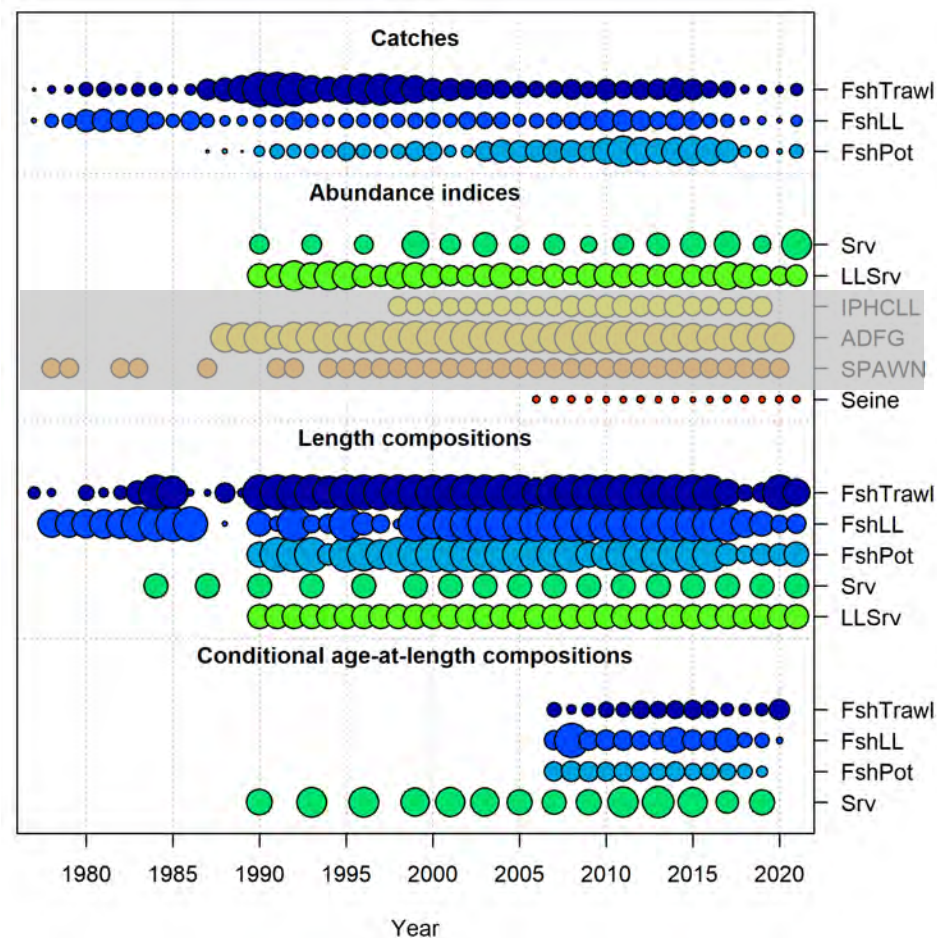


Gulf of Alaska Pacific cod



**Steven Barbeaux, Bridget Ferriss, Ben Laurel, Mike Litzow,
Susanne McDermott, Julie Nielsen, Wayne Palsson, Kalei
Shotwell, Ingrid Spies, and Muyin Wang**

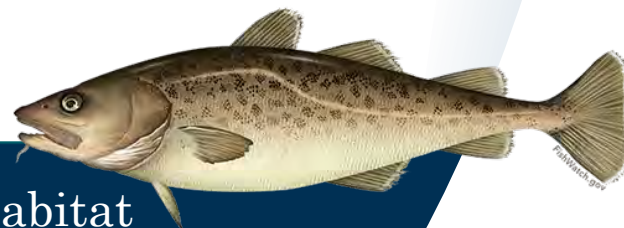
November 2021



- Federal and state catch data updated;
- Fishery size composition data updated;
- Bottom trawl survey abundance and length composition data for 2021 included;
- Longline survey abundance index and length composition data for 2021 were included;
- Age-0 beach seine survey index was included in one alternative model.

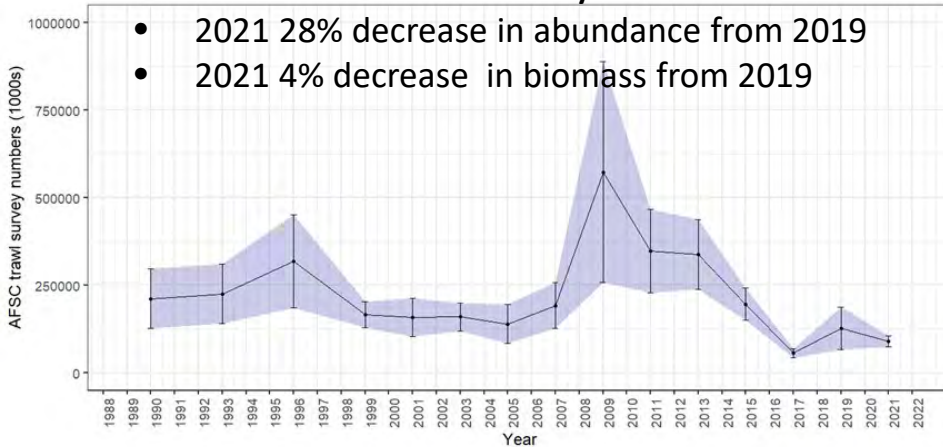
2021 data changes

- IPHC Longline, ADF&G trawl, and the spawning habitat indices were included in the data files, however they are not included in any model likelihood.

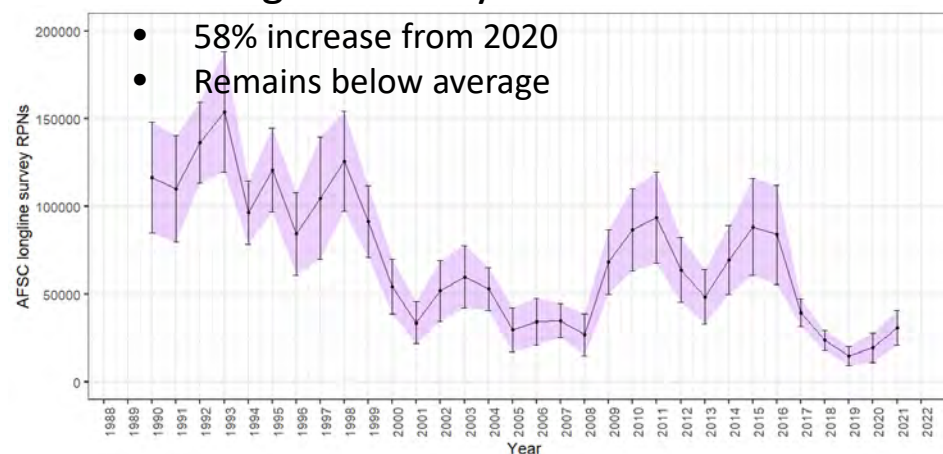


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AFSC bottom trawl survey

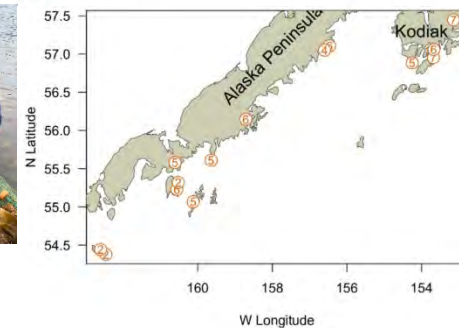
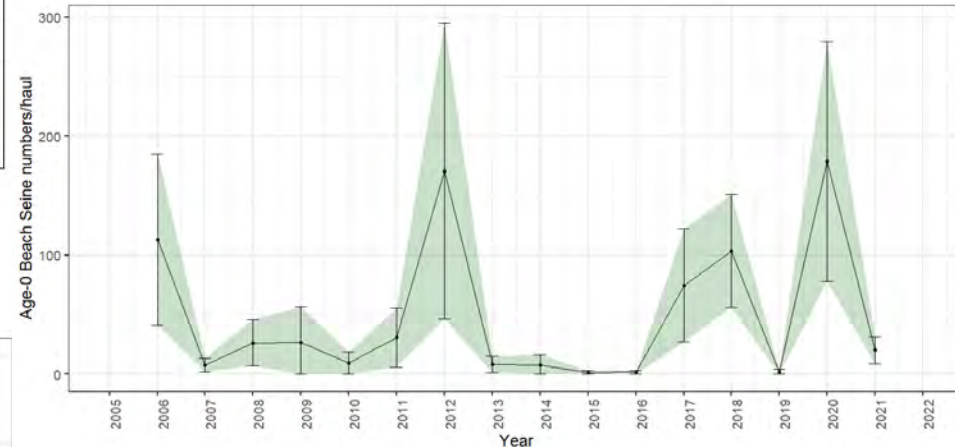


AFSC longline survey



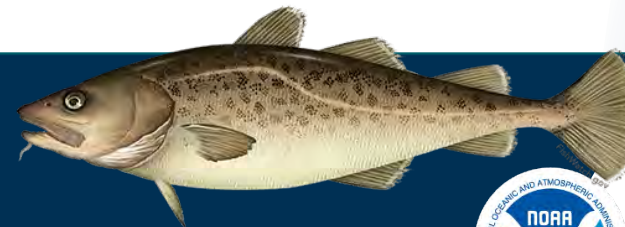
Age-0 beach seine survey

- Low 2013-2016 and 2019
- High 2012, 2017, 2018 and 2020
- Near average 2021

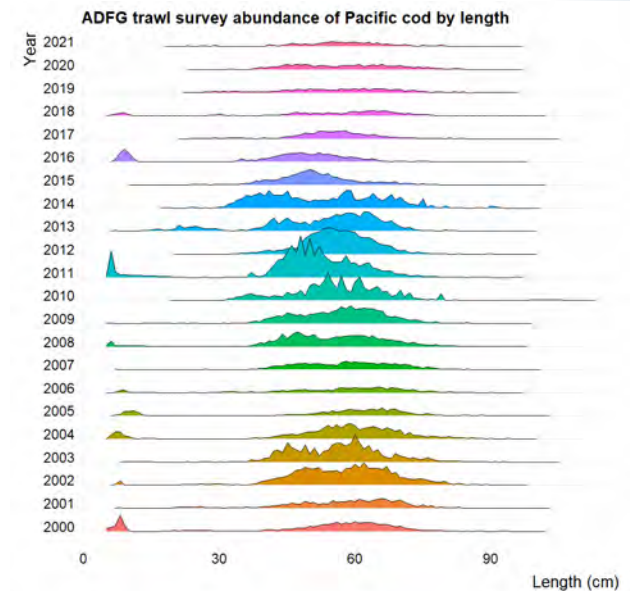
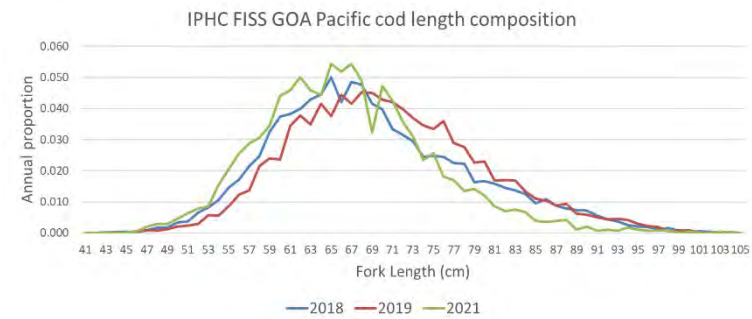
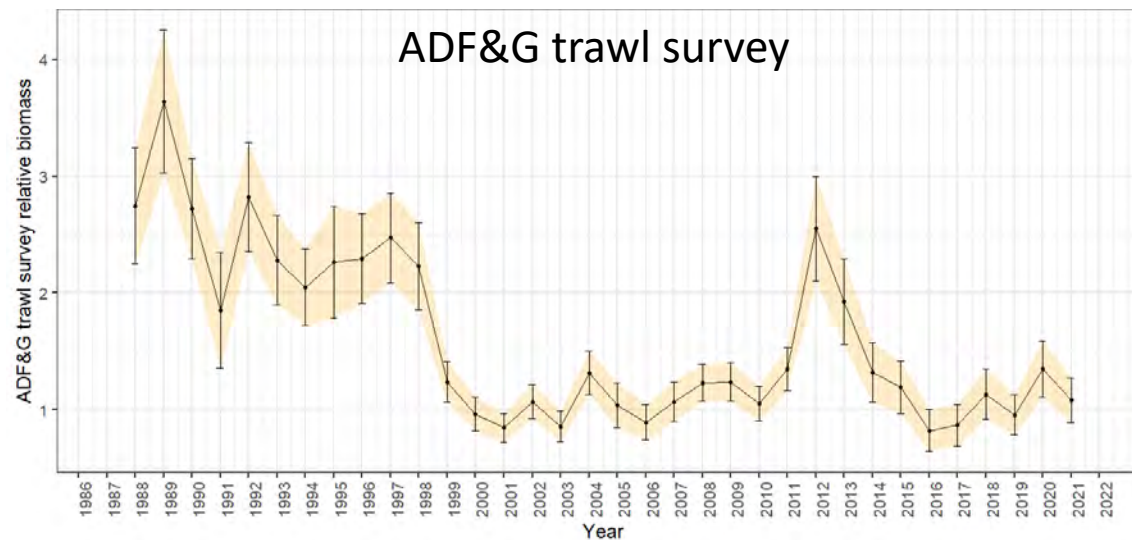
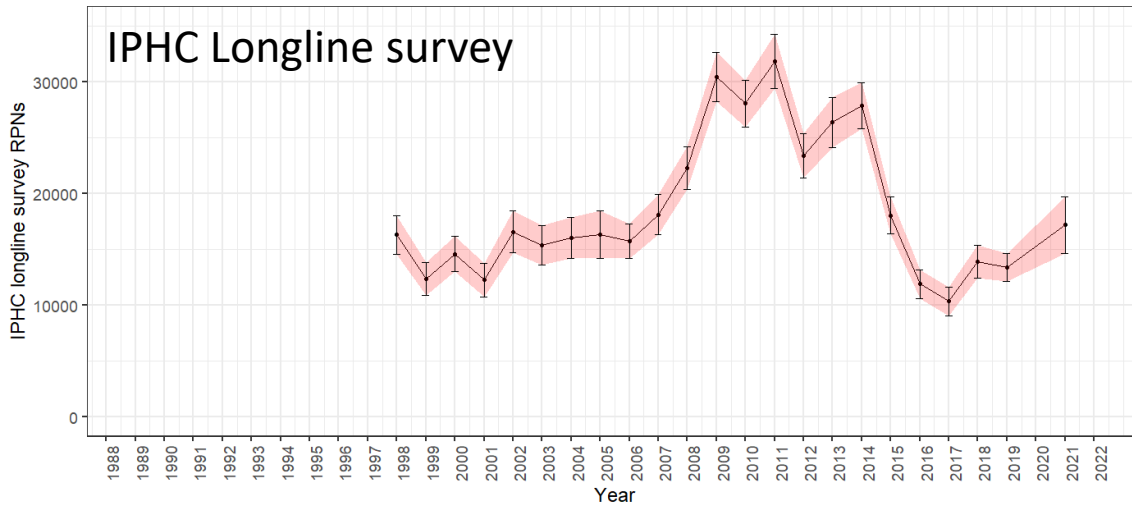


Survey indices

- Mixed signals from adult surveys
- Age-0 survey new to assessment



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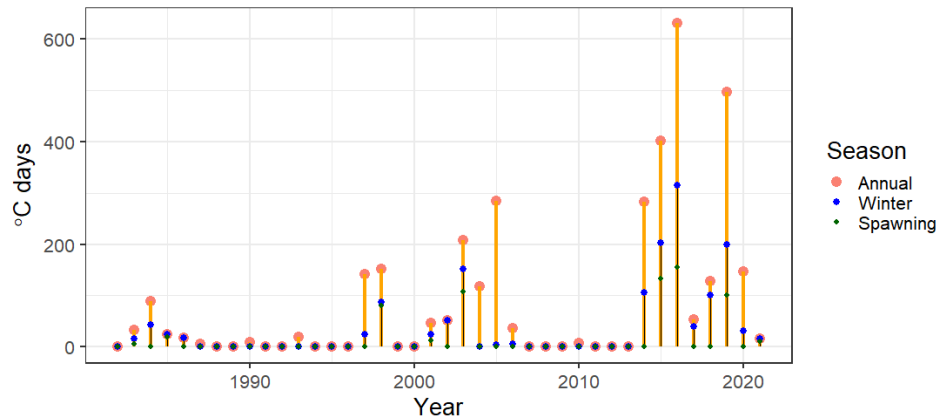
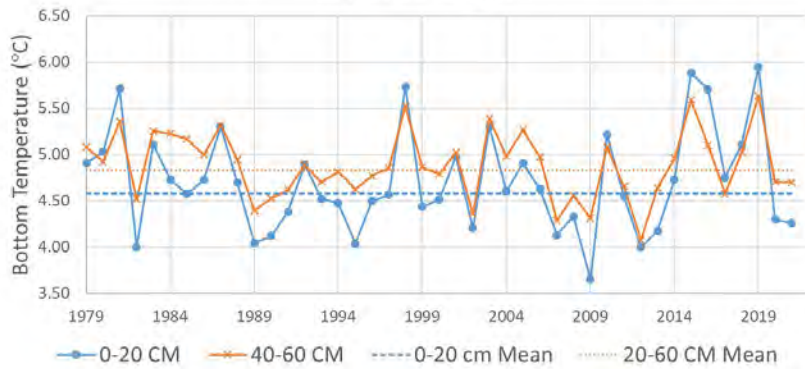
Other Surveys (not included in models)

