An analysis of the North Sea International Bottom Trawl Survey Data

Abstract

The North Sea International Bottom Trawl Survey (IBTS) was started by the International Centre for the Exploration of the Sea (ICES) in 1990. Seven research vessels using standardized fishing methods participates in the survey. The survey with these vessels, which allows fishing also on rough ground provides information on seasonal distribution of stocks and abundance, which forms the basis for stock assessments. Estimates of abundance indices based on age-length keys (ALK) are provided without any assessment of their accuracy. We present a model-based ALK estimator, and a stratified design-based ALK estimator for estimating abundance at age. Both estimators take into the spatial differences in age-length structures. These estimators are compared with the designed-based ALK estimator proposed by ICES for IBTS, which does not account for spatial differences in the age-length structure. As the proposed ALK estimator by ICES is a combination of age data over a large area, this can result in biased estimates of numbers-at-age. An example of cod (*Gadus morhua*) in ICES subareas IVa and IVb is used to illustrate spatial differences in the proportions of age-at-length, and estimates of uncertainty are presented using nonparametric bootstrapping. In general, the model-based ALK estimator provides a more accurate coverage probabilities compared with the other estimators.

1 INTRODUCTION

Fish stock assessments are used by fishery managers for making management decisions regarding catch quotas. The 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. Associated with the parameters used in fish stock assessment is their uncertainty, which should not be ignored when formulating management policies (Walters and Ludwig, 1981; Ludwig and Walters, 1981). This uncertainty can arise from many sources including natural variability, estimation procedures and lack of knowledge regarding the parameter (Ehrhardt and Legault, 1997). The North Sea International Bottom Trawl Survey (IBTS) data, coordinated by the International Council for the Exploration of the Sea (ICES), provides information on seasonal distribution of stocks and estimates of abundance indices and catch in numbers of fish per age-class without an assessment of the accuracy of these estimates. As pointed out by Ludwig and Walters (1981) estimates of parameters relating to stock size are of little value unless they are accompanied by uncertainty estimates.

Indices of abundance at age from IBTS are based on data obtained from a stratified **semi-random** sampling approach of trawl stations, and it is essential to account for the sampling approach so as to produce reliable variance estimates (Lehtonen and Pahkinen, 2004). If the sampling approach is ignored, the effect on the variance of the parameters could be substantial. In particular, the variance could be greatly inflated due to the clustering effect, which involves intra-cluster correlation of the variables (Aanes and Vølstad, 2015; Lehtonen and Pahkinen, 2004). Currently, abundance indices from IBTS are estimated using an age-length key (ALK) method (Fridriksson, 1934), which is assumed to be constant over relatively large areas. In this paper we give a strong case for assuming variation in the ALK within these areas (see Figure 1, which shows the estimated age probabilities of a 40 cm cod (*Gadhus morhua*) in the first quarter of 2015). Figure 1 shows that the age distribution clearly varies for a 40 cm cod within Central North Sea and Northern North Sea (see second graph in the first panel). We propose two ALK estimators, which consider spatial variation: 1) a nonparametric ALK estimator, and 2) a spatial model-based ALK estimator, which we describe in Section (2). Section 1.1 gives an overview of the North Sea International Bottom Trawl Surveys. A brief description of the data is given in Section 3. The current estimators for ALK and catch per unit effort (CPUE) used by

ICES in their database for trawl surveys (DATRAS) and our proposed ALK estimators are given in Section 2. The results are given in Section 4 and a discussion is given in Section 5.

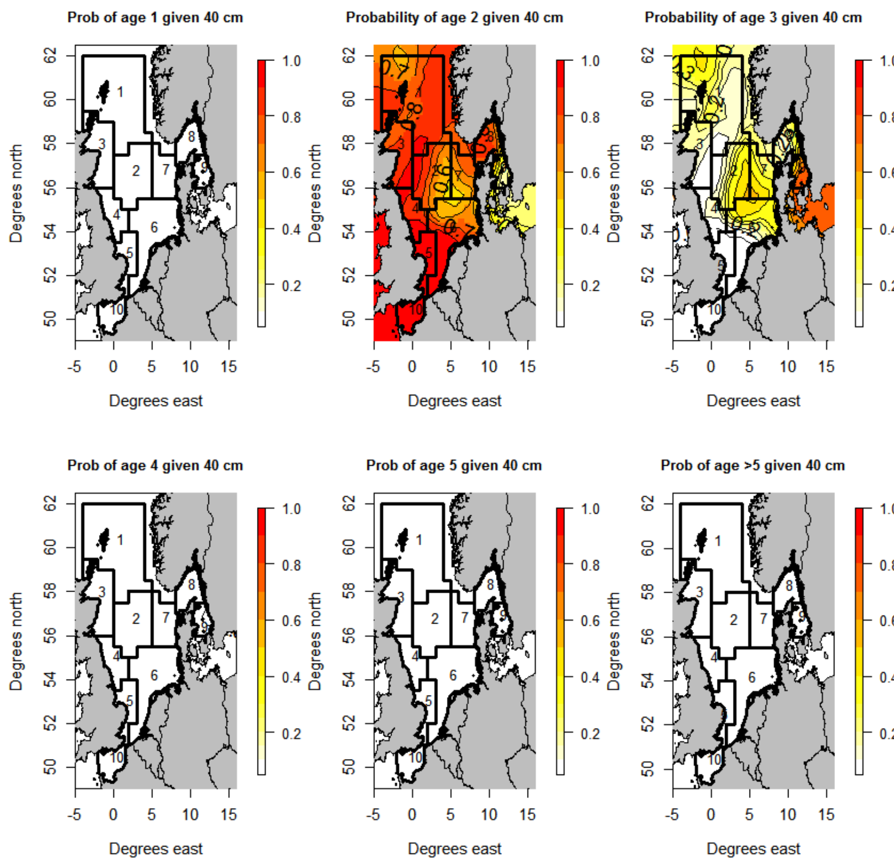


Figure 1: Estimated probability of age of a 40 cm long cod in the first quarter of year 2015. The probability of age three or older is approximately zero. The polygones marked 1 to 10 is the round fish areas (RFAs) where the ALK is assumed constant in the currently used estimators of the official CPUEs.

1.1 Overview of the North Sea International Bottom Trawl Surveys

The North Sea International Bottom Trawl Survey was formed in 1991, which is a combination of the International Young Herring Survey (IYHS) and eight national surveys in the North Sea, Skagerrak and Kattegat areas. These surveys began in the 1960's, and the 1970's and 1980's, respectively. The IYHS was developed with the aim of obtaining annual recruitment indices for the combined North Sea herring *Clupea harengus* stock (ICES, 2012), but yielded valuable information on other fish species such as cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*.

The North Sea IBTS began with quarterly surveys providing information on seasonal distribution of stocks sampled, hydrography and the environment, which allows changes in fish stock to be monitored and abundance of all fish species (Table 1) to be determined. These quarterly surveys, however became difficult to sustain as countries experienced budget cuts making it impossible to maintain high levels of research vessel effort. As such, in 1997 countries carried out a survey only twice a year; a first quarter survey (January-February) and a third quarter survey (August-September). Table 1 gives the common names (scientific names in parentheses) of the target species that are sampled during the quarterly North Sea International Bottom Trawl Surveys. The common names of the species in parentheses will be used in the rest of paper.

Table 1: Species fished in the NS-IBTS from 1991-2017.

