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How many trawl hauls, and how many fish from each haul are needed to obtain a given precision in the age structure estimate for Norwegian spring spawning herring? A bootstrap approach

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Abstract

The Norwegian spring spawning herring is assessed each year from acoustic surveys. The age structure in the stock is estimated from trawl samples. Typically, about 10 trawl samples are taken per survey, and 100 fish from each sample are age measured. The uncertainty in the age structure estimate depends both on the number of trawl hauls and the number of fish for which the age is measured within each haul. The same is true for the length structure. Length is much easier to measure than age, and in the Vestfjorden survey in December 2002, more than 6000 fish distributed on 72 trawl samples were length measured, making possible the investigation undertaken in this paper, where the bootstrap is applied to estimate the number of hauls/fish needed to obtain a given precision in the length distribution. It is reasonable to believe that the precision in the age distribution will depend on the number of fish/hauls in the same way. The sampling intensity needed to obtain a given CV for the most abundant length groups was much lower than for the less abundant length groups. In terms of standard errors it was the other way round. A doubling of number of fish measured per haul from 1 to 2 allowed for about 50% decrease in the number of hauls needed to keep the same precision. A doubling from 128 to 256 allowed for about 10% decrease.

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Introduction

When the abundance of Norwegian spring spawning herring is assessed, an estimate of the total biomass is obtained from acoustic data, and the age structure in the stock is estimated from trawl samples. The uncertainty in the final estimate of numbers per age has many components: uncertainty in the acoustic echo abundance due to vessel avoidance, shadowing, and depth dependent target strength, uncertainty in age structure due to age reading and sampling errors, and uncertainty in both abundance and age structure due to limited spatial-temporal coverage. This paper focuses on the trawl sampling: how many trawl hauls are needed, and for how many fish from each haul do we need to know the age to obtain a given precision in the age structure? However, the analysis is done in terms of length rather than age because a much more extensive data material is available on length. The length groups are defined so that they roughly correspond to age groups, and it seems reasonable to believe that if all the length measured fish also were age measured, the uncertainty in the age structure would have depended on the sampling rate in approximately the same way as the uncertainty in the length structure does.

Materials and methods

Data

The data were collected in the Vestfjorden system in December 2002 (Fig 1) using a multi-sampler equipment allowing for sampling of three batches of fish at separate depths during one towing operation (Engås et al 1997). The aim was to get catches from the top, middle and bottom area of the schools by aid of echograms. A total of 72 batches were sampled. Typically, 100 fish were sampled at random from each batch and length measured, but some batches contained less than 100 fish (Fig 1b), so totally 6161 fish were measured. The batches (serial numbers 32538-32610 in the Institute of marine research database) were distributed on area, day/night and depth according to Table 1 and Figure 1). Since measuring age is much more expensive than measuring length, only 528 fish from 3 hauls were age measured, and therefore we have used length data rather than age data in this paper. The data are described in more detail in Mazzi and Høst (2003). In the following, a haul means a batch.

The 528 age measured fish were used to obtain a rough correspondence between age and length, and the length groups were defined according to Table 2 (same as Table 3.2 in Mazzi and Høst 2003). In the sequel the length groups are referred to using their corresponding age names (age 1, age 2, etc.).

Methods

To check for effects of depth, time of day, and region on the length distribution, estimates of the relative length distribution (proportions in each length group) were calculated stratified on these factors using the bootstrap.

To investigate how the precision in the length structure estimate depends on the number of hauls and the number of fish measured in each haul, the fraction of fish in each length group was estimated using the following algorithm, exemplified by the estimate of the fraction of length group corresponding to 4-year-old fish:

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do $n$ = 1, 2, 4, 8, …, 256 (number of hauls sampled)
do $k$ = 1, 2, 4, …, 256 (number of fish sampled from each haul)
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    do $i$ = 1, $m$ (number of bootstrap replicas)
            draw $n$ hauls at random with replacement from the 72 hauls
            draw $k$ fish at random with replacement from each haul
            let $a^{*}_{ikn}$ = $kn$ = the total number of fish in the $n$ hauls
            let $a^{4*}_{ikn}$ = the total number of fish corresponding to age 4 in the $n$ hauls
        let $p^{4*}_{ikn} = a^{4*}_{ikn} / a^{*}_{ikn}$
        end do
    from the bootstrapped fractions $p^{4*}_{1kn}, p^{4*}_{2kn}, ..., p^{4*}_{mkn}$, calculate
          o the mean (proportion) $\hat{p}^{4*}_{kn} = \frac{1}{m}\sum_{i=1}^{m} p^{4*}_{ikn}$
          o the standard error of the mean $se\left(\hat{p}^{4*}_{kn}\right) = \frac{1}{m-1}\sum_{i=1}^{m}\left(p^{4*}_{ikn} - \hat{p}^{4*}_{kn}\right)^{2}$
          o the confidence interval $\left[p^{4*}_{(m*0.025)kn} \ , \ p^{4*}_{(m*0.975)kn}\right]$ for the mean, where $p^{4*}_{(1)kn}, p^{4*}_{(2)kn}, ..., p^{4*}_{(m)kn}$ is the ordered sequence of $p^{4*}_{1kn}, p^{4*}_{2kn}, ..., p^{4*}_{mkn}$, so that $p^{4*}_{(i)kn} \le p^{4*}_{(i+1)kn}, \ i = 1, ..., m-1$
          o the CV $se\left(\hat{p}^{4*}_{kn}\right) / \hat{p}^{4*}_{kn}$
    end do
end do
```

The same calculations were done for each length group and for the mean length. To investigate the relative effect of number of hauls and number of fish measured at each haul, the length distribution was calculated using bootstrap samples of n = 1, 2, 4, 8, …, 256 hauls and k=1, 2, 4, …, 256 fish.

