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ABUNDANCE ESTIMATION OF HERRING HIBERNATING IN A FJORD

by

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ABSTRACT

A series of acoustic surveys of the adult component of the Norwegian spring-spawning herring was conducted in Ofotfjorden and Tysfjorden in December 1992. Preliminary results are reported. These include compensation for the effect of extinction when estimating mean abundance, and allowance for autocorrelation when estimating associated variance by means of geostatistics.

RESUME: EVALUATION D'ABONDANCE D'UN STOCK HIVERNAL DE HARENG DANS UN FJORD

Une série d'évaluations acoustiques de la composante principale du stock de hareng norvégien frayant au printemps a été effectuée dans Ofotfjorden et Tysfjorden en décembre 1992. Les résultats préliminaires sont donnés. Ils comprennent la compensation de l'effet d'extinction dans l'estimation d'abondance moyenne et la prise en compte de l'autocorrélation dans l'estimation de la variance associée par méthode géostatistique.

INTRODUCTION

In recent years the adult component of Norwegian spring-spawning herring (Clupea harengus) has spent the late autumn - early winter period in the Ofotfjord-Tysfjord system. Since the stock has literally confined itself to a limited geographical region, which is moreover protected from the open ocean, and since the admixture with other species is minimal, conditions for its acoustic surveying must be ideal (Foote 1991). The stock has been surveyed annually in the course of the comprehensive survey of western Norwegian fjords and at other times and places too (Røttingen 1988). However, the vastness of the annual fjord survey has generally precluded spending much time in any one fjord, and the other surveys of herring have been performed at sea over considerably larger areas.

The cruise reported on here is an attempt to remedy this situation, by allowing more time to be spent on surveying, but - importantly - without a formal obligation to perform a survey in the conventional manner. Rather, the aim has been to develop methods and instruments to assist the fishery biologist in surveying this and other stocks.

In fact, the herring stock in Ofotfjorden and Tysfjorden was surveyed, and repeatedly, by means of several experimental designs. The goal here is to describe the various survey grids and respective abundance estimates.

MATERIALS AND METHODS

The primary acoustic measurements on fish were made with the SIMRAD EK500 echo sounder system (Bodholt et al. 1989), operating at 38 kHz but also at other frequencies. Preprocessed values of mean volume backscattering strength were stored by means of the Bergen Echo Integrator (Foote et al. 1991), or BEI, for postprocessing. This included retrieval, display of the data in echograms on a workstation screen, classification of echo traces according to scatterer type, computation of the corresponding area backscattering coefficient, and storage of the results of the interpretation in a database.

Secondary acoustic measurements on standard targets effected a calibration. This was done according to the ICES-recommended procedure (Foote et al. 1987), in advance of the cruise. Conditions were good.

Biological measurements were made at a total of eight pelagic trawl stations, with five performed in Ofotfjorden and three in Tysfjorden. The usual length measurements were made, with smaller samples taken for weight measurement and later determination of fat content.

The platform for the measurements was R/V "JOHAN HJORT". Cruising speed during acoustic surveying in Ofotfjorden was 8 knots, and less in Tysfjorden owing to frequent narrow passages or the presence of gill nets set by local fishermen.

Seven experimental surveys were conducted in Ofotfjorden. Some details of these are given in Table 1. The actual survey grids are shown in Fig. 1. Values of the area backscattering coefficient s_A for herring are displayed at the basic resolution distance of 0.1 nautical miles (NM) by cross bars whose length is proportional to $\log(1+s_A)$. The coverage of the herring stock in Tysfjorden was much less, owing to limitations of time and its apparently weaker strength there. As the data have not yet been analyzed, these are not considered further here.

To lessen the chance of biasing the abundance estimates in survey grids 4 and 6, a variant of each is considered in which the segments between the parallel transects are eliminated. These modified survey grids are denoted 4- and 6-.

Table 1. Some parameters of seven experimental survey grids applied in Ofotfjorden in December 1992.

