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Review Article

Evaluation of sampling strategies for age determination of cod (*Gadus morhua*) sampled at the North Sea International Bottom Trawl Survey

N. O. A. S. Jourdain [1]*, O. Breivik[2], E. Fuglebakk[1], S. Aanes[2], and J. H. Vølstad[1]

[1]*Institute of Marine Research, Fisheries Dynamics, P.O. Box 1870 Nordnes, N-5817 Bergen, Norway*
[2]*Norwegian Computing Center, P.O. Box 114 Blindern, N-0314 Oslo, Norway*

**Corresponding author: tel: +4747483234; e-mail: jourdain.natoya@hi.no.*

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The North Sea cod stock assessment is based on indices of abundance-at-age from fishery-independent bottom trawl surveys. The age structure of the catch is estimated by sampling fish for otoliths collection in a length-stratified manner from trawl hauls. Since age determination of fish is costly and time consuming, only a fraction of fish is sampled for age from a larger sample of the length distribution and an age–length key (ALK) is then used to obtain the age distribution. In this study, we evaluate ALK estimators for calculating the indices of abundance-at-age, with and without the assumption of constant age–length structures over relatively large areas. We show that the ALK estimators give similar point estimates of abundance-at-age and yield similar performance with respect to precision. We also quantify the uncertainty of indices of abundance and examine the effect of reducing the number of fish sampled for age determination on precision. For various subsampling strategies of otoliths collection, we show that one fish per 5-cm-length group width per trawl haul is sufficient and the total number of fish subsampled for age from trawl surveys could be reduced by at least half (50%) without appreciable loss in precision.

Keywords: abundance-at-age estimation, fishery, otolith sampling, uncertainty

Introduction

Fish stock assessments are used by fishery managers for making management decisions regarding catch quotas. These assessments provide fundamental information about the status of the stock, for instance, whether the stock is increasing and support for increased levels of harvest should be given, or whether the stock is decreasing and stricter control on harvest should be implemented (Bonfil, 2005, pp 6–14). Associated with the parameters used in the fish stock assessment are their uncertainties, which can arise from many sources including natural variability, estimation procedures and statistical fitting, sampling errors and biases in data collection, and incomplete, or less than ideal quality of, data sets (Bonfil, 2005, p. 8). These uncertainties should not be ignored when formulating management policies (Ludwig and Walters, 1981; Berg *et al.*, 2014). Within fisheries research, multi-stage sampling is generally used to obtain data on fish stocks to determine the estimates of parameters such as abundance-at-age. While these sampling designs allow the estimation of variability at different scales within strata (e.g. habitats) (Barnes, 1991, p. 44), Schweigert and Sibert (1983) showed that careful consideration of the number of hierarchical levels is required when applying multi-stage sampling designs over large areas as the effect on the variance could be substantial. Furthermore, if all levels of the multi-stage sampling design are not considered in the estimation process, bias in estimated paramters could be introduced and, the effect on the variance of estimated parameters could be substantial due to clustering effect (Pennington and Volstad, 1994; Lehtonen and Pahkinen, 2004; Nelson, 2014; Aanes and Vølstad, 2015).

The North Sea International Bottom Trawl Survey (IBTS), coordinated by the International Council for the Exploration of the Sea (ICES), is an example where multi-stage sampling is employed to provide information on the seasonal distribution of fish stocks and to determine abundance-at-age indices and their uncertainties. These indices are estimated using data obtained from a stratified semi-random sampling design of primary sampling units, known as trawl hauls, taken within ICES statistical rectangles (≈30 × 30 nautical miles) and ICES round fish areas (RFAs)—each of which is a unique combination of these statistical rectangles (ICES, 2018a, b). Within each strata (rectangles and RFAs), there exists a list of a large number of trawlable locations that could be sampled, but not all possible locations within a strata have an equal chance of being sampled. An assessment of the precision of estimated abundance-at-age indices of the North Sea fish stocks is also provided by ICES, but the approach used to determine precision does not account for the multi-stage sampling design of the North Sea IBTS (ICES, 2006). There are two separate stages for generating indices of abundance-at-age from the North Sea IBTS. The first stage consists of calculating indices per *length* group, which are obtained by trawling in a stratified manner, sorting the catch by taxa and taking the biological measurement of the sorted catch. Then, that knowledge is transformed into indices with respect to age. The latter part is achieved with an age–length key (ALK) (Fridriksson, 1934; Aanes and Vølstad, 2015), which is constructed by subsampling otoliths from fish for age determination in a length-stratified manner from each haul and/or RFA. Subsampling of otoliths for age determination is quite extensive for both demersal and pelagic species. For cod (*Gadus morhua*), in particular, otoliths from a subsample of *one* fish per 1-cm-length group width are collected from a larger length sample of ∼100 cod per trawl haul. Since these fish are caught in clusters, their ages are more likely to be similar than those in the entire population and, hence, intra-cluster correlation is positive. Because of this intra-cluster correlation, the additional information obtained by taking more samples will decrease with the sample size (Pennington and Volstad, 1994; Aanes and Vølstad, 2015; Francis, 2017). The typical IBTS strategy for age sampling from 1991 to 2017 was quota sampling. For cod, eight age samples per 1-cm-length group width within an RFA were taken. This sampling strategy is not necessarily representative of the population as the inclusion probabilities of fish in the samples are unknown and since quotas could be reached before the entire survey area is covered.

Given the potential biases associated with the historical quota sampling, we determine the precision of estimates of relative abundance-at-age of the North Sea IBTS cod (*G. morhua*) by applying two different ALK estimators. We also focus on the spatial variation in the ALK. Up to 2014, the North Sea IBTS index used in ICES stock assessments was calculated using an ALK that implicitly was assumed to be constant within RFAs (ICES, 2006). From 2015, ICES has employed a spatial ALK method (Berg *et al.*, 2014) to estimate the abundance-at-age of several target species, including cod, that are used in stock assessment, but the estimates published in ICES database for trawl surveys (DATRAS, https://datras.ices.dk) are computed using the standard approach that assumes constant ALKs within RFAs. A comparison of this spatial ALK methodology with the standard approach of estimating ALKs that are constant within RFAs showed consistency in estimated survey indices for the North Sea cod (ICES, 2015b, p. 21; ICES, 2017b, pp. 79–81). Here, we propose a design-based ALK estimator that accounts for spatial variation of the age–length structure and compare this with the standard approach used by ICES for estimating ALKs. We assume simple random sampling of trawl locations within each strata as in Berg *et al.* (2014) and Moriarty *et al.* (2018). We also propose variance estimators for the North Sea abundance index that consider the multi-stage sampling design of the North Sea IBTS. In addition, because the age determination of fish is time consuming, we examine whether the number of fish aged from each haul could be reduced without significantly reducing the precision of the estimates. We investigate the effect on estimated precision by using simulations to sample *one* fish randomly from various length group widths (e.g. 1, 2, and 3 cm) and by fixing a length group (e.g. 5 cm) and sampling various numbers of fish (e.g. 1, 2, and 3) randomly for age determination. We also mimick a sampling procedure of the North Sea IBTS with fewer (or more) primary sampling units to evaluate the effect on relative abundance and estimation precision.

