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Estimating F_{msy} from an ensemble of data sources to account for density-dependence in Northeast Atlantic fish stocks

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GLMM analysis linking the ratio of exploitable biomass to SSB to life history parameters

Time-series of TB were used as inputs for fitting surplus production models, but some assessments provided only time-series of SSB instead of TB. To estimate TB time-series from SSB, a series of regression models was constructed to predict TB from SSB and other covariates using the subset of assessments in which both TB and SSB were available. Different models included different predictor variables as covariates. The variety of predictor variables included in some regression models were: ages and sexes of spawners, as they influence the degree to which SSB is a subset of TB; taxonomic group category; region, because assessment conventions are often consistent within a region; life history parameters; and lag terms for relative fishing mortality in previous years. Candidate models were constructed with various combinations and interactions of these factors and were compared based on AICc values. The preferred model, in terms of AICc scores, related the log-ratio ln(TB/SSB) to the following covariates: sex and age of spawners, natural mortality, maximum length, growth rate, three lag terms of U/UMSY (in years $t-1$, $t-2$, and $t-3$), interactions between natural mortality and these lag-terms, taxonomic group, and region. This preferred model was used for estimating TB from SSB; these estimates are only included in the "model-fits" version of the RAMLDB. Further details of candidate models and the biomass conversion procedure are provided in the documentation file "RAM B-Conversion Guide.docx" included in the release package of RAMLDB.

The GLM analysis of F_{msy} vs. life history parameters

F_{msy} has often been linked to life history parameters such as natural mortality and growth rate. We used General Linear Models (GLM) coded in R for the purpose. We tested a set of relevant life history parameters (age at 50% maturity – "a50mat", natural mortality of mature fish – "natM", $L_\infty \times K$ from the von Bertalanffy growth models - "Linf_K", preferred temperature -"prefT", trophic level of adult fish - "troph") against the F_{msy} values obtained from the methods mentioned above. The parameter values were based on ICES current input data to fish stock assessments (ICES, 2018, and reference therein) supplemented with data from FishBase (Froese and Pauly, 2018). We tested a few relevant groupings of species and found that a five-category grouping of species "taxg3" (cod and hake, other gadoids, flatfish, herring and sprat, and others) worked well with the model. Only a few parameters can be included in the model as we only have 53 F_{msy} "observations". We tested several relevant GLM models (see www.fmsyproject.net for detailed information). The final GLM model used were: log(Fmsy) ~ log(a50mat) + log(Linf_K) + taxg3.

The model explained 59% of the variation in the F_{msy} values. A model without taxg3 was almost as good, explaining 46% of the variation and had only two parameters. However, the AIC and AICc were better for the six-parameters model. Diagnostics from the final GLM run can be found in Table 2 and for these two others in Tables S1 and S2. Inclusion of Linf_K is just not significant, however, the AIC and the AICc indicate that the model should still include Linf_K. It is sensible to do also because it probably makes the predictions more robust using two rather than one life history parameter and because a GLM without taxg3 and only with these two parameters gives a quite good fit and with both parameters being highly significant.

Table S1. Diagnostics of the GLM model log(Fmsy) ~ log(a50mat) + taxg3 used to link life history parameters to F_{msy} i.e. logLinf_K omitted.

Variable name	**Coefficient**	**Standard error**	***t*-value**	***P*-value**
Intercept	0.2383	0.1935	1.232	0.2242
taxg3 (flatfish)	–0.8360	0.1573	–5.316	0.0000***
taxg3 (forage fish)	–0.8774	0.1650	–5.318	0.0000***
taxg3 (other gadoids)	–0.4797	0.1481	–3.239	0.0022**
taxg3 (other taxonomic groups)	–0.7476	0.1912	–3.910	0.0003***
a50mat	–0.5645	0.1149	–4.912	0.0000***
Null deviance	12.7648 on 52 degrees of freedom			
Residual deviance	5.6431 on 47 degrees of freedom			
AIC	45.695			
AICc	46.972			
Significance codes: * < 0.05, **<0.01, ***<0.001				

Table S2. Diagnostics of the GLM model log(Fmsy) ~ log(a50mat) + log(Linf_K) used to link life history parameters to F_{msy} i.e. taxg3 omitted.

