

₁ Optimising sampling effort of the North Sea International Bottom
₂ Trawl Survey Data

₃

₄ **Abstract**

₅ In this research we present nonparametric estimation procedures for calculating abundance at age
₆ indices, and investigate the sensitivity of these estimates with respect to the number of otoliths collected
₇ at sea. The procedures presented are applied to the North Sea International Bottom Trawls Survey data
₈ for cod (*Gadus morhua*) and saithe (*Pollachius virens*). We demonstrate how much information would
₉ be lost if the survey design was defined such that fewer otoliths were collected. Age length keys (ALKs)
₁₀ are used to map lengths to age, and we use ALKs with and without the assumption of constant age length
₁₁ structures over relatively large areas. All abundance at age indices are presented with variance estimates.

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₁₃ **1 Introduction**

₁₄ Fish stock assessments are used by fishery managers for making management decisions regarding catch
₁₅ quotas. The assessments provide fundamental information about the status of the stock, for instance,
₁₆ whether the stock is increasing and support for increased levels of harvest should be given, or whether the
₁₇ stock is decreasing and stricter control on harvest should be implemented. Associated with the parameters
₁₈ used in fish stock assessment is their uncertainty, which should not be ignored when formulating management
₁₉ policies (Walters and Ludwig, 1981; Ludwig and Walters, 1981; Berg et al., 2014). This uncertainty can arise
₂₀ from many sources including natural variability, estimation procedures and lack of knowledge regarding the
₂₁ parameter (Ehrhardt and Legault, 1997). The North Sea International Bottom Trawl Survey (IBTS) data,

²² coordinated by the International Council for the Exploration of the Sea (ICES), provides information on
²³ seasonal distribution of stocks and estimates of abundance indices and catch in numbers of fish per age-class
²⁴ without an assessment of the accuracy of these estimates. As stated by Ludwig and Walters (1981) it is
²⁵ relevant for managers to take into the uncertainty related to stock size when making management policies. The
²⁶ indices of abundance at age from IBTS are based on data obtained from a stratified semi-random sampling
²⁷ approach of trawl stations, and it is essential to account for the sampling approach so as to produce reliable
²⁸ variance estimates (Lehtonen and Pahkinen, 2004). If the sampling approach is ignored, the effect on the
²⁹ variance of the parameters could be substantial. In particular, the variance could be greatly inflated due
³⁰ to the clustering effect, which involves intra-cluster correlation of the variables (Aanes and Vølstad, 2015;
³¹ Lehtonen and Pahkinen, 2004).

³² There are two separate stages for generating abundance indices per age from the North Sea International
³³ Bottom Trawl Survey (IBTS) data. The first consist of calculating indices per *length* class, which are
³⁴ obtained by trawling in a stratified manner and counting the number of fish caught. Then that knowledge is
³⁵ transformed to indices with respect to age. The latter part is achieved with an age-length key (ALK), which
³⁶ is constructed by sampling otoliths in a stratified procedure from each haul and/or sub-area. To our best
³⁷ knowledge, there has been no research on how much the uncertainty of the abundance indices is related to
³⁸ these two distinct parts. The main contribution of this research is to shed light on how the indices estimates
³⁹ and their associated uncertainty estimates change if less effort was spent on collection of otoliths. We achieve
⁴⁰ the reduction of otoliths by mimicking a defined sampling procedure with less effort. We also focus on the
⁴¹ spatial distribution of the ALK, and such spatial structures in the ALK has also been investigated in Berg
⁴² and Kristensen (2012) and Hirst et al. (2012).

⁴³ Currently, abundance indices from IBTS are reported in DATRAS (ICES, 2018c) using an age-length key
⁴⁴ (ALK) (Fridriksson, 1934) which is assumed to be constant over relatively large areas. In this research we
⁴⁵ propose two ALKs which accounts for spatial variation: i) a nonparametric haul base ALK, and ii) a spatial
⁴⁶ model base ALK. These ALKs are described in Section 2. A spatial model base ALK (Berg and Kristensen,
⁴⁷ 2012; Berg et al., 2014) known as the NS-IBTS Delta-GAM index (ICES, 2016b) is currently being used
⁴⁸ to calculate standardized age-based survey indices used in assessment for the North Sea stock. And, as far

49 as we are aware the variance estimates of parameters estimated from NS-IBTS Delta-GAM index are *only*
50 utilized for assessment of Herring (*Clupea harengus*) in the North Sea.

51 The spatial ALK model introduced in Berg and Kristensen (2012) is similar to the model used in this
52 paper; the main difference is that we include the spatial structure through a spatial random field (Lindgren
53 et al., 2011) and not through two dimensional splines (Wood, 2017).

54 An overview of the North Sea International Bottom Trawl Survey is given in Section 1.1. The current
55 estimators for ALK and catch per unit effort (CPUE) used by ICES in their database for trawl surveys
56 (DATRAS) and our proposed ALK estimators are given in Section 2. We apply these ALK methods to two
57 case studies in Section 3, and a discussion is given in Section 4.

58 **1.1 Overview of the North Sea International Bottom Trawl Survey**

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

65 The North Sea IBTS began with quarterly surveys providing information on seasonal distribution of
66 stocks sampled, hydrography and the environment, which allows changes in fish stock to be monitored and
67 abundance of all fish species to be determined. These quarterly surveys, however became difficult to sustain
68 as countries experienced budget cuts making it impossible to maintain high levels of research vessel effort.

69 As such, in 1997 countries carried out a survey only twice a year; a first quarter survey (January-February)
70 and a third quarter survey (July-September). The target species of IBTS fished from 1991-2018 includes
71 standard pelagic species: Herring (*Clupea harengus*), Sprat (*Sprattus sprattus*) and Mackerel (*Scomber*
72 *scombrus*); and standard roundfish species: Cod (*Gadus morhua*), Haddock (*Melanogrammus aeglefinus*),
73 Saithe (*Pollachius virens*), Norway Pout (*Trisopterus esmarkii*) and Whiting (*Merlangius merlangus*). There
74 are also several by-catch species (see for example, ICES, 2006)

75 Research vessels from seven nations in the first quarter (Q1) and six nations in the third quarter (Q3)
76 are used for conducting surveys on all finfish species in the North Sea during January–February and July–
77 August, respectively, between 1997–2018 (Table S1.1 in Supplementary Materials S1 gives details of the
78 research vessels). The sampling frame is defined by the ICES index or roundfish areas (RFA) as shown
79 in Figure 1 numbered 1 to 10. These roundfish areas were substratified into small strata defined by non–
80 overlapping statistical rectangles of roughly 30×30 nautical miles (1° Longitude \times 0.5° Latitude), and
81 were convenient to use for IBTS as they were already being used for fisheries management purposes. Most
82 statistical rectangles contain a number of possible tows that are deemed free of obstructions, and vessels
83 are free to choose any position in the rectangles as long as the hauls are separated by at least 10 nautical
84 miles within and between rectangles. However, all countries select tows based on a semi-random approach
85 from databases of national safe tows or DATRAS or commercial fishing data, except Sweden who uses fixed
86 stations and in some cases depth-stratified semi-random sampling design (ICES, 2018b); and England who
87 also uses fixed stations and only conduct surveys during the third quarter. In some rectangles, sampling
88 may be further stratified due to significant changes in seabed depth which may, in turn, cause variations in
89 the fish population. In particular, the North Sea IBTS herring, saithe and sprat data are weighted by depth
90 strata in the statistical rectangle (see Table S3.1 in appendix S3). It is also a requirement that countries
91 avoid clustering their stations between adjacent rectangles in order to reduce positive serial correlation, and
92 thereby maximize survey precision. The latest major reallocation of rectangles occurred in 1991, but since
93 then the survey has tried to keep at least one vessel in every subarea in which it had fished in the most recent
94 years. Minor reallocation of rectangles between Norway, Scotland and Germany was done in 2013. Each
95 rectangle was typically sampled twice by two different countries before 1997, but after that target coverage
96 of two trawl hauls per rectangle per survey was introduced because of national financial constraints (ICES,
97 2015). But in some rectangles in the Eastern English Channel, Southern North Sea and Central North Sea
98 intensified sampling is carried out.

99 The recommended standard trawling gear of the North Sea IBTS is the mulitpurpose chalut à Grande
100 Ouverture Verticale (GOV) trawl (ICES, 2012), which has been used on all participating vessels since 1992,
101 while different pelagic and bottom trawls suitable for fishing finfish species were used before 1992. Standard–

102 ized trawling protocols were adopted with a towing speed of 4 knots but depending on vessel performance,
 103 tide and weather conditions the average towing speed can be at minimum 3.5 and maximum 4.5 knots. From
 104 2000-2018 trawling is done during the daylight hours, which are considered 15 minutes before sunrise to 15
 105 minutes after sunset (ICES, 2012). After each trawl the total catch of the different species is weighed on
 106 board and biological parameters such as length for all fish species caught (to 0.1 cm below for shellfish, to
 107 0.5 cm below for herring and sprat and to 1 cm below for all other species) are collected. Where the numbers
 108 of individuals are too large for all of them to be measured to obtain the length distribution, a representative
 109 subsample of 100 fish is selected. Otoliths are collected on board from a small fraction of all the target
 110 species from all RFAs (Figure 1) to retrieve age reading. Table S2.1 in Supplementary Materials S2 gives
 111 the minimum sampling levels of otoliths for the target species.

