Appendix B2

Replacement Yield Model Assessments of Gulf of Maine-Georges Bank Witch Flounder

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Introduction

The "replacement yield" (RY) assessment model is the simplest possible form of an age-aggregated dynamic surplus production model approach. The underlying rationale is that if a resource has been without trend in abundance over a period of time, the (average) annual sustainable yield from the resource over that period is given by the average annual catch. The term "replacement yield" is often used in this context rather than "sustainable yield", with the two being equivalent in an "average over time" sense, as technically RY is that catch which will leave (a specified component of) the resource biomass at the end of a year unchanged from the level at which it started that year. The approach extends naturally to a situation where the resource is trending up or down, in which case the RY will be either greater or less than the past average catch, and to an extent that depends on the size of the trend and the size of the underlying biomass.

This is formalised through a dynamic surplus production model in which the annual natural resource growth is taken to be a constant (here denoted by RY). Only limited information is used to then estimate RY: a time series of catches and of one or more indices of abundance (desirably with associated measures of precision). There are various ways possible to effect the estimation, with the one used here set out in Annex A, together with the specific data considered for implementation in this case. A key consideration is how to handle "estimation" of the index constant of proportionality to biomass q**.** Occasionally there is sufficient contrast in the data to estimate q directly, though more usually some prior has to be assumed or a fixed input value is used (with sensitivity to that value explored). In this application, where the survey indices of abundance available reflect swept area estimates of biomass in terms of tons, the approach has been to set q for those surveys equal to a fixed value on input (which is taken to be the same for both the autumn and spring surveys in question, with the choice q=1 implying those estimates to be unbiased).

The choice of the length of the period of years of data for which the approach is applied involves a trade-off. Since in reality there can be longer term trends in the natural growth of a resource over time, ideally one would want to use a short recent period only to get an RY estimate corresponding closely to that which applies at present. However, the shorter the series, the greater the variance of the RY estimate, so that some compromise decision needs to be made.

By construction the MSY concept is not built into the approach. It could equally be applied to a resource with present abundance either well above or well below B_{MSY}, and would provide the same output for both. In principle that might not be desirable; in practice however, that aspect is moot as in the circumstances where such an approach might be applied, one would generally be fairly uncertain as to on which side of B_{MSY} the resource biomass was. Regarding MSY-related reference points, at a stretch one might consider the RY estimate a surrogate for MSY. At a further stretch, since the approach provides a time series of (age-aggregated) biomass estimates, one could take the average biomass over the period considered as a surrogate for B_{MSY} , and then the corresponding surrogate for F_{MSY} (considered as an exploitation rate) would be given simply by MSY/ B_{MSY}.

Results and Discussion

Results from the application of the approach to Gulf of Maine-Georges Bank witch flounder are provided in Table 1 for three choices of period (from 1982, from 1996 and from 2006), four choices (1, 2, 3 and 4) for *q*, and with and without inclusion of the LCPUE series as well as the NEFSC survey abundance series. Plots of the model-estimated indices of abundance to show how well they fit the corresponding data are shown in Figures 1-6 for the six combinations of three periods x two data-choice scenarios (with and without LPUE data). Note that "fits" are shown to the LPUE data even when these data are not included – this is because a *q* value for the LPUE series is still implied in such cases (and provided by the limit of including the LPUE data in the likelihood, but with a vanishingly small weight).

Results for RY across these combinations show a number of the features that might have been expected:

- The longer the period the lower the SE.
- Including the extra (LPUE) series reduces the SE.

Features specific to this case are:

- Except for the shortest period considered (that starting in 2006 which is unable to discriminate), the negative log likelihoods for the fits favour *q*=1. These correspond to smaller estimates for RY compared to those for larger *q* values.
- The estimates of RY decrease as the period considered for the computations is reduced in length, suggesting that resource productivity may be lower more recently than further back in time.
- RY estimates that take account also of the LPUE data are larger.

As far as the period *vs* precision trade-off is concerned, the variability in the data is such that when only those from 2006 onwards are considered (see Figures 5 and 6), unsurprisingly standard error estimates for RY are so high as to make them of questionable value. On the other hand, the trend in the RY estimates with period length is such as to query use of the estimates from 1982 onwards. Over the set of results shown then, the best estimates would seem to be those for the intermediate period from 1996 onwards, and for *q*=1. Those yield RY (SE) estimates of 2.09 (0.72) and 1.20 (0.87) thousand tons for respective inclusion and exclusion of the LPUE index data.

