NOAA FISHERIES

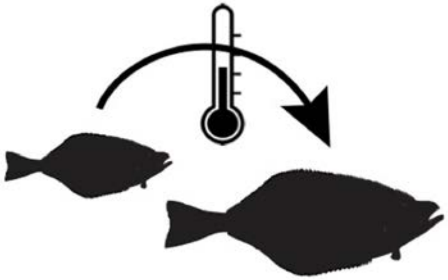
Alaska Fisheries Science Center

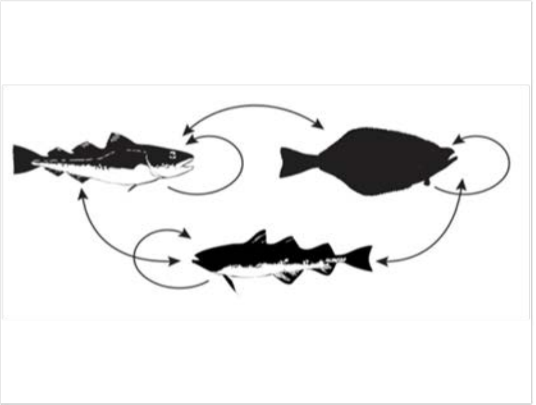
CEATTLE

Climate enhanced Age-based model with Temperature-specific Trophic linkages & Energetics

Kirstin K. Holsman, Jim Ianelli, Kerim Aydin, Grant Adams, Kelly Kearney, Kalei Shotwell, Grant Thompson, and Ingrid Spies

CEATTLE development team (alphabetical): Grant Adams, Kerim Aydin, Steve Barbeaux, Martin Dorn, Jim Ianelli, André Punt, Kalei Shotwell Ingrid Spies, Grant Thompson

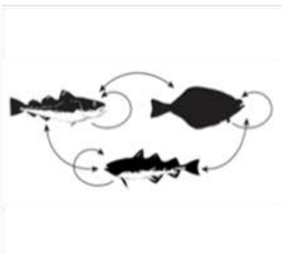




November 17, 2021

CEATTLE Options

Mortality

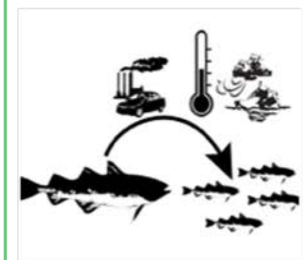


- Empirical diets
- Bioenergetics

Weight @ Age

- Empirical
- VonB with Temp

Rec



- Climate-S/R
- S/R
- mean R

HCRs

- Climate ABC
- MMSY
- MEY
- SPR
- Aggregate MSY

Two models presented each year:

SSM : without trophic interactions (single-species mode)

MSM : with trophic interactions (multi-species mode)

CEATTLE workflow features

- R and shell scripts used to run the model through projections:
  - Regular output includes ESR contribution (R markdown)
  - ESP indices
  - Assessment written in Rmarkdown using Rdata outputs
- Github repositories (* private)
  - *CEATTLE (ADMB):
    https://github.com/kholsman/CEATTLE
  - *2021 Assessment (will be archived via Zenodo with a doi):
    https://github.com/kholsman/2021_AFSC_multispp
  - Rceattle (G. Adams; R/TMB):
    https://github.com/grantdadams/Rceattle

CEATTLE Applications

- Operational advice:
  - Appendix to BSAI pollock assessment (2016 to now)
  - M2 index for EBS ecosystem status report (2016 to now)
  - M2 index for ESP (2020 to now)
- Research:
  - ACLIM - climate MSE
  - Lenfest NFS
  - Lenfest ocean wealth
- Bering Seasons
  - Forecasts under 9mo
- GOA
  - G. Adams (UW) : 3 and 4 species model for GOA (Adams et al, in review)
  - G. Adams (UW) : M2 index for GOA Ecosystem Status Report (2021)
  - MSE planned for 2022

Holsman, K. K. et al. Climate-informed multispecies assessment model methods for determining biological references points and Acceptable Biological Catch. *Protoc. Exch*. In press https://doi.org/10.21203/rs.3.pex-1084/v1 (2020).

ESR contribution

Multispecies model estimates of time-varying natural mortality

Kirstin K. Holsman, Jim Ianelli, Kerim Aydin, Ingrid Spies

kirstin.holsman@noaa.gov

Alaska Fisheries Science Center, NOAA, 7600 Sand Point Way N.E., Bld. 4, Seattle, Washington 98115

Last Updated: October 2019

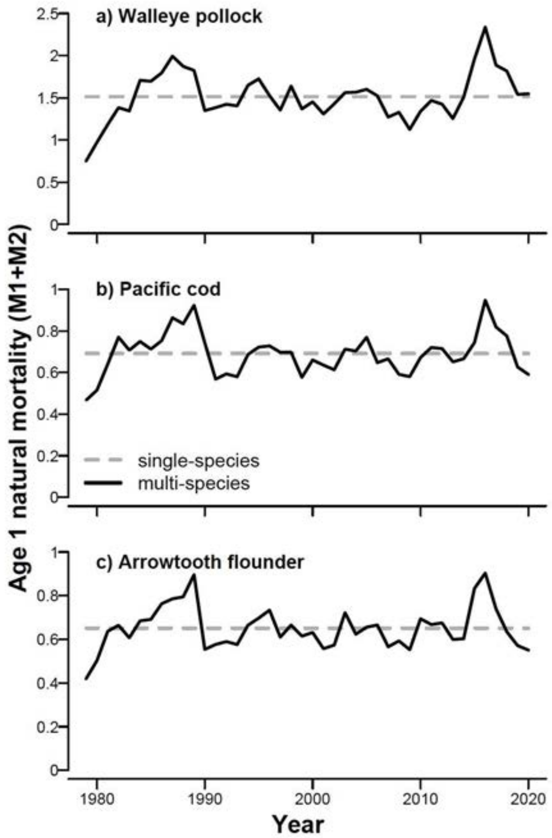
Summary statement:

The climate-enhanced multispecies model (CEATTLE) estimates of age 1 predation mortality for all three species (walleye pollock, Pacific cod, arrowtooth flounder) continue to decline from the recent 2016 peak mortality. Age 1 predation mortality for walleye pollock is at the long-term mean, while age 1 Pacific cod and arrowtooth flounder mortality rates remain below the long-term mean.

Status and trends:

Estimated age 1 natural mortality (i.e., M1+M2) for walleye pollock (hereafter "pollock"), Pacific cod (hereafter "P. cod"), and arrowtooth flounder peaked in 2016. At 1.49 yr^{-1}, age 1 mortality estimated by the model was greatest for pollock and lower for P. cod and arrowtooth, with total age 1 natural mortality at around 0.69 and 0.65 yr^{-1}. 2019 natural mortality across species is 23% to 33% lower than in 2016 and is no longer above average for pollock (relative to the long-term mean) (Fig. 1), while P. cod and arrowtooth mortality continue to decline and are well below the long-term mean.

ESR vs ESP products



Predation Index: e.g., pollock age 1 total mortality (M1+M2)

ESR: synergies across species

ESP: Specific index of age 1 mortality

SSC comments

Analyses for the Bering Sea suggest that the use of EBFM measures like the cap can forestall some of the negative impacts from changing climate conditions (Holsman et al. 2020, https://doi.org/10.1038/s41467-020-18300-3) and we suggest that similar analyses could be conducted by GOA CLIM. In ACLIM 2.0, the analysts propose an examination of a lower (1.6 MT) and a higher cap (2.4 MT) in the future. The SSC suggests that a re-estimation of the OY range in the Bering Sea under current climatic conditions may be fruitful as well. The analysts could consider a broader range of upper limits on removal such as no cap (as in Holsman et al., 2020), a new, revised cap based on best available information from single and multi-species models, a reduced cap to account for enhanced climate risks, and possibly a cap that is linked to current or recent estimates of overall system productivity (for example based on a combination of primary productivity estimates, food web complexity and transfer efficiency).

We appreciate the SSC suggestions and plan to evaluate various scenarios such as those outlined here as part of the second phased of the Alaska Climate Integrated Modeling project (ACLIM2.0). The CEATTLE model, which is the basis for this assessment, will be one of several models used in the multimodel comparison of the performance of various management and harvest control rules under climate change. We plan to provide an update to the SSC and Council on these results as they become available.

Model summary

1. NEBS (2010,2017-2021) are **NOT** included.
2. **Predation natural mortality is age specific and annually varying (M2).**
3. Residual (non-predation) natural mortality **(M1) is not estimated, is age specific but not-annually varying** and differs from current assessments for each species.
4. Predator **overlap index is set to 1** for all species (i.e., all prey are available to all predators).
5. Weights at age for pollock are based on values from the 2021 SAFE report; for Pacific cod and arrowtooth, they are calculated outside of the model using a temperature-dependent vonB to fill in for missing years between 1979-2012 and assume 2012 weight at ages for 2013-2021. For projections, **all three species use weights at age using the temperature-dependent vonB for 1979-2012.**
6. Acoustic trawl survey selectivity was set equal to the SAFE report model estimates.
7. Fisheries selectivity and survey selectivity are age specific but constant over time.
8. **Predator-prey suitability is age-specific but constant over time.**
9. **Arrowtooth flounder stock is treated as sexes combined** (weight at age and proportion mature is calculated separately for males and females and combined using a mortality-based mean).
10. **Maturity schedules are based on 2012 assessments** and differ slightly from SAFE assessments.
11. Projections to derive ABC include a sequential method for determining universal climate-naive B0 and include the constraint that $SSB_F > 0.35\ SSB_0$ for all years in the projection.
12. A moderately "climate-informed" approach is used to derive biological reference points through projecting the model forward with climate effects on weight at age and predation mortality but with a climate-naive Ricker stock recruitment curve (i.e., without environmental covariates).
13. Evaluation of F_{ABC} for 2022 and 2023 is performed using an ensemble of warming scenarios.

CEATTLE methods references

Original HCRs and approach:

- Holsman, KK, J Ianelli, K Aydin, AE Punt, EA Moffitt (2016). 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 (2016). 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

Climate enhanced - socioecon coupled projections:

- Holsman, K.K., A. Haynie, A. Hollowed, J. Reum, K. Aydin, A. Hermann, W. Cheng, A. Faig, J. Ianelli, K. Kearney, A. Punt. (2020) Ecosystem-based fisheries management forestalls climate-driven collapse. Nature Communications. DOI:10.1038/s41467-020-18300-3
- Holsman, K. K. et al. Climate-informed multispecies assessment model methods for determining biological references points and Acceptable Biological Catch. *Protoc. Exch*. In press https://doi.org/10.21203/rs.3.pex-1084/v1 (2020).

