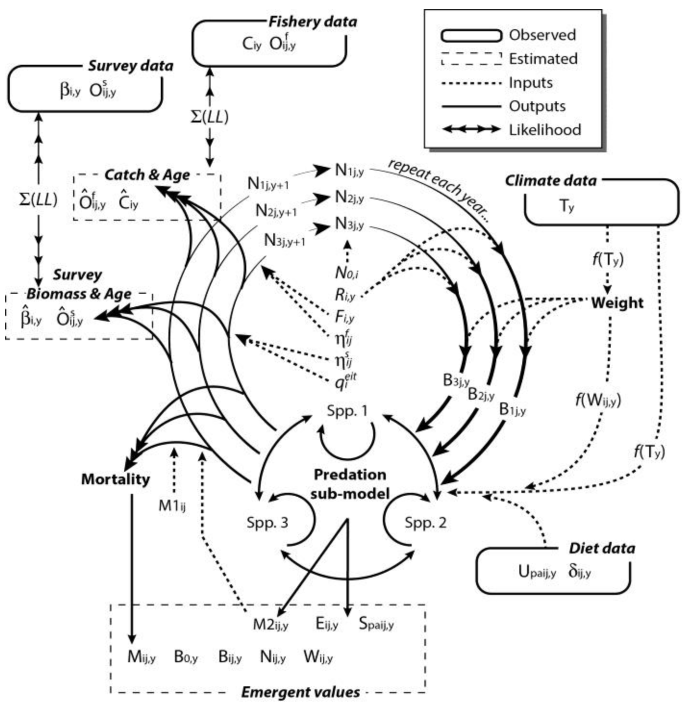
CEATTLE:
Climate enhanced Age-based model with Temperature specific Trophic linkages and Energetics

NOAA FISHERIES

AFSC, Seattle



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Sept. 2016, NPMFC PT

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Multi-species models for EBFM

- Quantify relative effects of climate variability, trophic interactions, and fisheries on species productivity
- Non-stationary mortality, B0, and MSY
- Can identify indirect effects on other species and fisheries
- Quantify trade-offs among fisheries

Holsman et al. in press. Deep Sea Res II

Photo: Mark Holsman

2016 multispecies assessment

- Appendix to 2016 pollock assessment as alternative model
- Provides comparative M, Rec, and SSB
- Captures climate and trophic impacts on BRPs

Photo: Mark Holsman

Outline:

- CEATTLE Overview
- 2016 Assessment
- Other applications

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CEATTLE overview

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CEATTLE methods references

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

ELSEVIER

A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models

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ARTICLE INFO

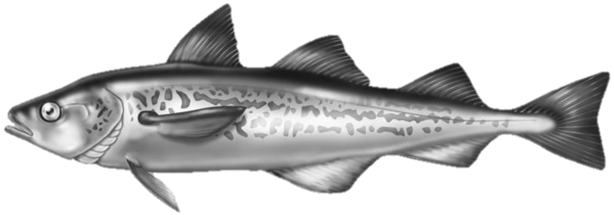
ABSTRACT

Multi-species statistical catch at age models (MSCAA) can quantify interacting effects of climate and

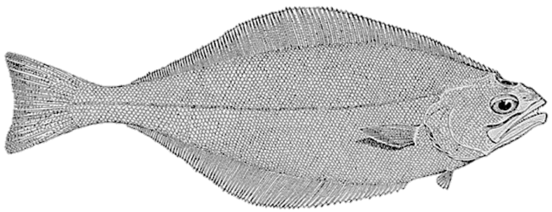
Holsman, KK, J Ianelli, K Aydin, AE Punt, EA Moffitt (2015). Comparative biological reference points estimated from temperature-specific multispecies and single species stock assessment models. Deep Sea Res II. doi:10.1016/j.dsr2.2015.08.001.

Moffitt, E, AE Punt, KK Holsman, KY Aydin, JN Ianelli, I Ortiz (2015). Moving towards Ecosystem Based Fisheries Management: options for parameterizing multi-species harvest control rules. Deep Sea Res II. doi:10.1016/j.dsr2.2015.08.002

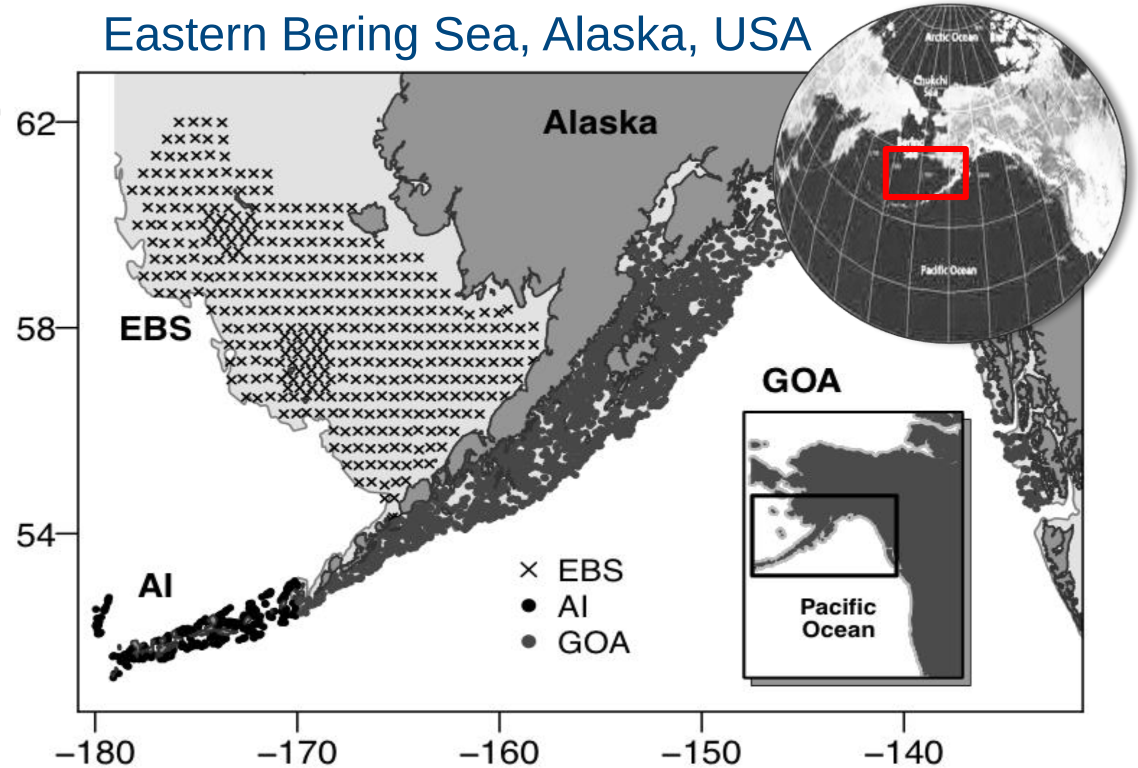
CEATTLE Multi-species model



Walleye pollock
(*Gadus chalcogrammus*)



Arrowtooth flounder
(*Atheresthes stomias)*



Pacific cod
(*Gadus macrocephalus*)

W@Age~*f*(Temperature)
Pred/prey~*f*(Temperature)

Climate-Enhanced, Age-based model with Temperature-specific Trophic Linkages and Energetics

Table 1: Model equations

Definition	Equation		
Recruitment	$N_{i1,y}=R_{i,y}=R_{0,i}e^{\tau_{i,y}}$	$\tau_{i,y}\sim N(0,\sigma^2)$	T1.1
Initial abundance	$N_{ij,1}=\begin{cases} R_{0,i}e^{(-j\,M1_{ij})}N_{0,ij} \\ R_{0,i}e^{(-j\,M1_{i,A_i})}N_{0,i,A_i}/\left(1-e^{(-j\,M1_{i,A_i})}\right)\end{cases}$	$y=1 \quad 1<j\le A_i$ $y=1 \quad j>A_i$	T1.2
Numbers at age	$N_{i,j+1,y+1}=N_{ij,y}e^{-Z_{ij,y}}$ $\quad 1\le y\le n_y \quad 1\le j<A_i$ $N_{i,A_i,y+1}=N_{i,A_i-1,y}e^{-Z_{i,A_i-1,y}}+N_{i,A_i,y}e^{-Z_{i,A_i,y}}$ $\quad 1\le y\le n_y \quad j>A_i$		T1.3
Catch	$C_{ij,y}=\frac{F_{ij,y}}{Z_{ij,y}}(1-e^{-Z_{ij,y}})N_{ij,y}$		T1.4
Total yield (kg)	$Y_{i,y}=\sum_{j}^{A_i}\left(\frac{F_{ij,y}}{Z_{ij,y}}(1-e^{-Z_{ij,y}})N_{ij,y}W_{ij,y}\right)$		T1.5
	$B_{ij,y}=N_{ij,y}W_{ij,y}$		
	$SSB_{ij,y}=B_{ij,y}\rho_{ij}$		
	$Z_{ij,y}=M1_{ij}+M2_{ij,y}+F_{ij,y}$		
	$F_{ij,y}=F_{0,i}e^{\varepsilon_{i,y}}s^f_{ij}$	$\varepsilon_{i,y}\sim N(0,\sigma^2_{F,i})$	
	$W_{ij,y}=W_{\infty,iy}\left(1-e^{(-K_i(1-d_{i,y})(j-t_{0,i}))}\right)^{\frac{1}{1-d_{i,y}}}$		
	$d_{i,y}=e^{(\alpha_{d,i,y}+\alpha 0_{d,i}+\beta_{d,i}T_y)}$		T1.10b
	$W_{\infty,iy}=\left(\frac{H_i}{K_i}\right)^{1/(1-d_{i,y})}$		T1.10c
BT survey biomass (kg)	$\hat{\beta}^s_{i,y}=\sum_{j}^{A_i}\left(N_{ij,y}e^{-0.5\,Z_{ij,y}}W_{ij,y}s^s_{ij}\right)$		T1.11
EIT surv...			T1.12
Fishery...			T1.13
BT surv...			T1.14
EIT surv...			T1.15
BT selectivity	$s^s_{ij}=\frac{1}{1+e^{(-b^s_i\cdot j-a^s_i)}}$		T1.16
Fishery selectivity	$s^f_{ij}=\begin{cases} e^{\eta_{ij}} & j\le A_{\eta,i} \\ e^{\eta_{iA_{\eta,i}}} & j>A_{\eta,i}\end{cases}$	$\eta_{ij}\sim N(0,\sigma^2_{f,i})$	T1.17
Proportion females	$\omega_{ij}=\frac{e^{-j\,M_{fem}}}{e^{-j\,M_{fem}}+e^{-j\,M_{male}}}$		T1.18
Proportion of mature females	$\rho_{ij}=\omega_{ij}\phi_{ij}$		T1.19
Weight at age (kg)	$W_{ij,y}=W^{fem}_{ij,y}\omega_{ij}+(1-\omega_{ij})W^{male}_{ij,y}$		T1.20
Residual natural mortality	$M1_{ij}=M^{fem}_{ij}\omega_{ij}+(1-\omega_{ij})M^{male}_{ij}$		T1.21

Residual Natural Mortality

Predation Natural Mortality

$$Z_{ij,y}=M1_{ij}+M2_{ij,y}+F_{ij,y}$$

Table 2: Pred. Mortality (M2)

Definition	Equation	
Predation mortality	$M2_{ij,y} = \sum_{pa} \left(\frac{N_{pa,y} \delta_{pa,y} \bar{S}_{paij}}{\sum_{ij} \left(\bar{S}_{paij} B_{ij,y} \right) + B_p^{other} \left(1 - \sum_{ij} \left(\bar{S}_{paij} \right) \right)} \right)$	T2.1
Predator-prey suitabilit		
Mean gravimetric diet proportion		T2.3
Individual specific ratio (kg kg^{-1} yr^{-1})		
Temperature scaling algorithm	$f(T_y) = V^X e^{(X(1-V))}$	T2.5
	$X = \left(Z^2 \left(1 + (1 + 40/Y)^{0.5} \right)^2 \right) / 400$	T2.5b
	$Z = ln \left(Q_p^c \right) \left(T_p^{cm} - T_p^{co} \right)$	T2.5c
	$Y = ln \left(Q_p^c \right) \left(T_p^{cm} - T_p^{co} + 2 \right)$	T2.5d

Age-specific prey selectivity

Size-specific annual ration

Temperature specific

Temperature specific VonB

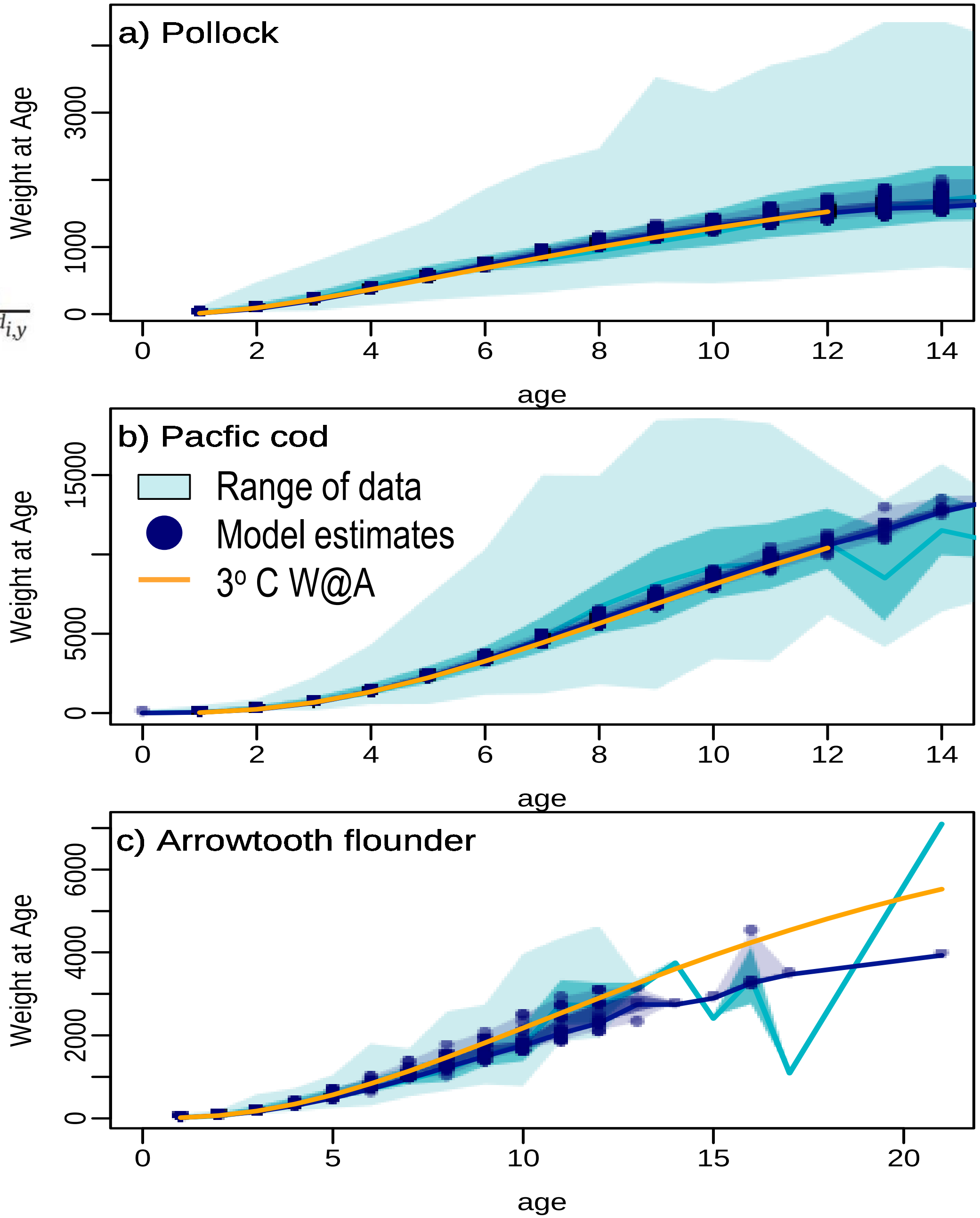
$$W_{ij,y} = W_{\infty,iy}\left(1 - e^{(-K_i(1-d_{i,y})(j-t_{0,i}))}\right)^{\frac{1}{1-d_{i,y}}}$$

$$d_{i,y} = e^{(\alpha_{d,i,y} + \alpha 0_{d,i} + \beta_{d,i} T_y)}$$

$$W_{\infty,iy} = \left(\frac{H_i}{K_i}\right)^{1/(1-d_{i,y})}$$

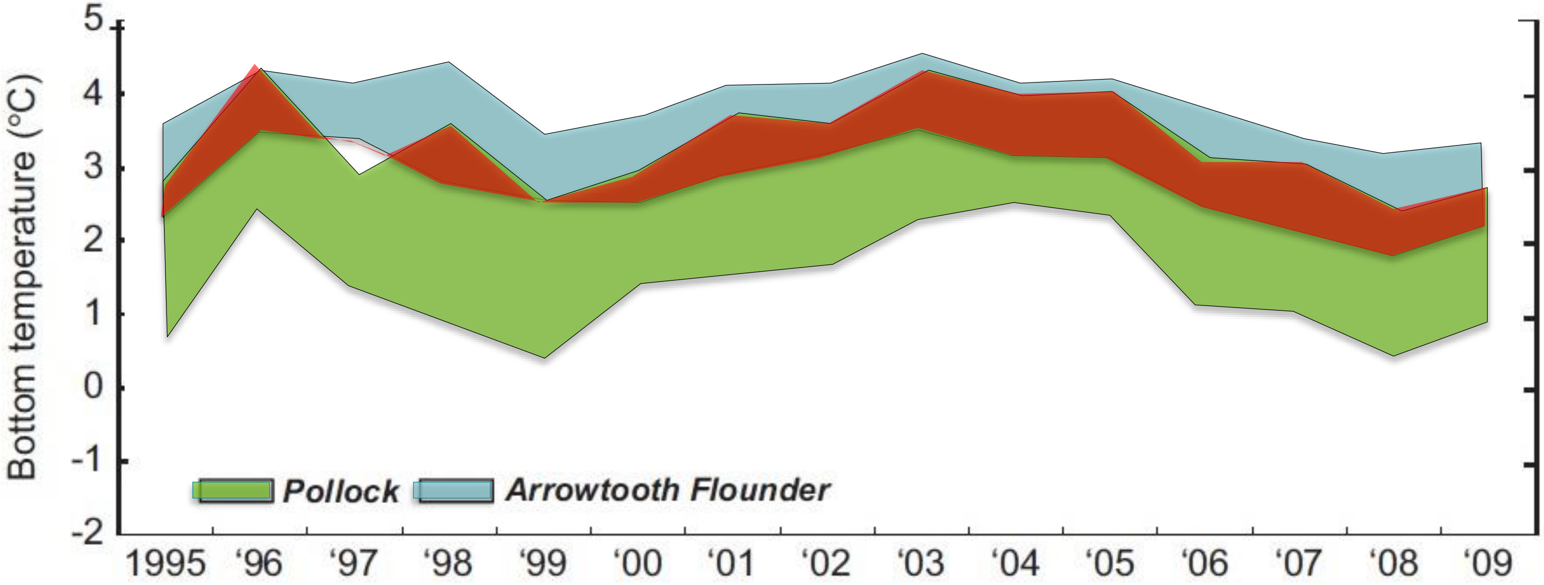
Bottom Temp

Fit outside of the model presently (expect for projections)



Predator- Prey Overlap

Set to 1.0 in this assessment



Stabeno et al. (2013) A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. Deep-Sea Res II 65-7014-30.

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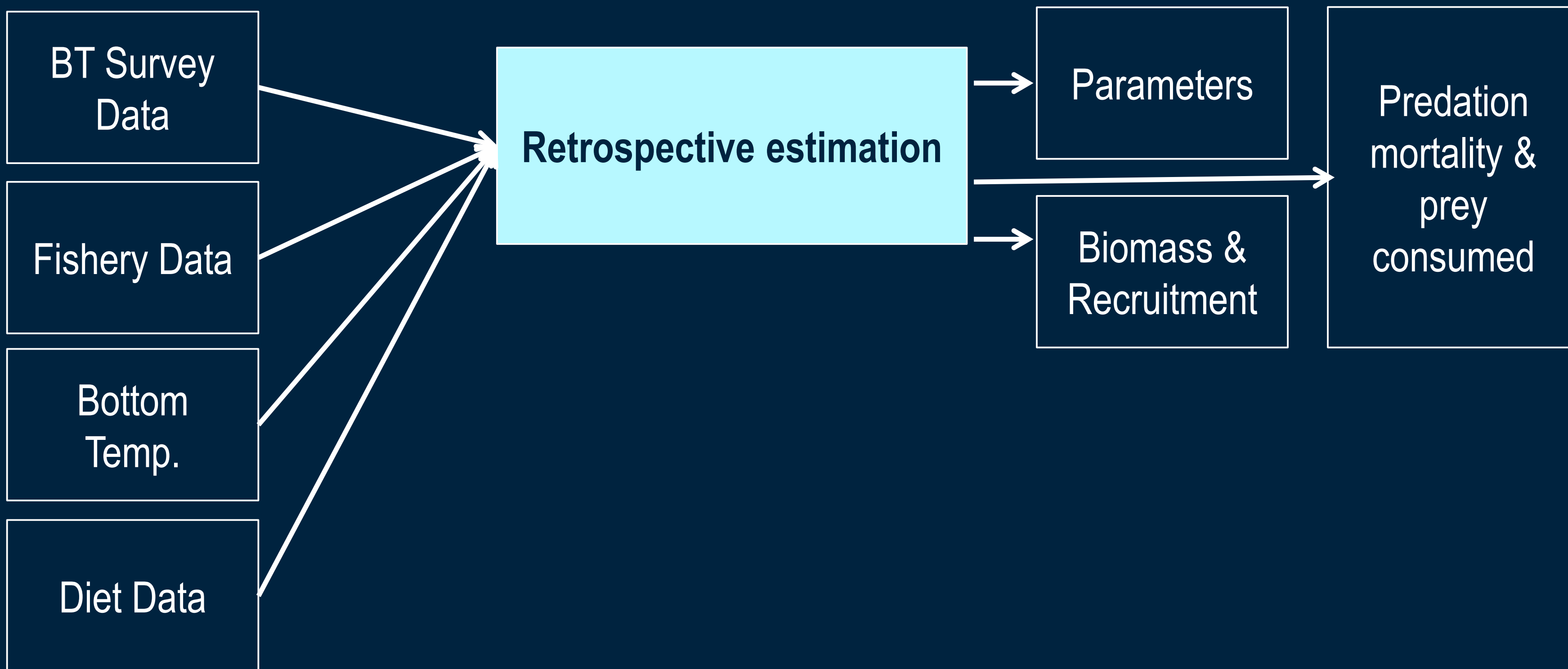
BT Survey Data
Fishery Data
Bottom Temp.
Diet Data
Retrospective estimation
Parameters
Biomass & Recruitment
Predation mortality & prey consumed

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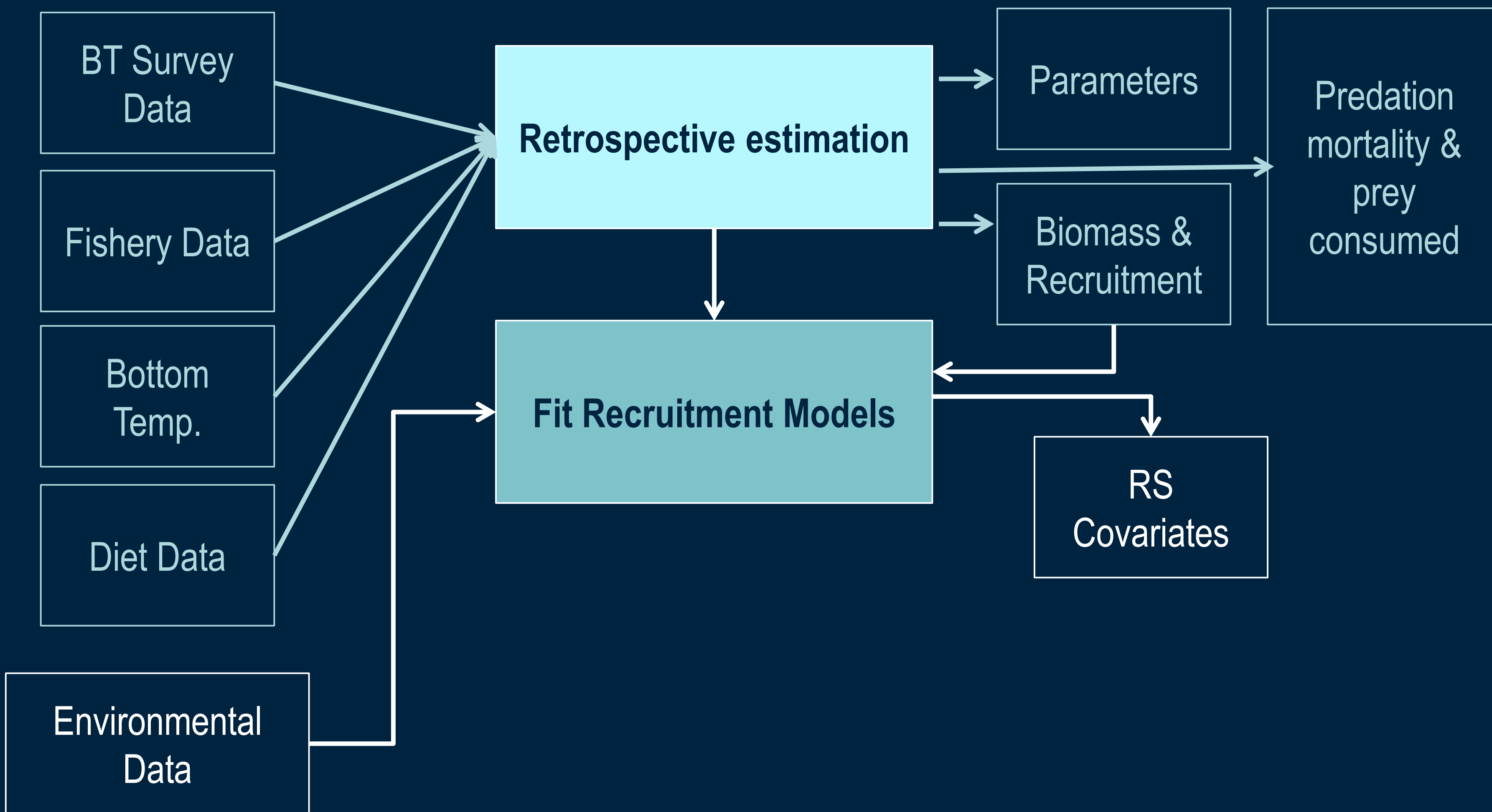
BT Survey Data
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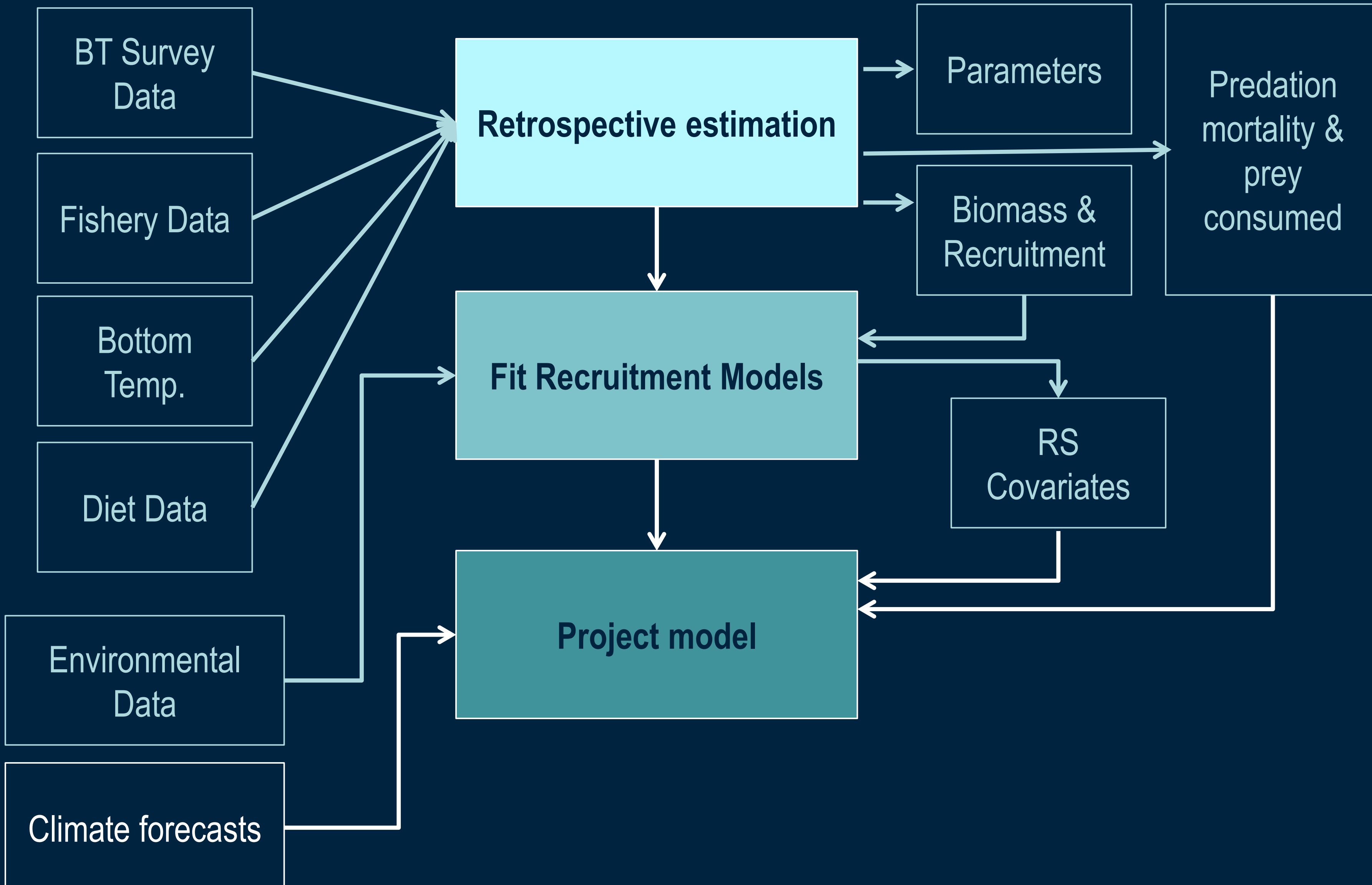
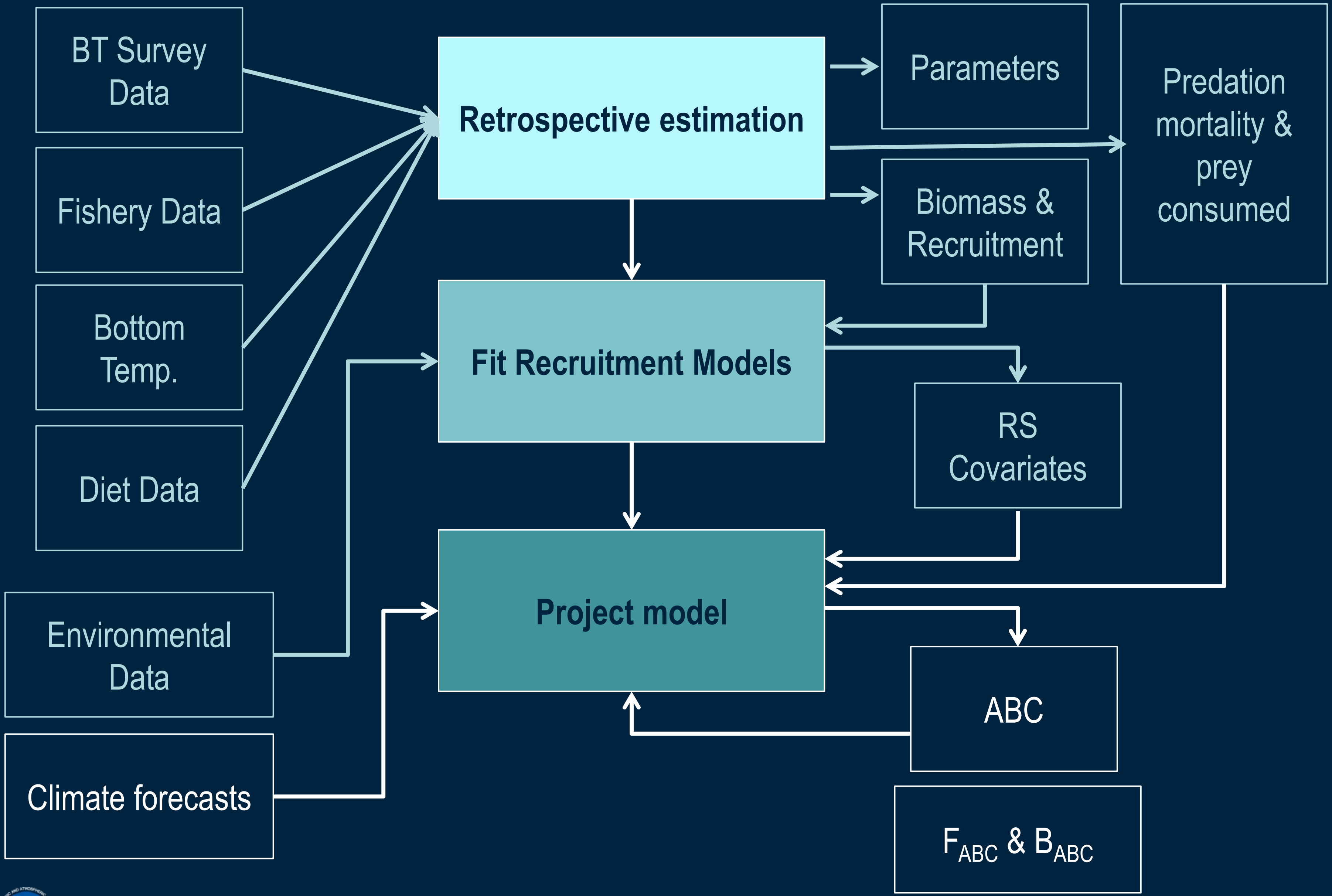
Environmental Data
Retrospective estimation
Fit Recruitment Models
Parameters
Biomass & Recruitment
Predation mortality & prey consumed
RS Covariates