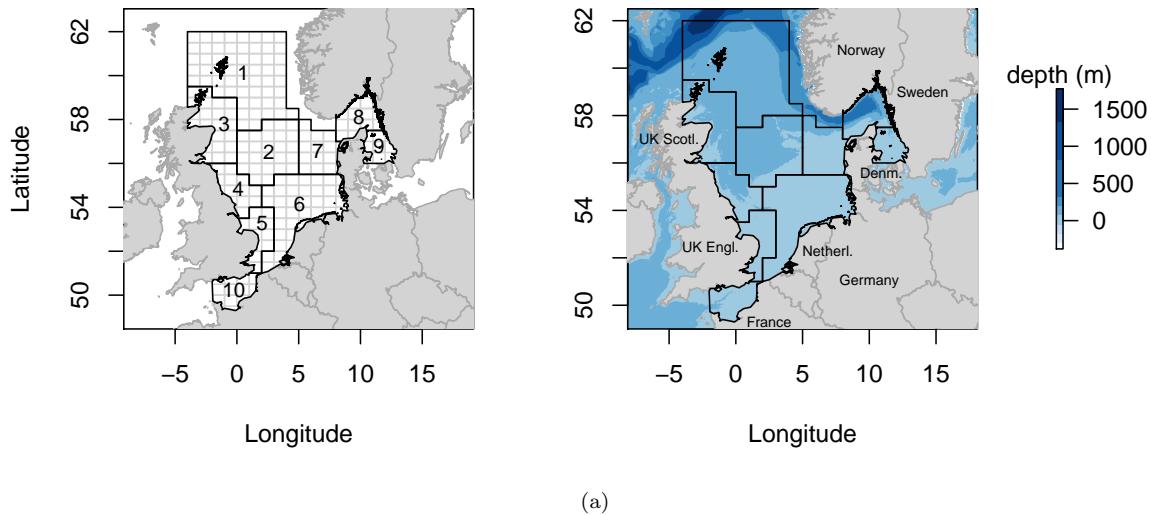


Figure 1: Standard roundfish areas (RFAs) used for roundfish since 1980 and for all standard species since 1991 (left panel). RFA 10 was added in 2009. The number 1, for example, indicates ICES RFA 1. The small grey rectangles in the left panel indicates the statistical rectangles of 30×30 nautical miles (1° Longitude \times 0.5° Latitude). The map in the right panel shows the Norwegian trench and shelf edge (depths 1000-1500).

112

2 METHODS

113 This section gives the estimators of abundance indices. The estimators are haul time-based and utilizes an
 114 ALK approach. We consider the ALK approach used in DATRAS and we propose two ALK estimators.

115 The ALK used in DATRAS for computing abundance indices does not account explicitly for the spatial
 116 distribution in the age-length composition, which may be different and would result in a biased ALK (Kimura,
 117 1977). This difference may be caused either by variation in length-at-age distributions or by variations in
 118 the relative abundance of age classes, that is age-at-length distributions (Gerritsen et al., 2006). To account
 119 for the spatial distribution we propose a design base ALK estimator that is haul dependent (Section 2.2.2)
 120 and a model base ALK estimator (2.2.3).

121 ***2.1 Catch per unit effort***

122 In this research, the catch per unit effort (CPUE) is defined as the number of fish of a certain species and
 123 age or length which are caught per hour trawl. In this section we define the CPUE mathematically, which
 124 explains how the index is calculated. For a given species of interest, let $n_{h,l}$ be the number of fish with
 125 length l caught by trawl haul h . The CPUE for a given length l by trawl haul h is defined as

$$\text{CPUE}_{h,l} = \frac{n_{h,l}}{d_h}, \quad (2.1)$$

126 where d_h is the duration of the trawl in hours. The CPUE per age class is further defined as

$$\text{CPUE}_{h,a} = \sum_{l \in \mathbf{L}} \text{CPUE}_{h,l} \times \text{ALK}_{a,l,h}, \quad (2.2)$$

127 where \mathbf{L} is the set of all length classes and $\text{ALK}_{a,l,h}$ is the age length key, which represents the estimated
 128 proportion of fish with age a in l th length class in haul h . For a given number of trawl hauls in a statistical
 129 rectangle, the mean CPUE defined as mCPUE in a statistical rectangle can be expressed as the average
 130 CPUE of the trawl hauls in the statistical rectangle:

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

131 Here H_s represents the set of trawl hauls taken in statistical rectangle s , and $|H_s|$ is the number of hauls
 132 taken in the rectangle. The mCPUE in p th RFA is further defined as

$$\text{mCPUE}_{p,a} = \sum_{s \in S_p} \frac{\text{mCPUE}_{s,a}}{|S_p|} \omega_s, \quad (2.4)$$

133 where S_p is the set of all statistical rectangles in RFA p , $|S_p|$ is the number of statistical rectangles in RFA
 134 p , and ω_s is a weight variable for each statistical rectangle. The weight variable ω_s varies between species.

¹³⁵ For some species ω equals 1 (e.g. *Gadus morhua*) for all s , and for other species it is the proportion of the
¹³⁶ statistical rectangle which has depth between 10 to 200 meters, for example *Pollachius virens* (see Table S3.1
¹³⁷ in Supplementary Materials S3). The mean catch per unit at age in the whole study area, λ_a , is defined by

$$\lambda_a = \frac{\sum_{p \in \mathbf{P}} A_p m \text{CPUE}_{p,a}}{A_{\text{total}}}. \quad (2.5)$$

¹³⁸ This is known as the index of abundance at age, where \mathbf{P} is the set of RFAs, A_p is the area of RFA p , and
¹³⁹ $A_{\text{total}} = \sum_{p \in \mathbf{P}} A_p$.

¹⁴⁰ 2.2 *ALK estimators*

¹⁴¹ The definition of the CPUE of age includes an ALK, see (2.2), which we described in this section. Three
¹⁴² ALK estimators are included in this research, which are named as follows: *i*) DATRAS ALK, *ii*) haul base
¹⁴³ ALK and *iii*) model base ALK.

¹⁴⁴ 2.2.1 *DATRAS ALK*

¹⁴⁵ Let ALK^D denote the DATRAS ALK. The ALK^D is defined as constant within each RFA, and is calculated
¹⁴⁶ for each RFA by aggregating the age observation from each RFA. $\text{ALK}_{a,l,h}^D$ used in equation (2.2) is defined
¹⁴⁷ as the proportion of observed fish with age a in length class l in the RFA h . If there are no observed
¹⁴⁸ fish in length class l in the RFA, ages from length classes close to l is used. The details of the procedure
¹⁴⁹ for borrowing strength from neighbouring length classes are given in Supplementary Materials S4.1. The
¹⁵⁰ underlying assumption of this ALK is that age-length compositions are homogeneous within the RFAs.
¹⁵¹ This is a rather strong assumption, and any violation would have an unknown impact on the estimates of
¹⁵² abundance indices. Aanes and Vølstad (2015) illustrated that violation of the assumption of constant ALK
¹⁵³ leads to biased estimates of CPUEs.

¹⁵⁴ 2.2.2 *Haul base ALK*

¹⁵⁵ We define a haul dependent ALK by ALK^H . The $\text{ALK}_{a,l,h}^H$ used in equation (2.2) is defined as the average
¹⁵⁶ proportion of observed fish with age a in length class l in haul h . If there are no observed ages of fish in a

₁₅₇ length class l in the haul, ages from the same length class in the haul close by is used (see Supplementary
₁₅₈ Materials S4.2 for the procedure).

₁₅₉ *2.2.3 Model base ALK*

₁₆₀ In this section we introduce a spatial model base ALK, which we define as ALK^M . Using such a model
₁₆₁ enables us to obtain smooth structures in the distribution of age given length. It further enables us to utilize
₁₆₂ spatial latent effects. Spatial model-based approach of age-lengths are widely used (Berg and Kristensen,
₁₆₃ 2012; Hirst et al., 2012; Rindorf and Lewy, 2001), and are used for stock assessment in the North Sea (Berg
₁₆₄ et al., 2014).

₁₆₅ Let the response variable of the age group of a fish be $a = M, \dots, A$ where M is the youngest age, and A
₁₆₆ is the oldest age which is typically defined as a "plus group". Suppose $y(l, \mathbf{s})$ is the age of a fish with length
₁₆₇ l caught at location \mathbf{s} . As in Berg and Kristensen (2012) we use a continuous ratio model for the spatial age
₁₆₈ given length model. However, in our application we assume for each species we know a length l_m such that
₁₆₉ all fish above length l_m are above age M , and all fish with length below l_m are of age below A . By including
₁₇₀ such a variable we reduce the number of parameters in the model by removing one linear predictor. Define
₁₇₁ the continuous ratio we are modelling as

$$\pi_a[y(l, \mathbf{s})] = \frac{p_a(l, \mathbf{s})}{p_a(l, \mathbf{s}) + \dots + p_A(l, \mathbf{s}) + p_M(l, \mathbf{s})} \quad \text{for } a = M + 1, \dots, A - 1, \quad (2.6)$$

₁₇₂ where $p_a(l, \mathbf{s})$ is the probability of a fish with length l at location \mathbf{s} to be of age a . Note that either $p_A(l, \mathbf{s})$
₁₇₃ or $p_M(l, \mathbf{s})$ is known to be equal to zero, and the other is selected such that $\sum_a p_a = 1$. We further assume
₁₇₄ the logit link

$$\log \left[\frac{\pi_a[y(l, \mathbf{s})]}{1 - \pi_a[y(l, \mathbf{s})]} \right] = f_a(l) + \gamma_a(\mathbf{s}). \quad (2.7)$$

₁₇₅ Here $f_a(l)$ is a continuous function of length and γ is a mean zero Gaussian spatial random field with Matérn
₁₇₆ covariance function. The spatial random field is intended to capture any spatial variation in the ALK.