Table 1: RY analysis results with Hessian-based CV in parenthesis (except for RY for which SE are given in parenthesis and italics). Estimates of biomass and RY are given in thousand mt (i.e. kt).

	1982, with LPUE				1982, no LPUE			
	q=1	q=2	q=3	q=4	q=1	q=2	q=3	q=4
-lnL_total	50.80	51.70	53.61	56.02	15.96	16.98	18.60	20.53
-lnL_surv1	8.93	9.42	10.21	11.16	8.67	9.25	10.10	11.09
-lnL_surv2	7.41	7.86	8.63	9.59	7.29	7.73	8.50	9.43
-lnL_LPUE	34.46	34.42	34.76	35.27	-	-	-	-
-lnL_q1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-lnL_q2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RY	2.57 *(0.30)*	2.69 *(0.17)*	2.73 *(0.12)*	2.75 *(0.09)*	2.23 *(0.41)*	2.52 *(0.22)*	2.63 *(0.15)*	2.69 *(0.11)*
q1	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
q2	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
B_{1982}	40.99 (0.16)	27.93 (0.12)	23.82 (0.10)	21.87 (0.08)	47.34 (0.18)	30.74 (0.15)	25.24 (0.12)	22.58 (0.10)
B_{1996}	22.04 (0.16)	10.56 (0.16)	6.99 (0.16)	5.29 (0.16)	23.49 (0.17)	11.04 (0.17)	7.07 (0.18)	5.18 (0.17)
B_{2006}	18.88 (0.19)	8.54 (0.22)	5.35 (0.24)	3.84 (0.26)	16.84 (0.21)	7.34 (0.26)	4.47 (0.29)	3.14 (0.31)
B_{2015}	31.75 (0.17)	22.43 (0.13)	19.58 (0.11)	18.24 (0.09)	26.56 (0.24)	19.73 (0.18)	17.85 (0.13)	17.01 (0.11)
B_{2015}/B_{1982}	0.77 (0.28)	0.80 (0.22)	0.82 (0.18)	0.83 (0.15)	0.56 (0.38)	0.64 (0.30)	0.71 (0.23)	0.75 (0.19)
B_{2015}/B_{1996}	1.44 (0.20)	2.12 (0.19)	2.80 (0.18)	3.45 (0.17)	1.13 (0.30)	1.79 (0.27)	2.53 (0.24)	3.29 (0.22)
B_{2015}/B_{2006}	1.68 (0.08)	2.63 (0.11)	3.66 (0.15)	4.75 (0.18)	1.58 (0.12)	2.69 (0.13)	3.99 (0.18)	5.42 (0.22)

	1996, with LPUE				1996, no LPUE			
	q=1	q=2	q=3	q=4	q=1	q=2	q=3	q=4
-lnL_total	29.31	30.73	32.60	34.74	8.16	9.13	10.48	12.12
-lnL_surv1	5.06	5.87	6.82	7.87	5.02	5.82	6.78	7.83
-lnL_surv2	3.62	3.86	4.36	5.07	3.15	3.31	3.70	4.28
-lnL_LPUE	20.63	21.01	21.41	21.80	-	-	-	-
-lnL_q1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-lnL_q2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RY	2.09 *(0.72)*	2.17 *(0.44)*	2.22 *(0.36)*	2.27 *(0.32)*	1.20 *(0.87)*	1.59 *(0.53)*	1.72 *(0.43)*	1.79 *(0.40)*
q1	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
q2	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
B_{1982}	-	-	-	-	-	-	-	-
B_{1996}	27.06 (0.30)	15.53 (0.31)	11.72 (0.32)	9.75 (0.34)	35.81 (0.30)	21.05 (0.30)	16.42 (0.30)	14.27 (0.32)
B_{2006}	19.01 (0.21)	8.34 (0.24)	5.06 (0.26)	3.55 (0.28)	18.91 (0.22)	8.09 (0.25)	4.75 (0.28)	3.22 (0.31)
B_{2015}	27.47 (0.28)	17.58 (0.25)	14.77 (0.24)	13.67 (0.22)	19.42 (0.39)	12.13 (0.37)	9.95 (0.37)	8.99 (0.37)
B_{2015}/B_{1982}	-	-	-	-	-	-	-	-
B_{2015}/B_{1996}	1.02 (0.50)	1.13 (0.51)	1.26 (0.52)	1.40 (0.54)	0.54 (0.62)	0.58 (0.63)	0.61 (0.64)	0.63 (0.67)
B_{2015}/B_{2006}	1.45 (0.24)	2.11 (0.26)	2.92 (0.27)	3.86 (0.29)	1.03 (0.40)	1.50 (0.43)	2.10 (0.47)	2.79 (0.51)