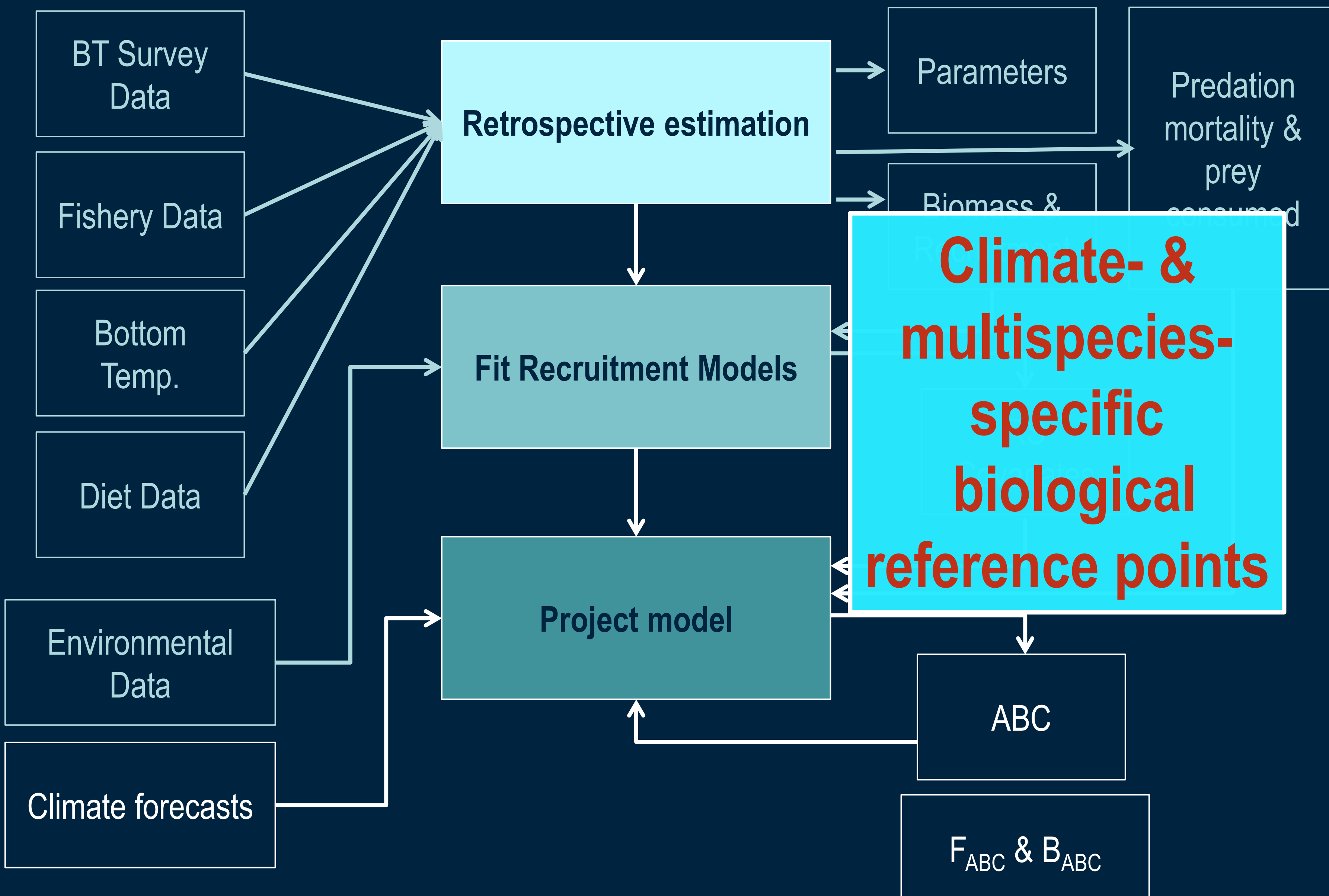
CEATTLE


BT Survey Data
Fishery Data
Bottom Temp.
Diet Data
Environmental Data
Climate forecasts
Retrospective estimation
Fit Recruitment Models
Project model
Parameters
Biomass & Recruitment
Predation mortality & prey consumed
RS Covariates

CEATTLE


BT Survey Data
Fishery Data
Bottom Temp.
Diet Data
Environmental Data
Climate forecasts
Retrospective estimation
Fit Recruitment Models
Project model
Parameters
Biomass & Recruitment
Predation mortality & prey consumed
RS Covariates
ABC
F_{ABC} & B_{ABC}

CEATTLE


BT Survey Data
Fishery Data
Bottom Temp.
Diet Data
Environmental Data
Climate forecasts
Retrospective estimation
Fit Recruitment Models
Project model
Parameters
Predation mortality & prey
Biomass &
ABC
F_{ABC} & B_{ABC}
Climate- & multispecies-specific biological reference points

CEATTLE: Options

- Trophic Interactions (on/off)

- Recruitment under projections (MCMC on/off):
  - Mean RS (Ricker or BevHolt), linear, linear+ B_{y-1}
  - Above + covariates (cold pool, BT, etc.)

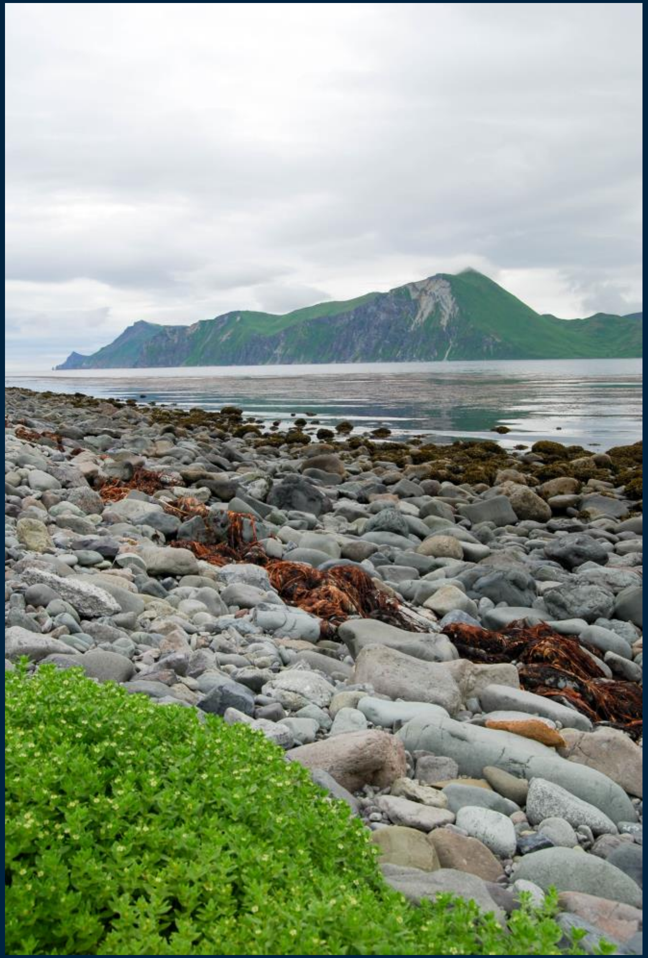
- Harvest scenarios (0, mean historical F or C, set F or C, F profile, and HCRs:
  - ABC proxy
  - SPR
  - Aggregate MSY
  - MEY (in development)

2016 Assessment

Photo: Mark Holsman

Changes from Holsman et al. 2016

- P. cod fish comp data based on lengths
- Bottom Temp: BTS & updated through 2015
- Projected Bottom Temp: constant avg (BT)
- Recruitment in projections is Ricker
- 2 harvest scenarios are presented here:
  1. F 40% of unfished biomass (for all three species simultaneously)
  2. aggregate multi-species MSY
- Survey and catch data updated from 2012



2016 multispecies data

Source	Type	Years
Fishery	Catch biomass	1979-2015
Fishery	Catch age composition	1979-2014 (plk &atf); 1979-2015 (P. cod)
EBS bottom trawl	Area-swept abundance (numbers) index by age	1982-2015
EBS bottom trawl	Gravimetric length-based diet data	1982-2105
Acoustic trawl	Population abundance (numbers) index by age	1979,1982,1985,1988, 1991, 1994, 1996-1997, 1999-2000, 2002 , 2004, 2006-2010

Bottom Temperature (BT Survey)

2016
4.5 deg

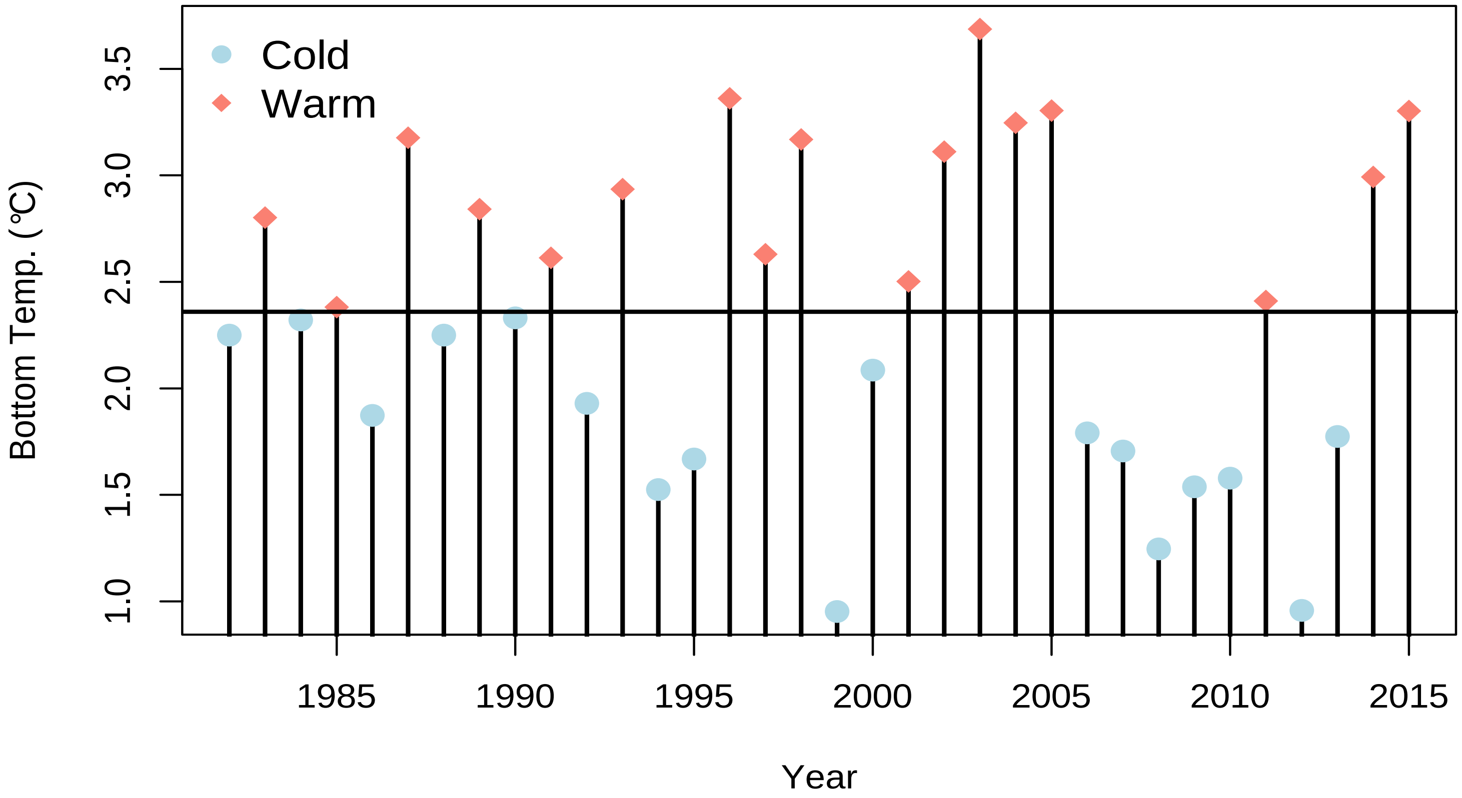


Table 4: Objective functions

Description	Equation	Data source	
Data components			
BT survey biomass	$\sum_i \sum_y \frac{\left[\ln\left(\beta^s_{i,y}\right)-\ln\left(\hat{\beta}^s_{i,y}\right)\right]^2}{2\sigma^2_{s,i}}$	NFMS annual EBS BT survey (1979–2012)	T4.1
BT survey age composition	$-\sum_i n_i \sum_y \sum_j \left(O^s_{ij,y}+v\right)\ln\left(\hat{O}^s_{ij,y}+v\right)$	NFMS annual EBS BT survey (1979–2012)	T4.2
EIT survey biomass	$\sum_y \frac{\left[\ln(\beta^{eit}_y)-\ln\left(\hat{\beta}^{eit}_y\right)\right]^2}{2\sigma^2_{eit}},\ \sigma_{eit}=0.2$	Pollock acoustic trawl survey (1979–2012)	T4.3
EIT age composition	$-n\sum_y \sum_j \left(O^{eit}_{1j,y}+v\right)\ln\left(\hat{O}^{eit}_{1j,y}+v\right)$	Pollock acoustic trawl survey (1979–2012)	T.4.4
Total catch	$\sum_i \sum_y \frac{\left[\ln\left(C^*_{i,y}\right)-\ln\left(C^*_{i,y}\right)\right]^2}{2\sigma^2_C},\ \sigma_C=0.05$	Fishery observer data (1979–2012)	T.4.5
Fishery age composition	$-\sum_i n_i \sum_y \sum_j \left(O^f_{ij,y}+v\right)\ln\left(\hat{O}^f_{ij,y}+v\right)$	Fishery observer data (1979–2012)	T4.6
Penalties			
Fishery selectivity	$\sum_i \sum_j^{A_i-1} \chi\cdot\left[\ln\left(\frac{\eta^f_{ij}}{\eta^f_{ij+1}}\right)-\ln\left(\frac{\eta^f_{ij+1}}{\eta^f_{ij+2}}\right)\right]^2,\ \chi=\begin{cases}20,\ if & \eta^f_{ij}>\eta^f_{ji+1}\\ 0,\ if & \eta^f_{ij}\le\eta^f_{ij+1}\end{cases}$		T4.7
Priors			
	$\sum_i \sum_y (\tau_{i,y})^2$		T4.8
	$\sum_i \sum_y (N_{0,ij})^2$		T4.9
	$\sum_i \sum_y (\varepsilon_{i,y})^2$		T4.10

$v=0.001$.

Description	Equation
Data components	
BT survey biomass	$\sum_i \sum_y \frac{\left[\ln\left(\beta_{i,y}^s\right) - \ln\left(\hat{\beta}_{i,y}^s\right)\right]^2}{2\sigma_{s,i}^2}$
BT survey age composition	$-\sum_i n_i \sum_y \sum_j \left(O_{ij,y}^s + v\right) \ln\left(\hat{O}_{ij,y}^s + v\right)$
EIT survey biomass	$\sum_y \frac{\left[\ln(\beta_y^{eit}) - \ln\left(\hat{\beta}_y^{eit}\right)\right]^2}{2\sigma_{eit}^2}, \ \sigma_{eit} = 0.2$
EIT age composition	$-n \sum_y \sum_j \left(O_{1j,y}^{eit} + v\right) \ln\left(\hat{O}_{1j,y}^{eit} + v\right)$
Total catch	$\sum_i \sum_y \frac{\left[\ln\left(C_{i,y}^*\right) - \ln\left(C_{i,y}^*\right)\right]^2}{2\sigma_C^2}, \ \sigma_C = 0.05$
Fishery age composition	$-\sum_i n_i \sum_y \sum_j \left(O_{ij,y}^f + v\right) \ln\left(\hat{O}_{ij,y}^f + v\right)$
Penalties	
Fishery selectivity	$\sum_i \sum_j^{A_i - 1} \chi \cdot \left[\ln\left(\frac{\eta_{ij}^f}{\eta_{ij+1}^f}\right) - \ln\left(\frac{\eta_{ij+1}^f}{\eta_{ij+2}^f}\right)\right]^2, \ \chi = \begin{cases} 20, \ if & \eta_{ij}^f > \eta_{ji+1}^f \\ 0, \ if & \eta_{ij}^f \le \eta_{ij+1}^f \end{cases}$
Priors	$\sum_i \sum_y \left(\tau_{i,y}\right)^2$
	$\sum_i \sum_y \left(N_{0,ij}\right)^2$
	$\sum_i \sum_y \left(\varepsilon_{i,y}\right)^2$

$v = 0.001$.

Definition	Equation		
Recruitment	$N_{i1,y}=R_{i,y}=R_{0,i}e^{\tau_{i,y}}$	$\tau_{i,y}\sim N(0,\sigma^2)$	T1.1
Initial abundance	$N_{ij,1}=\begin{cases} R_{0,i}e^{(-j\,M1_{ij})}N_{0,ij} & y=1 \quad 1<j\le A_i \\ R_{0,i}e^{(-j\,M1_{i,A_i})}N_{0,i,A_i}/\left(1-e^{(-j\,M1_{i,A_i})}\right) & y=1 \quad j>A_i \end{cases}$		T1.2
Numbers at age	$N_{i,j+1,y+1}=N_{ij,y}e^{-Z_{ij,y}}$ $\quad 1\le y\le n_y \quad 1\le j<A_i$ $N_{i,A_i,y+1}=N_{i,A_i-1,y}e^{-Z_{i,A_i-1,y}}+N_{i,A_i,y}e^{-Z_{i,A_i,y}}$ $\quad 1\le y\le n_y \quad j>A_i$		T1.3
Catch	$C_{ij,y}=\frac{F_{ij,y}}{Z_{ij,y}}(1-e^{-Z_{ij,y}})N_{ij,y}$		T1.4
Total yield (kg)	$Y_{i,y}=\sum_{j}^{A_i}\left(\frac{F_{ij,y}}{Z_{ij,y}}(1-e^{-Z_{ij,y}})N_{ij,y}W_{ij,y}\right)$		T1.5
Biomass at age (kg)	$B_{ij,y}=N_{ij,y}W_{ij,y}$		T1.6
Spawning biomass at age (kg)	$SSB_{ij,y}=B_{ij,y}\rho_{ij}$		T1.7
Total mortality at age	$Z_{ij,y}=M1_{ij}+M2_{ij,y}+F_{ij,y}$		T1.8
Fishing mortality at age	$F_{ij,y}=F_{0,i}e^{\varepsilon_{i,y}}s_{ij}^{f}$	$\varepsilon_{i,y}\sim N(0,\sigma_{F,i}^2)$	T1.9
Weight at age (kg)	$W_{ij,y}=W_{\infty,iy}\left(1-e^{(-K_i(1-d_{i,y})(j-t_{0,i}))}\right)^{\frac{1}{1-d_{i,y}}}$		T1.10a
	$d_{i,y}=e^{(\alpha_{d,i,y}+\alpha0_{d,i}+\beta_{d,i}T_y)}$		T1.10b
	$W_{\infty,iy}=\left(\frac{H_i}{K_i}\right)^{1/(1-d_{i,y})}$		T1.10c
BT survey biomass (kg)	$\hat{\beta}_{i,y}^{s}=\sum_{j}^{A_i}\left(N_{ij,y}e^{-0.5\,Z_{ij,y}}W_{ij,y}s_{ij}^{s}\right)$		T1.11
EIT survey biomass (kg)	$\hat{\beta}_{y}^{eit}=\sum_{j}^{A_1}\left(N_{1j,y}e^{0.5(-Z_{1j,y})}W_{1j,y}s_{1j}^{eit}q_{1j}^{eit}\right)$	(pollock only)	T1.12
Fishery age composition	$\hat{O}_{ij,y}^{f}=\frac{C_{ij,y}}{\sum_j C_{ij,y}}$		T1.13
BT survey age composition	$\hat{O}_{ij,y}^{s}=\frac{N_{ij,y}e^{0.5(-Z_{ij,y})}s_{ij}^{s}}{\sum_j\left(N_{ij,y}e^{0.5(-Z_{ij,y})}s_{ij}^{s}\right)}$		T1.14
EIT survey age composition	$\hat{O}_{1j,y}^{eit}=\frac{N_{1j,y}e^{0.5(-Z_{1j,y})}s_{1j}^{eit}q_{1}^{eit}}{\sum_j\left(N_{1j,y}e^{0.5(-Z_{1j,y})}s_{1j}^{eit}q_{1}^{eit}\right)}$	(pollock only)	T1.15
BT selectivity	$s_{ij}^{s}=\frac{1}{1+e^{\left(-b_i^s\cdot j-a_i^s\right)}}$		T1.16
Fishery selectivity	$s_{ij}^{f}=\begin{cases} e^{\eta_{ij}} & j\le A_{\eta,i} \\ e^{\eta_{iA_{\eta,i}}} & j>A_{\eta,i} \end{cases}$	$\eta_{ij}\sim N(0,\sigma_{f,i}^2)$	T1.17
Proportion females	$\omega_{ij}=\frac{e^{-j\,M_{fem}}}{e^{-j\,M_{fem}}+e^{-j\,M_{male}}}$		T1.18
Proportion of mature females	$\rho_{ij}=\omega_{ij}\phi_{ij}$		T1.19
Weight at age (kg)	$W_{ij,y}=W_{ij,y}^{\text{fem}}\omega_{ij}+(1-\omega_{ij})W_{ij,y}^{\text{male}}$		T1.20
Residual natural mortality	$M1_{ij}=M_{ij}^{\text{fem}}\omega_{ij}+(1-\omega_{ij})M_{ij}^{\text{male}}$		T1.21

Definition	Equation		
Recruitment	$N_{i1,y} = R_{i,y} = R_{0,i}e^{\tau_{i,y}}$		$\tau_{i,y} \sim N(0, \sigma^2)$
Initial abundance	$N_{ij,1} = \begin{cases} R_{0,i}e^{(-j\,M1_{ij})}N_{0,ij} \\ R_{0,i}e^{(-j\,M1_{iA_i})}N_{0,i,A_i} / \left(1 - e^{(-j\,M1_{iA_i})}\right) \end{cases}$		$y = 1 \quad 1 < j \le A_i$ $y = 1 \quad j > A_i$
Numbers at age	$N_{i,j+1,y+1} = N_{ij,y}e^{-Z_{ij,y}}$	$1 \le y \le n_y \quad 1 \le j < A_i$	
	$N_{i,A_i,y+1} = N_{i,A_i-1,y}e^{-Z_{i,A_i-1,y}} + N_{i,A_i,y}e^{-Z_{i,A_i,y}}$	$1 \le y \le n_y \quad j > A_i$	
Catch	$C_{ij,y} = \frac{F_{ij,y}}{Z_{ij,y}}(1 - e^{-Z_{ij,y}})N_{ij,y}$		
Total yield (kg)	$Y_{i,y} = \sum_j^{A_i} \left(\frac{F_{ij,y}}{Z_{ij,y}}(1 - e^{-Z_{ij,y}})N_{ij,y}W_{ij,y}\right)$		
Biomass at age (kg)	$B_{ij,y} = N_{ij,y}W_{ij,y}$		
Spawning biomass at age (kg)	$SSB_{ij,y} = B_{ij,y}\rho_{ij}$		
Total mortality at age	$Z_{ij,y} = M1_{ij} + M2_{ij,y} + F_{ij,y}$		
Fishing mortality at age	$F_{ij,y} = F_{0,i}e^{\varepsilon_{i,y}}s_{ij}^{f}$		$\varepsilon_{i,y} \sim N(0, \sigma_{F,i}^2)$
Weight at age (kg)	$W_{ij,y} = W_{\infty,iy}\left(1 - e^{(-K_i(1-d_{i,y})(j-t_{0,i}))}\right)^{\frac{1}{1-d_{i,y}}}$		
	$d_{i,y} = e^{(\alpha_{d,i,y} + \alpha 0_{d,i} + \beta_{d,i}T_y)}$		
	$W_{\infty,iy} = \left(\frac{H_i}{K_i}\right)^{1/(1-d_{i,y})}$		
BT survey biomass (kg)	$\hat{\beta}_{i,y}^{s} = \sum_j^{A_i}\left(N_{ij,y}e^{-0.5\,Z_{ij,y}}W_{ij,y}s_{ij}^{s}\right)$		

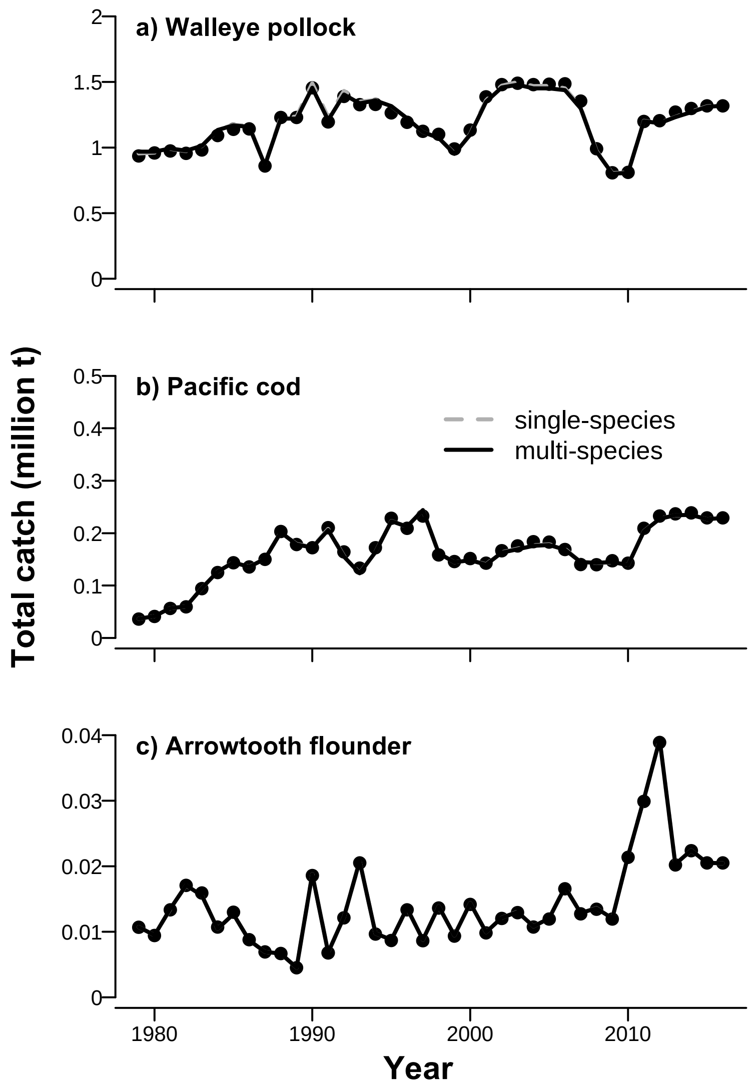
BT survey biomass (kg)	$\hat{\beta}^{s}_{i,y} = \sum_{j}^{A_i} \left(N_{ij,y} e^{-0.5 \, Z_{ij,y}} W_{ij,y} s^{s}_{ij} \right)$	
EIT survey biomass (kg)	$\hat{\beta}^{eit}_{y} = \sum_{j}^{A_1} \left(N_{1j,y} e^{0.5(-Z_{1j,y})} W_{1j,y} s^{eit}_{1j} q^{eit}_{1j} \right)$	(pollock only)
Fishery age composition	$\hat{O}^{f}_{ij,y} = \frac{C_{ij,y}}{\sum_j C_{ij,y}}$	
BT survey age composition	$\hat{O}^{s}_{ij,y} = \frac{N_{ij,y} e^{0.5(-Z_{ij,y})} s^{s}_{ij}}{\sum_j \left(N_{ij,y} e^{0.5(-Z_{ij,y})} s^{s}_{ij} \right)}$	
EIT survey age composition	$\hat{O}^{eit}_{1j,y} = \frac{N_{1j,y} e^{0.5(-Z_{1j,y})} s^{eit}_{1j} q^{eit}_{1}}{\sum_j \left(N_{1j,y} e^{0.5(-Z_{1j,y})} s^{eit}_{1j} q^{eit}_{1} \right)}$	(pollock only)
BT selectivity	$s^{s}_{ij} = \frac{1}{1 + e^{\left(-b^{s}_{i} \cdot j - a^{s}_{i}\right)}}$	
Fishery selectivity	$s^{f}_{ij} = \begin{cases} e^{\eta_{ij}} & j \le A_{\eta,i} \\ e^{\eta_{i,A_{\eta,i}}} & j > A_{\eta,i} \end{cases}$	$\eta_{ij} \sim N(0, \sigma^2_{f,i})$
Proportion females	$\omega_{ij} = \frac{e^{-j \, M_{fem}}}{e^{-j \, M_{fem}} + e^{-j \, M_{male}}}$	
Proportion of mature females	$\rho_{ij} = \omega_{ij} \phi_{ij}$	
Weight at age (kg)	$W_{ij,y} = W^{\text{fem}}_{ij,y} \omega_{ij} + (1 - \omega_{ij}) W^{\text{male}}_{ij,y}$	
Residual natural mortality	$M1_{ij} = M^{\text{fem}}_{ij} \omega_{ij} + (1 - \omega_{ij}) M^{\text{male}}_{ij}$	

Table 8. Proportion mature and residual natural mortality for each species in the model.