₁₇₇ The continuous function $f_a(l)$ in (2.7) is modelled with usage of P-splines (Wood, 2017), and these
₁₇₈ spline regression coefficients are included as a Gaussian random effect. The precision matrix for the spline
₁₇₉ regression coefficients is constructed such that the variability (or wryggliness) in the spline is penalized, see
₁₈₀ Wood (2017, page 239) for details. The R package mgcv (Wood, 2015) is used for extracting the precision

181 matrix needed for the spline regression coefficients. We assume that the spatially Gaussian random field in
182 (2.7), γ , follows a stationary Matérn covariance structure:

$$\text{Cov}(\gamma(\mathbf{s}_1), \gamma(\mathbf{s}_2)) = \frac{\sigma_\gamma^2}{2^{\nu-1}\Gamma(\nu)} (\kappa_\gamma \|\mathbf{s}_1 - \mathbf{s}_2\|)^\nu K_\nu(\kappa_\gamma \|\mathbf{s}_1 - \mathbf{s}_2\|), \quad (2.8)$$

183 where σ_γ^2 is the marginal variance, $\|\cdot\|$ is the Euclidean distance measure in kilometres, ν is a smoothing
184 parameter, κ_γ is a spatial scale parameter and $K_\nu(\cdot)$ is the modified Bessel function of the second kind with
185 $\nu = 1$. The spatial field is estimated with the stochastic partial differential equation (SPDE) procedure
186 described in Lindgren et al. (2011). The main concept behind the SPDE procedure is that the precision
187 matrix of a spatial field with Matérn covariance function can be approximated by a sparse matrix on a grid
188 covering the area of interest. Such a grid and sparse precision matrix are constructed with use of the R-INLA
189 package (Rue et al., 2009).

190 The species specific constant l_m (**what is m?**) is selected as the mid point between the shortest fish of
191 age A and the longest fish of age M in the corresponding year and quarter. **As a sensitivity analysis of**
192 **this constant** we adjusted it up and down 5 cm for cod in year 2018. The point estimate of the mCPUEs
193 then changed in the forth decimal, which is negligible.

194 The model base ALK estimate is obtained by maximizing the likelihood. We maximize the likelihood
195 with use of an R-Package called Template Model Building TMB (Kristensen et al., 2015), combined with the
196 optimizing function `nlminb` in R. In this application TMB is advantageous as it uses Laplace approximation
197 for the latent fields gaining computational efficiency, it also utilizes sparse structures in the latent fields, and
198 uses automatic derivation.

199 **2.3 Uncertainty estimation**

200 In this section we describe how the uncertainty of the CPUE estimates are calculated. We use nonparametric
201 bootstrapping to quantify the uncertainty of the CPUEs. In nonparametric bootstrapping independent sam-
202 ples of lengths and age are drawn with replacement from the original data and approximate 95% confidence
203 intervals are obtained using bias-corrected percentile method (Carpenter and Bithell, 2000). Nonparamet-
204 ric resampling allows us to estimate the sampling distribution of the CPUE empirically without making
205 assumptions concerning the data. The bias-Corrected method adjusts for the bias and skew of the sam-

206 pling distribution of the data (Puth et al., 2015; Karlsson, 2009). The bootstrap procedure is given in
207 Supplementary Materials S5.

208 A bootstrap procedure for estimating the uncertainty of CPUEs in the North Sea is suggested in ICES
209 (2013a). This procedure is given in Supplementary Materials S5. In the rest of this research, we refer
210 to this procedure as DATRAS bootstrap procedure. The DATRAS procedure is divided into two parts;
211 one part which samples CPUE per length (2.1), and another part which samples the ALK used in (2.2).
212 The DATRAS bootstrap procedure is based on the assumption of homogeneous CPUE within RFAs. This
213 assumption is likely to be wrong, and would typically cause an overestimation of the uncertainty. Therefore,
214 we have included a bootstrap procedure, defined as the stratified bootstrap procedure, which instead assumes
215 constant CPUE within each statistical rectangle.

216 *2.3.1 DATRAS and Stratified bootstrap procedure*

217 In this section we describe the bootstrap procedure for catch at length proposed by *DATRAS* (ICES, 2013a)
218 and the stratified procedure, and elaborate how the ALK is simulated. Assume there are N_s trawl hauls
219 in a statistical rectangle. The DATRAS bootstrap procedure consists of sampling with replacement N_s of
220 all trawl hauls in the corresponding RFA, and place them in the statistical rectangle. This procedure is
221 performed independently across all statistical rectangles. It should be remembered that this procedure is
222 based on the assumption that ALK is homogeneous in the whole RFA, and the implication of DATRAS
223 bootstrap procedure on indices of abundance is two-fold. Firstly, DATRAS bootstrap procedure ignores the
224 fine-scale stratification in the sampling process. This would lead to an overestimation of the uncertainty.
225 Secondly, it ignores the sampling procedure of age-length data collected at the haul level. This would lead to
226 an underestimation of the uncertainty. So there are biases in both directions, which are difficult to quantify.
227 The Stratified bootstrap procedure is a modification of the DATRAS bootstrap procedure. Rather than
228 sampling hauls from the whole RFA, we sample the N_s trawl hauls from the list of hauls within the same
229 statistical rectangle. If there is only one trawl haul within a statistical rectangle, we sample either that haul
230 or the closest haul.

231 To estimate DATRAS ALK we sample with replacement age observations within each RFA stratified

232 with respect to length. If there is only one observed age from a given length class, we sample either that age
233 or, at random, an age of the closest length class with observed ages. For both the haul based ALK and the
234 model based ALK, we use the ages in the sampled hauls obtained when simulating the CPUE per length.

235 2.4 Reducing sampling effort

236 The current sampling procedure for the North Sea IBTS data is the sampling of one otolith from every
237 observed length group in every trawl (see Table S2.1 in Supplementary Materials S2). We investigate the
238 effect on the estimated mCPUE and its variance if the sampling procedure of otoliths changes such that
239 fewer otoliths were collected. To determine this effect we remove otoliths in a stratified manner, mimicking
240 a sampling procedure where fewer otoliths are collected. For sampling fewer otoliths, we define wider length
241 groups, for example 2 cm, or 3 cm, or 5 cm and so on, and simulate the otolith collection such that only one
242 otolith is sampled from every wider length group. Estimated mCPUE's with summary statistics, based on
243 the simulated reduced data sets are then compared with the parameters estimated from using all of data.
244 In principle, we are free to define any length class to reduce the number of observed otoliths. For simplicity
245 we propose two procedures: i) sample at random one otolith from every 2 cm length group, and ii) sample
246 at random one otolith from every 5 cm length group.

247 3 Case studies

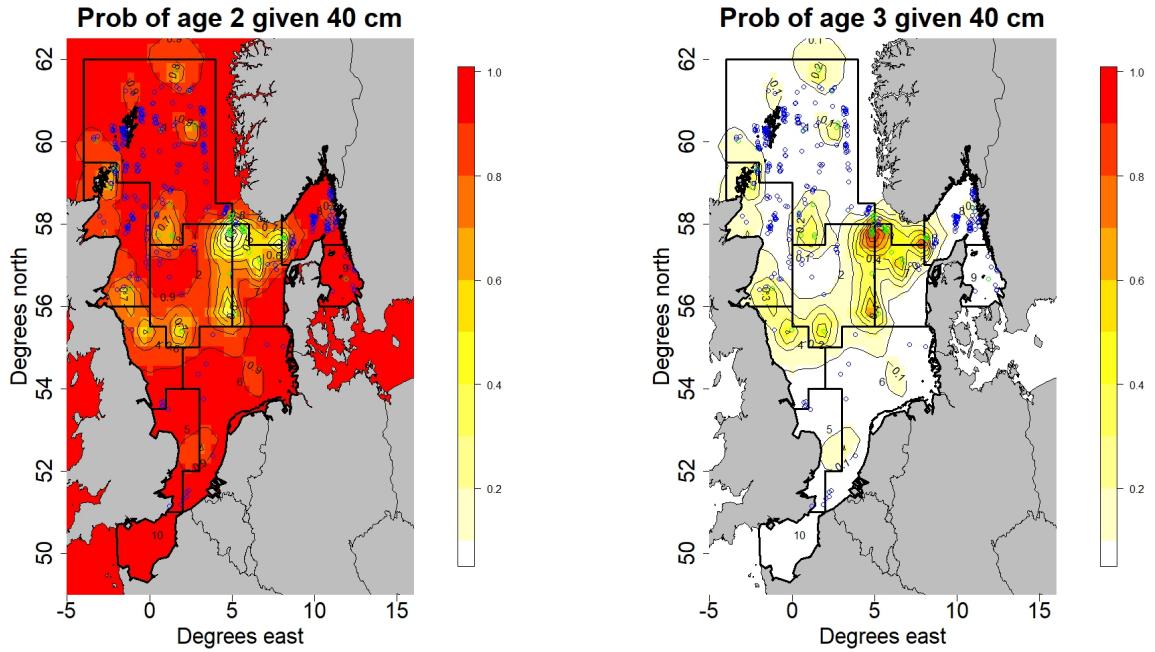
248 In this section we apply the methods described in Section 2 to data from the International Bottom Trawl
249 Survey for the years 2017-2018, which is obtained from the DATRAS database (ICES, 2018c). These years
250 are chosen for two reasons. The first is that in year 2018 new sampling procedures proposed by ICES
251 for the collection of otoliths were introduced in the surveys. For instance, one otolith per length group is
252 sampled for most target species (see Table S2.1 in Supplementary Materials S2 for the sampling procedures
253 for each target species), and this data is appropriate for the application of our proposed sample optimization
254 procedure described in Section 2.4. The second is that IBTS included Age 0 in Q3 surveys, and since data
255 for year 2018 Q3 is not yet available, the data for years 2017 Q3 and 2018 Q1 will be used in our analyses.
256 Also, some species such as saithe that occupies the deeper waters in the northern part of the North Sea

257 and in the Skagerrak and Kattegat, along the shelf edge (ICES, 2018a), the IBTS Q3 data is relevant for
258 analyses compared with data from IBTS Q1 surveys, which do not adequately cover these areas where saithe
259 is distributed (see Figure 1). Note that both IBTS Q1 and Q3 surveys do not adequately cover the whole
260 stock distribution of saithe but the data collected is considered generally representative (ICES, 2016a).