GOA CEATTLE model:

- Adams et al. In review. (Application of RCeattle() to GOA via TMB)

Data used to fit model parameters

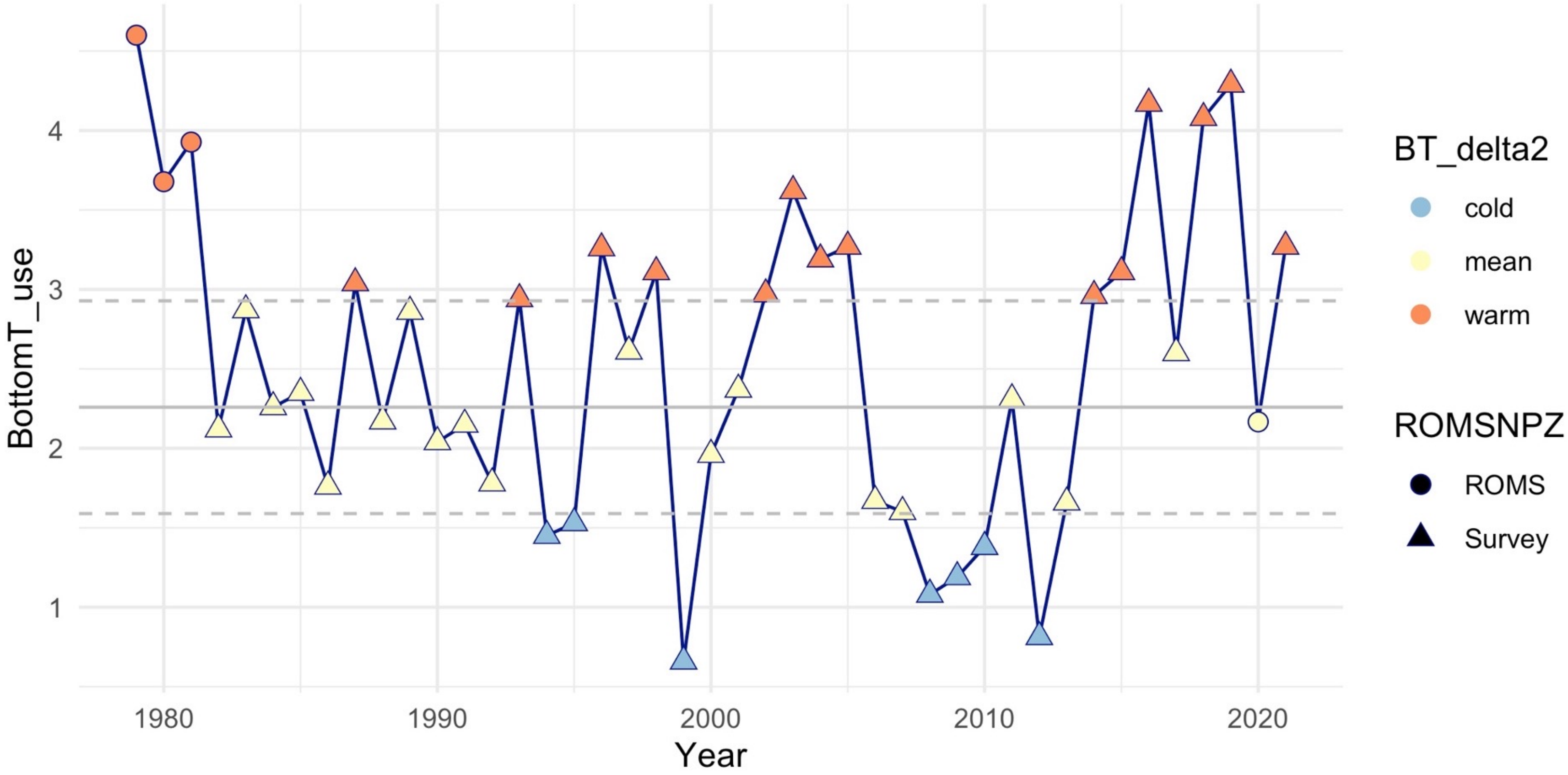
Data	Pollock	P. cod	Arrowtooth
Survey Age comp.	1982-2019,2021 (39 y)		
Survey Length comp.		1982-2019,2021 (39 y)	1982-2019,2021 (39 y)
Survey Biomass Index	1982-2019,2021 (39 y)	1982-2019,2021 (39 y)	1982-2019,2021 (39 y)
Fishery total catch (biomass)	1979-2021 (43 y)	1979-2021 (43 y)	1979-2021 (43 y)
Fishery Age comp.	1979-2020 (42 y)		
Fishery Length comp.		1979-2021 (43 y)	1979-1988, 1990-2014, 2016, 2018-2021 (40 y)
Acoustic survey Index	1994,1996,1997, 1999, 2000,2002,2004, 2006-2010, 2012, 2014, 2016, 2018, 2020		
Acoustic survey age composition	1994,1996,1997, 1999, 2000,2002,2004, 2006-2010, 2012, 2014, 2016, 2018, 2020		

Likelihood equations

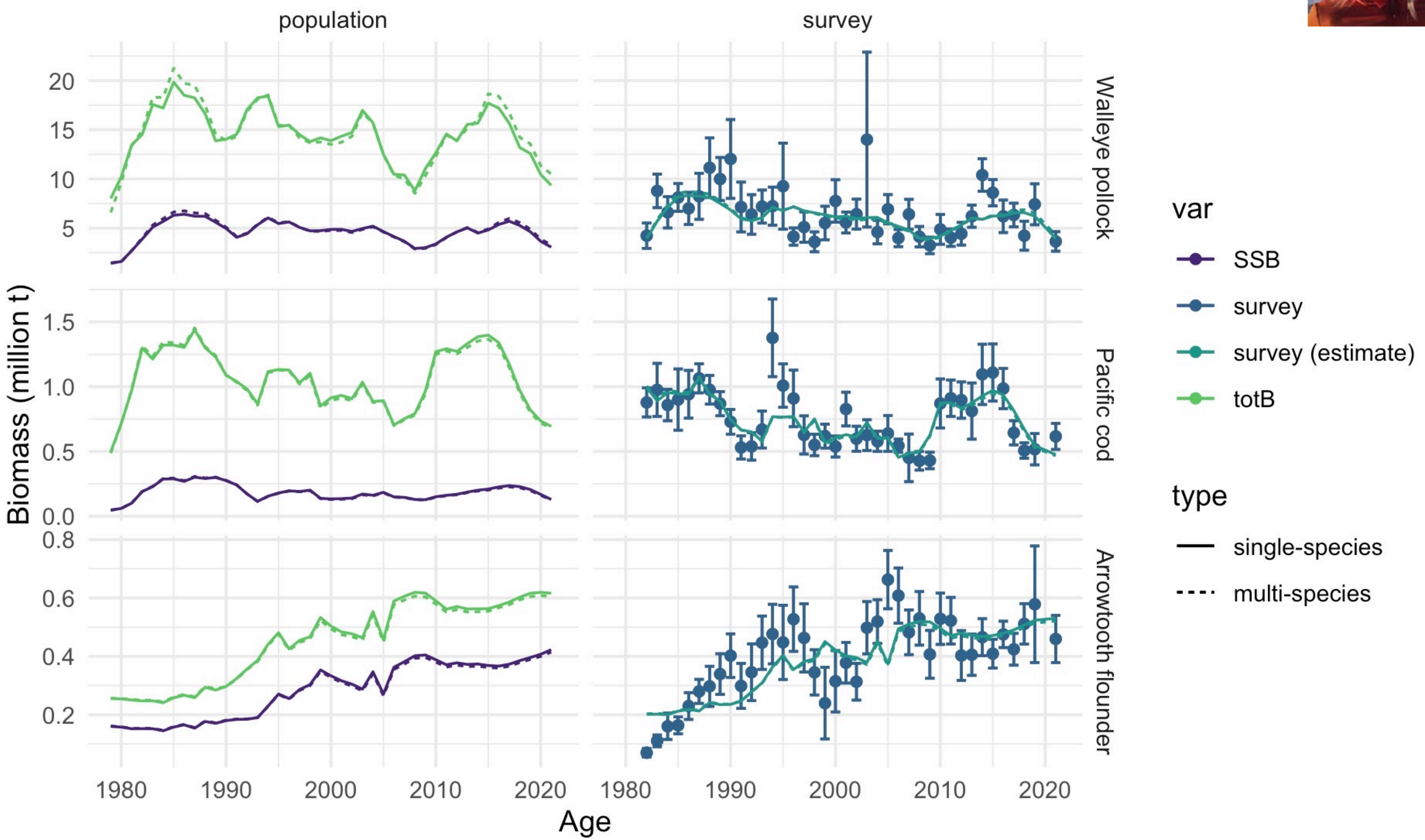
Description	Equation
Data components	
BT survey biomass	$\sum_i \sum_y \frac{\left[\ln\left(\beta^s_{i,y}\right)-\ln\left(\hat{\beta}^s_{i,y}\right)\right]^2}{2\sigma^2_{s,i}}$
BT survey age composition	$-\sum_i n_i \sum_y \sum_j \left(O^s_{ij,y}+v\right)\ln\left(\hat{O}^s_{ij,y}+v\right)$
EIT survey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