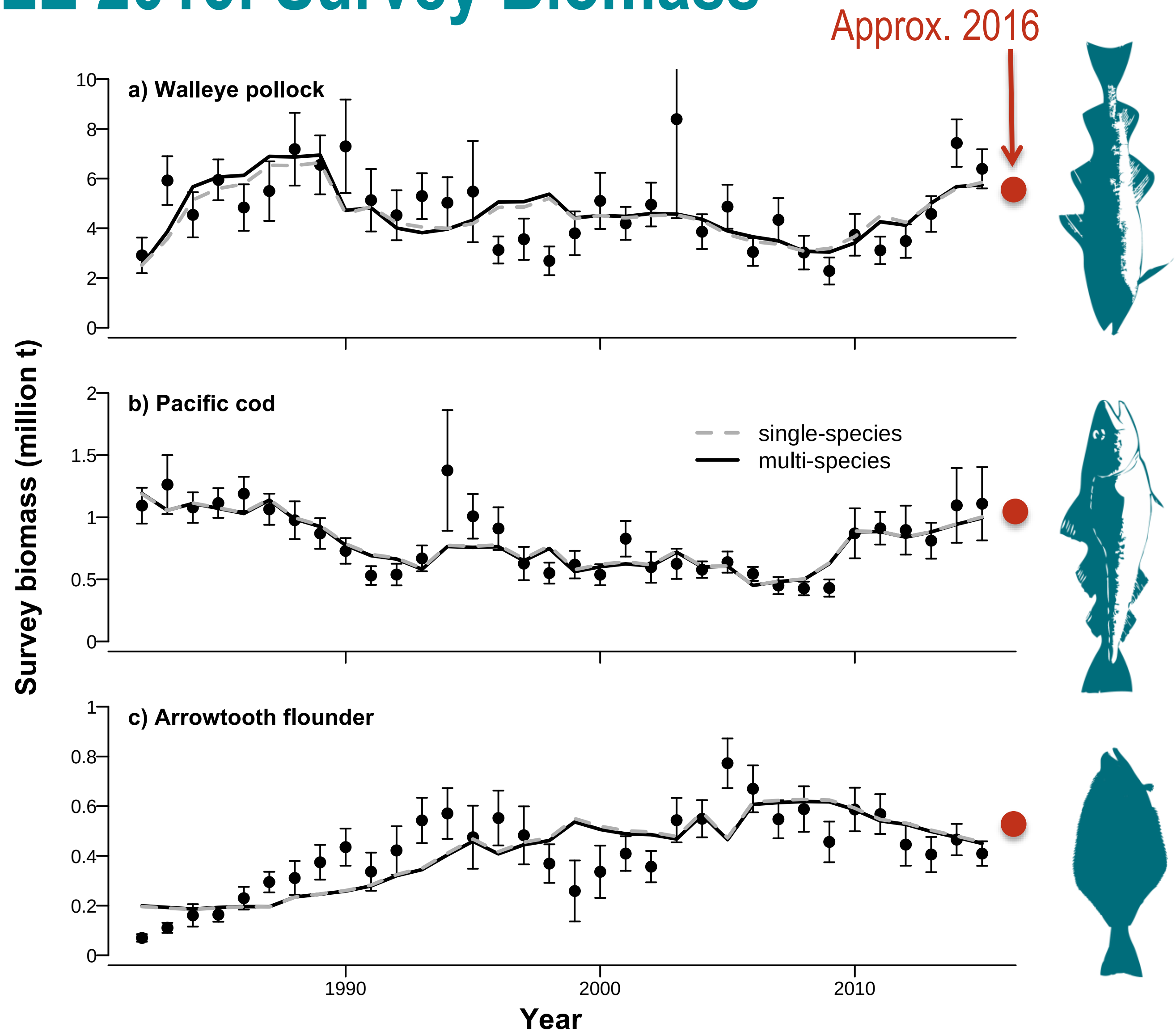
Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Proportion mature																					
Walleye pollock	0.00	0.01	0.29	0.64	0.84	0.90	0.95	0.96	0.97	1.00	1.00	1.00									
Pacific cod	0.00	0.02	0.06	0.14	0.30	0.53	0.75	0.89	0.95	0.98	0.99	1.00									
Arrowtooth flounder	0.00	0.00	0.01	0.02	0.06	0.16	0.34	0.59	0.80	0.92	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Residual mortality (M1)																					
Walleye pollock	0.52	0.52	0.45	0.26	0.26	0.27	0.28	0.28	0.27	0.29	0.30	0.30									
Pacific cod	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37									
Arrowtooth flounder	0.27	0.26	0.26	0.25	0.25	0.24	0.24	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Definition	Equation	
Predation mortality	$M2_{ij,y} = \sum_{pa} \left(\frac{N_{pa,y}\delta_{pa,y}\overline{S}_{paij}}{\sum_{ij}\left(\overline{S}_{paij}B_{ij,y}\right) + B_p^{other}\left(1 - \sum_{ij}\left(\overline{S}_{paij}\right)\right)} \right)$	T2.1
Predator-prey suitability	$\overline{S}_{paij} = \frac{1}{n_y}\sum_{y} \left(\frac{\frac{\overline{U}_{paij}}{B_{ij,y}}}{\sum_{ij}\left(\frac{\overline{U}_{paij}}{B_{ij,y}}\right) + \frac{1+\sum_{ij}\overline{U}_{paij}}{B_p^{other}}} \right)$	T2.2
Mean gravimetric diet proportion	$\overline{U}_{paij} = \frac{\sum_y U_{paij,y}}{n_y}$	T2.3
Individual specific ration (kg kg^{-1} yr^{-1})	$\delta_{pa,y} = \hat{\varphi}_p \alpha_\delta W_{pa,y}{}^{(1+\beta_\delta)} f(T_y)_p$	T2.4
Temperature scaling algorithm	$f(T_y)_p = V^X e^{(X(1-V))}$	T2.5
	$V = \left(T_p^{cm} - T_y\right) / \left(T_p^{cm} - T_p^{co}\right)$	T2.5a
	$X = \left(Z^2\left(1 + (1 + 40/Y)^{0.5}\right)^2\right)/400$	T2.5b
	$Z = ln\left(Q_p^c\right)\left(T_p^{cm} - T_p^{co}\right)$	T2.5c
	$Y = ln\left(Q_p^c\right)\left(T_p^{cm} - T_p^{co} + 2\right)$	T2.5d

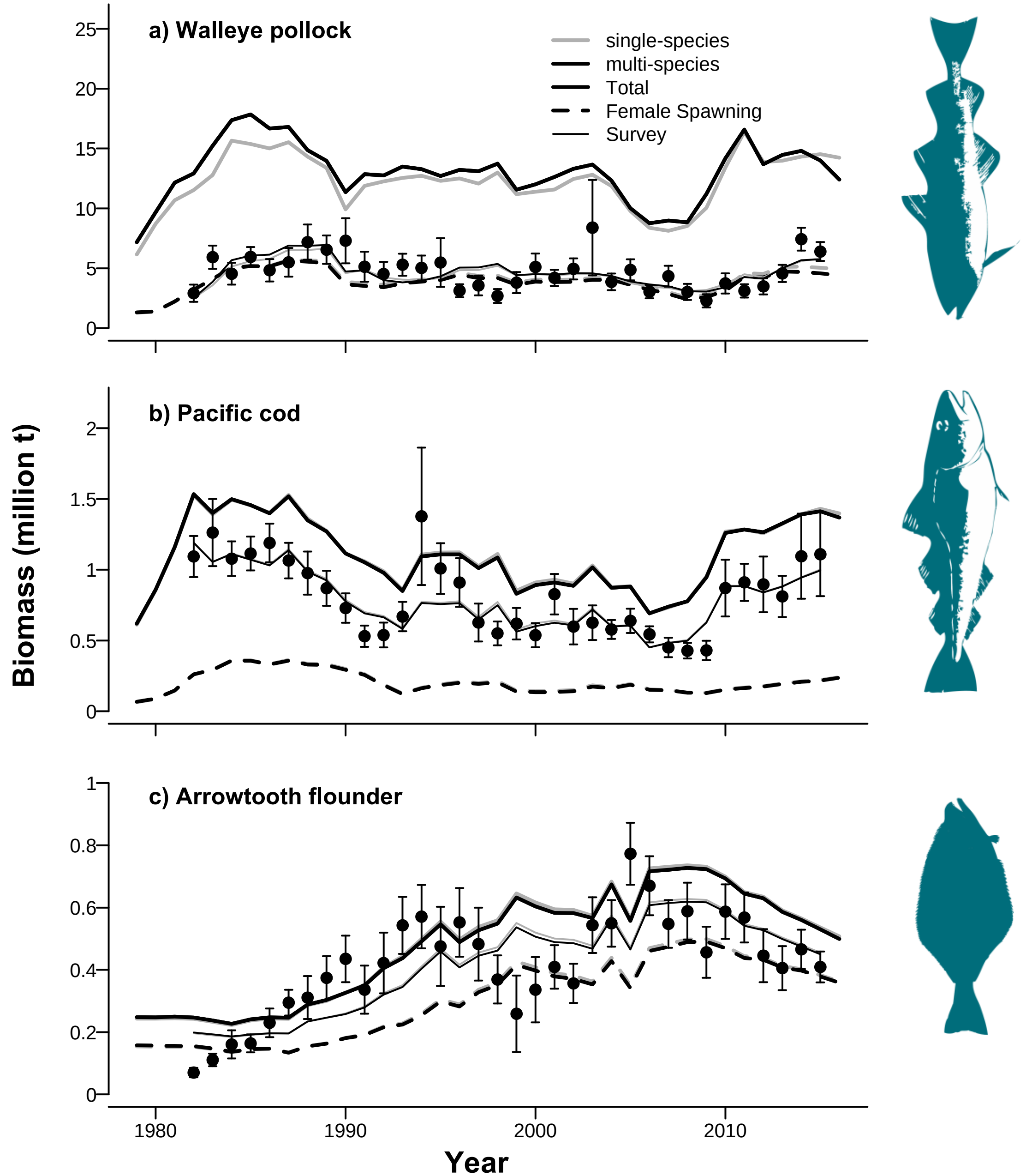
CEATTLE 2016: Catch



CEATTLE 2016: Survey Biomass



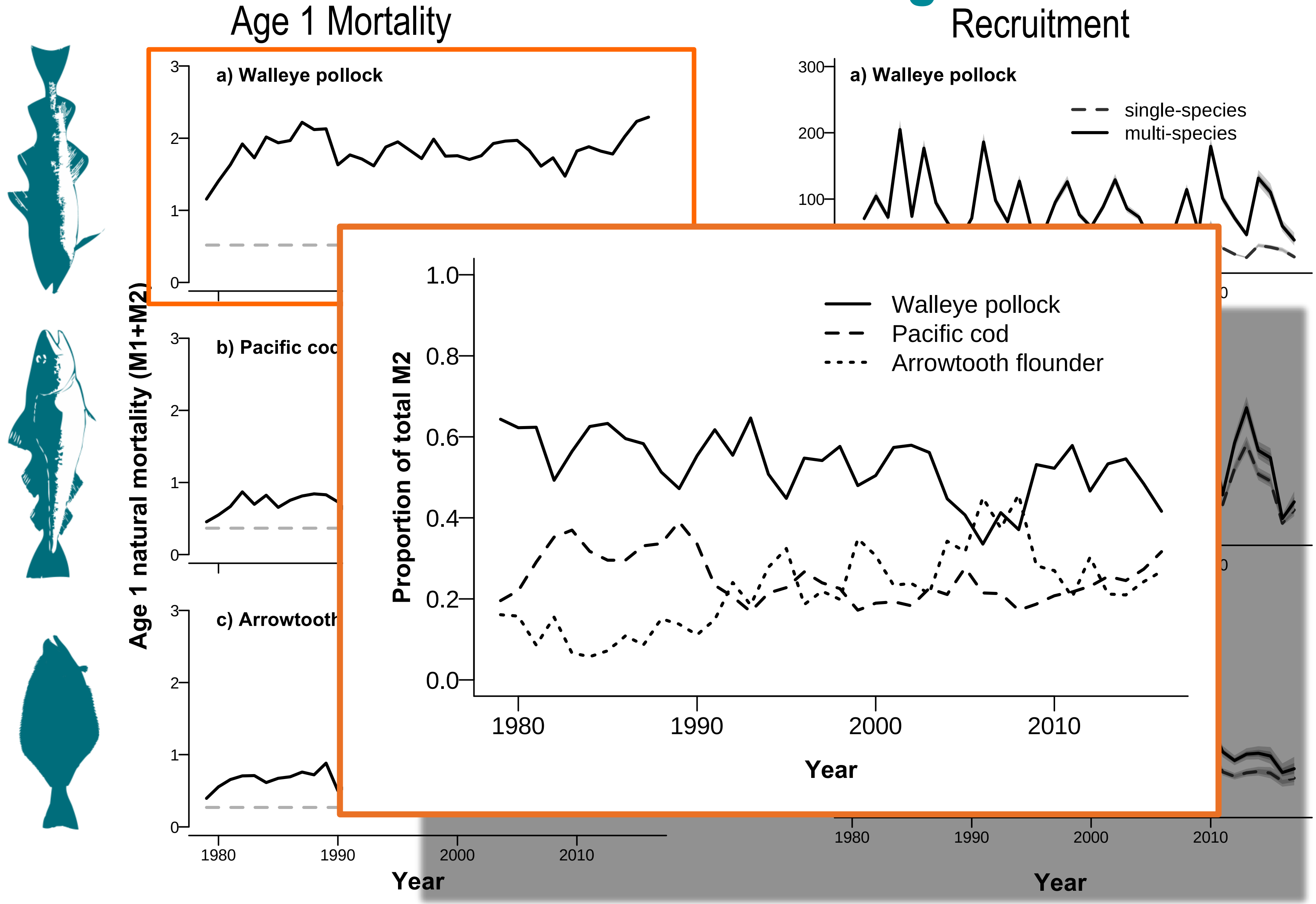
Biomass



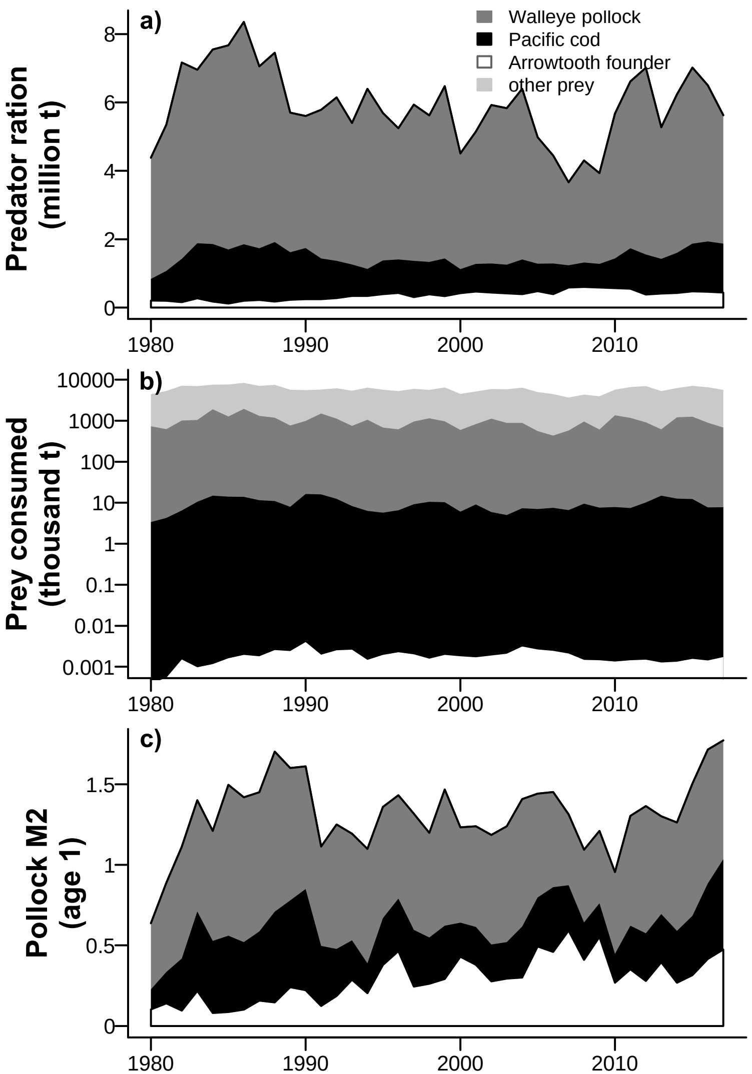
a) Walleye pollock
single-species
multi-species
Total
Female Spawning
Survey
b) Pacific cod
c) Arrowtooth flounder
Biomass (million t)
Year
0
5
10
15
20
25
0.5
1
1.5
2
0.2
0.4
0.6
0.8
1980
1990
2000
2010

Understand mechanisms of change

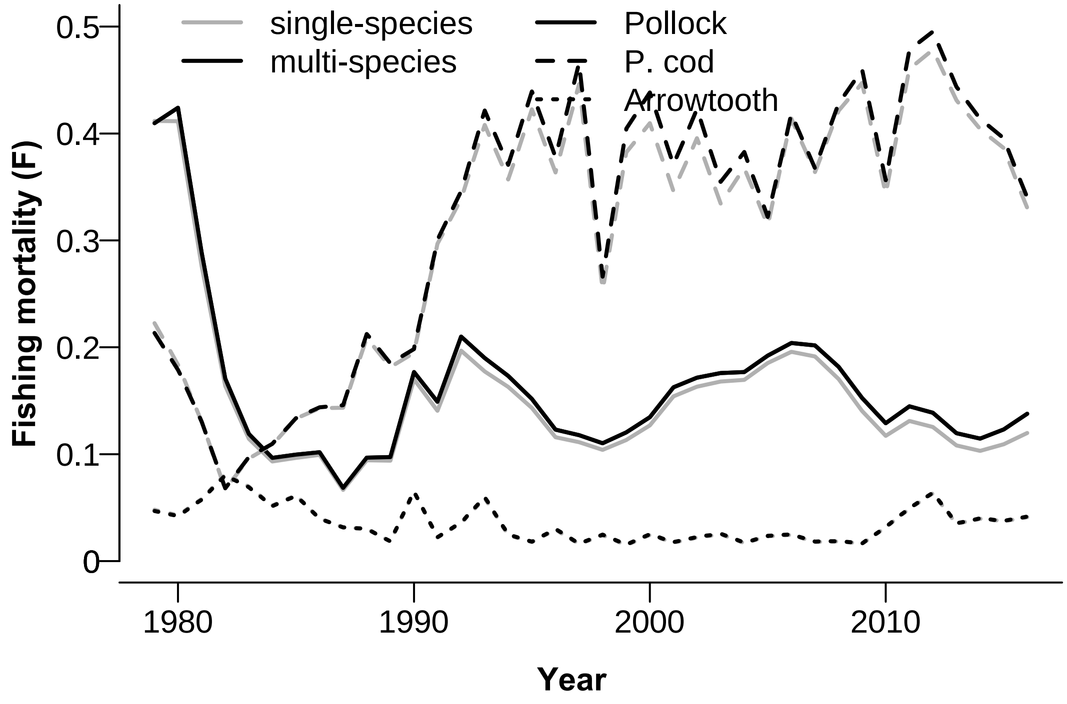
Understand mechanisms of change



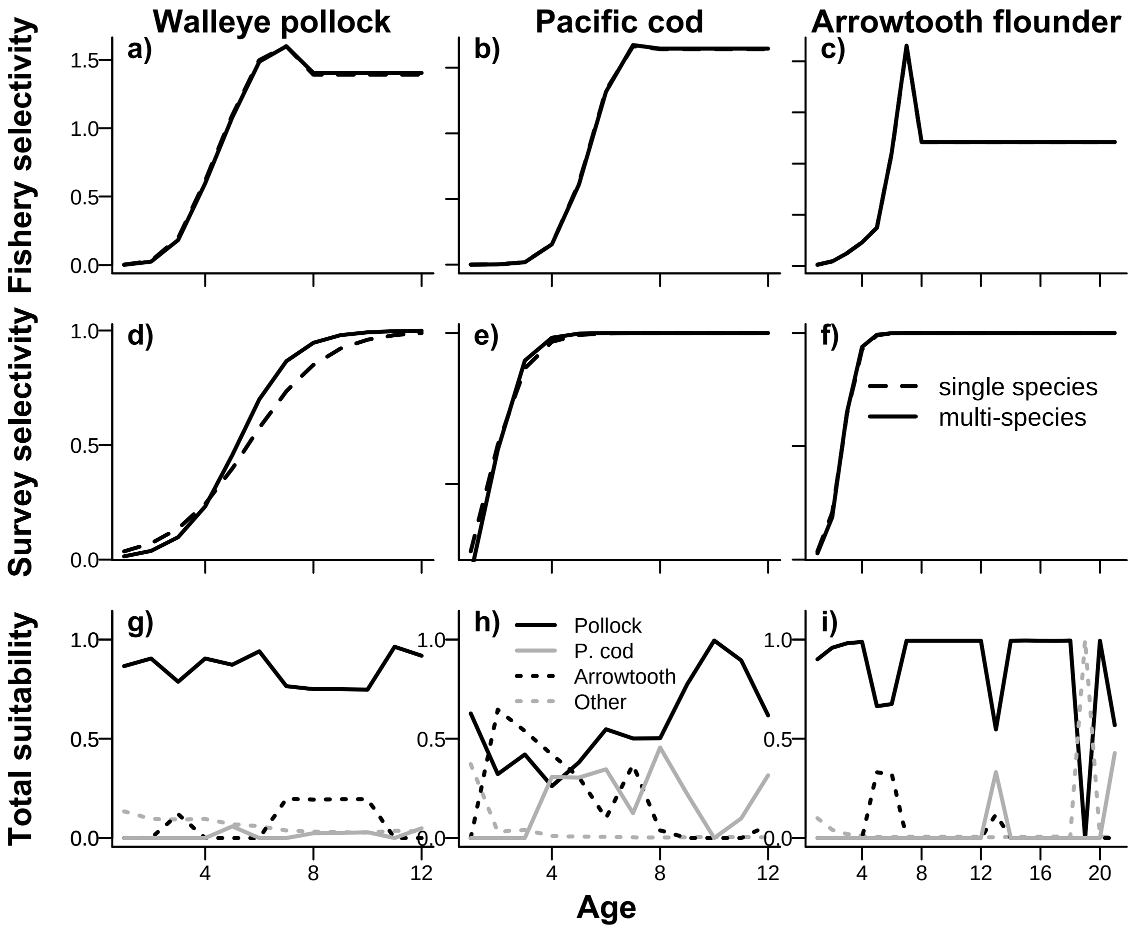
Understand mechanisms of change



Fishing mortality



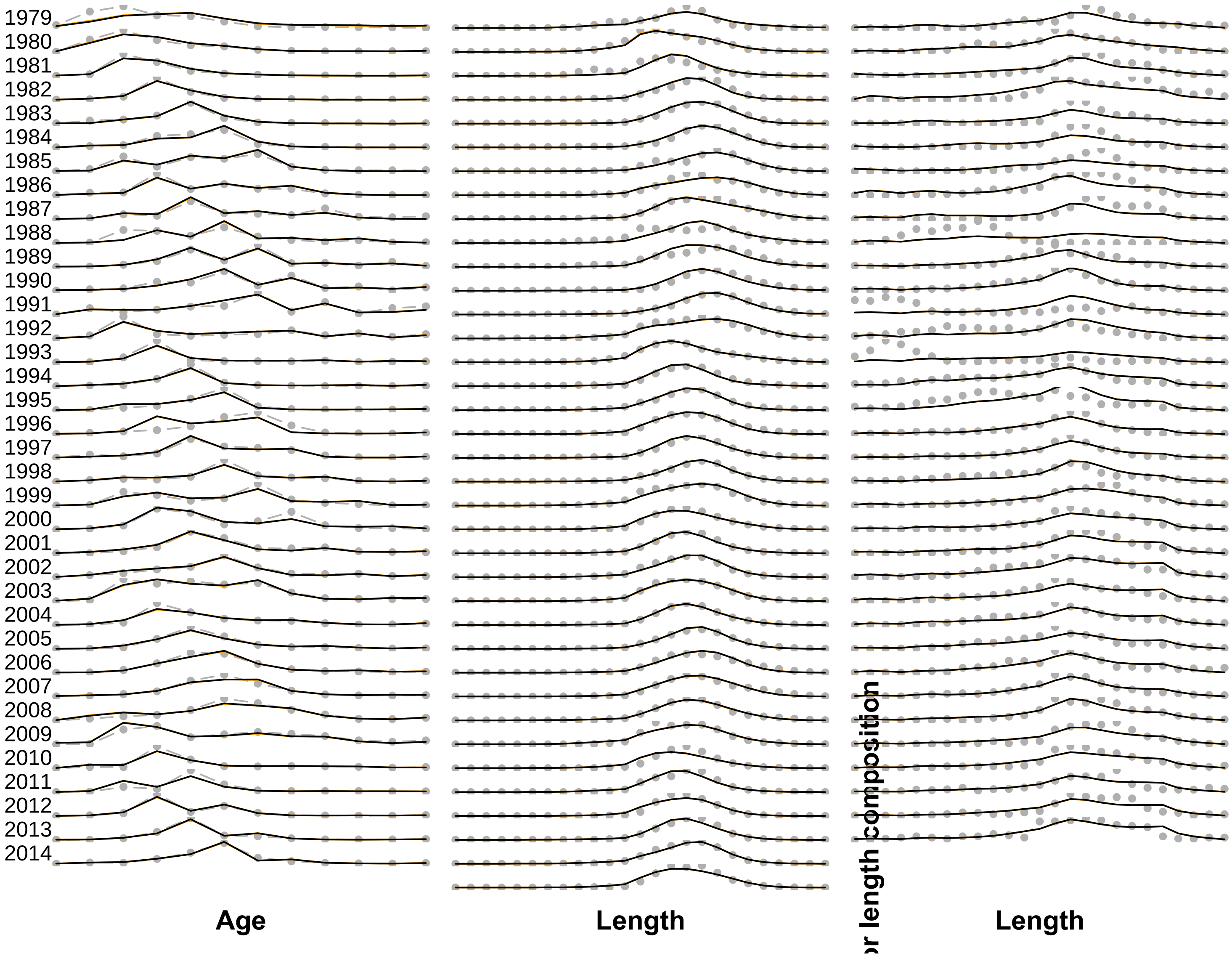
Selectivity



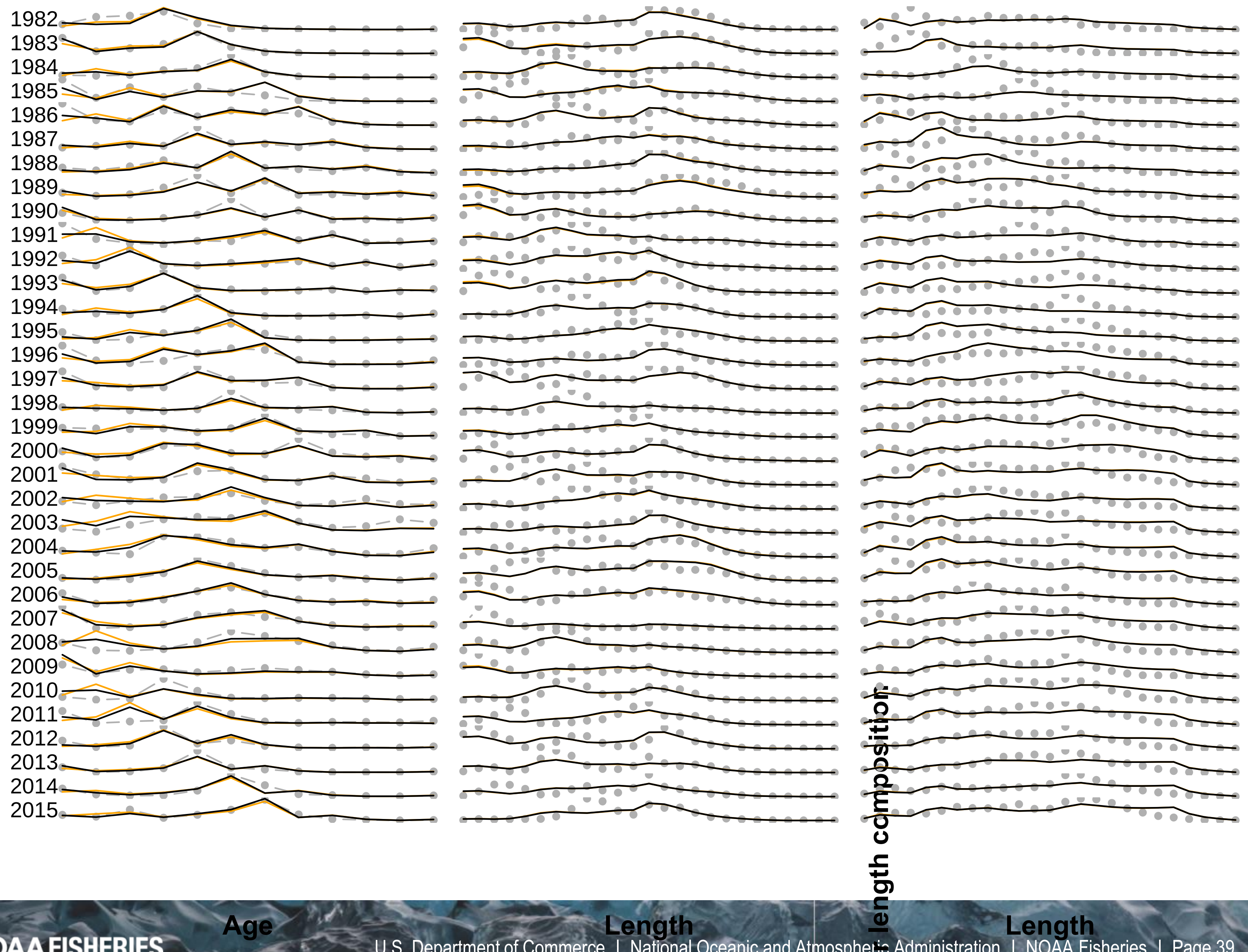
CEATTLE 2016: Pollock age classes

years	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12+
1979	1.732	1.739	1.022	0.583	0.552	0.354	0.206	0.181	0.205	0.197	0.171	0.231
1980	0.933	3.884	2.283	0.988	0.498	0.356	0.181	0.095	0.088	0.098	0.091	0.177
1981	1.385	1.650	5.164	2.249	0.857	0.325	0.183	0.084	0.047	0.042	0.045	0.118
1982	0.955	1.914	2.056	4.925	1.992	0.610	0.192	0.099	0.046	0.025	0.022	0.080
1983	2.710	1.000	2.295	2.004	4.785	1.669	0.446	0.131	0.067	0.031	0.016	0.062
1984	0.993	3.639	1.299	2.457	2.203	4.698	1.466	0.369	0.108	0.055	0.025	0.058
1985	2.352	0.945	4.202	1.205	2.301	1.856	3.539	1.028	0.254	0.072	0.036	0.051
1986	1.246	2.378	1.091	3.914	1.146	1.958	1.413	2.520	0.722	0.175	0.048	0.055
1987	0.850	1.264	2.955	1.104	4.053	1.073	1.648	1.119	1.968	0.555	0.131	0.075
1988	0.508	0.652	1.402	2.730	1.063	3.592	0.865	1.252	0.830	1.437	0.394	0.143
1989	0.943	0.441	0.758	1.361	2.764	0.981	2.985	0.679	0.963	0.632	1.067	0.396
1990	2.375	0.704	0.404	0.571	1.053	1.928	0.607	1.715	0.379	0.525	0.335	0.759
1991	1.285	3.376	0.936	0.444	0.637	1.037	1.674	0.496	1.410	0.309	0.421	0.836
1992	0.866	1.549	4.165	0.916	0.435	0.544	0.778	1.175	0.346	0.969	0.206	0.792
1993	1.685	1.131	2.026	4.246	0.903	0.363	0.389	0.518	0.787	0.228	0.621	0.597
1994	0.722	2.344	1.432	1.961	3.970	0.708	0.245	0.244	0.325	0.486	0.136	0.701
1995	0.642	0.772	2.919	1.402	1.882	3.247	0.503	0.163	0.162	0.212	0.305	0.487
1996	1.265	0.670	1.009	3.083	1.486	1.733	2.638	0.384	0.124	0.121	0.154	0.552
1997	1.666	1.428	0.810	0.970	2.975	1.254	1.296	1.842	0.265	0.084	0.079	0.429
1998	1.016	2.186	1.853	0.841	1.018	2.753	1.036	1.005	1.416	0.200	0.061	0.346
1999	0.751	0.928	2.429	1.619	0.734	0.777	1.860	0.652	0.620	0.853	0.117	0.217
2000	1.155	0.912	1.197	2.505	1.688	0.672	0.635	1.429	0.497	0.465	0.621	0.231
2001	1.690	1.387	1.142	1.192	2.503	1.467	0.517	0.458	1.022	0.349	0.316	0.578
2002	1.130	2.216	1.825	1.195	1.241	2.243	1.154	0.381	0.337	0.743	0.246	0.600
2003	0.970	1.433	2.917	1.899	1.229	1.093	1.723	0.829	0.274	0.239	0.509	0.547
2004	0.470	1.017	1.759	2.840	1.816	1.002	0.773	1.134	0.545	0.176	0.149	0.635
2005	0.336	0.453	1.147	1.581	2.509	1.365	0.651	0.465	0.679	0.319	0.100	0.410
2006	0.743	0.325	0.520	1.075	1.483	2.019	0.949	0.421	0.302	0.433	0.198	0.293
2007	1.516	0.863	0.404	0.525	1.090	1.288	1.513	0.663	0.297	0.210	0.293	0.318
2008	0.666	2.198	1.088	0.399	0.513	0.904	0.920	1.005	0.443	0.195	0.134	0.377
2009	2.421	0.897	2.934	1.151	0.419	0.462	0.708	0.674	0.739	0.322	0.137	0.338
2010	1.375	4.306	1.234	3.156	1.225	0.385	0.372	0.535	0.507	0.548	0.230	0.321
2011	0.978	1.751	5.858	1.319	3.369	1.137	0.316	0.287	0.408	0.382	0.398	0.384
2012	0.607	1.023	1.937	4.935	1.073	2.320	0.678	0.174	0.155	0.215	0.192	0.378
2013	1.739	0.701	1.266	1.924	4.915	0.927	1.768	0.484	0.123	0.108	0.145	0.364
2014	1.461	2.087	0.866	1.257	1.931	4.335	0.727	1.301	0.352	0.088	0.075	0.331
2015	0.781	1.377	2.535	0.851	1.260	1.710	3.421	0.538	0.952	0.253	0.061	0.262
2016	0.504	0.596	1.623	2.464	0.845	1.106	1.332	2.496	0.389	0.675	0.174	0.206