Below a "k-fish-haul" means a haul where k fish are measured. To estimate the number of k-fish-hauls (m_k) needed to get the estimates within a given precision, the CV was modelled as a function of number of hauls as

(1) $CV(m_k) = a_k m_k^{-1/2}$,

and the coefficient a_k was estimated from the bootstrapped CVs. To obtain a given CV, say CV_0, we then need

(2) $m_k = a_k^{2}\, CV_0^{-2}$

hauls. To obtain the same precision when doubling the number of fish measured at each haul, we have that

(3) $CV(m_k) = CV(m_{2k}) \Rightarrow a_k m_k^{-1/2} = a_{2k} m_{2k}^{-1/2} \Rightarrow m_{2k} = m_k a_{2k}^{2}\, a_k^{-2}$

where m_{2k} is the number of hauls needed when k is increased to $2k$.

The coefficients a_k, k=1, 2, 4, …, 256, were estimated by fitting (1) to CV's calculated from 1000 bootstrap replicas.

Results

Figure 2 shows that there is a tendency of getting relatively more old fish (9+) and less young fish (8-) in deep water than at shallow and medium depths in the Tysfjord/Vestfjorden region, and for age 10 the difference is significant. For the Barøya/Ofotfjord region there is no systematic trend. No day/night effect is discernable. However, there is a highly significant region effect, with high proportions of 3, 4 and 5 year old fish in Barøya and Ofotfjord, and high proportions of 10 year old fish and older in Vestfjorden, Tysfjord and Ofotfjord.

Figure 3 and 4 show how the width of the confidence intervals and the CV decrease as the number of hauls and the number of fish measured increase. Generally, the confidence intervals are widest for the length groups with the highest proportions of fish, whereas the CV is smallest for these groups. The fit of eq. 1 was quite good (Fig. 5)

Figure 6 a-b) shows for each length group the number of hauls (m_k) needed to obtain a given CV as a function of the number of fish measured at each station. Eq. 2 was used to calculate m_k, which is much higher for the least abundant length groups. The number of k-fish-hauls needed to get a given CV for a given length group is of course higher for small values of k than for large values of k. However, the total number of measured fish that we need is highest when k is high (Fig. 6 c). This means that a doubling of the number of fish measured within each haul does not generally allow for a halving of the number of hauls needed to keep the same precision. If k is low at the outset, this is in fact the case (a doubling of k from 1 to 2 allows for about 50% reduction in the number of hauls needed; Fig 6 d), but if k is originally high it is not (a doubling from 128 to 256 only allows for about 10% reduction; Figure 6 d). The allowed reduction is smallest for the most abundant length groups. For the mean length, the gain by doubling the number of fish measured at each haul is generally smaller than for the length proportions.

Since the length structure in the Vestfjorden/Tysfjord area differed somewhat from that in the Ofotfjord/Barøya area (Fig. 2), we also did the same analysis using only data from the Vestfjorden/Tysfjord area, but the results were very similar (Fig. 7).

Discussion

The question posed in the title concerns the age structure for Norwegian herring. Since relatively few age-measured fish are available, we have used length-measured fish in the analysis, grouped in length intervals that approximately reflect the age structure of the stock. We assume that if the age was known for all the length-measured fish and used in the analysis instead of length, the trends in the results would have been the same. Therefore, we discuss the results in terms of age structure instead of length structure.

Unfortunately, there is no simple answer to the question of how many trawl hauls and how many fish from each haul we need to obtain a given precision in the age structure estimate for Norwegian spring spawning herring. Firstly, the answer depends on the uncertainty measure used (e.g. standard error or CV). Secondly, the answer is different for different age groups, with a lower sampling effort needed to obtain a given CV for the most abundant age groups than for the least abundant age groups (whereas the opposite is the case to obtain a given standard error). Thirdly, the effect of increasing the number of measured fish per haul on the number of hauls needed to obtain the same precision depends on the number of fish measured at the outset. If originally one or two fish is measured per haul, a doubling of this number allows for 50% reduction in the number of hauls needed, whereas if the number of measured fish is increased from 100 fish to 200 fish per haul, this only allows for a 10% reduction in the number of hauls needed to obtain the same precision. This can probably be explained by the phenomenon that fish caught together tends to have more similar characteristics than those in the entire population (Pennington et al 2001). Thus, there is more information in 1000 fish distributed on 10 trawl hauls than in 1000 fish distributed on 5 trawl hauls. However, 10 fish distributed on 5 trawl hauls give approximately the same information as 10 fish distributed on 10 trawl hauls. This is because the within-haul variation is much better described by 2 fish than by 1 fish, whereas the decrease in within-haul uncertainty obtained by increasing the number of fish measured in each haul from 100 to 200 is small compared to the between-haul variance.