Standard Pelagic	Standard Roundfish	By-Catch Gadoid
Herring (Clupea harengus)	Cod (Gadus morhua)	Pollock (Pollachius)
Sprat (Sprattus sprattus)	Haddock (Melanogrammus aeglefinus)	Pouting (Trisopterus luscus)
Mackerel (Scomber scombrus)	Norway Pout (Trisopterus esmarkii)	Trisopterus minutus (Poor Cod)
	Saithe (Pollachius virens)	Blue Whiting (Micromesistius poutassou)
	Whiting (Merlangius merlangus)	Hake (Merluccius merluccius)
		Ling (Molva molva)
		Tusk (Brosme brosme)

Research vessels from seven nations in the first quarter (Q1) and six nations in the third quarter (Q3) are used for conducting surveys on all finfish species in the North Sea during January-February and July-August, respectively, between 1997-2017 (see Table 7 in appendix B). The sampling frame is defined by the ICES index or roundfish areas (RFA) as shown in Figure 2 numbered 1 to 10, and which we refer to as superstrata (Nottestad et al., 2015; Fuller, 2011). These roundfish areas were substratified into small strata defined by non-overlapping statistical rectangles of roughly 30×30 nautical miles (1^o Longitude $\times$ 0.5^o Latitude), and were convenient to use for North Sea IBTS as they were already being used for fisheries management purposes. Most statistical rectangles contain a number of possible tows that are deemed free of obstructions, and vessels are free to choose any position in the rectangles as long as the hauls are separated by at least 10 nautical miles within and between rectangles. However, all countries select tows based on a semi-random approach from databases of national safe tows or DATRAS or commercial fishing data, except Sweden who uses fixed stations and in some cases depth-stratified semi-random sampling design (ICES, 2018), and England who also uses fixed stations and only conduct surveys during the third quarter. In some rectangles, sampling may be further stratified due to significant changes in seabed depth which may, in turn, cause variations in the fish population. In particular, the North Sea IBTS herring, saithe and sprat data are weighted by depth strata in the statistical rectangle (see Table 6 in appendix E). It is also a requirement that countries avoid clustering their stations between adjacent rectangles in order to reduce positive serial correlation, and thereby maximize survey precision. The latest major reallocation of rectangles occurred in 1991, but since then the survey has tried to keep at least one vessel in every subarea in which it had fished in the most recent years. Minor reallocation of rectangles between Norway, Scotland and Germany was done in 2013. Each rectangle was typically sampled twice by two different countries before 1997, but after that target coverage of two trawl hauls per rectangle per survey was introduced because of national financial constraints (ICES, 2015). But in some rectangles in the Eastern English Channel, Southern North Sea and Central North Sea intensified sampling is carried out.

The recommended standard trawling gear of the North Sea IBTS is the mulitpurpose chalut à Grande Ouverture Verticale (GOV) trawl (ICES, 2012), which has been used on all participating vessels since 1992, while different pelagic and bottom trawls suitable for fishing finfish species were used before 1992. Standardized trawling protocols were adopted with a towing speed of 4 knots but depending on vessel performance, tide and weather conditions the average towing speed can be at minimum 3.5 and maximum 4.5 knots. From 2000-2018 trawling is done during the daylight hours, which are considered 15 minutes before sunrise to 15 minutes after sunset (ICES, 2012). After each trawl the total catch of the different species is weighed on board and biological parameters such as length for all fish species caught (to 0.1cm below for shellfish, to 0.5cm below for herring and sprat and to 1cm below for all other species) are collected. Where the numbers of individuals are too large for all of them to be measured to obtain the length distribution, a representative subsample of 100 fish is selected. Otoliths are collected on board from a small fraction of all the target species from all round fish areas (RFAs) (Figure 2) to retrieve age reading. Table 8 in appendix ?? gives the minimum sampling levels of otoliths for the target species.

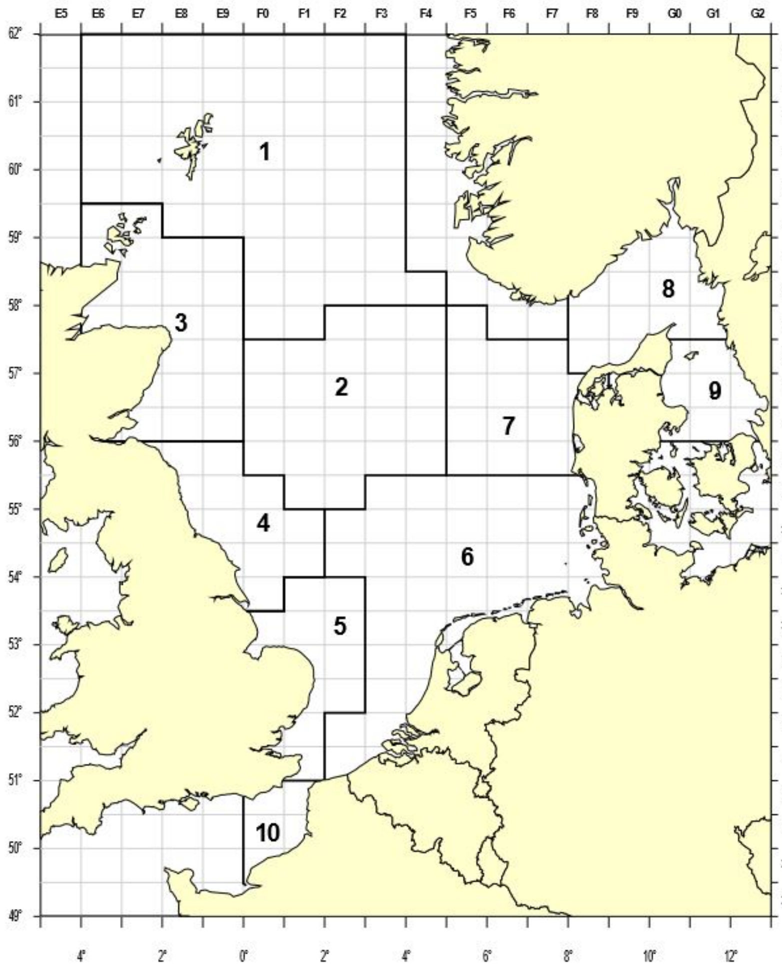


Figure 2: Standard roundfish areas used for roundfish since 1980, for all standard species since 1991. Additional RFA 10 added in 2009. For example, the number 1 indicates ICES Index Area 1, and an ICES Statitical rectangle (ST) in IA 1 is 43F1 (ICES, 2015).

2 METHODS

This section gives the estimators of abundance indices. The estimators are haul time-based and utilizes an ALK approach. We consider the ALK approach used in DATRAS and we propose two ALK estimators. The ALK used in DATRAS for computing abundance indices does not account explicitly for the spatial distribution in the age-length composition, which may be different and would result in a biased ALK. This difference may be caused either by variation in length-at-age distributions or by variations in the relative abundance of age classes, that is age-at-length distributions (Gerritsen et al., 2006). To account for the spatial distribution we propose a design-based ALK estimator that is haul dependent (Section 2.2.2) and a model-based ALK estimator (2.2.3).

2.1 CPUE Estimators

For a given species of interest, define $n_{h,l}$ to be the number of fish with length l caught by the hth trawl haul. Define the CPUE for a given trawl h to be

$$\text{CPUE}_{h,l} = \frac{n_{h,l}}{d_h}, \tag{2.1}$$

were d_h is the duration of the trawl in hours. The cpue per age class is further defined as

$$\text{CPUE}_{h,a,l} = \sum_{l \in \mathbf{L}} \text{CPUE}_{h,l} \times ALK_{a,l,h}, \tag{2.2}$$

where $ALK_{a,l,h}$ is an age length key which represents the estimated proportion of fish with age a in lth length class in haul h, and $\mathbf{L}$ is the set of all length classes. The mean CPUE in a statistical rectangle is further defined as the average of the CPUE for each trawl haul in the rectangle:

$$\text{mCPUE}_{s,a,l} = \sum_{h \in H_s} \frac{\text{CPUE}_{h,a,l}}{|H_s|}. \tag{2.3}$$