Survey grid	Start date	Start hour	End date	End hour	Vessel log (NM)	Type
1	6/12	0625	6/12	1746	2215.6-2317.7	Large-scale, slack zigzag, day
2	6/12	1841	7/12	0802	2319.7-2333.4 2349.3-2437.5	Repetition of grid 1 but night
3	7/12	0927	7/12	1547	2451.3-2507.0	Ad-hoc, severely time-limited
4	9/12	1947	10/12	0346	2849.6-2910.2	Equidistant parallel transects
5	10/12	0347	10/12	0736	2910.3-2940.3	Two mid-fjord transects
6	10/12	1906	11/12	0210	2989.7-3044.1	Truncated version of grid 4
7	11/12	0211	11/12	0656	3044.2-3081.9	Zigzag based on grid 6, connecting every other vertex

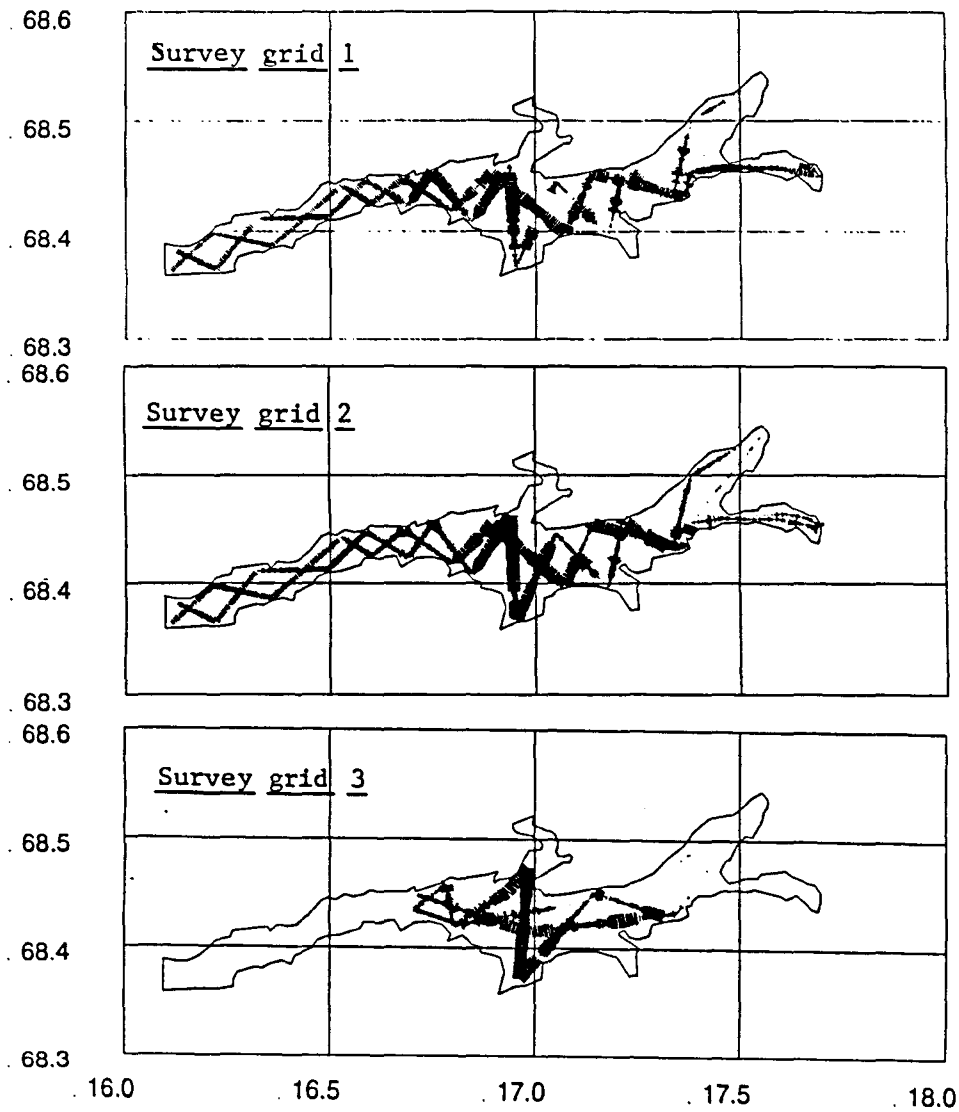

Fig. 1. (First part).