Material and methods

Data

The data set consists of 7 years (1997–1999 and 2015–2018) of quarter 1 (Q1) and quarter 3 (Q3) trawl survey data for cod from the North Sea IBTS, which is obtained from the DATRAS database (https://datras.ices.dk). These years are chosen for three reasons. First, in the year 2018, new sampling procedures proposed by ICES for the collection of otoliths for age determination were introduced in the surveys. Second, the years 2015–2018 provide extensive sample data with quarterly sampling effort varying between 345 and 387 trawl hauls and provide an empirical basis for simulation studies. Third, the years 1997–1999 allow us to further investigate sampling strategies of otoliths and primary sampling units as these years consist of a wider range of trawl hauls (274–405) compared with the years 2015–2018. The North Sea IBTS employs a stratified semi-random design, where research vessels from seven nations in Q1 and six nations in Q3 are used to collect data on all finfish species in the North Sea (see Supplementary Table S1.1 for nations). The sampling frame is defined by the ICES RFAs as shown in Figure 1, numbered 1–10. These RFAs were substratified into small strata defined by non-overlapping statistical rectangles of ∼30 × 30 nautical miles (1° longitude × 0.5° latitude) (ICES, 2006). Most statistical rectangles contain a number of possible trawl hauls or tows that are deemed free of obstructions, but ideally, two tows per rectangle, taken by two different countries, and separated by at least ten nautical miles, are required (ICES, 2015a, 2018b). While nations are free to choose any position within a statistical rectangle to sample, tows are generally based on a random selection of tow locations that are regarded as "safe-tows" (ICES, 2018b). These safe-tows are taken from national databases of participating countries, DATRAS (https://datras.ices.dk) or commercial fishing data (ICES, 2019). Trawling is done during the daylight hours, defined as 15 min before sunrise to 15 min after sunset (ICES, 2012). After each trawl, the total catch of the different species is weighed on board and concurrent length measurements and otoliths for age determination are obtained from a subsample of all target species.

In the stock assessment of the North Sea cod, ICES considers age groups 1–5 in quarter 1 and age groups 1–4 in quarter 3. However, the North Sea IBTS samples ages 0–6+, where the last group is referred to as a "plus group" and which consists of fish of age 6 or older. In this research, we consider age groups 1–6+ in quarter 1 and 0–6+ in quarter 3 in the analyses. A summary of the North Sea cod data is given in Table A1.

Abundance indices

In this research, the catch per unit effort (CPUE) is defined as the number of fish of a certain species and by age or length, which are caught per hour trawled. For a given species of interest, let $n_{h,l}$ be the number of fish with length l caught by trawl haul h. The CPUE for a given length l by trawl haul h is defined as

$$\mathrm{CPUE}_{h,l} = \frac{n_{h,l}}{d_h}, \tag{1}$$

where d_h is the duration of the trawl in hours. Using (1), the CPUE per age group can be expressed as

$$\mathrm{CPUE}_{h,a} = \sum_{l=1}^{L} \mathrm{CPUE}_{h,l} \times \mathrm{ALK}_{a,l,h}, \tag{2}$$

where L is the set of all length groups and $\mathrm{ALK}_{a,l,h}$ represents the estimated proportion of fish with age a in the lth length group in haul h. The mean CPUE per age in a statistical rectangle s is then defined as

$$\mathrm{mCPUE}_{s,a} = \frac{\sum_{h=1}^{H_s} \mathrm{CPUE}_{h,a}}{H_s}. \tag{3}$$

Here, H_s is the number of hauls taken in the rectangle. The mCPUE in pth RFA is further defined as

$$\mathrm{mCPUE}_{p,a} = \frac{\sum_{s=1}^{S_p} \mathrm{mCPUE}_{s,a}}{S_p} \omega_s, \tag{4}$$

where S_p is the number of statistical rectangles in RFA p and ω_s is a weight factor for each statistical rectangle (ICES, 2013). The mean CPUE-at-age in the whole study area is defined as

$$\mathrm{mCPUE}_a = \frac{\sum_{p=1}^{P} A_p \mathrm{mCPUE}_{p,a}}{A_{\mathrm{total}}}, \tag{5}$$

which we refer to as the index of abundance-at-age. Here, P is the set of all RFAs, A_p is the area of RFA p, and $A_{\mathrm{total}} = \sum_{p=1}^{P} A_p$. This index takes into account the entire survey area of the North Sea IBTS (Figure 1).

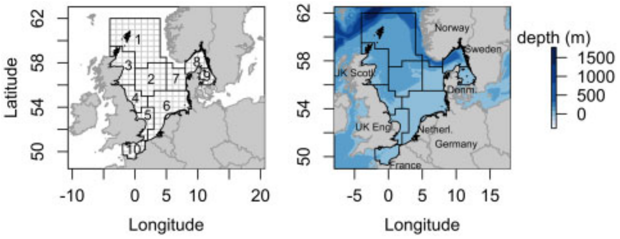

Figure 1. Standard RFAs used for round fish since 1980 and for all standard species since 1991 (left panel). Number 1, for example, indicates ICES RFA 1. The small grey rectangles in the left panel indicate the statistical rectangles of ~30 × 30 nautical miles (these vary from 28-nm wide in the north to 40-nm wide in the south of North Sea) (1° longitude × 0.5° latitude). The map in the right panel shows the Norwegian Trench and Shelf Edge (depths 1000–1500).

We consider two ALK estimators that can be used to obtain CPUE-at-age in (2) per age group. The first is an ALK estimator currently used by ICES in DATRAS for estimating IBTS abundance indices of the North Sea cod (ICES, 2013). We refer to this ALK estimator as the "area-based" ALK. The second is a "haul-based" ALK estimator, which we propose to account for spatial variation in age–length compositions. We compare the area-based ALK with our haul-based ALK. We use the area-based ALK so that (i) estimates of abundance indices published by ICES could be reproduced and their uncertainty could be estimated using an appropriate variance estimator that accounts for the multi-stage sampling design and (ii) we could evaluate sampling strategies of otoliths for age determination using the standard approach of estimating ALKs of the North Sea fish stocks.

