Biased stock assessment when using multiple, hardly overlapping, tuning series if fishing trends vary spatially

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Fishing-effort distributions are subject to change, for autonomous reasons and in response to management regulations. Ignoring such changes in a stock-assessment procedure may lead to a biased perception. We simulated a stock distributed over two regions with inter-regional migration and different trends in exploitation and tested the performance of extended survivors analysis (XSA) and a statistical catch-at-age model in terms of bias, when spatially restricted tuning series were applied. If we used a single tuning index that covered only the more heavily fished region, estimates of fishing mortality and spawning-stock biomass were seriously biased. If two tuning series each exclusively covering one region were used (without overlap but together covering the whole area), estimates were also biased. Surprisingly, a moderate degree of overlap of spatial coverage of the two tuning indices was sufficient to reduce bias of the XSA assessment substantially. However, performance was best when one tuning series covered the entire stock area.

Keywords: North Sea plaice, simulation, spatial effort variation, statistical catch-at-age, stock-assessment performance, tuning indices, XSA.

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Introduction

Management of exploited fish stocks depends largely on knowledge of the historical development in their status. Population parameters such as current and historical biomass, plus fishing mortality, are usually estimated by analytical stock-assessment models founded on virtual population analysis (VPA). Based on these estimates, advice may be given on implementing appropriate harvest control rules and management measures such as total allowable catches (TACs; ICES, 2007). The appropriateness of the management advice depends critically on the accuracy of the historical and current population estimates. If estimates are biased, management measures may drive the population away from the desired state rather than bringing it closer, or exploitation may be unnecessarily restricted. Therefore, potential sources of bias in the assessment need to be avoided.

Many assessment methods use fishery-dependent data, particularly commercial catch-at-age in numbers, but incorporate fisheries-independent data too, specifically indices of abundance from research-vessel surveys. Therefore, extended survivors analysis (XSA; Shepherd, 1999), a calibrated variant of VPA commonly used in the Northeast Atlantic (ICES, 2007), needs as input the catch-at-age in numbers and one or more calibration (tuning) series of catch per unit effort (cpue) by age group. The tuning series may be derived from commercial catch and effort data or from research-survey data. Multiple series are often used together. In the latter case, different indices may sometimes cover different parts of a stock's distribution area or its age classes (e.g. young fish surveys).

Here, we investigate how the use of one or more spatially restricted tuning indices may affect the stock assessment in terms of bias, in the situation that fishing trends vary spatially. We approach this question generically with a simulation model that does not aim to reflect a real stock, but we illustrate the issue by referring to the example of North Sea plaice (*Pleuronectes platessa*) to show that the question has current relevance.

The North Sea plaice stock is assessed annually using XSA (ICES, 2008). Currently, plaice are taken mainly in a mixed flatfish fishery by beam trawlers in the southern and southeastern North Sea. Directed fisheries are also carried out with seines, gillnets, and twin-trawls, and by beam trawlers in the central North Sea, but the number of vessels participating in these fisheries generally declined over the past 10 years. In particular, the Dutch beam trawl fleet, one of the major operators in the mixed flatfish fishery, has shifted its main effort from the central North Sea towards more inshore fishing grounds in the south (Rijnsdorp *et al.*, 2008). This shift may have been caused by a range of factors, including the implementation of effort restrictions (days-at-sea), the increase in fuel price, and relative changes in the TACs for the two target species, sole (*Solea solea*) and plaice (ICES, 2008; Rijnsdorp *et al.*, 2008). Important to our question is that over the past decade, fishing intensity has decreased in one part of the stock's distribution area, whereas it has remained constant or may even have increased in the other part. Moreover, the plaice box has been closed to vessels >300 hp (Pastoors *et al.*, 2000) since 1995, and fishing diminished abruptly there.

Table 1. Maturity-at-age, weight-at-age (units are irrelevant), and relative *F*-at-age.