In a survey situation, a limited effort is available, and the question is how this should be distributed on trawl sampling (necessary for obtaining the age structure) and acoustic data collection (necessary for obtaining the total abundance). It should in principle be possible to find an optimal effort distribution that minimize some uncertainty measure like

$$\sigma_{age} = \sqrt{\sum_a \sigma_a^2}; \quad \sigma_a = \mathrm{sd}(\hat{N}_a)$$

where $\hat{N}_a$ is the abundance-at-age estimate for age *a* (Aldrin et al 2006).

Acknowledgements

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Table 1. Number of hauls distributed on area, day/night and depth. Each cell shows the number of day hauls + night hauls for a given area and depth category.

Area	**deep**	**medium**	**shallow**	**total**
Vestfjorden	3 + 5 = 8	3 + 5 = 8	3 + 4 = 7	9 + 14 = 23
Tysfjord	1 + 6 = 7	1 + 4 = 5	0 + 4 = 4	2 + 14 = 16
Barøya	5 + 7 = 12	4 + 3 = 7	4 + 4 = 8	13 +14 = 27
Ofotfjord	1 + 1 = 2	1 + 1 = 2	0 + 1 = 1	2 + 3 = 5
Others	0 + 1 = 1	0 + 0 = 0	0 + 0 = 0	0 + 1 = 1
Total	10 + 20 = 30	9 + 13 = 22	7 + 13 = 20	26 + 46 = 72

Table 2. Definition of length groups in terms of approximate age.

Length (mm)	**125-229**	**230-269**	**270-289**	**295-319**	**320-329**	**330-339**	**340-344**	**345-349**	**350-359**	**360-364**	**365-369**	**370-374**	**375-400**
Age	1	2	3	4	5	6	8	9	10	12	13	15	17

Table 3. Number of hauls in which the various length groups (in terms of approximate age) are represented.

age1	**age2**	**age3**	**age4**	**age5**	**age6**	**age8**	**age9**	**age10**	**age12**	**age13**	**age15**	**age17**
18	15	44	70	65	71	69	71	70	72	56	44	49

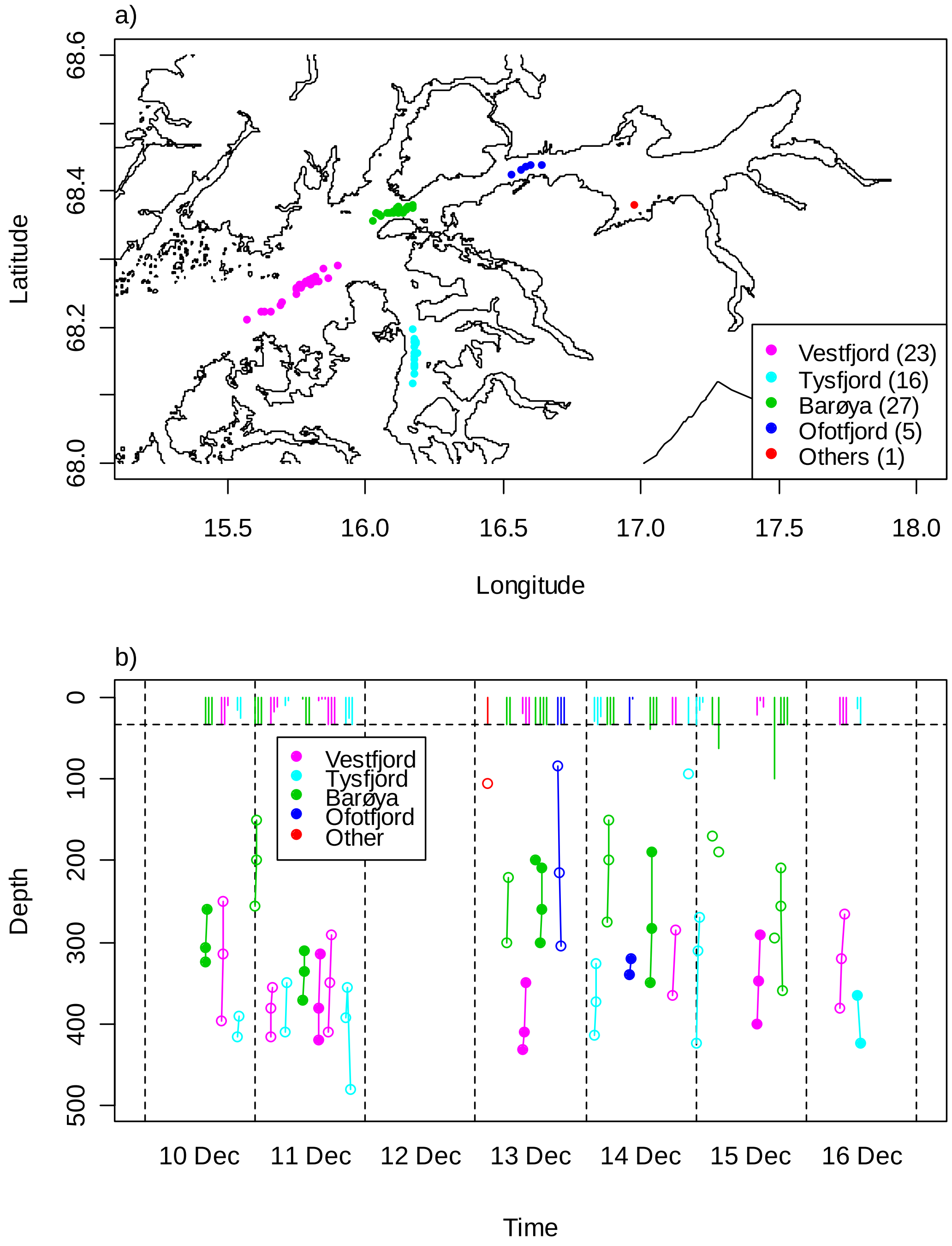

Figure 1. a) Map of sampling locations. b) Depth and time at which the trawl stations were taken. Stations connected with lines were taken during the same towing operation. Stations drawn with open circles are defined as night stations. The bars at the top indicate number of fish sampled at each trawl station, divided by 3 (the dotted line indicates 100 fish sampled).

