainty in GPS positions define a basic sampling resolution of 0.2 nautical miles. For each stratum, therefore, s_A-values after compensation for extinction and summation over the water column were assigned to blocks or statistical squares of constant side length 0.2 nautical miles in north-south and east-west directions according to the start position of the interval. These assigned s_A-values were averaged first by block, and the block-averaged values were then averaged for each particular stratum. Division of the resulting number by the characteristic average backscattering cross section $\bar{\sigma}_b$ for the rms fish length determines the area fish density ρ_A according to Equation (1). When multiplied by the stratum area A, the total number of fish in the stratum is found,

$$N = A \rho_A \quad . \tag{4}$$

Multiplication of N by the length distribution, as determined from trawl sampling, for example, determines the number distribution, hence abundance by length.

The associated estimation variance σ_E^2 is determined by the ordinary geostatistical procedure (Matheron 1971, Cressie 1991). Assuming isotropy in the individual strata, the two-dimensional experimental variogram, normalized to the sample variance s^2, is computed according to the definition,

$$\gamma(h) = \frac{1}{2s^2} E[(z_i - z_j)^2] \quad , \tag{5}$$

where h is the distance between datum z_i and datum z_j. This is modeled by the sum of a nugget term $\mathcal{N}(h)$ and spherical function $\mathcal{S}(h)$,

$$\gamma(h) = \mathcal{A}_N \mathcal{N}(h) + \mathcal{A}_S \mathcal{S}(h) \quad , \tag{6}$$

where the amplitudes $\mathcal{A}_N$ and $\mathcal{A}_S$ are non-negative and sum to unity, $\mathcal{N}(h)=0$ for h=0 and 1 for h>0, and $\mathcal{S}(h)=1.5h/a-0.5(h/a)^3$ for h≤a and 1 for h>a. The quantity a is the characteristic scale size of aggregation, beyond which there is judged to be no structure. The estimation variance is then computed according to the expression,

$$\sigma_E^2 = (2\bar{\gamma}_{tv} - \bar{\gamma}_{tt} - \bar{\gamma}_{vv}) s^2 \quad , \tag{7}$$

where $\bar{\gamma}$ is the average of the variogram model. The averaging is performed over two sets of points, designated by t for transect or sampled sites and v for volume or total area of the stratum.

The estimation variance σ_E^2 is typically normalized by the mean s_A-value, forming the ratio $\sigma_E/\overline{s}_A$. This may be compared with the variance of of the mean, also normalized to the mean s_A-value, namely $s/(n_s^{\frac{1}{2}}\,\overline{s}_A)$, where n_s is the number of acoustic samples, that is, the number of blocks or statistical squares containing values of s_A, as defined above.

Compounding of local estimates of abundance and variance

If N_j denotes the total number of herring in stratum j, then the total number of herring over all m strata is

$$N_{tot} = \sum_{j=1}^{m} N_j \quad . \qquad (8)$$

A more interesting quantity is the corresponding number distribution. If $n(\ell)$ denotes the total number of fish with lengths between $\ell-\Delta\ell/2$ and $\ell+\Delta\ell/2$, for $\Delta\ell$ small compared with ℓ,

$$n(\ell) = \sum_{j=1}^{m} N_j f_j(\ell) \quad . \qquad (9)$$

The composite length distribution is just

$$f(\ell) = n(\ell) \Big/ \sum_{j=1}^{m} N_j \quad . \qquad (10)$$

The estimation variance associated with N_{tot} is

$$\sigma_{E,tot}^2 = \sum_{j=1}^{m} \sigma_{E,j}^2 \quad , \qquad (11)$$

where $\sigma_{E,j}^2$ denotes the estimation variance for stratum j. This equation applies under the reasonable assumption that the variances of individual strata estimates N_j are independent. As in the case of estimates for σ_E^2 in the individual strata, $\sigma_{E,tot}$ is conveniently compared with the corresponding mean for the total area, namely

$$\overline{s}_{A,tot} = \frac{\sum_{j=1}^{m} A_j \overline{s}_{A,j}}{\sum_{j'=1}^{m} A_{j'}} \quad . \qquad (12)$$

RESULTS

The results are presented in a series of tables and figures. First, summary results are arranged by stratum in Table 2 for the cruise in December 1994. Corresponding results for the cruise in January 1995 are presented in Table 3.

Strata-based results are combined by fjord in Table 4. These numbers are further combined to form stock estimates in Table 5, distinguished by cruise. Component survey series respect the sequence of surveying and evident dynamic situation during the cruise in January 1995.

Corresponding to the summary results in Table 5 are the abundance distributions by length in Fig. 6. These were computed according to the method described above in Equations (8) and (9).

DISCUSSION

Comparison of abundance estimates and length distributions

Inspection of Table 5 shows a remarkable agreement of results for the abundance of mature herring wintering in the Ofotfjord-Tysfjord system, as measured in December 1994 and January 1995. The length distributions, derived by normalizing the number distributions in Fig. 6 according to Equation (10), are statistically indistinguishable, as determined by applying the Smirnov test (Wilks 1962). According to this nonparametric test, the largest difference in cumulative distribution functions is found. Since the basic number of data underlying each of the respective strata-based length distributions is n=100 except in a few cases, which number is unaffected by the weighting operation in Equation (9), the probability that D exceeds $\delta(n/2)^{\frac{1}{2}}$ is given by the expansion applicable to large n,

$$P[D > \delta(n/2)^{\frac{1}{2}}] = -2 \sum_{k=1}^{\infty} (-1)^k \exp(-2k^2\delta^2) \quad ,$$

where δ is a parameter. For the two distribution functions, D=0.06714 and P=0.978. That is, the observed difference in distributions is small and consistent with the two being drawn from the same population.

The agreement appears especially remarkable because of the quite variable results for the abundance estimates during the three surveys in Ofotfjord in December 1994, shown in Table 4. The abundance appears to have changed dramatically, decreasing by about a factor of two from the first to third surveys. Closer inspection of the data underlying Fig. 2, including the segments connecting the parallel transects, may reveal a source for the discrepancy: a skewed spatial distribution. The densest concentrations of herring were often near the shore, where they were most likely undersampled in the second and third surveys compared to the first. The initial zigzag design may achieve better sampling than the north-south transects used in the second and third surveys, because navigational considerations precluded the same close approach to the shore in the second and third surveys. In addition, use of ordinary GPS with its inherent jitter limited positioning resolution to that of the integrator, namely 0.1 nautical mile.