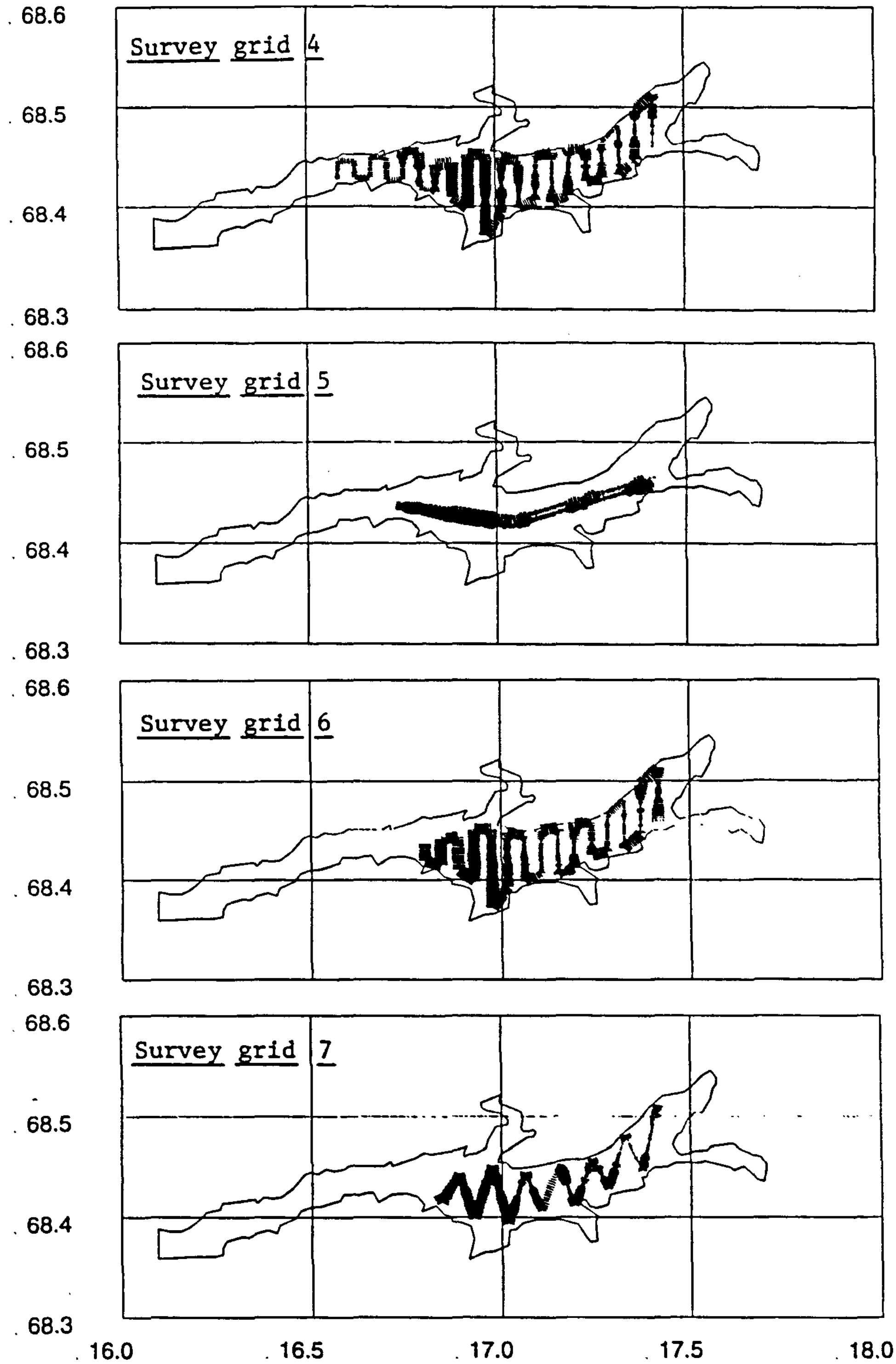

Fig. 1. Seven experimental survey grids applied in Ofotfjorden in December 1992, with values of acoustic density indicated by cross bars of length proportional to $\log(1 + s_A)$. Scales are degrees of latitude north and degrees of longitude east.