- IPHC Longline
 - 28% increase from 2019
- ADF&G trawl indices.
 - 19.8% decrease from 2020

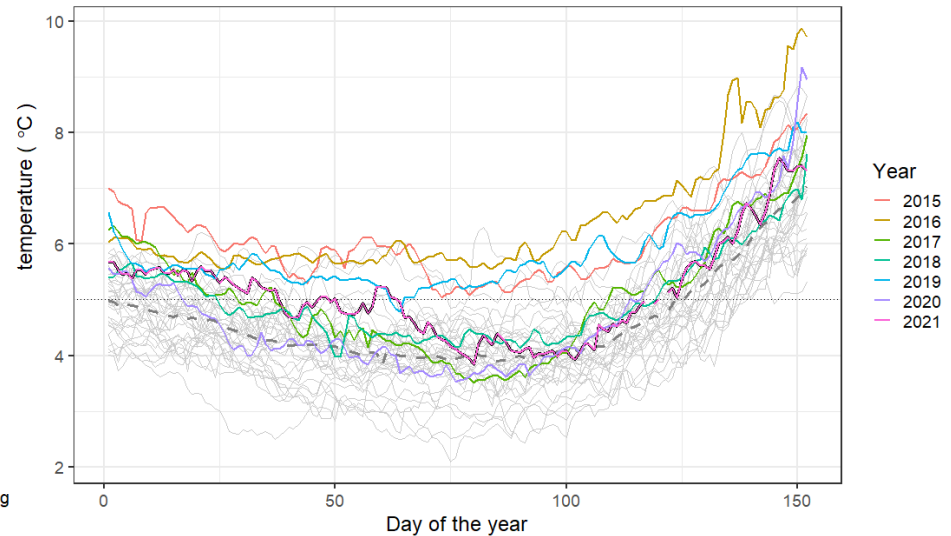


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CFSR Temperatures in June for Pacific cod at mean depth for length



January through May 1981-2021

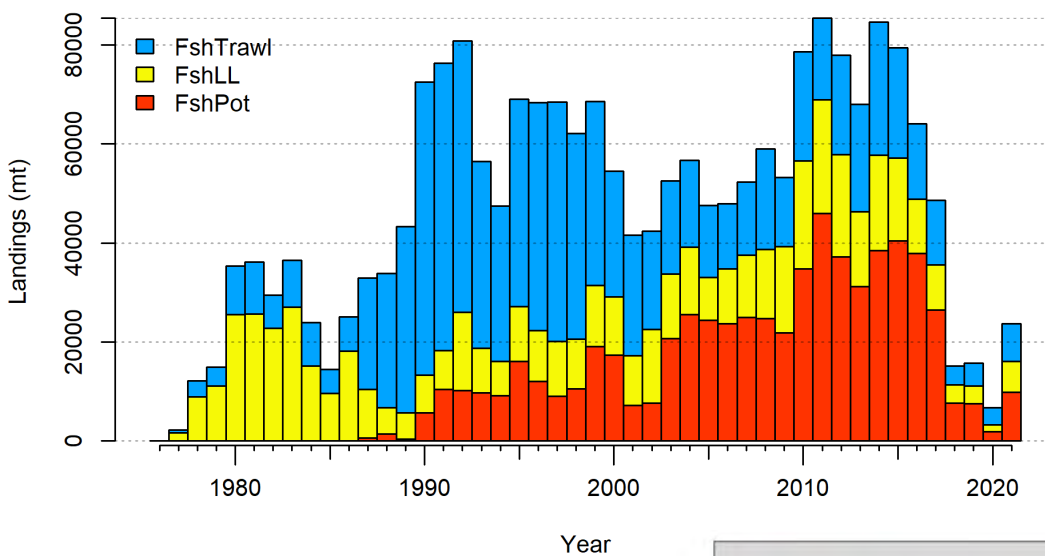


Environmental Indices used in models

- CFSR Temperatures for 0-20cm Pacific cod
 - Cooler in 2020 and 2021
- Heatwave indices
 - Short and low intensity heatwave in Jan-Feb 2021
 - Cooler for remainder of year

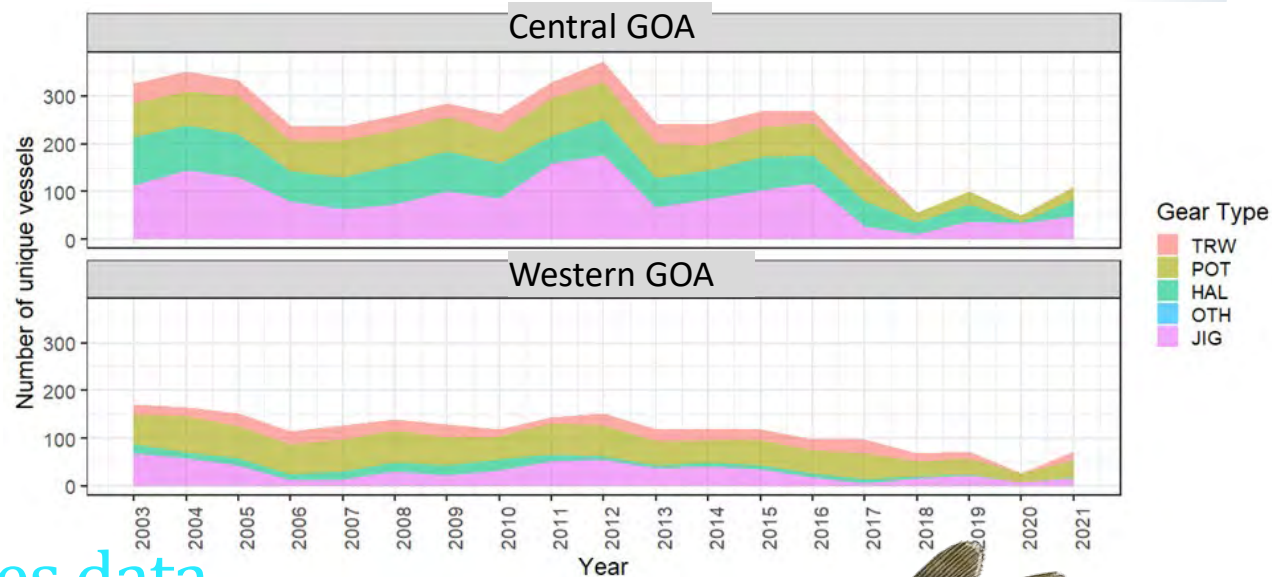


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2020 Total catch = 6,233 t
 2021 Total Catch = 18,040 t*
 *As of Nov 15

- Overall descending trend in participation
- More vessels targeting cod in 2021 than 2020



Commercial fisheries data

- Catch remains low, but increasing in 2021
- Number of participating vessels increased in both regions in 2021



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- **Model 19.1**
 - Same as last year's base model
- **Model 21.1**
 - Same as 19.1 except:
 - Natural mortality block for 2015-2017
- **Model 21.2**
 - Same as Model 19.1 except:
 - Age-0 beach seine index,
 - Annual heatwave linked Natural mortality,
 - Spawning heatwave linked recruitment,
 - June CFSR temp linked growth.

M-block 2015-2017	Temperature			Beach seine index
	Growth	M	Recruits	

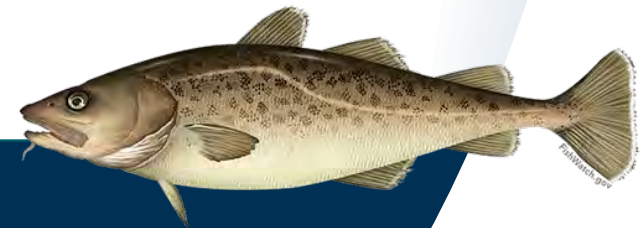
Base

21.1

21.2

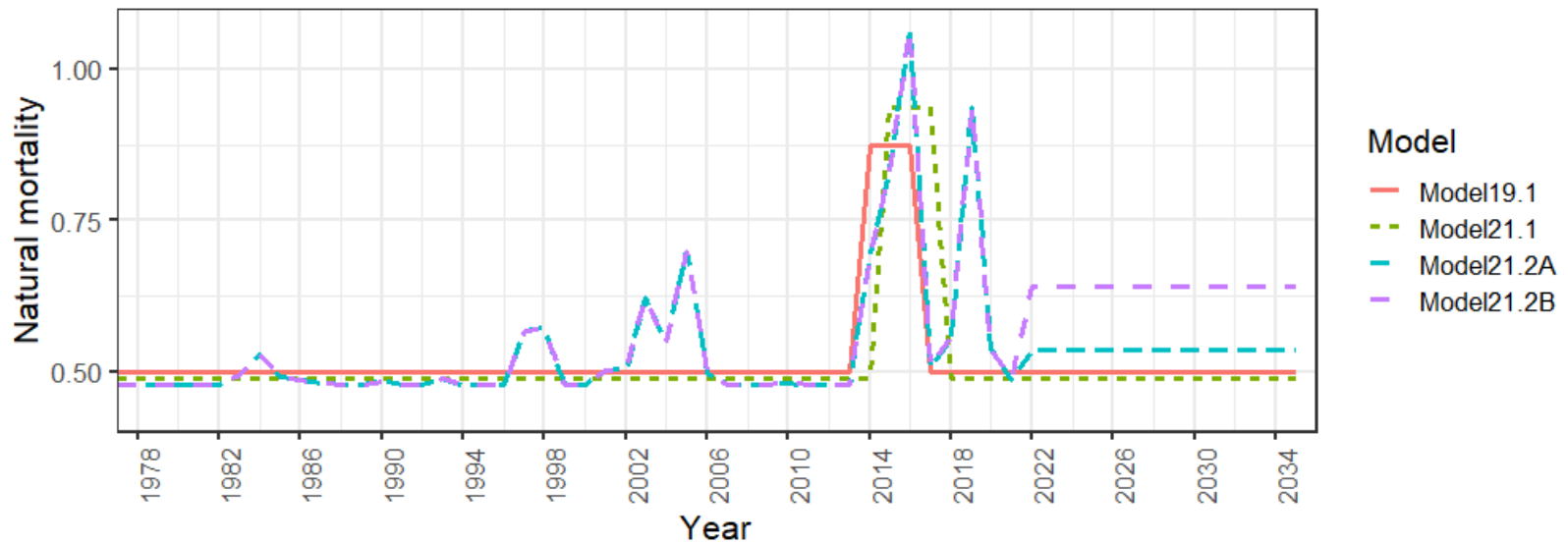
2021 model configurations

- Based on September, 2021 model explorations (Appendix 2.7)
- Note: Reweighting of models was not conducted as explorations using the Dirichlet multinomial indicated current were weights appropriate



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Natural mortality by model



- Model 21.2: annual heatwave linked natural mortality with asymptote

$$M_y = \hat{M} + \eta l_y$$

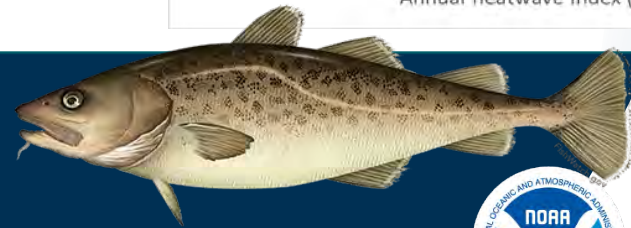
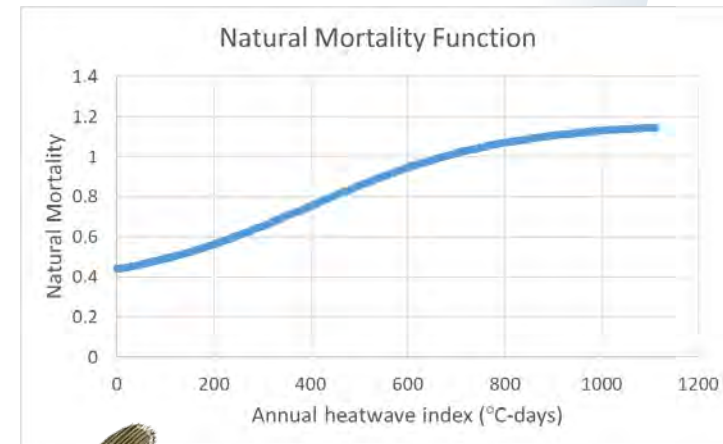
$$l_y = \lambda / \left(1 + e^{-\varsigma(I_{Ay} - \psi)} \right)$$

- Logistic function fit iteratively

- $\lambda = 0.65$
- $\varsigma = 0.05$
- $\psi = 400$

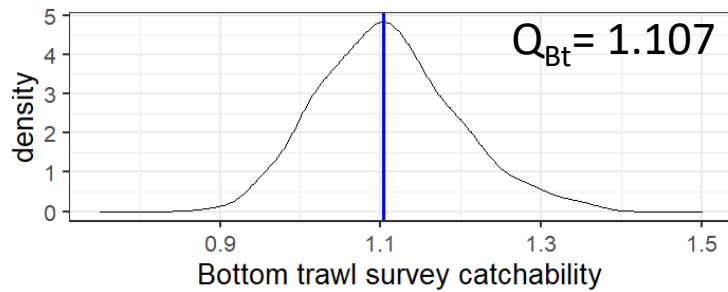
Natural Mortality

- 19.1 – 2014-2016 block
- 21.1 – 2015-2017 block
- 21.2 – Annual heatwave index link

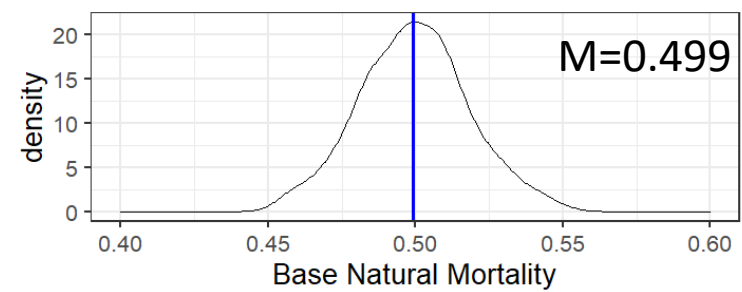


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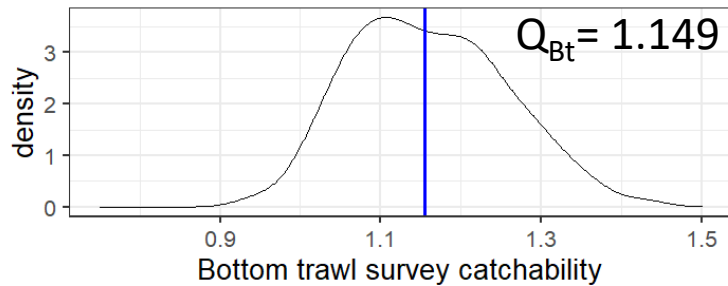
Model 19.1



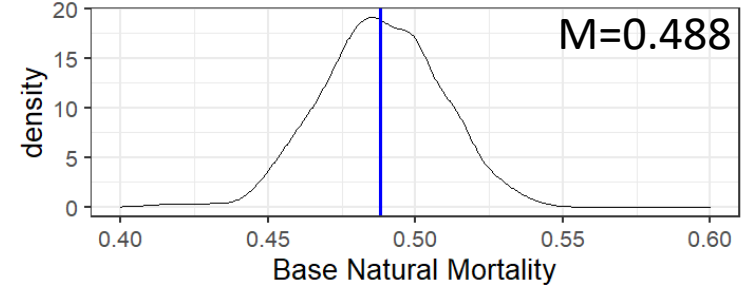
Model 19.1



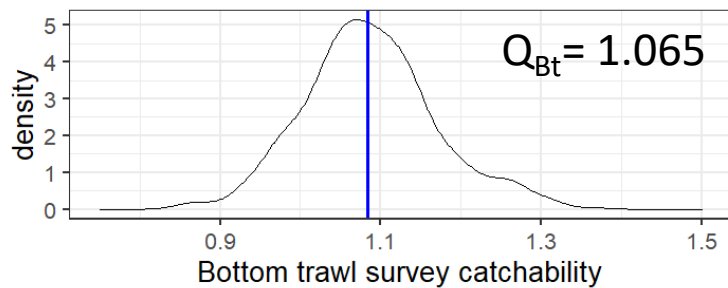
Model 21.1



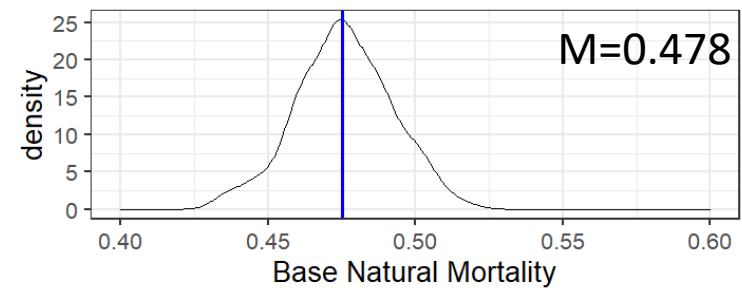
Model 21.1



Model 21.2



Model 21.2

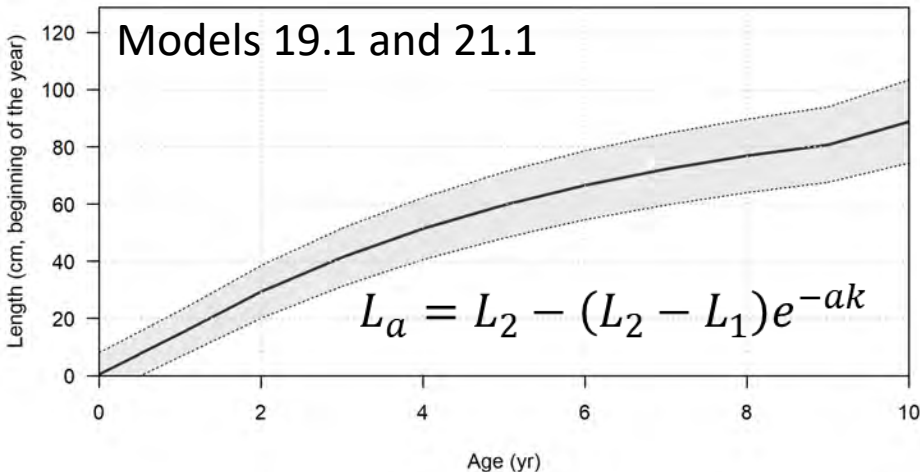


Posterior catchability and natural mortality

- Similar bottom trawl survey abundance index catchability (Q_{Bt})
 - Posterior distributions are wide
 - Lowest estimate from Model 21.2
- Lowest base natural mortality in Model 21.2