$v=0.001.$

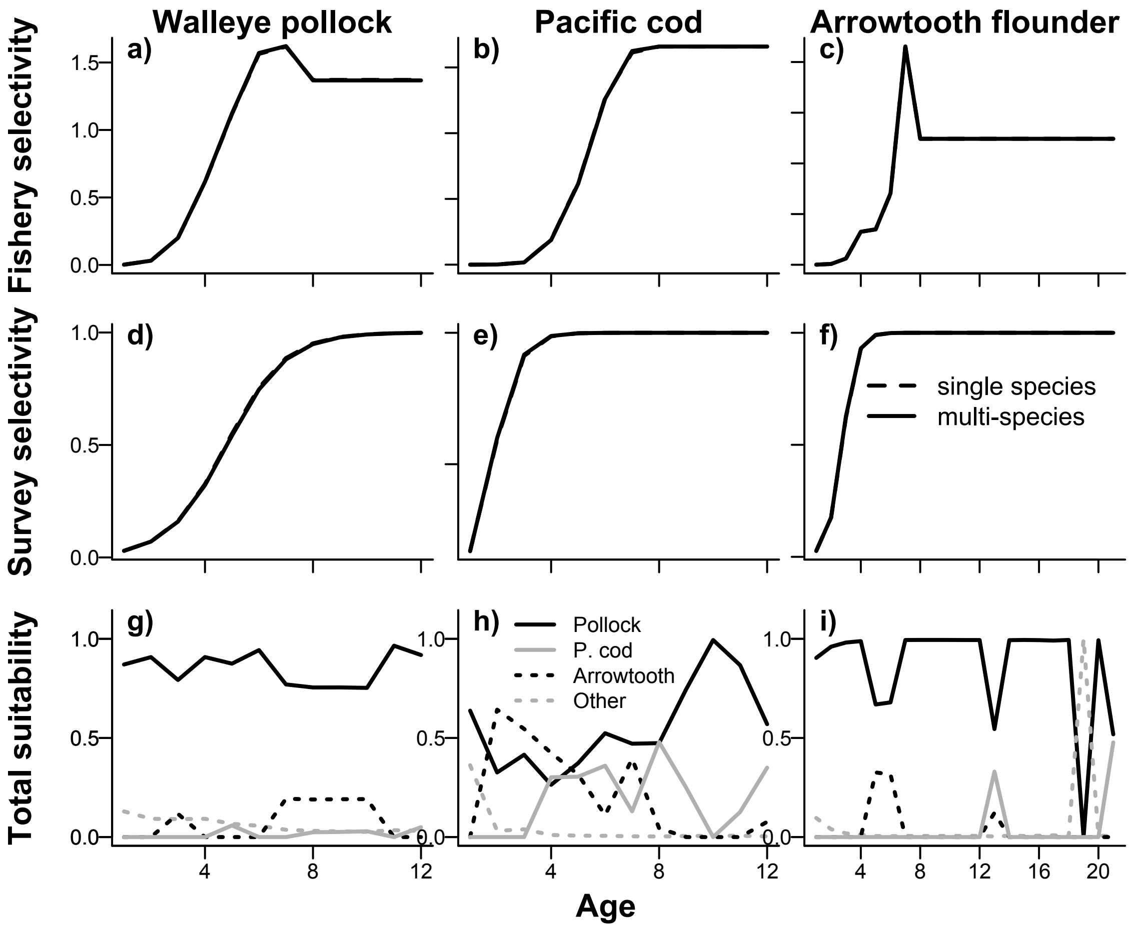
Bottom Temperature



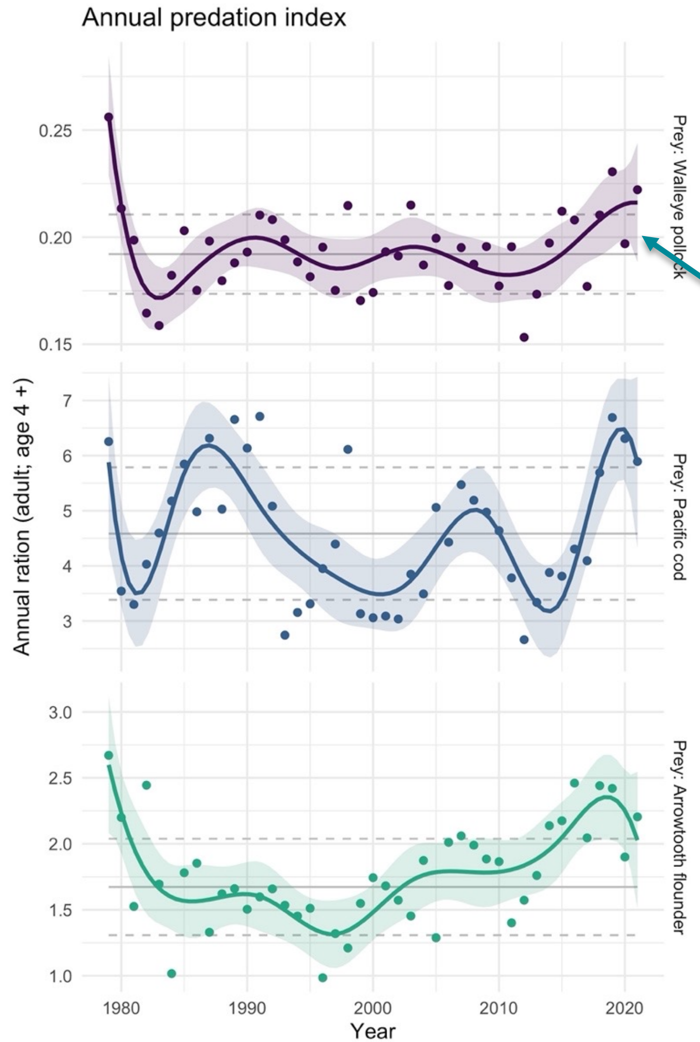
Results


population
survey
Walleye pollock
Pacific cod
Arrowtooth flounder
Biomass (million t)
Age
20
15
10
5
1.5
1.0
0.5
0.0
0.8
0.6
0.4
0.2
1980
1990
2000
2010
2020
var
SSB
survey
survey (estimate)
totB
type
single-species
multi-species

Selectivity and suitability



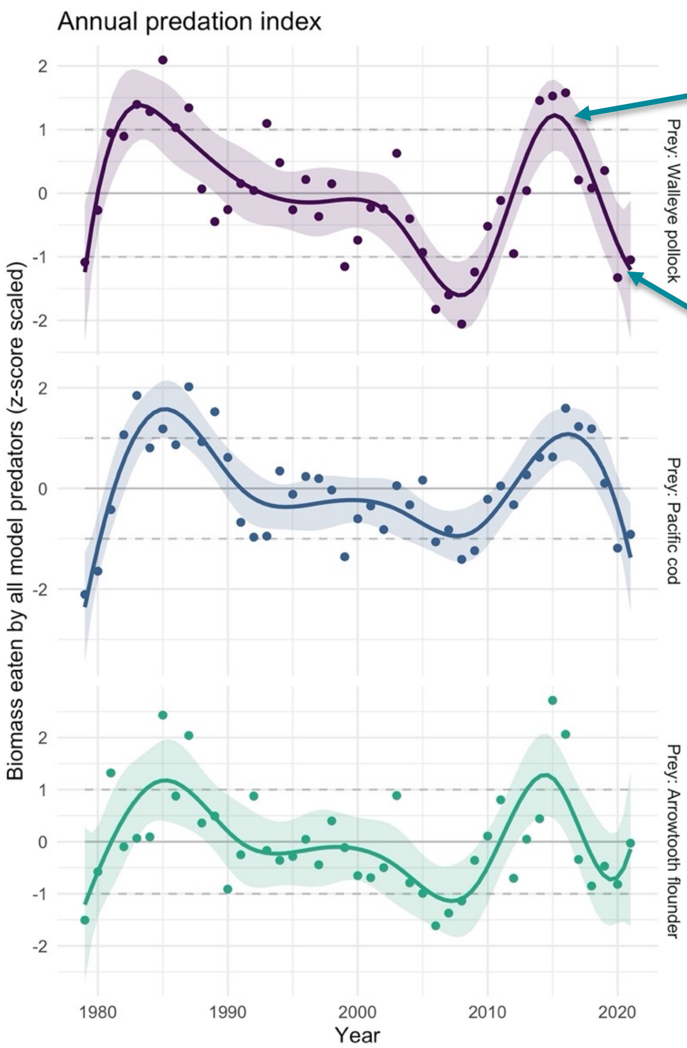
Increase in energetic demand (ration)