Two remedies for surveying near-shore herring are the use of Differential GPS for the accurate registration of vessel position, and use of sonar with side-looking or other steerable beam or beams. In fact, use of the SIMRAD SA950 sonar (Misund et al. 1995) is planned for survey cruises to Ofotfjord and Tysfjord in winter 1995-96.

Assignment of backscattering and extinction cross sections

Further reasons for the discrepancies in abundance estimates of herring in Ofotfjord during the first cruise may be found in the values assumed for the backscattering and extinction cross sections. These are additionally dynamic quantities, varying with herring behavior, as through depth, depth history, and orientation distributions, among other influences (Ona 1990). The very evident movement of the herring about Ofotfjord in December 1994, observed in Fig. 2, and rapid and systematic movements in Ofotfjord and Vestfjord due to the onset of migration in January 1995, observed in Figs. 2 and 4, are suggestive of the working of unknown, internal mechanisms. It is plausible that these are accompanied by changes in scattering properties. Yet the single dependence applied here, or known for that matter, is that of size, described in Equation (2). Better knowledge of target strength and like quantities and their dependences may be expected to improve abundance estimates by reducing measurement errors in the area density derived from Equation (1).

Definition of strata

Discrepancies in abundance estimate with survey number in Ofotfjord, indicated in Table 4, may also be due to stratification. Sampling of the distributions by physical capture is generally difficult. Obtaining representative samples during the cruises was problematical due to the classic dilemma of having to perform both intensive acoustic measurements and trawling from the same vessel. Lacking sufficient trawl stations, only a small number of biological strata may be defined, witness especially Fig. 2.

Some vertically separated strata were also defined, for example, in Ofotfjord and Vestfjord in January 1995. A new sampling problem is thus introduced, for representativity in trawl sampling is undoubtedly influenced by behavior, as through the noise field (Ona and Godø 1990). Changing behavior from December to January most likely affects abundance estimates for individual strata, if only through their correct delineation.

One remedy for improving strata definition is clear: use of two vessels to perform the survey, one to conduct acoustic measurements and the other to perform trawling on the basis of the acoustic observations. Such two-vessel surveying may be attempted in winter 1995-96.

Combining strata-based estimates of abundance

The mathematical problem of compounding local, stock-based estimates of abundance to form fjord-based or global estimates of abundance is, according to the above mathematics, simple. Choosing what to combine, clearly, is critical.

In deriving global estimates of abundance for the December 1994 cruise, it is assumed that there is no movement of herring between Ofotfjord and Tysfjord in the course of the repeated surveys of Ofotfjord. The presence of basins separated by thresholds makes this hypothesis plausible, but it remains unproven. The global estimate may be formed by averaging the three estimates for Ofotfjord and combining this with the single estimate for Tysfjord, or by averaging the global estimates formed by combining each

Ofotfjord estimate with the single Tysfjord estimate. The result is equivalent in this case.

Movement of herring cannot be ignored in the second cruise. The particular sequence of surveying, however, makes combination of the several fjord-based estimates problematical. Vestfjord was first surveyed in the northeast direction. The next fjord to be surveyed, Ofotfjord, was covered from east to west. The western end of the fjord, or mouth opening out onto Vestfjord, was not reached until about 1½ days after the survey in Vestfjord was completed. Rough sea conditions precluded continuing the Ofotfjord survey into Vestfjord as planned. Ofotfjord was thus surveyed a second time, again from east to west, but continuing out onto Vestfjord, revealing a dramatic degree of migration over a period of days. Tysfjord was then surveyed. Two global estimates of abundance were formed from the described first and second survey pairs, each compounded with the same Tysfjord survey.

The importance of timing in performing the surveys is evident, especially during the period of migration, but possibly also during the presumed quiescent period of wintering. The magnitude of errors introduced into the present global estimates cannot be quantified.

Geostatistical variance

The error that is assessed in this work is that due to the spatial distribution of herring, a process error. According to Equation (7), this error consists of three parts, associated respectively with degree of sampling or coverage relative to the spatial extent of the fjord region, degree of sampling per se, and total stratum area as a geometrical entity. The sensitivity of σ_E^2 to these terms is illustrated by the surveys of Vestfjord in January 1995. In the first, the sampling by zigzag was quite sparse, while that in the second was both systematic and intensive. The respective values for $\sigma_E/\overline{s}_A$ were 0.188 and 0.097.

Common to each term in Equation (7) is the variogram, which is established on the basis of observations along line transects. Modeling by Equation (6) gives terms in Tables 2 and 3 which are similar to those obtained in earlier surveys of the same fish stock in the same fjord system.

So far, the two-dimensional isotropic variogram has been used. Some justification for this may be found in the distribution of herring relative to the strata, shown in Figs. 2-4, and in previous experience, but the mentioned shoreward tendency of the herring in Ofotfjord at times suggests the usefulness of examining anisotropy. Direct measurement, as by sonar, will also contribute to definition of the density distribution.

Other research studies aimed at improving stock abundance estimation

Additional use of the sonar as a multiple-beam echo sounder system may enable possible avoidance reactions to be quantified, an outstanding matter for herring surveys conducted in fjords. Other special studies, such as in situ photographic and sonar measurement of fish density (Røttingen et al. 1994, Huse and Ona 1995) and multiple-frequency measurement (Foote et al. 1993), may also contribute to a general improvement in stock estimates, hence their continued pursuit.

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Table 1. Basic survey design types used during the cruises in December 1994 and January 1995.

Fjord	Period	Fjord survey no.	Start time Date	Start time UTC	Stop time Date	Stop time UTC	Sailed distance (NM)	Design type
Ofotfjord	9412	1	1201	2250	1202	1157	107.9	Zigzag
Ofotfjord	9412	2	1205	2045	1207	0204	194.7	Equally spaced parallel transects
Ofotfjord	9412	3	1209	0848	1210	1107	194.1	Equally spaced parallel transects
Ofotfjord	9501	4	0106	2100	0108	0100	199.7	Equally spaced parallel transects
Ofotfjord	9501	5	0108	0901	0109	1256	204.5	Equally spaced parallel transects
Tysfjord	9412	1	1202	2324	1204	0749	211.8	Composite
Tysfjord	9501	2	0110	1433	0112	0545	208.0	Composite
Vestfjord	9501	1	0105	2330	0106	1316	126.6	Zigzag
Vestfjord	9501	2	0109	1256	0110	0932	188.3	Equally spaced parallel transects except at migration front where search pattern applied

Table 2. Summary of measurement and computational results for the cruise in December 1994, arranged by stratum. Depth strata are indicated by the suffix d1 or d2, denoting respectively the upper 100 m or depths greater than 100 m.