DATA ANALYSIS

The three salient parts of this involve correction for extinction, abundance estimation, and variance estimation. A further, hidden component, which is also important, is checking and cross-checking to guarantee the quality of the interpreted values of area backscattering coefficient s_A.

Extinction correction The magnitude of some values of s_A, exceeding 100000 units of square meters of backscattering cross section per square nautical mile, denoted m^2/NM^2, suggests the need to compensate for the effect of extinction. This was done according to the method described by Foote (1990), but for the cumulative echo quantity per 0.1 NM, as resolved in depth in 10-m thick intervals. Briefly, if the result of echo integration over the j-th depth layer $[z_j, z_j+\Delta z_j]$ is described by $s_{a,j}=s_{A,j}/(4\pi 1852^2)$, then the extinction-compensated value is

$$\hat{s}_{a,n} = s_{a,n} \exp[2 \sum_{j=1}^{n-1} \rho_{a,j} \sigma_{e,j}] \quad , \qquad (1a)$$

where $\rho_{a,j}=\rho_{A,j}/1852^2$ is the estimated area fish density over the j-th depth layer, and $\sigma_{e,j}$ is the extinction cross section associated with the scatterers in the j-th layer. The area fish density for this layer is given by

$$\rho_{a,j} = -\frac{1}{2\sigma_{e,j}} \ln [1 - 8\pi \hat{s}_{a,j} \sigma_{e,j} / \sigma_{b,j}] \quad , \qquad (1b)$$

where $\sigma_{b,j}$ is the respective backscattering cross section. Compensation for extinction is effected by employing equations (1a) and (1b) as a recursion, where it is understood that the exponential term in equation (1a) for n=1 is unity. The value of σ_b, assumed constant over depth, is derived from the standard equation for clupeoids (Foote 1987),

$$TS = 20 \log \ell - 71.9 = 10 \log (\sigma_b / 4\pi) \quad , \qquad (2)$$

where TS is the average target strength for a herring of mean length ℓ. Each of three values of the extinction cross section have been examined (Foote et al. 1992), according to the ratio σ_e/σ_b: 1.17, 1.7, and 2.24, which like σ_b is assumed to be constant independent of depth.

Abundance estimation The pattern of coverage in the seven experimental surveys is quite irregular or limited in some instances, for example, survey grids 3 and 5, and more uniform in others, although with potentially significant differences between the zigzag design in survey grids 1, 2 and 7, and the sets of equidistant parallel transects in survey grids 4 and 6. In addition, analysis of the extinction-compensated data with a basic resolution in sailed distance of 0.1 NM and the need to attach a specific geographical coordinate to each suggests the need to perform a preliminary averaging over blocks. This has been done over squares with a side length of 0.2 NM. Averaging of these block-averaged data yields a number which is assumed to represent the sought global average. When divided by the backscattering cross section σ_b, the area density ρ_A results,

$$\rho_A = \bar{s}_A/\sigma_b \quad , \tag{3}$$

for this is just the fundamental equation of echo integration. Multiplication of ρ_A by the total area gives the total number of fish in the delimited area, which is determined by observation of the fish distribution relative to the bottom depth and bottom topography, or accessibility of the fjord area to the fish.

Variance estimation Geostatistics has already exerted its influence in the matter of averaging the extinction-compensated data in small blocks at twice the resolution distance. It offers a consistent method of treating correlation due to sampling in the estimation of variance. The basic formula for the estimation variance is (Matheron 1971, Cressie 1991)

$$\sigma_E^2 = 2\bar{\gamma}_{tv} - \bar{\gamma}_{tt} - \bar{\gamma}_{vv} \quad , \tag{4}$$

where γ denotes the variogram, or expectation of squared differences in values of s_A at different points with respect to the distance between these, $\bar{\gamma}$ is the average of the model of the experimental variogram, where the averaging is performed over two sets of points, designated by the subscript t for transect and v for volume or total area. Each is defined by a finite set of points, the one by the represented intervals of sailed distance, the other by characteristic points of the imposed block grid for averaging s_A-values. The convenient model adopted for use represents γ as the sum of an intrinsic nugget term and a spherical function term (Guillard et al. 1990, Foote and Rivoirard 1992). The nugget term represents a constant variance at all distance lags except at the very sampling point, where it vanishes. Explicitly,