Area-based ALK

We denote the area-based ALK used in DATRAS as $\mathrm{ALK}^{A}_{a,l,h}$. The area-based ALK is assumed to be constant within each RFA and is calculated for each RFA by aggregating the age observation from each RFA. This assumption is rather strong, and any violation could introduce bias in parameter estimates (Gerritsen *et al.*, 2006; Aanes and Vølstad, 2015). The $\mathrm{ALK}^{A}_{a,l,h}$ used in (2) is defined as the proportion of observed fish with age a in length group l in the corresponding RFA. ICES (2013) recommends an approach for "borrowing" ALKs (Aanes and Vølstad, 2015; Catchpole *et al.*, 2017) for imputation when age data are missing:

(i) If l is between the minimum length and the maximum length, the age is set to be equal the ALK to the closest length group with observed ages in the RFA. In cases where there are two equally close length groups with observed ages, the average of those two ALKs is used.

(ii) If l is smaller than the smallest measured fish in the RFA, the age is set to the minimum age.

(iii) If l is larger or equal to the maximum length, the age is set to the maximum age.

Haul-based ALK

We denote the haul-dependent ALK by $\mathrm{ALK}^{H}_{a,l,h}$. The $\mathrm{ALK}^{H}_{a,l,h}$ used in (2) is defined as the proportion of observed fish with age a in length group l in haul h in a statistical rectangle. If there are no observed ages of fish in a length group l in the haul, we propose the following for filling missing ALKs in the haul-based procedure, in sequential order:

(i) If there exists an age reading of that length group ≤60 nautical miles in the same RFA, the ALK from the closest haul with such an age reading is used.

(ii) If there exists a fish with length in the interval $l \pm 1$ cm with age information in the same haul, that observed age is used.

And, if there exists a fish in both $l + 1$ cm and $l - 1$ cm, the average age in these length group widths is used.

(iii) If steps (i) and (ii) do not produce an ALK for l, there exists little information close in space and length and the area-based ALK is used.

Uncertainty estimation

We use nonparametric bootstrapping to quantify the uncertainty of the CPUEs (Restrepo *et al.*, 2000; Efron, 2003). A bootstrap procedure, "ICES-IBTS", for estimating the uncertainty of CPUEs in the North Sea is suggested in ICES (2006). The ICES-IBTS bootstrap procedure ignores the fine-scale stratification by statistical rectangles in the North Sea in the first stage and, instead, resamples hauls by RFAs. ICES-IBTS bootstrap also ignores the multi-stage survey design in the resampling of age data, where trawl hauls are the primary sampling units. Ignoring the sampling approach in the estimation process could introduce bias in the estimated parameters, with substantial effects on their variance (Lehtonen and Pahkinen, 2004; Aanes and Vølstad, 2015). We investigate the effect of ignoring the sampling design on the variance by implementing the ICES-IBTS bootstrap procedure along with a modification that accounts for the stratification by the statistical rectangle. We refer to this procedure as the "modified ICES-IBTS" bootstrap procedure. We also implement a bootstrap procedure that accounts for stratification at all stages in the North Sea IBTS design. This procedure is referred to as the "stratified" bootstrap procedure. The stratified bootstrap procedure differs from the modified ICES-IBTS bootstrap procedure in the resampling strategy of age observations. These procedures are described in detail in "Bootstrap procedure" section. Approximate 95% confidence intervals are obtained using the bias-corrected percentile method (Gavaris and Ianelli, 2002; Magnusson *et al.*, 2013).

Bootstrap procedures

The bootstrap procedures are constructed as follows:

(i) For each statistical rectangle s, sample H_s hauls and assigns them to statistical rectangle s. We implement the following two procedures for this step. The procedure (a) is suggested by ICES (2006), and procedure (b) is our suggestion for the modified ICES-IBTS and the stratified bootstrap procedures, which are intended to account for the sampling design:
   (a) sample H_s hauls with replacement from the corresponding RFA and
   (b) sample H_s hauls with replacement from the corresponding statistical rectangle. If there is only one haul within a statistical rectangle, sample either that haul or the closest haul in space.

(ii) Sample age observations from the resampled hauls obtained in step (i). We implement the following two procedures for this step. Again, the procedure (a) is suggested by ICES (2006) and is implemented for ICES-IBTS bootstrap and the modified ICES-IBTS bootstrap procedures. Procedure (b) is our suggestion for the stratified bootstrap procedure, which is intended to account for sampling design:
   (a) For each *RFA* and length group l, sample with replacement $n_{\mathrm{RFA},l,a}$ age observations stratified with respect to *RFA* and length group. Here, $n_{\mathrm{RFA},l,a}$ is the total number of age observations in length group l in the corresponding RFA. If there is only one observed age from a given length group, i.e. $n_{\mathrm{RFA},l,a} = 1$, we sample either that age or age in the closest length group with observed ages within the RFA. If there exist more than one closest length group, we sample randomly, either that age or age in the closest length group width (s) with observed ages in the RFA.
   (b) For each haul and length group, sample without replacement $n_{l,a,h}$ age observations stratified with respect to haul and length group using a pseudo-population bootstrap procedure (Mashreghi *et al.*, 2016). Here, $n_{l,a,h}$ is the total number of age observations in length group l in the corresponding haul. We use pseudo-population bootstrapping to account for the finiteness of the population at the second stage (subsampling for length and age in a haul). Drawing bootstrap samples from the pseudo population ensures that the variance estimator encompasses the finite population correction factors (Cochran, 1977; Nane and Kooijman, 2018). The pseudo-bootstrap procedure is presented in Supplementary Material S2. If there is only one observed age within a length group in a haul, that age is sampled.

(iii) Calculate the relative abundance-at-age, mCPUE$_a$ in (5), using the sampled data.

(iv) Repeat (i–iii) B times, where B is the number of bootstrap replications.