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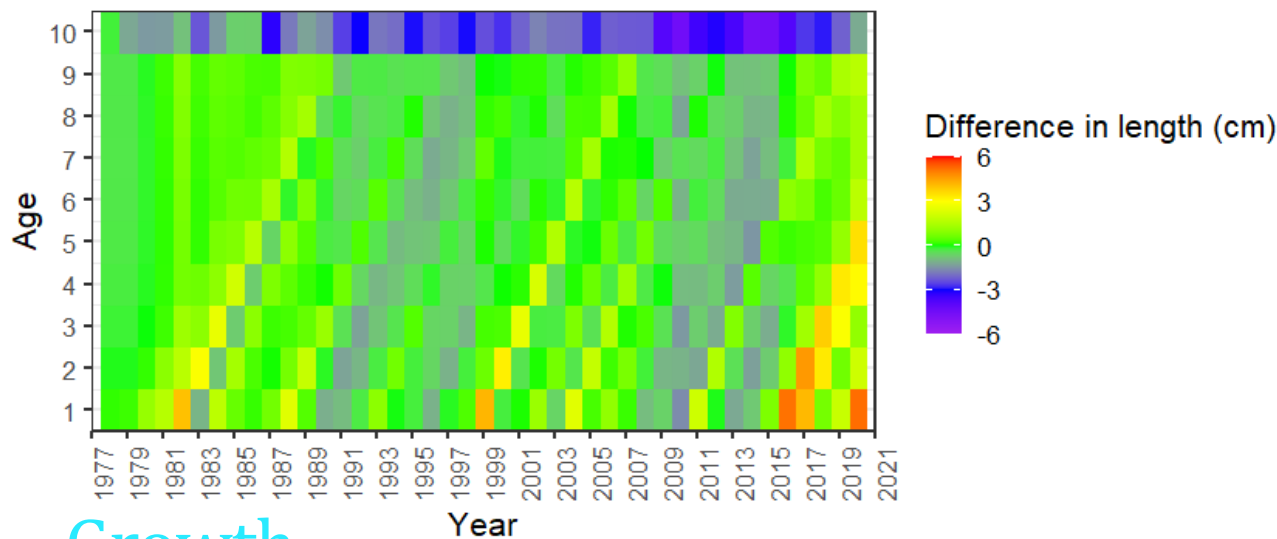
Models 21.2

$$L_{ay} = L_{2y} - (L_{2a} - L_{1a})e^{-ak}(e^{-\varphi f_{jy}})$$

$$L_{1a} = \bar{L}_1 \left(\gamma \frac{e^{(0.2494 + 0.3216(\bar{t} + f_{jy}) - 0.0069(\bar{t} + f_{jy})^2 - 0.0004(\bar{t} + f_{jy})^3)}}{e^{(0.2494 + 0.3216(\bar{t}) - 0.0069(\bar{t})^2 - 0.0004(\bar{t})^3)}} \right)$$

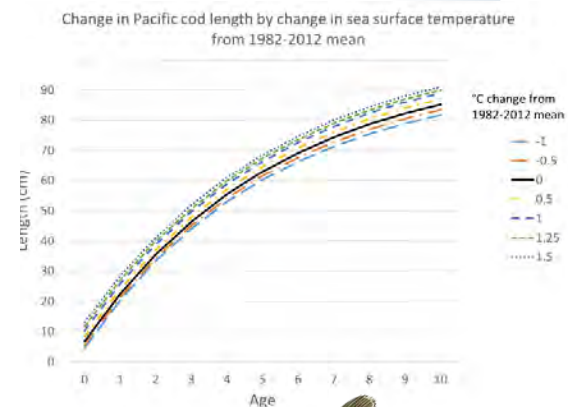
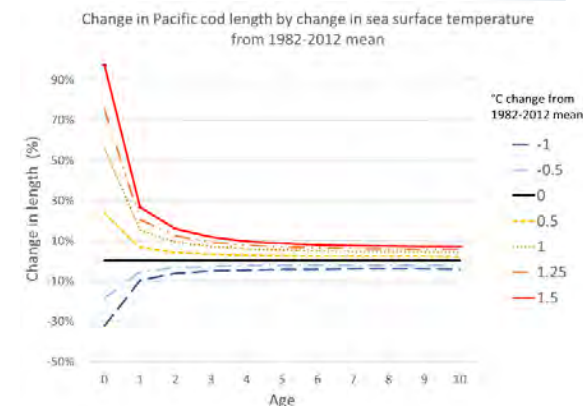
$$L_{2y} = \bar{L}_2 e^{\varphi f_{jy}}$$

Model 21.2 vs Model 19.1



Growth

- Model 19.1 and Model 21.1 standard von Bertalanffy growth
- Model 21.2 temperature dependent von Bertalanffy growth
 - L_{1a} based on Laurel et al. (2015) larval growth rate by temperature



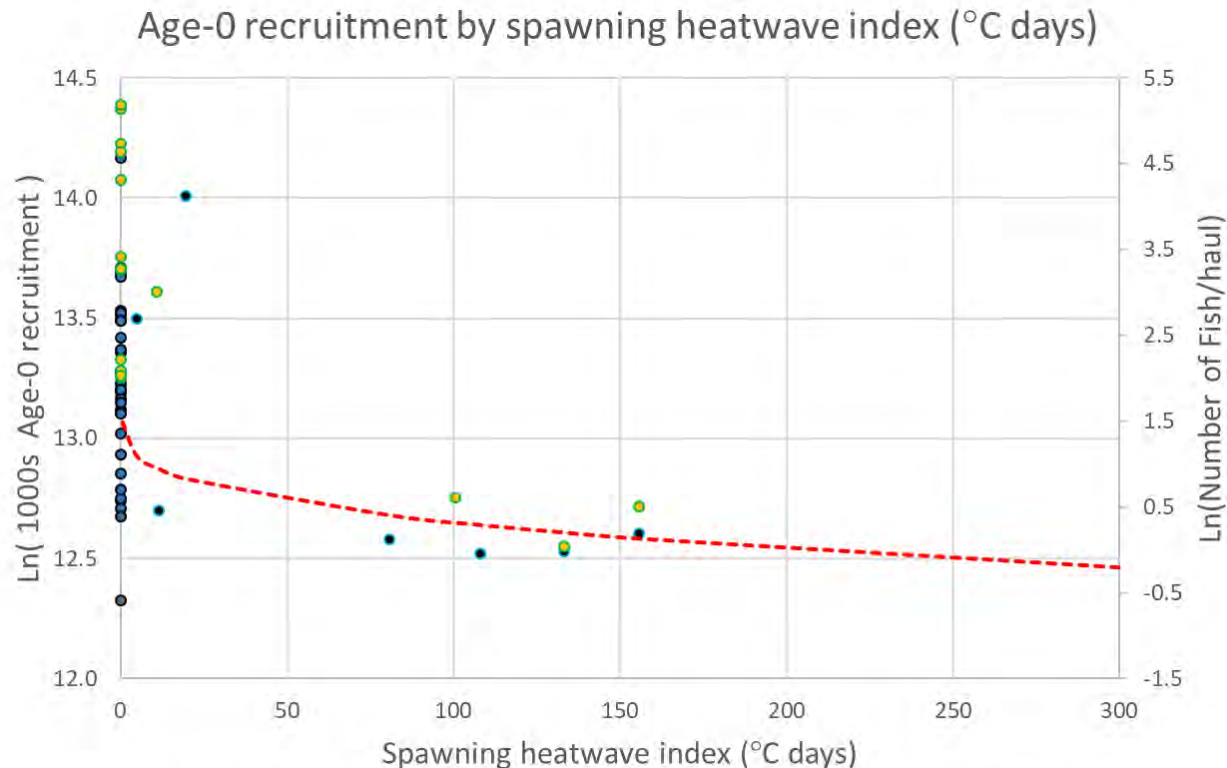
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Models 19.1 and 21.1

$$R_y = (R_0 e^{\vartheta}) e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}$$

Model 21.2

$$R_y = e^{\vartheta + \ln \left(R_0 e^{\omega I_{Sy}^{\frac{1}{3}}} \right)} e^{-0.5 b_y \sigma_R^2 + \tilde{R}_y}$$

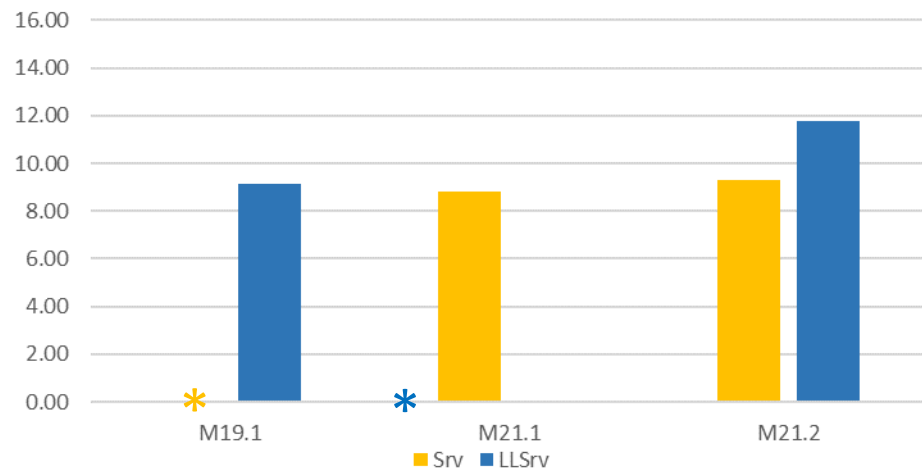


Recruitment

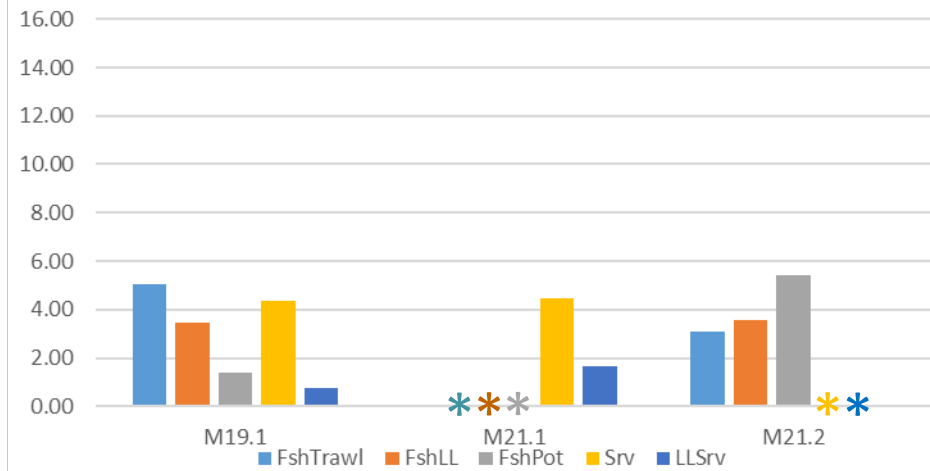
- Model 19.1 and Model 21.1 standard Beverton-Holt with steepness $h = 1$ and $\sigma_R = 0.44$
- Model 21.2 – Spawning heatwave index linked Beverton-Holt with steepness $h = 1$ and $\sigma_R = 0.44$