	2006, with LPUE				2006, no LPUE			
	q=1	q=2	q=3	q=4	q=1	q=2	q=3	q=4
-lnL_total	13.07	13.08	13.09	13.11	3.15	3.14	3.13	3.13
-lnL_surv1	1.89	1.88	1.87	1.87	1.79	1.78	1.77	1.76
-lnL_surv2	1.31	1.32	1.32	1.33	1.36	1.36	1.37	1.37
-lnL_LPUE	9.86	9.88	9.90	9.92	-	-	-	-
-lnL_q1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-lnL_q2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RY	0.71 *(1.28)*	0.90 *(0.65)*	0.96 *(0.44)*	0.99 *(0.34)*	0.18 *(1.57)*	0.62 *(0.80)*	0.77 *(0.54)*	0.84 *(0.41)*
q1	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
q2	1.00	2.00	3.00	4.00	1.00	2.00	3.00	4.00
B_{1982}	-	-	-	-	-	-	-	-
B_{1996}	-	-	-	-	-	-	-	-
B_{2006}	20.83 (0.37)	10.91 (0.36)	7.61 (0.35)	5.97 (0.34)	23.40 (0.41)	12.21 (0.39)	8.49 (0.38)	6.64 (0.37)
B_{2015}	16.96 (0.41)	8.69 (0.40)	5.94 (0.40)	4.56 (0.39)	14.69 (0.50)	7.52 (0.49)	5.13 (0.48)	3.93 (0.48)
B_{2015}/B_{1982}	-	-	-	-	-	-	-	-
B_{2015}/B_{1996}	-	-	-	-	-	-	-	-
B_{2015}/B_{2006}	0.81 (0.61)	0.80 (0.60)	0.78 (0.59)	0.76 (0.58)	0.63 (0.76)	0.62 (0.75)	0.60 (0.73)	0.59 (0.72)