Reducing the number of otoliths sampled for age determination

Here, we investigate the effect of reducing sampling effort, with respect to otolith collection, on the expected relative standard error (RSE) of estimated relative abundance-at-age of the North Sea cod. We sample realizations of data obtained from a resampling procedure with fewer age readings by choosing the number of age observations in length group l in the corresponding haul, $n_{l,a,h}$ [defined in step (ii)(b) in Bootstrap procedure] to be equal to a pre-defined number. By doing that, the sampled data sets in the bootstrap procedure are possible realizations of data obtained by collecting a pre-defined number of otoliths for age determination. We investigate the effect on estimated relative abundance and its variance by considering two sampling procedures: first, we sample *one* fish for age determination from length group width 1, 2, 3, 4, or 5 cm; second, we set a length group width of 5 cm and sampled *one*, *two*, *three*, *four*, or *five* fish for age determination. These procedures would capture the sampling variability in age–length data and allow sufficient sample sizes of otoliths required to give information on relative abundance-at-age in the North Sea to be determined. For all experiments, we apply the haul-based ALK and estimates are provided for 500 bootstrap replications.

Evaluating the effect of the number trawl hauls on relative abundance

Several research studies have shown that the precision in estimates of age compositions is primarily driven by the number of trawl hauls and not the number of fish measured for age (Aanes and Pennington, 2003; Stewart and Hamel, 2014; Aanes and Vølstad, 2015). We, therefore, investigate the effect of reducing the number of fish sampled for age determination and reducing (or increasing) the number of hauls on the expected RSE of abundance-at-age of the North Sea cod. We use the resampling procedure described in "Reducing the number of otoliths sampled for age determination" section to sample fish per length group width for age determination. The bootstrap procedure used to sample trawl hauls is described below. Let *N* be the number of trawls to be sampled:

(i) Sample *N* hauls, stratified with respect to RFA, such that the proportion of hauls between RFAs is approximately the same as in the original survey design. In the resampling procedure, *N* was set to 50, 75, 100, 150, 200, 300, 400, or 500 such that the proportion of hauls in the RFAs is the approximately the same as real survey design and no fewer than two hauls are taken in an RFA.

(ii) Sample age, stratified with respect to length, from the hauls sampled in step (i) above using the pseudo-bootstrap procedure described in "Bootstrap procedure" section and in Supplementary Material S2. Here, the length group width was set to 5 cm, where *one* or *five* were sampled from each trawl haul. It is important to note here that, although the recommended sampling strategy of otoliths for North Sea cod, by ICES, from 2018 Q1 is *one* fish per 1-cm-length group width from each trawl haul (ICES, 2018b), some nations continued to sample *more than one* fish per 1 cm for age determination.

(iii) Calculate CPUE per age using the area-based ALK. The area-based ALK, which is the current estimator used by ICES for North Sea IBTS abundance-at-age indices (ICES, 2013), is used as a demonstration for reducing sampling effort. One could also use the haul-based ALK estimator.

(iv) Repeat i–iii B times, where $B = 500$ is the number of bootstrap replicates.

Results

Evaluation of ALK estimators

The area-based and haul-based ALKs yield equivalent estimates of abundance-at-age and precision (Figure 2, left panel). With regard to the bootstrap procedures for variance estimation, ICES-IBTS procedure gave higher estimates of the variance compared with the modified ICES-IBTS and stratified bootstrap procedures (Figure 2, right panel). Recall that ICES-IBTS bootstrap procedure ignores the fine-scale stratification at the first stage [step (i)(a) in "Bootstrap procedure" section] and, thus, overestimates the uncertainty. ICES-IBTS bootstrap procedure also ignores age–length data collected at the haul level, resulting in an underestimation in the uncertainty. So, there is bias in both directions, but, as illustrated in Figure 2, the underestimation due to the ALK seems to be small. The modified ICES-IBTS and stratified bootstrap procedures sample hauls at the level of the statistical rectangle, and these procedures gave lower variance estimates possibly because too few hauls, in relatively proximity, are available for resampling (i.e. maximum two hauls per statistical rectangle, some ten nautical miles apart).

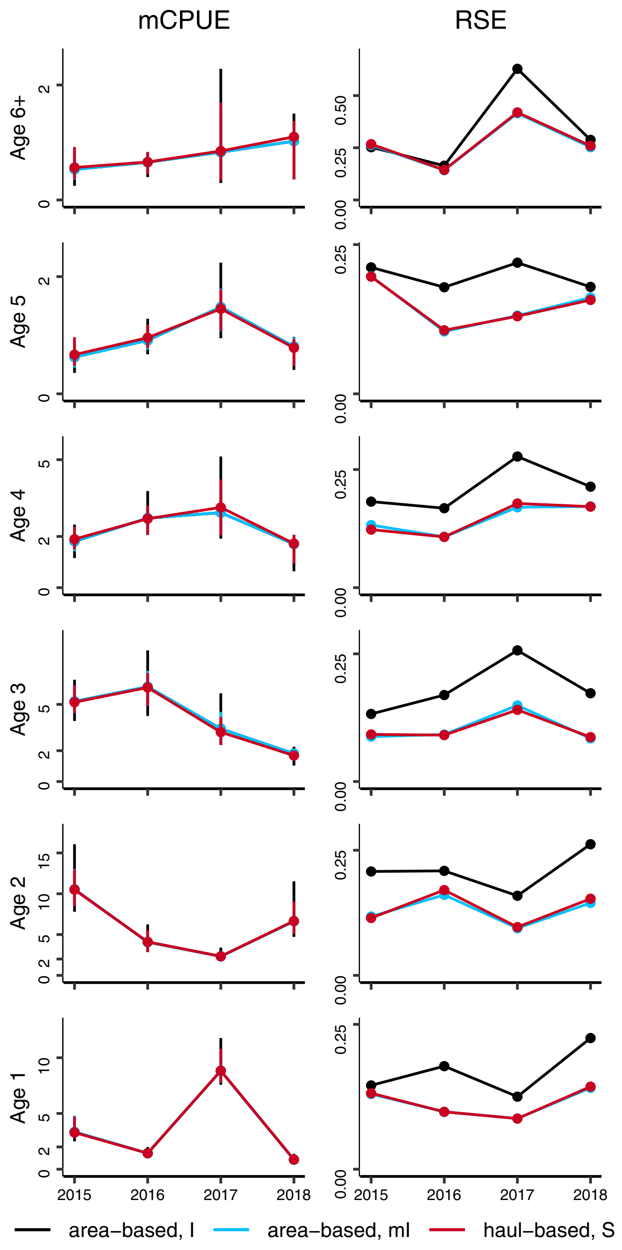

Figure 2. Estimated mean catch per unit effort at the age of North Sea cod from the two ALK estimators based on the data from the IBTS in 2015–2018 Q1 (left panel). The error bars are estimated 95% confidence intervals using the bias-corrected method (see "Material and methods" section) and 500 bootstrap samples. Expected RSE for estimated abundance-at-age (mCPUE_a) is also given in the right panel. The ICES-IBTS (I) or modified ICES-IBTS (mI) bootstrap procedures are applied to the area-based ALK and the stratified (S) bootstrap procedure is applied to the haul-based ALK.