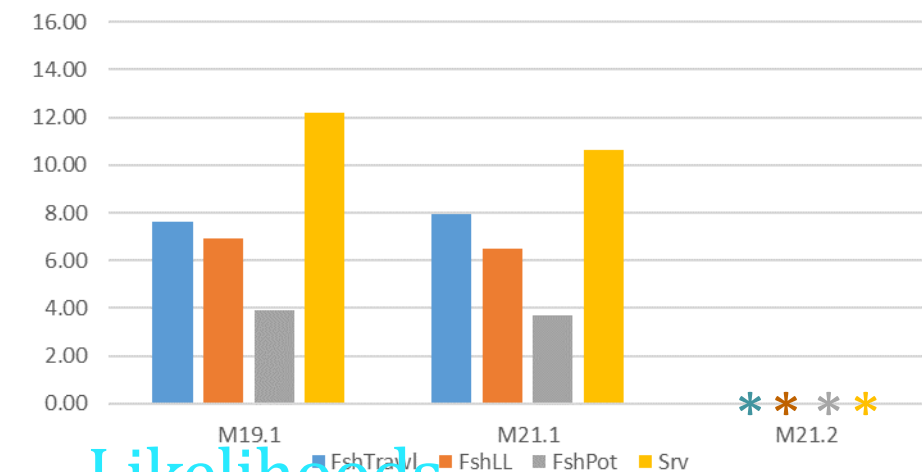
Indices



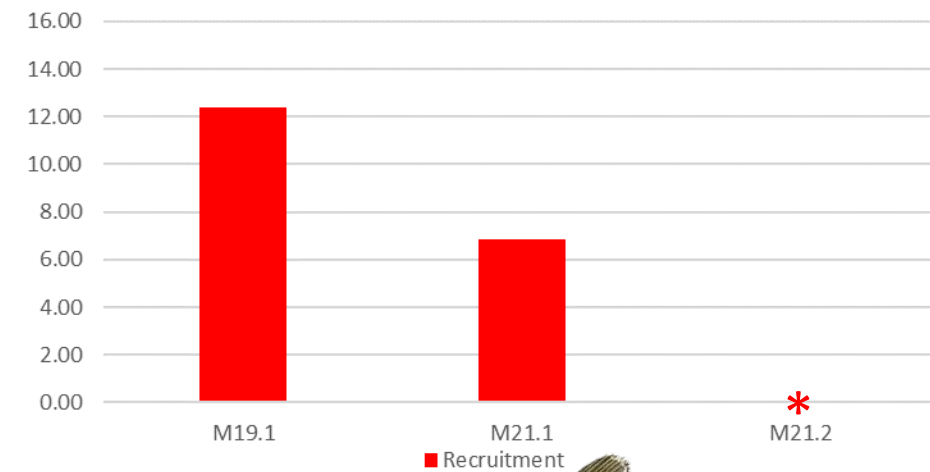
Length Composition



Conditional Length at age



Recruitment

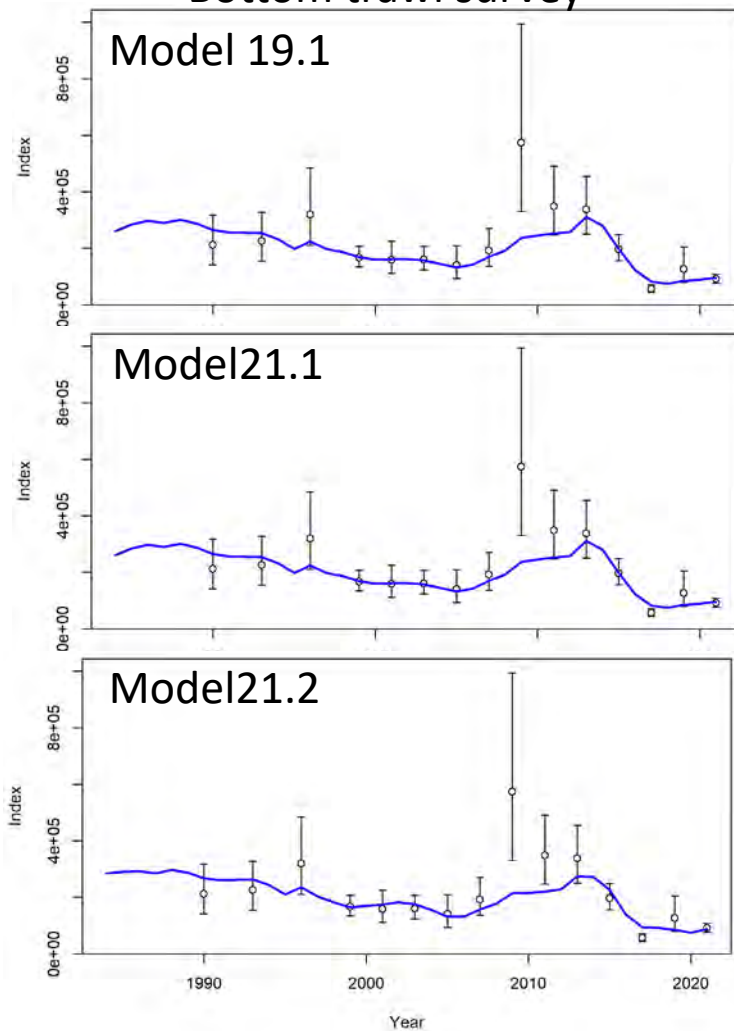


Likelihoods

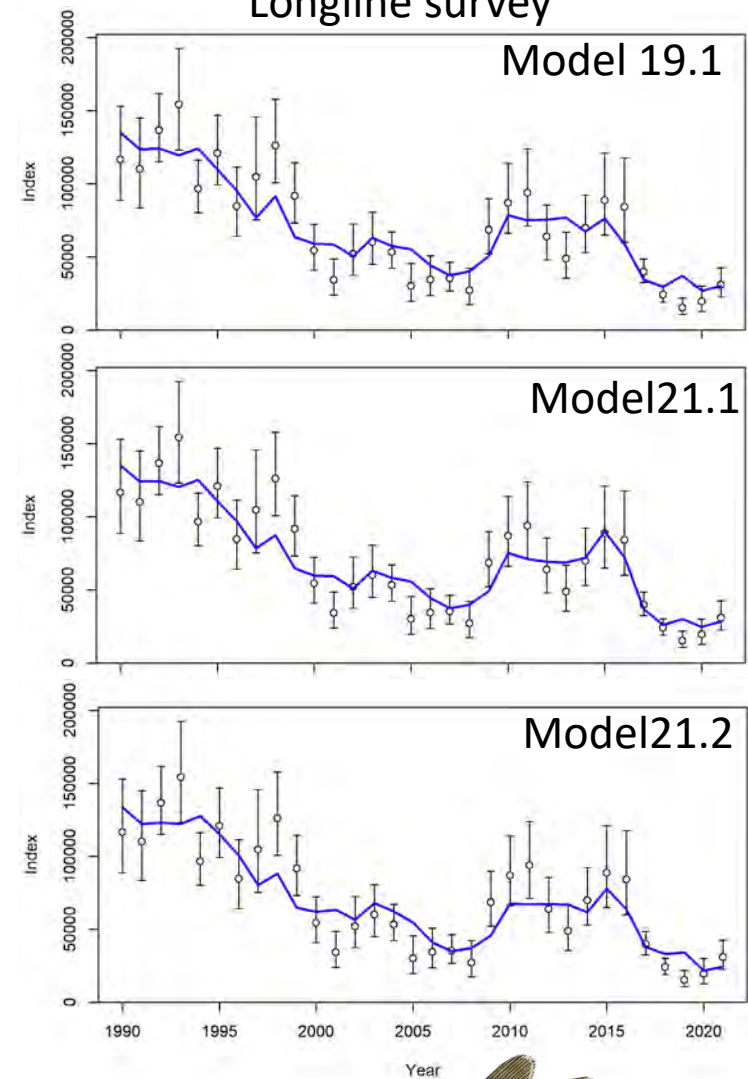
- Model 21.2 has best overall fit
 - Worst fit to trawl and longline survey indices
 - Best fit to Survey length composition
 - Best fit to length at age data
 - Best fit to Recruitment



Bottom trawl survey



Longline survey



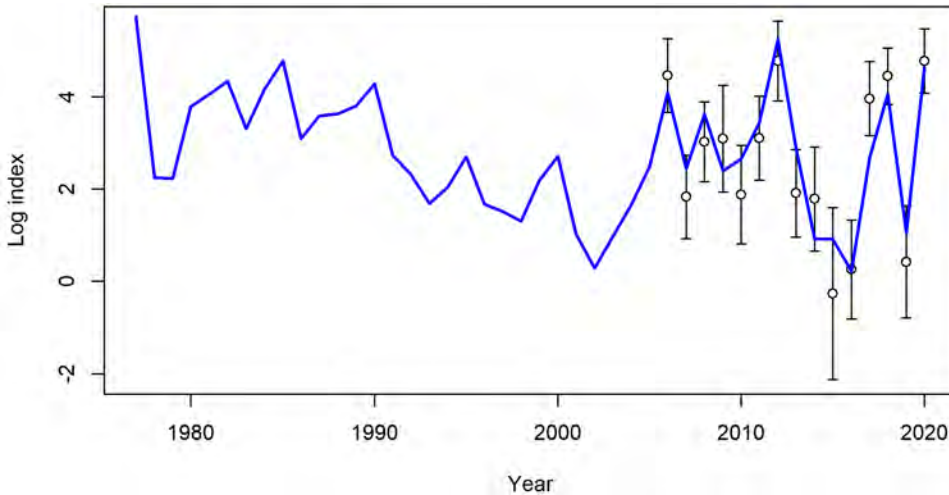
Survey index fits

- Model 19.1 better fit to bottom trawl survey
- Model 21.1 better fit to longline survey
- Model 21.2 included beach seine and fits both worse

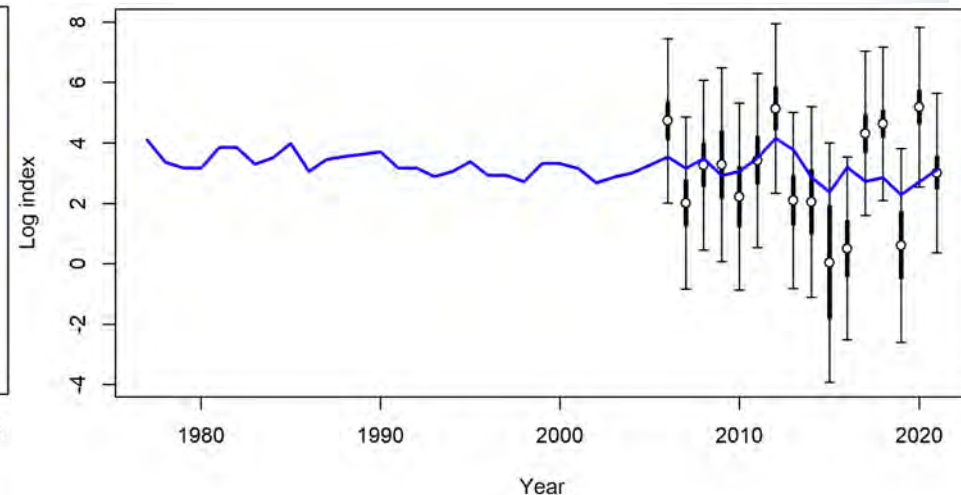


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September beach seine index fit



Model 21.2 beach seine index fit



Beach seine index

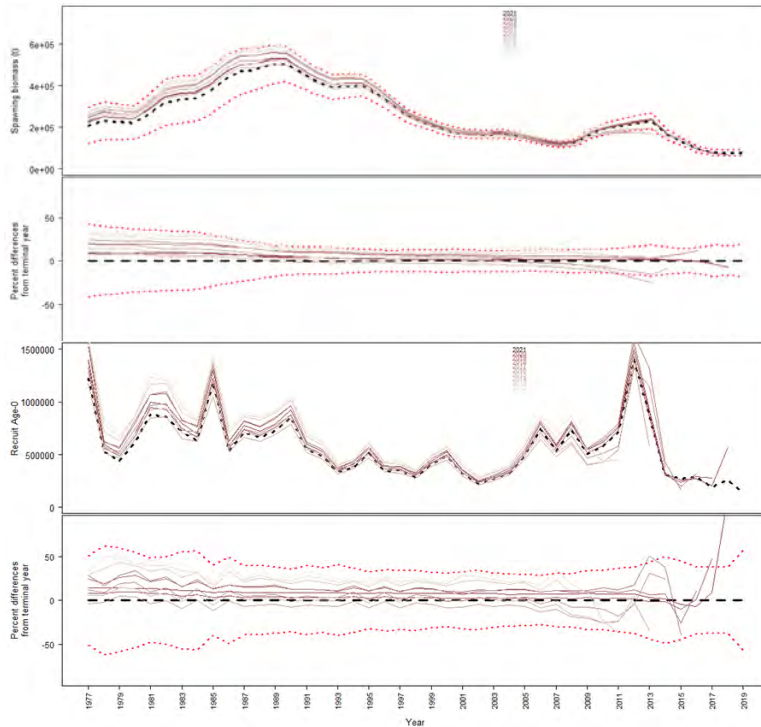
- Added constant fit to survey standard deviation as per SSC request
 - 138% increase in index standard deviation
 - Little influence in the model



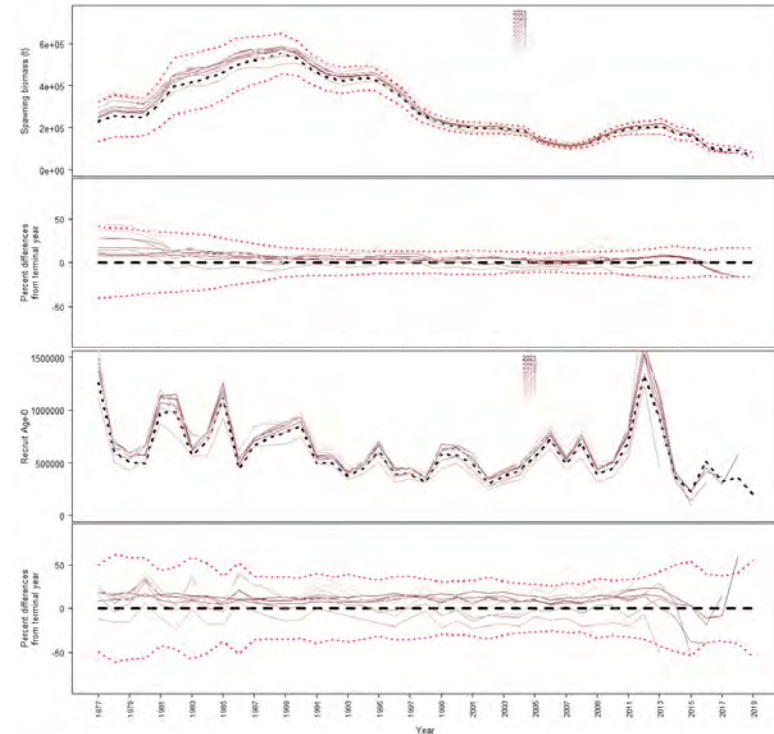
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	Spawning stock biomass			Age-0 Recruitment		
Model	Mohn's ρ	Woodshole ρ	RMSE	Mohn's ρ	Woodshole ρ	RMSE
19.1	-0.0002	0.0837	0.1159	0.1084	0.1195	0.1737
21.1	0.0440	0.1280	0.1476	0.0564	0.1339	0.1503
21.2	0.0557	0.0841	0.1230	0.0448	0.1034	0.1716

Model 19.1



Model 21.2



Retrospectives and jitter

- Model 19.1 has best Mohn's ρ for SSB
- Model 21.2 has best Mohn's ρ for Age-0 recruitment
- All models within acceptable bounds with low bias
- Jitter 50 runs at 0.05

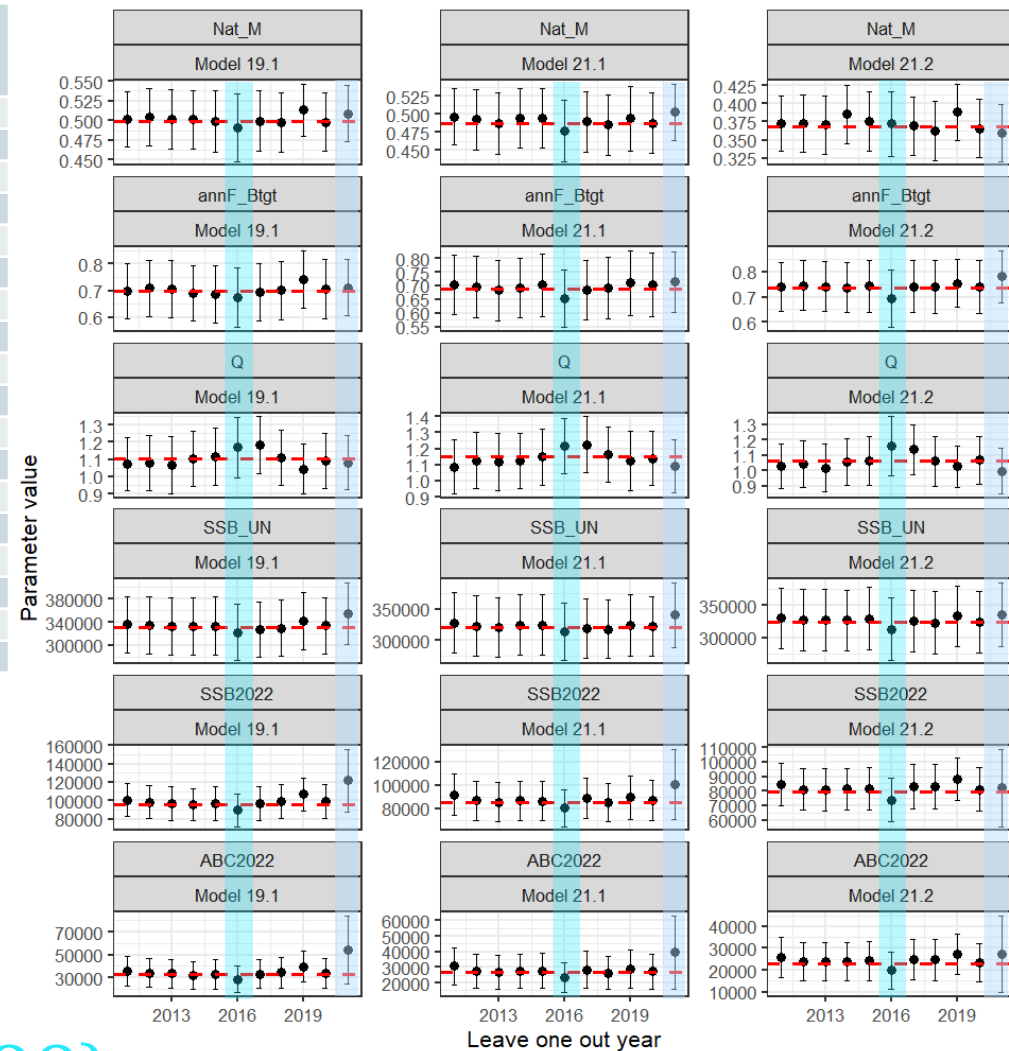
Model	#	Not Conv.	At MLE	Below MLE	% converged at MLE
19.1	50	1	32	0	65%
21.1	50	3	37	0	79%
21.2	50	12	23	0	61%



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Label	MLE			Leave-one-out		Model
	Value	σ	CV	Mean bias	Mean bias/ML Value	
ABC ₂₀₂₂	32811	6335	0.193	2860.32	0.0872	19.1
ABC ₂₀₂₂	26759	5513	0.206	1873.84	0.0700	21.1
ABC ₂₀₂₂	23099	4345	0.188	1378.89	0.0597	21.2
F _{40%}	0.696	0.054	0.077	0.0054	0.0078	19.1
F _{40%}	0.687	0.056	0.086	0.0067	0.0098	21.1
F _{40%}	0.734	0.051	0.082	0.0066	0.0090	21.2
M _{base}	0.499	0.019	0.038	0.0024	0.0049	19.1
M _{base}	0.499	0.022	0.044	0.0032	0.0066	21.1
M _{base}	0.369	0.020	0.054	0.0033	0.0090	21.2
Q _{Rt}	0.101	0.081	NA	-0.0045	-0.0041	19.1
Q _{Rt}	0.091	0.088	NA	-0.0060	-0.0052	21.1
Q _{Rt}	0.063	0.080	NA	-0.0055	-0.0052	21.2
SSB _{Unfish}	165508	12407	0.075	1755.86	0.0106	19.1
SSB _{Unfish}	159948	12114	0.076	1645.18	0.0103	21.1
SSB _{Unfish}	162426	12205	0.075	1178.41	0.0073	21.2
SSB ₂₀₂₂	48061	4476	0.093	1934.96	0.0403	19.1
SSB ₂₀₂₂	42763	4175	0.098	1354.25	0.0317	21.1
SSB ₂₀₂₂	39873	3651	0.092	1109.95	0.0278	21.2

- Low bias across all three models
- 2016 data are highly influential
- 2021 data are highly influential on Biomass estimates



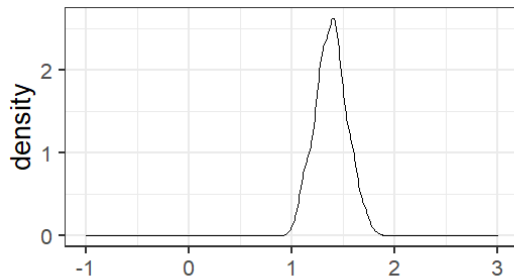
Leave-one-out analyses (LOO)

- Remove single year's data from models iteratively
- Investigate impacts on key model parameters and results