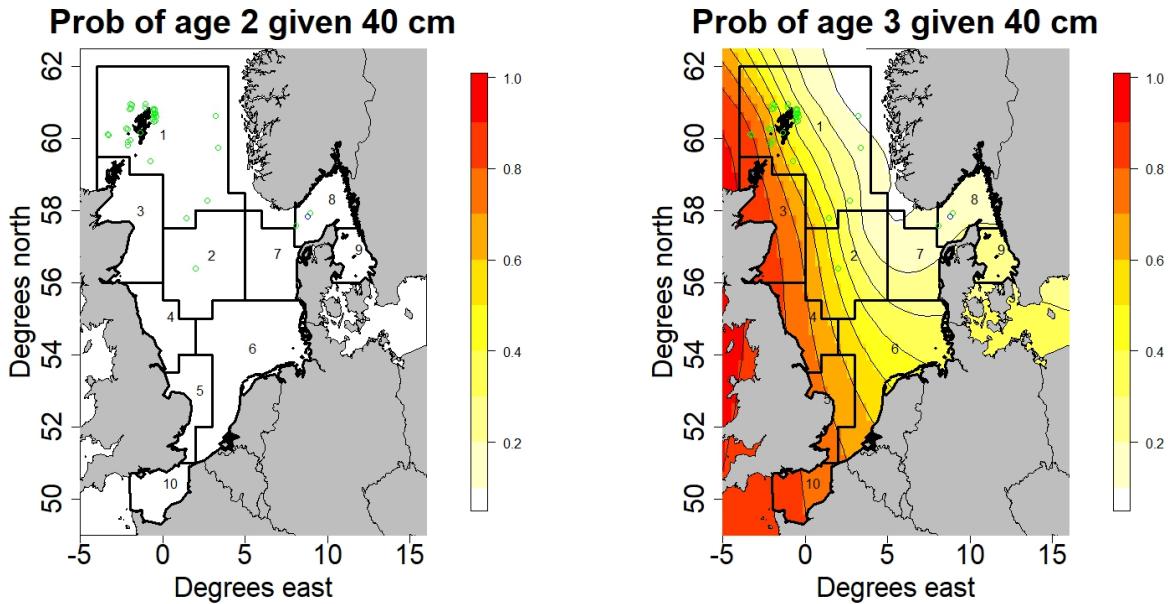
261 In this research, the species of interest are cod and saithe. All samples are caught using the standard
262 GOV gear described in Section 1.1. Table S6.1 gives a brief description of the data for year 2018 in the first
263 quarter and year 2017 in the third quarter. Cod can be as old as 12 years in the first quarter and 11 years in
264 the third quarter; and saithe as old as 18 years in the first quarter and 17 years in the third quarter. In our
265 analyses we consider the age groups 1 to 6+ in Q1 and 0 to 6+ in Q3 for all ALK methods, where the last
266 group consists of fish of age 6 or older. Saithe are typically older than cod but smaller in length, particularly
267 in Q1. Catch rates are higher in the third quarter, 48% for cod and 164% for saithe, compared with the first
268 quarter.

269 ***3.1 Estimated indices of abundance and variability for cod and saithe***

270 In this section we apply the three ALK methods given in section 2.2 for abundance estimation, and the
271 bias-corrected bootstrap method, given in Section 2.3.1 for estimating variability of estimated indices of
272 abundance. The main assumption of DATRAS ALK is that the age-length compositions of species over
273 large areas are the same. To illustrate that this assumption may not be valid, we used the spatial ALK
274 model (2.7) to predict probabilities of age given length of a 40 cm long cod and a 40 cm long saithe in the
275 North Sea (Figure 2). These plots provide strong evidence against a null hypothesis of no spatial effect in
276 the ALKs, as the likelihood of age given length changes in some areas. Figure 2 (a) shows that the eastern
277 North Sea in RFAs 7 and 8 (the regions in yellow) is one of the areas where a 40 cm cod is more likely to
278 be age 3. A saithe of 40 cm is more likely to be 3 years or older. The plots also show that cod is distributed
279 in all areas of the North Sea, except RFA 10 (Figure 2 (a)), whereas saithe is more likely to inhabit deeper
280 areas in the northern North Sea, specifically RFA 1, and Skagerrak in RFA 8 (Figure 2 (b) and Figure 1,
281 right panel).



(a) Probability plot of 40 cm cod in year 2018 Q1.



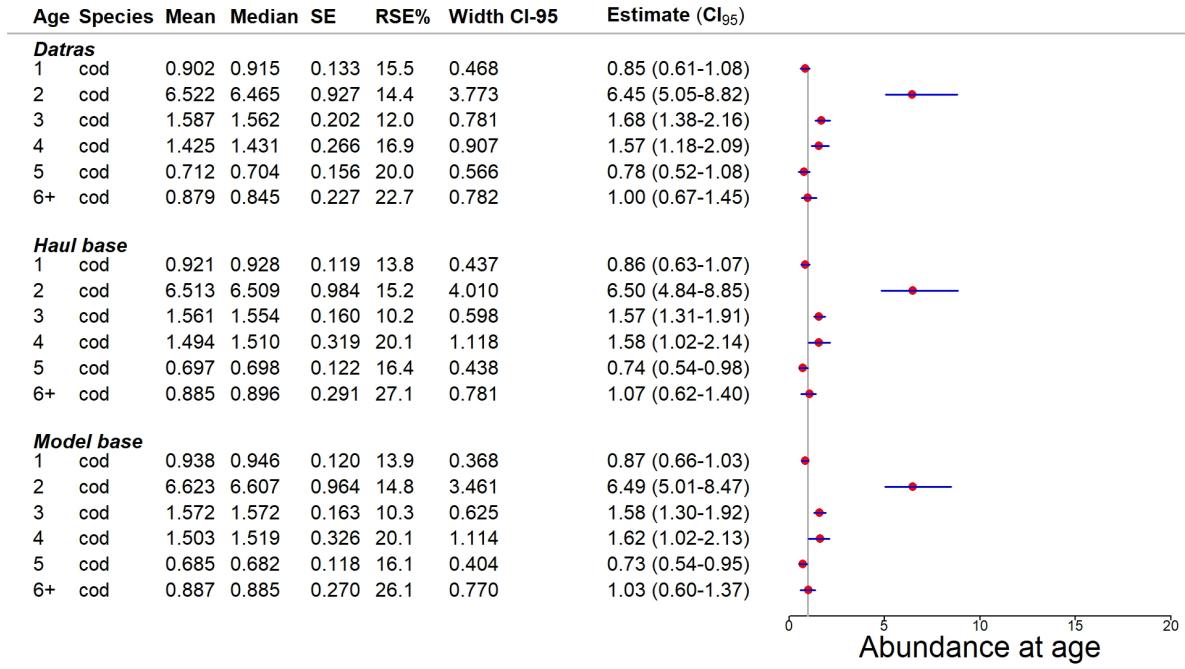
(b) Probability plot of 40 cm saithe in year 2018 Q1

Figure 2: Predicted probabilities of age given length using model (2.6) and (2.7) for the year 2018 Q1. Graph (a) gives probabilities of predicted age of a 40 cm long cod, and graph (b) gives probabilities of predicted age of a 40 cm saithe in RFAs 1 to 10 in the North Sea. The small coloured circles (\circ , blue or green) are the trawl hauls with cod or saithe data.

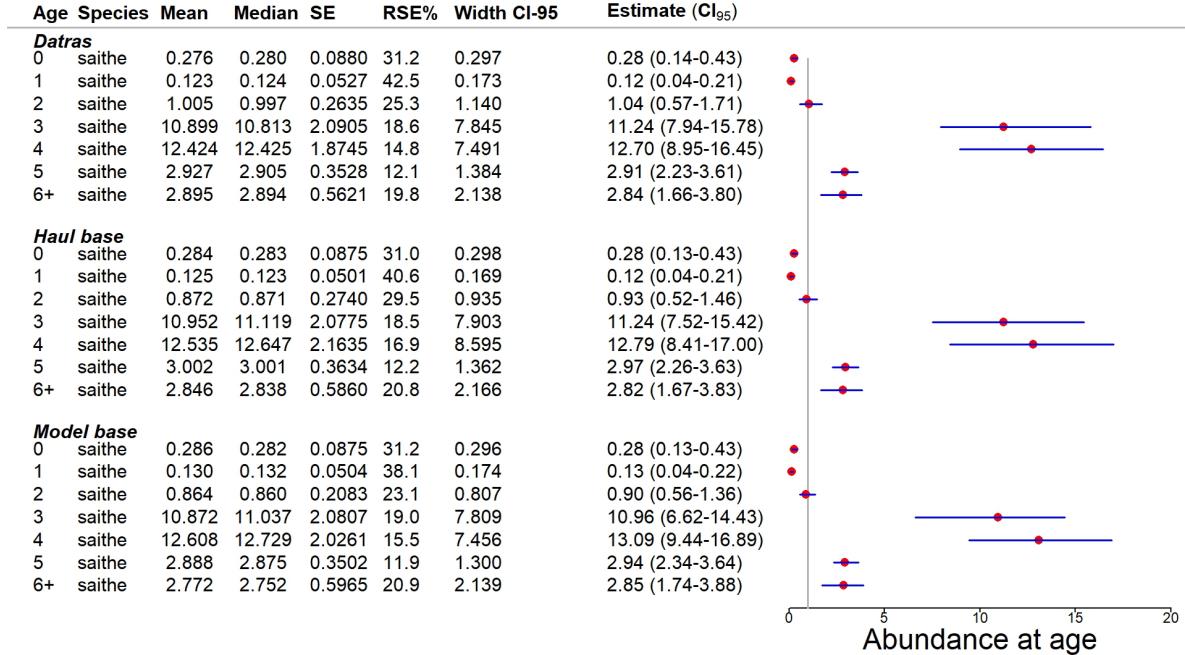
Figures 3 gives estimates of indices of abundance for cod in years 2018 Q1 and for saithe in year 2017 Q3. Approximate 95% confidence intervals from the bias-corrected bootstrap method for 200 bootstrap replication are estimated from the three ALK methods. The stratified procedure described in 2.3.1 is used in the sampling process to estimate bootstrap confidence intervals. Figures 3 shows that the resulting indices of abundance for cod and saithe turned out to be similar for all ALKs. IBTS is a complex multistage survey design, and since the ALKs are estimated from cluster-correlated data the resulting effective sample for estimating age-composition of fish would be lower than the number of fish measured (ICES, 2013b). Hence, the ALKs are subject to large sampling errors. For example, the estimated percentage relative standard errors from the spatial ALKs for the plus group (6+) for cod are > 25%, suggesting high sampling error in the ALKs. Also, it should be remembered that DATRAS ALK is constant. Aanes and Vølstad (2015) showed that in such cases, and where only the variability of length compositions are allowed for, the estimated age-distributions may appear to be more precise than they truly are since the ALK itself is subject to sampling errors, see for example the estimated relative standard standard errors for ages 2, and the older fish (4, 5 and 6+) for both species.