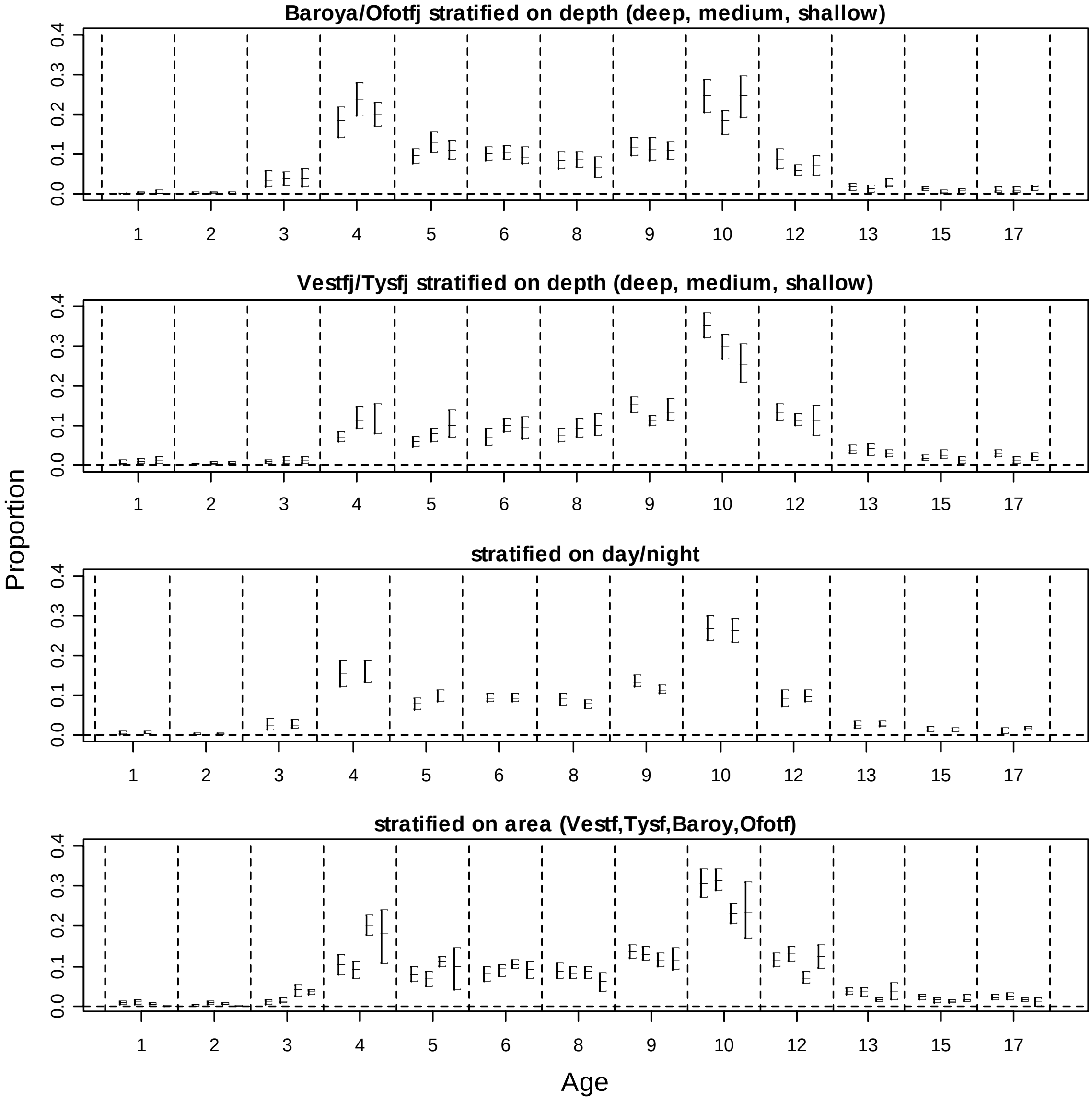

Figure 2. Estimated proportions of fish in different length groups, stratified on depth, day/night and region, with 95 % confidence intervals based on 1000 bootstrap replicas. All hauls for each stratum are used (see Table 1 for number of hauls).