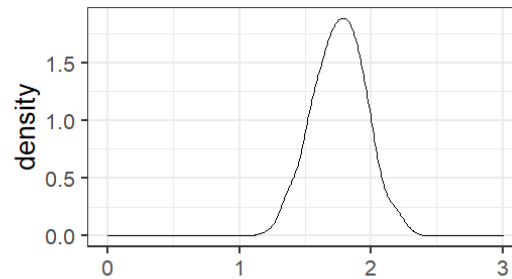


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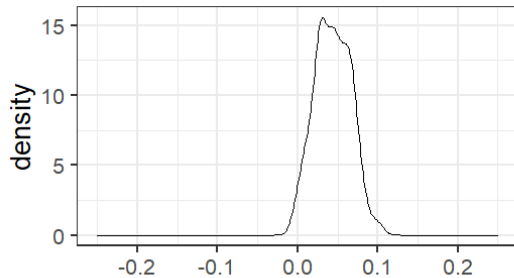
		MCMC link posterior percentile				Link MLE		
Parameter	Link	2.50%	50%	97.50%	p	Value	σ	Gradient
M	η	1.0974	1.3865	1.7005	< 0.002	1.4098	0.14725	-3.91E-06
L ₁	γ	1.3676	1.7659	2.1559	< 0.002	1.8003	0.20917	5.98E-07
L ₂	ν	0.0023	0.0434	0.0854	0.02	0.0476	0.02208	2.68E-06
K	ϕ	-0.0893	-0.0235	0.0423	0.25	-0.0299	0.03510	1.32E-06
R ₀	ω	-0.0141	-0.0076	-0.0015	0.002	-0.0072	0.00351	-2.66E-06
Q _{BT}	τ	0.5235	1.1259	2.2078	< 0.002	1.3188	0.56170	9.55E-08



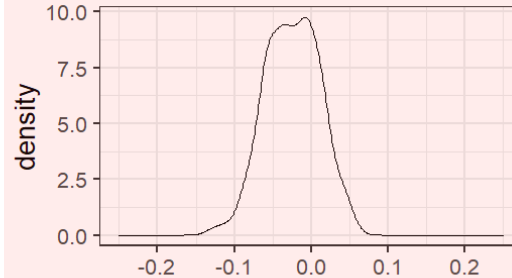
M environmental link



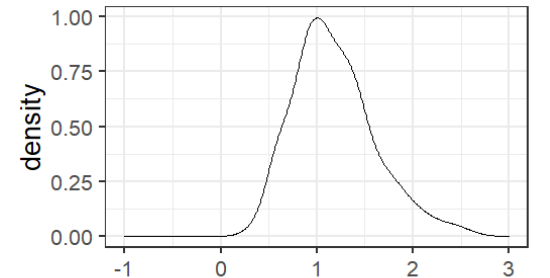
Lmin environmental link



Lmax environmental link



K environmental link



Longline survey Q environmental link

Model 21.2 Environmental links

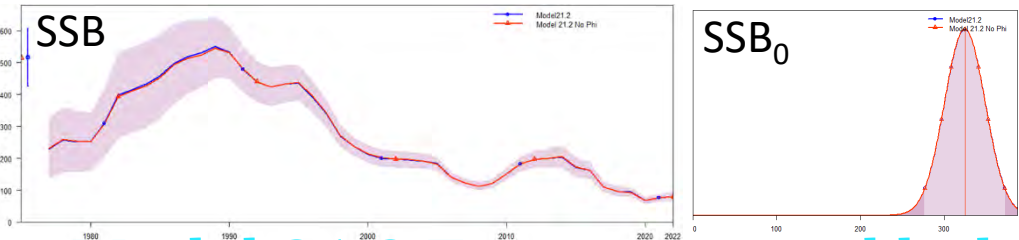
- Link parameters fit with uninformative priors
- Inverse Hessian and MCMC results agree
- ϕ link to K not significantly different from 0



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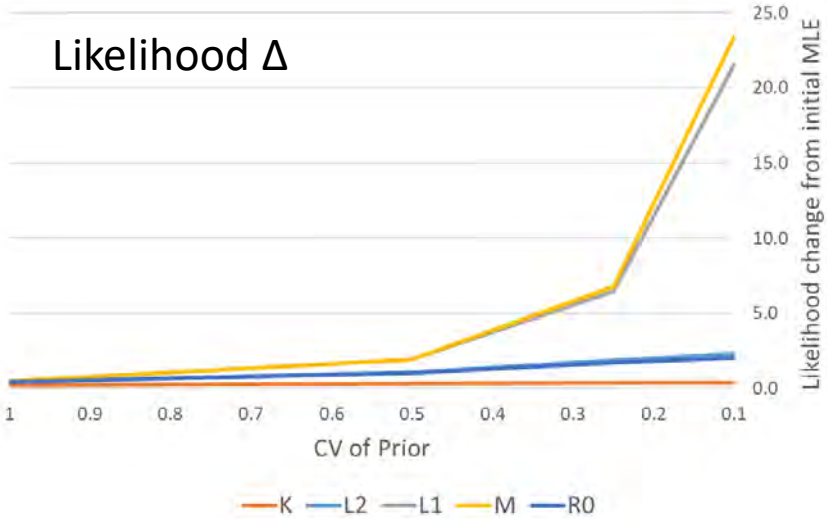
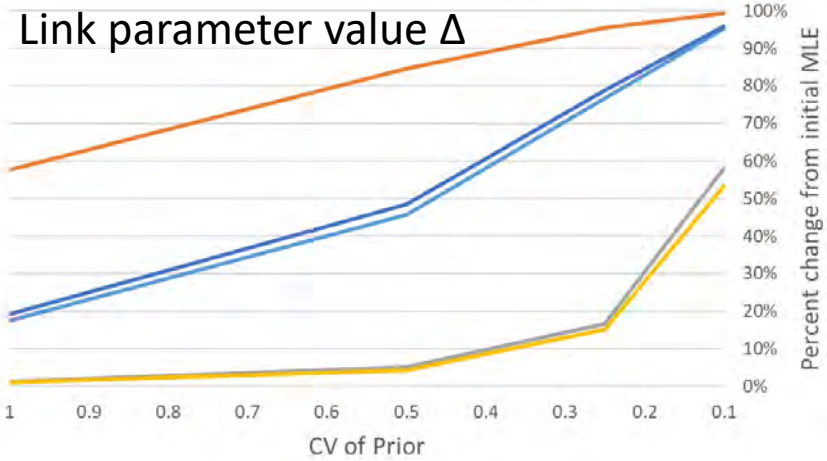
Prior CV	Prior σ	Param	Link	Value	% Δ	LL Δ
0.1	0.002990	K	ϕ	-0.00022	99.3%	0.364
0.25	0.007474	K	ϕ	-0.00131	95.6%	0.350
0.5	0.014949	K	ϕ	-0.00464	84.5%	0.309
1	0.029898	K	ϕ	-0.01264	57.7%	0.211
0.1	0.004763	L ₂	v	0.002230	95.3%	2.301
0.25	0.011909	L ₂	v	0.011098	76.7%	1.843
0.5	0.023817	L ₂	v	0.025918	45.6%	1.084
1	0.047635	L ₂	v	0.039279	17.5%	0.412
0.1	0.180026	L ₁	Y	0.755919	58.0%	21.564
0.25	0.450065	L ₁	Y	1.499503	16.7%	6.434
0.5	0.900130	L ₁	Y	1.709467	5.0%	1.899
1	1.800260	L ₁	Y	1.776392	1.3%	0.493
0.1	0.140976	M	η	0.656814	53.4%	23.445
0.25	0.352440	M	η	1.197071	15.1%	6.799
0.5	0.704880	M	η	1.350543	4.2%	1.916
1	1.409760	M	η	1.394530	1.1%	0.495
0.1	0.000716	R ₀	ω	-0.00030	95.9%	2.046
0.25	0.001791	R ₀	ω	-0.00151	78.8%	1.679
0.5	0.003581	R ₀	ω	-0.00369	48.5%	1.026
1	0.007163	R ₀	Ω	-0.00578	19.3%	0.404

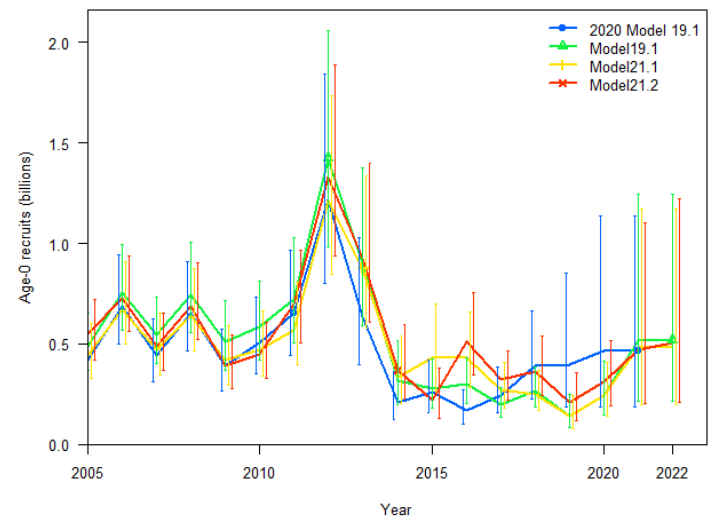
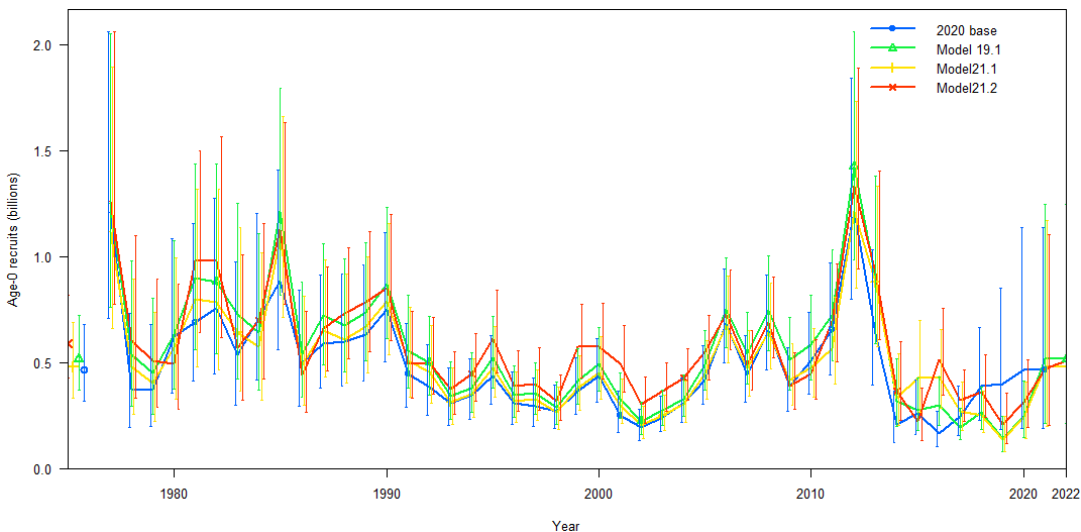
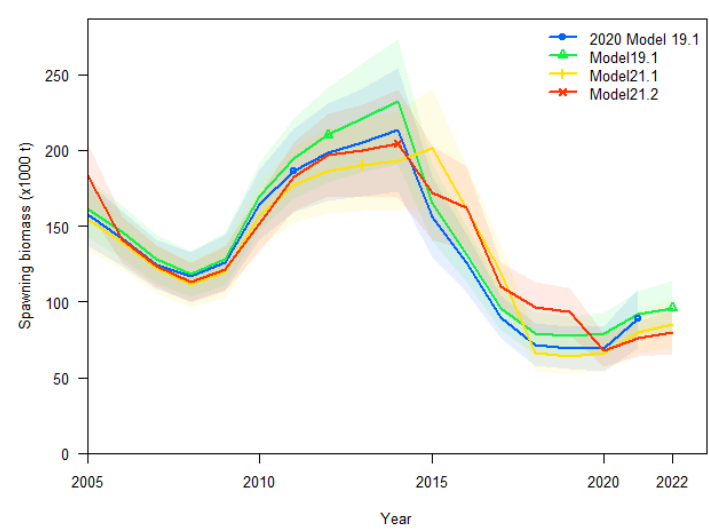
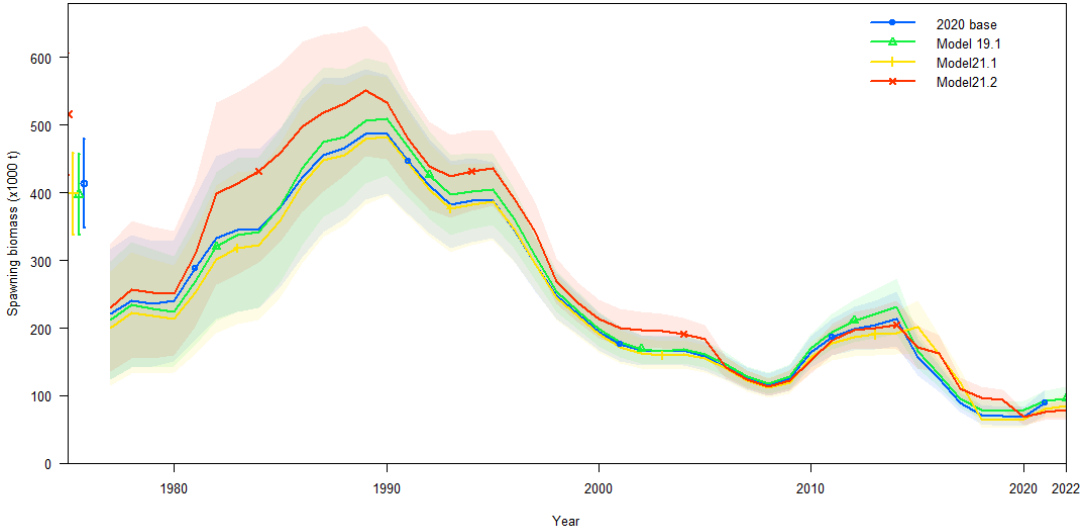
Removal of ϕ link on K makes little to no difference in model results



Model 21.2 Environmental links

- Normal prior with mean of 0.0 fit iteratively with decreasing CV on prior for each link parameter
- Suggested by SSC





Summary model selection

- All models relatively similar
 - Later drop in biomass for Models 21.1 and 21.2
 - Slower drop for Model 21.2
 - Recruitment low for all three models since 2014



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- Model 21.2 had the best overall fit to all of the data where direct comparisons are possible
- All models performed well in retrospective
- All models had little overall bias in LOO analysis
 - Model 21.2 ending year data was less influential
- Environmental links in Model 21.2 are well fit and should improve projections

Summary model selection

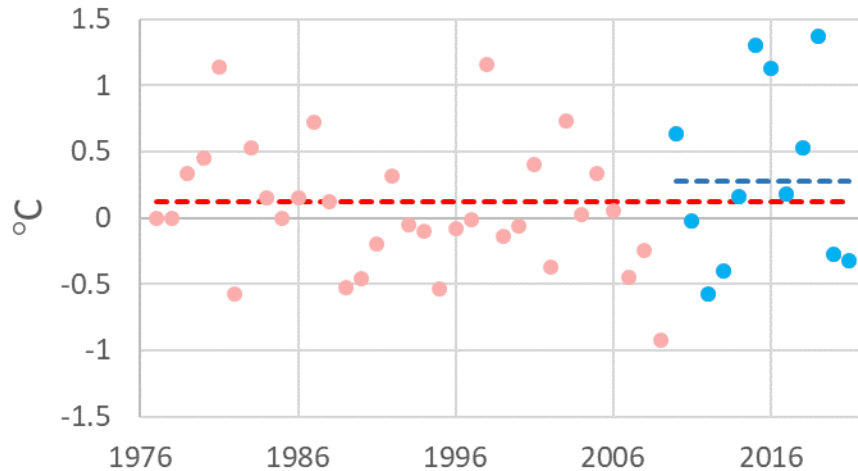
- Likelihood
- Retrospective
- Leave-one out
- Model behavior



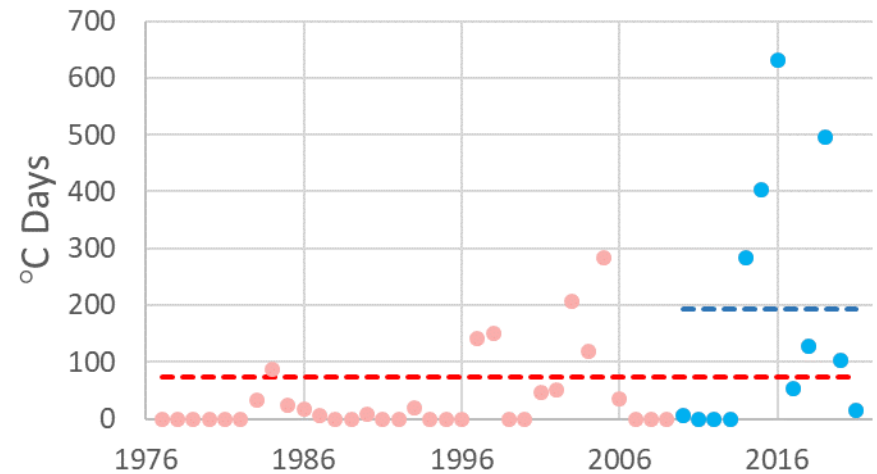
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For projections the environmentally linked Model 21.2 requires assumptions about future conditions