Kg/yr

Warm temp → increases in individual ration

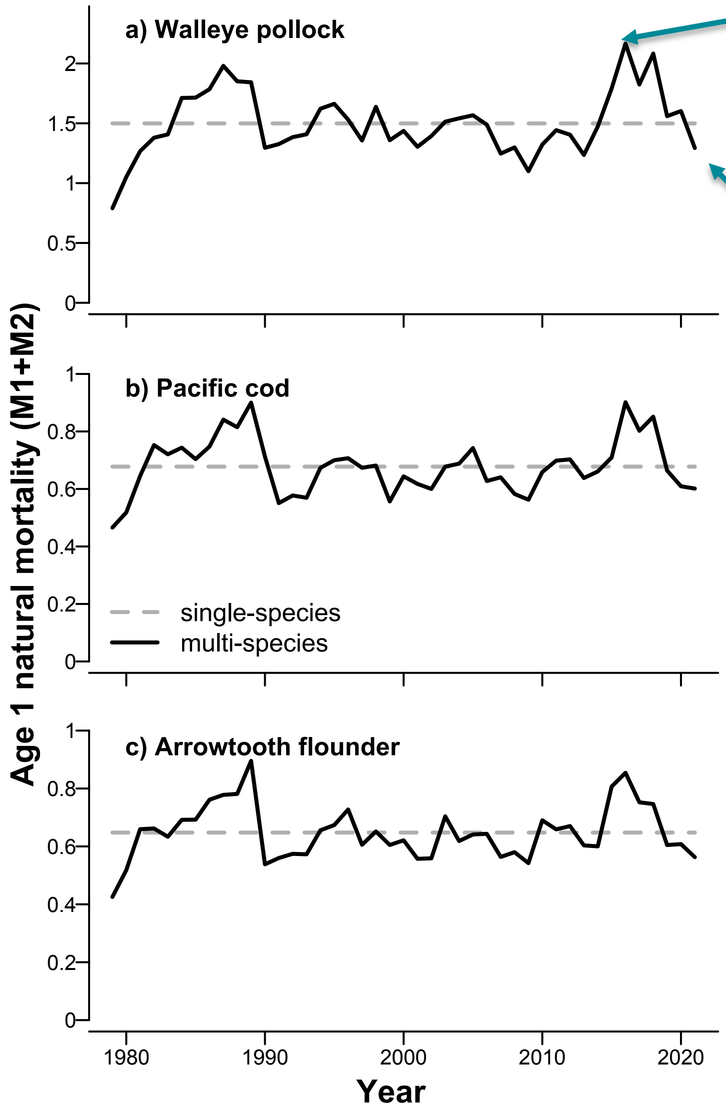
Declines in predation index



Warm temp + high predator biomass = high predation

Warm temp + low predator biomass = lower predation

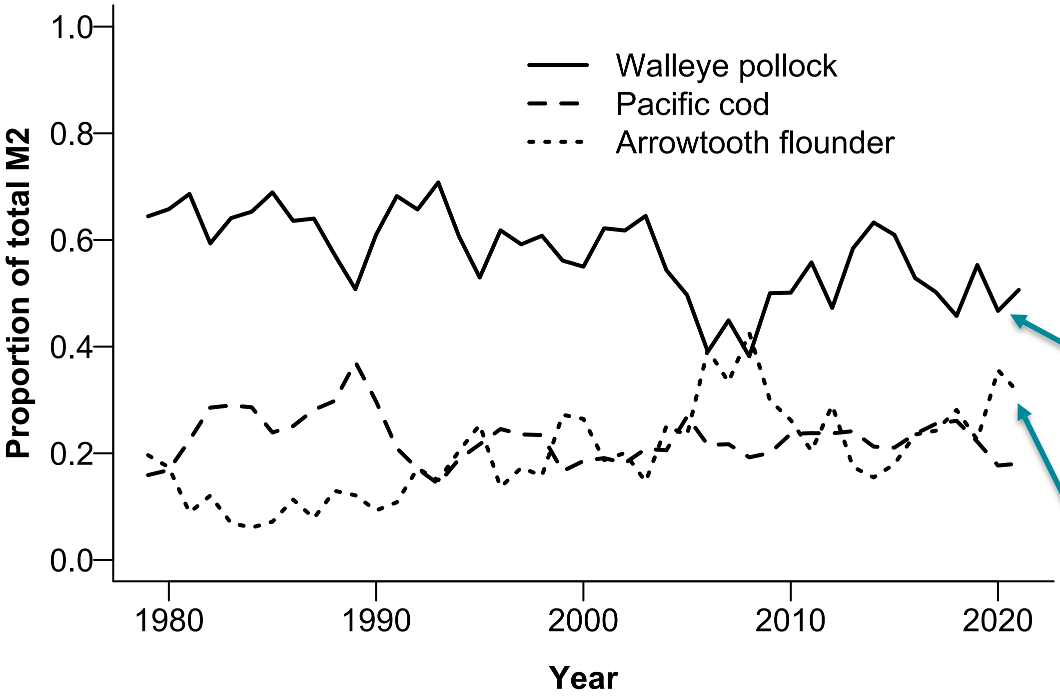
Natural Mortality



Warm temp + high predator biomass = high predation

Warm temp + low predator biomass = lower predation

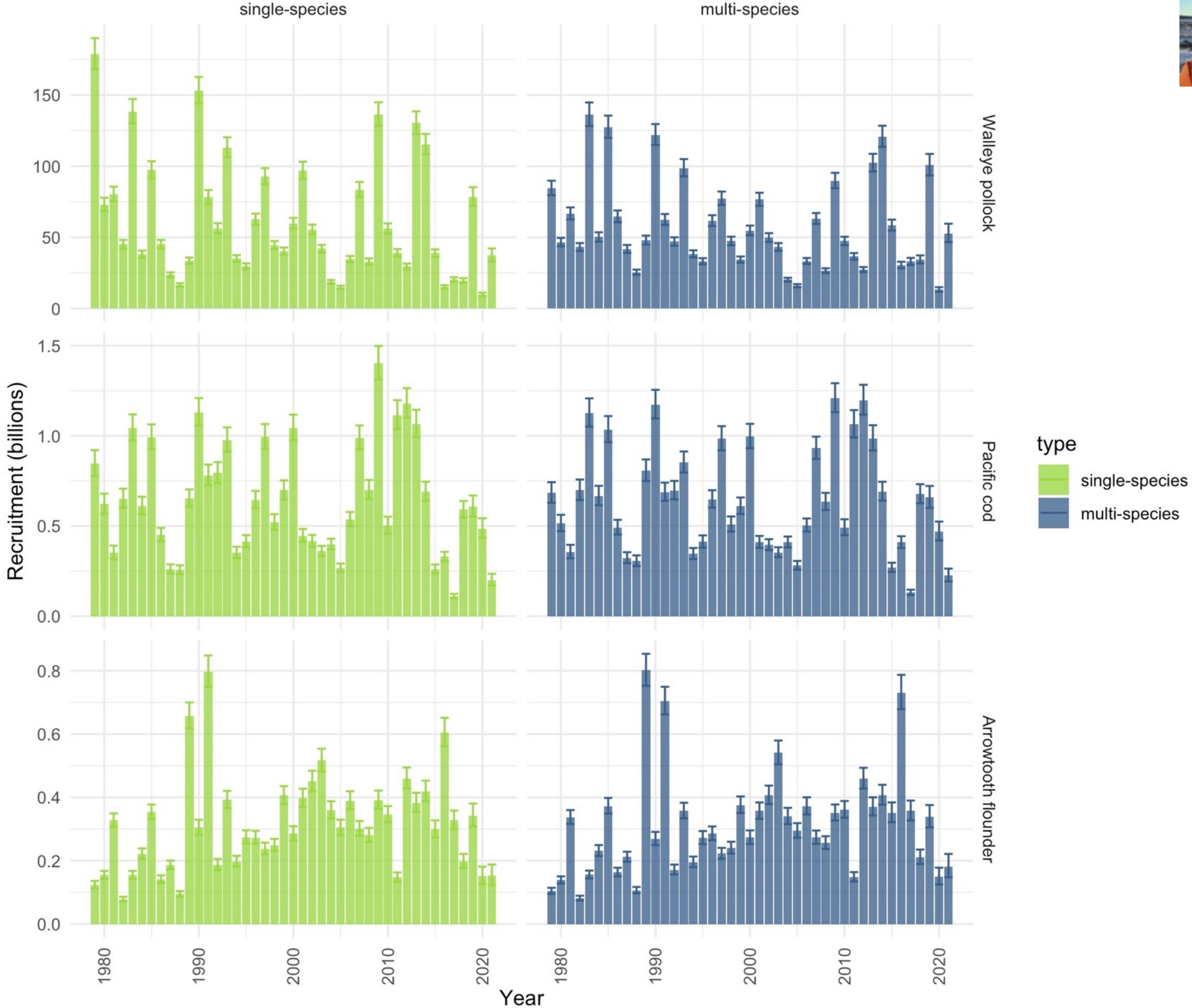
Pollock Predation Mortality



Cannibalism

Arrowtooth predation on pollock

Age 1 recruitment



2021 Summary

Quantity	Walleye pollock		Pacific cod		Arrowtooth flounder	
	SSM	MSM	SSM	MSM	SSM	MSM
2021 M (age 1)	1.499	1.294	0.678	0.601	0.648	0.563
2021 Average 3+ M	0.307	0.307	0.38	0.38	0.227	0.227
Projected (age 3+) B_{2022} (t)	7,141,601	8,088,508	655,159	652,583	598,656	589,122
SSB_{2021} (t)	3,061,910	3,299,820	129,021	123,288	422,839	414,591
% change in SSB (t)	-16.2	-14.8	-23.1	-23.6	3.9	3.7
Projected SSB_{2022} (t)	3,329,160	3,721,910	117,419	112,099	426,477	417,848
Projected SSB_{2023} (t)	2,552,270	2,903,910	102,772	96,460	412,721	402,119
*Projected $SSB_{0,2100}$ (t)	5,723,024	4,507,314	352,992	349,624	437,467	437,629
*Projected $SSB_{target,2100}$ (t)	2,471,490	2,248,868	162,714	151,427	174,954	175,028
**Target 2100 B/B_0	0.432	0.499	0.461	0.433	0.4	0.4
F_{target}	0.57	0.884	0.369	0.429	0.083	0.095
$F_{ABC,2022}$	0.378	0.42	0.614	0.709	0.033	0.039
ABC_{2022}	2,284,280	2,761,060	163,586	172,480	21,195	24,346
ABC_{2023}	1,809,310	2,198,350	159,045	166,335	19,356	22,147

** $SSB_{0,2100}$ and $SSB_{target,2100}$ are based on the projected SSB at 2100 (equilibrium) given $F = 0$ and $F = F_{target}$, respectively.*
*** Target ratios in 2100 are based on B/B_0=0.4, given that $B/B_0 > 0.35$ for all future yr.*
Projected SSB_{2022} (t) refers to SSB at the start of 2022 and Projected SSB_{2023} (t) refers to SSB at the start of 2023 using $F_{ABC,2022}$ for 2022

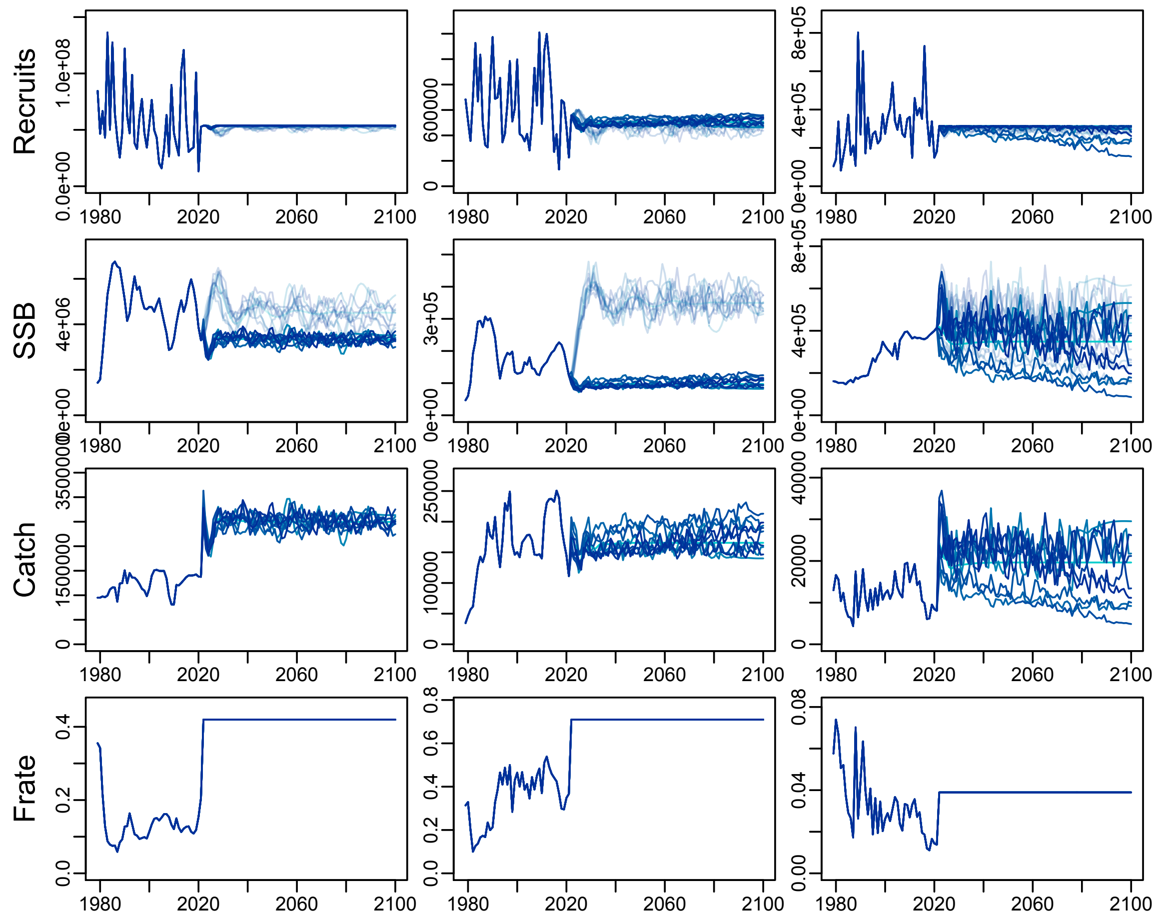
CEATTLE Future directions

- Update model to include NEBS
- Transition to Rceattle (TMB version)
- Update vonB and diet matrix approach
- Continue to improve ROMSNPZ forecast to model workflow
- Include climate-recruitment projections in assessment (towards climate informed advice)
- MSE on climate informed approach
- Additional risk / probability metrics

EXTRA SLIDES FROM HERE OUT

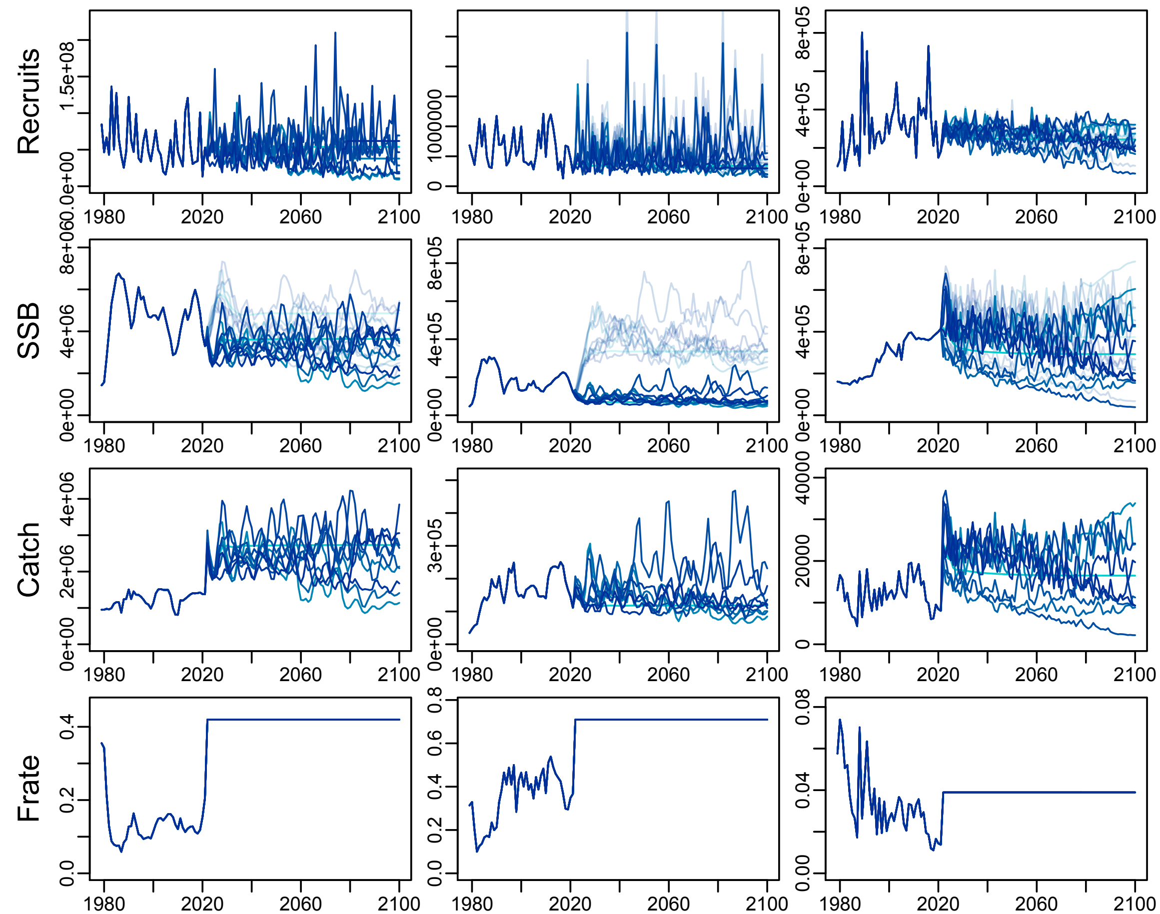
ABC Climate-informed approach (Holsman et al. 2020 a,b)