Variable name	**Coefficient**	**Standard Error**	**t-value**	**P value**
Intercept	–1.5432	0.2382	–6.479	0.0000***
Linf_K	0.4586	0.0917	5.001	0.0000***
A50mat	–0.4969	0.1009	–4.926	0.0000***
Null deviance	12.7648 on 52 degrees of freedom			
Residual deviance	6.9457 on 50 degrees of freedom			
AIC	50.702			
AICc	50.942			
Significance codes: * < 0.05, **<0.01, ***<0.001				

Development in catch and fishing pressure since 1950

The development in catch and fishing pressure since 1950 in the Northeast Atlantic are illustrated in Figure S1. The fishing pressure is now the lowest observed in the time-series and is close to the planned fishing pressure if the current F_{msy} values are applied. The new F_{msy} values suggested by the present study are about 0.12 higher and around the fishing pressure in the 1960s. The current catch is about 5 million tonnes below the catch in the period 1970–2000, which is regarded as the period of overfishing.

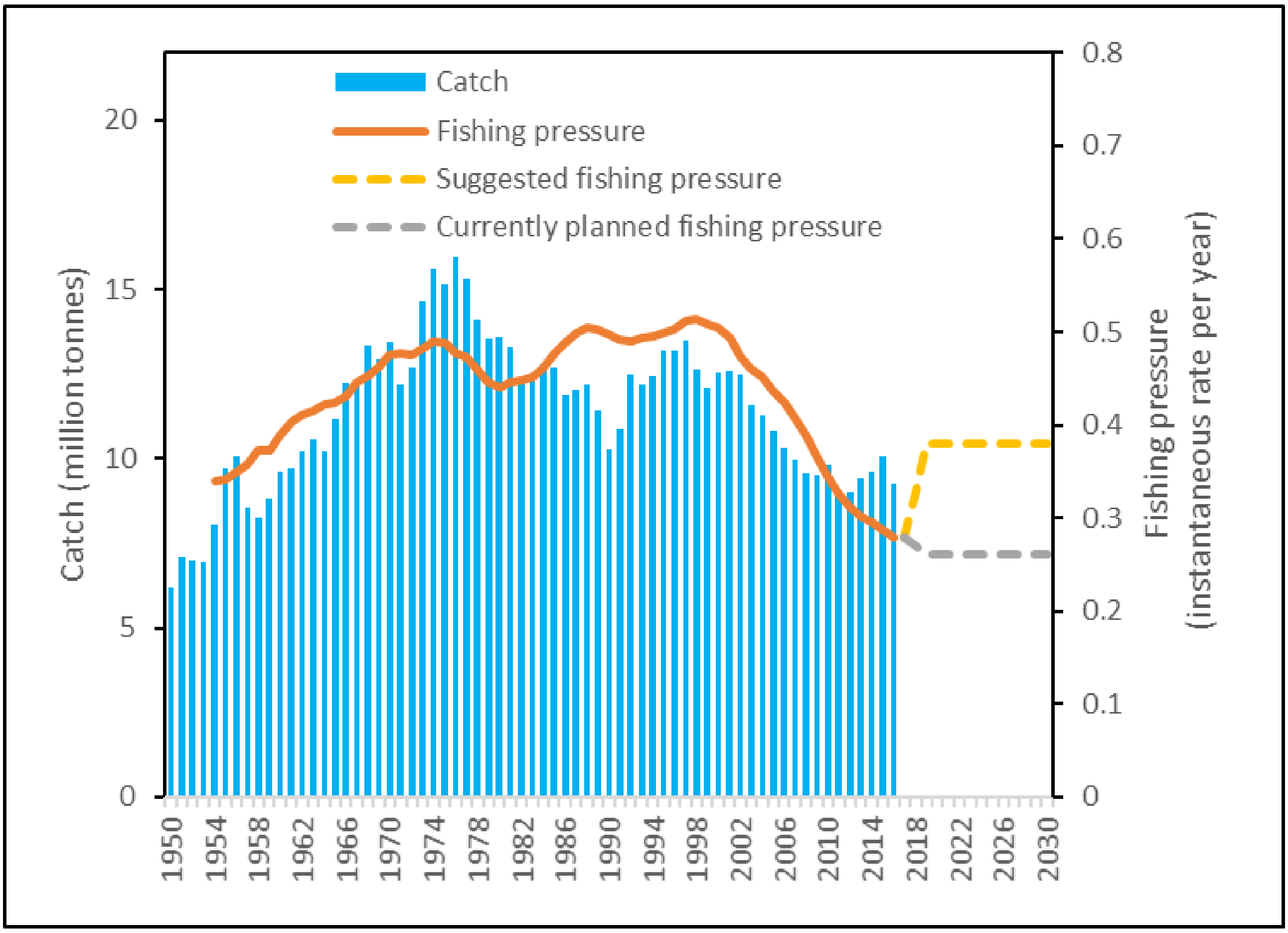

Figure S1. Catch by year in the Northeast Atlantic (FAO Area 27. From ICES database (http://www.ices.dk/marine-data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx) except unreported catch (discards and IUU catch) which is from the "Sea Around Us"- database (http://www.seaaroundus.org/). Average fishing (5-year running means) for 53 data-rich Northeast Atlantic fish stocks. Until 2017, the values are historic values based on actual catches (ICES, 2018). From 2018 and onward, it is forecasts. The "Currently planned fishing pressure" curve is the development forecasted if the current F_{msy} values are used in management, and the "Suggested fishing pressure" curve is the forecasted fishing pressure if the new F_{msy} values suggested in the present study are used.

Various analysis

Further sensitivity analysis was performed of the stability over time-periods of F_{msy} estimates based on surplus production models for cod, haddock, and saithe in Faeroes waters. These were based on time-series of catch and stock biomass going back several hundred years. Details can be found in Sparholt *et al.* (2019a).