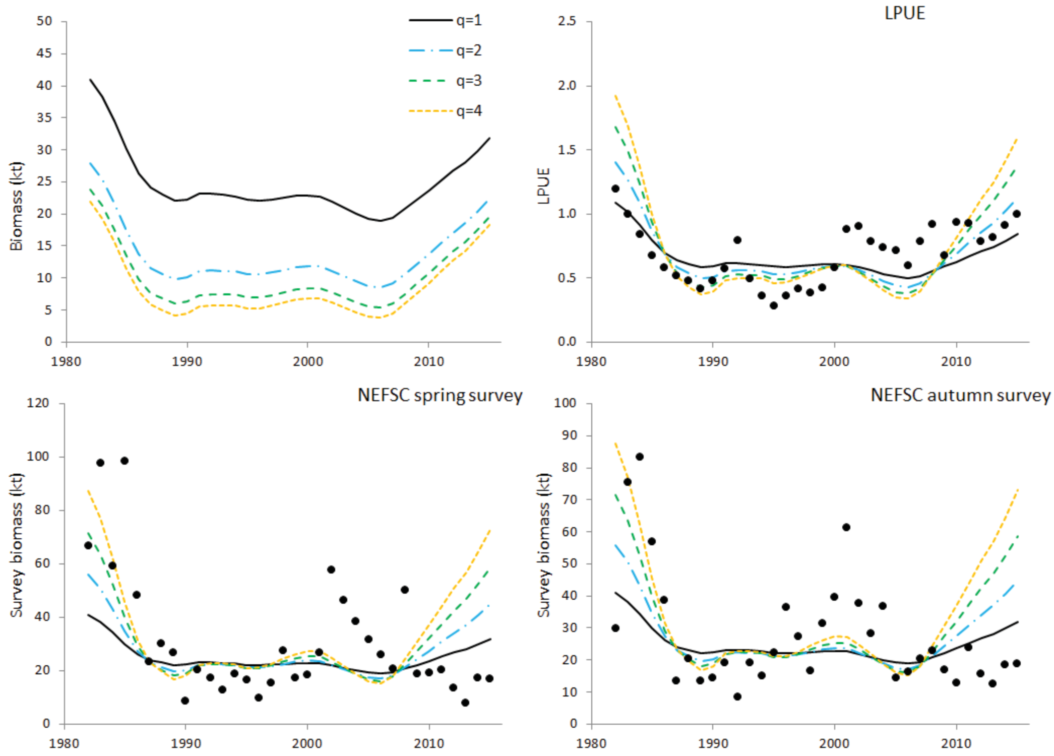

Figure 1: Plots of the estimated biomass trajectories and fits to the abundance indices for the “With LPUE, 1982 start” scenario.

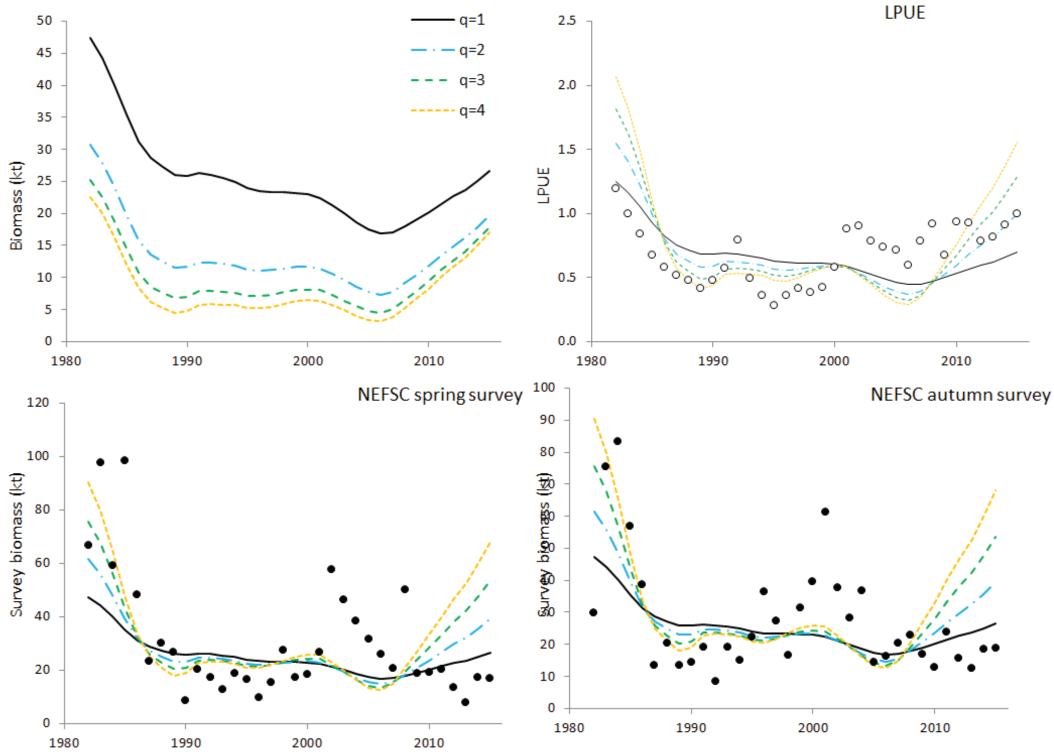

Figure 2: Plots of the estimated biomass trajectories and fits to the abundance indices for the “No LPUE, 1982 start” scenario. Note that the fits shown to the LPUE index are implied by an estimate of q^{LPUE} external to the basic model fitting procedure.