In general, we expect some intra-haul correlation as fish caught at a trawl station are more likely to have similar age given length than those in the entire population and even at low levels can greatly increase the variance of the estimated mean CPUE-at-age (Pennington and Volstad, 1994; Aanes and Pennington, 2003). Therefore, resampling age and length data at the haul level is required to obtain realistic estimates of the precision of abundance-at-age indices. The reason is that the precision in estimates of abundance-at-age primarily is driven by the number of trawl hauls, and not by the number of fish measured for

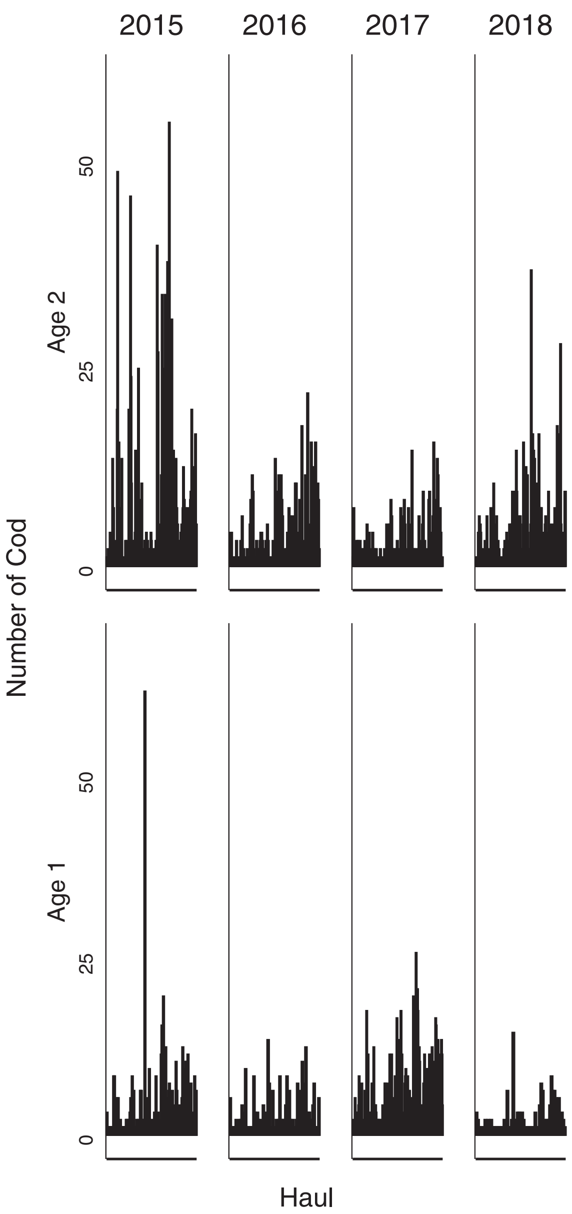

Figure 3. Hauls containing juvenile North Sea cod (ages 1 and 2) in the years 2015–2018 Q1. The haul-to-haul variation in the numbers-at-age 1 is quite high, as only a few hauls contain most of the catches, but the haul-to-haul variation in catch rates of 2-year olds is much higher compared with 1-year olds in 2015 and 2018.

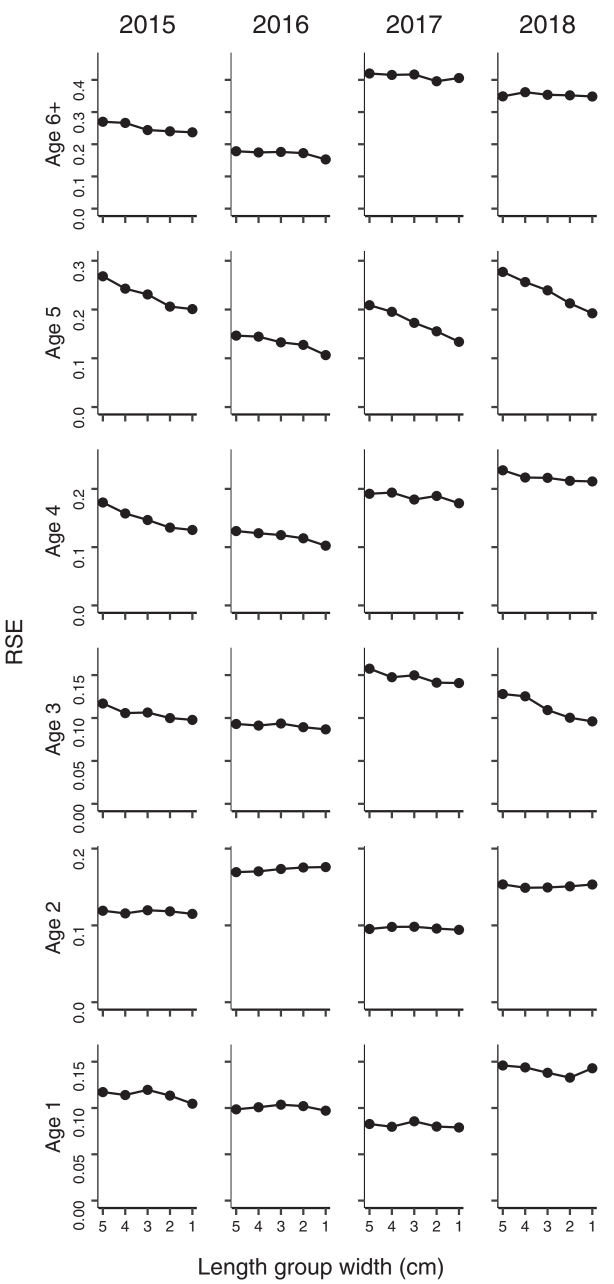

Figure 4. Expected RSE of mean catch per unit effort at age of North Sea cod in the years 2015–2018 Q1 with different length group widths for 500 bootstrap samples. We sample *one* fish in the following length group widths: 5, 4, 3, 2, or 1 cm, which is represented by the circles.

age (Aanes and Vølstad, 2015). This is confirmed by the high estimated RSEs from the ICES-IBTS bootstrap procedure (Figure 2, right panel) and the distribution of juvenile cod across hauls (Figure 3).

Similar trends in estimated abundance and uncertainty are observed in quarter 3 (Supplementary Figure S4.2). In 2018 Q3, the uncertainty in 4-year-old cod is high compared with the younger age groups, with expected RSE exceeding 25% for all three bootstrap procedures. This high variance is driven by a single haul, which dominates the catch of 4-year-old cod (Supplementary Figure S4.1, upper panel and Supplementary Figure S4.2, right panel).