CEATTLE 2016: Fish age / length comp



CEATTLE 2016: Srvy age / length comp



Projections for BRPs

Photo: Mark Holsman

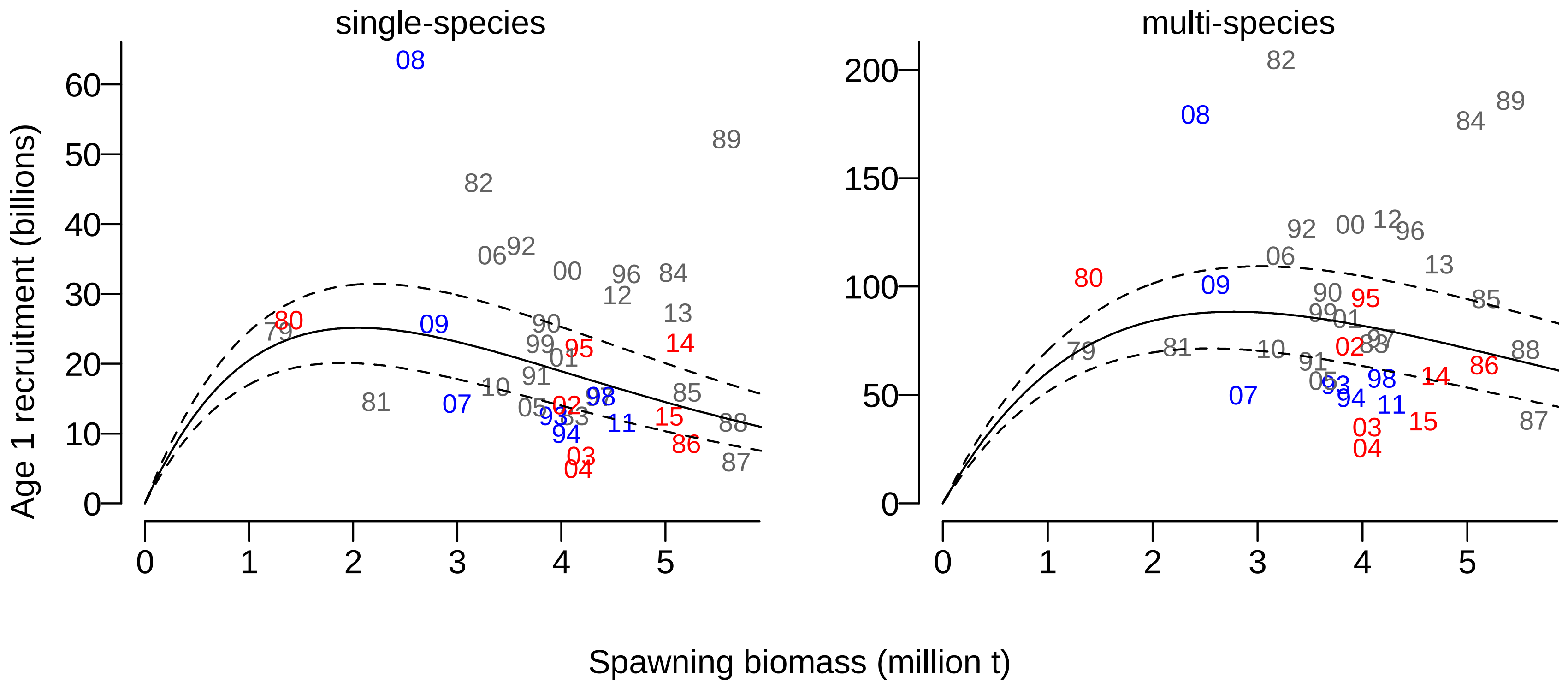
CEATTLE results

Summary of assessment results for 2016:

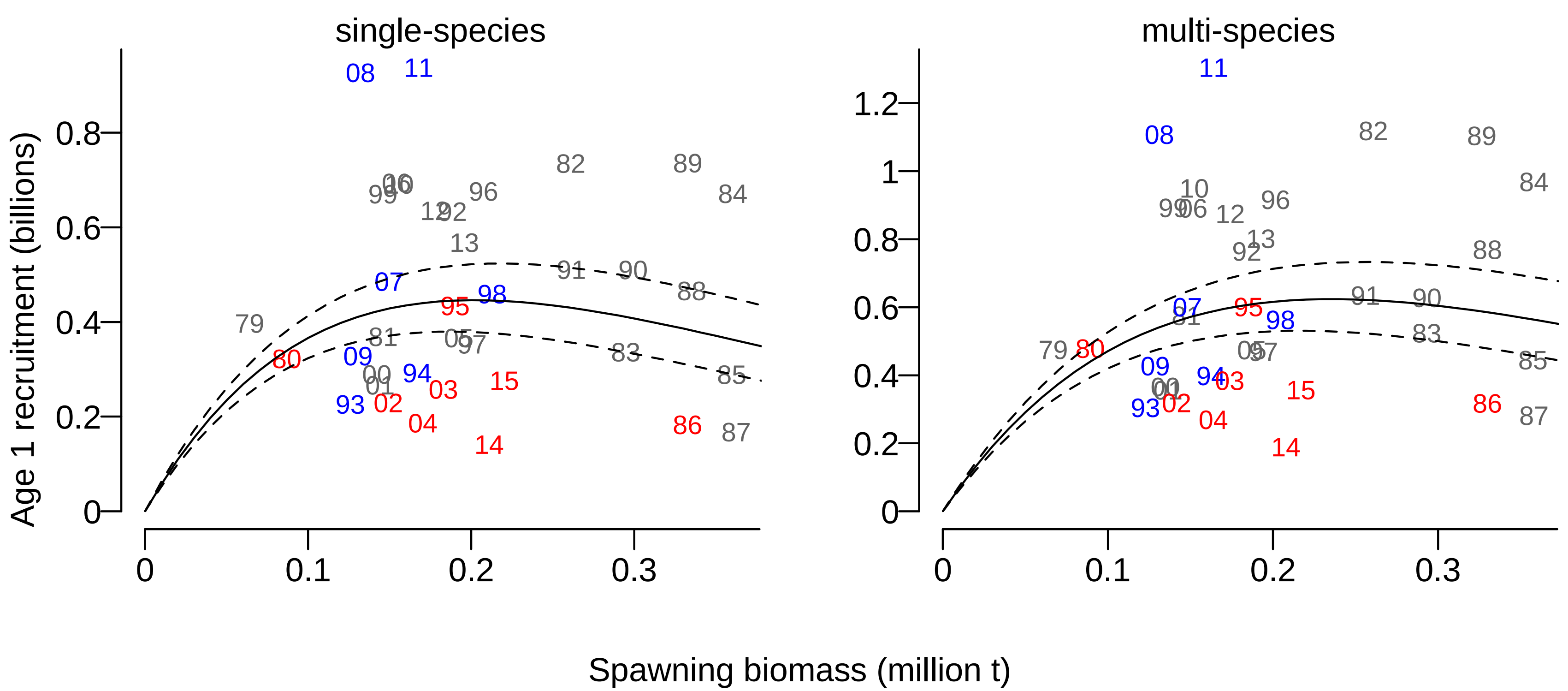
	Walleye pollock		Pacific cod		Arrowtooth flounder	
Quantity	**SSM**	**MSM**	**SSM**	**MSM**	**SSM**	**MSM**
2016 M (natural mortality age 1)	0.518	2.291	0.367	0.979	0.269	0.852
2016 Average 3+ M (across ages)	0.297	0.315	0.370	0.370	0.226	0.229
2016 total (age 3+) biomass (t)	12,765,196	11,310,126	1,364,563	1,335,013	500,469	493,279
2016 SSB (female spawning biomass; t)	4,973,790	4,429,230	241,188	236,601	362,375	358,115
**Projected SSB_0 (t)*	5,037,200	3,016,240	419,961	382,908	500,716	456,072
**Projected $SSB_{40\%}$ (t)*	2,014,460	1,206,530	168,253	153,163	200,284	182,426
***Projected SSB_{mMSY}*	2,482,140	2,781,050	146,696	141,982	2,229	6,717
ABC_{2100} (t)	1,884,950	1,683,130	172,056	167,148	34,880	36,005
**$mMSY_{2100}$ (t)	1,817,130	2,363,310	170,896	168,683	1,095	3,282
$F_{40\%}$	0.577	1.155	0.372	0.404	0.115	0.130
F_{mMSY}	0.405	0.518	0.434	0.447	0.322	0.317

* SSB is based on the projected SSB at 2100 (equilibrium).
** mMSY is aggregate multi-species yield

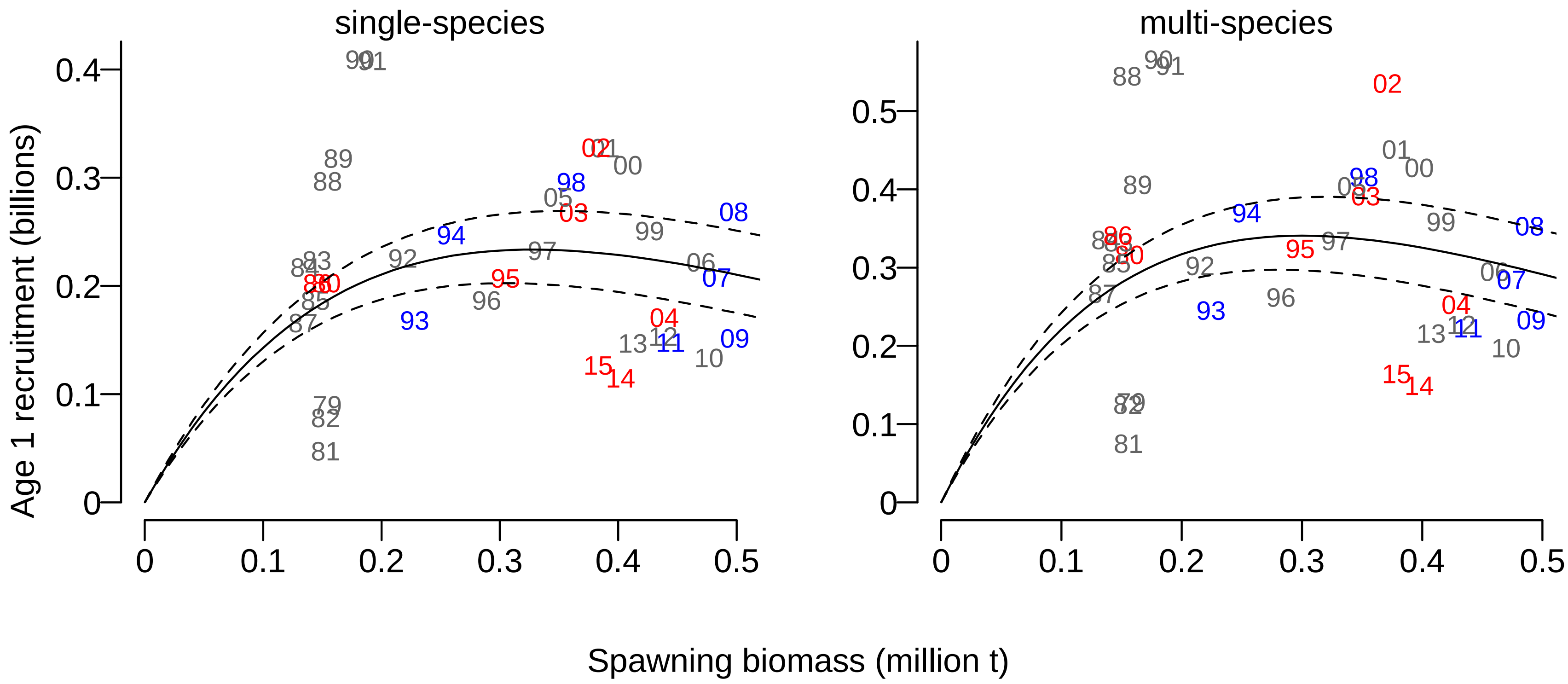
CEATTLE Recruitment: Pollock



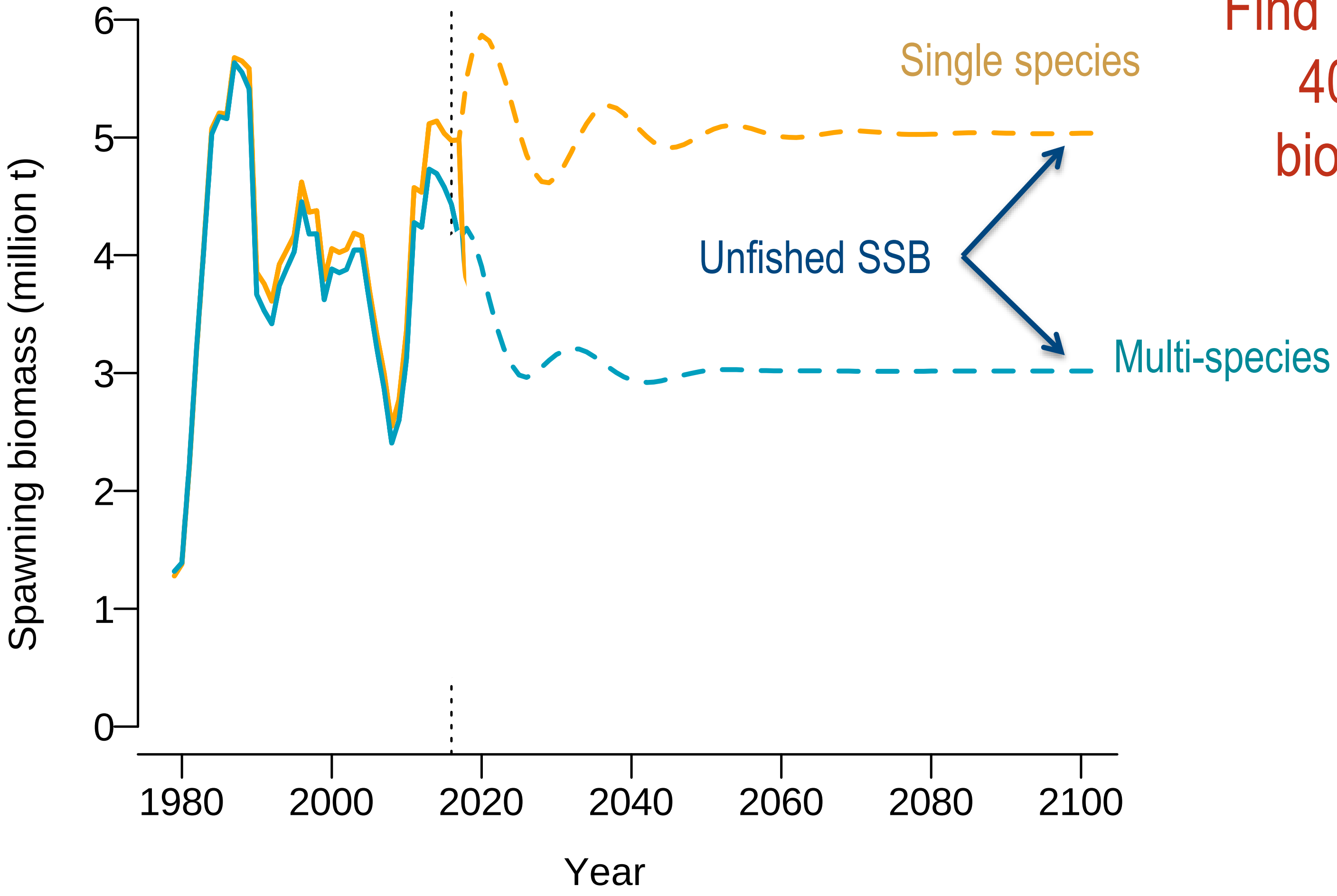
CEATTLE Recruitment: P. cod



CEATTLE Recruitment: Arrowtooth

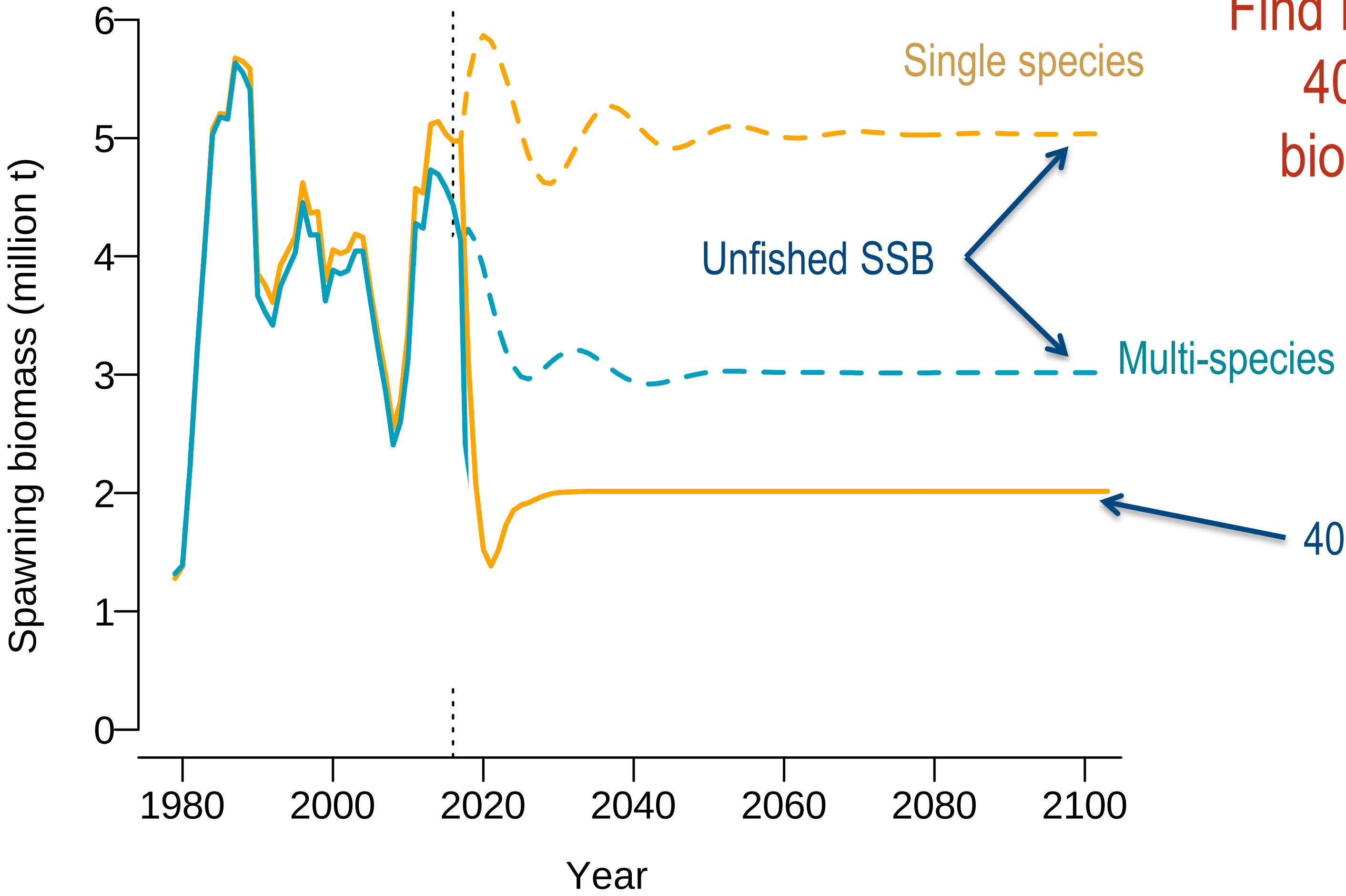


ABC multi-species proxy approach (Moffitt et al. in press)



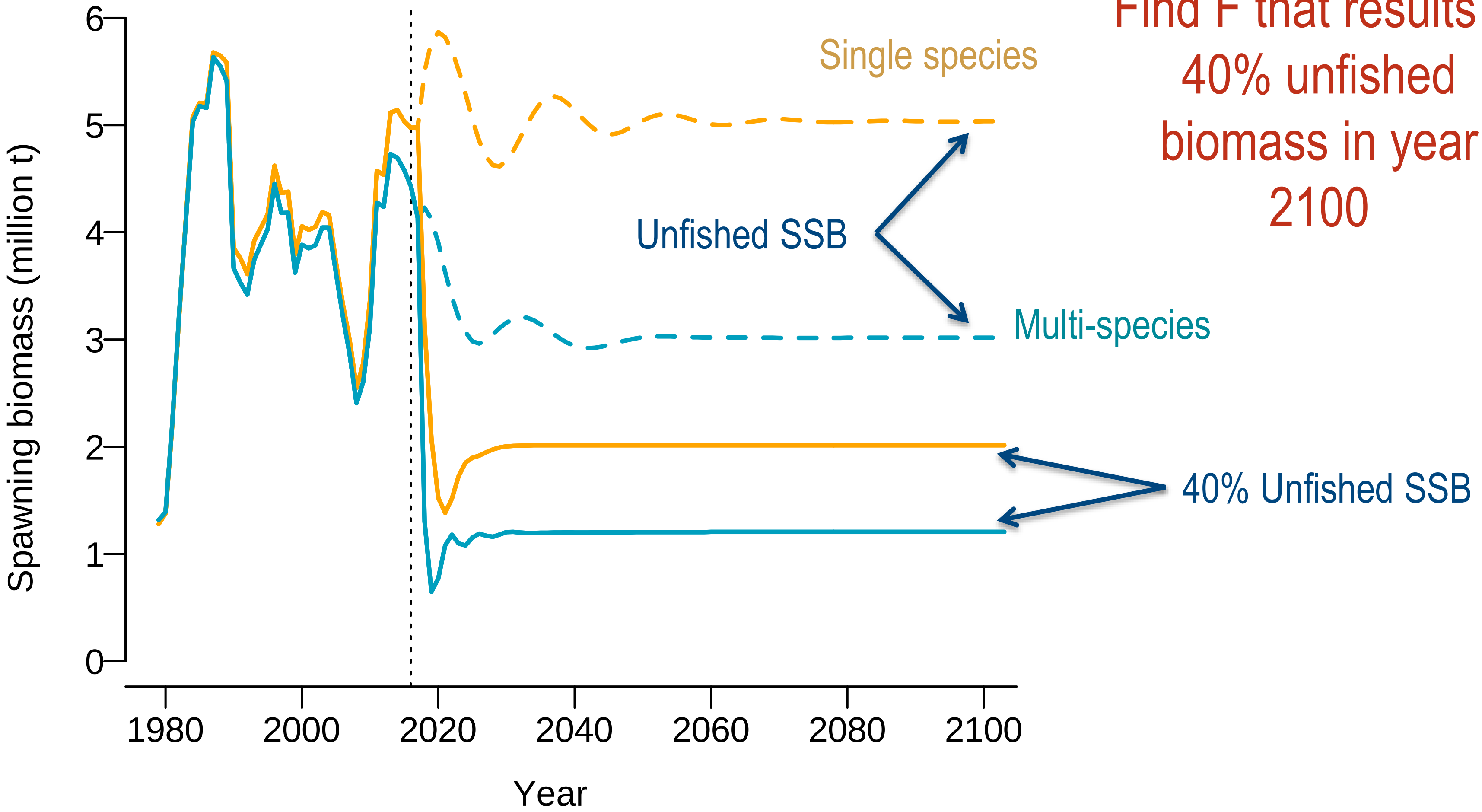
Find F that results in 40% unfished biomass in year 2100

ABC multi-species proxy approach (Moffitt et al. in press)



Find F that results in 40% unfished biomass in year 2100

ABC multi-species proxy approach (Moffitt et al. in press)

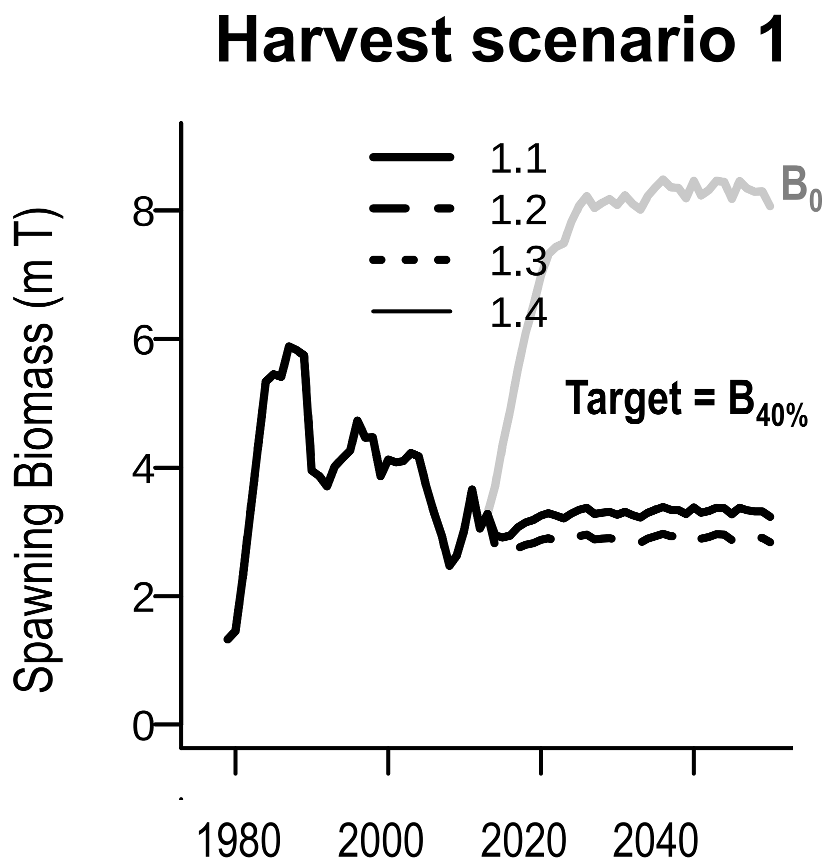


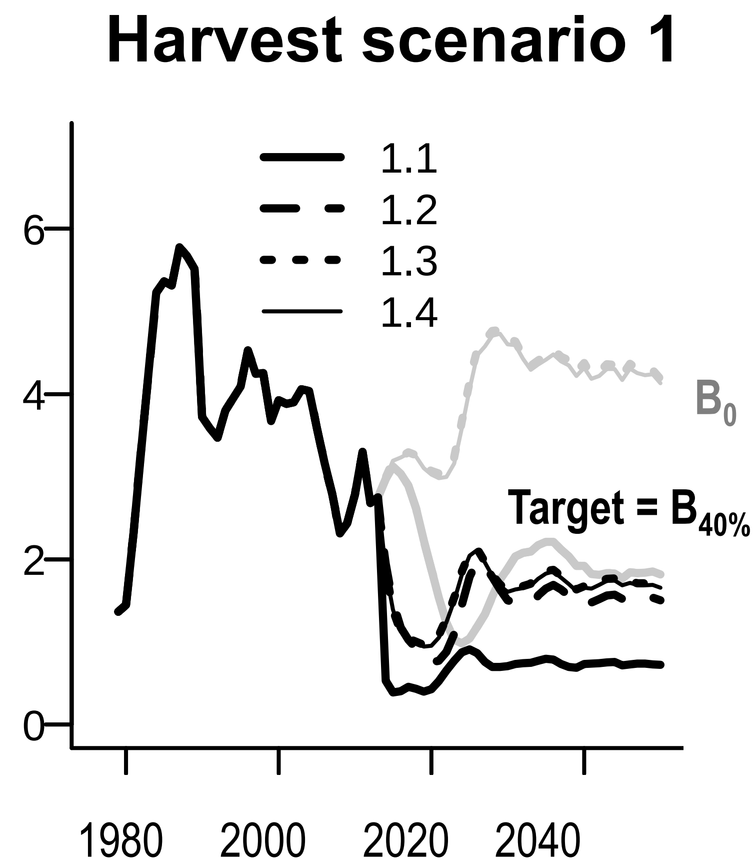
Find F that results in 40% unfished biomass in year 2100