June CFSR Central GOA Anomaly



Annual Heatwave Index



Projection A: 1977-2021 mean conditions

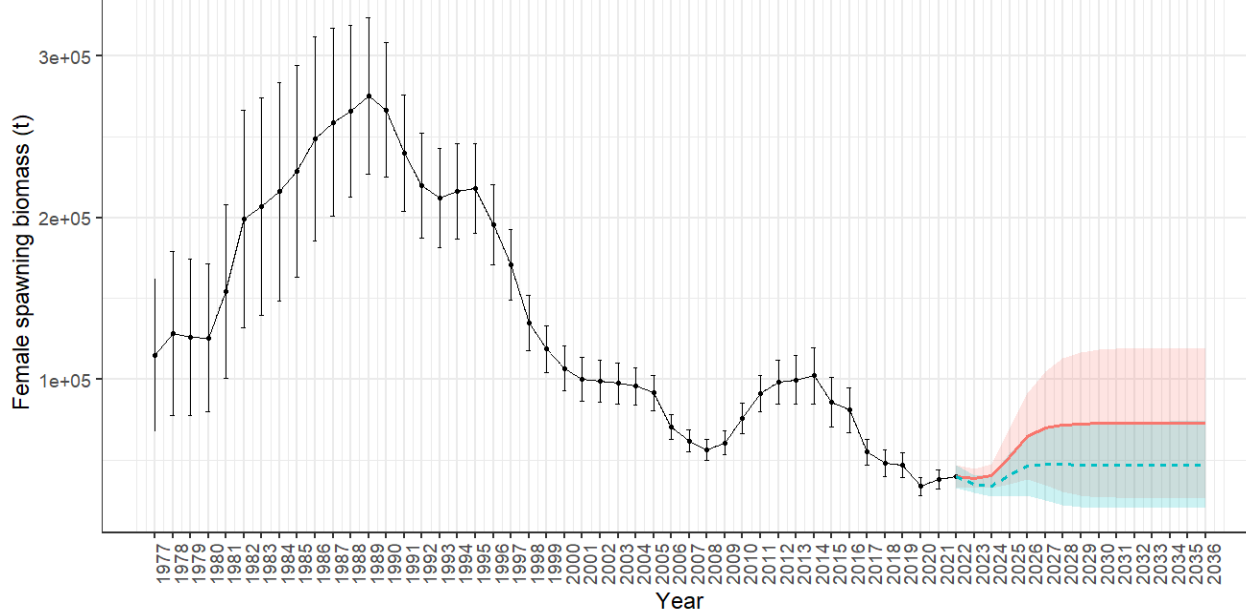
Projection B: 2010-2021 mean conditions

Model 21.2 Projection decision

- 1977-2021 matches timeframe for setting reference points
- 2010-2021 may better reflect future conditions under IPCC scenarios with increasing temperature trends for Central GOA

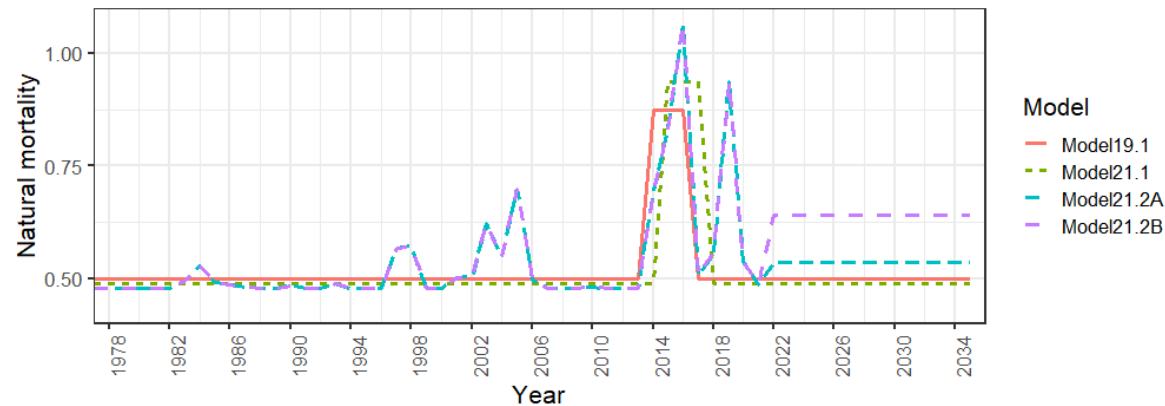


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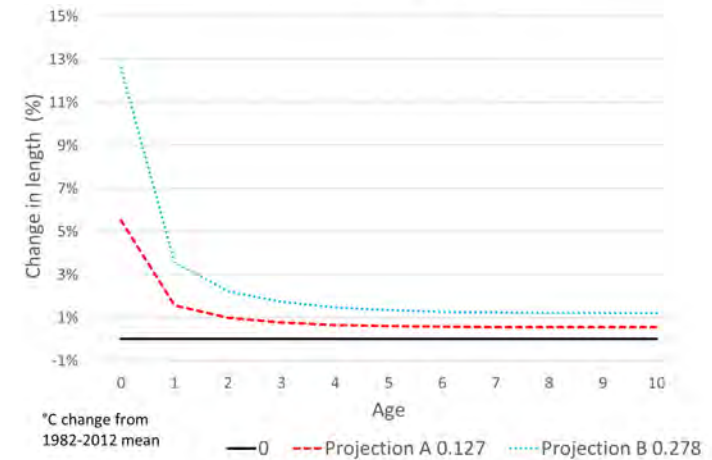


2022 spawning
biomass at $B_{24.5\%}$

Natural mortality by model



Pacific cod length by projection

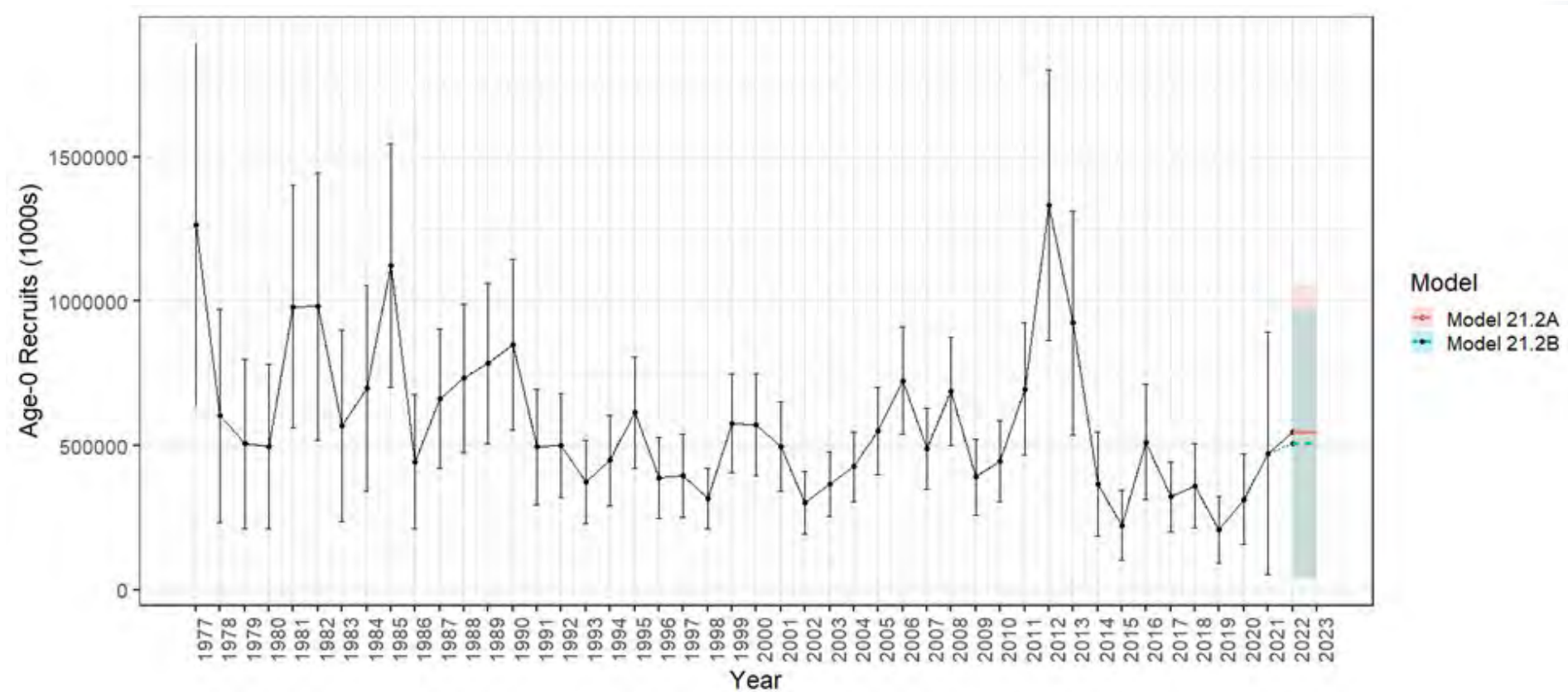


Model 21.2 Results spawning biomass

- Both projection have increased M and growth
- Increase in growth is small between projections



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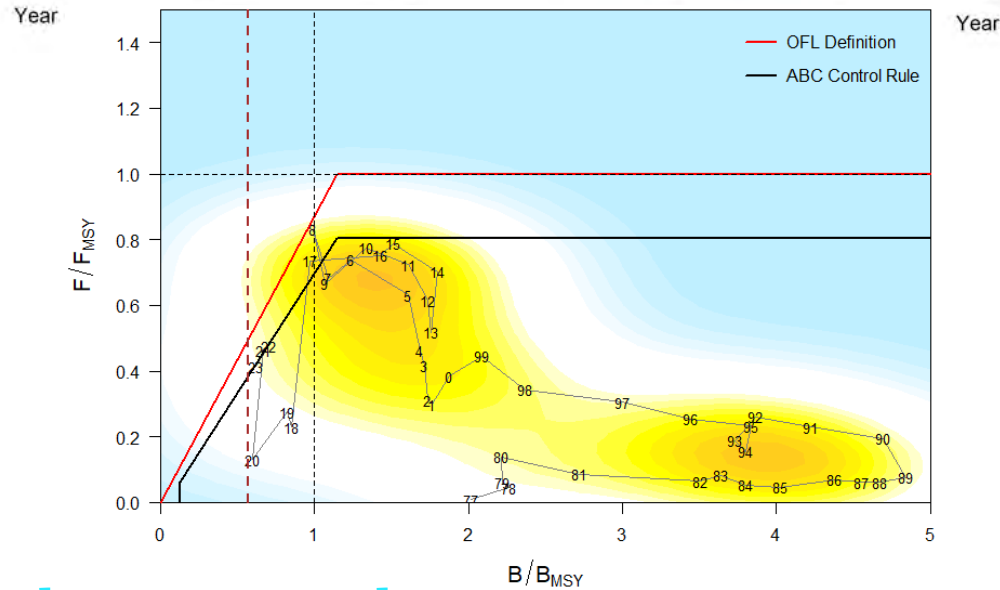
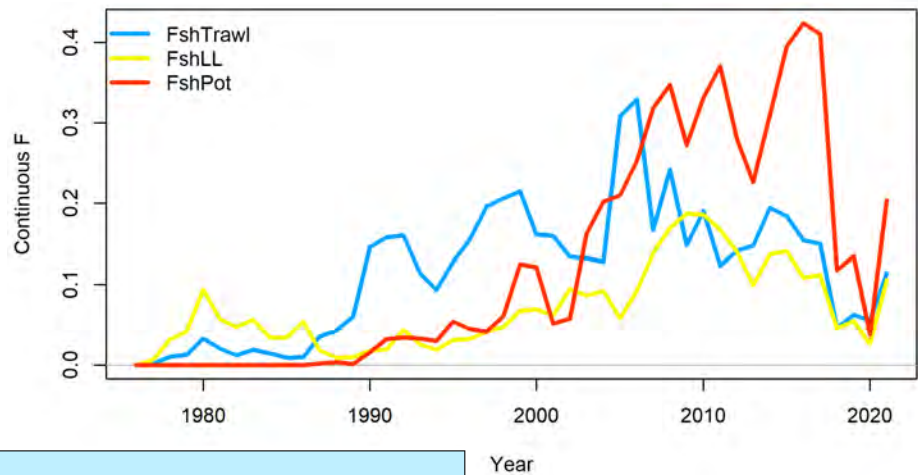
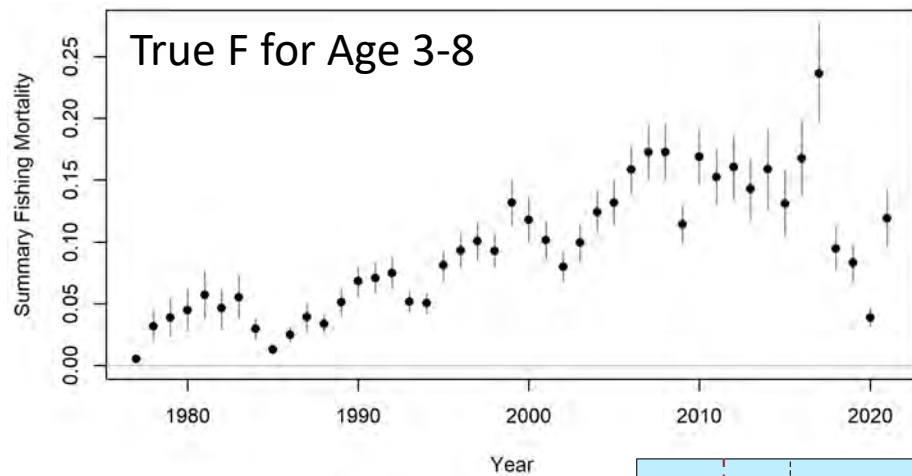


Model 21.2 Results recruitment

- Both projection have decreased recruitment
- Difference is small



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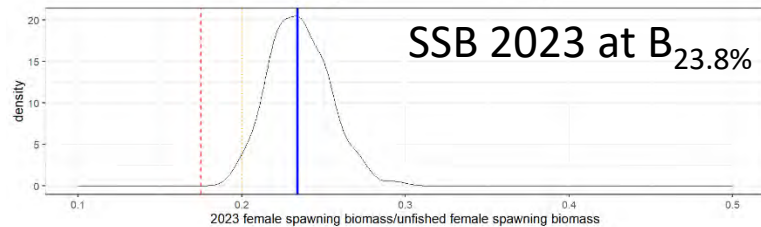
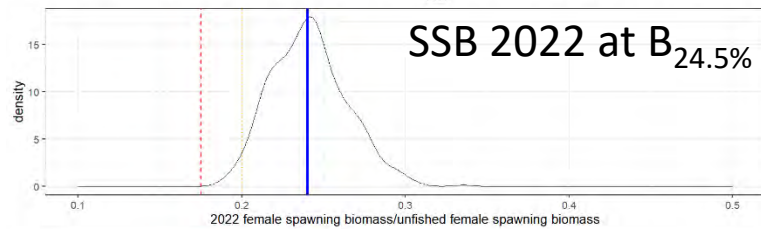
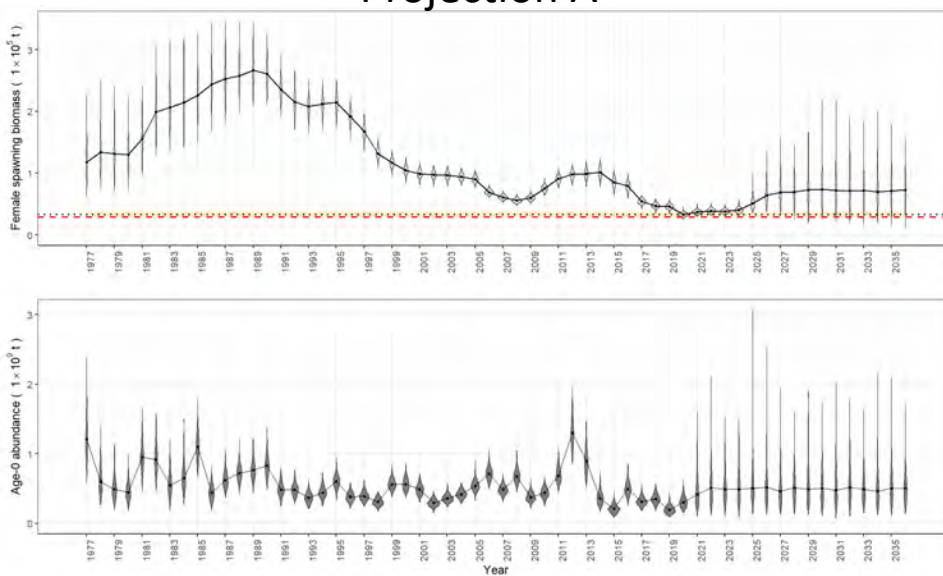
Model 21.2 Fishing mortality

- Increasing F over time however overall relatively low fishing mortality
- Highest F in 2017 as stock collapsed
- 2018-2021 continued low fishing mortality