Stratum	Area (NM^2)	n_s	$\bar{s}_A$	CV	se/$\bar{s}_A$	A_N	a(NM)	$\sigma_E/\bar{s}_A$	ℓ_{rms} (cm)	$\Delta\ell_{rms}$ (cm)	N(10^9)
o14	68.20	375	148000	1.9	0.096	0.30	1.70	0.133	32.14	3.65	12.1
o15	24.76	167	156000	2.2	0.174	0.00	0.90	0.215	34.18	3.63	4.06
t11d1	19.80	105	12400	1.9	0.184	0.00	1.80	0.273	26.73	2.52	0.425
t11d2	19.80	105	266	1.5	0.150	0.10	2.40	0.223	35.31	2.42	0.00520
t12d1	17.08	141	5110	2.2	0.184	0.00	1.80	0.231	26.73	2.52	0.151
t12d2	17.08	141	36900	1.9	0.157	0.00	0.90	0.198	35.31	2.42	0.624
t13	14.52	117	4940	1.1	0.104	0.00	1.80	0.155	35.31	2.42	0.0709
t14	2.16	34	1610	2.4	0.405	0.00	1.00	0.260	35.31	2.42	0.00345
t15	5.64	64	104000	1.4	0.172	0.00	0.90	0.172	35.31	2.42	0.582
t16	4.72	50	652	3.5	0.497	0.00	0.50	0.547	35.31	2.42	0.00304
t17	1.04	16	2060	1.8	0.440	0.00	0.30	0.421	35.31	2.42	0.00212
t18	3.64	47	133000	2.0	0.298	0.60	0.60	0.313	34.62	2.75	0.500
t19	3.64	45	178000	1.2	0.177	0.00	1.00	0.155	26.73	2.52	0.112
t20	4.56	52	45700	0.6	0.080	0.70	1.70	0.074	26.73	2.52	0.360
t21	1.60	24	153000	0.9	0.193	0.00	0.60	0.163	26.73	2.52	0.423
t22	2.56	26	18500	0.5	0.091	0.00	0.60	0.087	26.73	2.52	0.0820
o24	68.20	567	106000	2.2	0.091	0.30	1.70	0.099	32.14	3.65	8.64
o25	28.44	246	78900	1.9	0.123	0.30	3.30	0.091	34.18	3.63	2.36
o34	68.20	564	86100	2.5	0.105	0.35	0.90	0.102	32.14	3.65	7.02
o35	28.44	240	42600	1.7	0.108	0.00	2.40	0.076	34.18	3.63	1.28

Table 3. Summary of measurement and computational results for the cruise in January 1995, arranged by stratum. Depth strata are indicated by the suffix d1 or d2, denoting respectively the upper 100 m or depths greater than 100 m.

Stratum	Area (NM^2)	n_s	$\bar{s}_A$	CV	$se/\bar{s}_A$	$\mathcal{A}_N$	a (NM)	$\sigma_E/\bar{s}_A$	ℓ_{rms} (cm)	$\Delta\ell_{rms}$ (cm)	N(10^9)
v11	22.88	42	10800	1.3	0.207	0.40	0.75	0.274	35.17	2.72	0.245
v12	22.08	68	206000	1.2	0.151	0.30	3.50	0.198	35.17	2.72	4.53
o44	68.20	606	51200	3.5	0.141	0.50	1.60	0.148	31.00	3.50	4.48
o46	6.12	58	243000	1.3	0.165	0.20	1.00	0.135	33.05	3.90	1.68
o47d1	22.32	195	4280	1.9	0.138	0.55	2.80	0.129	28.27	2.04	0.147
o47d2	22.32	195	57300	1.2	0.087	0.20	1.00	0.082	33.05	3.90	1.45
o54	68.20	599	36700	2.5	0.103	0.70	4.80	0.111	31.00	3.50	3.21
o58	31.84	303	116000	1.5	0.085	0.25	1.00	0.086	31.22	3.88	4.68
v21d1	134.32	666	13300	5.5	0.212	0.20	3.90	0.192	28.27	2.04	2.76
v21d2	134.32	666	34200	2.9	0.112	0.20	4.70	0.104	35.81	2.53	4.57
v22d2	25.12	72	1040	2.3	0.269	0.00	1.35	0.424	35.81	2.53	0.0260
t31	41.60	281	33200	2.4	0.141	0.70	4.80	0.130	34.65	2.99	1.42
t32	7.24	62	48300	1.9	0.236	0.00	0.90	0.261	34.65	2.99	0.360
t33	1.80	17	80200	1.7	0.416	0.50	0.30	0.422	34.65	2.99	0.149
t34	1.80	34	15000	2.6	0.451	0.60	0.90	0.391	34.65	2.99	0.0278
t35	2.40	18	6400	1.1	0.255	0.00	0.60	0.261	34.65	2.99	0.0158
t36	5.36	67	38500	3.3	0.404	1.00	-	0.404	34.65	2.99	0.213
t37	2.28	32	65000	2.2	0.390	0.00	0.75	0.289	34.65	2.99	0.153

Table 4. Summary of results for the cruises in December 1994 and January 1995, arranged by fjord and survey. The geostatistical variance is expressed through the normalized quantity $\Delta N/N$.

Period	Fjord	Series no.	$N(10^9)$	$\Delta N/N$
9412	Ofotfjord	10	16.2	0.113
9412	Tysfjord	10	3.34	0.079
9412	Ofotfjord	20	11.0	0.080
9412	Ofotfjord	30	8.30	0.087
9501	Vestfjord	10	4.78	0.188
9501	Ofotfjord	40	7.76	0.092
9501	Ofotfjord	50	7.89	0.068
9501	Vestfjord	20	7.36	0.097
9501	Tysfjord	30	2.34	0.102

Table 5. Abundance estimates of the mature component of the stock of Norwegian spring spawning herring wintering in the Ofotfjord-Tysfjord system in December 1994 and beginning its spawning migration in January 1995.