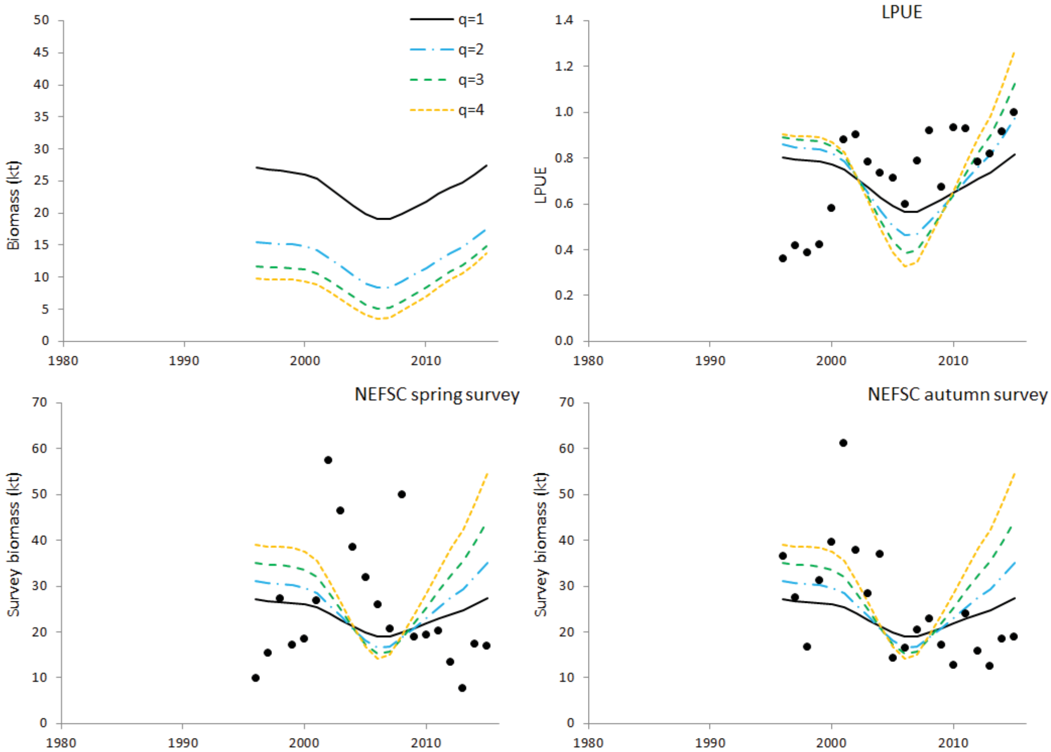

Figure 3: Plots of the estimated biomass trajectories and fits to the abundance indices for the "With LPUE, 1996 start" scenario.