Harvest

Single-species

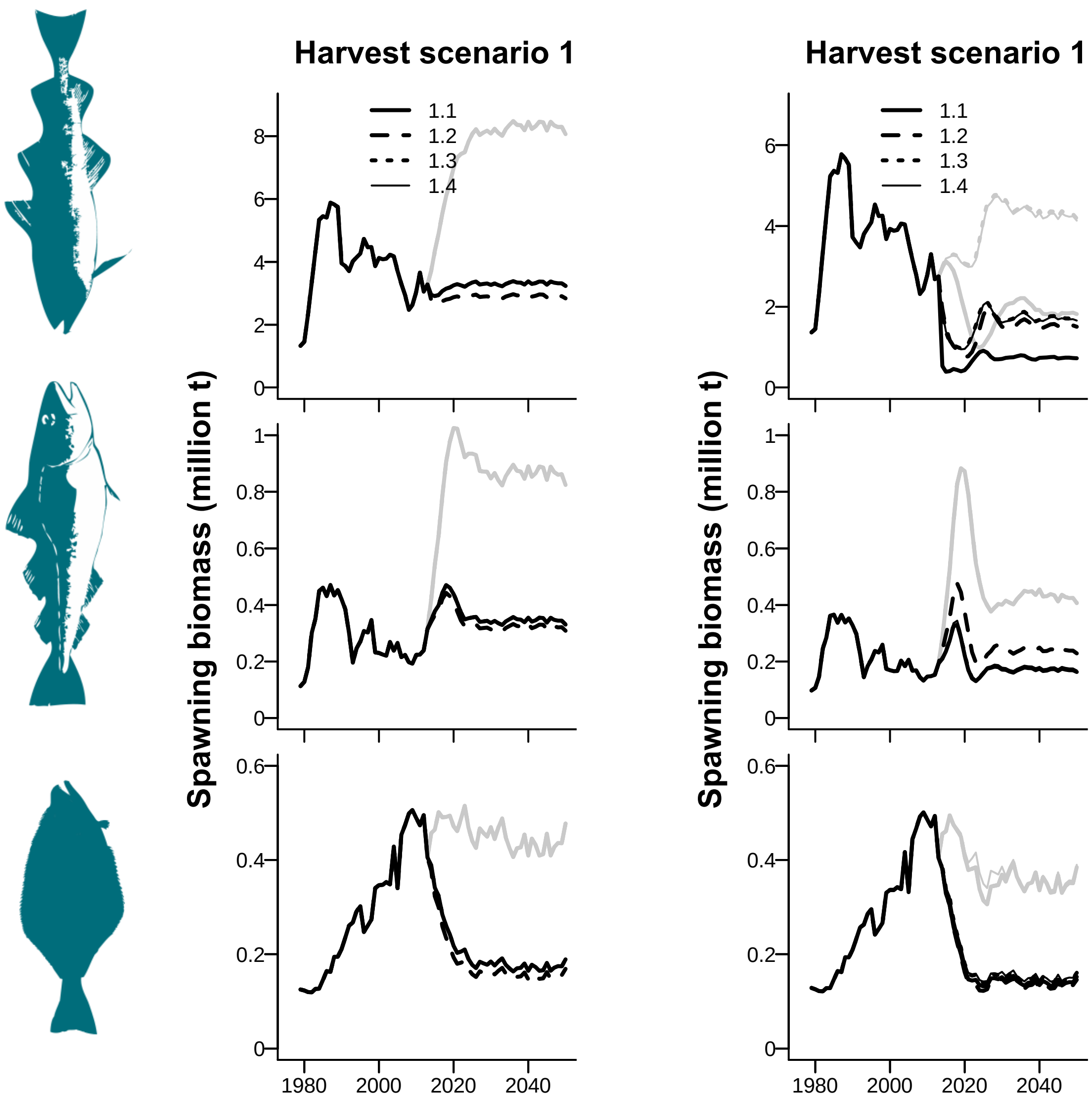
Multi-species





Holsman et al. *in press*

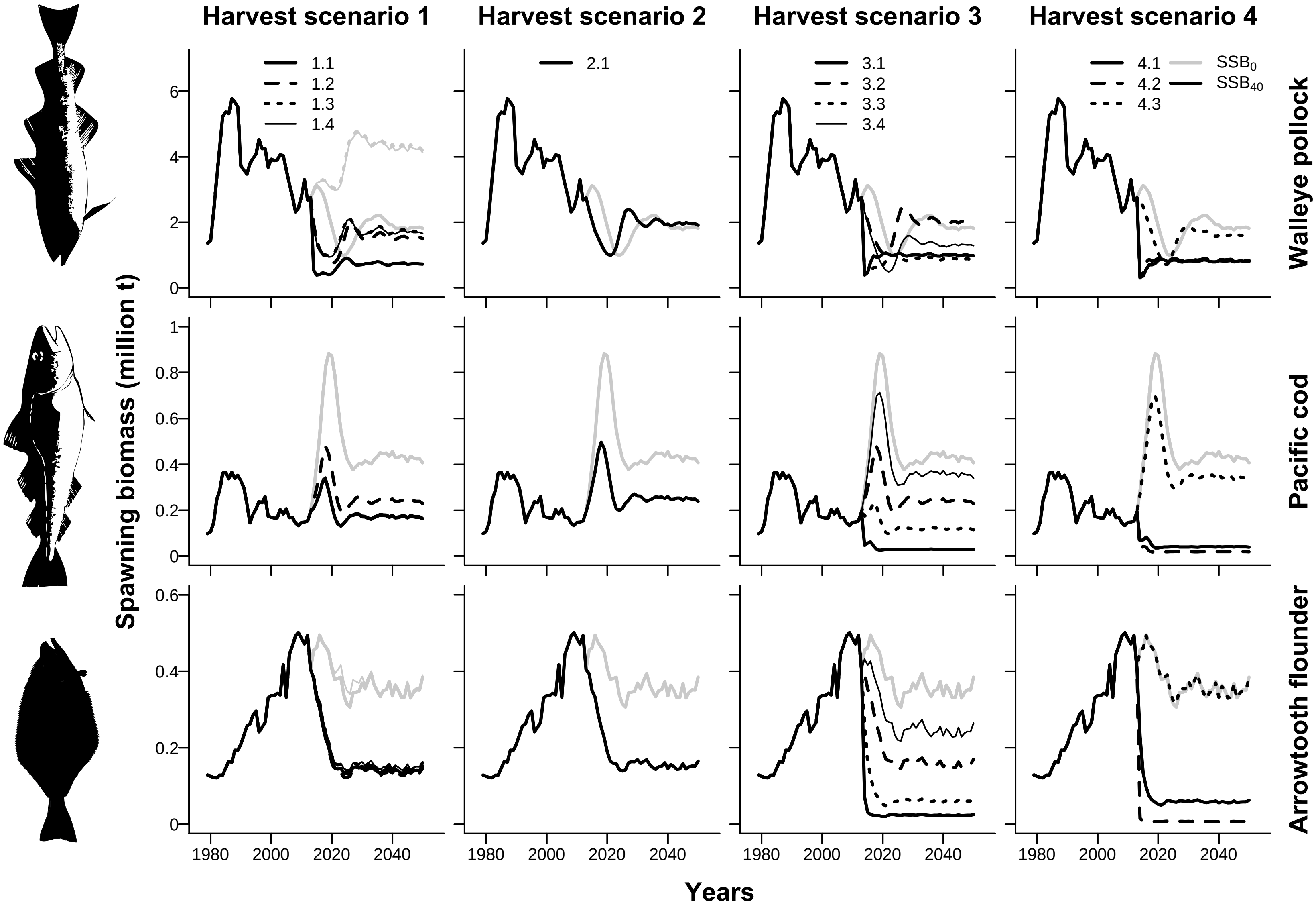
Single-species   Multi-species



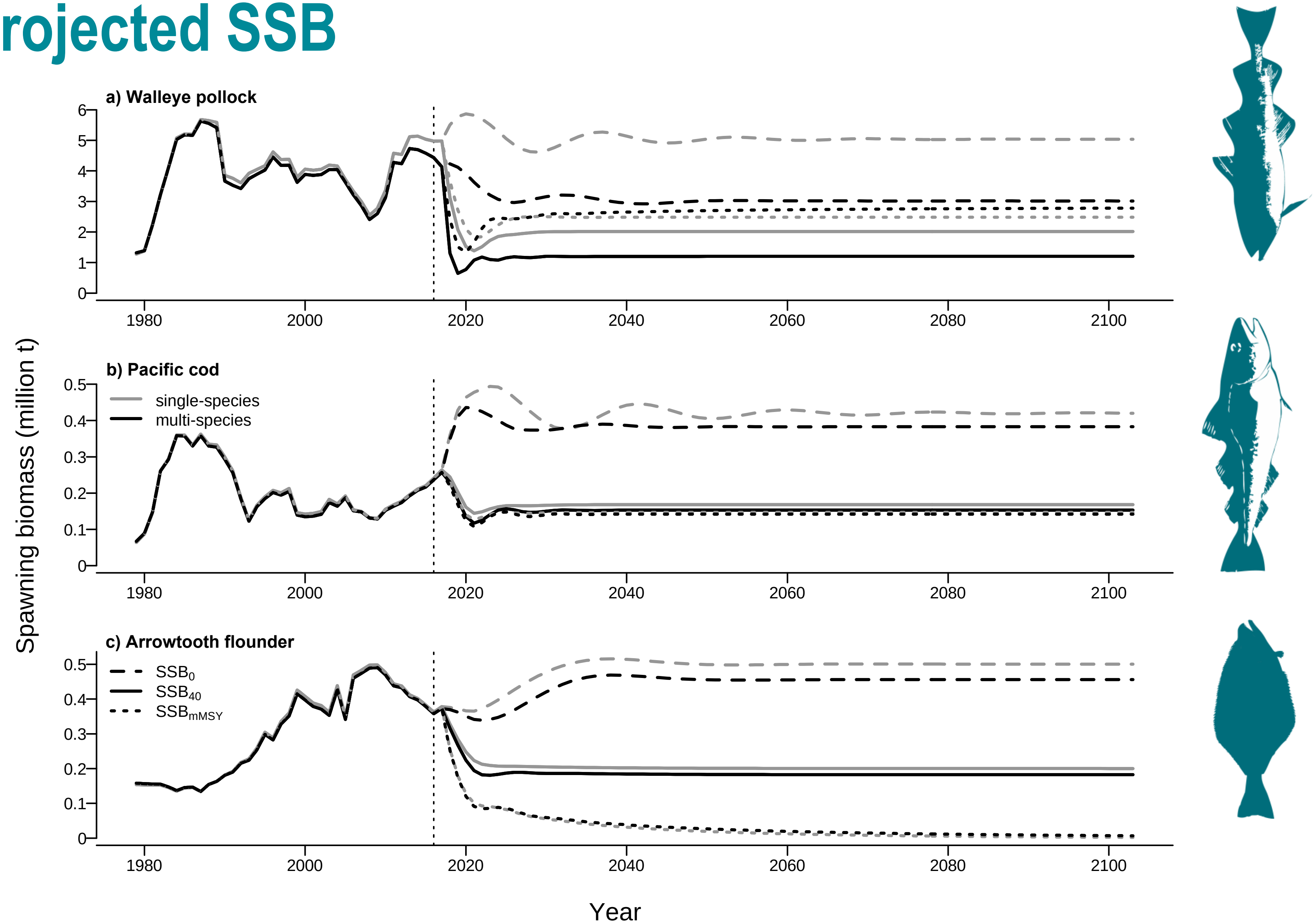
Differences between
Harvest Scenarios
Is greatest for prey spp

Holsman et al. *in press*

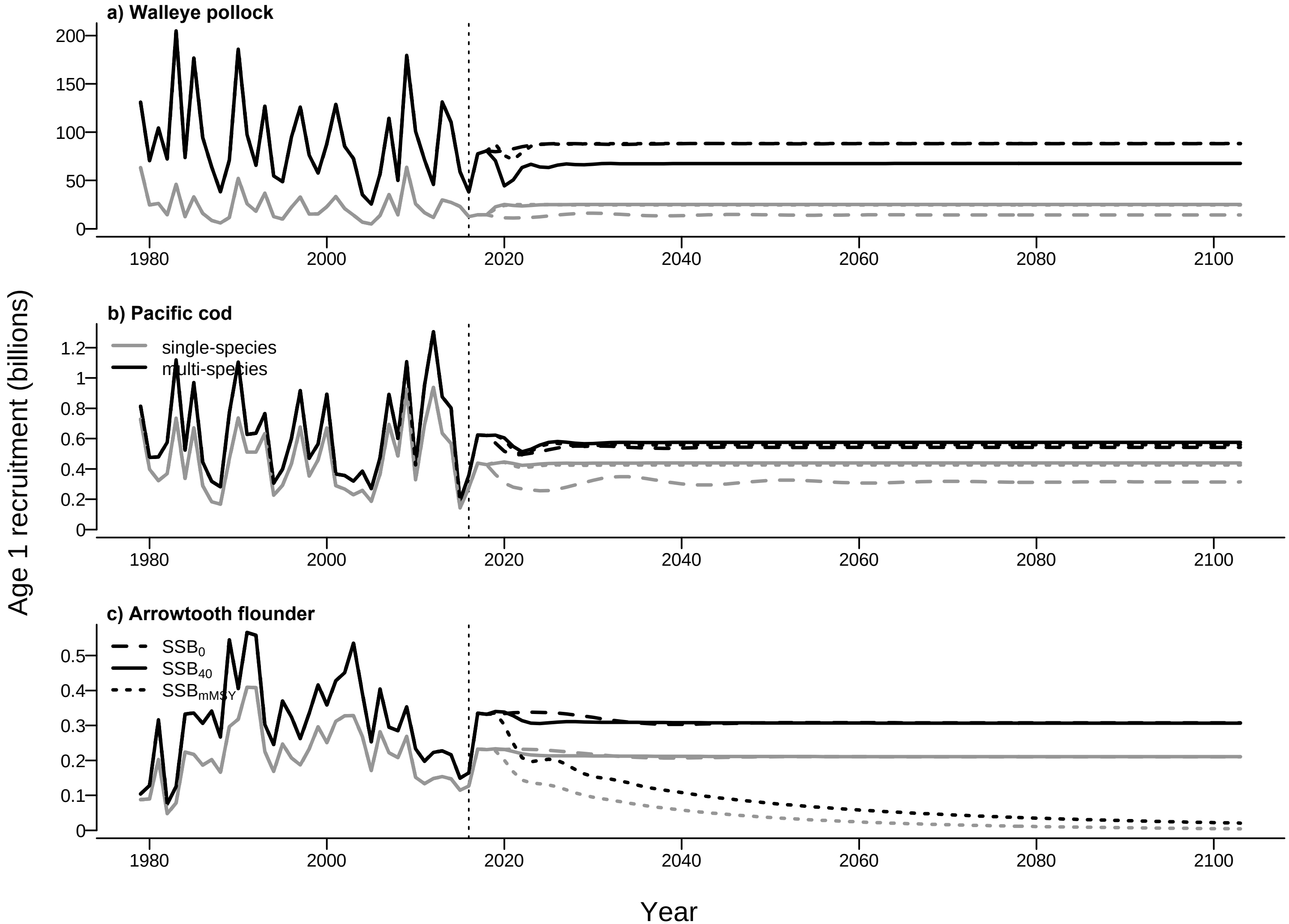
Multispecies control rules (Holsman et al. in press)



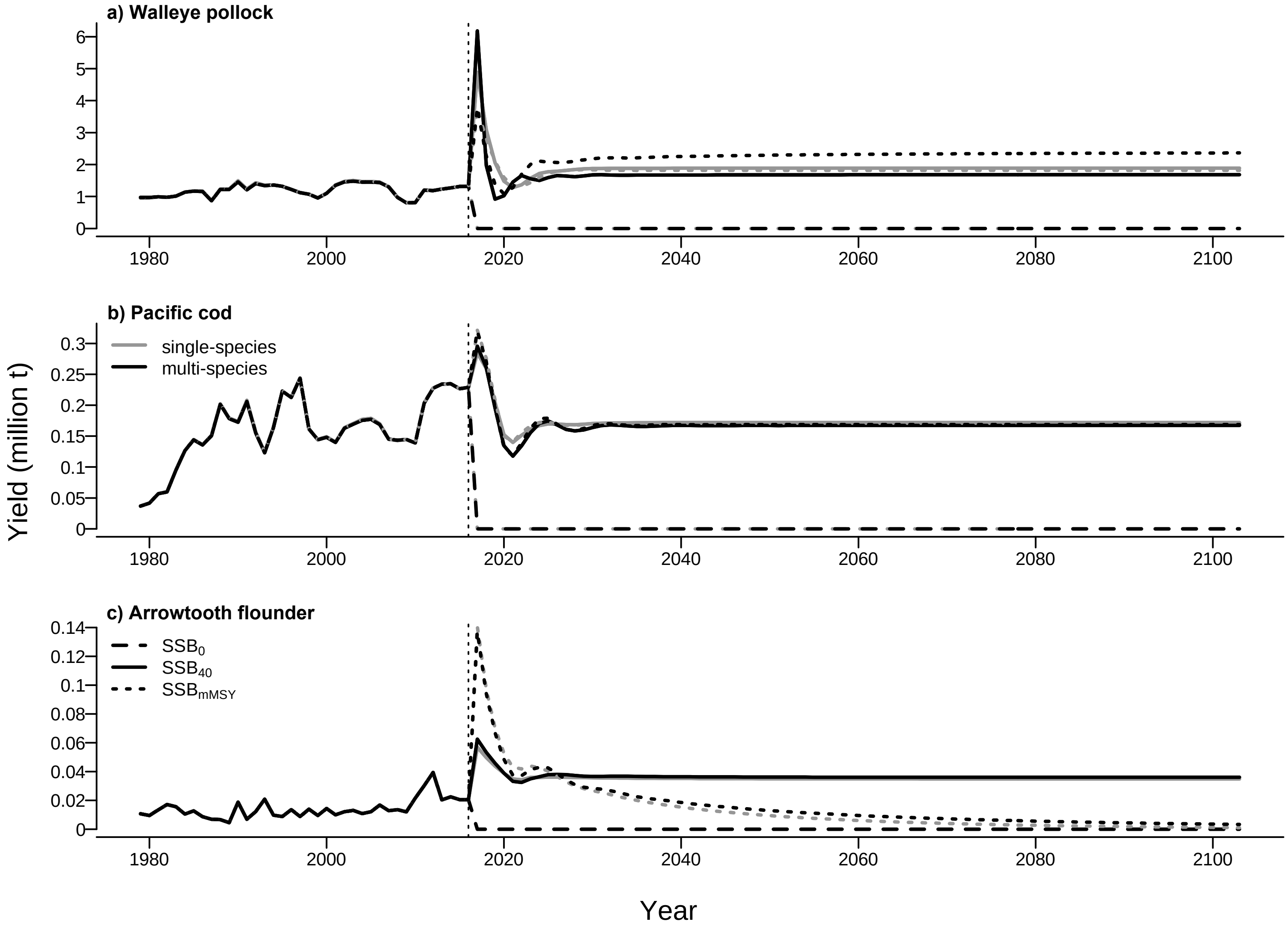
Projected SSB



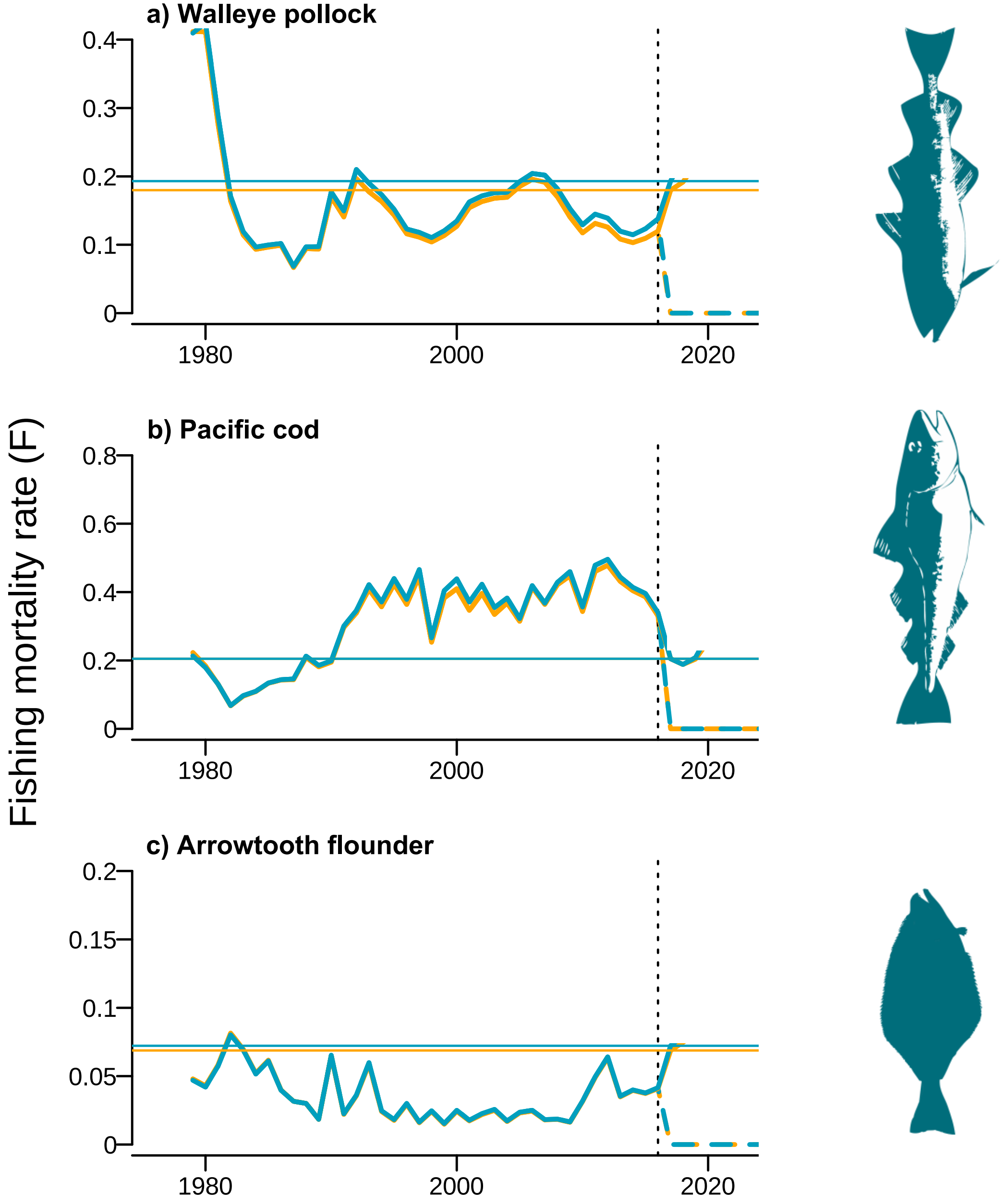
Projected Recruitment (age 1)



Projected Yield



max F_{ABC}



a) Walleye pollock
0.4
0.3
0.2
0.1
0
1980
2000
2020
b) Pacific cod
0.8
0.6
0.4
0.2
0
1980
2000
2020
Fishing mortality rate (F)
c) Arrowtooth flounder
0.2
0.15
0.1
0.05
0
1980
2000
2020

CEATTLE Applications

Photo: Mark Holsman

Ianelli et al. in press: Blended Forecasts

Deep-Sea Research II ∎ (∎∎∎∎) ∎∎∎–∎∎∎

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Multi-model inference for incorporating trophic and climate uncertainty into stock assessments

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A R T I C L E   I N F O

Keywords:
Model averaging
Model ensemble
Multi-species model

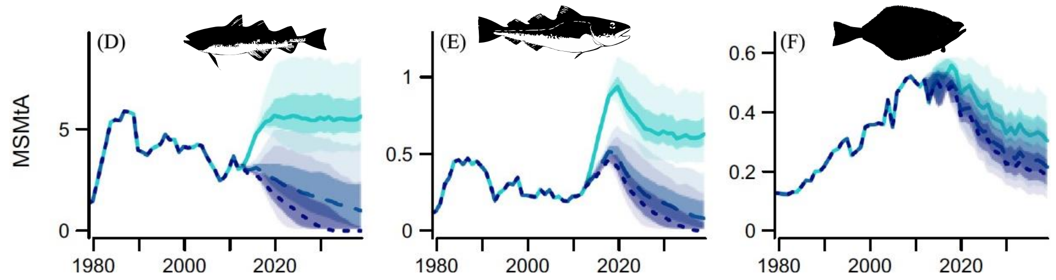
A B S T R A C T

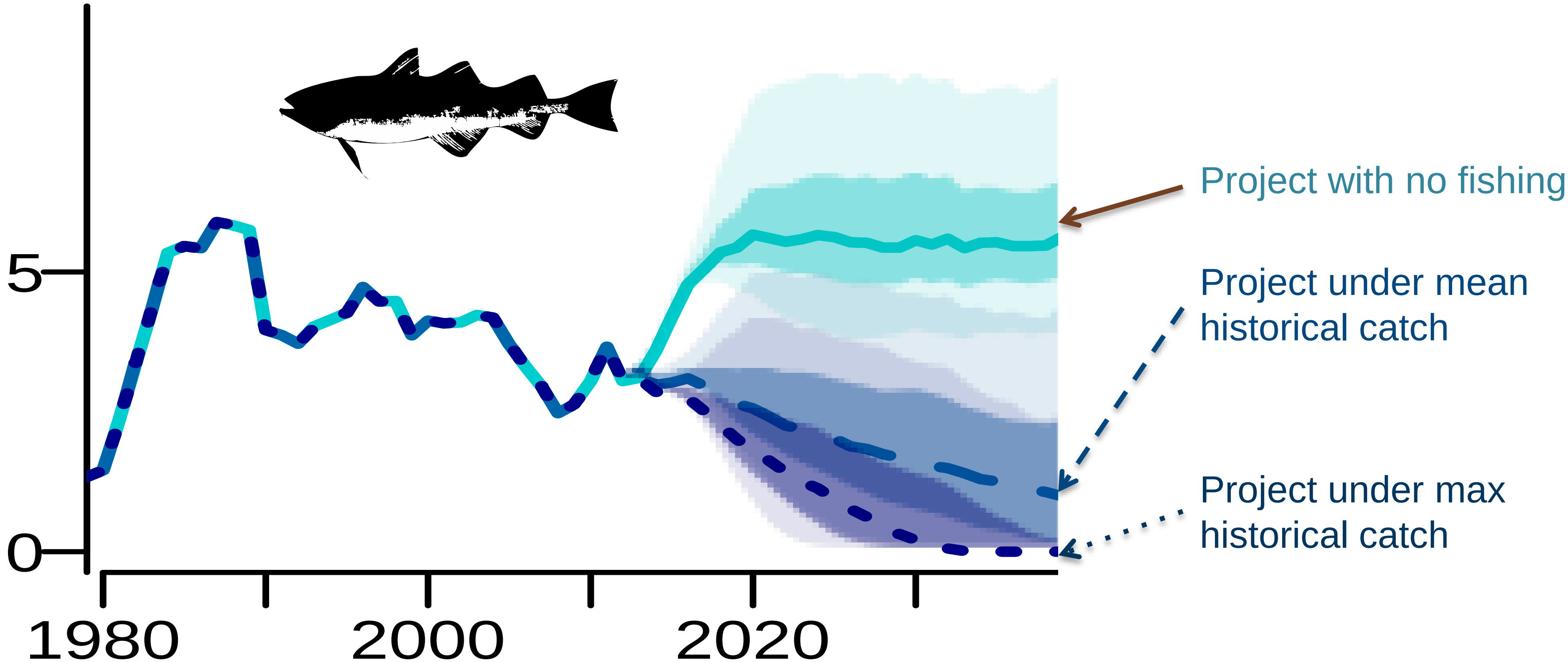
Ecosystem-based fisheries management (EBFM) approaches allow a broader and more extensive consideration of objectives than is typically possible with conventional single-species approaches. Ecosystem linkages may include trophic interactions and climate change effects on productivity for the relevant species within the system. Presently, models are evolving to include a comprehensive set of fishery and ecosystem information to address these broader management considerations. The increased

CEATTLE: Single-species

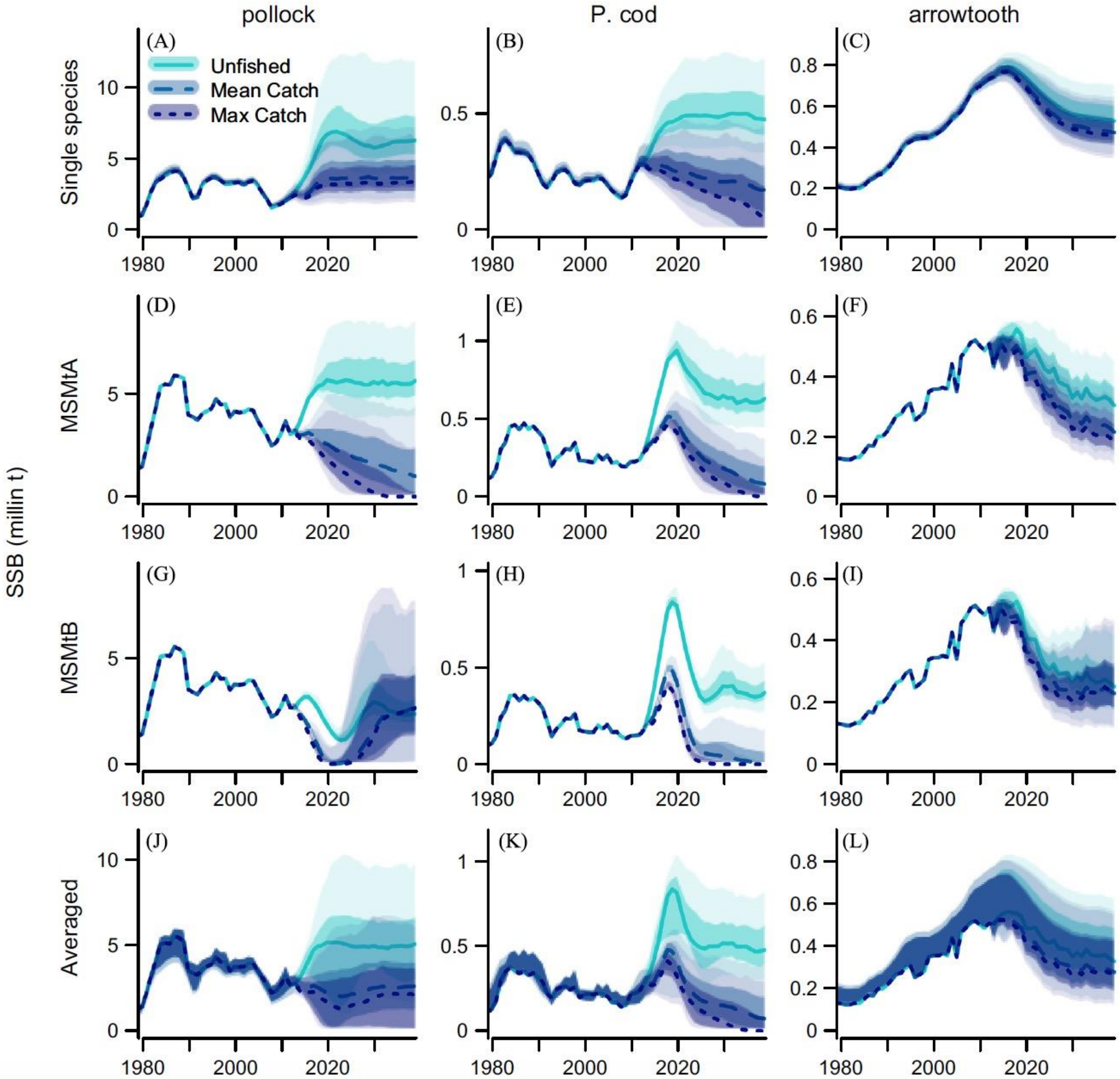
Mean R

Temp→W@A

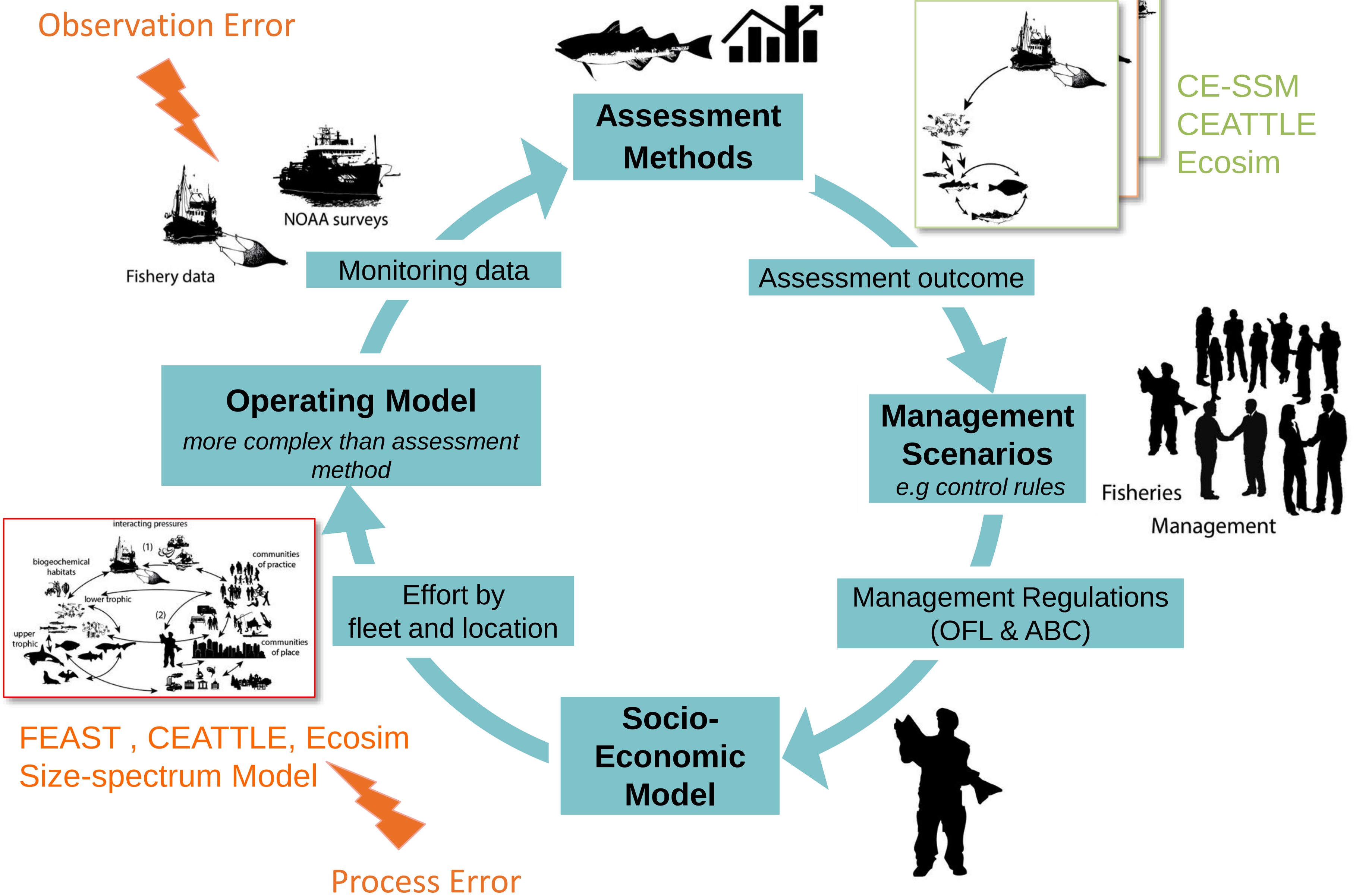




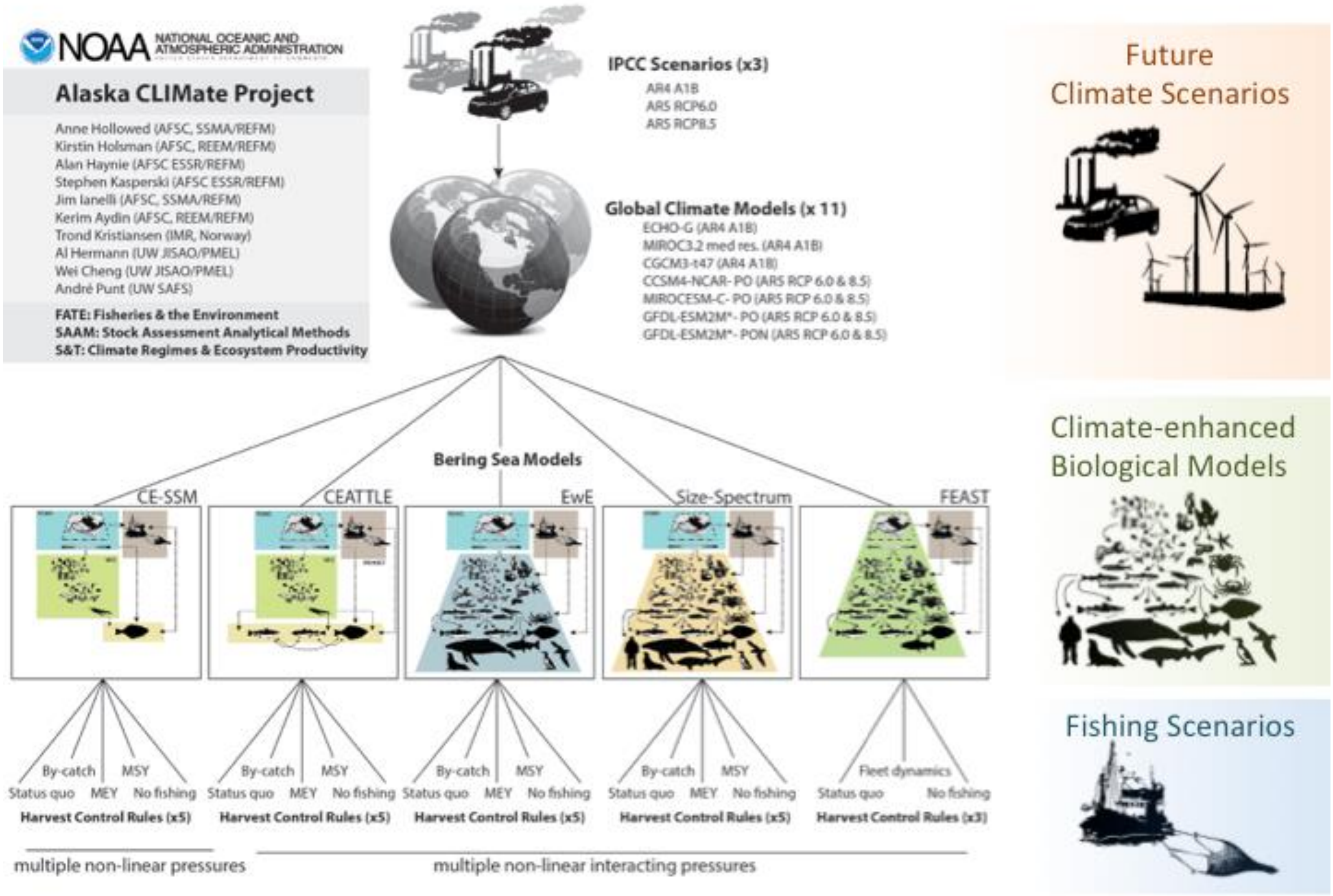
Blended results (all three models)