$$\gamma(h) = A_N N(h) + A_S S(h) \quad , \tag{5}$$

where the amplitudes sum to unity, $A_N + A_S = 1$, and $S(h) = 1.5h/a - 0.5(h/a)^3$ for $h \leq a$ and 1 for $h > a$. The quantity a describes the range of the spherical function, which is judged to be the least distance lag beyond which there is no structure. The chosen variogram model parameters are presented in Table 2.

RESULTS

The overall effect of extinction was to reduce the apparent quantity of fish by about 5%, assuming the mean extinction coefficient $\sigma_e = 1.7\sigma_b$. The extinction-compensated values for s_A were used throughout the reported analyses. Combination of the density values after averaging over square blocks of side length 0.2 NM gives the results shown in Table 3.

Table 2. Variogram model parameters for analyzed experimental survey grids in Ofotfjorden.

Survey grid	A_N	A_S	a (NM)
1	0.20	0.80	1.5
2	0.20	0.80	2.4
3	0.11	0.89	2.4
4	0.14	0.86	1.9
4-	0	1.00	2.5
5	0.12	0.88	3.0
6	0.13	0.87	1.8
6-	0	1.00	1.8
7	0.20	0.80	1.8

Table 3. Results for the abundance and associated estimation variance for the experimental survey grids. The standard error of the mean density is included as a statistic without regard to correlations, denoted se.

Survey grid	(NM^2)	n	N(10^9)	σ_E(%)	se(%)
1	103.9	573	1.94	17.6	11.8
2	103.9	608	2.09	14.5	9.2
3	66.9	313	4.16	23.2	12.2
4	71.4	339	3.18	10.5	8.7
4-	71.4	255	2.71	14.3	10.5
5	66.1	159	2.09	35.7	13.6
6	64.7	283	3.92	10.4	7.5
6-	64.7	217	3.17	13.9	9.9
7	64.7	203	2.33	18.2	10.3

DISCUSSION

Abundance estimation

The first survey grid design is based on that used by I. Røttingen in November 1992. It includes the midday period of twilight. The second survey grid design is a repetition of the first, intended to determine whether the first result could be repeated under night-time conditions, which it did.

Clearly the coverage of the third survey grid is poor. Its design was motivated by the desire to learn something more about the spatial structure, as suggested by the first two survey grids, but in a rather limited time period dictated by a mid-cruise stop in Narvik. The coverage of the fifth survey grid is also poor. Its choice derived from a frequently used minimalist approach to surveying, when there is only time to sail to the end of a fjord and out again, without crisscrossing. The poor coverage that is evident from Fig. 1 is reflected in both cases in the quite large estimates of σ_E in Table 3. Consequently, neither of these survey grids is interesting for further discussion here.

The fourth survey grid was designed by G. A. Rose based on the fish distribution observed in the preceding surveys. Both survey grids 4 and 6 give relatively high abundance estimates, which may be attributed to a skewed fish distribution, with tendency toward higher concentrations along the north side of the fjord. By eliminating the segments of the two grids that link the parallel transects, it is believed that biasing is avoided and more realistic estimates of abundance are obtained. These modified survey grids are designated 4- and 6-.

Survey grid 7, surprisingly perhaps, gives an estimate that is roughly midway between the rather low estimates of the first two surveys and substantially higher estimates of survey grids 4- and 6-.

Variance estimation

Repeated surveying of the herring in Ofotfjorden permits independent estimation of a variance. Based on survey grids 1, 2, 4-, 6- and 7, the result is that the corresponding standard deviation is 22.3% relative to the mean, since the overall average is $(2.45 \pm 0.50)\,10^9$. This number is higher than the estimates for σ_E in Table 3 for the particular grids.