Multispecies : with temp effects on G, M2 only

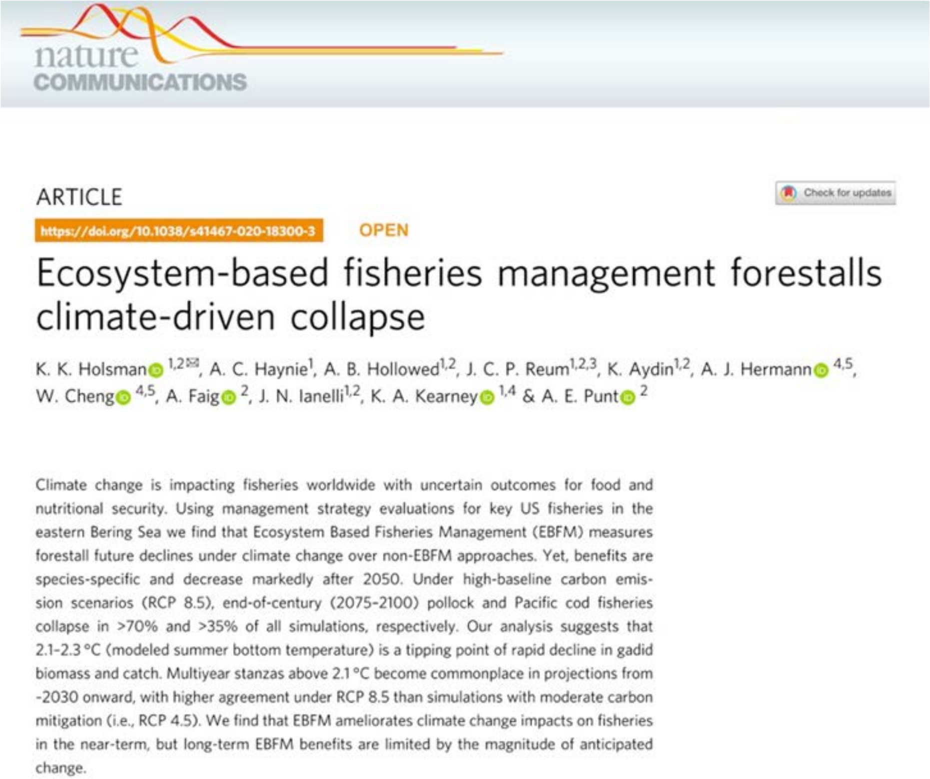


ABC Climate-informed approach (Holsman et al. 2020 a,b)

Multispecies : with climate effects on recruitment and G, M2



Coupled climate-social-economic projections



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ARTICLE

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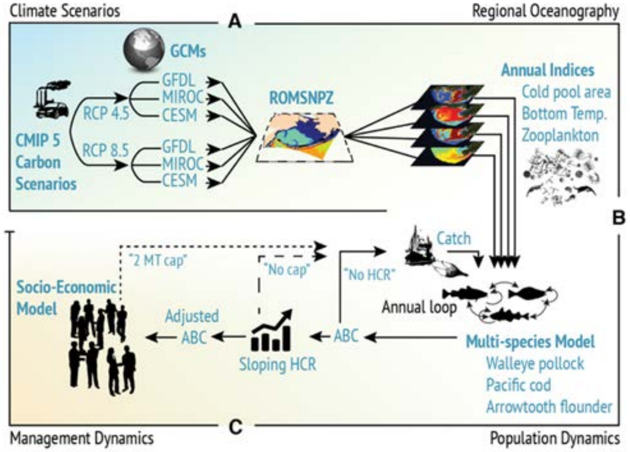
https://doi.org/10.1038/s41467-020-18300-3 OPEN

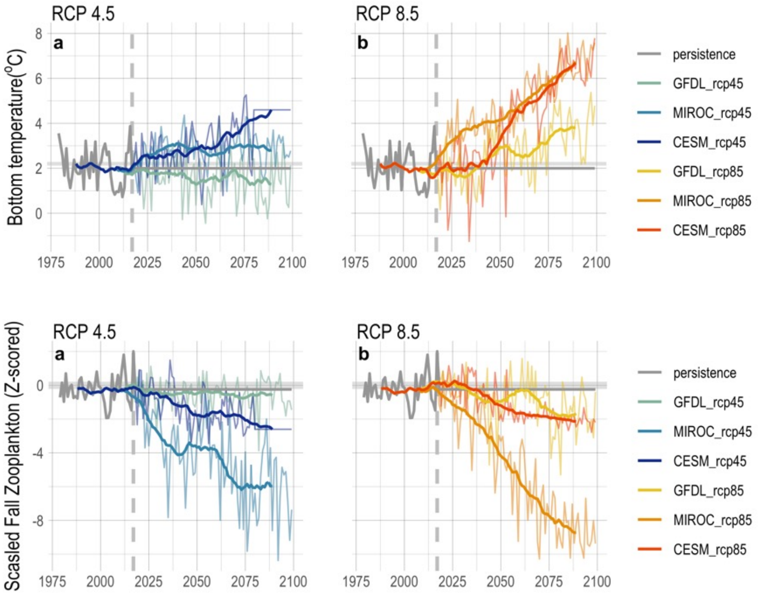
Ecosystem-based fisheries management forestalls climate-driven collapse

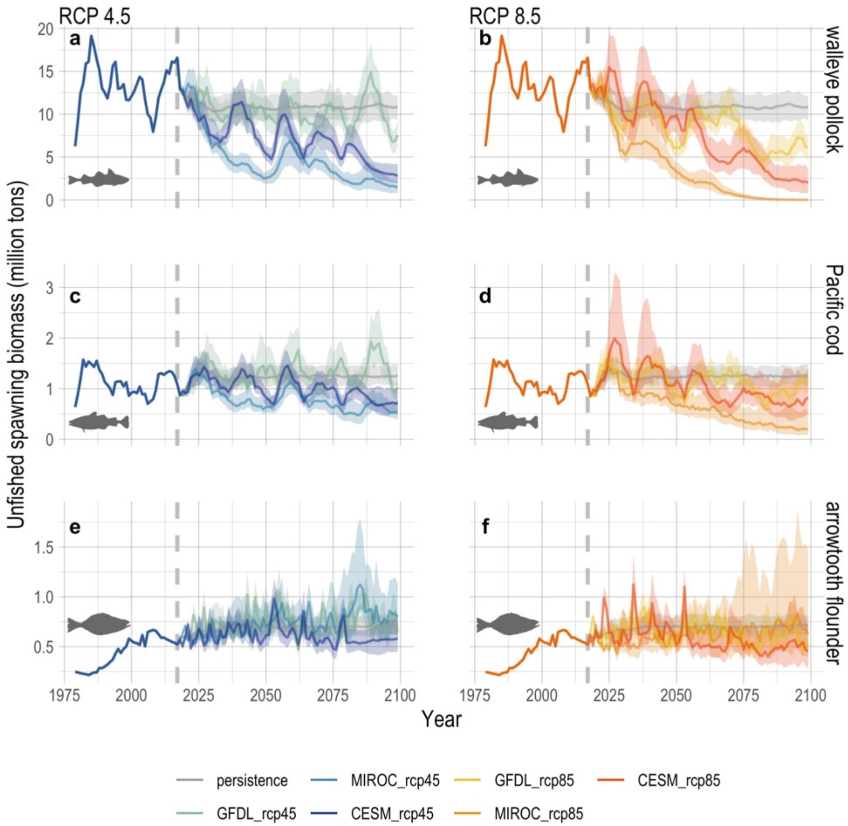
K. K. Holsman[1,2✉], A. C. Haynie[1], A. B. Hollowed[1,2], J. C. P. Reum[1,2,3], K. Aydin[1,2], A. J. Hermann[4,5], W. Cheng[4,5], A. Faig[2], J. N. Ianelli[1,2], K. A. Kearney[1,4] & A. E. Punt[2]

Climate change is impacting fisheries worldwide with uncertain outcomes for food and nutritional security. Using management strategy evaluations for key US fisheries in the eastern Bering Sea we find that Ecosystem Based Fisheries Management (EBFM) measures forestall future declines under climate change over non-EBFM approaches. Yet, benefits are species-specific and decrease markedly after 2050. Under high-baseline carbon emission scenarios (RCP 8.5), end-of-century (2075–2100) pollock and Pacific cod fisheries collapse in >70% and >35% of all simulations, respectively. Our analysis suggests that 2.1–2.3 °C (modeled summer bottom temperature) is a tipping point of rapid decline in gadid biomass and catch. Multiyear stanzas above 2.1 °C become commonplace in projections from ~2030 onward, with higher agreement under RCP 8.5 than simulations with moderate carbon mitigation (i.e., RCP 4.5). We find that EBFM ameliorates climate change impacts on fisheries in the near-term, but long-term EBFM benefits are limited by the magnitude of anticipated change.



Unfished biomass (no harvest)





Holsman, K.K., Haynie, A.C., Hollowed, A.B. et al. Ecosystem-based fisheries management forestalls climate-driven collapse. Nat Commun 11, 4579 (2020). https://doi.org/10.1038/s41467-020-18300-3

ABC Climate-informed approach (Holsman et al. 2020 a,b)

1. For each environmental covariate create the "persistence" projection using the average of the last 10 years of the hindcast ROMSNPZ model or bottom temperature (i.e., constant future climate conditions).