	Value at age										
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11+**
Maturity	0.0	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Weight	0.15	0.20	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05
Relative *F*	0.10	0.35	0.60	0.80	0.95	1.00	1.00	1.00	1.00	1.00	1.00

The problem addressed arises when fishing intensity changes differentially among subareas, gradually or abruptly. In such a situation, the recent commercial catch-at-age data used as input for the stock assessment are mainly from the subarea where fishing intensity is highest and do not reflect the total distribution of the stock. Because the regions with relatively high fishing intensity tend to be dominated by younger age groups, whereas most of the surviving older fish are in the low-effort regions, the age composition of the commercial catches cannot be representative for the entire population, and this could bias the assessment. Here, we investigate the role of the tuning series in representing the abundance of the stock over the entire area and in remedying the potential bias.

We constructed a simple model in which the population dynamics were simulated under exploitation levels that could be varied independently in two subareas, allowing for different rates of exchange between the two. Simulated catch data were equal to the "true" catch numbers, and simulated abundance indices were proportional to the true numbers present. These data were fed into XSA to investigate how well the stock development could be assessed (note that for the assessment, the subpopulations were viewed as a single stock). As catch numbers and tuning indices used as input were not subject to error or bias, any discrepancy between the true and the perceived stock development must be caused by flaws in the assessment model. To test whether any resulting bias is specific to the use of the XSA model, we also carried out assessments using a statistical catch-at-age model (Fournier and Archibald, 1982; Deriso *et al.*, 1985; ICES, 2005).

Methods

Simulated population dynamics

The deterministic simulation ran in time-steps of 1 year over a period of 20 years. Annual recruitment at age 1 (R) was set constant at 20 000. Maturity-at-age, weight-at-age, the selection pattern (Table 1), and natural mortality ($M = 0.1$ at all ages) were also set as constant. The fishing mortality (F) on fully recruited ages (>5 years) was set constant at 0.5 for the first 15 years of the simulation ($F_{2-8} = 0.41$), and modified thereafter (see below). Annual exchange between the two subareas was mimicked by allowing a constant proportion (E) of the population present at the start of the year in each subarea to shift to the other. The starting population and its distribution over the subareas in year 1 were set to be in equilibrium under the given mortality and migration rates. These dynamics determine population numbers-at-age, catch numbers-at-age, and spawning-stock biomass (SSB) for each subarea separately as well as for the total area. The equations used are given in Appendix A.

Various scenarios were explored in which we independently varied (i) the distribution of recruits over the two subareas, (ii) the respective emigration rates E_{12} and E_{21} from subarea 1 into subarea 2 and vice versa, and (iii) the change in F during the final 5 years of the simulation. We report on results from simulations where the recruits are either equally divided among the two subareas (10 000 in each) or where young fish mainly recruit into subarea 1 (18 000 recruits into subarea 1, 2000 into subarea 2). The first type of simulation was used to mimic the situation where exploitation differs in two (more or less equally sized) parts of the stock's distribution area. Here, E_{12} and E_{21} were either set at 0.3 and 0.1, respectively, or at 0.1 and 0.3, respectively. Simulations with $E_{12} = E_{21}$ yielded results that were qualitatively intermediate between the cases reported here. The simulations with an unequal distribution of recruits were intended to mimic the introduction of a closed area. The interpretation is that subarea 2 covers 10% of the total distribution area. For unequal recruitment, a 10× smaller fraction of the bigger subgroup migrated to the smaller subgroup than vice versa: $E_{12} = 0.03$ and $E_{21} = 0.3$.

F was modified differently for the two recruitment scenarios. For subareas of equal size, F was gradually reduced by 60% over the final 5 years in subarea 2, whereas F gradually increased by the same extent in subarea 1, so reflecting a shift in spatial effort allocation. This scenario mimics the situation for North Sea plaice where exploitation is supposed to have decreased in the north and increased in the south. Specifically, the setting of $E_{12} > E_{21}$, mimicking the tendency of fish to move into deeper water in the north (Bolle *et al.*, 2005), allowed a build-up of older fish in subarea 2. The reverse setting ($E_{12} < E_{21}$) was used only to explain the results from the closed-area case (see below). In the simulations mimicking area closure, F in the smaller subarea 2 was abruptly reduced to zero, then kept at zero during the final 5 years. F in the main subarea 1 was increased by 10% at the start of the closure of subarea 2, mimicking effort re-allocation from the closed area into the main (open) area. Hence, we report on three distinct simulation scenarios: (i) a gradual shift in effort, equally distributed recruits, and $E_{12} > E_{21}$; (ii) a gradual shift in effort, equally distributed recruits, and $E_{12} < E_{21}$; and (iii) a closure of subarea 2, with 10% of the recruitment, and $E_{12} < E_{21}$.