Period	$N(10^9)$	$\Delta N/N$
9412	15.2	0.084
9501	16.2	0.065

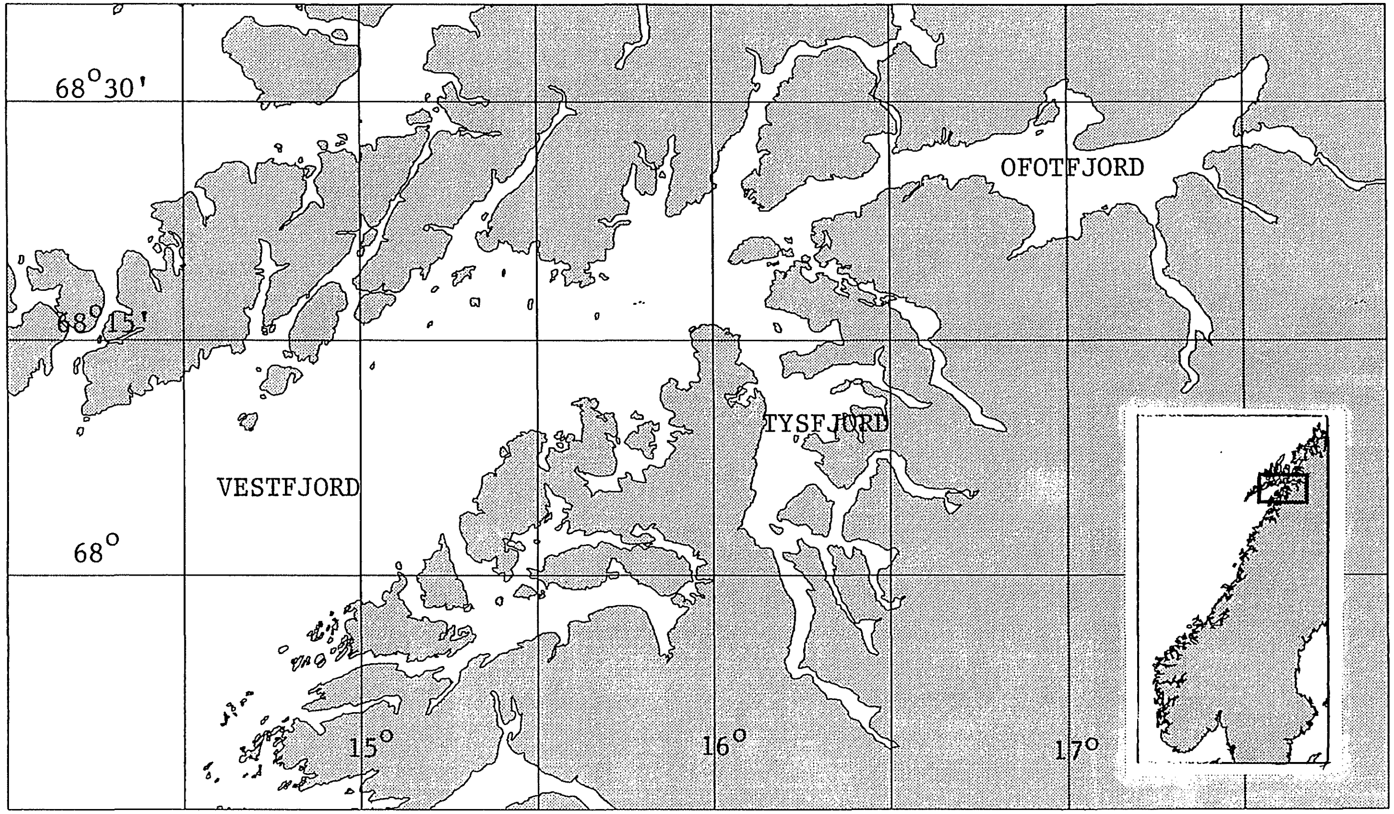
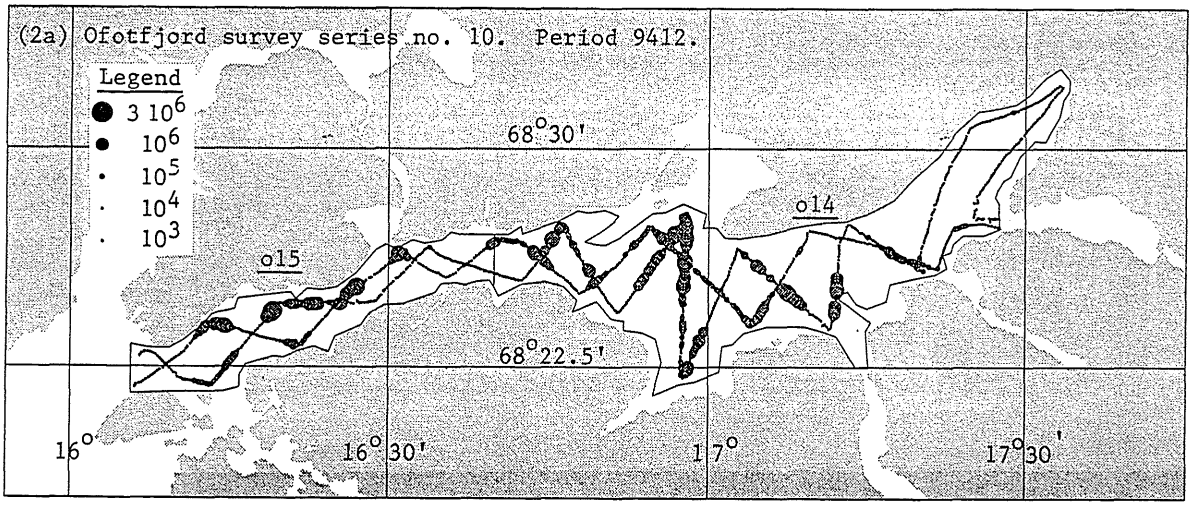
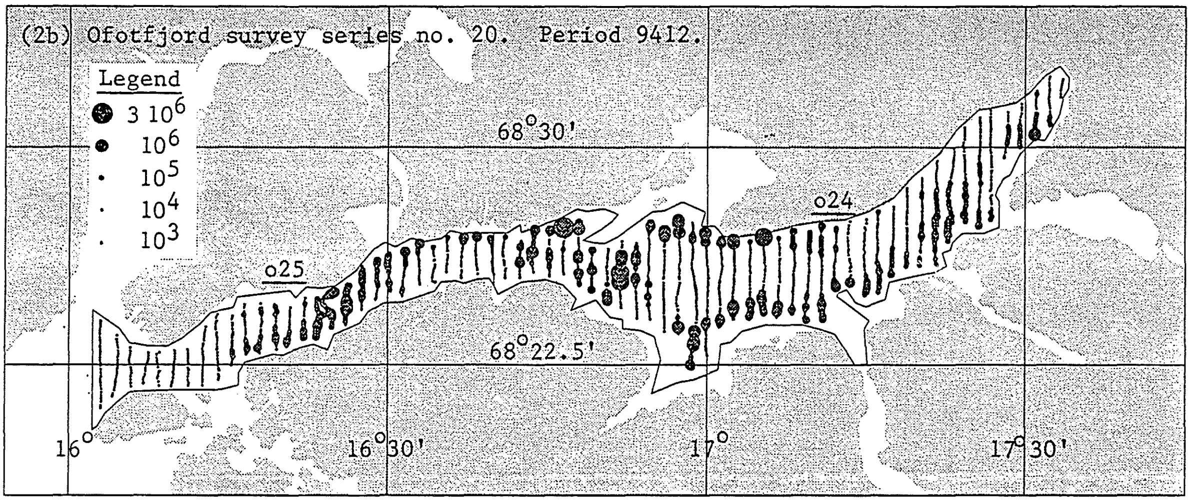