Here H_s represents the set of trawl hauls taken in statistical rectangle s, and $|H_s|$ is the number of hauls taken in the rectangle. The mean CPUE in pth RFA is further defined as

$$\text{mCPUE}_{p,a,l} = \sum_{s \in S_p} \frac{\text{mCPUE}_{s,a,l}}{|S_p|}, \tag{2.4}$$

where S_p is the set of all statistical rectangles in pth RFA and $|S_p|$ is the number of statistical rectangles in pth RFA. An index of abundance by age per round fish area is computed by taking the sum of the length classes for a given age within the round fish area. This is the mean catch per unit effort for age a in superstratum p, which is expressed as

$$\text{mCPUE}_{p,a} = \sum_{l \in L} \text{mCPUE}_{p,a,l}. \tag{2.5}$$

Abundance at age in the whole study area, $mCPUE_{N,a}$ is derived by the ratio of the sum of the product of abundance at age in each superstratum (p) and the area per superstratum, A_p (for $p = 1, 2, ..., P$), divided by the total area ($\sum_{p=1}^{P} A_p$) defined by A_N of the study area. That is,

$$mCPUE_{N,a} = \frac{\sum_{p=1}^{P} A_p \text{mCPUE}_{p,a}}{A_N} \tag{2.6}$$

For known variances of $\text{mCPUE}_{p,a}$, the variance of the mean abundance at age across supuerstrata, $mCPUE_{N,a}$, can be computed directly as

$$\text{Var}\left(mCPUE_{N,a}\right) = \frac{\sum_{p=1}^{P} A_p^2 \text{Var}\left(\text{mCPUE}_{p,a}\right)}{A_N^2}. \tag{2.7}$$

a combined ratio estimator with suitable variance estimator may be more appropriate than this current separate ratio estimator for the north sea

2.2 ALK Estimators

Three ALK estimators are presented in this section. The first is the DATRAS ALK estimator and two estimators that consider spatial variation in the data; a Haul based ALK estimator and a Model based ALK estimator.

2.2.1 DATRAS ALK Estimator

Let ALK^{D} be the ALK used in DATRAS, which is currently used for producing offical CPUE per age estimates. This is an aggregation of individual samples from a haul combined over a larger area, in this a round fish area (RFA). The $ALK^{\mathrm{D}}_{a,l,h}$ is defined as the proportion of observed fish with age a in length class l in the RFA. If there are no observed fish in length class l in the RFA, ages from length classes close to l is used. The details of the procedure for borrowing strength from neighbouring length classes are given in appendix D.1. The underlying assumption of this ALK^{D} approach is that age-length compositions are homogeneous within the RFAs. This is a rather strong assumption, and any violation have an unknown impact on the estimates of abundance indices. In fact, Kimura (1977) showed that the application of an age-length key to a population where the age composition differs from that of the population from which the age-length key was drawn will give bias results. Because the age-length key may be haul dependent we propose an ALK method that is based on trawl hauls, which we denote by ALK^{H}.

2.2.2 Haul Dependent ALK Estimator

We define a haul dependent ALK by ALK^{H}. The $ALK^{H}_{a,l^*,h}$ is defined as the average proportion of observed fish with age a in a pooled length class l^* in haul h. We use pooled length classes for this estimate since there are typically few observed length classes in a single haul. We define a pooled length class to consist of five length classes, the first pooled length class consist of the five smallest length classes and so on. If there are no observed ages of fish in a pooled length class l^* in the haul, ages from the same pooled length class in the haul closest in air distance from the hth haul is used. If there are no observed fish within the pooled length class in the closes haul, the next closes haul is used and so on. The details of borrowing strength from length classes in hauls closest in space is given in appendix D.2.

2.2.3 Spatial Model-Based ALK Estimator

The ALK approaches defined in Sections 2.2.1 and 2.2.2 use the method of "borrowing" age-length compositions within or between hauls for estimating abundance indices when data points for age-length combinations are missing. In this section we propose a statistical model-based approach to fill in missing values in an objective and robust manner, while accounting for the uncertainty that arises due to sampling variability. The statistical model allows the creation of a smooth distribution of age given length and location, and can include other covariates such as the random effect of the trawl haul. Spatial model-based approach of age-lengths has been widely used in fisheries assessment (Berg and Kristensen, 2012; Kvist et al., 2000; Rindorf and Lewy, 2001), where Continuous ratio logit (CRL) models were applied and where Generalized Linear Models (GLMs) have been used for estimation. Berg and Kristensen (2012) for example used Generalized Additive Models (GAMs) with......spline to model spatial effect of the data. While GAMs are .... there are some dangers when using these to model spatial effects.

We consider Logits (Dyke and Patterson, 1952; Agresti, 2003), which is a type of model for categorical response data (such as age groups) and, which have been previously used for modelling ALKs and estimating uncertainty (Gerritsen et al., 2006).

Let the response variable of the age group of a fish be $a = M, ..., A$ where M is the youngest age and A is the oldest age, which is typically defined as a "plus group". Suppose $y(l, \mathbf{s}, h)$ is the age of a fish with length l, caught at location $\mathbf{s}$ by trawl haul h, then the the probability of age a in a given year and quarter is given by:

$$\pi_a(y(l,\mathbf{s},h)) = \begin{cases} \frac{\exp(\mu_a)}{1+\sum_{i=M}^{A-1}\exp(\mu_a)}, & a < A \\ \frac{1}{1+\sum_{i=M}^{A-1}\exp(\mu_a)}, & a = A. \end{cases}, \tag{2.8}$$

where

$$\mu_a(l,\mathbf{s},h) = f_a(l) + \gamma_a(\mathbf{s}) + \nu_a(h). \tag{2.9}$$

Here $f_a^l(l)$ is a continuous function of length, $\boldsymbol{\gamma}$ is a mean zero Gaussian spatial random field with Matérn covariance function, and $\boldsymbol{\nu}$ is an independent identically distributed Gaussian random haul effect. The spatial random field is intended to capture any spatial variation in the ALK. The haul random effect is intended to capture any haul variations, for example, a haul may by chance hit a school of fish of a certain age.

We assume that the spatially correlated Gaussian field in (2.9), $\boldsymbol{\gamma}$, follows a stationary Matérn covariance structure:

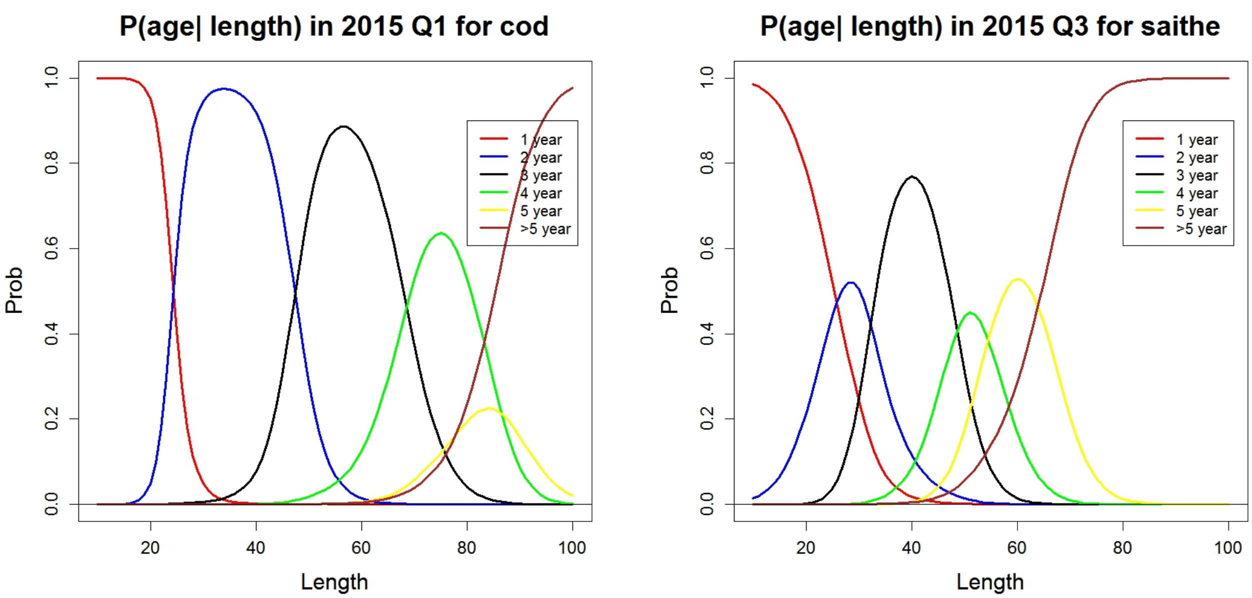
$$\text{Cov}(\gamma(\mathbf{s}_1),\gamma(\mathbf{s}_2)) = \frac{\sigma_\gamma^2}{2^{\nu-1}\Gamma(\nu)}(\kappa_\gamma||\mathbf{s}_1-\mathbf{s}_2||)^\nu K_\nu(\kappa_\gamma||\mathbf{s}_1-\mathbf{s}_2||), \tag{2.10}$$

where σ_γ^2 is the marginal variance, $||\cdot||$ is the Euclidean distance measure in kilometres, ν is a smoothing parameter, κ_γ is a spatial scale parameter and $K_\nu(\cdot)$ is the modified Bessel function of the second kind with $\nu = 1$. The spatial range parameter and marginal variances in the spatial fields are assumed to be equal across ages.

