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A state-space age-structured assessment model that accommodates environmental effects on demographic parameters and biological reference points

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Summary

The state-space model framework provides a natural probabilistic approach to modeling the stochastic nature of population survival and recruitment and sampling error inherent in observations of the population. Such models can be expanded to also model error in environmental covariates and their effects on demographic parameters. We present a state-space age-structured assessment model that can incorporate effects of observed covariates on recruitment and apply the model to Southern New England (SNE) yellowtail flounder and Gulf of Maine (GOM) Atlantic cod using data from the most recent benchmark assessments to evaluate evidence for environmental effects on stock productivity. Based on AIC, models that included environmental effects on recruitment performed better for both stocks and led to annual variation in estimated reference points.

Introduction

State-space models have long been used to separately model the stochastic nature of populations and error in observations that arises due to sampling. These models are increasingly being used within ICES to manage fish stocks (Nielsen and Berg 2014). Other existing stock assessment models have been generalized to include environmental effects on basic population dynamics parameters, but dealing with missing environmental observations has been problematic and accounting for associated sampling error is rare. Here we present a hierarchical state-space model that incorporates the unknown true environmental covariate as an additional state and any associated observations we may have. We fit and compare models with and without environmental effects to data on SNE yellowtail flounder and GOM Atlantic cod.

Materials and Methods

There are 3 components of the state-space in the general model: the numbers at age and the natural mortality at age of the of the fish stock and any environmental covariate that may influence recruitment to the stock. We model the state of the environmental covariate as a normal random walk $E\left(X_{t+1}|X_t\right) = X_t$ on which we have observations $y_t \sim \mathrm{N}(X_t, \sigma^2_{y,t})$ for at least a subset of years in the model. Similar to Nielsen and Berg (2014), we assume the log-abundance of all ages is normally distributed. For ages > 1 the conditional expectations are $E\left(\log N_{a,t+1}|N_{a-1,t}\right) = \log N_{a-1,t} - F_{a-1,t} - M_{a-1,t}$ for ages $1 < a < A$ and

$$E\left(\log N_{A,t+1}|N_{a-1,t}, N_{A,t}\right) = \log\left(N_{a-1,t}e^{-F_{a-1,t}-M_{a-1,t}} + N_{A,t}e^{-F_{A,t}-M_{A,t}}\right)$$

for the final age class (plus group). We allow two alternative models of the recruitment processes (the state corresponding to the numbers at age 1). The first recruitment model is independent annual normal random effects about a mean log-recruitment with additive effects of the environmental covariate, $E\left(\log N_{1,t}|X_t\right) = \log R_0 + \beta_R X_t$. The second model assumes a Beverton-Holt stock-recruit relationship with environmental covariate effects on the productivity parameter,

$$E\left(\log N_{1,t+1}|\mathrm{SSB}_t, X_t\right) = \log\left[\frac{a(X_t)\mathrm{SSB}_t}{1 + b\mathrm{SSB}_t}\right]$$

where $\log\left[a(X_t)\right] = a_0 + \beta_R X_t$.

Log-observations of aggregate catch and indices are normally distributed conditional on the abundance at age in the respective years and associated age composition data are multinomial distributed. Variances of annual index observations and environmental covariates are given based on the survey design or particular estimation procedure. Catchability, annual fishing mortality, selectivity and recruitment parameters, and process error variances are the parameters estimated by maximum likelihood.

For analyses of Southern New England (SNE) yellowtail flounder and Gulf of Maine Atlantic cod we used the same survey and catch data from the respective benchmark assessments (NEFSC 2012, 2013). However, we made some simplifications to the selectivity models for catch and indices to reduce the number of estimated parameters. Previous work has suggested a relationship between recruitment strength and the extent of the Mid-Atlantic summer cold pool (Sullivan *et al.* 2005). We compared four models with the two alternative recruitment assumptions with and without effects of an index of the Mid-Atlantic cold pool that was considered at the last benchmark assessment (R_0 , $R_0 + CP$, SR, and $SR + CP$). Friedland *et al.* (2013) found *Centropages typicus* abundance to be correlated with the ratio of estimated recruitment and spawning stock biomass (survival ratio) for Gulf of Maine Atlantic cod. Similar to SNE yellowtail flounder, we compare four models with different recruitment assumptions and effects of *C. typicus* abundance (R_0 , $R_0 + Ct$, SR, and $SR + Ct$).

Results and Discussion

The best performing model for SNE yellowtail flounder included effects of both spawning stock size and the Mid-Atlantic Bight cold pool index on recruitment (Table 1). The best performing model for GOM cod included effects of *C. typicus* but not of spawning stock size on recruitment. Annual estimates of spawning stock size, recruitment, and fishing mortality from the best performing state-space models for the two stocks were generally comparable to the corresponding results from the benchmark assessment models, but there were differences in estimated precision of these estimates.

The inclusion of spawning stock size effects on recruitment in the best performing model model for SNE yellowtail flounder, allowed estimation of the effect of the cold pool index on MSY-based reference points (Figure 1). There was substantial interannual variation in estimated $\mathrm{SSB}_{\mathrm{MSY}}$ and $\mathrm{F}_{\mathrm{MSY}}$ and precision of the estimates. Stock size effects did not provide better model performance for GOM cod, but effects of *C. typicus* on SPR-based spawning biomass reference points still occur due to effects on mean recruitment. The short term trends in estimated *C. typicus* abundance are reflected in co-occurring trends in $\mathrm{SSB}_{40\%}$.

Table 1. Relative performance of models based on AIC.

Model	$-\log(L)$	n_p	AIC	Δ(AIC)
SNE yellowtail				
R_0	1189.44	54	2486.88	11.54
$R_0 + CP$	1186.05	55	2482.10	6.76
SR	1185.60	55	2481.20	5.86
$SR + CP$	1181.67	56	2475.34	0.00
GOM cod				
R_0	1072.57	52	2249.14	2.14
$R_0 + Ct$	1070.50	53	2247.00	0.00
SR	1071.25	53	2248.50	1.50
$SR + Ct$	1070.48	54	2248.96	1.96

The ability to statistically compare different assumptions about effects on recruitment or other demographic parameters is an important feature of state-space assessment models. The approach we used to include environmental effects extends the state-space to account for uncertainty in the observations and provides a statistically satisfactory way of dealing with missing observations either during the time period when other data exists or into the future for projections that are functions of the covariates.

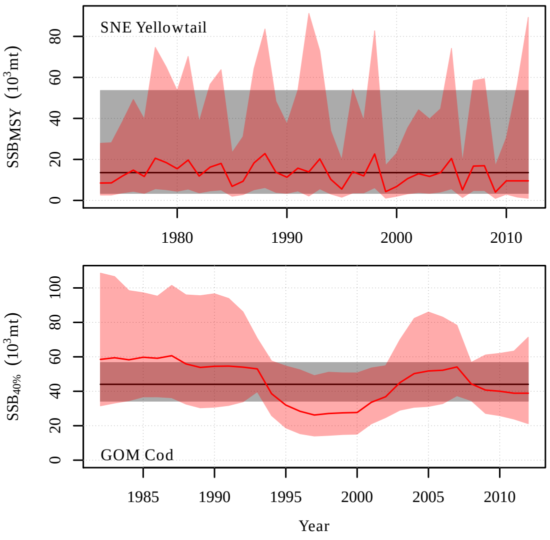

Figure 1. SSB reference points with (red) and without environmental effects (black).

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