Stock assessment

SSB and F_{2-8} of the population as a whole were estimated, using as input the exact catch numbers-at-age and one or two tuning series of relative abundance-at-age. The surveys took place at the start of the year. We investigated the assessment results under different configurations of coverage of the tuning series:

(i) one tuning series covering the whole area, such that the index values were proportional to the total population numbers;

(ii) one tuning series covering only subarea 1 (where fishing was not reduced), such that the index values were proportional to the population numbers in that subarea only;

(iii) two separate tuning series, together covering the entire area, such that the index values were proportional to the population numbers in subareas 1 and 2, respectively;

(iv) in configuration (iii), there was no overlap in area coverage between the two indices (0%), so we investigated some additional configurations with spatial overlap between the two indices of 25, 50, and 75%. The index values were proportional to the weighted average of the population numbers over both subareas, with one subarea receiving a weight of 1 and the other a weight corresponding to the extent of overlap. In that way, index 1 covered subarea 1 plus a part of subarea 2, whereas index 2 covered subarea 2 plus a part of subarea 1.

The equations covering the tuning indices are given in Appendix A.

Assessments were performed using the XSA suite (Darby and Flatman, 1994) with the settings given in Appendix B, and using a statistical catch-at-age model (Fournier and Archibald, 1982; Deriso *et al.*, 1985). The latter model was run in an excel spreadsheet ("xModel"; ICES, 2005) with selectivity modelled using a double-half Gaussian function (legs of two normal distributions with different "slopes" on each side of the age of full selectivity). Details are given in Appendix C.

Results

Figure 1 depicts the deviations of the perceived *F* and SSB from their true values in the final year of the simulation based on the two assessments for each of tuning series configurations (i)–(iii). XSA estimated both parameters precisely so long as one tuning series was used that was representative of the distribution of the total stock over the two subareas [configuration (i)]. The statistical catch-at-age method was notably less accurate except for the scenario with gradual effort reallocation and $E_{21} > E_{12}$, where all fish tended to concentrate in the more heavily fished area.

As expected, the perceived status of the stock in terms of *F* and SSB was heavily biased for all three scenarios if the tuning series was provided by a survey that only covered the intensively fished subarea [configuration (ii)]. In that case, the catch-at-age model did slightly better than XSA, but for both methods the bias was large. *F* and SSB in the final years were overestimated and underestimated, respectively. Apparently, it is essential that the tuning series continues to cover the subarea where fishing intensity declined. The same applies to an area that has been closed to fishing. Neither the true increase in SSB nor the true decline in total *F* resulting from shifting the effort from one area to the other can be detected using a tuning series only covering the subarea in which intensive fishing continues (Figure 2a).

More surprisingly, the perception of stock development was also markedly biased when two non-overlapping tuning series were used that together covered the whole area [configuration (iii)]. The direction of the bias depended on whether migration was stronger from the intensively fished subarea into the less-fished subarea, or vice versa. In the first case, *F* was overestimated and SSB underestimated, as before. If a larger proportion of fish emigrated out of the less-fished subarea ($E_{21} > E_{12}$), as in the simulation that mimics area closure (Figure 2b), the bias was reversed: *F* was underestimated and SSB overestimated. Apparently, the practice of using multiple tuning series, each