For each trawl haul, an ALK is obtained by maximizing the likelihood of the model in (2.8). The maximum likelihood estimate of μ_a is obtained using the R-package TMB (Kristensen et al., 2015) combined with the optimizing function *nlminb* in R. Advantages of using TMB in this application is that it utilizes the sparse structure in the precision matrix for the spatial field, it utilizes the Laplace approximation for the latent fields (both the spatial and the haul effect) for fast optimization of the hyperparameters, and it utilizes automatic derivation. Using such theory makes a good starting point for modeling of age distribution. A laptop with processor intel(R) Core(TM) i5-6300 CPU @ 2,40 GHz, used approximately 10 minutes to find the maximum likelihood estimate of the age given length model.

The spatial random field in the linear predictor for the age given length model (2.9) is estimated with the stochastic partial differential equation (SPDE) procedure described in (Lindgren et al., 2011). The theory behind the SPDE procedure is based on the precision matrix of a spatial field with Matérn covariance function can be approximated by a sparse matrix. This matrix is found by usage R-INLA package (Rue et al., 2009), and we further extracted the relevant parts needed from INLA to estimate the model in TMB.

Fish of a certain age might have a larger mean length in one area than another as a consequence of differential growth rates or size-specific migration. This is also the case for different species as can be seen in 3 which shows the age-length distributions of cod (left panel) and saithe (right panel). (**is the plot below a prediction of the whole north sea or specific areas of the North sea?**)



(a) age-length distribution of cod

(b) age-length distribution of saithe

Figure 3: Predicted probabilities of age given length using the model described in (2.8) for cod (left panel) and saithe (right panel) in Q1 and Q3, respectively for year 2015.

2.3 Uncertainty estimation

We use nonparametric bootstrapping to estimate the uncertainty of age of estimated CPUEs. Nonparametric resampling allows us to estimate the sampling distribution of the catch per unit effort empirically without making assumptions concerning the data. The percentile method is used to estimate 95% confidence intervals of the estimated CPUEs,. To obtain sufficiently accurate 95% bootstrap percentile confidence intervals, the number of bootstrap samples should be on the order of 1000 or more (see Carpenter and Bithell, 2000).

We start with the bootstrap procedure proposed by *DATRAS* (ICES, 2013) for this complex survey data. To construct the bth replicate, take a simple random sample with replacement of N_{p} trawl hauls from the original data in the combined strata in the round fish area (RFA) and placing it into the relevant statistical rectangle (stratum s); repeat independently across strata; estimate the parameter of interest, for example in (2.1); assuming O_i is the number of age observations from the ith length class in the RFA, sample with replacement O_i of these observations, and, if there is only one observed age in that length class sample either that fish or one which is closest in "length class distance"; estimate the parameters of interest: ALK defined in (2.2.1) and catch per unit effort per age class in (2.2), followed by the parameters defined for each stratum s and superstratum p in (2.3), and (2.4) and (2.5), respectively; repeat B times; and estimate the variance using

$$\frac{\sum_{b=1}^{B}\left(\theta^{*}{}_{(b)}-\theta^{*}{}_{(\cdot)}\right)^{2}}{(B-1)} \tag{2.11}$$

where $\theta^{*}{}_{(b)}$ is the bootstrap version of the statistic of interest. An example in this case is the mean catch per unit effort for age a in superstratum p given in (2.5); and $\theta^{*}{}_{(\cdot)}$ is the average of the bootstrapped statistics, that is, $\sum_{b=1}^{B}\theta^{*}{}_{(b)}/B$. This bootstrap procedure does not preserve the location of the trawl hauls, that is, stratification of trawl hauls is ignored, hence it is a simple nonparametric resampling procedure. Given the complex nature of the survey, this simple nonparametric resampling is not suitable (Kolenikov et al., 2010). The procedure is also based on the assumption that age-length structures are the same across strata within a round fish area

We propose the *naive* bootstrap procedure (Kolenikov et al., 2010) for complex survey data as an alternative to the DATRAS procedure for the ALK approach given in (2.2.1). To construct the bth replicate, take a simple random sample with replacement N_{s} trawl hauls from the original data in stratum s; repeat independently across strata; estimate the parameter of interest in (2.1); sample the age observations O_i as is done by the DATRAS procedure and estimate the ALK defined in (2.2.1) followed by the parameters of interest in (2.2), (2.3), (2.4) and (2.5); repeat B times; and estimate the variance using (2.11).

For our proposed ALK estimators in (2.2.2) and (2.2.3) we consider two bootstrap procedures. The first procedure, which we call the *stratified* bootstrap procedure is similar to the naive bootstrap described above. To construct the bth replicate, take a simple random sample with replacement N_{s} trawl hauls from the original data in stratum s, and if there is only one trawl haul in stratum s sample either that trawl haul or one closest in "air distance"; repeat independently across strata; estimate the parameter of interest in (2.1); the ALKs defined in (2.2.2) and 2.2.3) are also estimated from this sample; estimate further the parameters of interest in (2.2), (2.3), (2.4) and (2.5) and estimate the variance using (2.11). The stratified bootstrap procedure accounts for the variation within stratum s but does not account for the variation between strata.

The second procedure is a *hierarchical* bootstrap procedure by (Ren et al., 2010). The current data structure of IBTS is hierarchical in nature and such data types often includes multiple sources of variation. As such such, it would be important to take careful account of the multiple sources of variation as we are interested in abundance-at-age in North sea, which is computed based estimates obtained from strata and superstrata. The North Sea IBTS data has three level; haul, statistical rectangle (stratum s) and round fish area (superstratum p) but since an estimator for catch-at-age is provided for superstratum p we use a two-level hierarchical sampling strategy (hauls and statistical rectangle) for estimating uncertainty at the superstratum level, and a combined ratio estimator approach, described in ...., is used for estimating the uncertainty for the whole North Sea area. To construct the bth replicate assume there are S statistical rectangles (strata) in the pth RFA, and H_s trawl hauls in the sth statistical rectangle. At the first stage a random integer S^* from $\{1, 2, ..., S\}$ is chosen. At the second stage, we select H_{s^*} random integer .....(**both statistical rectangle and haul and sample 1 to n inclusive is chosen to be in the sample)**...

explain how confidence intervals are formed (percentile method)

2.4 Optimizing Sampling Effort

The North sea IBTS is carried twice a year: quarter 1 (January -February) and quarter 3 (July-September). We examined the sampling effort carried out over a five year period for IBTS for both quarters. From 2013 to 2018, on average there were 368 valid trawl hauls taken over an average period of 43 ship days in the first quarter between 6 nations, and 346 valid trawl hauls taken over an average of... ship days in third quarter between 7 nations. The number of otolith sampling per species per varies per length group and by nation. Some nations, for example......have been sampling otoliths per round fish area according the ICES guidelines

(ICES, 2006) during the years 2013-2017, while other nations such as Norway, UK Scotland and Netherlands have adopted a per-haul basis of sampling otoliths (see Table 8 in appendix C). From 2018 all nations are required to sample otoliths per specified length, for a given species, from each trawl haul. For example, for ....1 otolith per 1 cm length class, for herring and sprat 1 otoliths per 0.5 cm length class and (haddock, whiting and Norway pout - shell fish?) 2 otoliths per 5 cm length class.

In this Section we propose the following procedure for removing otoliths and or trawl hauls from the data to determine whether this would have an effect, and if any, how significant this effect is on the variance and the parameter estimates.