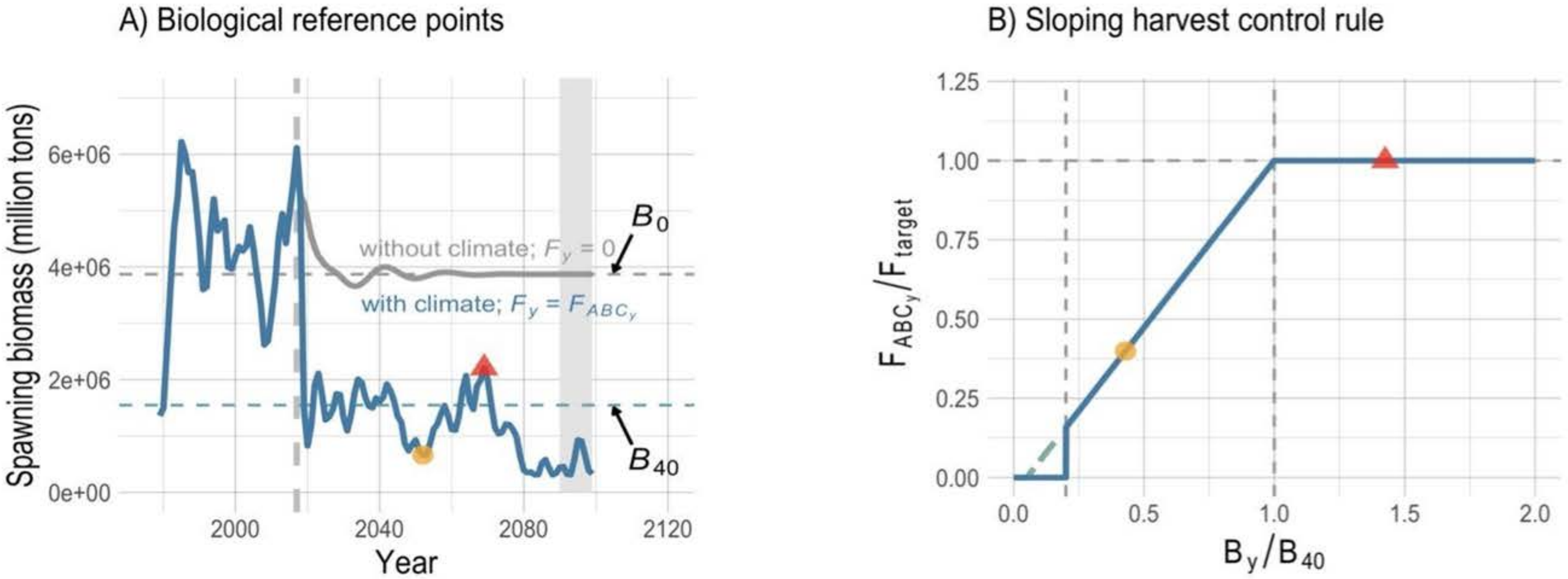
2. Determined average climate-naive B_0 values in years 2095-2099 by projecting the model forward without harvest (i.e. F = 0) for each species under the persistence scenario (i.e., mean historical climate conditions).

3. Iteratively solve for $F_{40\%,}$ i.e., the harvest rate that results in an average spawning biomass ($B40_{\%}$) during 2095-2099 that is 40% of B_0 for pollock and Pacific cod simultaneously with arrowtooth flounder set to the historical average (as arrowtooth flounder is a major predator of pollock and historical F for arrowtooth flounder is much lower than $F_{40\%}$)
4. Once $F_{40\%}$ for pollock and Pacific cod are found, iteratively solve for $F_{40\%}$ for arrowtooth flounder.
   For 3 and 4 include the constraint that $SSB_F > SSB_{35\%}$ during the projection period. ("Target B/B0").

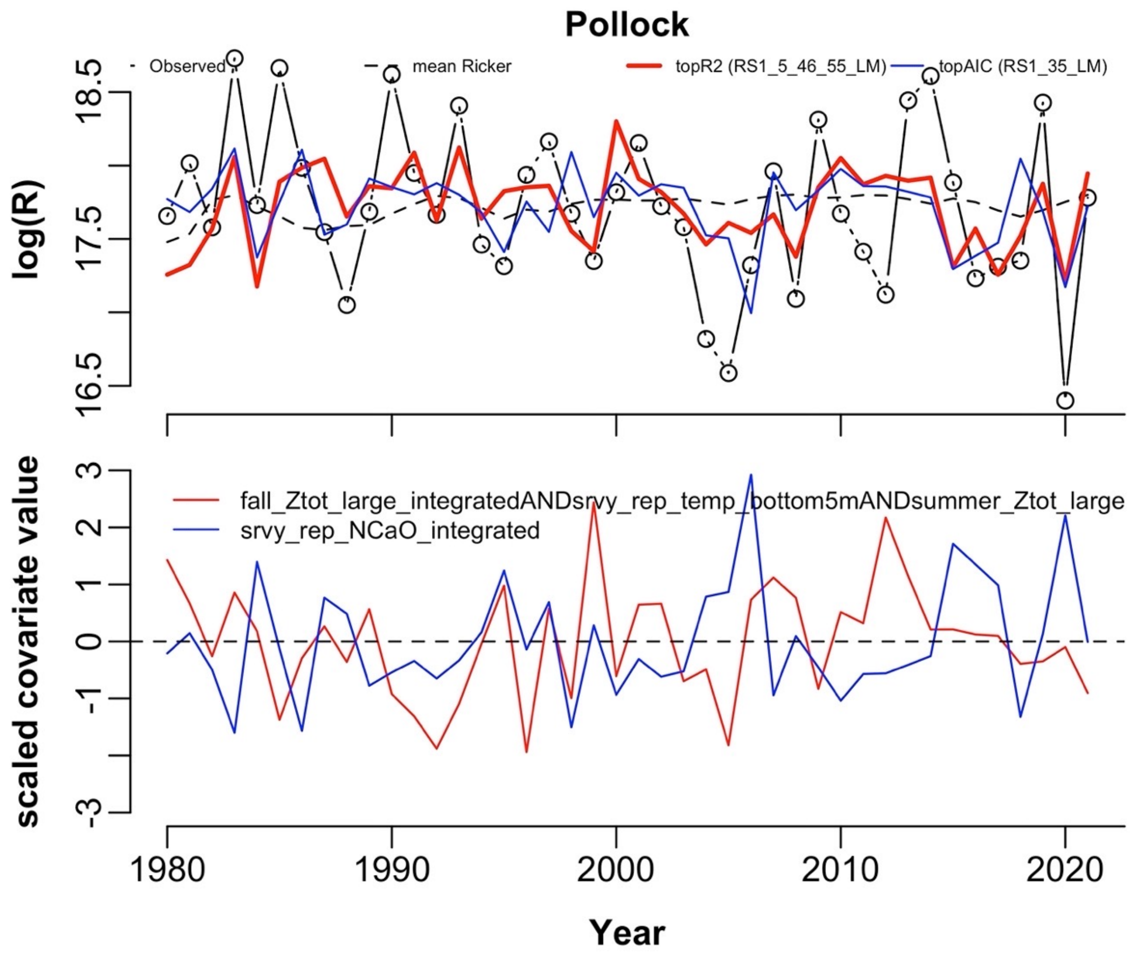
5. *Use the corresponding ABC proxy (catch that corresponds to F_{Target}) reproject WITH climate effects under each scenario to determine the F_{ABC} (and given the sloping harvest control rule)*

ABC Climate-informed approach (Holsman et al. 2020 a,b)

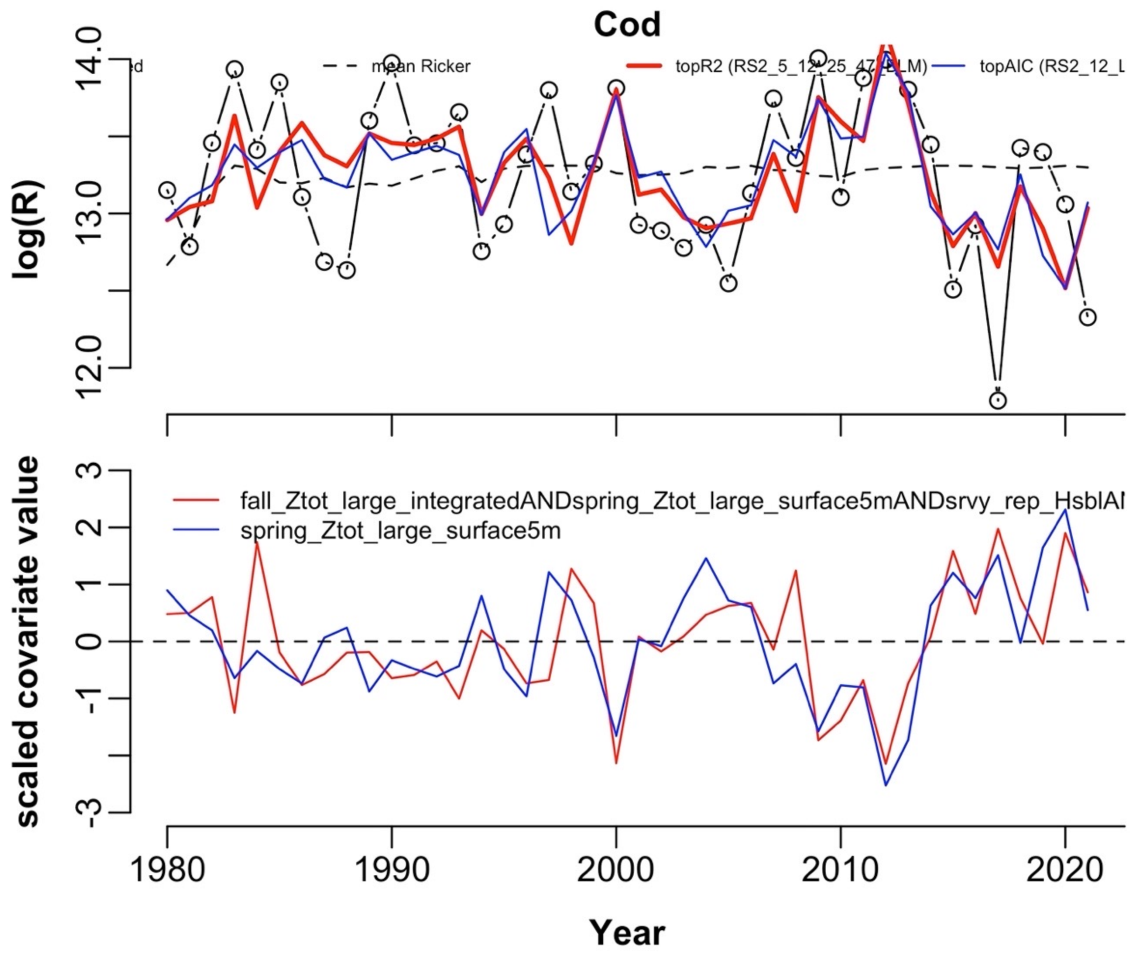
Climate naive B0/B40 and climate informed ABC