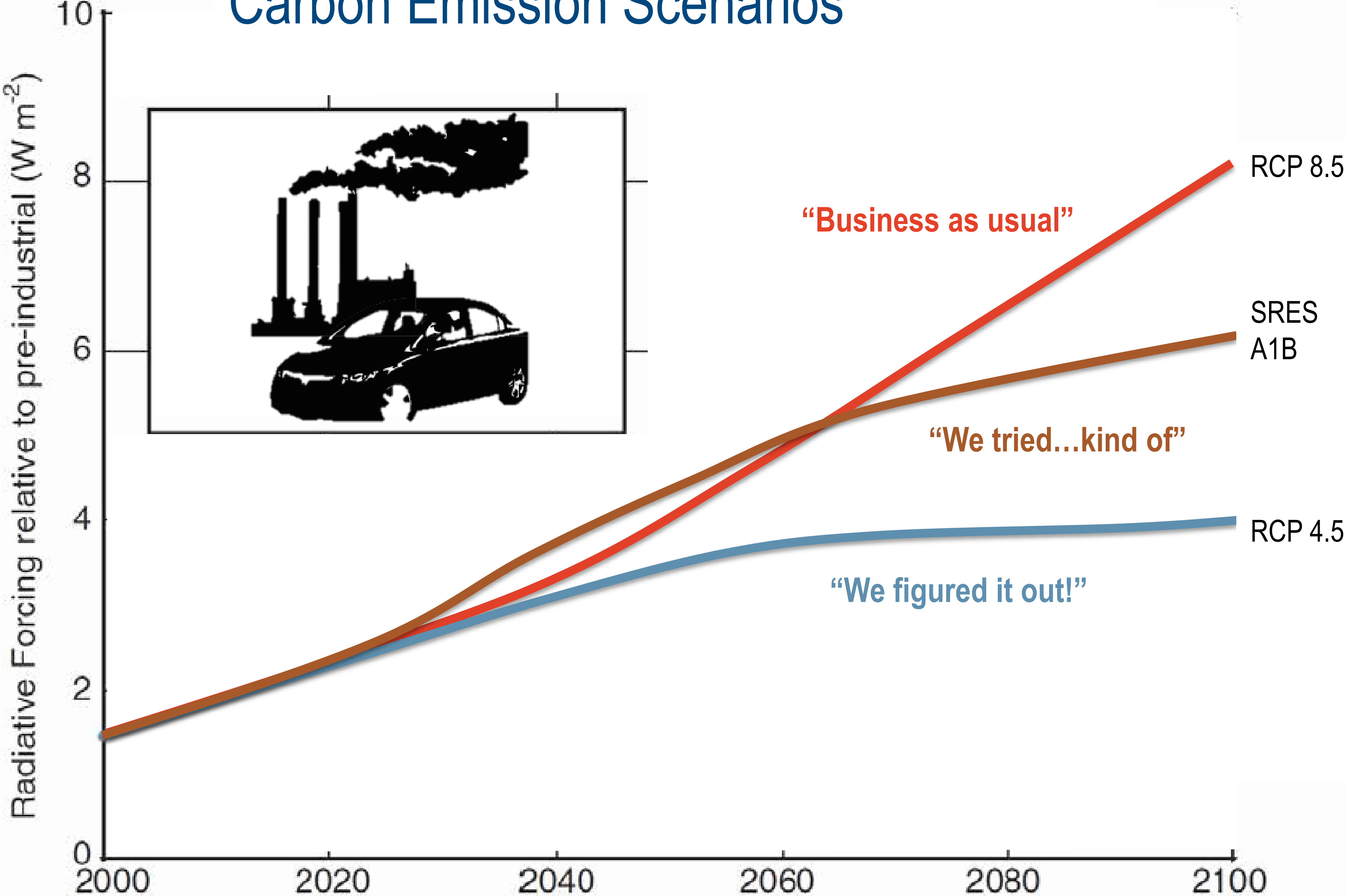
Management Strategy Evaluations



ACLIM: *Alaska Climate-change Integrated Modeling project*

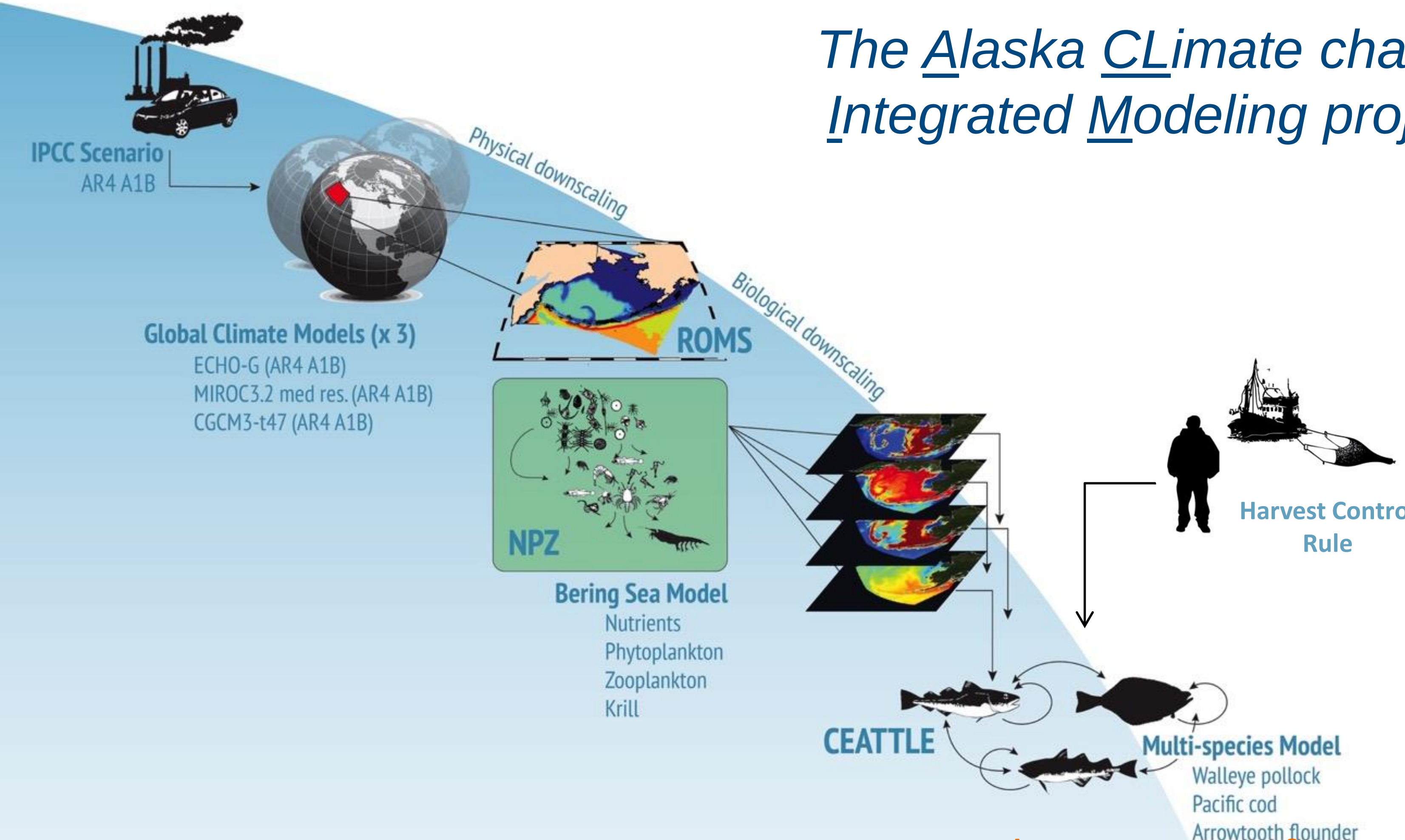


Carbon Emission Scenarios



ACLIM

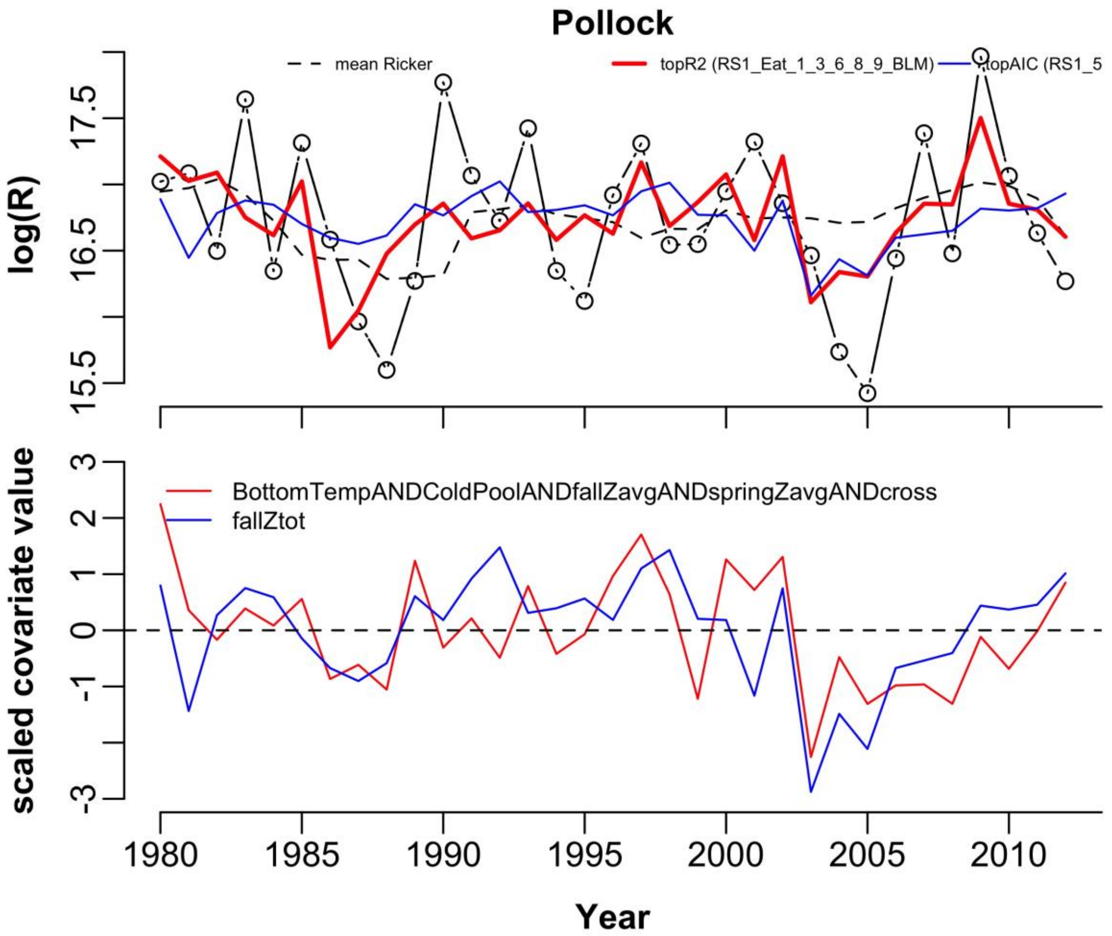
The Alaska CLimate change Integrated Modeling project



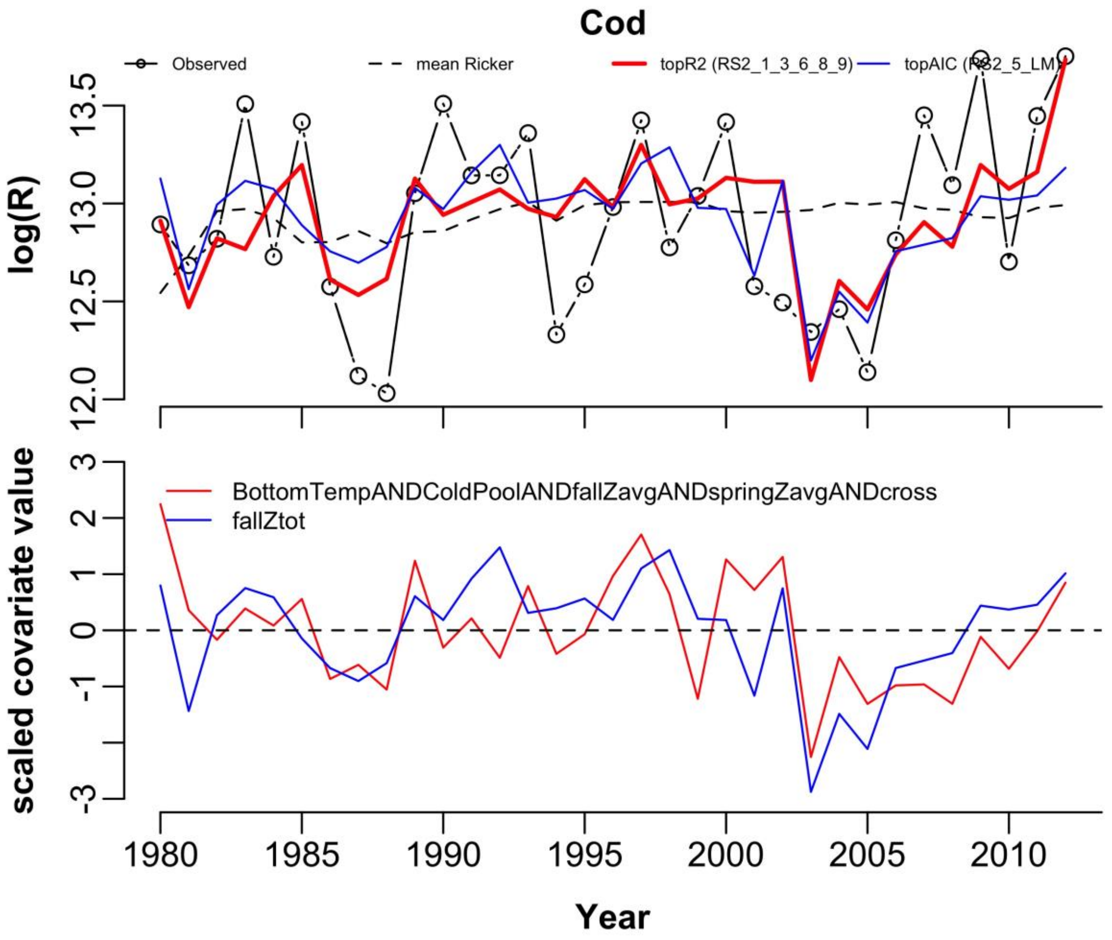
Holsman et al. in prep

Climate-specific Harvest & Population Projections

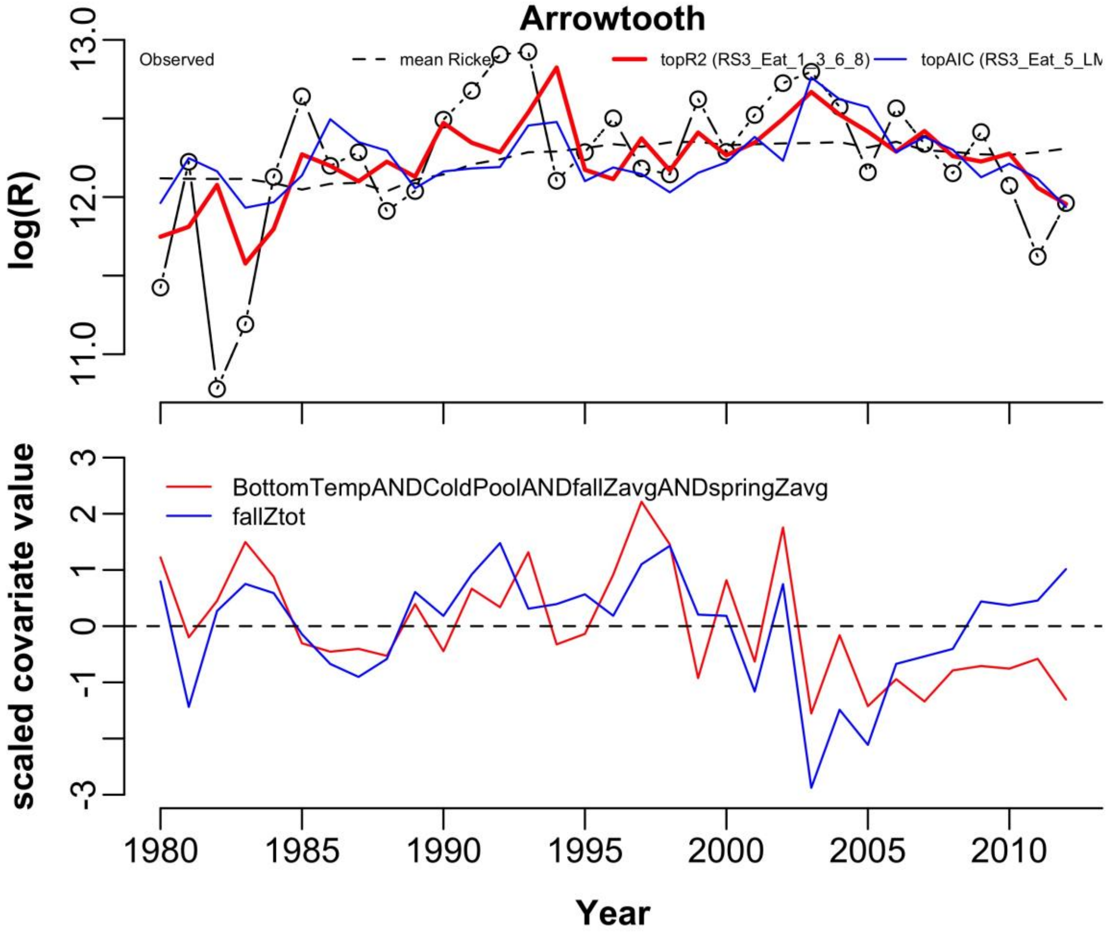
CEATTLE: Options

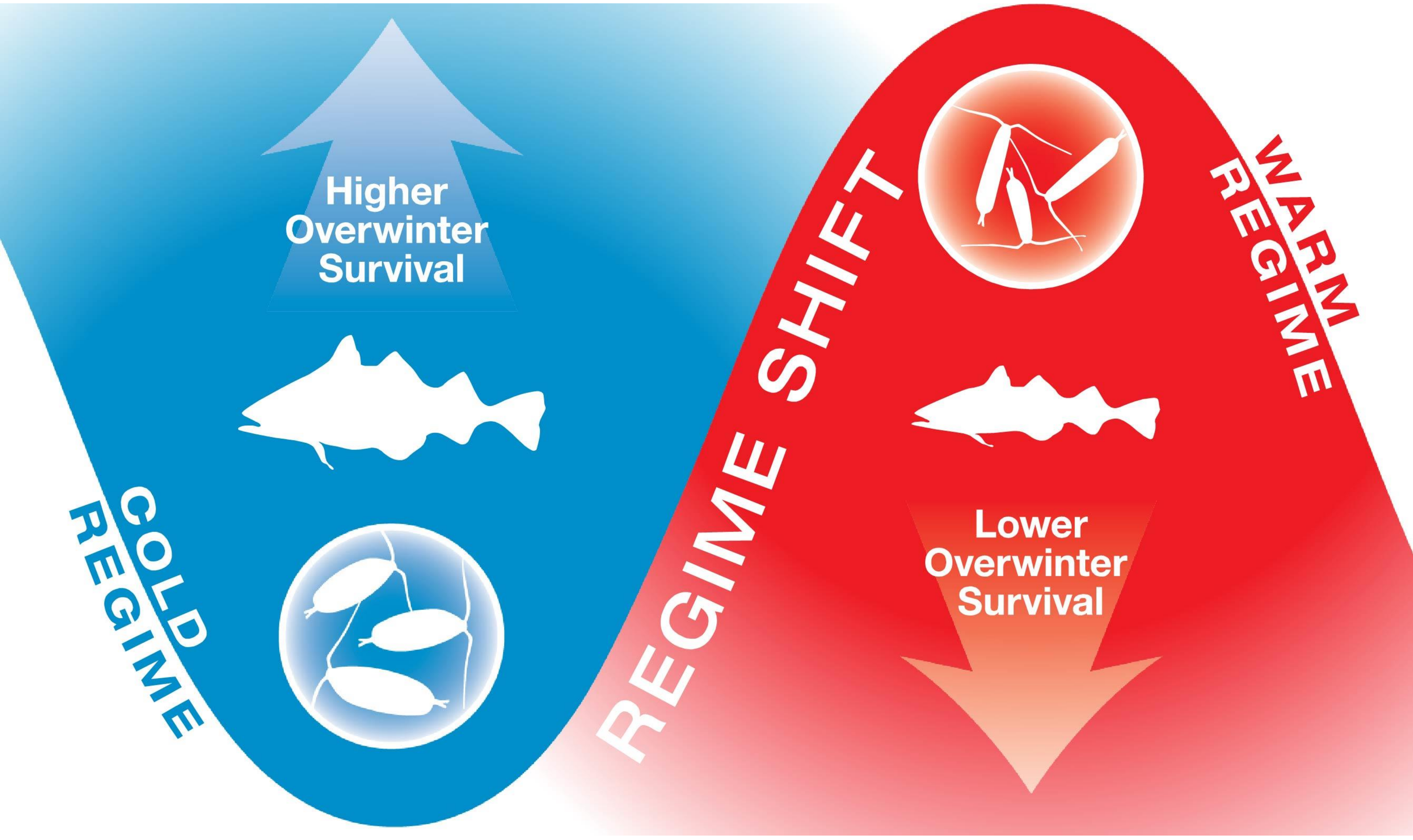


CEATTLE: Options



CEATTLE: Options





Slide courtesy of J. Duffy-Anderson

Thanks!

Photo: Mark Holsman

NOAA IEA program
FATE 13-07
SAAM 02

INTEGRATED ECOSYSTEM ASSESSMENT

"Behind these numbers lies, of course, an infinity of movements and of destinies."
– von Bertalanffy 1938

…and of people!

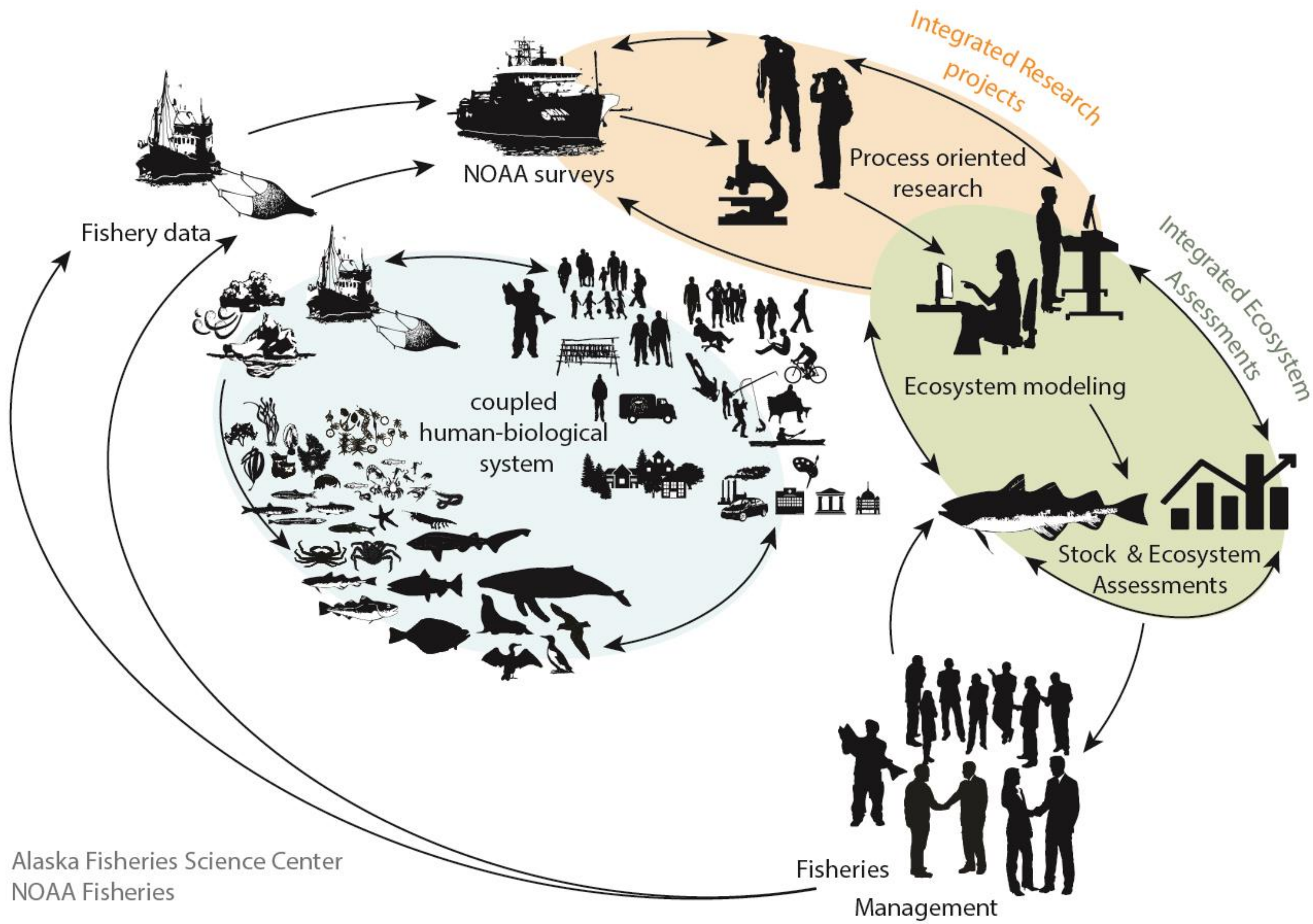
Jim Ianelli, K. Aydin, Ingrid Spies, Grant Thompson

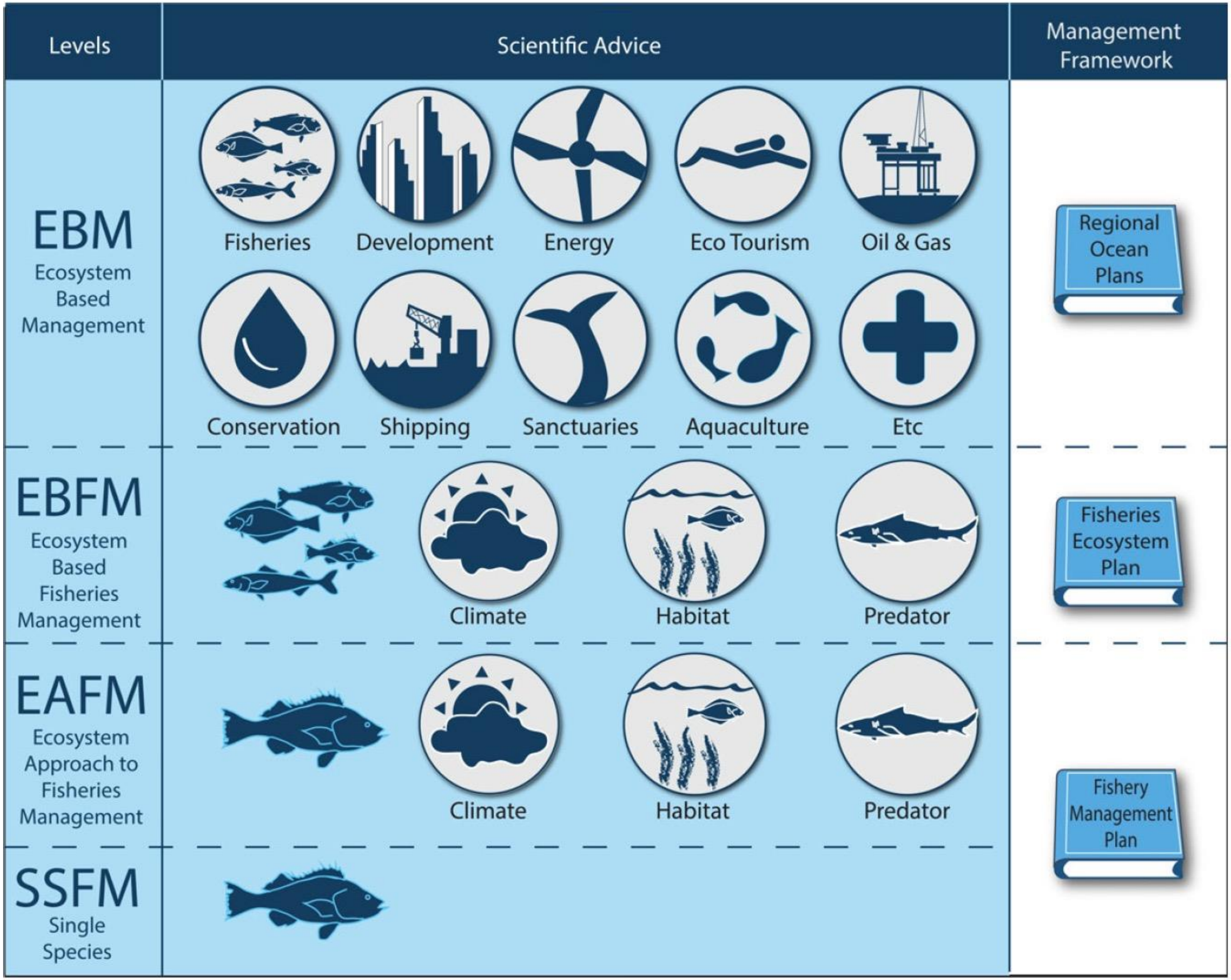
Stephanie Zador, Paul Spence, A. Hobday, A. Hollowed,, Isaac Kaplan, Troy Buckley, Matt Baker, Buck Stockhausen, P. Sean McDonald

Mark Holsman (Brother; photos)