Evaluation of sampling strategy of otoliths

Figure 4 gives the expected RSE of estimated abundance-at-age indices from sampling *one* fish in length group widths: 5, 4, 3, 2, or 1 cm for age determination. In Figure 4, we see that the difference in expected RSE is marginal, suggesting that the current extensive age reading can be reduced with minor loss in information on relative abundance-at-age. For age groups 1–4, the change in estimated precision of the mean CPUE is minor when the length group width is reduced to 1 cm. For age group 5

Table 1. Number of trawl hauls with age samples of North Sea cod of age group 5 and the plus group (6+) in the years 2015–2018 Q1 (percentages are in parentheses).

	Number of hauls with age data		Number sampled at age			
Year	Age 5	Age 6+	Age 5	Age 6+	Total catch sampled for age	Total hauls with age samples
2015	45 (15)	38 (13)	103 (3.6)	77 (2.7)	2 877	301
2016	79 (33)	56 (23)	153 (7.5)	97 (4.7)	2 044	243
2017	86 (29)	46 (16)	194 (7.8)	99 (3.5)	2 501	293
2018	61 (27)	45 (20)	102 (6.4)	124 (7.8)	1 596	229

The number of fish measured for these age groups is also given.

and the plus group (6+), which accounts for a marginal proportion of the fish (Table 1), there is a slight improvement in precision for shorter length group widths (e.g. 3, 2, or 1 cm). This is likely due to ageing error, and one might, therefore, consider sampling more than one fish per 5-cm-length group for the older fish. The higher variances in estimates of mCPUE for age groups 5 and 6+ are largely driven by the relatively few trawl haul samples (Table 1) containing cod in these age groups.

Figure 5 confirms that one fish per 5 cm is sufficient to estimate the age composition as improvement in precision from sampling more than one fish per 5-cm-length group width is marginal. A similar trend is observed in 2015–2018 Q3 surveys, and these results are presented in Supplementary Material S4.1.2. In all years and quarters, except 2016 Q3, the average number of fish sampled for age determination, under the one fish per 5-cm-length group width scenario, is ≤51% of the total number of fish sampled at the North Sea IBTS for that given year and quarter (Table 2 and Supplementary Table S4.1 for Q3 estimates).

Evaluation of sampling strategy of otoliths and hauls

At least 349 hauls were sampled in the years 2015–2018 at the North Sea IBTS (Table A1), but as shown in Figure 6, there is little gain in increasing the number of trawl hauls (>300). If the number of trawl hauls is reduced (<300), however, the expected RSE, particularly for older cod, increases quickly, indicating that gains can still be had by sampling more hauls. The analyses further show that there is no real difference in expected RSE if *one* or *five* fish are sampled in a 5-cm-length group width, supporting the recommendation that *one* fish per 5-cm-length group width per trawl haul is sufficient for age determination. We conduct analysis for quarter 3 in 2015–2018 and several earlier years (1997–1999) for which fewer or more hauls were sampled and higher proportions of missing age samples in RFAs and hauls, compared to 2015–2018 (Table A1), with similar results. These results are presented in Supplementary Materials S4.1.3 and S4.1.4. Furthermore, analyses using the haul-based ALK (not reported here, but available upon request) also gave similar results.

Discussion and conclusion

We have developed estimators and bootstrap procedures that differ slightly from those previously proposed for the North Sea IBTS. Our intention has been to better align the design of estimators with the design of the sampling for both the ALK definitions and the resampling procedures. In particular, this better reflects the spatial structure of the sampling, taking into account any spatial and haul-based variations in age–length relationships. For the particular examples we have analysed, the differences between the

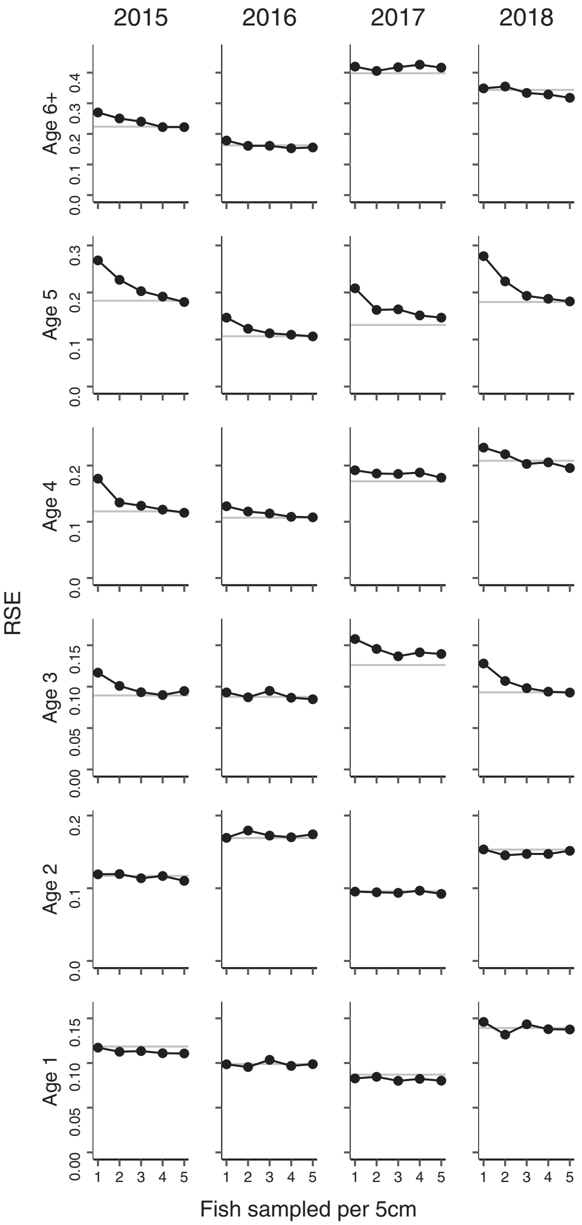

Figure 5. Expected RSE of mean catch per unit effort at age of North Sea cod in the years 2015–2018 Q1 for varying numbers of fish sampled for age in a 5-cm-length group width: *one, two, three, four,* or *five*. This is represented by the black lines. The expected RSE for all fish currently sampled per length group in the North Sea is represented by the grey lines. Estimates are provided for 500 bootstrap replicates.

Table 2. Average number of fish sampled for age determination from 500 bootstrap replicates in length group widths: 5, 4, 3, 2, or 1 cm (percentages are in parentheses).