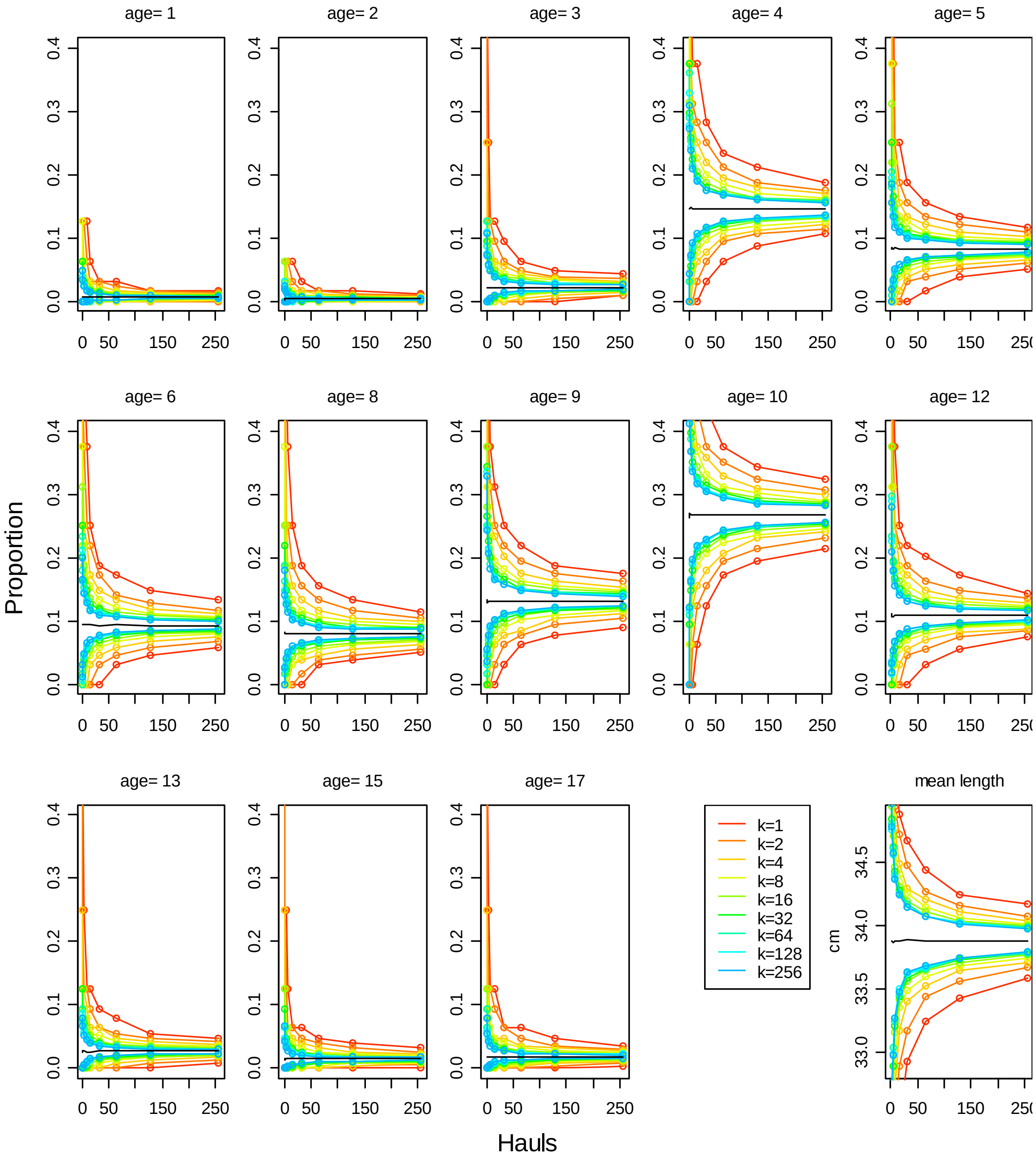

Figure 3. Uncertainty (bootstrapped 95 % confidence intervals) in the estimated proportions of fish in different length groups, and of mean fish length, as a function of number of hauls (1,2,4,…,256), and number of fish measured in each haul. The results are based on 1000 bootstrap replicas.