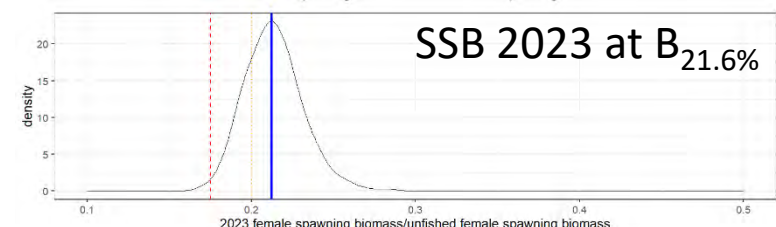
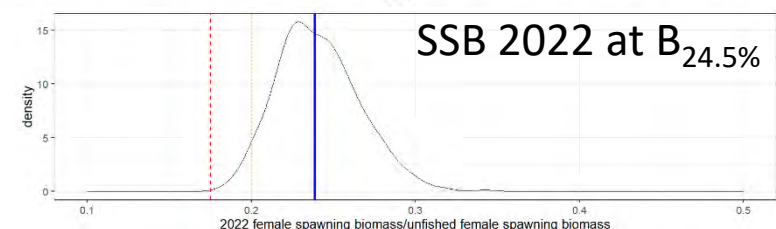
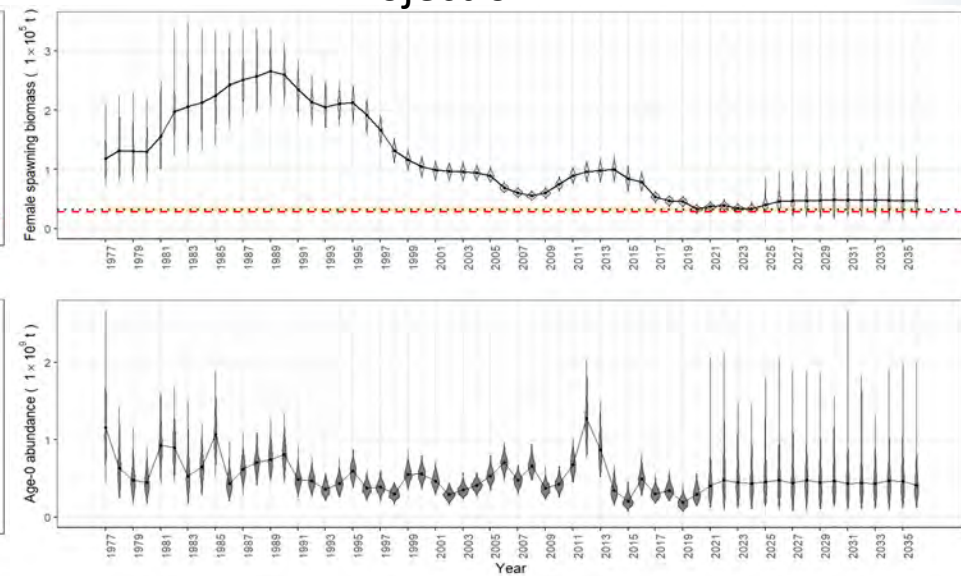


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Projection A



Projection B

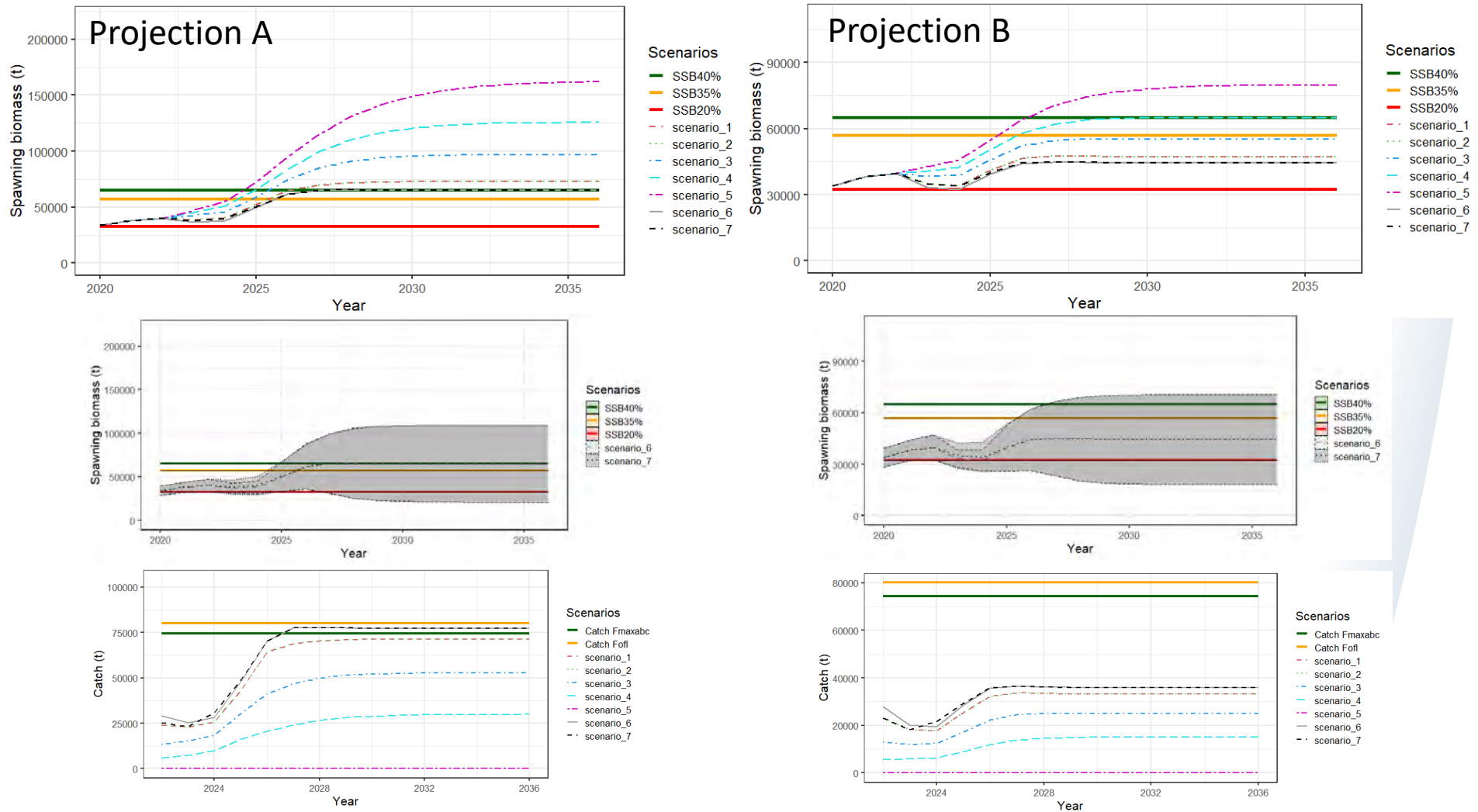


Model 21.2 Results

- MCMC 1 million draws, burn in of 10,000, thinned at 2,000
- Projection A: 2% probability of $<B_{20\%}$ in 2023
- Projection B: 22% probability of $<B_{20\%}$ in 2023



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Model 21.2 status projections

- Both projections are highly uncertain after 2025
- Projection A: Not overfished or approaching an overfished condition
- Projection B: Overfished and approaching an overfished condition



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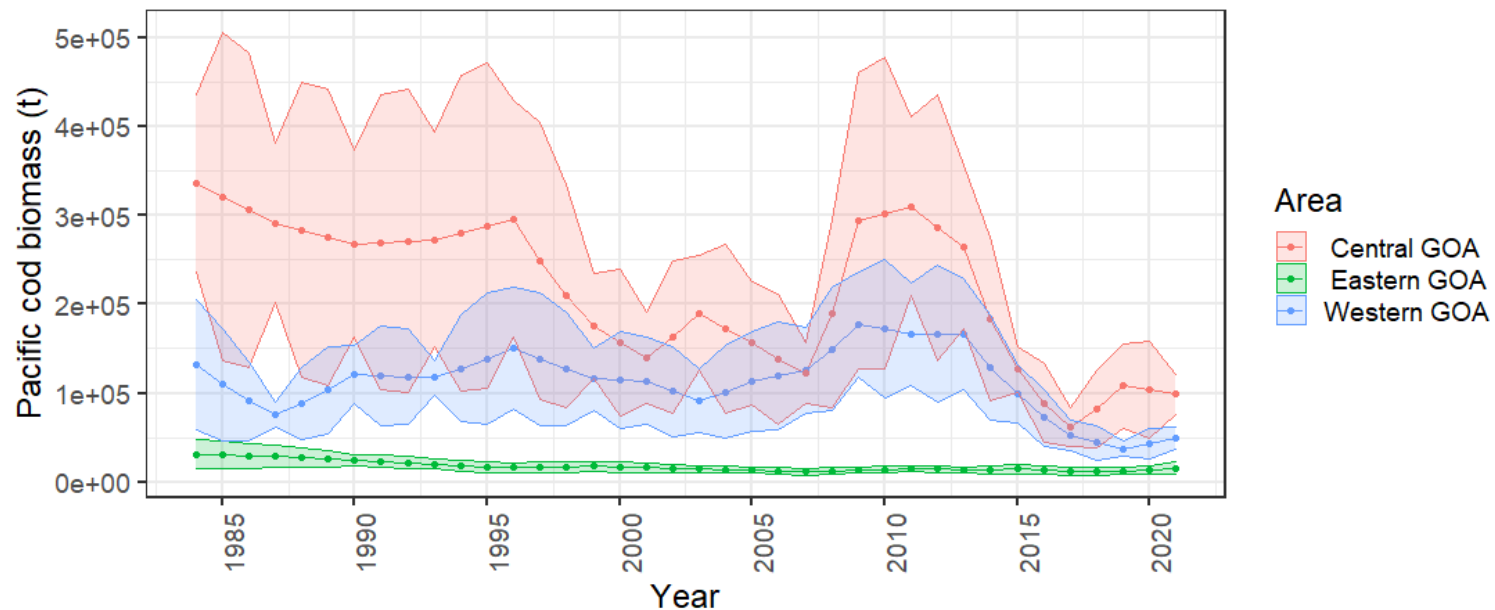
Model21.2	Projection A (Mean 1977-2021 conditions projected)		Projection B (Mean 2010-2021 conditions projected)	
Quantity	2022	2023	2022	2023
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	159,837	185,745	160,755	169,832
Female spawning biomass (t)				
Projected	39,873	38,594	39,873	35,050
$B_{100\%}$	162,426	162,426	162,426	162,426
$B_{40\%}$	64,970	64,970	64,970	64,970
$B_{35\%}$	56,849	56,849	56,849	56,849
F_{OFL}	0.54	0.52	0.54	0.47
$\max F_{ABC}$	0.44	0.42	0.44	0.38
F_{ABC}	0.44	0.42	0.44	0.38
OFL (t)	29,131	27,715	28,000	22,072
$\max ABC$ (t)	24,043	22,882	23,099	18,170
ABC (t)	24,043	22,882	23,099	18,170
Status				
	2020	2021	2020	2021
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	Yes
Approaching overfished	n/a	No	n/a	Yes

Model 21.2 Recommendations

- Assumed 2021 catch at the ABC, 23,627t. For 2023 projections the 2022 catch was assumed to be at the projected ABC.



AFSC bottom trawl survey RE model for allocation



		Western	Central	Eastern	Total
Random effects area apportionment		30.3%	60.2%	9.5%	100%
Projection A	2022 ABC	7,285	14,474	2,284	24,043
	2023 ABC	6,933	13,775	2,174	22,882
Projection B	2022 ABC	6,999	13,905	2,194	23,099
	2023 ABC	5,505	10,938	1,726	18,170

Model 21.2 area allocation

- Random effects model used for allocation
- Increase in Western GOA over previous survey



Extra slides for questions follow



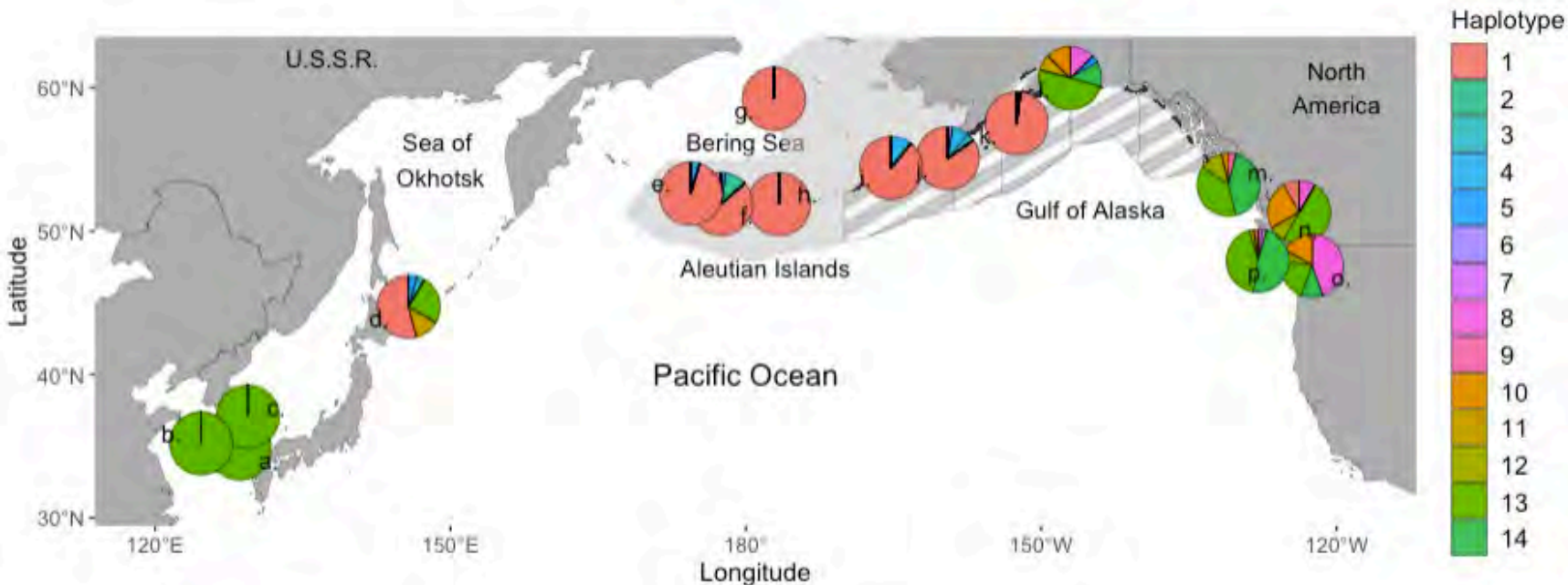
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Quantity	Model 19.1		Model 21.1	
	2022	2023	2022	2023
Tier	3b	3b	3b	3b
Projected total (age 0+) biomass (t)	178,961	199,841	166,852	194,580
Female spawning biomass (t)				
Projected	48,061	44,530	42,763	42,872
B _{100%}	165,508	165,508	159,948	159,948
B _{40%}	66,203	66,203	63,979	63,979
B _{35%}	57,928	57,928	55,982	55,982
F _{OFL}	0.62	0.57	0.56	0.56
maxF _{ABC}	0.50	0.46	0.45	0.45
F _{ABC}	0.50	0.46	0.45	0.45
OFL (t)	39,554	34,673	32,366	32,869
maxABC (t)	32,811	28,708	26,759	27,195
ABC (t)	32,811	28,708	26,759	27,195
Status				
	2020	2021	2020	2021
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

Model 19.1 and 21.1 Recommendations

- Assumed 2021 catch at the ABC, 23,627t. For 2023 projections the 2022 catch was assumed to be at the respective projected ABCs.