Fig. 1. Geographical site of acoustic abundance estimation surveys of Norwegian spring spawning herring in December 1994 and January 1995.


(2a) Ofotfjord survey series no. 10. Period 9412.
Legend
3 10^6
10^6
10^5
10^4
10^3
68°30'
o14
o15
68°22.5'
16°
16°30'
17°
17°30'


(2b) Ofotfjord survey series no. 20. Period 9412.
Legend
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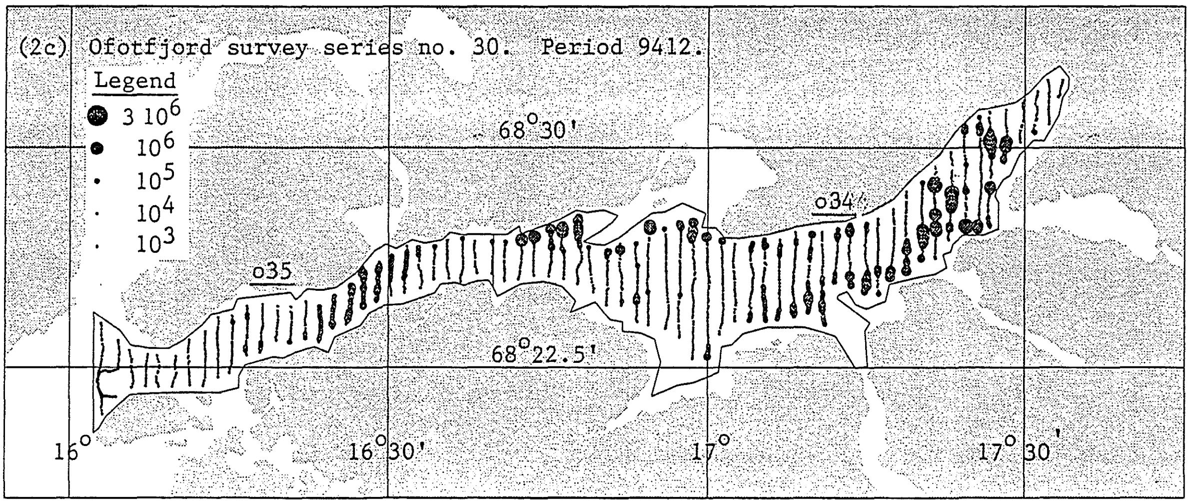
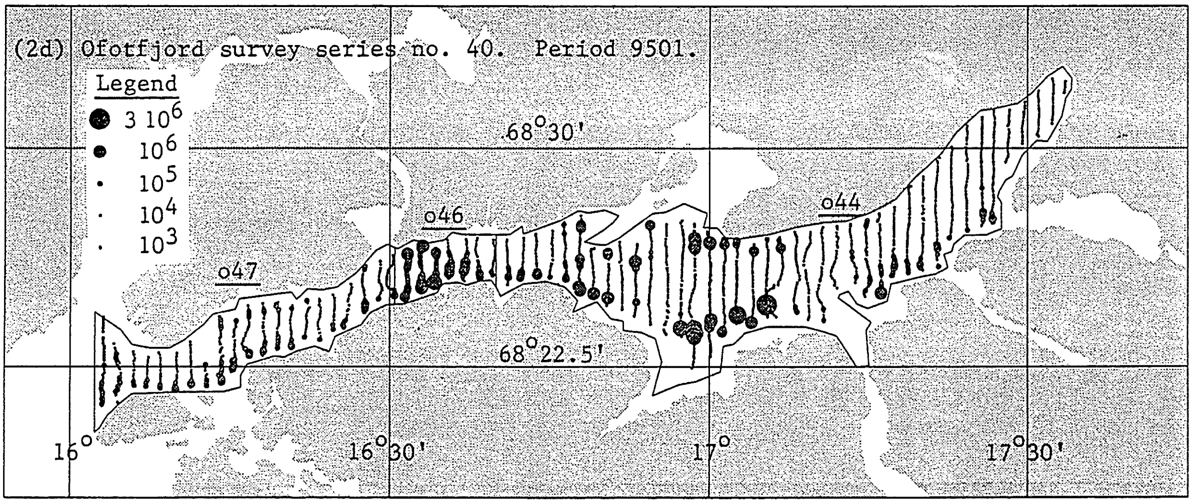
10^6
10^5
10^4
10^3
68°30'
o24
o25
68°22.5'
16°
16°30'
17°
17°30'


(2c) Ofotfjord survey series no. 30. Period 9412.
Legend
3 10^6
10^6
10^5
10^4
10^3
68°30'
o34
o35
68°22.5'
16°
16°30'
17°
17°30'