It is easy to find possible explanations for this discrepancy. One lies in the nature of σ_E^2. This depends on the degree of sampling of the fish distribution by transects in relation to the area to be covered and the covariance properties of the subject fish distribution. Insofar as the sampling is wanting, i.e., is non-representative, a condition for computing σ_E^2 may be violated. Use of alternate variogram model parameters, which is allowed because of the subjective nature of their determination, has however failed to significantly change the σ_E-estimate.

Another explanation may lie in the backscattering cross section σ_b in equation (3). Any error in this will have a first-order effect on ρ_A, hence on the overall abundance. It is not hard to imagine dependences of σ_b that are being neglected, for example, those of depth or lighting, not to mention the known one of physiological state through fat content (Ona 1990). It is indeed hard to imagine equation (2) applying in any arbitrary situation, yet that is precisely what is done here, to a series of successive surveys. Even if equation (2) were applicable, a nominal range of variation in this would boost the overall estimation error.

It is observed that the estimate for σ_E in Table 3 is larger than the standard error of the mean, which is a pure statistic that regards each measurement s_A to be an independent estimate of the mean. This result is due to the field size being much larger than the range of the data (Petitgas and Rivoirard 1991).

Another way to compute the estimation variance for survey grids 4- and 6- would be to consider the result for each transect as a sampling unit. A geostatistical analysis could then be conducted on the set of transect results in one dimension (Petitgas 1990, 1991). This has not yet been done.

Summary estimates

All in all, survey grids 4- and 6- seem most applicable for abundance estimation of the herring stock in Ofotfjorden, if only providing partial coverage. The mean of the respective results is 2.93 10^9 animals, with estimated variance of about 20%.

Structural analysis

Interestingly, the variograms for survey grids 1 and 2 reflect the basic day-night differences already observed for 0-group herring (Foote and Rivoirard 1992). The daytime structure is more clumped and variable than the night-time structure, when the fish tend to be more uniformly distributed. This is seen quantitatively through the variogram model parameters in Table 2, with longer range for the night-time data.

Additional analyses

It is apparent from Fig. 1 that survey grids 1 and 2 achieve the most comprehensive coverage of Ofotfjorden. These suffer inevitably from a rather weak coverage of the region of highest fish concentration. Survey grids 4 and 6, specifically their derivatives 4- and 6-, represent a second-tiered coverage of the fjord region of highest concentration. The results from analysis of grids 4- and 6- should be supplemented by results from the other fjord areas that are covered by grids 1 and 2. Only a rather small difference, however, is expected. Grid 7 should be similarly treated. Comparison of the results through a repeated-survey estimate of variance will yield new abundance and variance estimates.

The adult component of the stock of Norwegian spring-spawning herring is also distributed in Tysfjord, whose data have not been analyzed. The fish abundance in Tysfjord should be computed and presented with the Ofotfjord data.

Two related analyses of some interest would be an estimation based on the pooled data and a study of data from different survey grids in the vicinity of a common point. It would be valuable to know just how comparable the so-called point or near-point measurements are, whether they are consistent with the variograms, whether a stability is observed over the duration of the cruise.

Multiple-frequency data

The present work has reported on measurements at 38 kHz. Data were also collected simultaneously at 18, 120 and 200 kHz for much of the time. In a number of instances these are sufficient to form an abundance estimate. Although the backscattering cross section of herring at frequencies other than 38 kHz is poorly known if at all, the numbers themselves show a stability to within ±10% of the respective estimate at 38 kHz, using the values for σ_b determined by Foote et al. (1993). The numbers are thus not independent, hence the present emphasis on their relative stability.

The potential for using multiple-frequency data in ordinary echo integration surveys can hardly be overestimated. These can offer (1) valuable redundance in the usual single-frequency operation, (2) the possibility of finding errors by checking data across-frequency, and (3) increased power of discrimination of scatterers, especially when mixed in species or size. An additional attraction of multi-frequency data would be (4) use in specifying the *in situ* target strength at any survey frequency, as by application of an acoustic scattering model to simultaneous measurements at different frequencies.

Future work

The described additional analyses should be performed. In cruises planned for December 1993 and January 1994, the problem of consistency in estimates from coverage to coverage should be addressed. Obtaining realistic measures of certainty should be a goal of abundance estimation.

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