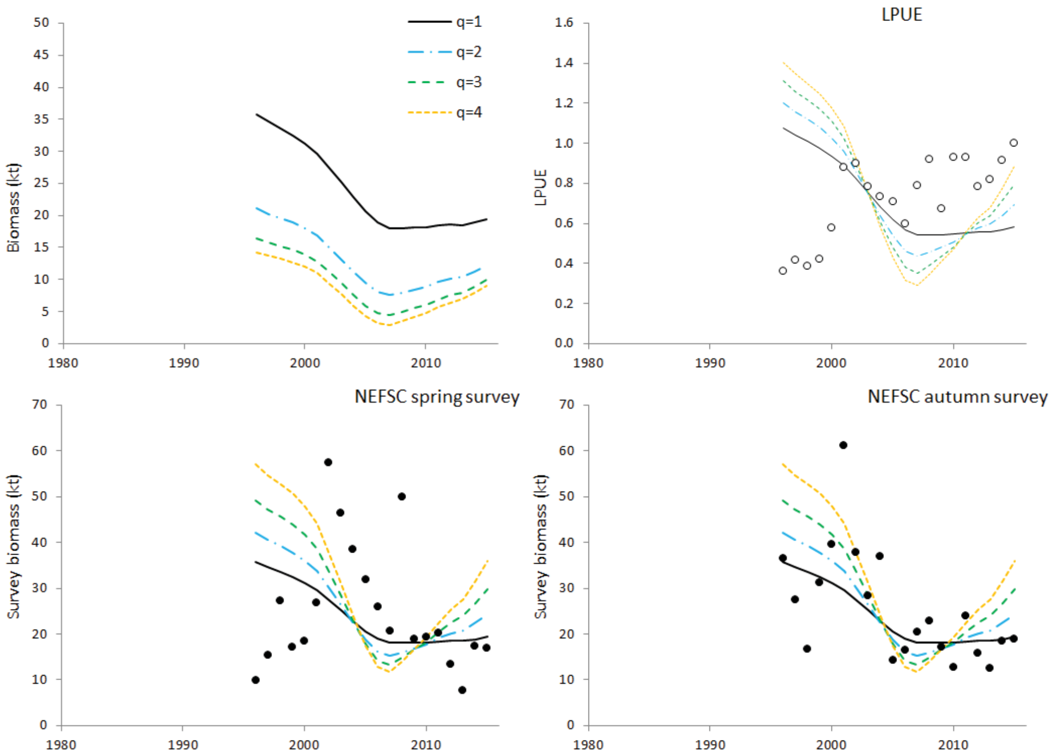

Figure 4: Plots of the estimated biomass trajectories and fits to the abundance indices for the "No LPUE, 1996 start" scenario.

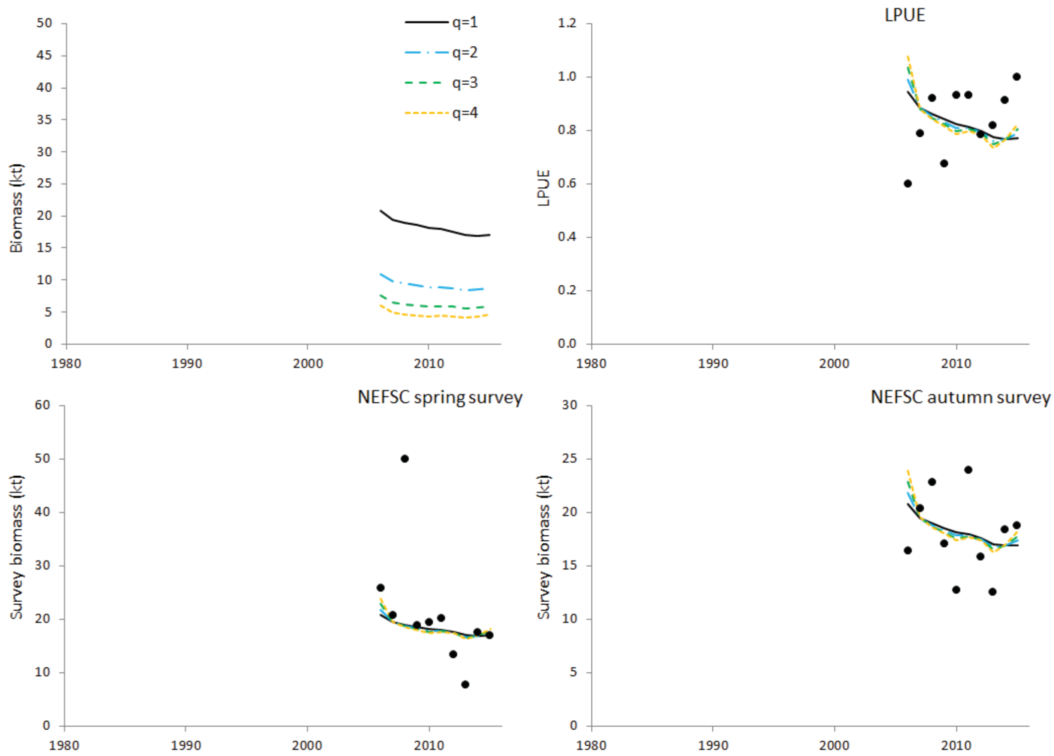

Figure 5: Plots of the estimated biomass trajectories and fits to the abundance indices for the "With LPUE, 2006 start" scenario.