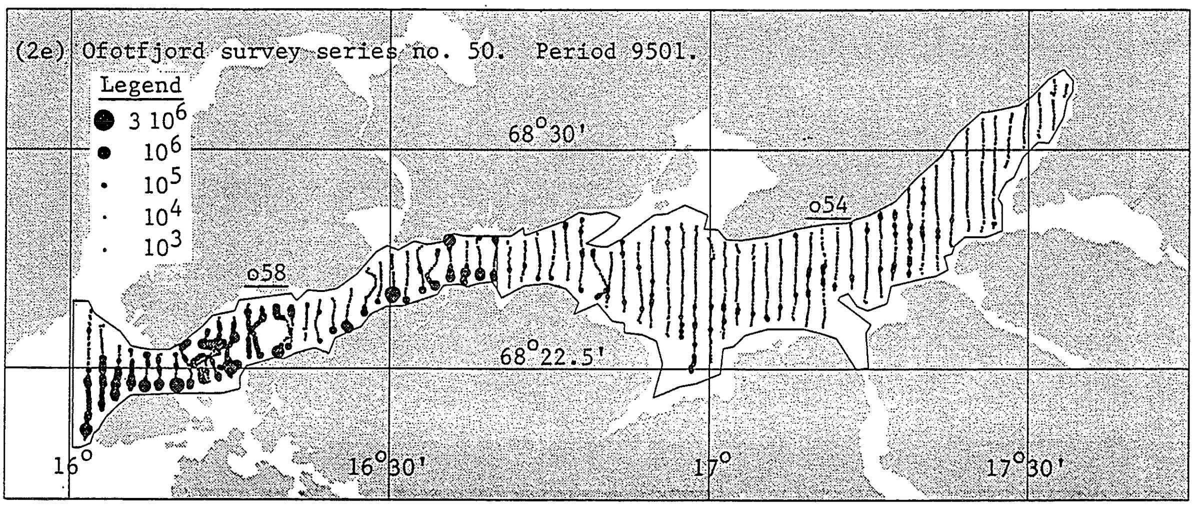


Fig. 2. Distribution of herring in Ofotfjord in December 1994 and January 1995, with square-root-transformed s_A-values indicated in the legend. Strata are designated by underlined codes.

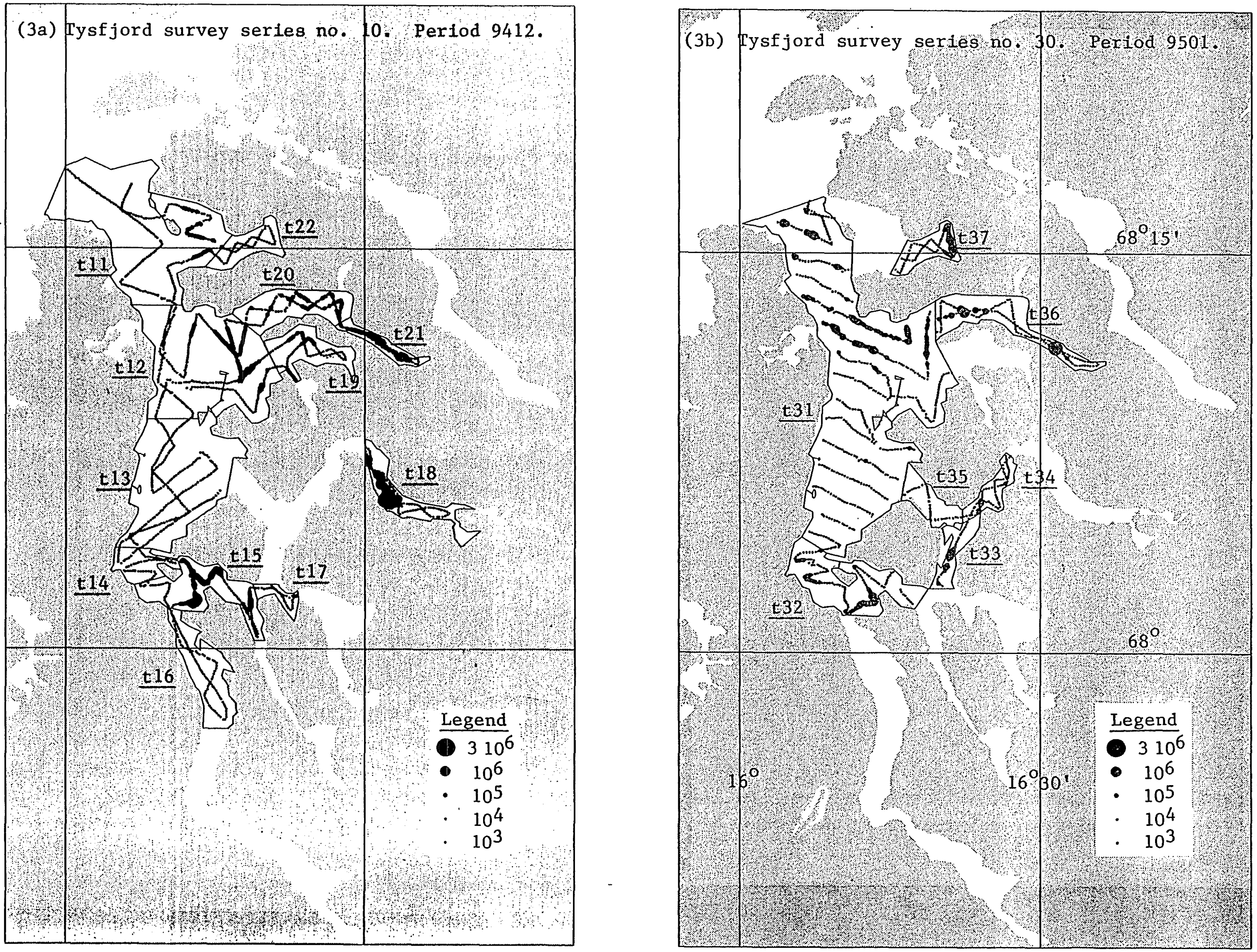
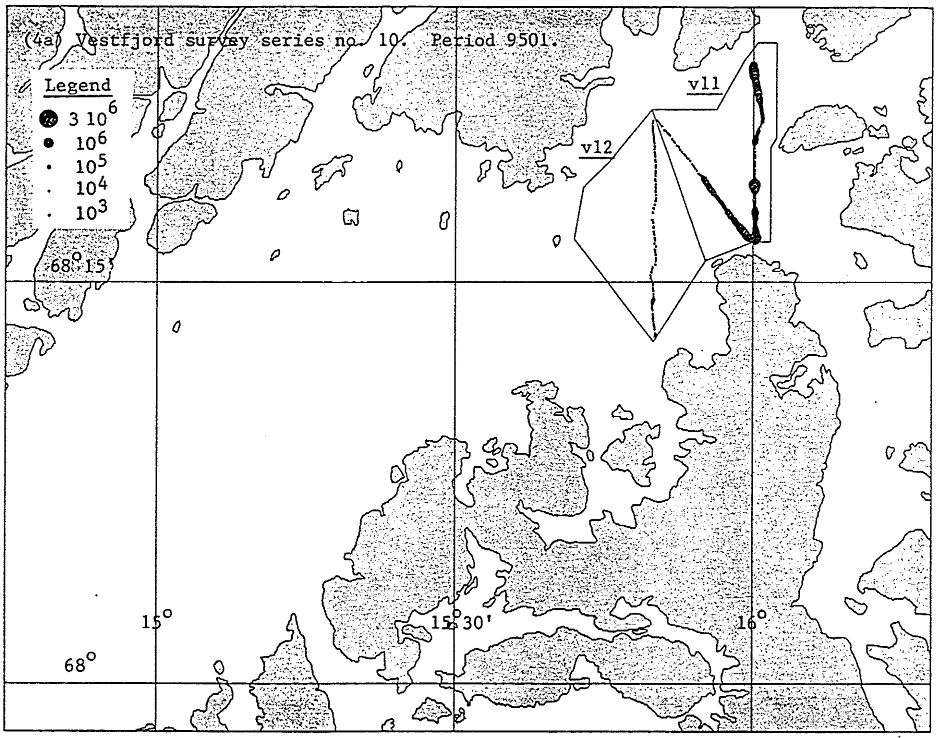