END

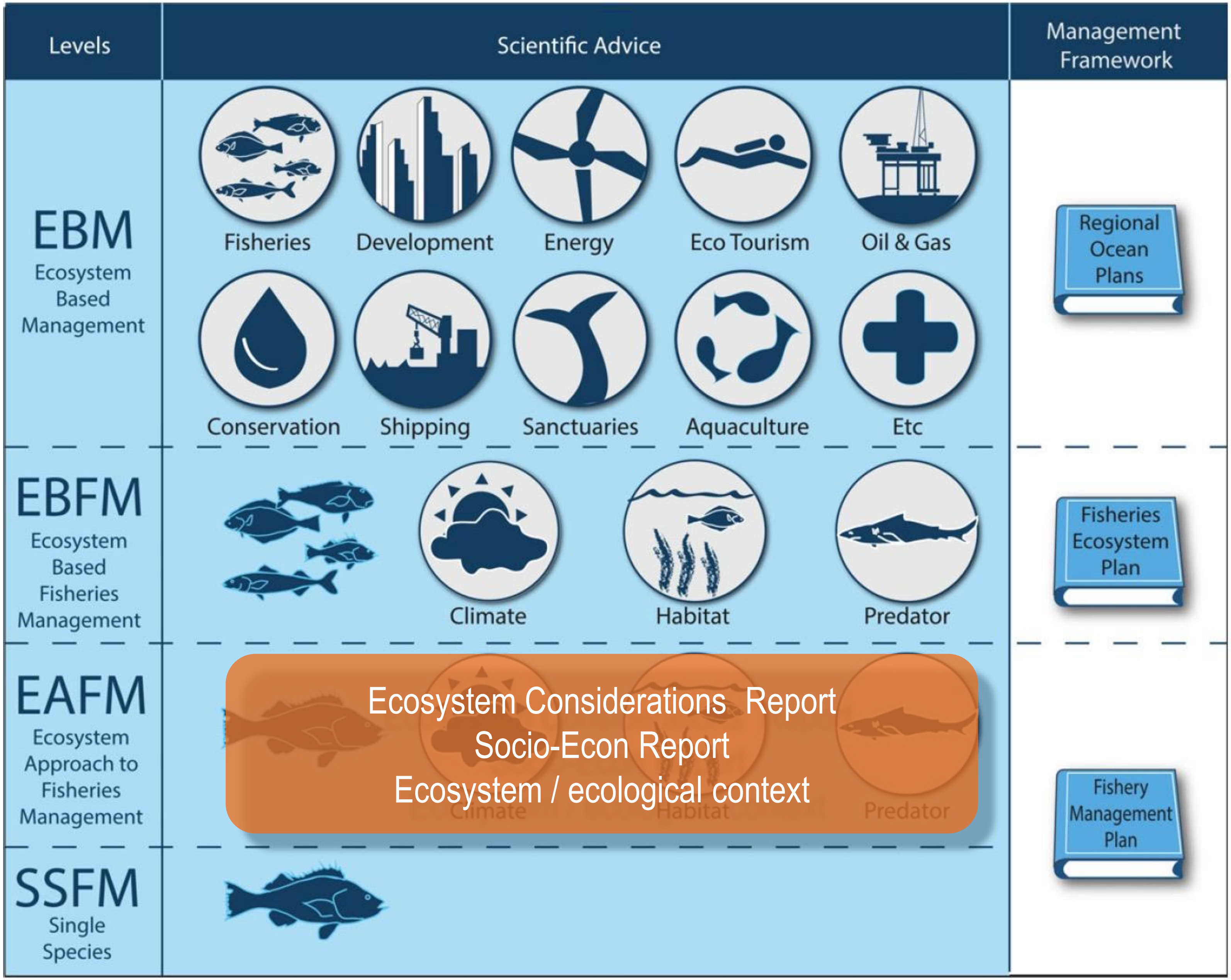
AFSC Ecosystem Based Fisheries Management



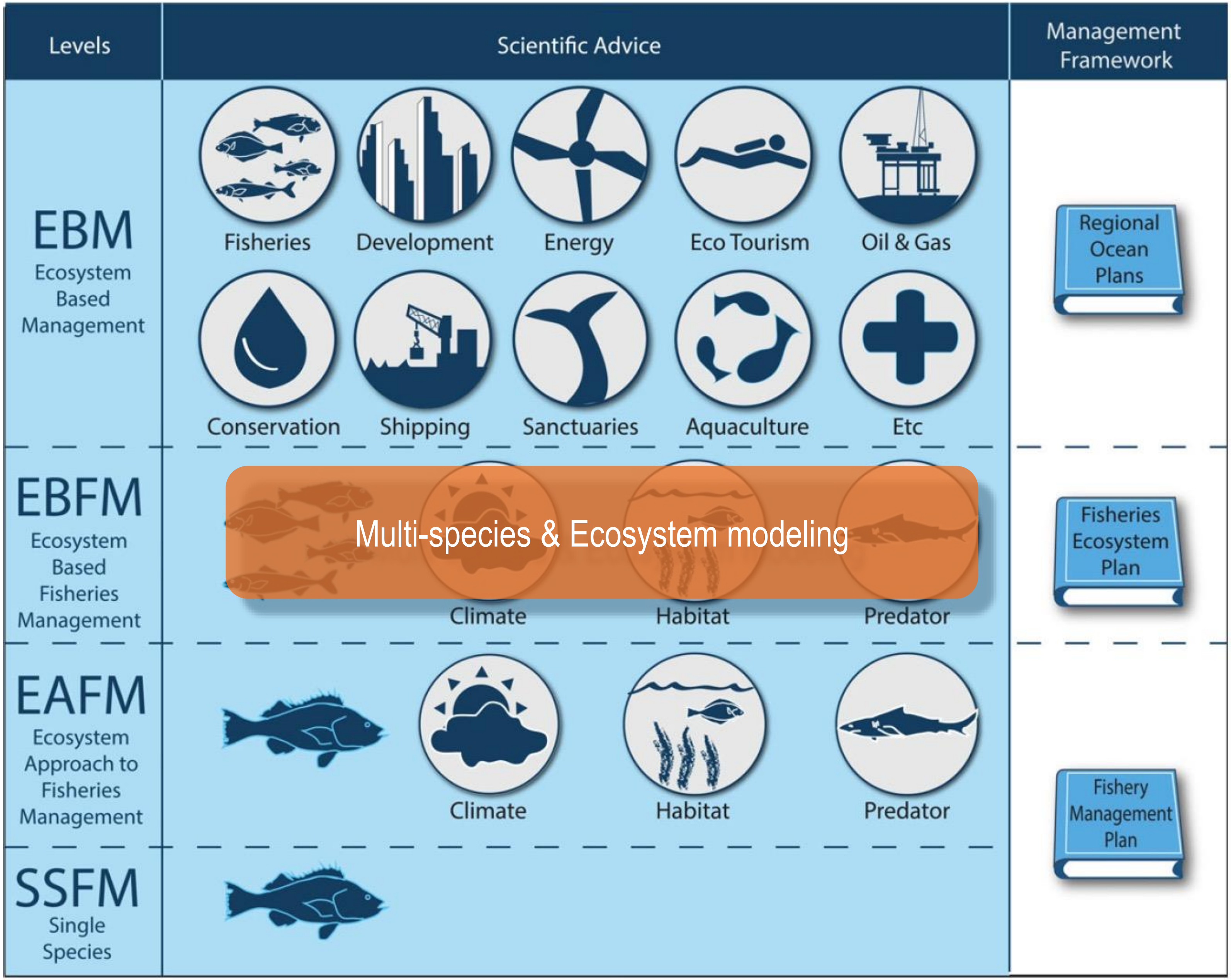


NOAA FISHERIES

Dolan et al. (2016) ICES J Mar Sci 73(4):1042-1050



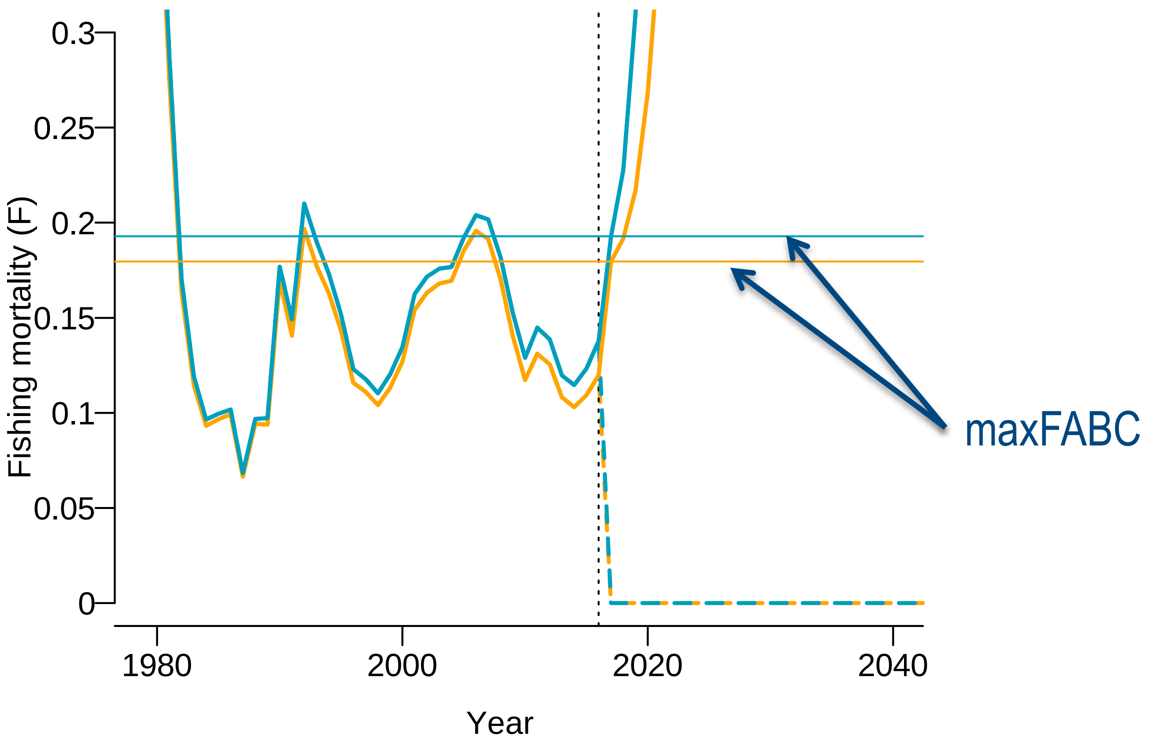
Dolan et al. (2016) ICES J Mar Sci 73(4):1042-1050



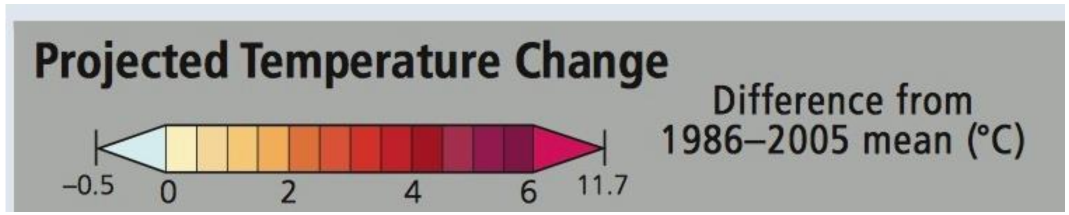
Dolan et al. (2016) ICES J Mar Sci 73(4):1042-1050

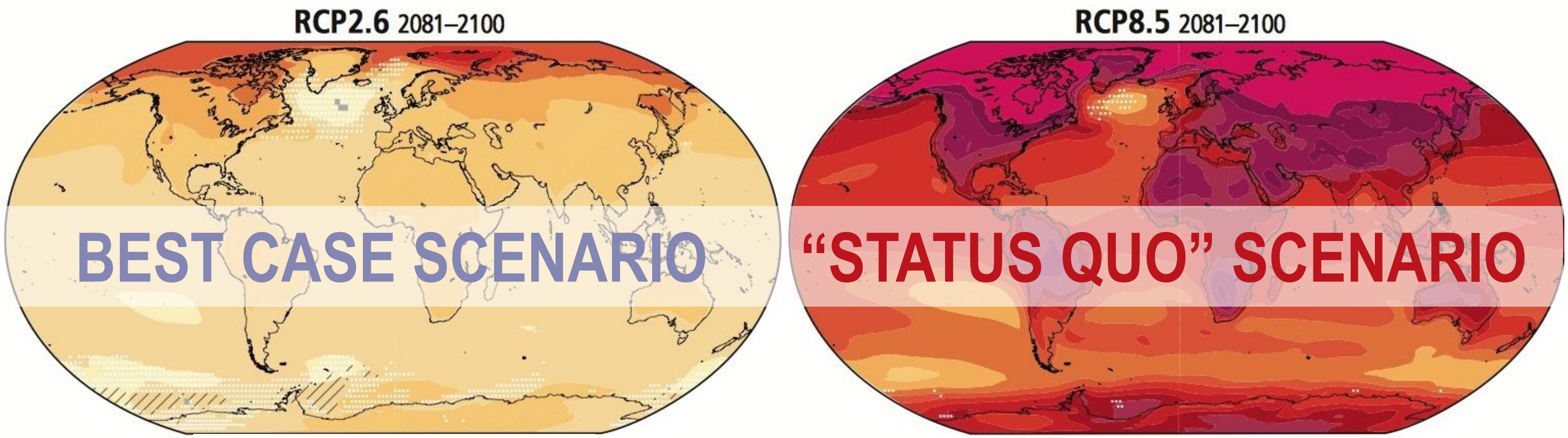
When to use multi-species models:

- When there is sufficient data/information
- When expert advice is not enough
- Relationships are non-linear and complex
- Species are fully exploited
- Pressures/impacts are high, efficiency is needed
- Scope for fishery response to management is high
- When management is ready for tradeoffs analysis


0.3
0.25
0.2
0.15
0.1
0.05
0
Fishing mortality (F)
1980
2000
2020
2040
Year
maxFABC

Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report



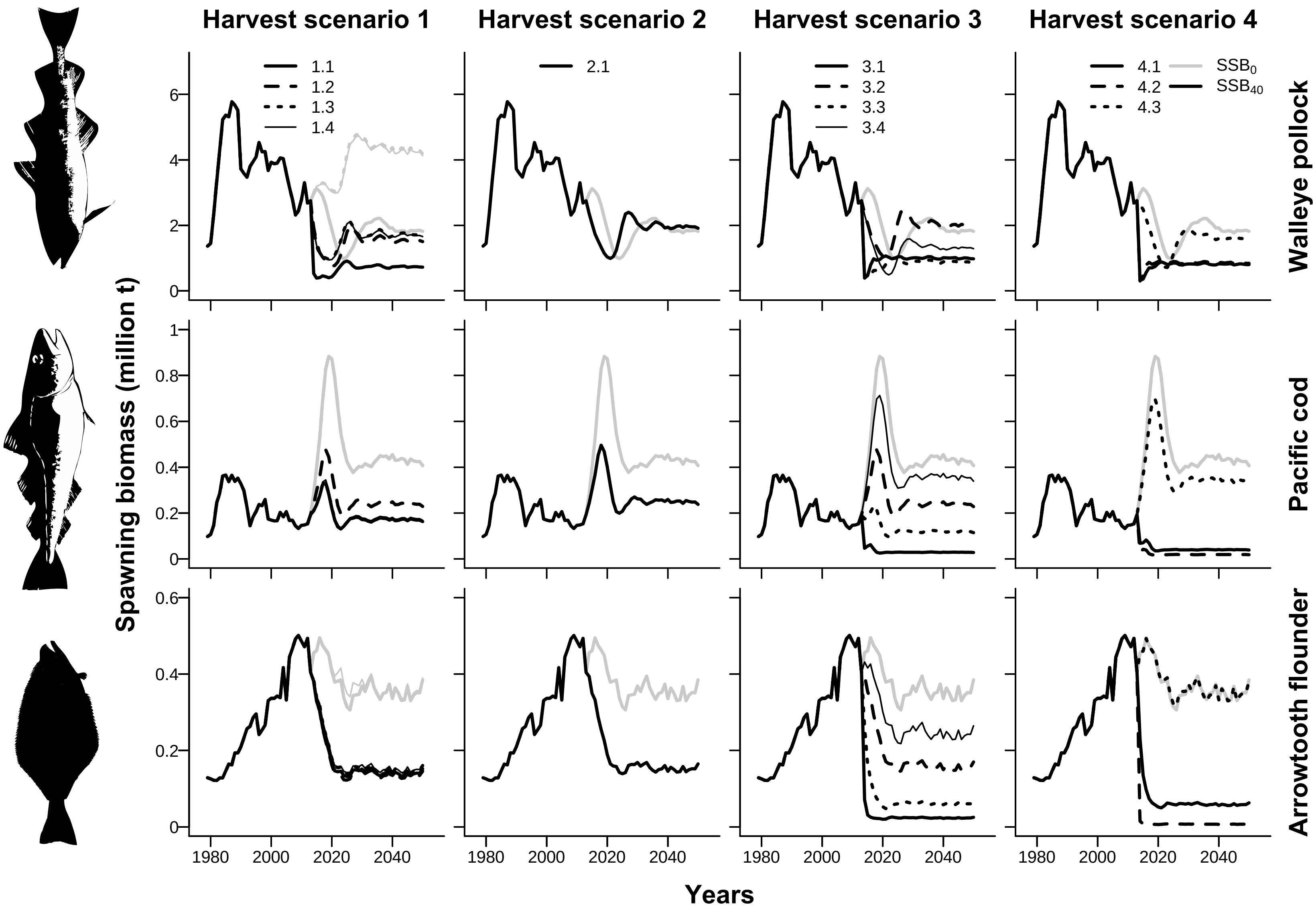


“We figured it out!”	“Business as usual”
+ 1.8 ºC	**+4 ºC**

Table 4
Components of the likelihood fusnction for each species i of age j in year y. EBS: Eastern Bering Sea. See Tables 2–4 for parameter definitions.

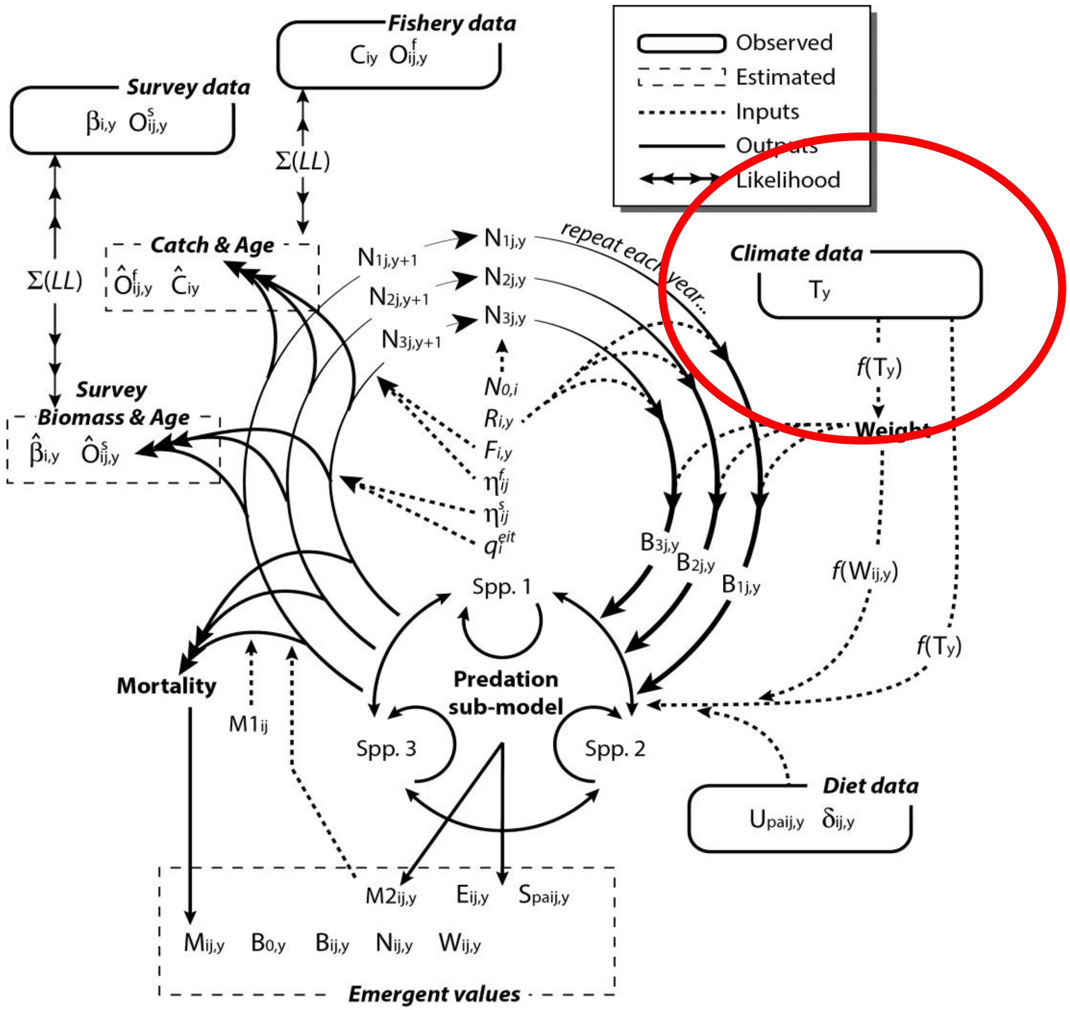
Description	Equation	Data source	
Data components			
BT survey biomass	$\sum_i \sum_y \frac{\left[\ln\left(\beta^s_{i,y}\right)-\ln\left(\hat{\beta}^s_{i,y}\right)\right]^2}{2\sigma^2_{s,i}}$	NFMS annual EBS BT survey (1979–2012)	T4.1
BT survey age composition	$-\sum_i n_i \sum_y \sum_j \left(O^s_{ij,y}+v\right)\ln\left(\hat{O}^s_{ij,y}+v\right)$	NFMS annual EBS BT survey (1979–2012)	T4.2
EIT survey biomass	$\sum_y \frac{\left[\ln(\beta^{eit}_y)-\ln\left(\hat{\beta}^{eit}_y\right)\right]^2}{2\sigma^2_{eit}}, \sigma_{eit}=0.2$	Pollock acoustic trawl survey (1979–2012)	T4.3
EIT age composition	$-n\sum_y \sum_j \left(O^{eit}_{1j,y}+v\right)\ln\left(\hat{O}^{eit}_{1j,y}+v\right)$	Pollock acoustic trawl survey (1979–2012)	T.4.4
Total catch	$\sum_i \sum_y \frac{\left[\ln\left(C^*_{i,y}\right)-\ln\left(C^*_{i,y}\right)\right]^2}{2\sigma^2_C}, \sigma_C=0.05$	Fishery observer data (1979–2012)	T.4.5
Fishery age composition	$-\sum_i n_i \sum_y \sum_j \left(O^f_{ij,y}+v\right)\ln\left(\hat{O}^f_{ij,y}+v\right)$	Fishery observer data (1979–2012)	T4.6
Penalties			
Fishery selectivity	$\sum_i \sum_j^{A_i-1} \chi\cdot\left[\ln\left(\frac{\eta^f_{ij}}{\eta^f_{ij+1}}\right)-\ln\left(\frac{\eta^f_{ij+1}}{\eta^f_{ij+2}}\right)\right]^2, \chi=\begin{cases}20\text{, if} & \eta^f_{ij}>\eta^f_{ji+1}\\ 0\text{, if} & \eta^f_{ij}\leq\eta^f_{ij+1}\end{cases}$		T4.7
Priors			
	$\sum_i \sum_y \left(\tau_{i,y}\right)^2$		T4.8
	$\sum_i \sum_y \left(N_{0,ij}\right)^2$		T4.9
	$\sum_i \sum_y \left(\varepsilon_{i,y}\right)^2$		T4.10

$v=0.001$.



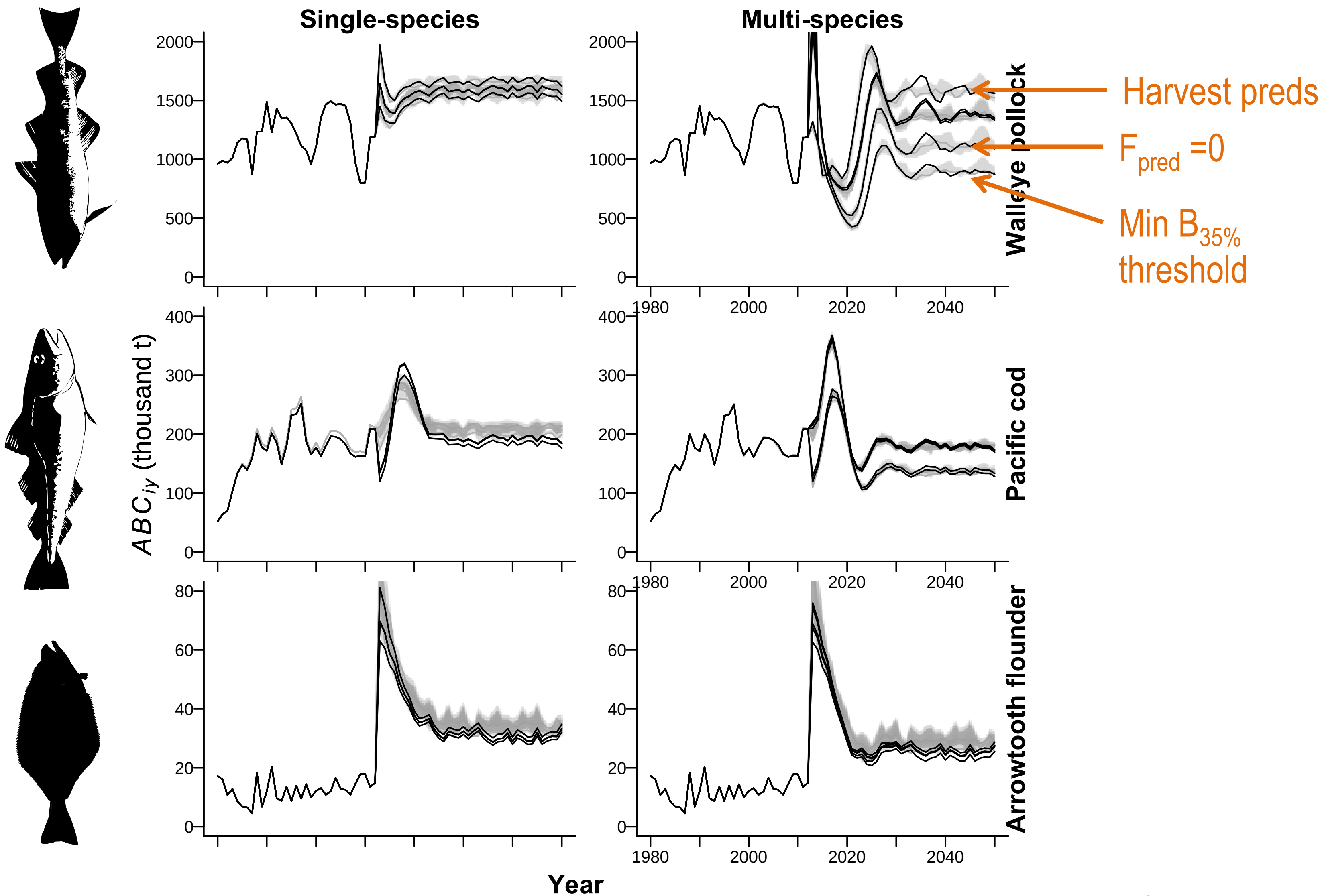
Harvest scenario 1
Harvest scenario 2
Harvest scenario 3
Harvest scenario 4
1.1
1.2
1.3
1.4
2.1
3.1
3.2
3.3
3.4
4.1
4.2
4.3
SSB0
SSB40
Walleye pollock
Pacific cod
Arrowtooth flounder
Spawning biomass (million t)
Years

Weight at Age

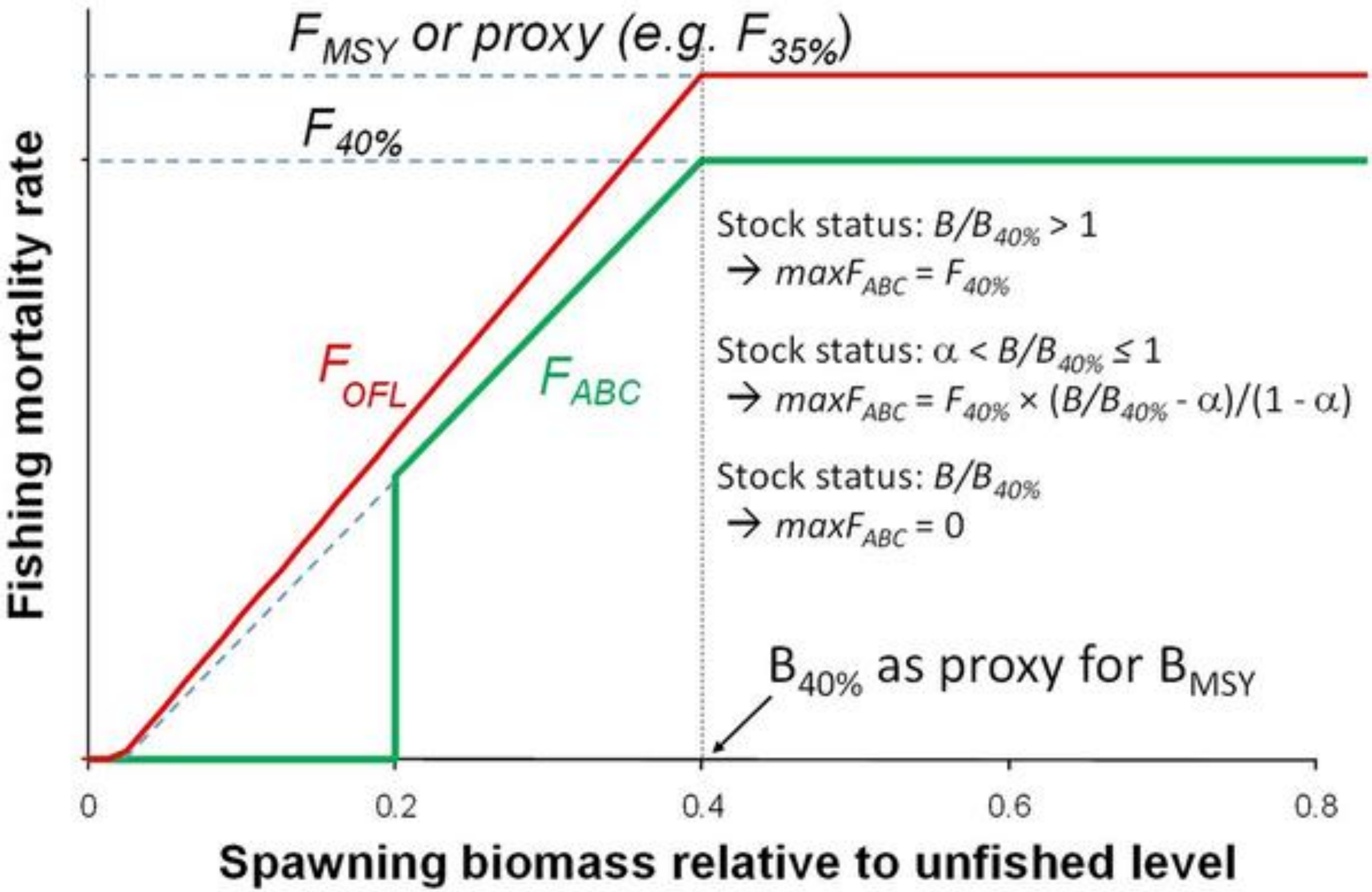


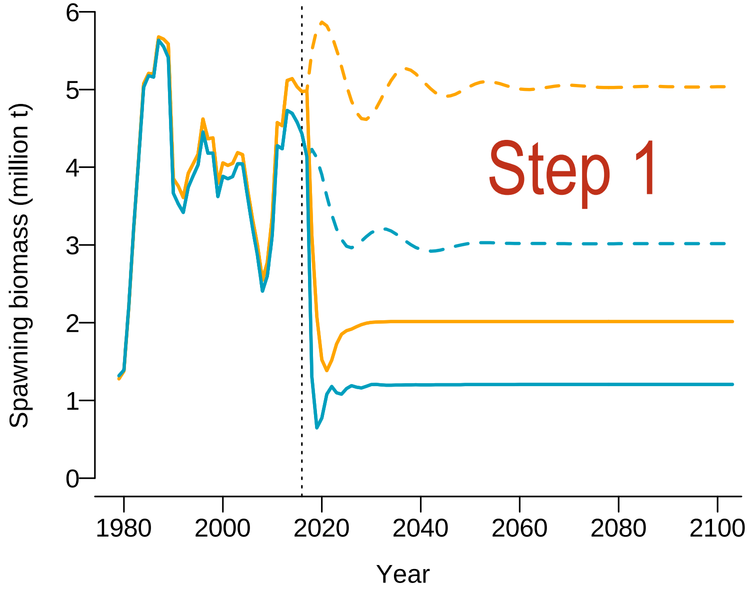
Evaluate projection sensitivity

Temp effect << F effect

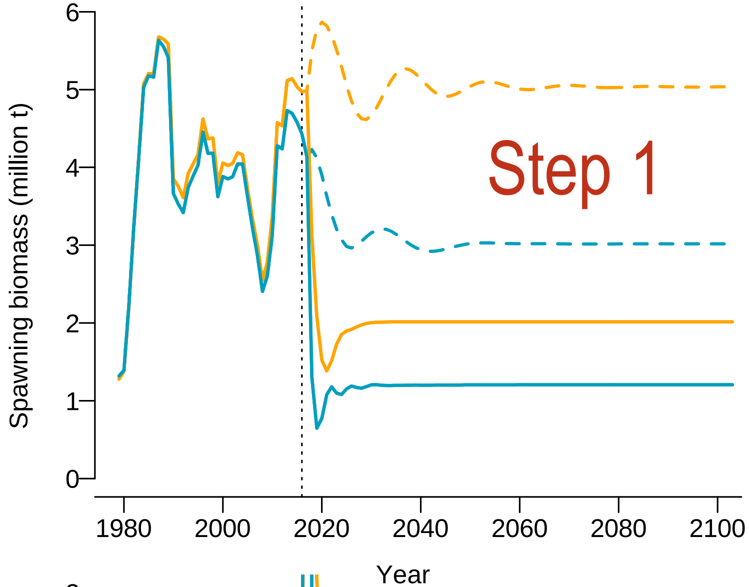


Holsman et al. in press. Deep Sea Res II

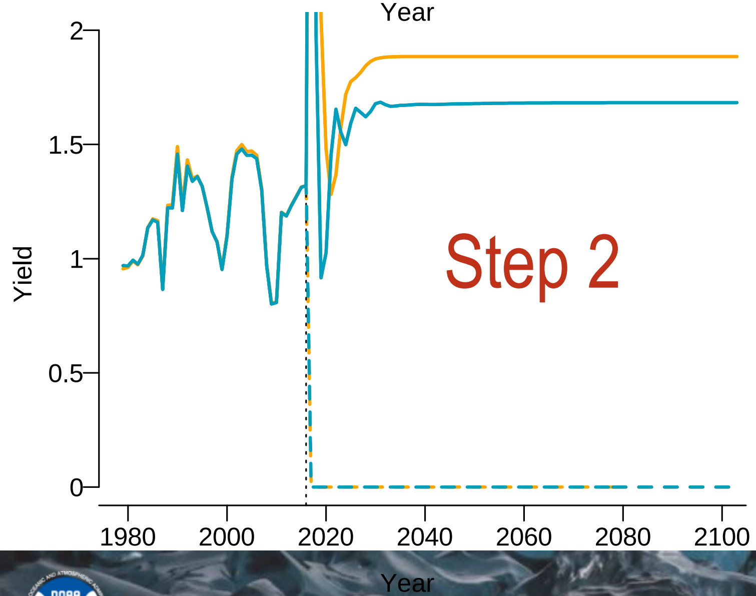

F_{MSY} or proxy (e.g. $F_{35\%}$)
$F_{40\%}$
F_{OFL}
F_{ABC}
Stock status: $B/B_{40\%} > 1$
→ $maxF_{ABC} = F_{40\%}$
Stock status: $\alpha < B/B_{40\%} \leq 1$
→ $maxF_{ABC} = F_{40\%} \times (B/B_{40\%} - \alpha)/(1 - \alpha)$
Stock status: $B/B_{40\%}$
→ $maxF_{ABC} = 0$
$B_{40\%}$ as proxy for B_{MSY}
Fishing mortality rate
0
0.2
0.4
0.6
0.8
Spawning biomass relative to unfished level