As regards to which spatial ALK method to adopt, it is difficult to identify a method that gives the best performance over all age groups. While both methods seem to give reasonable estimates, the model base ALK generally gave shorter interval widths for both species. Uncertainty of relative abundance from the spatial ALK model is calculated using bootstrapping, as approximation of the joint distribution of the regression coefficient and spatial effect, in some cases, fails to account for the negative correlations between ages. Also, estimating relative abundance at age and its precision from the spatial ALK model is computationally intensive. For these reasons we recommend the haul base ALK method for estimating age-distributions.

We also demonstrate the implications of using DATRAS bootstrap procedure for estimating the uncertainty around indices of abundance (see Figure S1 in Supplementary Materials S7). Compared with the stratified bootstrap procedure, DATRAS bootstrap procedure gives an overestimation of the uncertainty for all age groups, suggesting that it is highly relevant to account for the variation in the data over large areas.



(a) Cod in year 2018 Q1



(b) Saithe in year 2017 Q3

Figure 3: Estimated confidence intervals (CI₉₅) from bias-corrected bootstrap method for cod in year 2018 Q1 and saithe in year 2017 Q3. Estimated indices of abundance (Estimate), and its standard error (SE), percentage relative standard error (RSE%), bootstrap mean (Mean) and Median estimates and the width of the confidence interval (Width CI-95) are also given.

307 ***3.2 Optimum sampling effort for North Sea Cod and Saithe***

308 To determine optimum sampling levels of otoliths for saithe and cod in the North Sea, ALKs are estimated
309 using the haul base method. As shown in Figure 3 the haul base ALK and the model base ALK gave similar
310 estimates of abundance indices and precision as both approaches are attempting to capture spatial variation
311 in the data. But, the spatial model base ALK is quite complex, and model fitting would be computer-
312 intensive since the model must be fitted for each bootstrap run and each simulated sampling procedure that
313 mimics the real data collection procedure. For this reason, the model base ALK approach will not be used
314 in this analysis. Also, the assumption of no difference in regional compositions of age-length structures is
315 invalid, as shown in Figure 2, so DATRAS ALK is not use for further analyses. The removal procedure for
316 otolith sampling described in Section 2.4 is applied to data in year 2018 Q1 for cod and year 2017 Q3 for
317 saithe. We sample one otolith per length group: 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm or 7 cm. Recall that
318 the standardized IBTS sampling procedure is one otolith per length group for standard round fish as of year
319 2018 Q1, except for haddock and Norway Pout where 2 otoliths per cm is to be sampled (see Table S2.1 in
320 Supplementary Materials S2).

321 Table1 compares estimates of relative abundance ($\hat{\lambda}_a$) for the original sample of otolith data with es-
322 timated indices for the reduced sample of otolith data ($\hat{\lambda}_a^*$) where a pair of otoliths are sampled from the
323 following sampling procedures: 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm or 7 cm length group. Estimated stan-
324 dard errors of the estimated indices of abundance from the reduced data, with approximate bias-corrected
325 bootstrap 95% confidence intervals and percentage relative standard error are given for 200 simulations and
326 200 bootstrap replication. Similar estimates are given for saithe in Table 2. A total of 1600 pairs of otoliths
327 were sampled for cod in year 2018 Q1, while 2163 pairs of otoliths were sampled for saithe in year 2017 Q3
328 (see Table S6.1 in Supplementary Materials S6). The proportion of otoliths removed for cod from each of
329 the sampling procedures stated above is: 14.4%, 28.6%, 38.4%, 44.5%, 49.3%, 52.6% or 55.6%, respectively,
330 while for saithe the following proportions of otoliths are removed: 27.1%, 48.9%, 59.5%, 65.6%, 69.8%, 73.1%
331 or 75.2%, respectively.

332 The results (Table 1) show that the difference between ($\hat{\lambda}_a$) and ($\hat{\lambda}_a^*$) is marginal for all sampling pro-
333 cedures for ages 1-4. For the older fishes (ages 5 and 6+) this difference is clear, particularly for sampling

procedures \geq 5 cm. This is supported by the percentage relative standard error, but for all ages RSE% < 25%, suggesting that the variability in the estimates is low. A similar pattern emerges for saithe (Table 2), except for estimated relative abundance of age 2 saithe. It can be seen that the RSE% is substantially larger than those of the neighbouring age groups, for example 1 or 3 year-olds. Almost all the RSE% > 30% for two-year olds, suggesting high variability in the parameter estimates (see $\hat{\lambda}_a$ and $\hat{\lambda}_a^*$ for age 2 saithe). As shown in Figure (**insert probability plot**) the predicted probabilities of age-given-length of 2-year old saithe overlaps with older fishes, for example 3 or 4-year olds, and the proportion of otoliths of 2-year olds sampled during IBTS 2017 Q3 survey is a mere 3% compared with 25% and 35% of 3-year and 4-year olds (see Table S6.2 in Supplementary Materials S6). And, given that a pair of otoliths (irrespective of age) is randomly selected from each of the following sampling procedures: 1 cm, 2 cm,...,7 cm, the older fishes (3 or 4-year olds) are more likely to be sampled, resulting in fewer samples utilised in the optimization procedure, and hence higher variability in the estimates. Furthermore, the sampling variability in lengths of 2-year olds are high compared with 1-year olds and are comparable with 3-year and 4-year olds, so the standard error estimates of the estimated abundance indices may be dominated by this uncertainty.

It can be seen also (Tables 1 and 2) for the older fishes (\geq 3 – years) the confidence intervals are wider compared with the younger fishes. This could be for several reasons. The nonparametric bias-corrected bootstrap method is adopted for estimating confidence intervals of indices of abundance, and although this method has the advantage of correcting for the bias and skew of the sampling distribution of the data; accounting for some of the variability in the sampling distribution of the CPUE; and does not assume any distribution for the data, there are some limitations of the bootstrap approach. The most important limitation is the assumption that the distribution of the data represented by the sample is a reasonable estimate of the population function from which the data are sampled. If this assumption is violated the random sampling performed in the bootstrap procedure may add another level of sampling error, resulting in invalid statistical estimations (Haukoos and Lewis, 2005). As discussed in Section 1.1 the selection of the trawling locations for IBTS surveys is semi-random where cruise leaders selects "clear" tow locations or "blind" tow locations if no clear tow exists by checking the proposed trawl track for hazardous seabed obstructions with acoustic methods. More recently, selection of tow locations is based on pre-proposed

361 valid tow locations with start and end positions executed in the period 2000-2018. Hence, the lack of a
362 fully randomized sampling process has the potential to result in biased estimates of parameters and their
363 uncertainty. Additionally, prior to 2013, all nations were sampling 8 pairs of otoliths per 1 cm length group
364 for our focal species (Table S2.1 in Supplementary Materials S2), and these samples could be acquired from,
365 for example the first haul (or first few trawl hauls), resulting in an unrepresentative sample of the population.
366 From 2013, some nations adopted the current sampling procedure outlined by ICES for IBTS 2018 surveys of
367 1 pair of otolith per 1 cm length group from each haul, while other nations continued with sampling 8 pairs of
368 otoliths per 1 cm length group. So, bias was still introduced via the sampling procedure. Another limitation
369 of the bootstrap is the smaller the original sample the less likely it is to represent the entire population, thus
370 the more difficult it becomes to compute valid confidence intervals. Note that the bootstrap relies heavily
371 on the tails of the estimated sampling distribution when computing confidence intervals, and using small
372 samples may jeopardize the validity of this computation. As explained above, in 2017 Q3 data for 2-year old
373 saithe, for example, 65 pairs of otoliths out of 2163 were sampled (a mere 3%) and because of overlapping-
374 age-length keys among neighbouring age groups, the probability of selecting 2-year olds is smaller, resulting
375 in larger estimates of the variance, and hence wider confidence intervals.