Fig. 3. Distribution of herring in Tysfjord in December 1994 and January 1995, with square-root-transformed s_A-values indicated in the legend. Strata are designated by underlined codes.



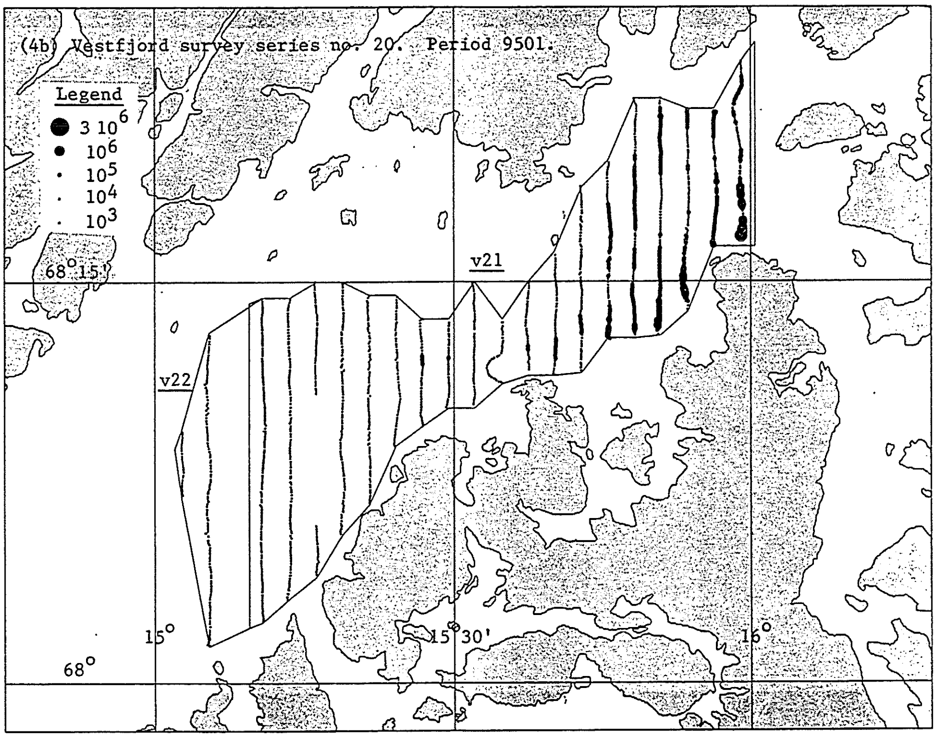


Fig. 4. Distribution of herring in Vestfjord in January 1995, with square-root-transformed s_A-values indicated in the legend. Strata are designated by underlined codes.