3 Case studies

In this section the method will be applied to data from the International Bottom Trawl Survey for the year 2015, which is obtained from the DATRAS database (`www.dtras.ices.dk`). The species of interest are cod and saithe and the samples are collected in the first and third quarters, respectively of the year 2015. All samples are caught using the standard GOV gear described in Section 1.1. Section 3.1 gives a brief description of the data

3.1 Summary of cod and saithe data in 2015

Otoliths are usually collected from a fraction of the fish sampled (see Table 8 in appendix **??**), but in some cases only a small number of fish are caught so otoliths are taken from all catches. (**include legend on plots and number of trawl hauls with length only and age data**)

Table 2: Summary of North Sea IBTS cod and saithe data for first and third quarters, respectively of 2015.

Data	**Description**
Trawl hauls	Total of 374 (387) trawl hauls in Q1 of 2015 (303 with length and or age information of cod) and total of 352 trawl hauls in Q3 of 2015 (...with length and or age information of saithe)
Age	The age of cod varied between 1 to 8 years, while saithe age ranged from 1 to ....
Length	Length information in cm of each cod varied between 8 to 112 cm while saithe varied between ... to ... cm
Date	Date of catch in Q1 varied between 13.01.2015 to 19.02.2015 and in Q3 between 26.07.2015 to 06.09.2015
Statistical rectangle	The stratum in which at least two trawl hauls are made
Coordinates	Geographic coordinates of each trawl haul in a statistical rectangle
Duration of haul	Mean duration is 25.9 minutes, with 15 to 30 minutes as 90% coverage interval.
Total count for all ages	7605 cod in Q1 of 2015 and ....saithe in Q3 of 2015.

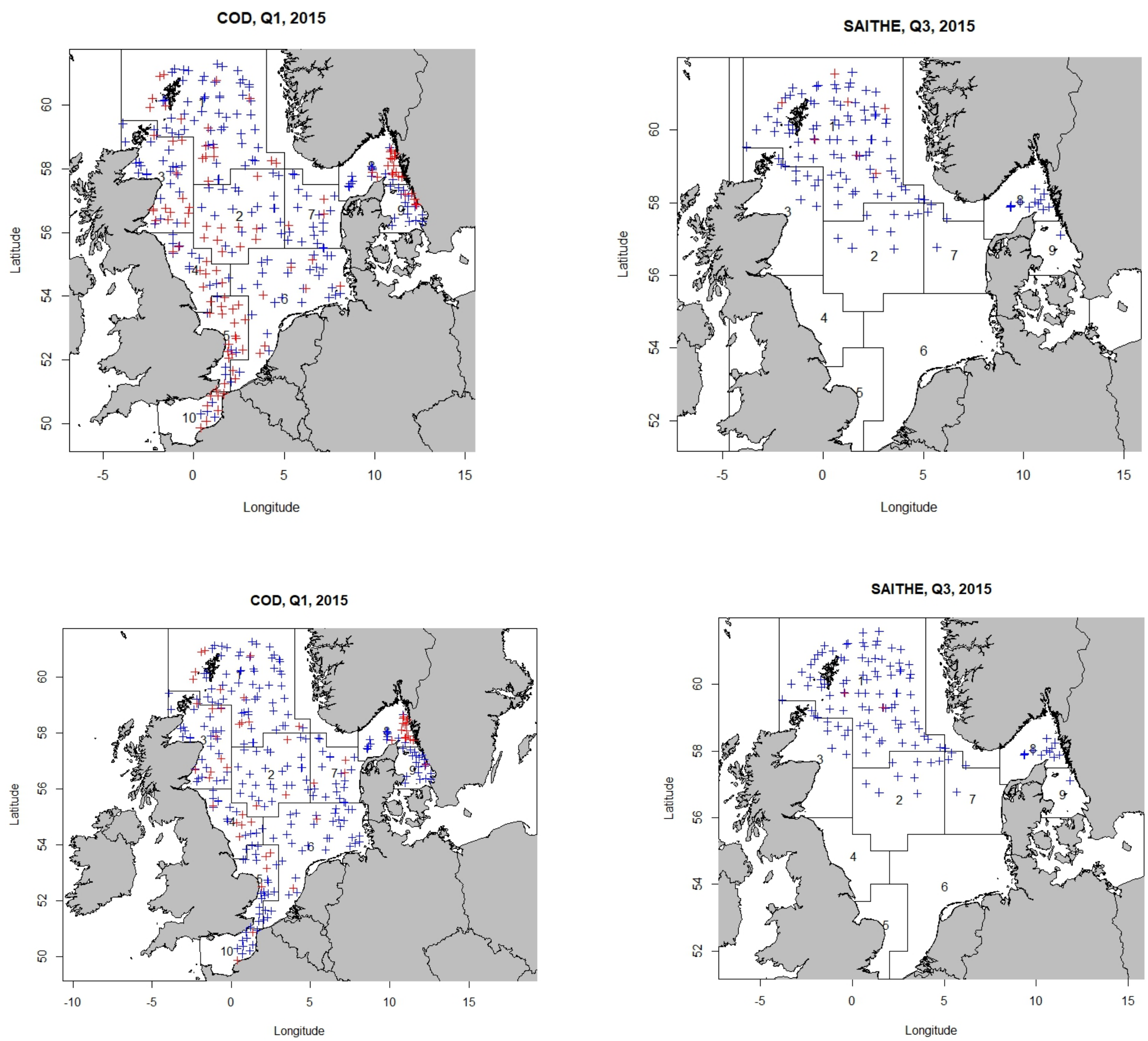


Figure 4: cod with length class 1 cm (upper left) and length class 5 cm (lower left), and saithe with length class 1cm (upper right) and length class 5 cm (lower right)

4 RESULTS

4.1 Estimates of abundance-at-age and their uncertainty

Table 3: Estimates of abundance indices (Index), and estimated standard errors for 400 bootstrap samples from the following bootstrap procedures: DATRAS, Naive, Stratified, and Hierarchical for cod in RFA 1 in the first quarter of year 2015. Approximate 95% confidence intervals (CI) are also given.

	DATRAS ALK DATRAS Bootstrap			**Haul-based ALK** Stratified Bootstrap			**Model-based ALK** Stratified Bootstrap		
Age (a)	Abundance estimate	Standard error	Relative standard error	Abundance estimate	Standard error	Relative standard error	Abundance Estimate	Standard error	Relative standard error
0	0	0	–	0	0	–	0	0	–
1	0.764	0.26	34%	0.60	0.24	40%	0.70	0.36	51%
2	21.989	6.76	31%	22.21	4.15	19%	22.11	4.28	19%
3	11.285	2.19	19%	10.58	1.20	11%	10.99	1.77	16%
4	3.265	0.71	22%	3.67	1.28	35%	3.50	0.87	25%
5	1.147	0.34	30%	1.27	0.42	33%	1.20	0.48	40%
6+	1.276	0.38	30%	1.40	0.70	50%	1.21	0.42	35%
				Approximate 95% CI from bootstrap procedures					
0	0	(0, 0)		0	(0, 0)		0	(0, 0)	
1	0.764	(0.31, 1.33)		0.60	(0.31, 0.91)		0.70	(0.35, 1.48)	
2	21.898	(12.73, 37.15)		22.21	(15.64, 30.72)		22.11	(14.76, 30.36)	
3	11.285	(6.31, 15.02)		10.58	(8.74, 13.65)		10.99	(8.61, 15.42)	
4	3.265	(1.49, 4.21)		3.67	(2.81, 4.74)		3.50	(1.96, 5.60)	
5	1.147	(0.40, 1.75)		1.27	(0.67, 2.31)		1.20	(0.56, 2.78)	
6+	1.276	(0.44, 1.82)		1.40	(0.78, 2.69)		1.21	(0.70, 2.43)	

Table 4: Estimates of abundance indices (Index), and estimated standard errors for 400 bootstrap samples from the following bootstrap procedures: DATRAS, Naive, Stratified, and Hierarchical for cod in RFA 1 in the first quarter of year 2015. Approximate 95% confidence intervals (CI) are also given.