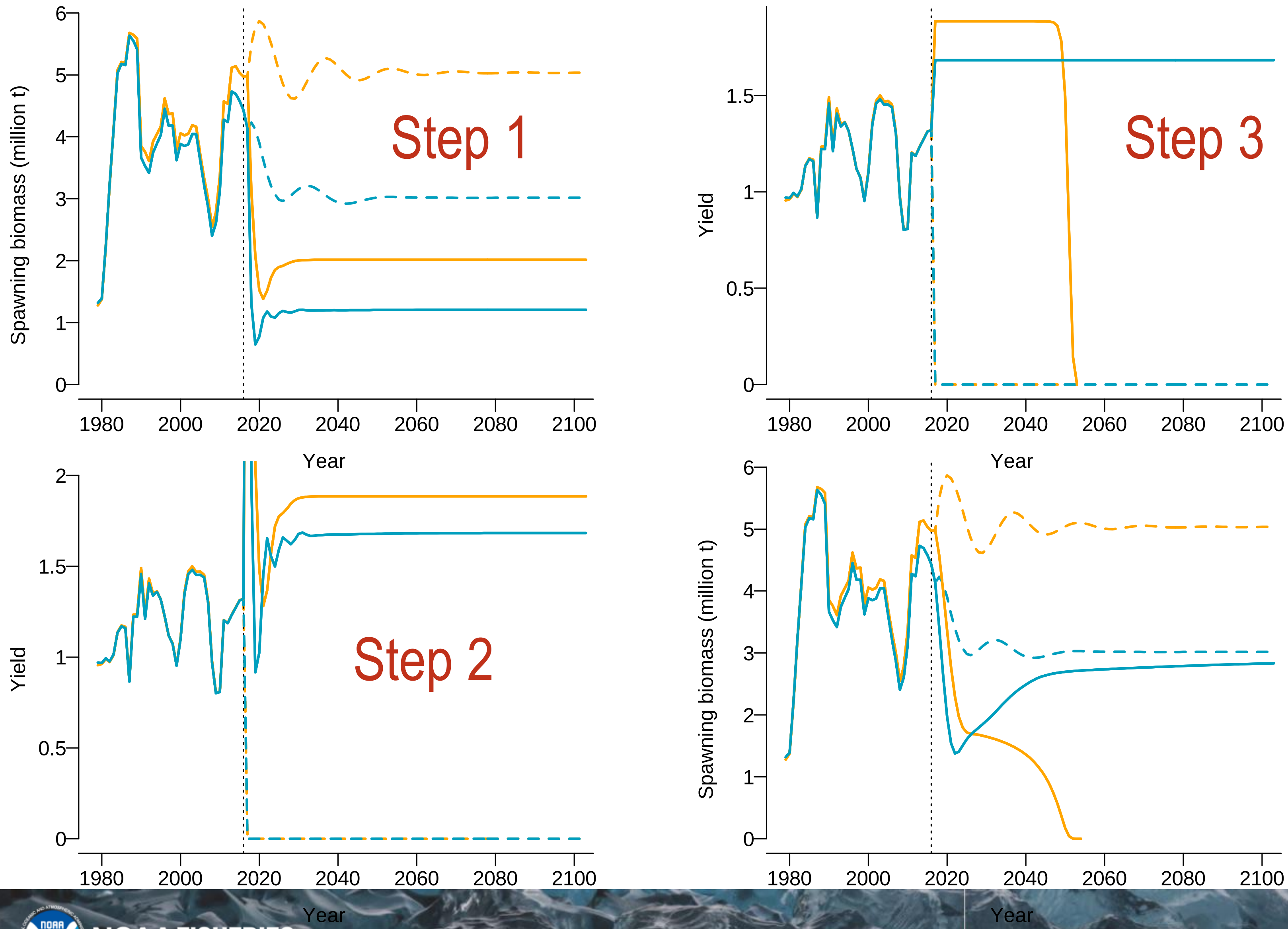
Get constant future F rate that results in 40% unfished biomass in year 2100



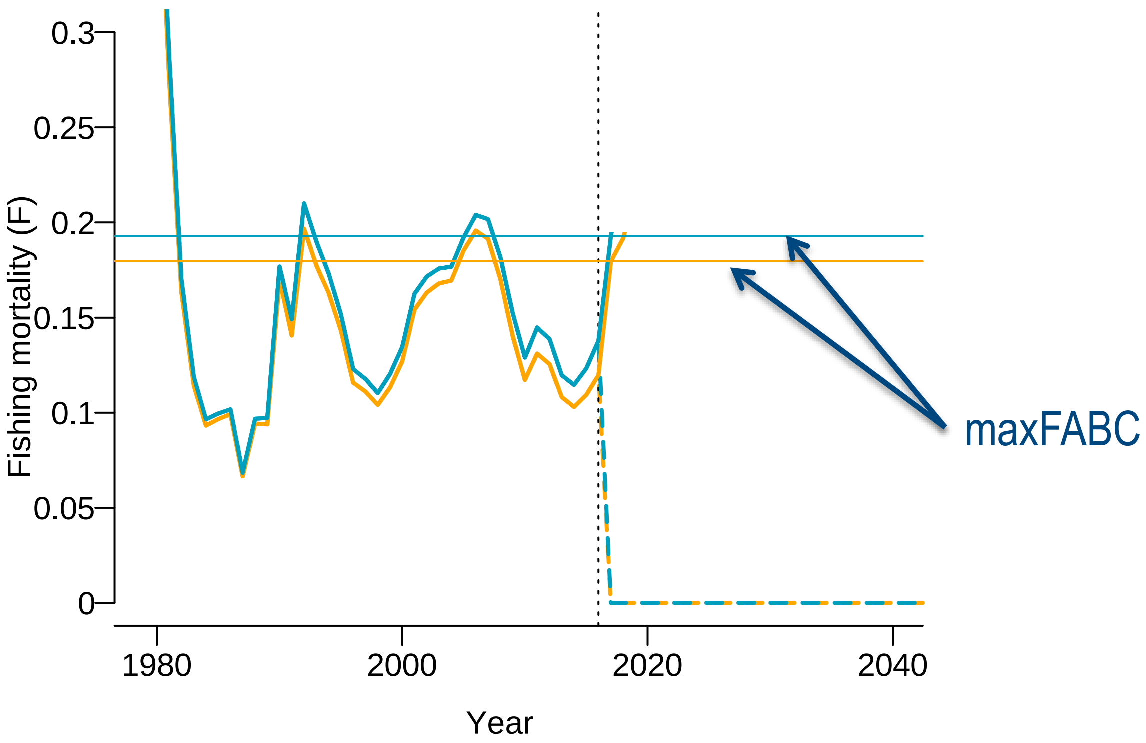
Find F rate that results in 40% unfished biomass in year 2100



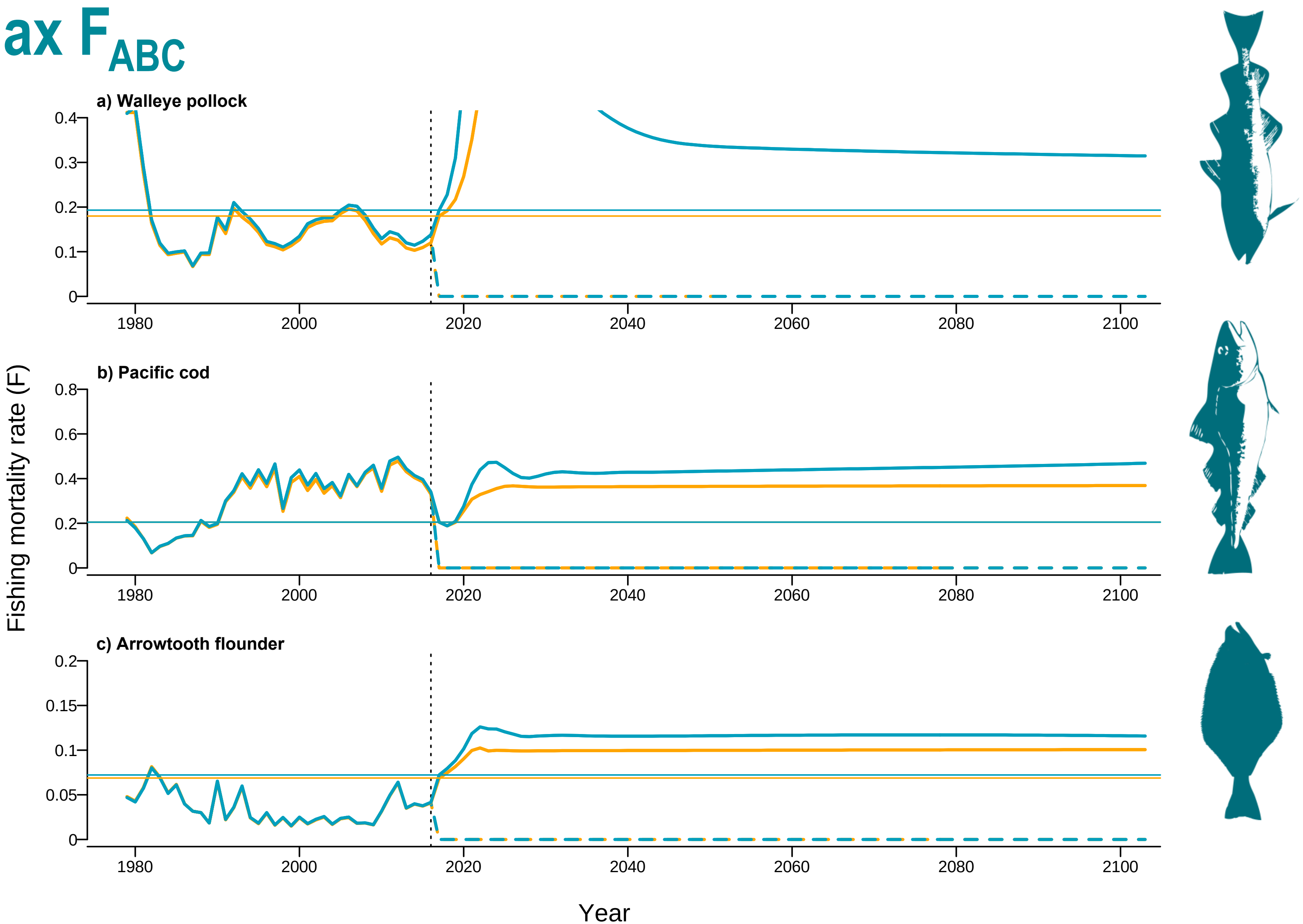
Take yield in 2100 and plug it back into model to derive FABC



Step 1
Spawning biomass (million t)
6
5
4
3
2
1
0
1980
2000
2020
2040
2060
2080
2100
Year
Step 3
Yield
1.5
1
0.5
0
1980
2000
2020
2040
2060
2080
2100
Year
Step 2
Yield
2
1.5
1
0.5
0
1980
2000
2020
2040
2060
2080
2100
Year
Spawning biomass (million t)
6
5
4
3
2
1
0
1980
2000
2020
2040
2060
2080
2100
Year

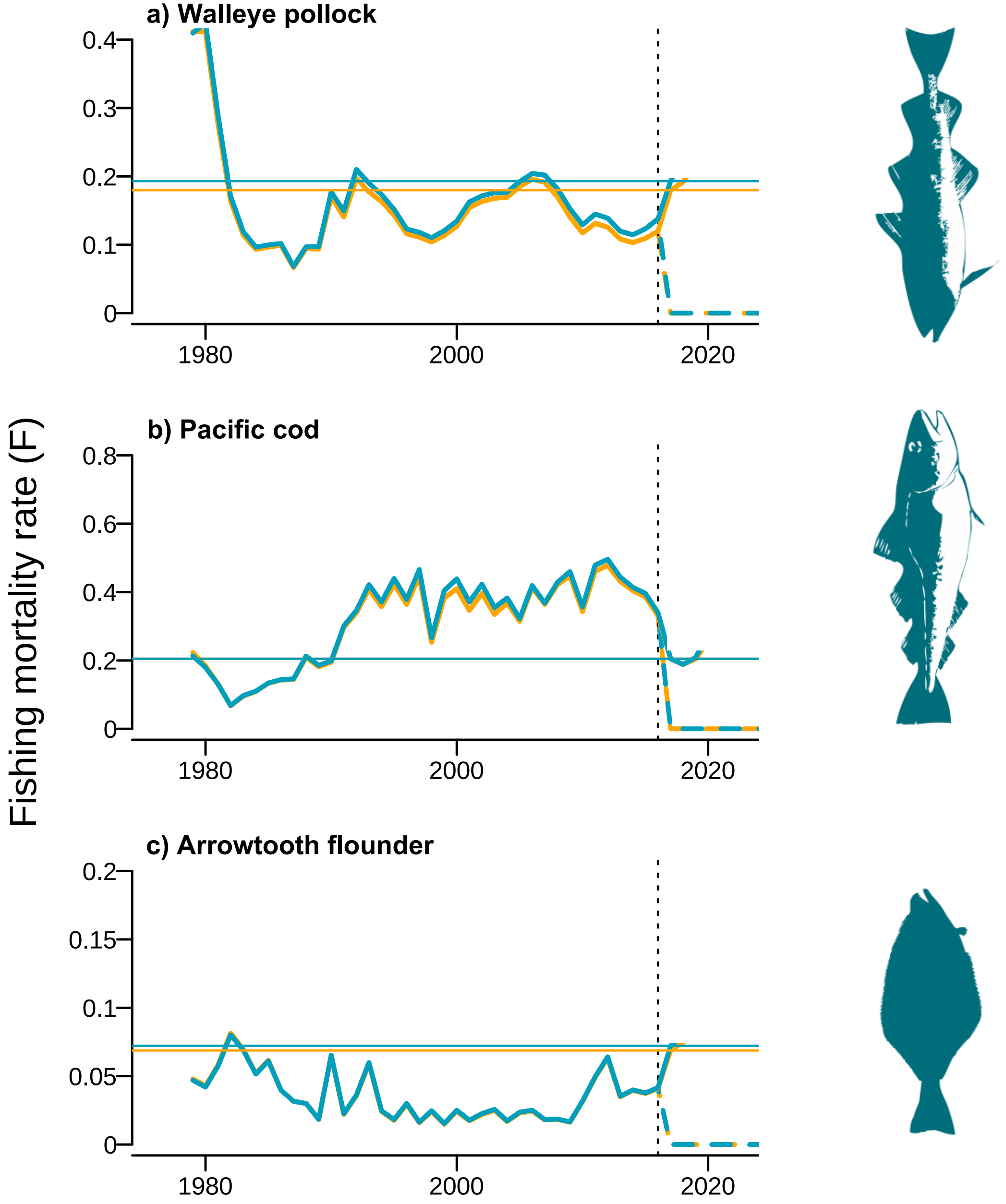

0.3
0.25
0.2
0.15
0.1
0.05
0
Fishing mortality (F)
1980
2000
2020
2040
Year
maxFABC

max F_{ABC}

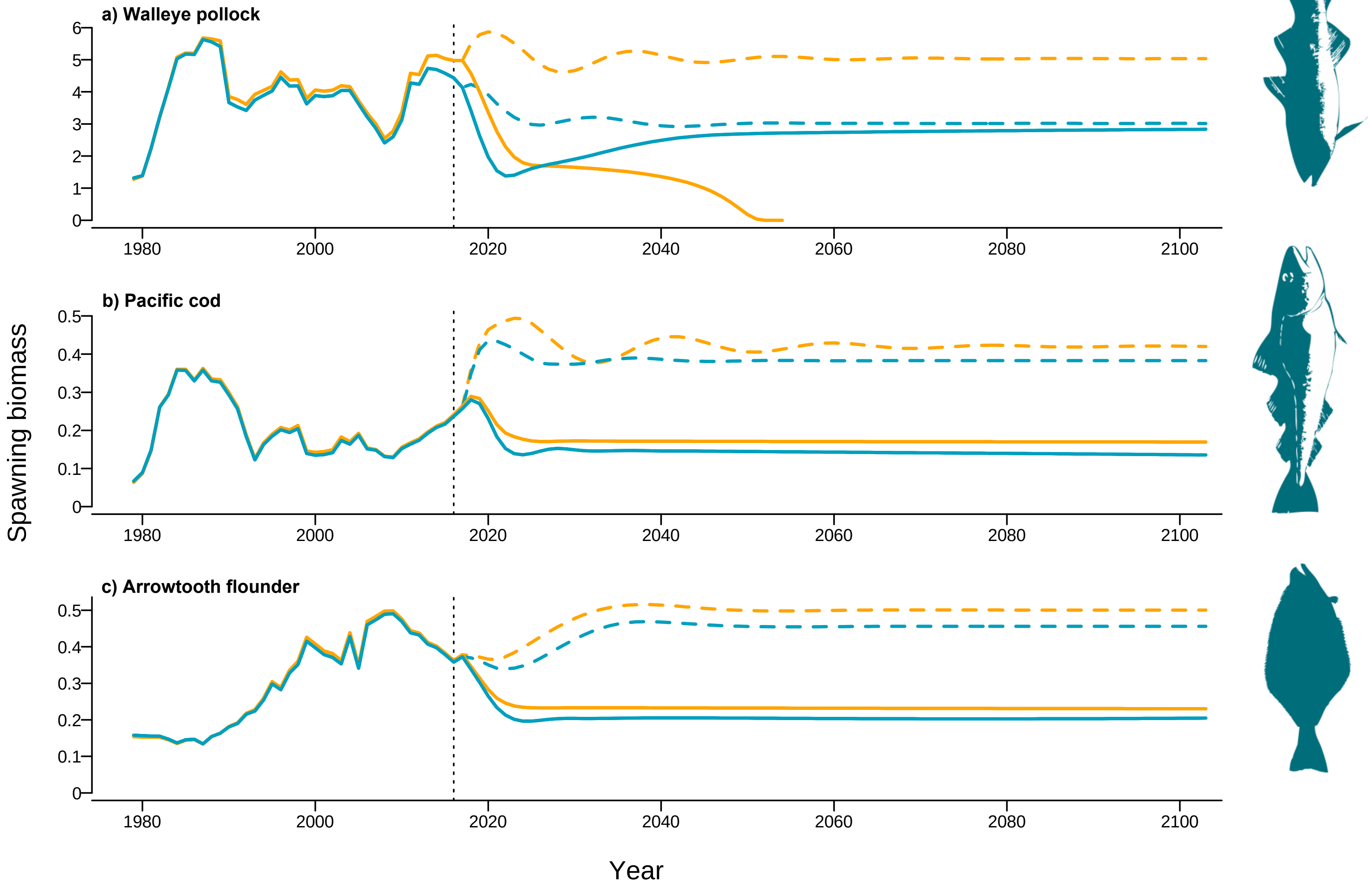


a) Walleye pollock
b) Pacific cod
c) Arrowtooth flounder
Fishing mortality rate (F)
Year
0.4
0.3
0.2
0.1
0
0.8
0.6
0.4
0.2
0
0.2
0.15
0.1
0.05
0
1980
2000
2020
2040
2060
2080
2100

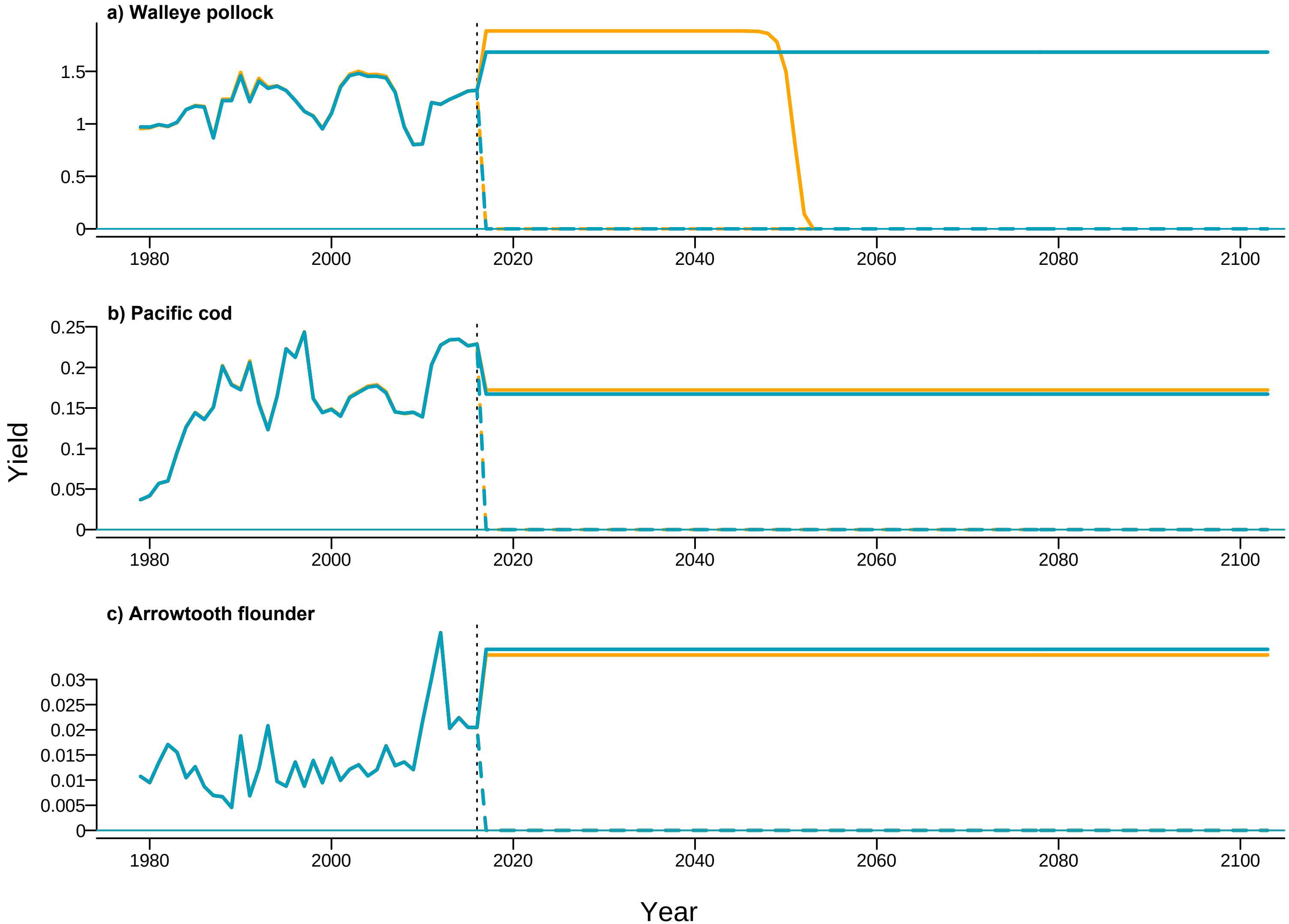
max F_{ABC}


a) Walleye pollock
b) Pacific cod
c) Arrowtooth flounder
Fishing mortality rate (F)
0.4
0.3
0.2
0.1
0
0.8
0.6
0.4
0.2
0
0.2
0.15
0.1
0.05
0
1980
2000
2020

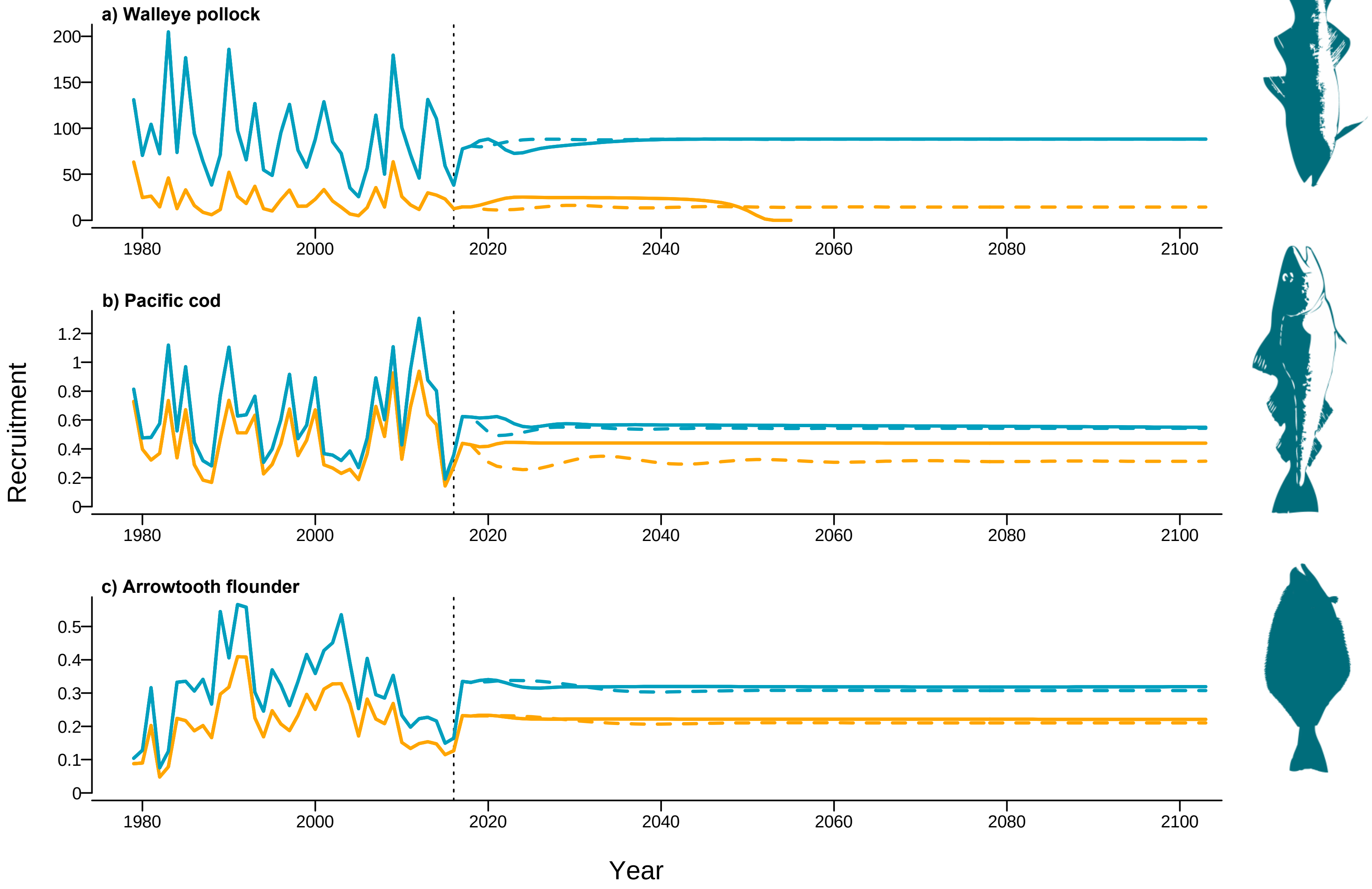
SSB at max ABC

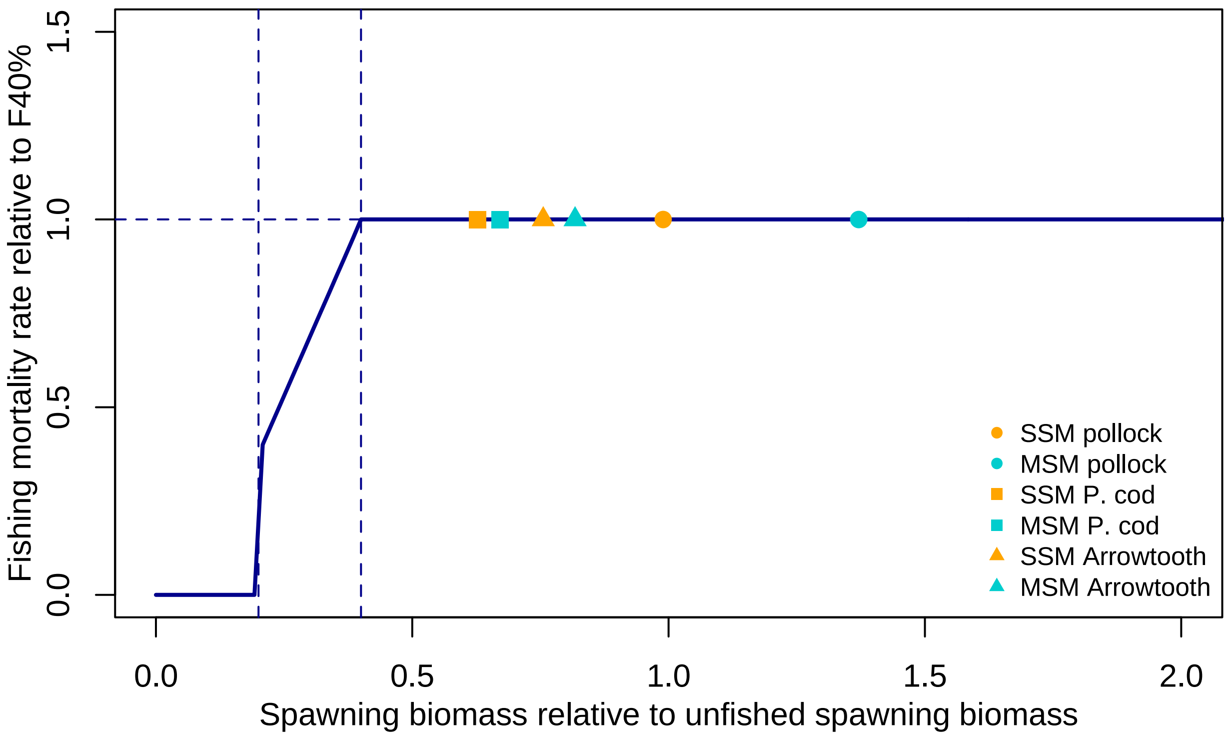


Max ABC


a) Walleye pollock
b) Pacific cod
c) Arrowtooth flounder
Yield
Year
0
0.5
1
1.5
0.05
0.1
0.15
0.2
0.25
0.005
0.01
0.015
0.02
0.025
0.03
1980
2000
2020
2040
2060
2080
2100

Recruitment at max ABC




Fishing mortality rate relative to F40%
0.0
0.5
1.0
1.5
Spawning biomass relative to unfished spawning biomass
0.0
0.5
1.0
1.5
2.0
SSM pollock
MSM pollock
SSM P. cod
MSM P. cod
SSM Arrowtooth
MSM Arrowtooth