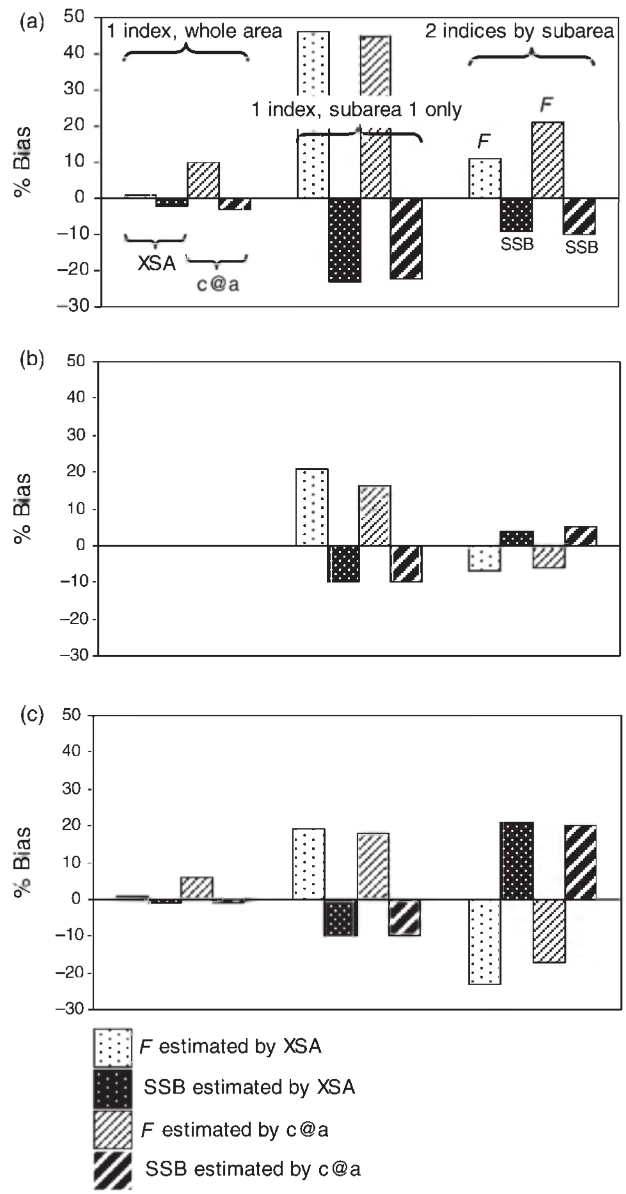

Figure 1. Percentage bias of the perceived value relative to the true value of stock parameters in the last year. (a) Gradual shift in effort, equally distributed recruits, and $E_{12} > E_{21}$. (b) Gradual shift in effort, equally distributed recruits, and $E_{12} < E_{21}$. (c) Closure of subarea 2 with 10% of the recruits and $E_{12} < E_{21}$. c@a, catch-at-age.

covering a complementary part of the stock's distribution area, yields biased stock assessments if fishing trends vary spatially.

XSA might provide incorrect estimates owing to the automatic weighting of the tuning fleets. We expected that the tuning series that more closely resembled the commercial catch composition, i.e. the series reflecting the more intensively fished subarea from which most of the commercial data were derived, received more weight than the other, more deviant one. However, checking the diagnostics of the XSA runs revealed that this was not the case: the tuning series received exactly equal weights (ranging from 0.482 to 0.498; the remaining weight was attributed to shrinkage). Moreover, the statistical catch-at-age model, which has no automatic weighting, gave similarly incorrect estimates. Nevertheless, the sum of squares in the objective function from the subarea 2