	DATRAS ALK			**Haul-based ALK**				**Model-based ALK**			
Age (a)	Index	DATRAS	Naive	Index	Naive	Stratified	Hierarchical	Index	Naive	Stratified	Hierarchical
1	0	0	0	0	0	0	0	0	0	0	0
2	0.764	0.26	0.23	0.60	0.24	0.16	0.81	0.70	0.36	0.31	0.78
3	21.989	6.76	4.08	22.21	4.15	4.20	13.23	22.11	4.28	4.26	10.69
4	11.285	2.19	1.27	10.58	1.20	1.28	5.85	10.99	1.77	1.84	4.53
5	3.265	0.71	0.57	3.67	1.28	0.56	3.02	3.50	0.87	0.94	2.46
6	1.147	0.34	0.33	1.27	0.43	0.43	1.59	1.20	0.48	0.62	0.83
7	1.276	0.38	0.39	1.40	0.70	0.53	2.01	1.21	0.42	0.46	0.85
					Approximate 95% **CI from bootstrap procedures**						
1	0	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)
2	0.764	(0.31, 1.33)	(0.40, 1.22)	0.60	(0.20, 1.18)	(0.31, 0.91)	(0, 3.81)	0.70	(0.37, 1.81)	(0.35, 1.48)	(0.05, 2.05)
3	21.898	(12.73, 37.15)	(14.90, 30.01)	22.21	(15.01, 30.09)	(15.64, 30.72)	(11.34, 61.57)	22.11	(14.56, 30.61)	(14.76, 30.36)	(7.12, 41.41)
4	11.285	(6.31, 15.02)	(9.63, 14.42)	10.58	(8.75, 13.54)	(8.74, 13.65)	(0, 17.73)	10.99	(8.45, 15.43)	(8.61, 15.42)	(3.90, 19.99)
5	3.265	(1.49, 4.21)	(2.45, 4.50)	3.67	(2.42, 7.35)	(2.81, 4.74)	(0, 8.26)	3.50	(2.11, 5.56)	(1.96, 5.60)	(0.87, 8.10)
6	1.147	(0.40, 1.75)	(0.67, 1.95)	1.27	(0.50, 2.14)	(0.67, 2.31)	(0, 4.35)	1.20	(0.58, 2.50)	(0.56, 2.78)	(0.15, 2.98)
7	1.276	(0.44, 1.82)	(0.72, 2.24)	1.40	(0.71, 3.42)	(0.78, 2.69)	(0, 5.15)	1.21	(0.70, 2.27)	(0.70, 2.43)	(0.09, 3.22)

Table 5: Estimates of abundance indices (Index), and estimated standard errors for 200 bootstrap samples from the following bootstrap procedures: DATRAS, Naive, Stratified, and Hierarchical for cod in RFA 1 in the first quarter of year 2015. Approximate 95% confidence intervals (CI) are also given.

	DATRAS ALK			**Haul-based ALK**				**Model-based ALK**			
Age (a)	Index	DATRAS	Naive	Index	Naive	Stratified	Hierarchical	Index	Naive	Stratified	Hierarchical
1	0	0	0	0	0	0	0	0	0	0	0
2	0.764	0.26	0.24	0.60	0.23	0.17	2.55	0.70	0.34	0.45	0.48
3	21.989	7.30	3.89	22.21	4.14	4.19	9.61	22.11	4.46	4.10	13.23
4	11.285	2.29	1.30	10.58	1.18	1.29	4.72	10.99	2.37	1.94	5.20
5	3.265	0.74	0.57	3.67	1.18	0.58	2.00	3.50	0.93	0.89	3.28
6	1.147	0.35	0.37	1.27	0.42	0.42	0.91	1.20	0.46	0.56	1.28
7	1.276	0.41	0.40	1.40	0.73	0.52	0.85	1.21	0.42	0.43	2.63
					Approximate 95% **CI from bootstrap procedures**						
1	0	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)
2	0.764	(0.27, 1.29)	(0.40, 1.34)	0.60	(0.31, 1.15)	(0.31, 0.93)	(0, 7.22)	0.70	(0.40, 1.72)	(0.38, 1.89)	(0.02, 1.72)
3	21.898	(12.70, 37.67)	(15.46, 29.63)	22.21	(15.22, 30.25)	(14.65, 30.18)	(3.65, 40.02)	22.11	(14.33, 3097)	(14.71, 29.90)	(3.71, 54.91)
4	11.285	(6.64, 15.33)	(9.47, 14.32)	10.58	(8.94, 13.54)	(9.14, 13.94)	(0, 15.63)	10.99	(8.44, 16.60)	(8.65, 16.07)	(1.84, 21.53)
5	3.265	(1.56, 4.46)	(2.43, 4.39)	3.67	(2.46, 6.59)	(2.75, 4.77)	(0, 7.18)	3.50	(2.18, 5.30)	(1.92, 5.07)	(0.10, 10.07)
6	1.147	(0.39, 1.77)	(0.64, 1.96)	1.27	(0.39, 2.02)	(0.69, 2.27)	(0, 3.83)	1.20	(0.54, 2.39)	(0.60, 2.79)	(0.01, 3.30)
7	1.276	(0.42, 2.13)	(0.75, 2.28)	1.40	(0.62, 3.23)	(0.78, 2.68)	(0, 2.38)	1.21	(0.70, 2.30)	(0.66, 2.26)	(0., 3.09)

Table 6: Estimates of abundance indices (Index), and estimated standard errors from the following bootstrap procedures: DATRAS, Naive, Stratified, and Hierarchical for saithe in RFA 1 in the third quarter of year 2015. Approximate 95% confidence intervals (CI) are also given.

	DATRAS ALK			**Haul-based ALK**				**Model-based ALK**			
Age (a)	Index	DATRAS	Naive	Index	Naive	Stratified	Hierarchical	Index	Naive	Stratified	Hierarchical
1	0	0	0	0	0	0	0	0	0	0	0
2	0.764	0.26	0.24	0.60	0.23	0.17	2.55	0.70	0.34	0.45	0.48
3	21.989	7.30	3.89	22.21	4.14	4.19	9.61	22.11	4.46	4.10	13.23
4	11.285	2.29	1.30	10.58	1.18	1.29	4.72	10.99	2.37	1.94	5.20
5	3.265	0.74	0.57	3.67	1.18	0.58	2.00	3.50	0.93	0.89	3.28
6	1.147	0.35	0.37	1.27	0.42	0.42	0.91	1.20	0.46	0.56	1.28
7	1.276	0.41	0.40	1.40	0.73	0.52	0.85	1.21	0.42	0.43	2.63
					Approximate 95% **CI from bootstrap procedures**						
1	0	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)	0	(0, 0)	(0, 0)	(0, 0)
2	0.764	(0.27, 1.29)	(0.40, 1.34)	0.60	(0.31, 1.15)	(0.31, 0.93)	(0, 7.22)	0.70	(0.40, 1.72)	(0.38, 1.89)	(0.02, 1.72)
3	21.898	(12.70, 37.67)	(15.46, 29.63)	22.21	(15.22, 30.25)	(14.65, 30.18)	(3.65, 40.02)	22.11	(14.33, 3097)	(14.71, 29.90)	(3.71, 54.91)
4	11.285	(6.64, 15.33)	(9.47, 14.32)	10.58	(8.94, 13.54)	(9.14, 13.94)	(0, 15.63)	10.99	(8.44, 16.60)	(8.65, 16.07)	(1.84, 21.53)
5	3.265	(1.56, 4.46)	(2.43, 4.39)	3.67	(2.46, 6.59)	(2.75, 4.77)	(0, 7.18)	3.50	(2.18, 5.30)	(1.92, 5.07)	(0.10, 10.07)
6	1.147	(0.39, 1.77)	(0.64, 1.96)	1.27	(0.39, 2.02)	(0.69, 2.27)	(0, 3.83)	1.20	(0.54, 2.39)	(0.60, 2.79)	(0.01, 3.30)
7	1.276	(0.42, 2.13)	(0.75, 2.28)	1.40	(0.62, 3.23)	(0.78, 2.68)	(0, 2.38)	1.21	(0.70, 2.30)	(0.66, 2.26)	(0., 3.09)