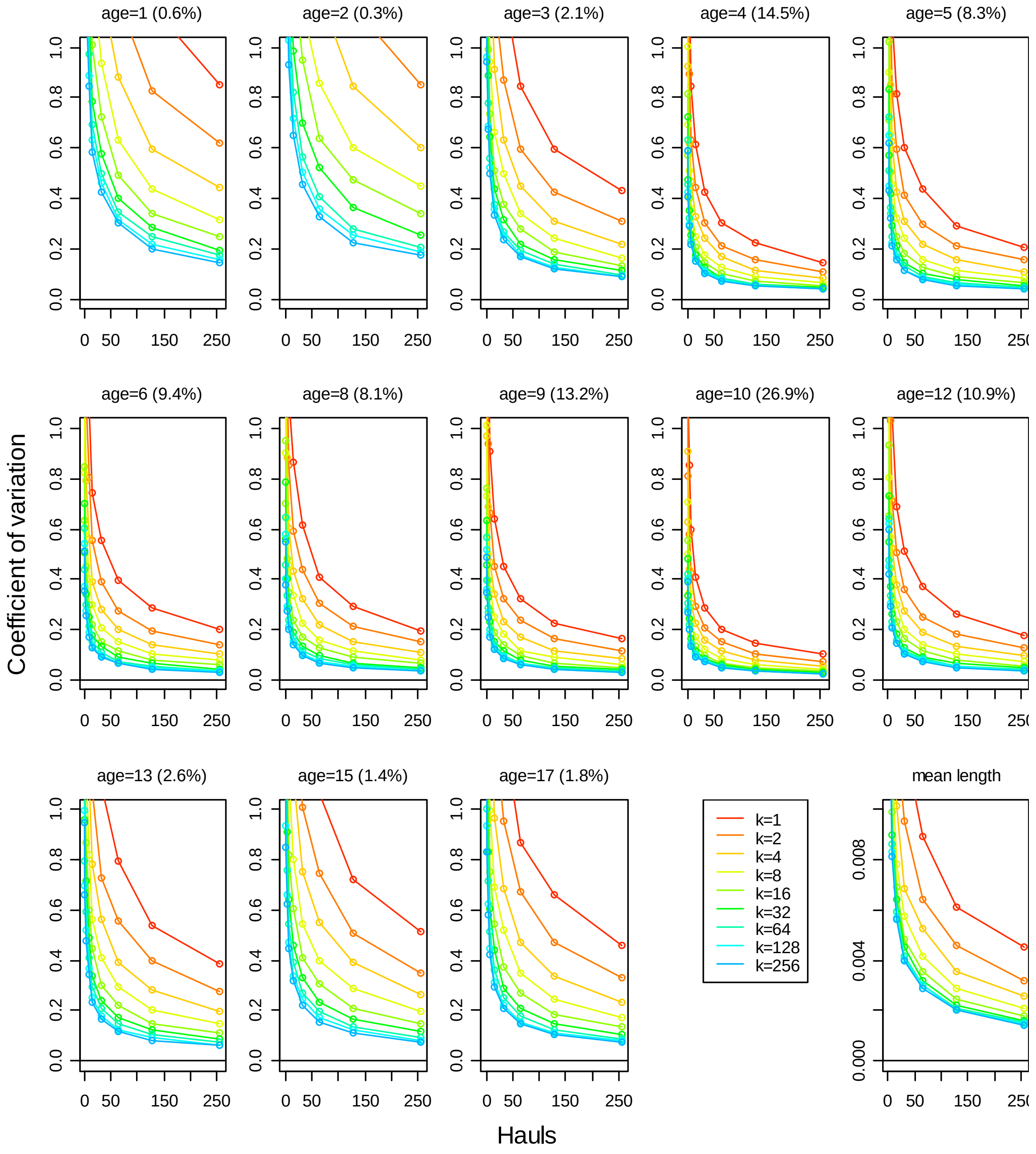

Figure 4. Bootstrapped CV of the proportions and mean length in Figure 2, as a function of number of hauls, and number of fish measured in each haul, based on 1000 bootstrap replicas. The proportion of fish in each length group is given in parentheses.

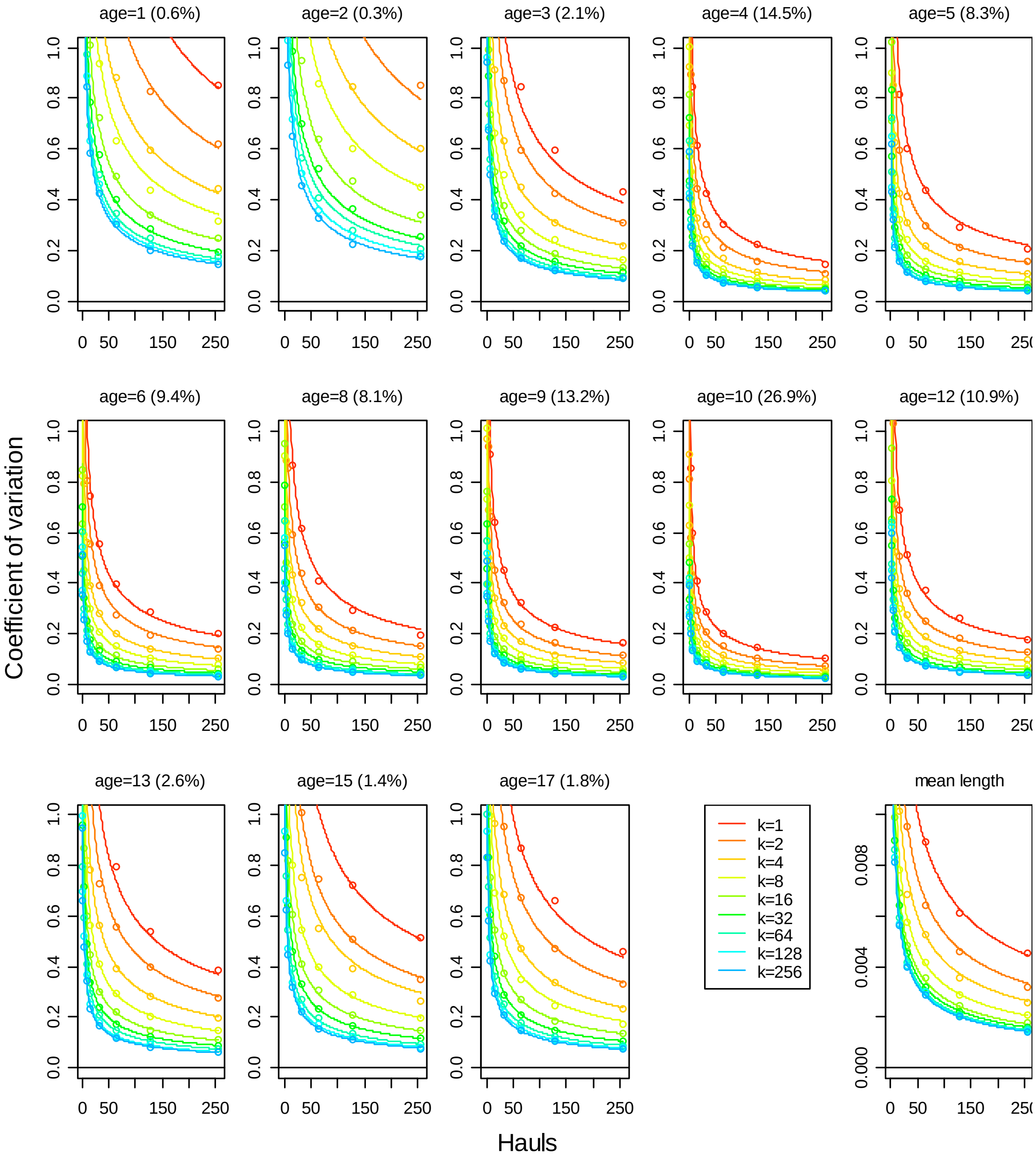

Figure 5. Points: bootstrapped CV of the proportions and mean length in Figure 2, as a function of number of hauls, and number of fish measured in each haul, based on 1000 bootstrap replicas. The proportion of fish in each length group is given in parentheses. Lines: eq. 1 fitted to the data.