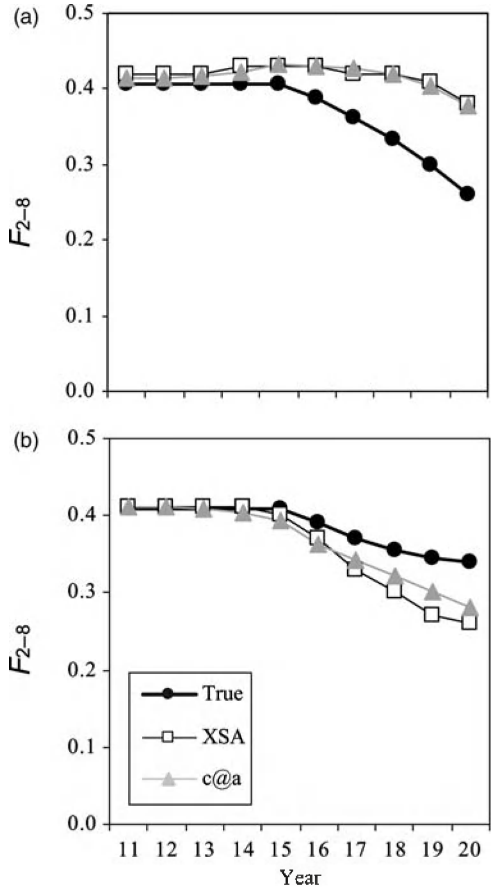

Figure 2. Time-series of true and perceived F_{2-8}. (a) Gradual shift in effort, equally distributed recruits, and $E_{12} > E_{21}$; the assessment uses one tuning series covering only subarea 1 [configuration (ii)]. (b) Closure of subarea 2 with 10% of the recruits and $E_{12} < E_{21}$; the assessment uses two tuning series covering subareas 1 and 2, respectively, without overlap [configuration (iii)]. c@a, catch-at-age.

Table 2. Sums of squares of the three components in the fitted statistical catch-at-age model.

Scenario	Commercial catch	Index subarea 1	Index subarea 2
Gradual shift in effort, equally distributed recruits, and $E_{12} > E_{21}$	1.41	0.42	0.43
Gradual shift in effort, equally distributed recruits, and $E_{12} < E_{21}$	1.36	0.36	0.52
Closure of subarea 2 with 10% of the recruits and $E_{12} < E_{21}$	1.38	1.05	2.64

Table 3. Relation between the extent of spatial overlap of the tuning indices and the resulting bias in stock parameters estimated using XSA.

	Spatial overlap between two indices				
Parameter	0%	25%	50%	75%	One index covering all
Scenario: Gradual effort shift, equally distributed recruits, $E_{12} > E_{21}$					
Bias in *F* (%)	11.5	4.9	2.6	1.8	1.4
Bias in SSB (%)	−9.1	−4.2	−2.7	−2.1	−1.7
Scenario: Closure of subarea 2 with 10% of the recruits and $E_{12} < E_{21}$					
Bias in *F* (%)	−23.2	−5.0	−0.4	1.2	1.0
Bias in SSB (%)	21.5	3.3	−0.2	−1.3	−1.0

index was always higher than that from subarea 1, demonstrating that the latter fitted the final model better (Table 2).

Results from statistical catch-at-age models are known to be sensitive to assumptions on the selection pattern, and the assumed "double-leg" selectivity contradicts the flat selection in the true population. This may cause the slight differences in results between XSA and the statistical catch-at-age model. Always, however, the σ_R was estimated about 3×10^8 times larger than σ_L (see Appendix C), so well reflecting the flat true selectivity on the right side.

Interestingly, the relation between the degree of spatial overlap between the indices and the resulting bias was not at all linear [configuration (iv); Table 3]. As spatial overlap increased, the initial reduction in bias was steep. An overlap of only 25% reduced the bias to quite moderate proportions (<5%), but a further increase in overlap failed to yield further gains in accuracy.

Discussion

Although the true temporal developments in population parameters may be approximated by XSA even if fishing varies spatially in time, we found that it matters crucially that the tuning series used represent the overall abundance over the whole area. If multiple series were used, each covering only part of the total area with hardly any overlap, there were serious biases in the parameter estimates. However, partial spatial overlap reduced these biases substantially. In closed areas, or in areas where the fishing intensity has declined notably, sampling needs to continue. If commercial data are used for tuning, it is important that the cpue is weighted appropriately over the whole area and not biased towards the regions where most fishing effort is deployed (Quirijns *et al.*, 2008). For closed areas, this becomes obviously impossible, so the tuning series needs to be derived from research-vessel surveys that continue to sample those areas.