4.2 Optimum Sampling Effort for North Sea cod and saithe

5 DISCUSSION

- We have investigated three ALK estimators: 1) DATRAS ALK, 2)Haul-based ALK and 3) Model-based ALK

- discuss ALK estimators, which of the three is the most appropriate at this time, discuss model-based ALK and compare with Berg and Kristensen (2012) as they are similar are both used on IBTS data

- How can estimators be improved, also computational time (1000 bootstrapped samples for each of the four estimators took hours (possibly more than ten, needs verification))

- Possibly consider hierarchical bootstrapping as done in Ren et al. (2010) - draft codes are available

- Discuss next steps for example, removal of otoliths or age information and trawl hauls: the effect may be substantial for larger fish (hence older fish) - as shown in table **??** fewer older fish are sampled and many younger ones are sampled so the effect would be marginal for younger fish). Draft codes are available for this. Wieland et al. (2009) found that considerable catches for cod of older ages were made where the IBTS reported low densities or no cod all (*this is based on data from collaborative fishermen-biologists project on cod in the north-eastern central North Sea*). Also smaller sample sizes would also have an effect on estimated bootstrapped confidence intervals. The smaller the original sample the less likely it is to represent the entire population, thus the more difficult it becomes to compute valid confidence intervals. The bootstrap relies heavily on the tails of the estimated sampling distribution when computing confidence intervals, and using small samples may jeopardize the validity of this computation.

- a possible full model-based approach for estimating abundance at age with variance simultaneously?

- *Note to us: include ICES references*

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Appendices

A Probability Plot for saithe in the North Sea in Q1 of 2015

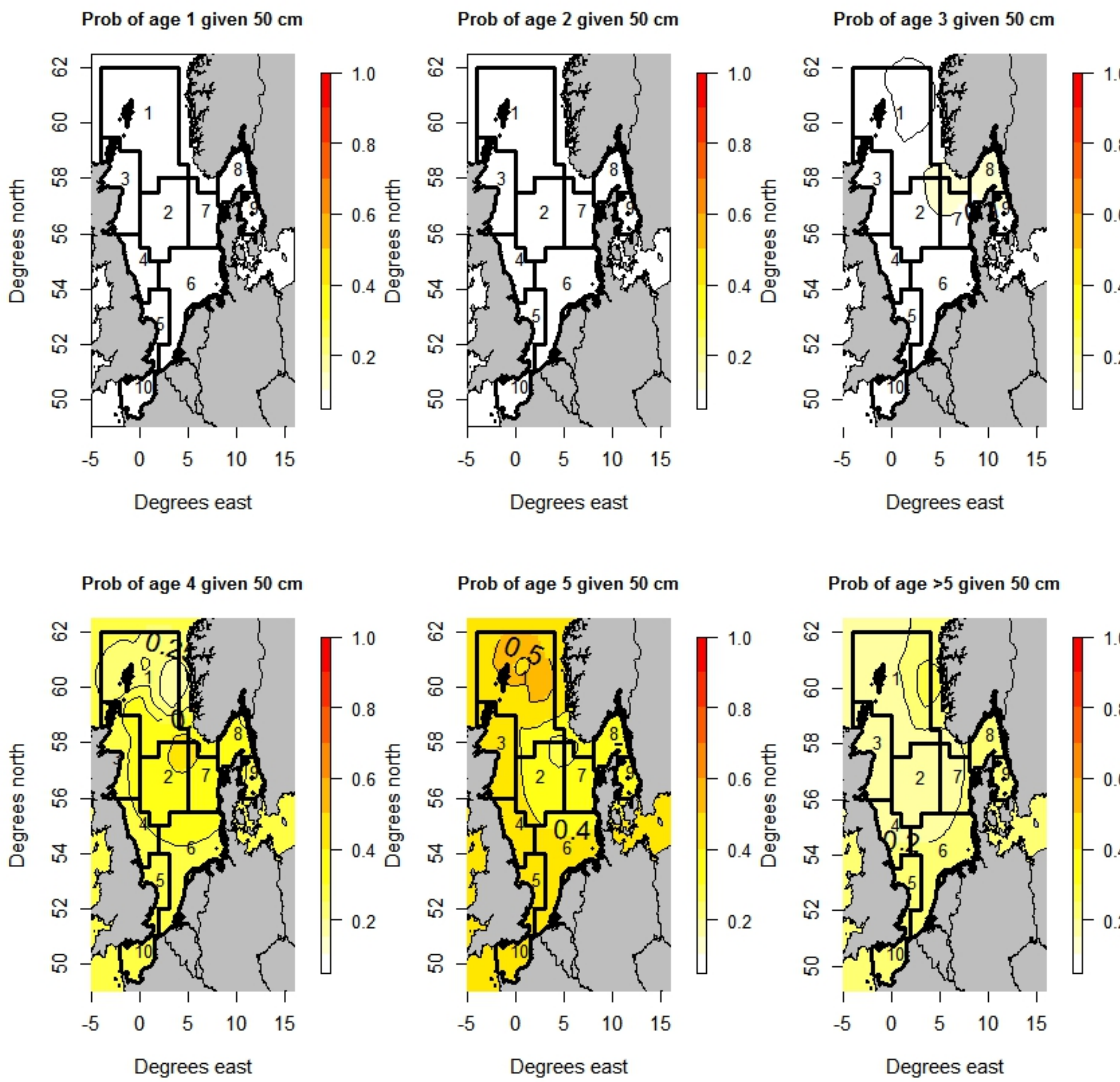

Figure 5: Estimated probability of age of a 50 cm long saithe in the first quarter of year 2015. The probability of age 1 to age 3 is approximately zero. The polygones marked 1 to 10 is the round fish areas (RFAs) where the ALK is assumed constant in the currently used estimators of the official CPUEs. The plots show that the age of saithe is more likely to be 5 given that it is 50 cm, particularly in RFA 1.

B Areas fished by different countries in the North Sea IBTS

Typically, two different countries fish each rectangle so that at least two trawl hauls are made per rectangle. But, intensified sampling is carried out in the following areas: at least 3 hauls per rectangle are taken in statistical rectangles 31F1, 31F2, 32F1, 33F4, 34F2, 34F3, 34F4, 35F3, 35F4; while six or more hauls per rectangle are taken in statistical rectangles 30F1, 32F2, 32F3, 33F2, 33F3 (ICES 1999). The Skagerrak and Kattegat is fished solely by Sweden, who sample more than once in every rectangle while the west of Shetland (in Q1 and Q3) and inshore areas (Q3) is fished solely by Scotland. The edge of the Norwegian Trench is fished solely by Norway, but inshore areas near Denmark is fished by Denmark. The southern North Sea is fished by Denmark, Germany and England. France, typically, is the only country that surveys the western English Channel. Areas are surveyed by a single country because of the large proportion of untrawalable area (and subsequent gear damage issues experienced by other nations) for efficient logistical purposes. Table 7 gives the countries and research vessels participating the North Sea IBTS.

Table 7: Survey countries, vessel name, and period research vessels participating in first quarter (Q1) and third quarter (Q3) during 1997-2017.

	First Quarter (Q1)		**Third Quarter (Q3)**	
Country	Vessel name	Period	Vessel name	Period
Denmark	Dana	January-February	Dana	July-August
France	Thalassa II	January-February	-	-
Germany	Walther Herwig III	January-February	Walther Herwig III	July-August
Netherlands	Tridens 2	January-February	-	-
Norway	G.O. Sars	January-February	Johan Hjort	July
UK England	-	-	Endeavour	August-September
UK Scotland	Scotia III	January-February	Scotia III	July-August
Sweden	Dana	January-February	Dana	August

C Otolith sampling per fish species

From 1991-2017, most countries conducted quota sampling of otoliths per length group in a RFA. But from 2013 Norway has been sampling one otolith per length class from each trawl haul (to 0.1cm below for shellfish, to 0.5cm below for herring and sprat and to 1cm below for all other species). From the first quarter in 2018 all countries are required to sample one otolith per length class per trawl haul. Table 8 gives the minimum sampling levels of otoliths for the target species. However, for the smallest size groups, that presumably contain only one age group, the number of otoliths per length class may be reduced, and more otoliths per length are required for the larger length classes.