	Length group width					
Year	**5 cm**	**4 cm**	**3 cm**	**2 cm**	**1 cm**	**Total ages sampled in Q1 in the year**
2015	1 166 (40)	1 278 (43)	1 457 (50)	1 714 (58)	2 185 (75)	2 895
2016	997 (49)	1 092 (54)	1 229 (61)	1 409 (70)	1 743 (86)	2 046
2017	1 183 (47)	1 297 (51)	1 465 (58)	1 722 (68)	2 178 (87)	2 501
2018	804 (51)	881 (56)	980 (63)	1 132 (72)	1 350 (86)	1 600
	Number of fish sampled for age per 5-cm-length group width					
Year	**1**	**2**	**3**	**4**	**5**	**Total ages sampled in Q1 in the year**
2015	1 166 (40)	1 705 (58)	2 033 (69)	2 271 (77)	2 423 (82)	2 895
2016	997 (49)	1 421 (70)	1 660 (82)	1 793 (88)	1 872 (91)	2 046
2017	1 183 (47)	1 727 (69)	2 035 (81)	2 225 (88)	2 331 (92)	2 501
2018	804 (51)	1 127 (72)	1 307 (83)	1 403 (89)	1 460 (93)	1 600

In each bootstrap replicate, *one* fish is sampled for age determination in each length group width in 2015–2018 Q1. Also, *one, two, three, four,* or *five* fish are sampled in a 5-cm-length group width and the average number is given. The total number of fish sampled in a given year of interest in IBTS is also given.

expected RSE estimates for different ALKs and resampling schemes are small with respect to common interpretation. This is expected because the uncertainty in the ALK estimation is considered. ALKs are generally subjected to large sampling errors since they are estimated from cluster-correlated data from multi-stage sampling. Aanes and Vølstad (2015) showed that if the ALK is fixed and only the variability of length compositions is allowed for, then the estimated age distributions will appear more precise than they truly are. This is in agreement with Gerritsen *et al.* (2006) and Berg and Kristensen (2012) who demonstrated large spatial variability in ALKs for several fish stocks, including cod, sampled at the North Sea.

The North Sea IBTS is, theoretically, based on a multi-stage sampling design, where trawling locations by each nation are selected using probability methods. In practice, however, trawl hauls are based on a large number of trawlable locations (or stations) within a statistical rectangle. A combination of a random selection; a random selection from historical tows, deemed valid with start to end position; opportunistic sampling (from using commercial survey information); and fixed-station sampling, particularly in the northern, central, and southern North Sea in quarter 3 and Kattegat/Skagerrak areas in quarter 1 and quarter 3 (ICES, 2018b), are used by each country. There are several advantages to using fixed-station sampling in the North Sea IBTS that are not realized with random sampling. The North Sea IBTS has a long time series of roughly three decades and are standardized by season, so there is the benefit of evaluating long-term trends in the CPUE from using fixed-station sampling. Fixed-station sampling could allow temporal trends in the CPUE to be better identified (Quist *et al.*, 2006; Li *et al.*, 2015) and, with greater power (Warren, 1994; Van der Meer, 1997), particularly when the correlation structure between time periods is high. Relatively small changes in CPUE could also be detected by using fixed-station sampling (Quist *et al.*, 2006). These advantages may, however, be limited for some species or in some systems. For instance, an aggregation of the North Sea cod might periodically occur at a fixed station through small-scale movement patterns, and this could confound any assessment that is based on sequential data at these stations (McShane, 1998). Also, such changes in habitat use would result in low correlation structures between time periods, hindering the detection of differences in cod abundance (Quist *et al.*, 2006). In cases of extremely low correlation, fixed-station sampling would provide little benefit relative to random sampling. In addition, fixed-station sampling at the North Sea could jeopardize precision, resulting in a decrease, when simple random sampling is assumed in the estimation of abundance and variance (Wickenberg-Bolin *et al.*, 2006; Patterson, 2014), but the effect of this decrease in precision in the whole survey could be small since only one nation (or two in Q3 surveys) out of seven nations samples fixed stations (ICES, 2018b).

Some randomization in the selection of trawling locations is, however, necessary to provide unbiased information that is useful for drawing inferences on fish populations in the North Sea. One of the main objectives of the North Sea IBTS is to provide information on the seasonal distribution of fish stocks, and a random selection of trawl locations in a given year that is revisited in succeeding years not only is useful to detect seasonal changes in abundance but also allows for improvement in precision. Van der Meer (1997) demonstrated that a smaller variance of the estimators of year-to-year change in abundance is achieved when trawl locations that are selected at random in the first year are revisited in succeeding years. This is supported by Cochran (1977, p. 345), who recommended a mixture of random sampling and replacement of part of the sampling locations on each occasion. Randomly selected trawling locations are also better able to capture spatial variability (Quist *et al.*, 2006; Pennino *et al.*, 2016). An alternative to the current North Sea IBTS sampling design could be partial replacement sampling by each nation, where 70% of the known trawlable locations are repeated and the remaining 30% is based on a simple random selection. And, through time this, sampling strategy could evolve, with an increasing number of randomly selected trawling locations. This would effectively reduce the cost of selecting trawling locations randomly, where a high proportion of those locations may be untrawlable.