376 **need to conclude on which sampling procedure is best based on estimated uncertainty**
377 **(RSE%), for example 5%?**

Table 1: Estimated abundance ($\hat{\lambda}_a$) for cod from the original data in year 2018 Q1 compared with estimated abundance ($\hat{\lambda}_a^*$) from the reduced data for different sampling procedures of length groups (l). The estimated standard error of $\hat{\lambda}_a^*$ ($SE(\hat{\lambda}_a^*)$) and the percentage relative standard error (RSE%) are also given.

| l | $\hat{\lambda}_a$ | $\hat{\lambda}_a^*$ | $SE(\hat{\lambda}_a^*)$ | RSE% | CI-95 ($\hat{\lambda}_a^*$) |
|---------------|-------------------|---------------------|-------------------------|--------|-------------------------------|
| age 1 | | | | | |
| 1 cm | 0.863 | 0.866 | 0.00910 | 1.051 | (0.84, 0.88) |
| 2 cm | 0.863 | 0.866 | 0.00969 | 1.119 | (0.84, 0.88) |
| 3 cm | 0.863 | 0.858 | 0.02476 | 2.886 | (0.81, 0.90) |
| 4 cm | 0.863 | 0.854 | 0.02993 | 3.507 | (0.81, 0.90) |
| 5 cm | 0.863 | 0.848 | 0.03712 | 4.379 | (0.81, 0.92) |
| 6 cm | 0.863 | 0.858 | 0.03646 | 4.249 | (0.80, 0.93) |
| 7 cm | 0.863 | 0.856 | 0.03920 | 4.582 | (0.80, 0.93) |
| age 2 | | | | | |
| 1 cm | 6.496 | 6.485 | 0.02055 | 0.317 | (6.47, 6.53) |
| 2 cm | 6.496 | 6.485 | 0.01968 | 0.303 | (6.46, 6.52) |
| 3 cm | 6.496 | 6.503 | 0.05023 | 0.772 | (6.38, 6.60) |
| 4 cm | 6.496 | 6.498 | 0.05852 | 0.901 | (6.39, 6.62) |
| 5 cm | 6.496 | 6.507 | 0.07121 | 1.094 | (6.36, 6.64) |
| 6 cm | 6.496 | 6.510 | 0.07415 | 1.139 | (6.34, 6.64) |
| 7 cm | 6.496 | 6.491 | 0.08395 | 1.293 | (6.33, 6.64) |
| age 3 | | | | | |
| 1 cm | 1.571 | 1.574 | 0.06955 | 4.418 | (1.46, 1.73) |
| 2 cm | 1.571 | 1.579 | 0.06785 | 4.429 | (1.45, 1.71) |
| 3 cm | 1.571 | 1.559 | 0.09708 | 6.228 | (1.41, 1.75) |
| 4 cm | 1.571 | 1.641 | 0.10051 | 6.124 | (1.41, 1.84) |
| 5 cm | 1.571 | 1.627 | 0.12505 | 7.686 | (1.31, 1.88) |
| 6 cm | 1.571 | 1.643 | 0.12598 | 7.670 | (1.31, 1.91) |
| 7 cm | 1.571 | 1.753 | 0.13991 | 7.979 | (1.44, 2.02) |
| age 4 | | | | | |
| 1 cm | 1.584 | 1.603 | 0.12104 | 7.550 | (1.37, 1.85) |
| 2 cm | 1.584 | 1.592 | 0.11493 | 7.218 | (1.37, 1.82) |
| 3 cm | 1.584 | 1.610 | 0.14425 | 8.960 | (1.31, 1.91) |
| 4 cm | 1.584 | 1.571 | 0.15284 | 9.729 | (1.31, 1.88) |
| 5 cm | 1.584 | 1.585 | 0.15010 | 9.468 | (1.32, 1.89) |
| 6 cm | 1.584 | 1.588 | 0.15178 | 9.560 | (1.26, 1.88) |
| 7 cm | 1.584 | 1.503 | 0.16675 | 11.094 | (1.38, 1.82) |
| age 5 | | | | | |
| 1 cm | 0.742 | 0.740 | 0.10729 | 14.504 | (0.56, 095) |
| 2 cm | 0.742 | 0.744 | 0.11047 | 14.848 | (0.57, 0.98) |
| 3 cm | 0.742 | 0.764 | 0.11675 | 15.287 | (0.55, 1.02) |
| 4 cm | 0.742 | 0.752 | 0.11398 | 15.158 | (0.58, 0.99) |
| 5 cm | 0.742 | 0.814 | 0.12034 | 14.789 | (0.53, 1.08) |
| 6 cm | 0.742 | 0.782 | 0.10975 | 14.043 | (0.57, 1.02) |
| 7 cm | 0.742 | 0.813 | 0.12545 | 15.425 | (0.59, 1.09) |
| age 6+ | | | | | |
| 1 cm | 1.074 | 1.063 | 0.10489 | 9.865 | (0.90, 1.28) |
| 2 cm | 1.074 | 1.065 | 0.10657 | 10.009 | (0.90, 1.29) |
| 3 cm | 1.074 | 1.037 | 0.12215 | 11.775 | (0.88, 1.25) |
| 4 cm | 1.074 | 1.015 | 0.11855 | 11.679 | (0.89, 1.24) |
| 5 cm | 1.074 | 0.950 | 0.12210 | 12.849 | (0.93, 1.21) |
| 6 cm | 1.074 | 0.951 | 0.11562 | 12.154 | (0.92, 1.19) |
| 7 cm | 1.074 | 0.914 | 0.12577 | 13.760 | (0.96, 1.18) |

Table 2: Estimated abundance ($\hat{\lambda}_a$) for saithe from the original data in year 2017 Q3 compared with estimated abundance ($\hat{\lambda}_a^*$) from the reduced data for different sampling procedures of length groups (l).

| l | $\hat{\lambda}_a$ | $\hat{\lambda}_a^*$ | SE($\hat{\lambda}_a^*$) | RSE% | CI-95 ($\hat{\lambda}_a^*$) |
|---------------|-------------------|---------------------|---------------------------|-------|-------------------------------|
| age 0 | | | | | |
| 1 cm | 0.282 | 0.282 | 0.00000 | 0.00 | (0.28, 0.28) |
| 2 cm | 0.282 | 0.282 | 0.00000 | 0.00 | (0.28, 0.28) |
| 3 cm | 0.282 | 0.288 | 0.00628 | 2.18 | (0.28, 0.29) |
| 4 cm | 0.282 | 0.291 | 0.00578 | 1.99 | (0.28, 0.29) |
| 5 cm | 0.282 | 0.282 | 0.00000 | 0.00 | (0.28, 0.28) |
| 6 cm | 0.282 | 0.297 | 0.00949 | 3.19 | (0.28, 0.31) |
| 7 cm | 0.282 | 0.290 | 0.00595 | 2.05 | (0.28, 0.29) |
| age 1 | | | | | |
| 1 cm | 0.123 | 0.123 | 0.00000 | 0.00 | (0.12, 0.12) |
| 2 cm | 0.123 | 0.123 | 0.00000 | 0.00 | (0.12, 0.12) |
| 3 cm | 0.123 | 0.117 | 0.00628 | 5.36 | (0.11, 0.12) |
| 4 cm | 0.123 | 0.117 | 0.00641 | 5.47 | (0.11, 0.13) |
| 5 cm | 0.123 | 0.125 | 0.00139 | 1.11 | (0.12, 0.13) |
| 6 cm | 0.123 | 0.112 | 0.00942 | 8.43 | (0.11, 0.13) |
| 7 cm | 0.123 | 0.115 | 0.00630 | 5.46 | (0.11, 0.13) |
| age 2 | | | | | |
| 1 cm | 0.929 | 0.917 | 0.17774 | 19.39 | (0.58, 1.25) |
| 2 cm | 0.929 | 0.892 | 0.28437 | 31.89 | (0.47, 1.50) |
| 3 cm | 0.929 | 0.985 | 0.33392 | 33.90 | (0.51, 1.65) |
| 4 cm | 0.929 | 0.982 | 0.33738 | 34.36 | (0.48, 1.55) |
| 5 cm | 0.929 | 1.003 | 0.34661 | 34.56 | (0.50, 1.61) |
| 6 cm | 0.929 | 0.945 | 0.33643 | 35.60 | (0.49, 1.77) |
| 7 cm | 0.929 | 0.982 | 0.33668 | 34.28 | (0.42, 1.62) |
| age 3 | | | | | |
| 1 cm | 11.238 | 11.272 | 0.53160 | 4.72 | (10.30, 12.15) |
| 2 cm | 11.238 | 11.161 | 0.93489 | 8.38 | (9.56, 13.11) |
| 3 cm | 11.238 | 11.091 | 1.17954 | 10.64 | (9.15, 13.39) |
| 4 cm | 11.238 | 10.903 | 1.05854 | 9.71 | (9.45, 13.27) |
| 5 cm | 11.238 | 10.857 | 1.12152 | 10.33 | (9.16, 12.95) |
| 6 cm | 11.238 | 10.937 | 1.10301 | 10.09 | (9.77, 12.88) |
| 7 cm | 11.238 | 10.724 | 1.04157 | 9.71 | (8.80, 13.07) |
| age 4 | | | | | |
| 1 cm | 12.789 | 12.773 | 0.52290 | 4.09 | (11.89, 13.74) |
| 2 cm | 12.789 | 12.874 | 0.91838 | 7.13 | (10.80, 14.54) |
| 3 cm | 12.789 | 12.877 | 1.14444 | 8.89 | (10.76, 14.84) |
| 4 cm | 12.789 | 13.019 | 1.09987 | 8.45 | (10.69, 15.09) |
| 5 cm | 12.789 | 13.033 | 1.15195 | 8.84 | (10.51, 15.25) |
| 6 cm | 12.789 | 13.111 | 1.09241 | 8.33 | (10.57, 15.13) |
| 7 cm | 12.789 | 13.278 | 1.07854 | 8.12 | (10.23, 15.64) |
| age 5 | | | | | |
| 1 cm | 2.971 | 2.967 | 0.12220 | 4.12 | (2.76, 3.24) |
| 2 cm | 2.971 | 3.036 | 0.29591 | 9.75 | (2.48, 3.58) |
| 3 cm | 2.971 | 2.970 | 0.29382 | 9.89 | (2.47, 3.61) |
| 4 cm | 2.971 | 3.045 | 0.38412 | 12.61 | (2.31, 3.99) |
| 5 cm | 2.971 | 3.077 | 0.43326 | 14.08 | (2.31, 3.87) |
| 6 cm | 2.971 | 2.936 | 0.38625 | 13.16 | (2.23, 3.77) |
| 7 cm | 2.971 | 2.971 | 0.42992 | 14.14 | (2.12, 3.81) |
| age 6+ | | | | | |
| 1 cm | 2.819 | 2.817 | 0.05126 | 1.82 | (2.73, 2.90) |
| 2 cm | 2.819 | 2.783 | 0.08525 | 3.06 | (2.70, 2.94) |
| 3 cm | 2.819 | 2.823 | 0.11729 | 4.15 | (2.64, 3.04) |
| 4 cm | 2.819 | 2.794 | 0.12590 | 4.15 | (2.61, 3.05) |
| 5 cm | 2.819 | 2.775 | 0.13938 | 5.02 | (2.54, 3.02) |
| 6 cm | 2.819 | 2.813 | 0.14435 | 5.13 | (2.53, 3.12) |
| 7 cm | 2.819 | 2.790 | 0.15922 | 5.71 | (2.54, 3.06) |