Sensitivity of estimates of F_{msy} in surplus production models to length of time-series of catch and stock biomass. These were based on shortened time-series of catch and stock biomass and showed that it is rare to get reliable F_{msy} estimates when the time-series are shorter than 25 years. Details can be found in Sparholt *et al.* (2019a).

Further details and diagnostics of the Ram Myers Database type surplus production model estimations used in the present studies can be found in Sparholt *et al.* (2019a).

Ecosystem and multispecies model F_{msy} estimate by fish stock for the six stocks, where such information is available and judged reliable and robust, are contributing to the new F_{msy} values suggested by the present study. The selection criteria and references to relevant scientific literature by stock is given in Sparholt *et al.* (2019a–c).

Basic data and further analysis

Basic data and further analysis can be found at the F_{msy}-project homepage, under "data-sets": https://www.fmsyproject.net/data-sets and in the following working group reports:
https://www.norden.org/en/publication/report-1st-working-group-meeting-optimization-fishing-pressure-northeast-atlantic .
https://www.norden.org/en/publication/report-2nd-working-group-meeting-optimization-fishing-pressure-northeast-atlantic .
https://www.norden.org/en/publication/report-3rd-working-group-meeting-optimization-fishing-pressure-northeast-atlantic-rhode .

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Sparholt, H., Bogstad, B., Christensen, V., Collie, J., van Gemert, R., Hilborn, R., Horbowy, J., *et al.* 2019b. Report of the 1st working group meeting on optimization of fishing pressure in the Northeast Atlantic, Copenhagen, June 2017. NORDIC WORKING PAPERS http://dx.doi.org/10.6027/NA2019-904 NA2019:902, ISSN 2311-0562. https://www.norden.org/en/publication/report-1st-working-group-meeting-optimization-fishing-pressure-northeast-atlantic

Sparholt, H., Bogstad, B., Christensen, V., Collie, J., van Gemert, R., Hilborn, R., Horbowy, J., *et al.* 2019c. Report of the 2nd working group meeting on optimization of fishing pressure in the Northeast Atlantic, Vancouver November 2017. NORDIC WORKING PAPERS http://dx.doi.org/10.6027/NA2019-905 NA2019:902, ISSN 2311-0562. https://www.norden.org/en/publication/report-2nd-working-group-meeting-optimization-fishing-pressure-northeast-atlantic-0

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