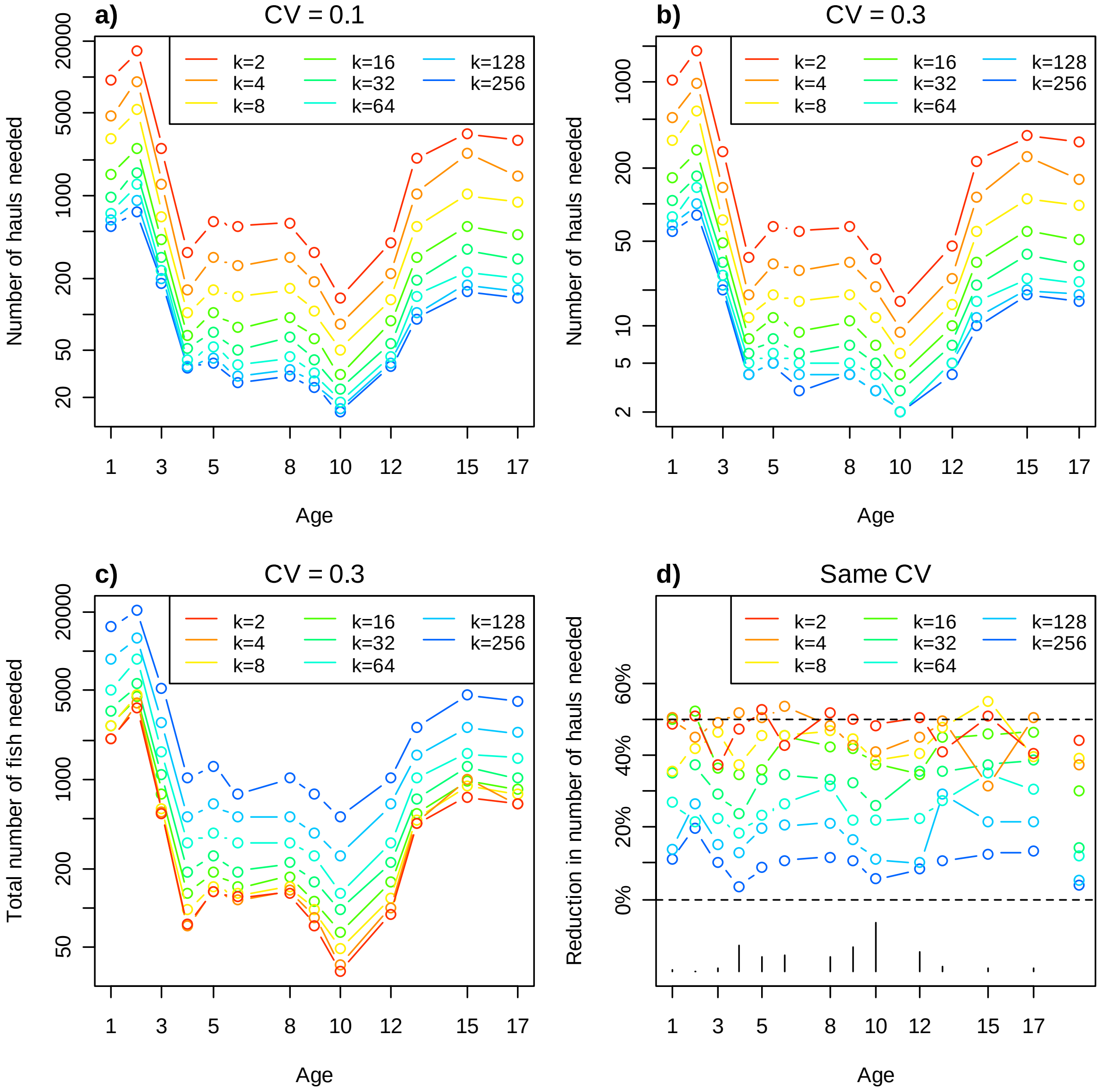

Figure 6. **a)** and **b)**: The number of hauls needed to obtain a CV of 0.1 and 0.3, respectively, when *k* fish are measured at each haul. **c):** The total number of fish needed to obtain a CV of 0.3 when *k* fish are measured at each haul (*k* x number of hauls in b)). **d):** The reduction in number of hauls needed to obtain the same precision when the number of fish measured per haul is doubled from *k*/2 to *k*. The bars at the bottom of the figure indicate the proportion of fish in each length group. The rightmost points are for the mean length.