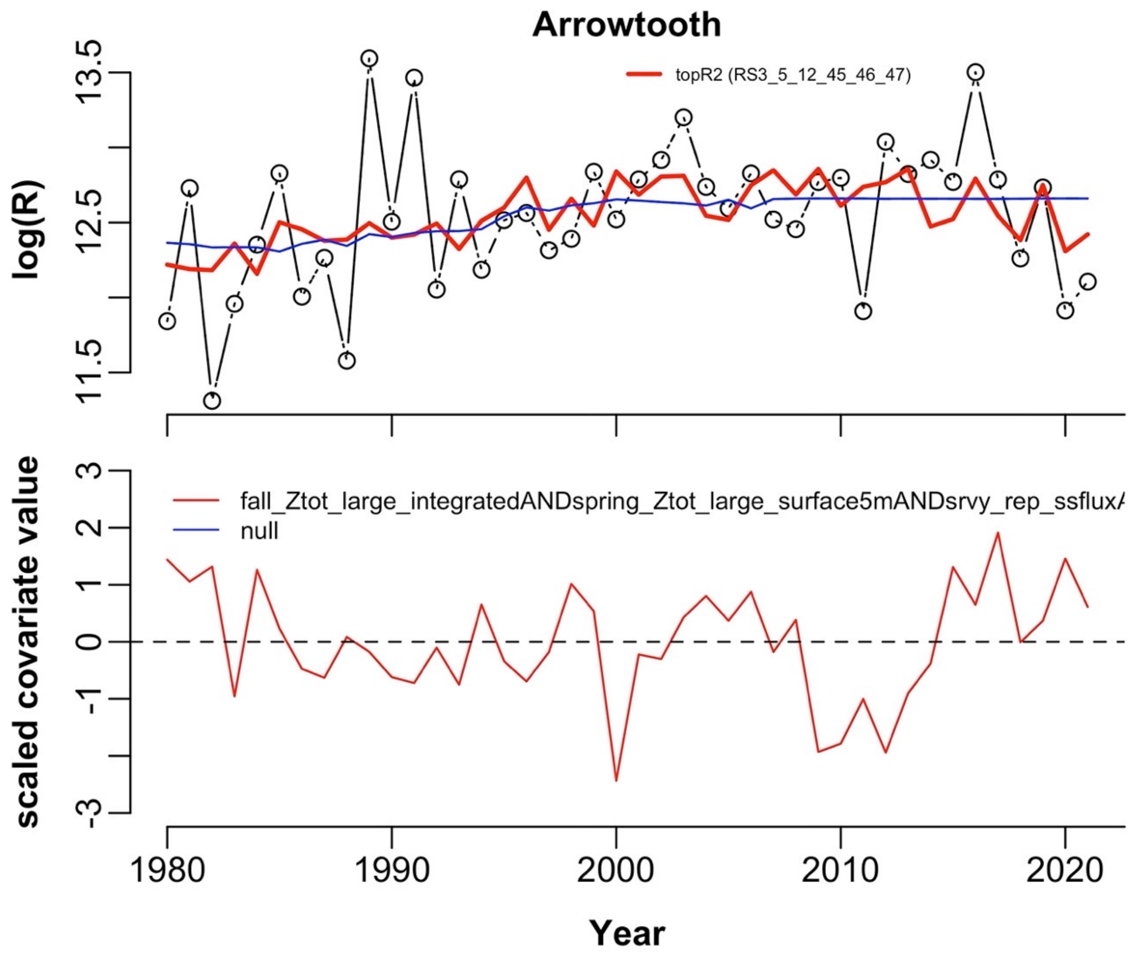
Recruitment



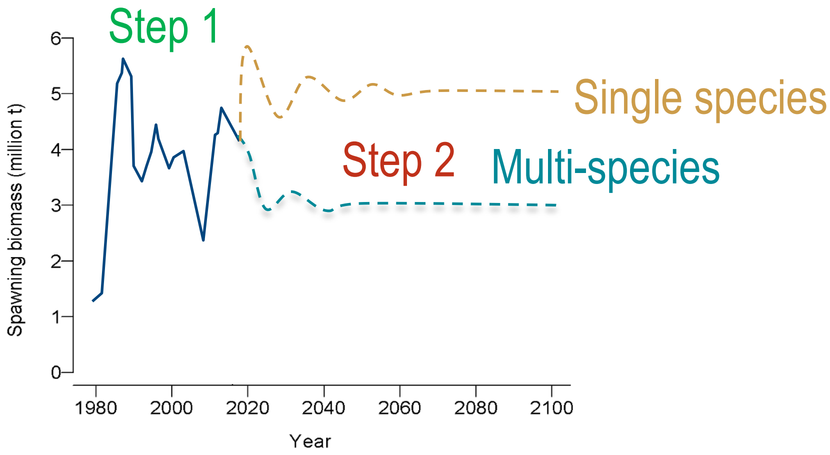
Recruitment



Recruitment

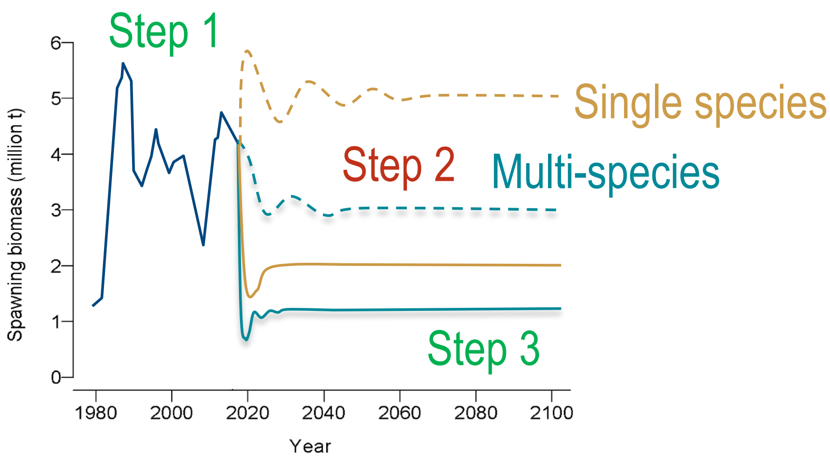


Climate informed approach to ABC



Eq. 4 $$\text{ABC}_{x,i,y} = \sum_j^{A_i}((F^*_{\text{ABC},x,i} s^{\text{f}}_{ij}/Z_{x,ij,y})(1 - e^{-Z_{x,ij,y}})N_{x,ij,y}W_{ij,y})$$

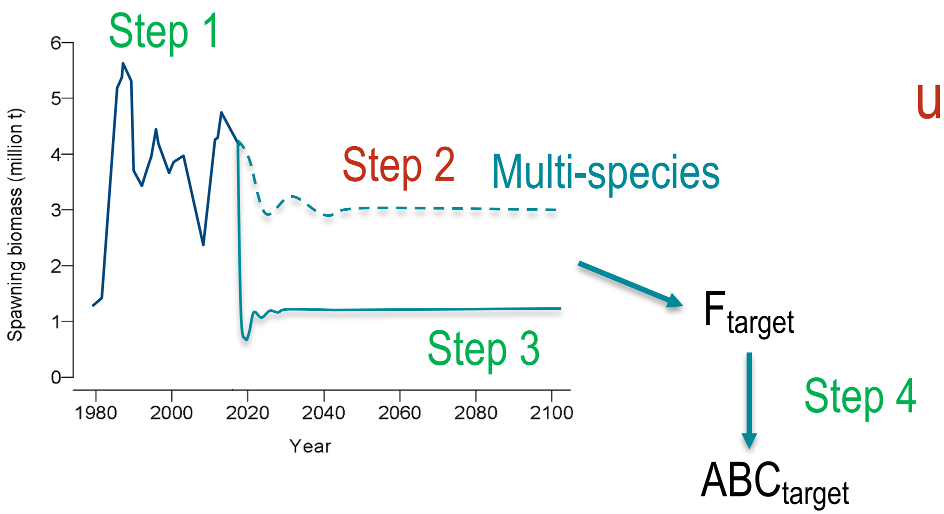
Climate informed approach to ABC



Find F that results in 40% unfished biomass in year 2100 with the restriction $B_{F,y}$ > 03.35% $B_{0,2100}$

$$\text{Eq. 4} \qquad \mathrm{ABC}_{x,i,y} = \sum_{j}^{A_i}((F^{*}_{\mathrm{ABC},x,i} s^{\mathrm{f}}_{ij} / Z_{x,ij,y})(1 - e^{-Z_{x,ij,y}}) N_{x,ij,y} W_{ij,y})$$

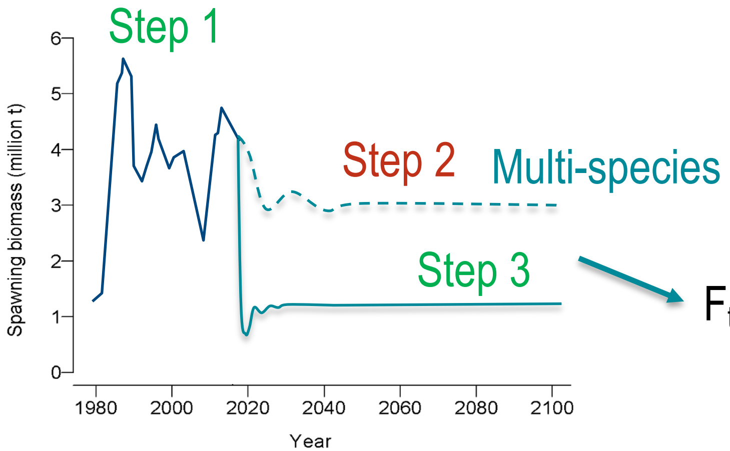
Climate informed approach to ABC



Find F that results in 40% unfished biomass in year 2100 with the restriction $B_{F,y}$ > 03.35% $B_{0,2100}$

$$\text{Eq. 4} \qquad \mathrm{ABC}_{x,i,y} = \sum_{j}^{A_i}((F^{*}_{\mathrm{ABC},x,i} s^{\mathrm{f}}_{ij} / Z_{x,ij,y})(1 - e^{-Z_{x,ij,y}}) N_{x,ij,y} W_{ij,y})$$

Climate informed approach to ABC



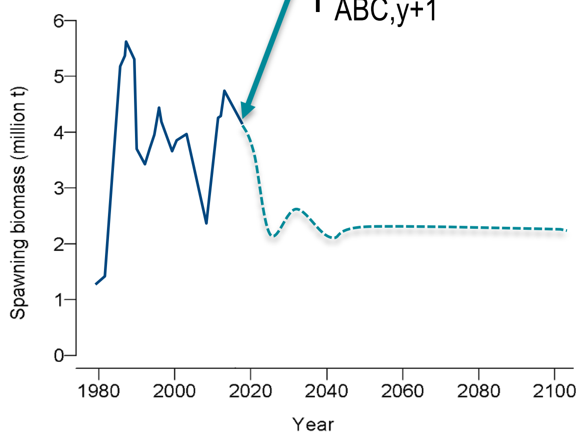
Find F that results in 40% unfished biomass in year 2100 with the restriction $B_{F,y}$ > 03.35% $B_{0,2100}$