Table 8: Minimum sampling levels of otoliths by species for RFA or per trawl haul.

Period	Species	Minimum sampling levels of otoliths per length class
1991-2017		**Number of otoliths per length class in a RFA**
	herring	8 otoliths per $\frac{1}{2}$ cm group
	sprat	16 otoliths per $\frac{1}{2}$ cm length class $8.0 - 11.0$ cm
		12 otoliths per $\frac{1}{2}$ cm length class ≥ 11.0 cm
	mackerel	8 otoliths per $\frac{1}{2}$ cm length class
	cod	8 otoliths per 1 cm length class
	haddock	8 otoliths per 1 cm length class
	whiting	8 otoliths per 1 cm length class
	Norway pout	8 otoliths per 1 cm length class
	saithe	8 otoliths per 1 cm length class
	All target species	From 2013 Norway and Scotland, and Netherlands from 2016 have been sampling 1 otoliths per length class from each trawl haul (to 0.1cm below for shellfish, to 0.5cm below for herring and sprat, and to 1cm below for all other species).
2018		**Number of otoliths per length class per trawl haul**
	herring	1 otoliths per $\frac{1}{2}$ cm group
	sprat	1 otoliths per $\frac{1}{2}$ cm length class $8.0 - 11.0$ cm
		1 otoliths per $\frac{1}{2}$ cm length class ≥ 11.0 cm
	mackerel	1 otoliths per 1 cm length class
	cod	1 otoliths per 1 cm length class
	haddock	2 otoliths per 5 cm length class $11 - 15,\ 16 - 20,\ 21 - 25,\ 26 - 30$ cm
	Norway pout	2 otoliths per 5 cm length class $5 - 10,\ 11 - 15$ cm
		2 otoliths per 1 cm length class > 15 cm
	saithe	1 otoliths per 1 cm length class
	plaice	1 otoliths per 1 cm length class

D Imputation for missing age samples

Catches of the target species are sampled (or subsampled with a size of 100 if the catches are too large) for length, and otoliths are typically collected from a subsample of the individuals sampled for length in the RFA, or per trawl haul as in the case of Norway for determining age of the fish (see Table 8). In the case of Norway where all trawl hauls are sampled for otoliths, missing age samples would still occur for the following two reasons: 1) the fish is below minimum length for otolith sampling (unreadable otoliths) or 2) otoliths are misplaced. Abundance indices by age group are estimated based on three age-length-keys (ALK): 1) DATRAS ALK estimator, 2) Haul dependent ALK estimator, and 3) Spatial model-based ALK estimator.

D.1 DATRAS ALK Borrowing Approach

The ALK proposed in DATRAS (ICES 2013), which is an aggregation of individual samples from a haul combined over a round fish area (RFA), and missing age samples are imputed as follows:

1. If there is no ALK for a length in the CPUE dataframe, age information is obtained accordingly
    - If length class (CPUE) $<$ minimum length class (ALK), then age=1 for the first quarter and age=0 for all other quarters
    - If minimum length class (ALK) $<$ length class (CPUE) $<$ maximum length (ALK) then age is set to the nearest ALK. If the ALK file contains values at equal distance, a mean is taken from both values.
2. If length class (CPUE) $>$ maximum length (ALK) age is set to the plus group.

The underlying assumption of this ALK approach is that age-length compositions are homogeneous within the superstrata.

D.2 Haul-based ALK Borrowing Approach

The second is an a haul dependent ALK estimator which we propose, and is denoted by ALK^H. Since the age-length composition of fish may be space-variant, that is, there may be variation in age-length compositions between trawl stations within a superstrata, the spatial dependence of the age-length composition must be accounted for to produce reliable estimates of the CPUE per age estimates. If this spatial dependence is ignored not only will estimates of abundance be biased but the impact on the variance may be substantial. So for each trawl haul an ALK^H is produced. Since there are few or none observations of ages for each length class in a trawl haul, length classes are therefore pooled in increasing order such that there are five length classes in each pooled length group. To replace missing values for the age distribution in the pooled length groups the method of "borrowing" ages from length groups in trawl hauls closest in air distance within the RFA is used. If there are no observed ages in the pooled length group in the RFA, missing values for the age distribution are replaced following the procedure outlined in the DATRAS ALK procedure (D.1) in step 1.

E Weightings of Statistical Rectangles

Weights of the statistical rectangle based on its surface area (10 – 200 meter in the North Sea and 10 -250 meter in the Skagerrak and Kattegat)

StatRec	Weight	StatRec	Weight	StatRec	Weight	StatRec	Weight	StatRec	Weight
31F1	0.6	38F0	1	41F6	1	44F1	1	47G0	0.3
31F2	0.8	38F1	1	41F7	1	44F2	1	47G1	0.02
31F3	0.05	38F2	1	41F8	0.1	44F3	1	48E6	1
32F1	0.8	38F3	1	41G0	0.2	44F4	1	48E7	1
32F2	1	38F4	1	41G1	0.97	44F5	0.9	48E8	0.9
32F3	0.8	38F5	1	41G2	0.53	44F8	0.25	48E9	1
32F4	0.01	38F6	1	42E7	0.4	44F9	0.8	48F0	1
33F1	0.3	38F7	1	42E8	1	44G0	0.94	48F1	1
33F2	1	38F8	0.3	42E9	1	44G1	0.6	48F2	1
33F3	1	39E8	0.5	42F0	1	45E6	0.4	48F3	0.5
33F4	0.4	39E9	1	42F1	1	45E7	1	48G0	0.02
34F1	0.4	39F0	1	42F2	1	45E8	1	49E6	0.8
34F2	1	39F1	1	42F3	1	45E9	1	49E7	1
34F3	1	39F2	1	42F4	1	45F0	1	49E8	0.4
34F4	0.6	39F3	1	42F5	1	45F1	1	49E9	1
35F0	0.8	39F4	1	42F6	1	45F2	1	49F0	1
35F1	1	39F5	1	42F7	1	45F3	1	49F1	1
35F2	1	39F6	1	42F8	0.2	45F4	0.6	49F2	1
35F3	1	39F7	1	42G0	0.32	45F8	0.3	49F3	0.5
35F4	0.9	39F8	0.4	42G1	0.89	45F9	0.02	50E6	0.1
35F5	0.1	40E7	0.04	42G2	0.64	45G0	0.24	50E7	0.6
36F0	0.9	40E8	0.8	43E7	0.03	45G1	0.55	50E8	0.7
36F1	1	40E9	1	43E8	0.9	46E6	0.4	50E9	0.9
36F2	1	40F0	1	43E9	1	46E7	0.9	50F0	1
36F3	1	40F1	1	43F0	1	46E8	1	50F1	1
36F4	1	40F2	1	43F1	1	46E9	1	50F2	1
36F5	1	40F3	1	43F2	1	46F0	1	50F3	0.2
36F6	0.9	40F4	1	43F3	1	46F1	1	51E6	0
36F7	0.4	40F5	1	43F4	1	46F2	1	51E7	0
36F8	0.5	40F6	1	43F5	1	46F3	0.8	51E8	0.5
37E9	0.2	40F7	1	43F6	1	46F9	0.3	51E9	1
37F0	1	40F8	0.1	43F7	1	46G0	0.52	51F0	1
37F1	1	41E6	0.03	43F8	0.94	46G1	0.2	51F1	1
37F2	1	41E7	0.8	43F9	0.41	47E6	0.8	51F2	0.5
37F3	1	41E8	1	43G0	0.21	47E7	0.6	51F3	0
37F4	1	41E9	1	43G1	0.7	47E8	1	52E6	0
37F5	1	41F0	1	43G2	0.3	47E9	1	52E7	0
37F6	1	41F1	1	44E6	0.5	47F0	1	52E8	0
37F7	1	41F2	1	44E7	0.5	47F1	1	52E9	0.1
37F8	0.8	41F3	1	44E8	0.9	47F2	1	52F0	0.2
38E8	0.2	41F4	1	44E9	1	47F3	0.6	52F1	0.5
38E9	0.9	41F5	1	44F0	1	47F9	0.01	52F2	0.1
								52F3	0

Figure 6