4 DISCUSSION

379 In this research we have determined optimal sampling efforts of otoliths for target species of the North Sea
 380 International Bottom Trawl Survey (IBTS). This was achieved by testing different sampling procedures that
 381 mimic the real data collection procedure but with a reduced number of otoliths. The estimated indices of
 382 abundance and their estimated uncertainty were investigated to determine if there is any real change in the
 383 precision of the estimates. Abundance indices were estimated using age-length keys (ALKs). The database
 384 for trawl surveys (DATRAS) manned by ICES includes an ALK that uses the raw proportions of age given
 385 length assuming constant age-length compositions over relatively large areas. We have developed two spatial
 386 ALK methods to estimate abundance indices and their variance that accounts for spatial variation in the
 387 data: 1) a haul base ALK that produces an ALK for each trawl haul, and which uses the raw proportions
 388 of age given length, and 2) a spatial ALK model that uses logits for modelling the age distribution in catch
 389 data from the length-stratified subsamples. Several studies have used spatial ALK modelling for estimating
 390 abundance indices of the North Sea stocks used in assessments (Berg and Kristensen, 2012; Berg et al., 2014;
 391 Gerritsen et al., 2006). These studies used continuous ratio logits with General Linear Model (GLM) or
 392 General Additive Models (GAMs) to model the spatial effects and found large spatio-temporal variability of
 393 the ALK and relative abundance at age. We proposed to use Gaussian Random Field Theory to model the
 394 spatial effects as a smooth surface to estimate age-at-length and relative abundance for the IBTS data. The
 395 spatial model base ALK and the design base spatial ALK (haul base) gave similar estimates as DATRAS
 396 estimator for relative abundance at age but the spatial ALK estimators gained better precision.

397 The spatial ALK model base estimator appears to be a useful tool to detect significant differences between
 398 ALKs over large areas, although estimation of the uncertainty in the ALK from the joint precision matrix
 399 is problematic. Including the uncertainty of the ALK in the model requires an approximation of the joint
 400 distribution of the regression coefficient and the spatial effect, but this approximation is only as good as
 401 the quality of the data in a given year and quarter, for example Figure (**insert probability plot**) shows
 402 that the approximation of the ALK for a cod of length 90 cm is likely to be 2 years old in year 2018 Q1.
 403 This occurs presumably because the approximation fails to account for the negative correlation structures
 404 between ages. So the uncertainty in the relative abundance was, therefore, calculated using bootstrapping

405 as done by Berg and Kristensen (2012); Berg et al. (2014). In future, the model might be expanded to
406 include the probability of recording inaccurate age-at-length data, so that uncertainty in the ALK could be
407 estimated using the joint precision matrix. The model might also be expanded to include covariates such as
408 trawl hauls to capture any haul variation, for example a trawl haul may "hit" a school of fish of a certain
409 age.

410 **discuss DATRAS and Haul base ALK and recommended optimum sampling level of otoliths**
411 **per length group**

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481 **Supplemental Materials: Optimizing sampling effort of the North**
482 **Sea International Bottom Trawl Survey.**

483 **S1 Areas fished by different countries in the North Sea IBTS**

484 Typically, two different countries fish each rectangle so that at least two trawl hauls are made per rectangle,
485 but intensified sampling is carried out in the following areas: at least 3 hauls per rectangle are taken in
486 statistical rectangles 31F1, 31F2, 32F1, 33F4, 34F2, 34F3, 34F4, 35F3, 35F4; while six or more hauls per
487 rectangle are taken in statistical rectangles 30F1, 32F2, 32F3, 33F2, 33F3 (ICES 1999). The Skagerrak
488 and Kattegat is fished solely by Sweden, who sample more than once in every rectangle while the west of
489 Shetland (in Q1 and Q3) and inshore areas (Q3) is fished solely by Scotland. The edge of the Norwegian
490 Trench is fished solely by Norway, but inshore areas near Denmark is fished by Denmark. The southern
491 North Sea is fished by Denmark, Germany and England. France, typically, is the only country that surveys
492 the western English Channel. Areas are surveyed by a single country because of the large proportion of
493 untrawalable area (and subsequent gear damage issues experienced by other nations) for efficient logistical
494 purposes. Table S1.1 gives the countries and research vessels participating the North Sea IBTS.

Table S1.1: Survey countries, vessel name, and period research vessels participating in first quarter (Q1) and third quarter (Q3) during 1997-2017.

| Country | First Quarter (Q1) | | Third Quarter (Q3) | |
|-------------|--------------------|------------------|--------------------|------------------|
| | 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 |

S2 Otolith sampling per fish species

497 From 1991-2017, most countries conducted quota sampling of otoliths per length group in a RFA. But from
 498 2013 Norway has been sampling one otolith per length class from each trawl haul (to 0.1cm below for shellfish,
 499 to 0.5cm below for herring and sprat and to 1cm below for all other species). From the first quarter in 2018
 500 all countries are required to sample one otolith per length class per trawl haul. Table S2.1 gives the minimum
 501 sampling levels of otoliths for the target species. However, for the smallest size groups, that presumably
 502 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 S2.1: 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 \geq 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 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). |
| 2018 | | Number of otoliths per length class per trawl haul |
| | herring | 1 otolith per $\frac{1}{2}$ cm group |
| | sprat | 1 otolith per $\frac{1}{2}$ cm length class 8.0 – 11.0 cm |
| | | 1 otolith per $\frac{1}{2}$ cm length class \geq 11.0 cm |
| | mackerel | 1 otolith per 1 cm length class |
| | cod | 1 otolith 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 otolith per 1 cm length class |
| | plaice | 1 otolith per 1 cm length class |

S3 Weightings of Statistical Rectangles

505 The weightings of the some statistical rectangles are allotted to species such as sprat, saithe and herring by
 506 depth strata. Table S3.1 gives these weights, which are used in the analysis of the saithe data.

Table S3.1: Weights used for *Pollachius virens* in equation (2.3).

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

508

S4 Imputation for missing age samples

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

516 ***S4.1 DATRAS ALK Borrowing Approach***

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

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

- 525 2. If length class (CPUE) > maximum length (ALK) age is set to the plus group.

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

528 ***S4.2 Haul base ALK Borrowing Approach***

529 The second is an a haul dependent ALK estimator which we propose, and is denoted by ALK^H . Since the age-
 530 length composition of fish may be space-variant, that is, there may be variation in age-length compositions
 531 between trawl stations within a superstrata, the spatial dependence of the age-length composition must be

532 accounted for to produce reliable estimates of the CPUE per age estimates. If this spatial dependence is
 533 ignored not only will estimates of abundance be biased but the impact on the variance may be substantial. So
 534 for each trawl haul an ALK^H is produced. Since there are few or none observations of ages for each
 535 length class in a trawl haul, length classes are therefore pooled in increasing order such that
 536 there are five length classes in each pooled length group. To replace missing values for the age
 537 distribution in the pooled length groups the method of "borrowing" ages from length groups
 538 in trawl hauls closest in air distance within the RFA is used. If there are no observed ages
 539 in the pooled length group in the RFA, missing values for the age distribution are replaced
 540 following the procedure outlined in the DATRAS ALK procedure (S4.1) in step 1.

541 S5 Nonparametric Bootstrap Sampling procedure

542 Nonparametric bootstrapping is attractive as it makes no distributional assumption, and is suitable for
 543 estimating confidence interval for indices of abundance. Suppose we have a vector \mathbf{x} of m independent obser-
 544 vations, and we are interested in estimating a parameter $\hat{\theta}(\mathbf{x})$ and its variance. The general nonparametric
 545 bootstrap algorithm is as follows:

- 546 1. Sample m observations randomly with replacement from \mathbf{x} to obtain a bootstrap data set, denoted by
 547 \mathbf{x}^* .
- 548 2. Calculate the bootstrap version of the statistic of interest, $\theta^* = \hat{\theta}(\mathbf{x}^*)$.
- 549 3. Repeat steps 1 and 2 a large number of times, say B , to obtain an estimate of the bootstrap distribution
- 550 4. calculate the average of the bootstrapped statistics, $\sum_{b=1}^B \theta^*_{(b)} / B$
- 551 5. compute the variance of the estimator $\hat{\theta}(\mathbf{x})$ through the variance of the set $\theta^*_{(b)}$, $b = 1, 2, \dots, B$, given
 552 by

$$\frac{\sum_{b=1}^B (\theta^*_{(b)} - \theta^*_{(\cdot)})^2}{(B - 1)} \quad (\text{S5.1})$$

553 where $\theta^*_{(\cdot)} = \sum_{b=1}^B \theta^*_{(b)} / B$.