These findings may have implications for some current stock assessments where multiple tuning series are used. Looking again at the example of North Sea plaice (ICES, 2008), three tuning series have been used for the assessment based on (i) the stations of the beam trawl survey fished by RV "Isis" and covering the southern North Sea (BTS Isis), (ii) the stations of the beam trawl survey fished by RV "Tridens" and covering the central North Sea (BTS Tridens), and (iii) the sole net survey covering the coastal areas and sampling only young age groups (SNS). As the spatial coverage by BTS Isis and BTS Tridens overlaps by only ~10% (Bogaards *et al.*, 2009), the true extent of change in stock status caused by the reduced fishing intensity in the central North Sea may not be detected by the assessment. Our results suggest that the stock may be in a more healthy state than is currently thought, if proportionally more fish migrate north rather than south. If the reverse were true, the stock might be in a worse state. However, the latter option is less likely because the older age groups of plaice are generally more abundant in the deeper, more northern waters (Bolle *et al.*, 2005). Bogaards *et al.* (2009) explored a purely survey-based assessment of North Sea plaice using the two alternative signals provided by BTS Isis and BTS Tridens (disregarding any commercial catch data). The model giving the best fit allowed for different trends in F between the two areas. Their findings suggest that the current ICES assessment of North Sea plaice may not be able to capture the overall trend within the population.

Although the estimates in some simulations deviated only a few percentage points from the true values, this should not lead to the conclusion that the assessments of stocks in the real world might be that accurate and precise given appropriate tuning series. In the simulations, we did not incorporate any uncertainty or bias in the input data, and these data reflected exactly the true population dynamics of the simulated (sub)population(s). In reality, this will never be the case because there is always uncertainty in the data, and often bias too (Dickey-Collas *et al.*, 2007). Moreover, the simulated population behaved very neatly without annual fluctuations in various parameters and only gradual or abrupt changes in F. The assumptions that are explicit or implicit in stock-assessment models, such as constant natural mortality (M), applied exactly to the simulated population. Therefore, our study addressed only the potential effect of spatially heterogeneous fishing in isolation of all the other possible factors that can contribute to uncertain and biased stock assessments (Kraak *et al.*, 2008). We conclude that changes in fishing behaviour, e.g. resulting from policy changes, do not necessarily give rise to biased stock assessments, if the tuning series are appropriate: they need, however, to cover the whole stock area, or if multiple series are used, they need to have a substantial extent of spatial overlap. The use of indices that represent the abundance in hardly overlapping subareas can give rise to serious biases.

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Appendix A

Population dynamics equations in the true population

$$N_1(a,y) = N_1(a-1,y-1) \times \exp[-Z_1(a-1),(y-1)] + T_2(a-1,y-1),$$

$$N_2(a,y) = N_2(a-1,y-1) \times \exp[-Z_2(a-1),(y-1)] + T_1(a-1,y-1),$$

$$Z_i = F_i + M + E_{ij},\ j \neq i,$$

$$T_1(a,y) = \frac{E_{1i}}{Z_1(a,y)} \times N_1(a,y) \times \{1-\exp[-Z_1(a,y)]\} \times \exp\{-0.5 \times [M+F_2(a,y)]\},\ i \neq 1,$$

$$T_2(a,y) = \frac{E_{2i}}{Z_2(a,y)} \times N_2(a,y) \times \{1-\exp[-Z_2(a,y)]\} \times \exp\{-0.5 \times [M+F_1(a,y)]\},\ i \neq 2,$$

$$N_{\text{total}}(a,y) = N_1(a,y) + N_2(a,y),$$

$$C_1(a,y) = \frac{F_1(a,y)}{Z_1(a,y)} \times N_1(a,y) \times \{1-\exp[-Z_1(a,y)]\} + \frac{F_1(a,y)}{M+F_1(a,y)} \times T_2(a,y) \times (\exp\{0.5 \times [M+F_1(a,y)]\}-1),$$

$$C_2(a,y) = \frac{F_2(a,y)}{Z_2(a,y)} \times N_2(a,y) \times \{1 - \exp[-Z_2(a,y)]\} + \frac{F_2(a,y)}{M + F_2(a,y)} \times T_1(a,y) \times (\exp\{0.5 \times [M + F_2(a,y)]\} - 1),$$

$$C_{\text{total}}(a,y) = C_1(a,y) + C_2(a,y),$$

$$F_{\text{total}}(a,y) = M \times \frac{C_{\text{total}}(a,y)}{N_{\text{total}}(a,y) - N_{\text{total}}(a+1,y+1) - C_{\text{total}}(a,y)}.$$