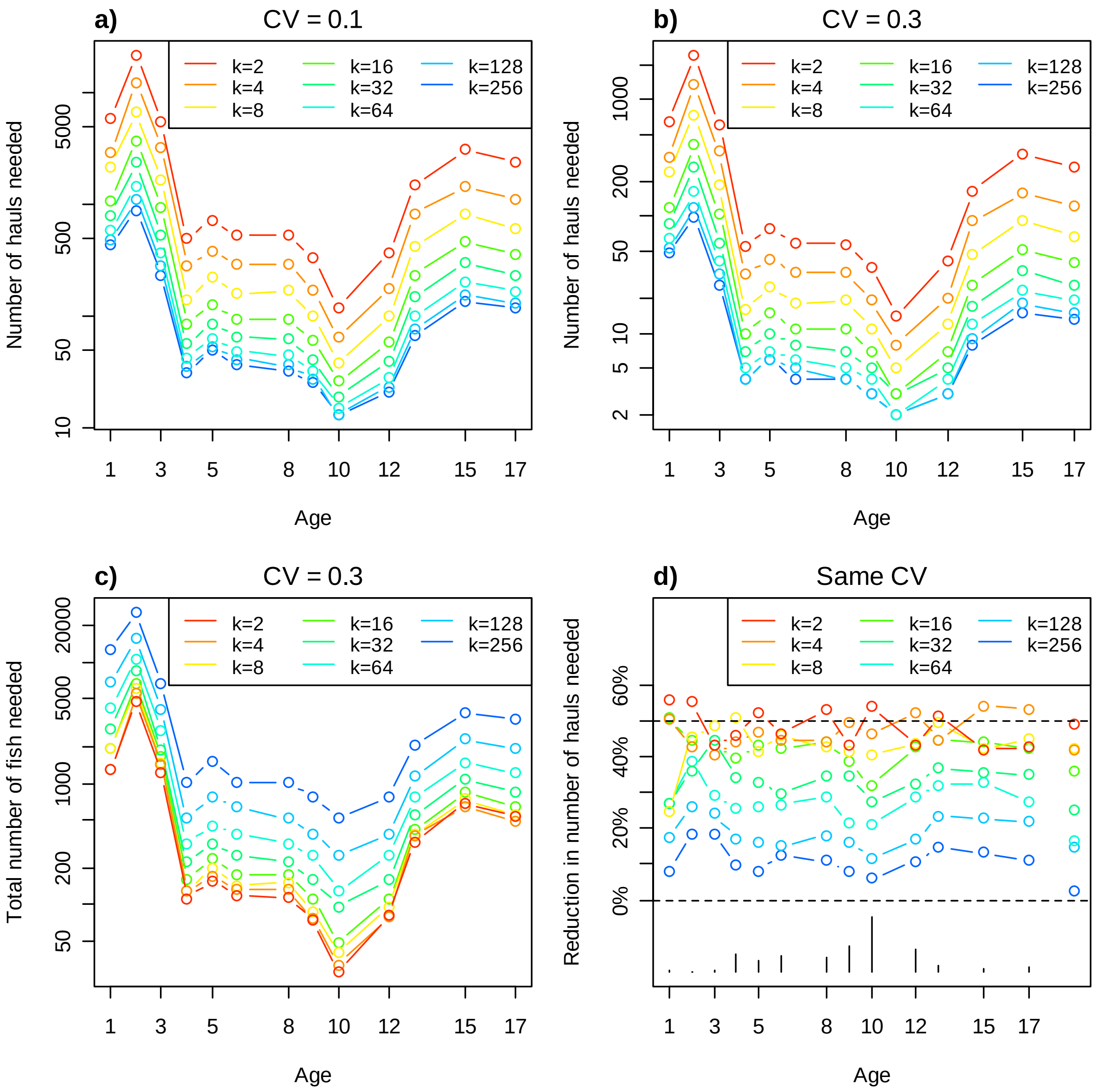

Figure 7. Same as Figure 6, but only data from the Vestfjorden/Tysfjord area were used.