554 The Bias-Corrected method assumes that there is a montonic increasing function and the estimator $\hat{\lambda}_a$ has
 555 a monotonic increasing function $f()$ such that the transformed values $f(\hat{\lambda}_a)$ are normally distributed with

556 mean $f(\lambda_a) - z_0$ and standard deviation one, where z_0 are the standard normal limits (Puth et al., 2015;
 557 Karlsson, 2009). Now, let $P^* \left(\hat{\theta}(\mathbf{x}^*) \leq \hat{\theta}(\mathbf{x}) \right)$ denote the proportion of $\hat{\theta}(\mathbf{x}^*)'$ s in the bootstrap sample that
 558 have a value lower than the value of the parameter estimate $\hat{\theta}(\mathbf{x})$, and let z_0 be defined as

$$z_0 = \Phi^{-1} \left\{ P^* \left(\hat{\theta}(\mathbf{x}^*) \leq \hat{\theta}(\mathbf{x}) \right) \right\}, \quad (\text{S5.2})$$

559 where Φ denotes the cumulative distribution function of the standard normal distribution. Also let $\tilde{\alpha}_1$ and
 560 $\tilde{\alpha}_2$ be defined as

$$\tilde{\alpha}_1 = \Phi(2z_0 + z_\alpha), \quad (\text{S5.3})$$

561 and

$$\tilde{\alpha}_2 = \Phi(2z_0 + z_{1-\alpha}), \quad (\text{S5.4})$$

562 respectively. A $100(1 - 2\alpha)$ percent confidence interval for $\theta(\mathbf{x})$ is then given by

$$\hat{\theta}_{(\tilde{\alpha}_1(B+1))}(\mathbf{x}^*) \leq \hat{\theta}(\mathbf{x}) \leq \hat{\theta}_{((\tilde{\alpha}_2-1)(B+1))}(\mathbf{x}^*). \quad (\text{S5.5})$$

563 S6 IBTS data set for cod and saithe

Table S6.1: Summary of North Sea IBTS cod and saithe (in parentheses) data for third quarter in year 2017 and first quarter in year 2018.

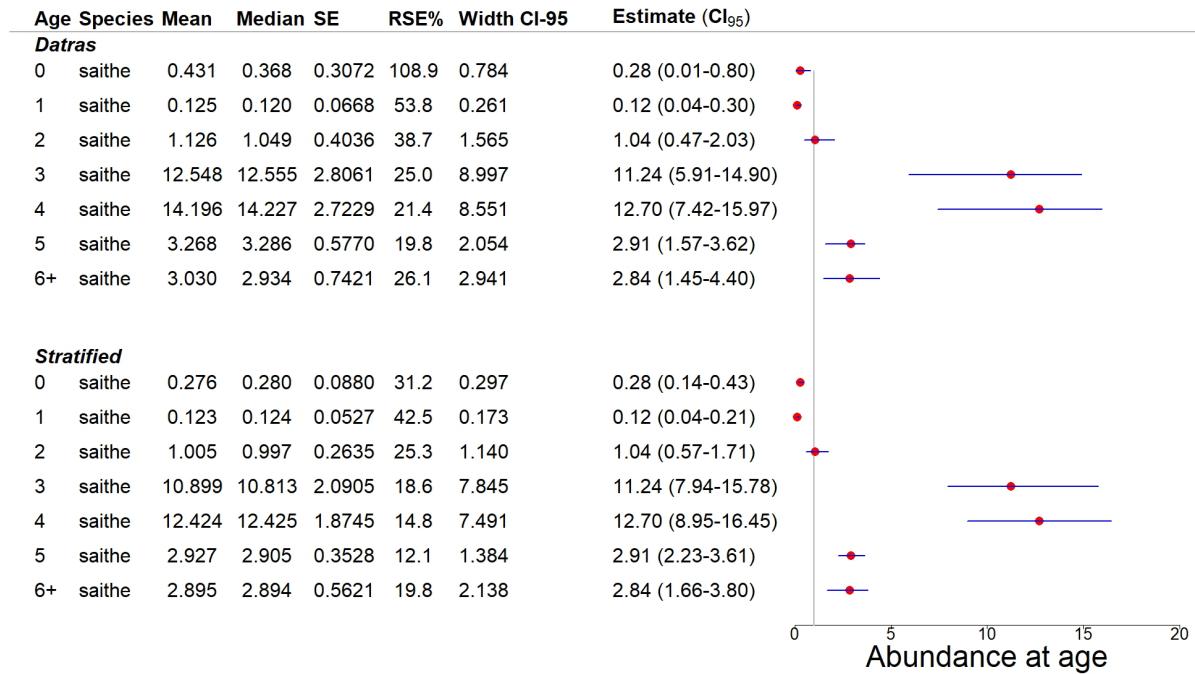
| Data | Description |
|--------------------------|--|
| Trawl hauls | Total of 372 trawl hauls in year 2018 Q1; 238 (83) with length and 230 (81) with age information. In 2017 Q3, a total of 345 trawl hauls were taken; 238 (129) with length and 237 (128) with age information. |
| Age | The age varied between 1 (1) to 12 (18) years in year 2018 Q1 and 0 (0) to 11 (17) in year 2017 Q3. |
| Length | Length information in cm varied between 11 (13) to 114 (106) cm in year 2018 Q1 and between 6 (10) to 112 (109) cm in year 2017 Q3. |
| Date | Date of catch in year 2018 Q1 varied between 15.01.2018 to 28.02.2018 and in year 2017 Q3 between 18.07.2017 to 31.08.2018 |
| Duration of haul | Mean duration is 29.37 minutes, with 30 minutes as 83% coverage interval in year 2018 Q1; and in 2017 Q3 with mean duration of 29.26 minutes with 30 minutes as 88% coverage . |
| Total count for all ages | 1600 (822) in year 2018 Q1 and 2330 (2163) 2017 Q3. |

Table S6.2: Age and length data for saithe in year 2017 Q3 and cod in year 2018 Q1. Data collected in the first quarter (Q1) has no age 0 group but this is collected in quarter 3 (Q3) surveys.

| Age | Numbers aged | saithe in year 2017 Q3 | | | | | Otoliths | cod in year 2018 Q1 | | | | |
|-----|--------------|------------------------|------------------|-------------------|-------|-------|----------|---------------------|------------------|-------------------|--------|-------|
| | | L _{min} | L _{max} | L _{mean} | Sd(L) | CV(L) | | L _{min} | L _{max} | L _{mean} | Sd(L) | CV(L) |
| 0 | 21 | 10 | 14 | 12.143 | 1.195 | 0.098 | | | | | | |
| 1 | 26 | 23 | 32 | 27.654 | 2.297 | 0.083 | 149 | 11 | 30 | 18.407 | 3.693 | 0.201 |
| 2 | 65 | 27 | 47 | 38.077 | 3.337 | 0.088 | 814 | 17 | 53 | 33.180 | 6.290 | 0.190 |
| 3 | 531 | 34 | 56 | 42.041 | 3.785 | 0.090 | 222 | 30 | 81 | 50.654 | 10.185 | 0.202 |
| 4 | 767 | 35 | 73 | 48.261 | 4.521 | 0.094 | 189 | 43 | 92 | 64.479 | 8.399 | 0.130 |
| 5 | 334 | 46 | 78 | 56.876 | 6.105 | 0.107 | 102 | 54 | 96 | 76.627 | 9.594 | 0.125 |
| 6 | 159 | 50 | 91 | 66.025 | 7.137 | 0.108 | 84 | 54 | 100 | 80.871 | 9.456 | 0.117 |
| 7 | 127 | 57 | 93 | 73.976 | 7.163 | 0.097 | 28 | 58 | 110 | 84.086 | 11.308 | 0.134 |
| 8 | 69 | 63 | 94 | 77.725 | 7.010 | 0.090 | 4 | 80 | 94 | 85.500 | 6.455 | 0.075 |
| 9 | 18 | 64 | 97 | 85.333 | 7.499 | 0.088 | 5 | 66 | 96 | 83.400 | 11.305 | 0.061 |
| 10 | 22 | 84 | 107 | 92.364 | 5.803 | 0.063 | 1 | 87 | 87 | - | - | - |
| 11 | 5 | 79 | 102 | 92.800 | 9.311 | 0.100 | 1 | 106 | 106 | - | - | - |
| 12 | 7 | 91 | 109 | 99.429 | 6.554 | 0.066 | | | | | | |
| 13 | 5 | 94 | 104 | 98.800 | 4.550 | 0.046 | | | | | | |
| 14 | 1 | 108 | 108 | 108 | - | - | | | | | | |
| 15 | 1 | 105 | 105 | 108 | - | - | | | | | | |
| 16 | 4 | 93 | 106 | 100.250 | 5.439 | 0.054 | | | | | | |
| 17 | 1 | 109 | 109 | 109 | - | - | | | | | | |

S7 Estimates from DATRAS and Stratified bootstrap procedures

The bootstrap procedure proposed by DATRAS lacks the potential to account for the spatial variation in the data. The DATRAS bootstrap procedure ignores the fine-scale stratification in the sampling process, leading to an overestimation of the uncertainty; and ignores the age-length data collected at the haul level, resulting in an underestimation of the uncertainty. The results (FigureS1) shows an overestimation of the uncertainty for all age groups, suggesting that it is relevant to account for the fine-scale stratification when resampling the data.



(a) Datras and Stratified bootstrap Procedures

Figure S1: Comparison of estimated confidence intervals (CI₉₅) from DATRAS and stratified bootstrap procedures. The bias-corrected bootstrap method is used to give estimates for saithe in year 2017 Q3. Estimated indices of abundance (Estimate), and its standard error (SE), bootstrap mean (Mean), Median estimates, percentage relative standard error (RSE %) and width of confidence intervals are also given.