In configuration (i):

$$I(a,y) = p \times (N_1(a,y) + N_2(a,y));$$

In configuration (ii):

$$I(a,y) = p \times N_1(a,y);$$

In configuration (iii):

$$I_1(a,y) = p \times N_1(a,y) \text{ and } I_2(a,y) = p \times N_2(a,y);$$

In configuration (iv):

$$I_1(a,y) = p \times (N_1(a,y) + s \times N_2(a,y))$$
$$I_2(a,y) = p \times (N_2(a,y) + s \times N_1(a,y)),$$

where N is the population number, Z the mortality rate, T the number of emigrants, F the fishing mortality rate, M the natural mortality rate, E the emigration rate, C the catch number, I the index value, a the age, y the year, i and j the indices, with value 1 for subarea 1, 2 for subarea 2, or "total" for the total area, p an arbitrary proportion (in this study we used $p = 0.005$, but the results do not depend on its value), and s the proportion of spatial overlap (we used values of $s = 0.25$, 0.5, and 0.75).

Appendix B

Settings in the XSA runs [Lowestoft VPA version 3.1 (Darby and Flatman, 1994)]

(i) Catch data for 20 years; ages 1–11 (last age is a plus group).

(ii) Tuning data for 20 years; ages 1–7; start of fishing at 0.01 and end of fishing at 0.02 of the year.

(iii) Tapered time weighting not applied.

(iv) Catchability independent of stock size for all ages.

(v) Catchability independent of age for ages ≥6.

(vi) Survivor estimates shrunk towards the mean F of the final 3 years or the five oldest ages; standard error of the mean to which the estimates are shrunk = 2.000.

(vii) Minimum standard error for population estimates derived from each fleet = 0.300.

(viii) For two tuning fleets, prior weighting was not applied.

Tuning never converged after 30 iterations, but total absolute residual between iterations 29 and 30 was always <0.06.

Appendix C

Details of the statistical catch-at-age model

We used the Excel spreadsheet xModel provided by Dankert Skagen and Einar Hjörleifsson (ICES, 2005). The model formulation used here disregards the possibility of differentiation between subareas and models the standard population dynamics of the entire population (equations are not provided here; the xModel tool can be found at www.ices.dk/reports/RMC/2005/WKAFAT). The objective function minimizes the sum of the squared deviations between the natural logarithms of the observed and predicted commercial catch- and survey numbers-at-age.

Data

(i) Catch data for 20 years; ages 1–11 (last age is a plus group).

(ii) Tuning data for 20 years; ages 1–7; start and end of fishing at 0.00 of the year.

Estimated parameters

(i) Selectivity (S) parameters: $\ln(\sigma_L)$, $\ln(\sigma_R)$, and $\ln(a_{\text{full}})$ (see below).

(ii) Level of fishing mortality: ln(F-at-age of full selectivity) for each of the 20 years.

(iii) Population numbers in the first year: ln(N in the first year) for each of the 11 age groups.

(iv) Number of recruits: ln(N at the first age) for each of the 20 years.

(v) Survey catchabilities: $\ln(q)$ for each of the 7 ages for each of the surveys.

Selectivity was modelled using a double-half Gaussian function, where each half is half of a normal distribution. The equation is

$$s_{a,y} = \begin{cases} e^{-(a-a_{\text{full},y})^2/\sigma_{L,y}} & \text{for } a \le a_{\text{full},y} \\ e^{-(a-a_{\text{full},y})^2/\sigma_{R,y}} & \text{for } a > a_{\text{full},y}. \end{cases}$$

The values of σ in this case are equivalent to the standard deviations and a_{full} the equivalent to the mean in the normal distributional sense. a_{full} is the age of full selectivity (=1.0), σ_L determines the shape factor of the left side of the curve, and σ_R determines the shape factor of the right side. Note that always, the σ_R was estimated ~3×10^8 times larger than σ_L, reflecting the fact that the true selectivity was flat on the right side.

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