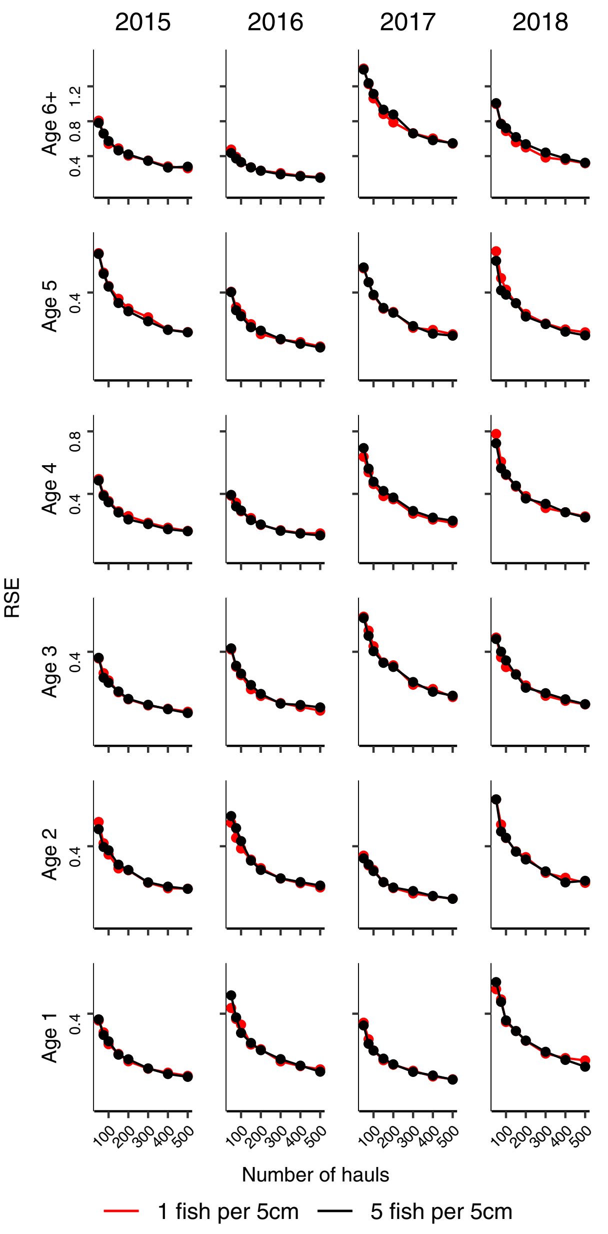

Figure 6. Expected RSE for North Sea cod in the years 2015–2018 Q1 when sampling *one* (red line) or *five* (black line) fish in the length group width 5 cm for age determination from each trawl haul for 500 bootstrap samples. For each sampling strategy of otoliths, the area-based ALK is used for the given number of hauls, $N = 50, 75, 100, 150, 200, 250, 300, 350, 400,$ or 500.

Faithfully mimicking the sampling design in simulations not only is useful for bootstrap estimates but also allows us to estimate the effect of reducing sampling effort. For age sample collection, consideration of what effort is necessary is a pressing issue as age reading is a demanding skill to develop and trained age readers are the resources shared with other surveys and potentially other species. Strained age-reading capacity prohibits the development of new surveys and may introduce unfortunate bias in otherwise unbiased samples if otoliths are not all read before advice is due. We, therefore, performed an analysis mimicking reduced otolith sampling. We have presented a range of options for less intensive otolith sampling to which the variance of abundance-at-age estimates is highly robust. We have in this respect been conservative in what options we have explored and limited ourselves to sampling reductions that appear to essentially preserve precision and, thus, not alter the usability of estimates. We find it important in that regard to not compromise on primary sampling units and have considered only sampling protocols that sample the target species the same way at all stations. We do note, however, that the variance of older fish has a larger response to sample reductions than smaller fish so that reductions in sampling are best considered first for short length-strata. These analyses were performed using 500 bootstrap replications, which we have considered to be sufficient since a smaller number of replications (e.g. 300) gave similar results (data not shown). It is also important to remember the appropriateness of interpreting parameter estimates as abundance estimates, and precision is contingent on species biology and growth patterns (Parmanne *et al.*, 1994; Möllmann *et al.*, 2004). At the North Sea IBTS, at least one otolith per 1-cm-length group width from all target species is taken for age determination, except herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), where one fish per 0.5-cm-length group width is sampled for age determination (ICES, 2018b). The main reason is that lengths at age of these species vary considerably, due to trends in environmental factors, particularly food availability, temperature, and abundance. Hunter *et al.* (2019) demonstrated that growth rates of the North Sea herring and sprat decrease in response to increases in abundance. Therefore, alternative subsampling schemes would be required for pelagic species.

In the future, more aggressive sample reductions could extend beyond the criteria of essentially keeping the same precision. Such analysis could be performed by coupling the resampling analysis to the effect of downstream use, such as stock assessment. An important caveat in that respect is that results will be sensitive to the choice of the stock assessment model. Stock assessment models are typically subject to change during the lifetime of a survey time series. The stock assessment model, state-space assessment model (SAM; Nielsen and Berg, 2014; Berg and Nielsen, 2016), for instance, has been widely used to assess many fish stocks. In particular, since 2011, various configurations of SAM are used to assess the North Sea cod stock (ICES, 2017a, b). Aldrin *et al.* (2019) presented a different formulation of SAM and found that there are significant differences in the estimated precision of numbers-at-age of North Sea cod compared with the formulation by Nielsen and Berg (2014). In addition, the subsampling schemes proposed in this research can be extended to other surveys such as the Barents Ecosystem and Winter Surveys, where a similar subsampling scheme of *one* cod per 5-cm-length group is currently employed to estimate proportions-at-age (Aanes and Vølstad, 2015); Atlantic cod stock in US waters (Gulf of Maine and Georges Bank), where otolith analyses are generally lacking (Zemeckis *et al.*, 2014), and where 20 cod per statistical rectangle is currently being sampled (NOAA, 2016); and Greenland cod, where ∼25 000 cod are aged annually and, where complex age structures exist, posing a challenge for age readings and stock assessment (ICES, 2009, pp. 2–3).

We conclude from this work that for routine IBTS data of the North Sea cod, the number of fish sampled for age determination could be reduced by at least 50% without appreciable loss of precision in abundance-at-age estimates. This could free up resources from a heavily strained age-reading staff and avoid bias introduced by incomplete readings in this survey or in other data collection programmes competing for the same age-reading capabilities.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Appendix 1

Summary of North Sea cod data

Table A1 gives a brief summary of data set used in this research.

Table A1. Summary of North Sea cod data in the years 2015–2018 and 1997–1999.

	Recent years and quarters							
	2015		2016		2017		2018	
	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3
Number of hauls	380	352	360	381	377	337	363	349
Total otoliths sampled for age determination	2 895	2 113	2 046	1 804	2 501	2 230	1 600	1 456
Number of hauls with length data	305	215	251	230	306	237	237	200
Number of hauls with age data	301	209	243	224	293	236	229	195
Cod with missing age in RFAs (%)	0.30	0.13	0.13	0.34	0.68	0.07	0.51	0.11
Cod with missing age in hauls (%)	10.06	14.20	6.18	6.32	2.25	0.27	1.40	0.77
	Earlier years and quarters							
	1997		**1998**		**1999**			
	Q1	**Q3**	**Q1**	**Q3**	**Q1**	**Q3**		
Number of hauls	363	253	405	274	358	366		
Total otoliths sampled for age determination	2 189	3 008	2 417	1 755	1 788	1 620		
Number of hauls with length data	339	236	363	215	302	244		
Number of hauls with age data	198	204	169	175	163	196		
Cod with missing age in RFAs (%)	6.56	0.74	8.89	17.76	5.45	1.07		
Cod with missing age in hauls (%)	59.11	23.25	37.74	49.12	27.51	13.62		