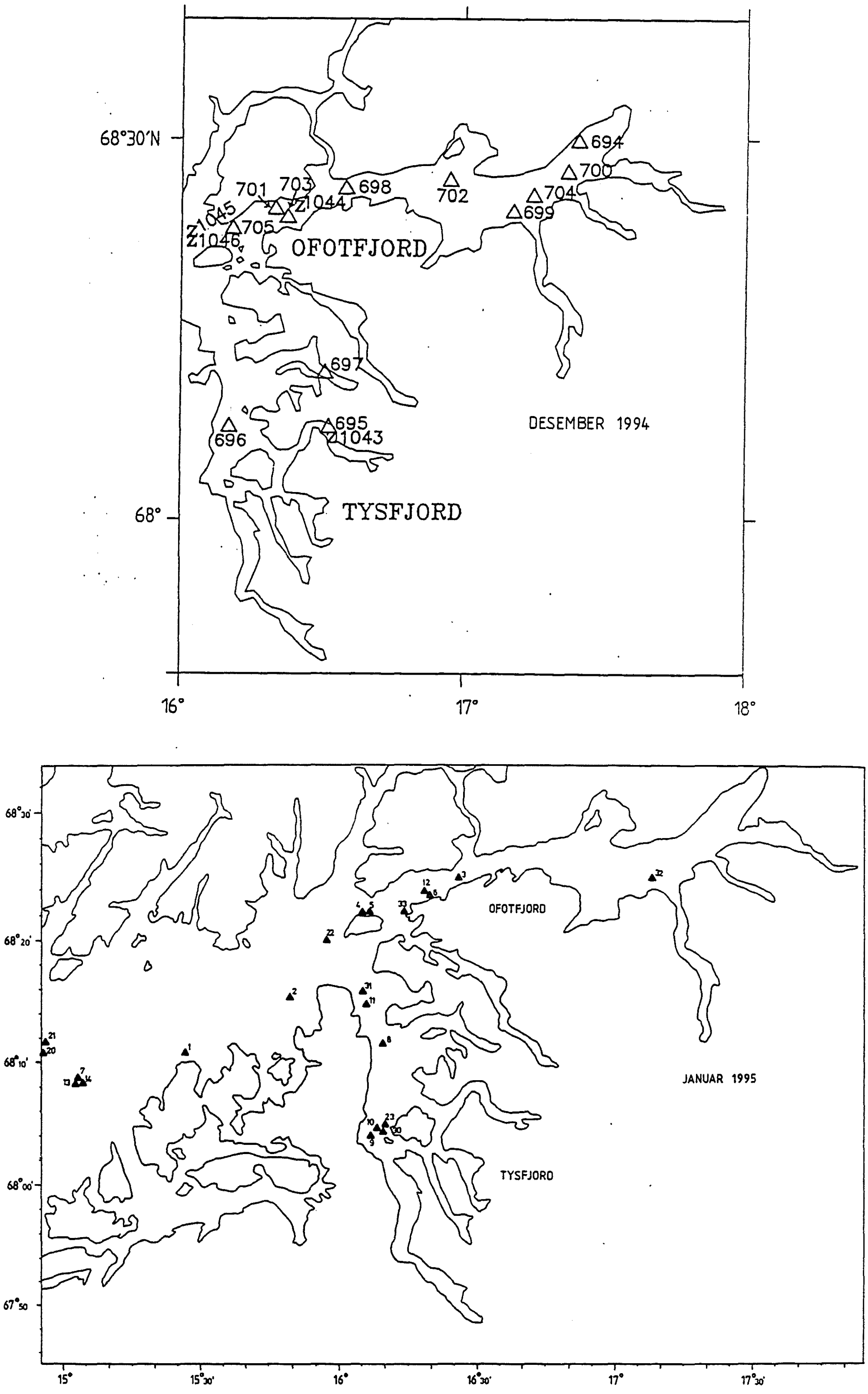


Fig. 5. Locations of pelagic trawl stations during the cruises in December 1994 and January 1995.

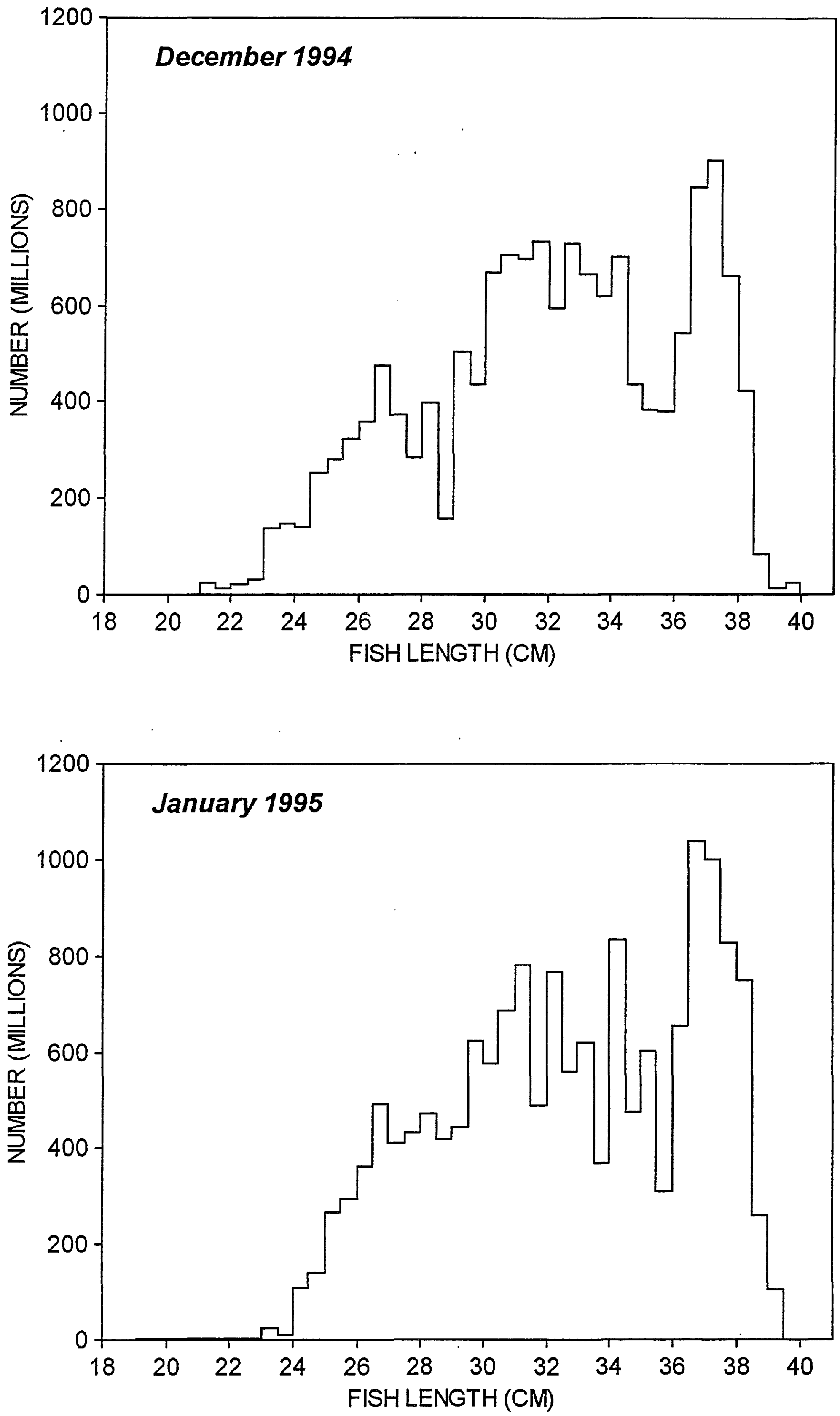


Fig. 6. Composite length frequency distributions for the stock of Norwegian spring spawning herring in December 1994 and January 1995.