F_{target}

Step 4

ABC_{target}

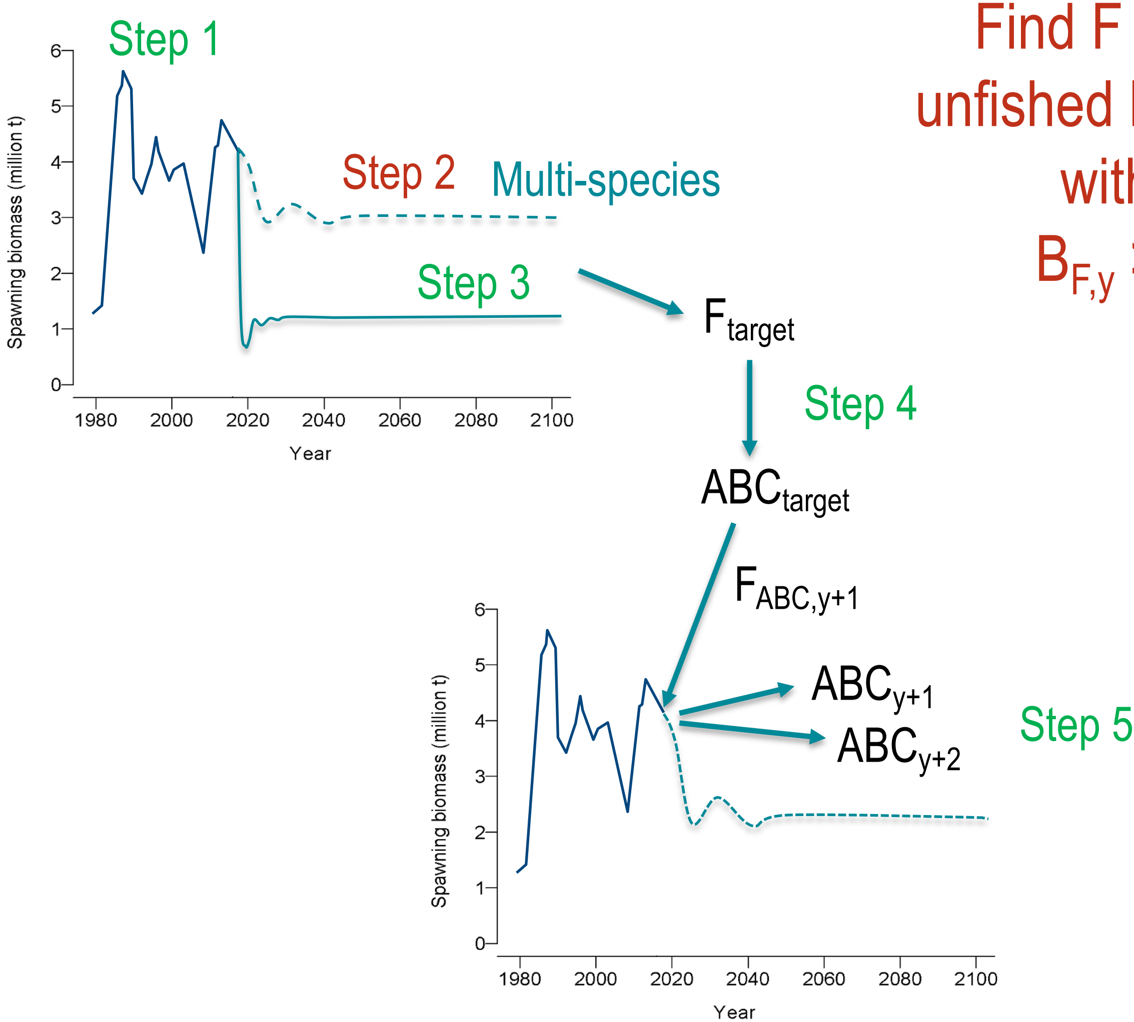
$F_{ABC,y+1}$



Eq. 4 $$ABC_{x,i,y} = \sum_{j}^{A_i}((F^*_{ABC,x,i} s^{f}_{ij} / Z_{x,ij,y})(1 - e^{-Z_{x,ij,y}}) N_{x,ij,y} W_{ij,y})$$

Climate informed approach to ABC

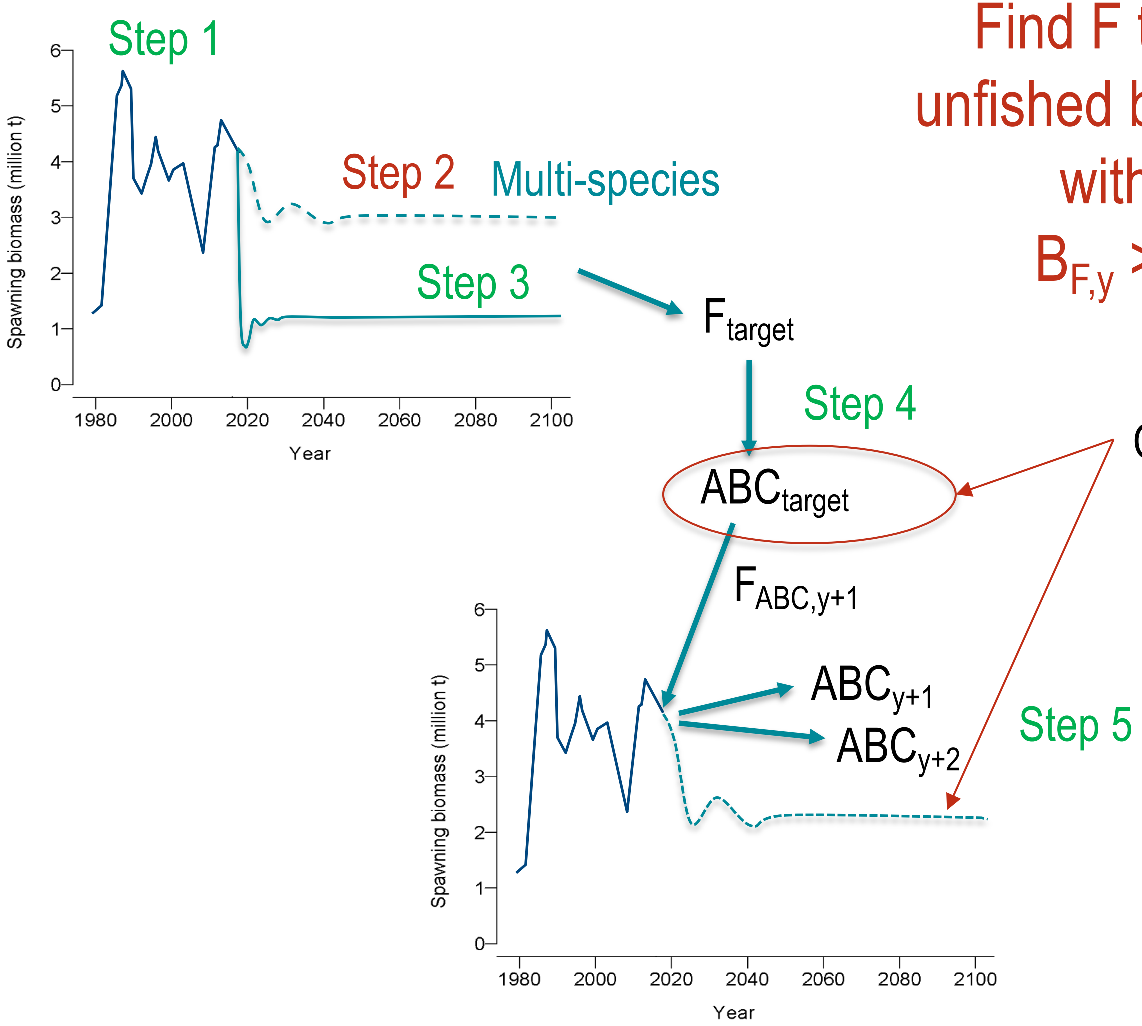
Find F that results in 40% unfished biomass in year 2100 with the restriction $B_{F,y} > 03.35\%\ B_{0,2100}$



Eq. 4 $$ABC_{x,i,y} = \sum_j^{A_i}((F^*_{ABC,x,i}s^{f}_{ij}/Z_{x,ij,y})(1-e^{-Z_{x,ij,y}})N_{x,ij,y}W_{ij,y})$$

Climate informed approach to ABC

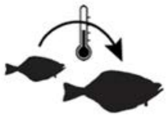
Find F that results in 40% unfished biomass in year 2100 with the restriction $B_{F,y} > 03.35\%\ B_{0,2100}$



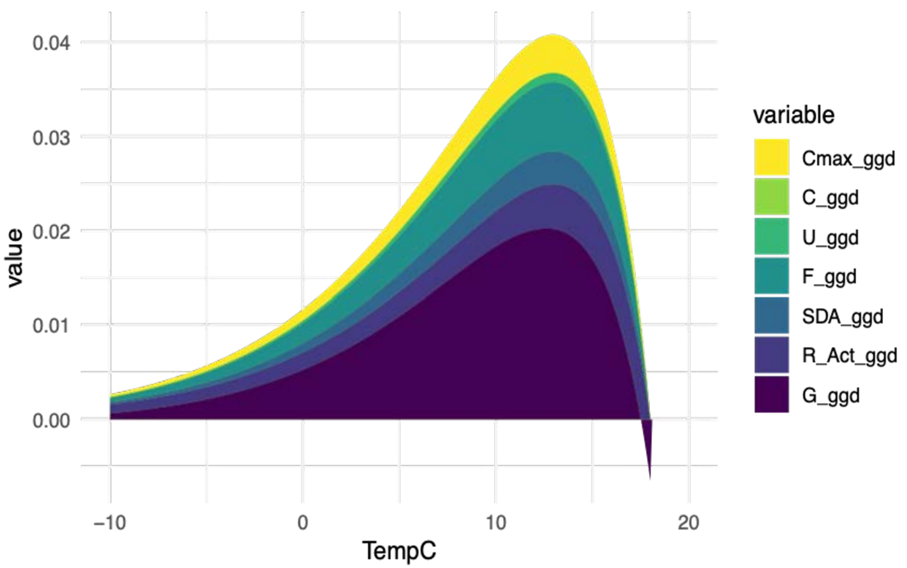
Could be climate ensemble

$$\text{Eq. 4} \qquad ABC_{x,i,y} = \sum_j^{A_i}((F^*_{ABC,x,i} s^{f}_{ij}/Z_{x,ij,y})(1 - e^{-Z_{x,ij,y}})N_{x,ij,y}W_{ij,y})$$

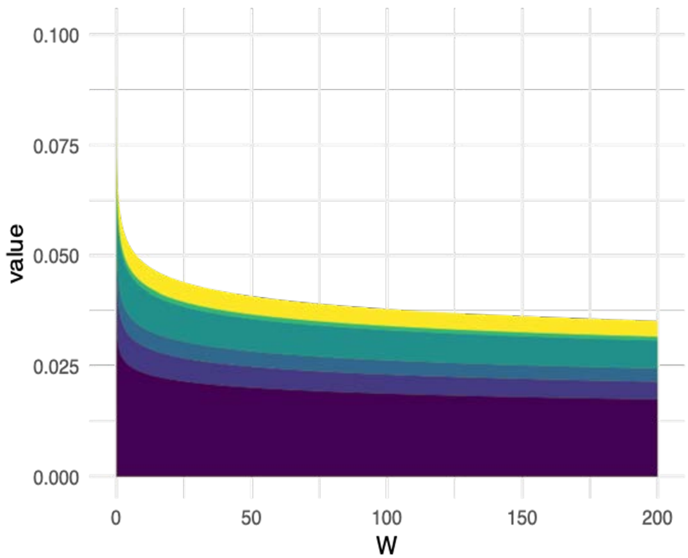
Bioenergetics



Temperature Specific Rates



Allometric rates



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