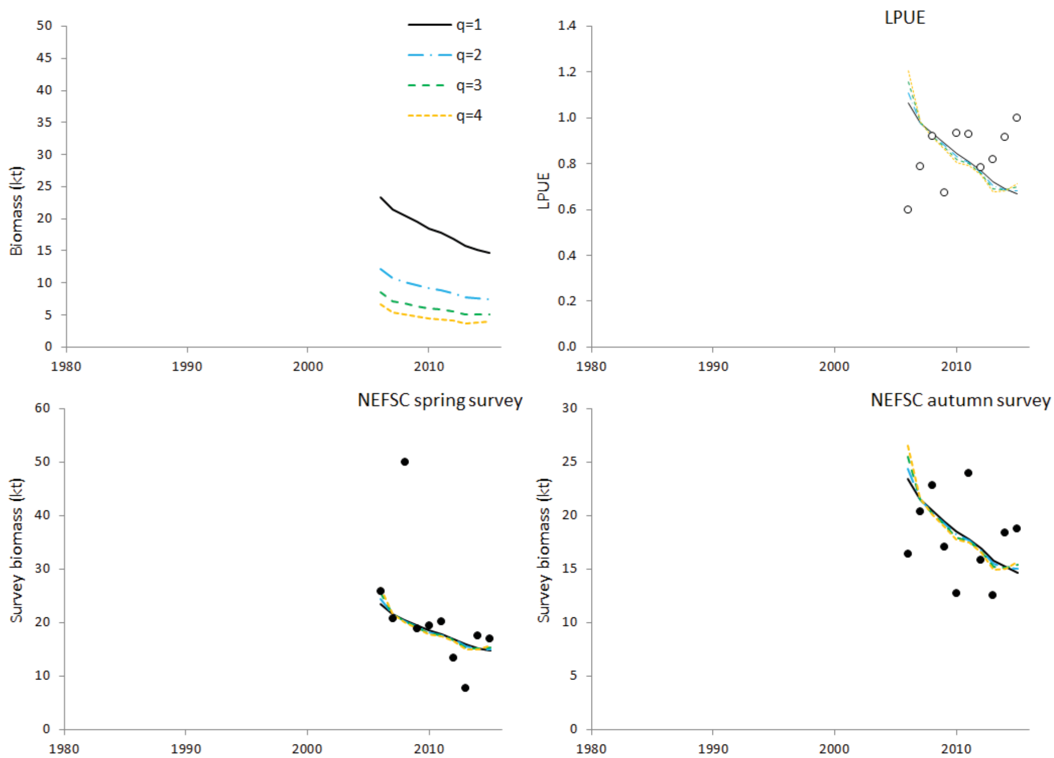

Figure 6: Plots of the estimated biomass trajectories and fits to the abundance indices for the "No LPUE, 2006 start" scenario.

APPENDIX B2: ANNEX A - REPLACEMENT YIELD MODEL

THE POPULATION DYNAMICS

The resource dynamics are modelled by the following equation:

$$B_{y+1} = B_y + RY - C_y \qquad \text{(A.1)}$$

where:

B_y is the biomass at the start of year *y*,

C_y is the catch in year *y*, and

RY is the replacement yield in year *y*, which is assumed to be constant over the period considered.

THE LIKELIHOOD FUNCTION

The model is fitted to survey abundance indices. Contributions by each of these to the negative of the log-likelihood ($-lnL$) are as follows.

Survey abundance data

The likelihood is calculated assuming that the observed abundance indices are log-normally distributed about their expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = ln\left(I_y^i\right) - ln\left(\hat{I}_y^i\right) \qquad \text{(A.2)}$$

where:

I_y^i is the abundance index for year *y* and survey series *i*,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y$ is the corresponding model estimated value,

$\hat{q}^i$ is a constant of proportionality (catchability) for abundance index *i*, and

ε_y^i is the observation error for survey *i* in year *y*, which is assumed to be normally distributed: $N\left(0, \left(\sigma_y^i\right)^2\right)$.

For the surveys, an estimate of the CV is available for each survey and the associated σ_y^i are given by $ln\left(1 + \left(CV_y^i\right)^2\right)$, where the CV_y^i are the coefficients of variation of the resource abundance estimate for index *i* for year *y*. These CVs are input and include the additional variance estimated in the SCAA Final BC (see Appendix B3). They are given in Table A1.

The contribution of the survey abundance data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-lnL^{surv} = \sum_{iy} \left\{ ln\left(\sigma_y^i\right) + \frac{\left(\varepsilon_y^i\right)^2}{2\left(\sigma_y^i\right)^2} \right\} \qquad \text{(A.3)}$$

LPUE data

As for the survey abundance data, the likelihood is calculated assuming that the LPUE index is lognormally distributed about its expected value:

$$I_y^{LPUE} = \hat{I}_y^{LPUE} e^{\varepsilon_y^{LPUE}} \quad \text{or} \quad \varepsilon_y^{LPUE} = ln\left(I_y^{LPUE}\right) - ln\left(\hat{I}_y^{LPUE}\right) \qquad \text{(A.4)}$$

where

I_y^{LPUE} is the LPUE index in year *y*,
$\hat{I}_y^{LPUE} = \hat{q}^{LPUE}\hat{B}_y$ is the corresponding model estimate, where
$\hat{q}^{LPUE}$ is the constant of proportionality for the LPUE index.

The contribution of the LPUE index data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-lnL^{LPUE} = \sum_y \left\{ ln\left(\sigma_y^{LPUE}\right) + \frac{\left(\varepsilon_y^{LPUE}\right)^2}{2\left(\sigma_y^{LPUE}\right)^2} \right\} \quad \text{(A5)}$$

The coefficient of proportionality $\hat{q}^{LPUE}$for is estimated by its maximum likelihood value:

$$ln\hat{q}^{LPUE} = \frac{1}{n_{LPUE}} \sum_y \left(lnI_y^{LPUE} - ln\hat{B}_y\right) \quad \text{(A6)}$$

***q* prior**

A very tight prior is included for the catchability coefficient q^i for each survey abundance index *i* so that these are basically fixed:

$$ln\left(q^i\right) \sim N\left(lnq^{mean}, \sigma^2_{lnq^{mean}}\right) \quad \text{(A.7)}$$

with $\sigma_{\sigma^2_{lnq^{mean}}} = 0.05$.

Table A1: Total catch (mt), NEFSC spring and autumn surveys swept area biomass estimates (mt) and LPUE each with CV. These CVs are from SCAA final BC results for the NEFSC series (see Appendix B3) and from a corresponding fit with LPUE replacing those series in the log likelihood.

	Total catch	NEFSC spring survey		NEFSC autumn survey		LPUE (40% trips)	
	(mt)	Swept area biomass (mt)	CV	Swept area biomass (mt)	CV	LPUE	CV
1982	5309	66648	0.554	29789	0.531	1.193	0.320
1983	6409	97751	0.575	75553	0.553	0.998	0.320
1984	6937	59375	0.532	83373	0.509	0.842	0.320
1985	6339	98269	0.543	56893	0.520	0.674	0.320
1986	4788	48131	0.531	38766	0.508	0.582	0.320
1987	3644	23230	0.558	13325	0.535	0.521	0.320
1988	3451	30193	0.558	20356	0.536	0.481	0.320
1989	2425	26554	0.552	13404	0.529	0.415	0.320
1990	1744	8441	0.591	14297	0.570	0.476	0.320
1991	2571	20499	0.566	19156	0.543	0.569	0.320
1992	2752	17210	0.539	8512	0.516	0.794	0.320
1993	2806	12836	0.537	19260	0.514	0.497	0.320
1994	3115	18974	0.556	15028	0.533	0.362	0.320
1995	2718	16664	0.535	22291	0.511	0.282	0.320
1996	2393	9894	0.535	36430	0.511	0.362	0.320
1997	2254	15468	0.573	27418	0.551	0.417	0.320
1998	2306	27318	0.537	16771	0.513	0.387	0.320
1999	2490	17210	0.547	31335	0.524	0.423	0.320
2000	2749	18535	0.526	39647	0.502	0.580	0.320
2001	3406	26808	0.533	61160	0.509	0.878	0.320
2002	3470	57529	0.547	37801	0.523	0.901	0.320
2003	3551	46399	0.532	28336	0.509	0.785	0.320
2004	3370	38405	0.523	36859	0.499	0.734	0.320
2005	2917	31803	0.547	14300	0.523	0.711	0.320
2006	2075	25883	0.526	16414	0.502	0.600	0.320
2007	1210	20759	0.534	20349	0.510	0.787	0.320
2008	1136	50009	0.566	22852	0.543	0.921	0.320
2009	1157	18828	0.528	17070	0.504	0.675	0.320
2010	912	19329	0.526	12727	0.502	0.931	0.320
2011	1071	20238	0.520	23917	0.496	0.930	0.320
2012	1258	13454	0.522	15827	0.498	0.785	0.320
2013	811	7767	0.525	12539	0.501	0.819	0.320
2014	675	17430	0.530	18353	0.506	0.914	0.320
2015	585	16896	0.528	18792	0.504	1.000	0.320