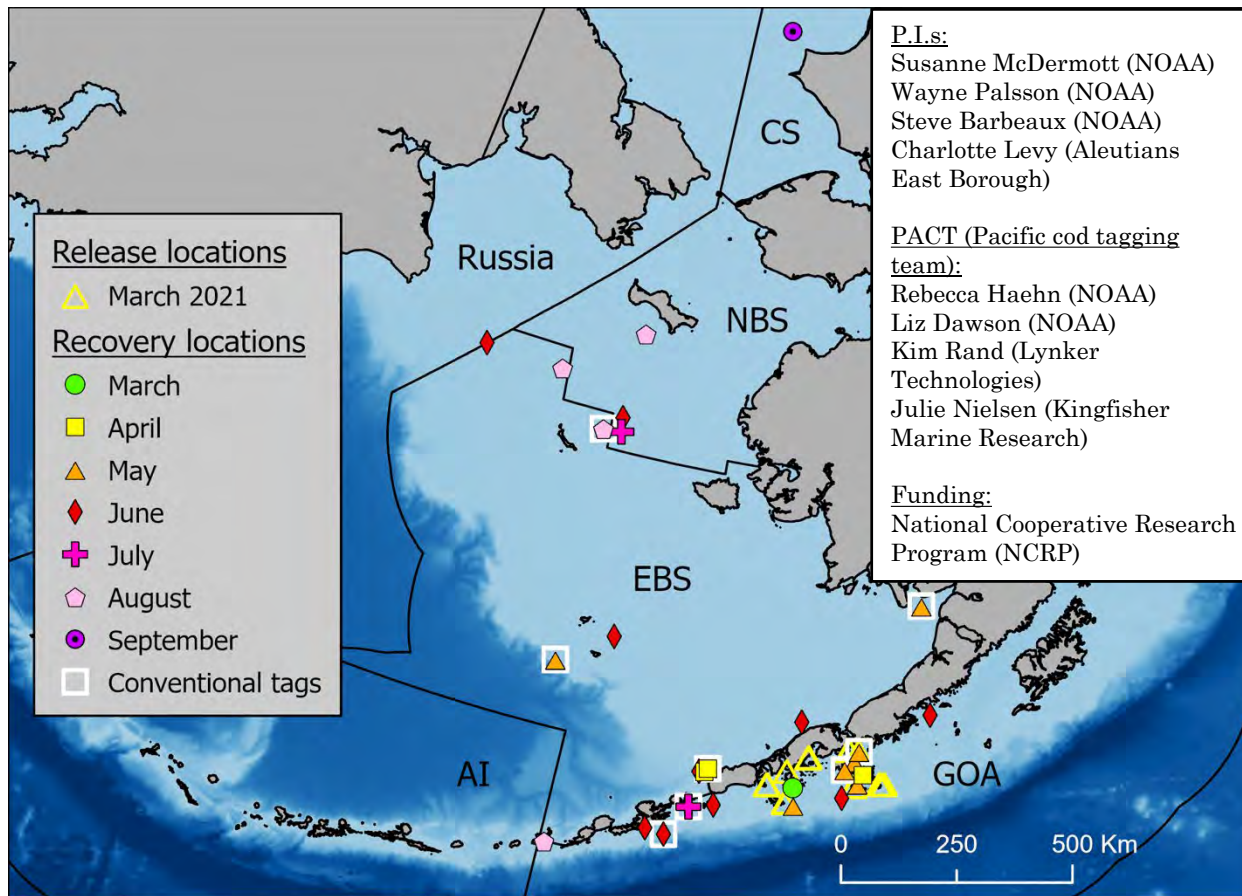
- Strong evidence for selective differentiation, including one that aligned to the zona pellucida glycoprotein 3 (ZP3)
- ZP3 a reproductive protein known to undergo rapid selection shown to neofunctionalize as an antifreeze protein in Antarctic icefishes (Spies et al. 2021).

Latest Pacific cod genetics

- 3,599 SNP loci and spawning samples throughout the range of Pacific cod off Alaska, as well as a summer sample from the Northern Bering Sea in August 2017 show significant differentiation among all spawning groups.
- The three spawning groups examined in the GOA, Hecate Strait, Kodiak Island, and Prince William Sound, were all genetically distinct and could be assigned to their population of origin with 80-90% accuracy.



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- More than half (10/17) of the tags recovered in the June-September in Bering Sea
- One tag recovered in the Chukchi Sea
- Indicates substantial connectivity between the WGOA and other regions

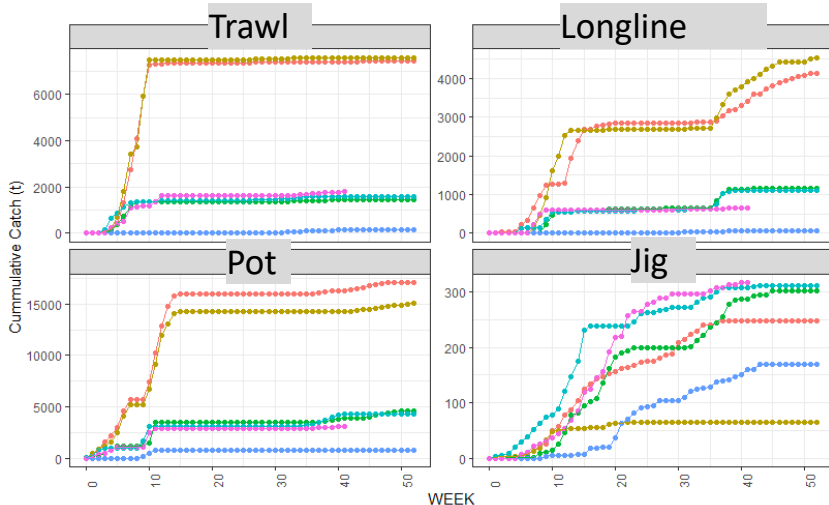
Western GOA PSAT tagging

- 25 satellite-tagged and 957 conventionally-tagged Pacific cod released in Western GOA.
- Satellite tags were programmed to pop-up and transmit data after 90, 180, or 365 days.
- Locations of tags recovered in March, April, and May in the vicinity of release area.
- Fish recovered June through September had moved west toward the Aleutian Islands and north into the EBS, Northern Bering Sea, Russia, and the Chukchi Sea.

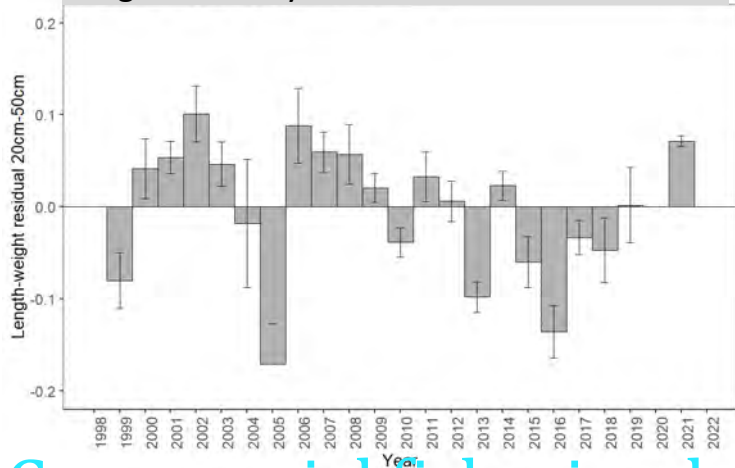


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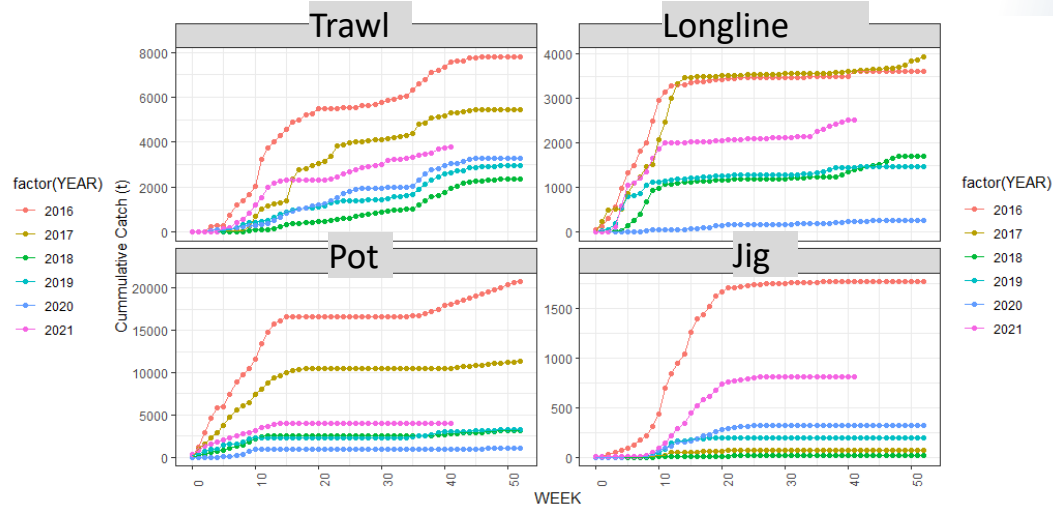
Western GOA



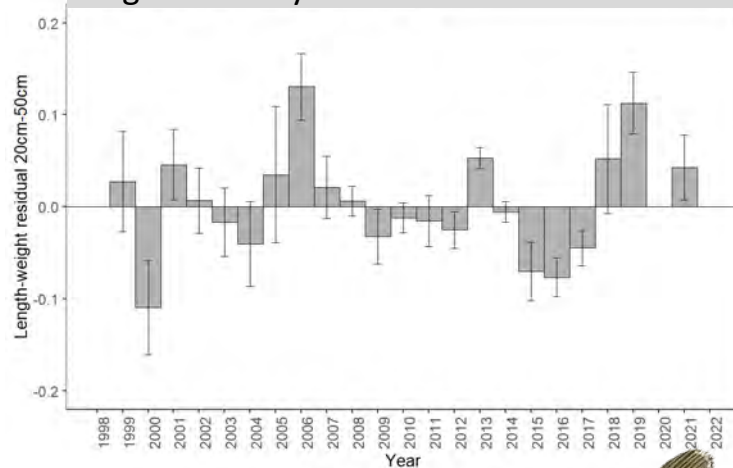
Longline fishery condition Western GOA



Central GOA



Longline fishery condition Central GOA



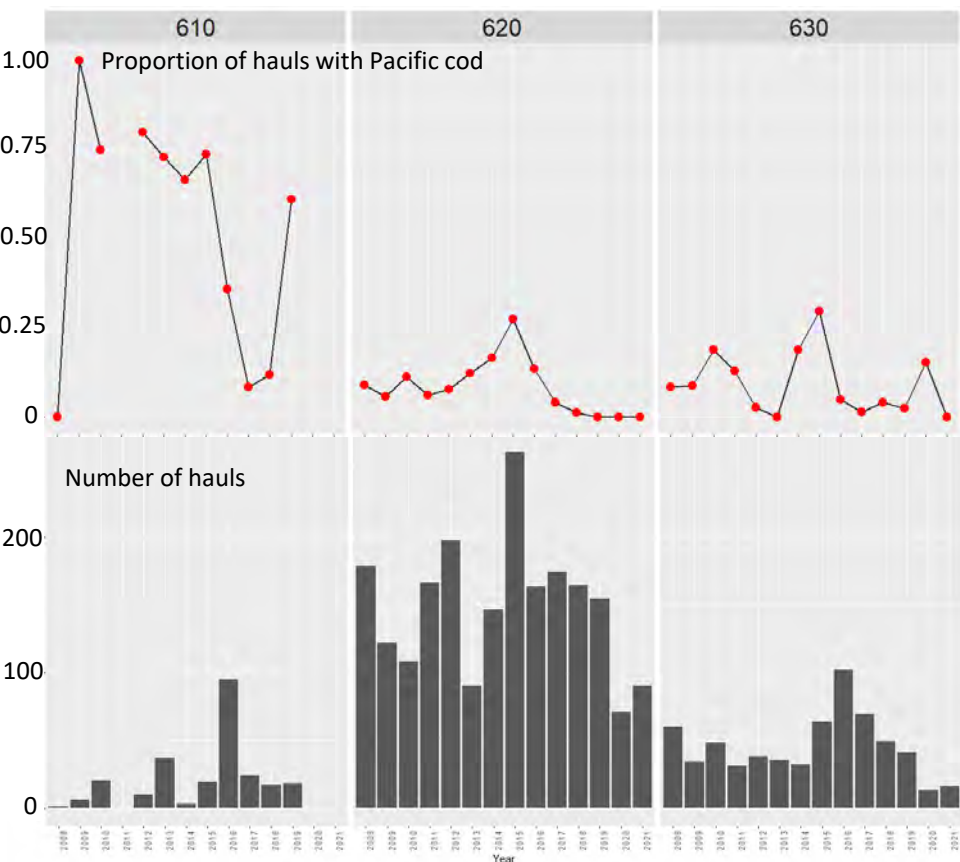
Commercial fisheries data

- Western and Central GOA fisheries appear to be recovering
 - For most gears fishing rate comparable or exceeding 2018-2019
- Condition (length-weight) were better than average

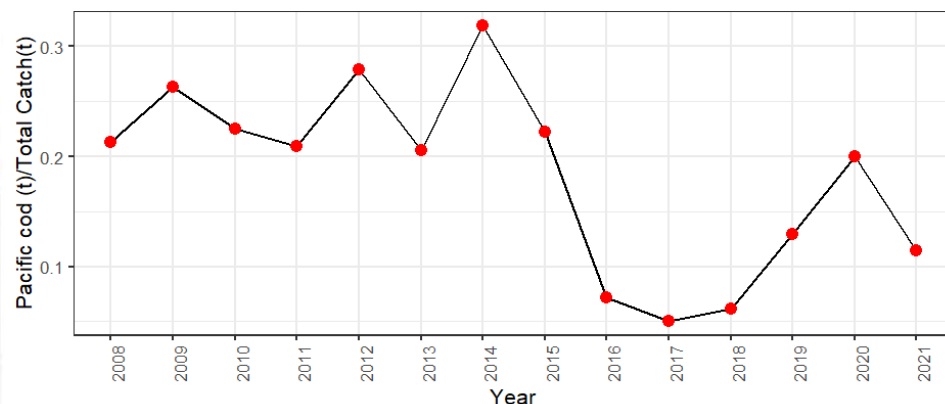


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Pelagic trawl fisheries



Shallow water flatfish fishery



Commercial fisheries data

- After increase in 2020, drop in Pacific cod bycatch in 2021



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- 1-10+ age bins
- 1-117+cm length bins
- Key estimated parameters:
 - M lognormal prior, mean -0.81, CV 0.41
 - Survey catchability uninformative prior
 - M anomaly for the 2014-2016 period
- Stock recruitment relationship: Beverton-Holt
 - $\sigma_R = 0.44$, steepness = 1.0
- Growth
 - Three-parameter von Bertalanffy growth (informative priors based on 2007-2018 survey size at age data)
- Selectivity: length-based double normal
 - Different periods for bottom trawl survey
 - Longline and trawl
 - pre-1990 annually varying
 - blocks for post-1990
- Longline survey catchability
 - scaled to CFSR temperatures for 0-10 cm Pacific cod mean depth

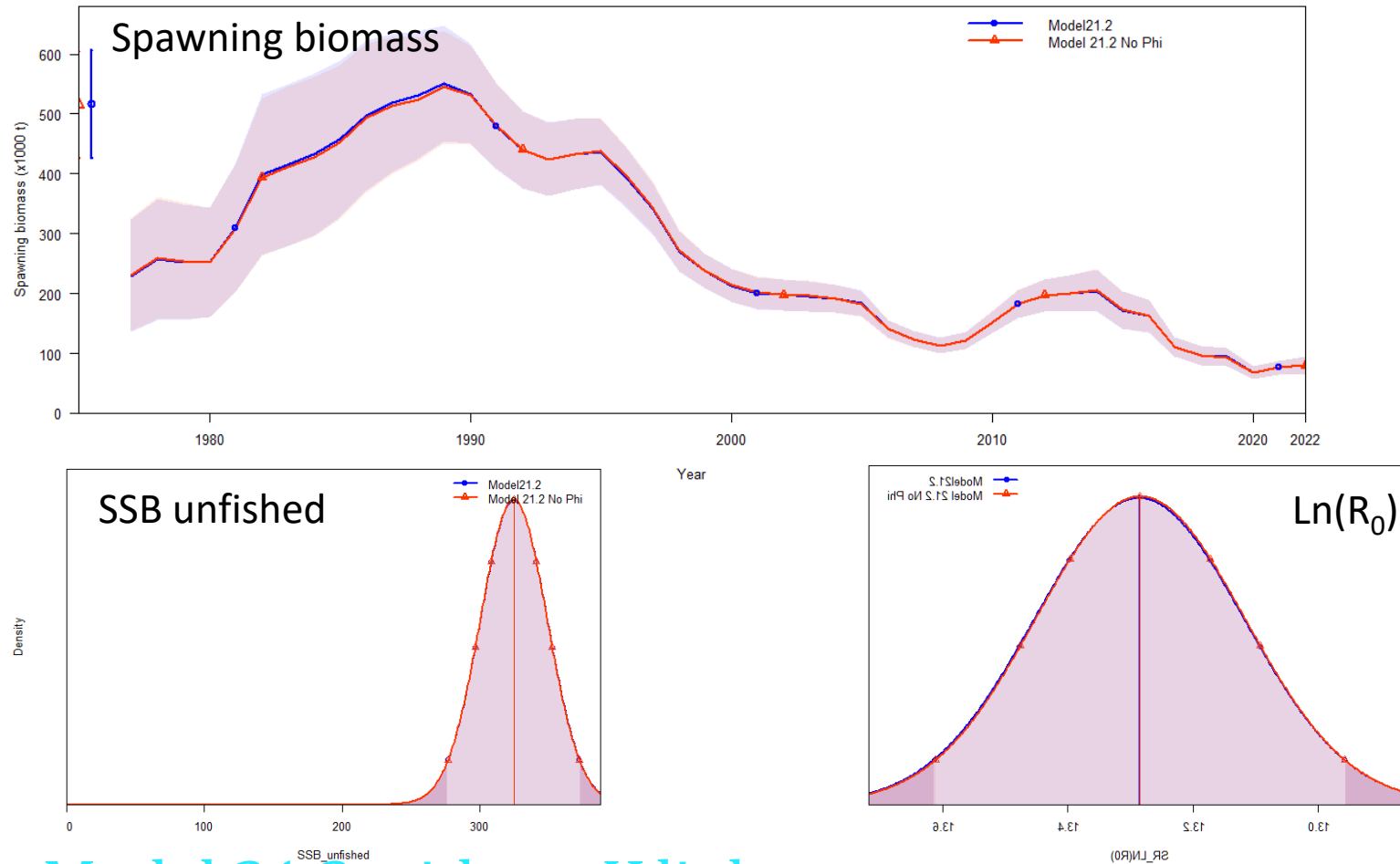
Last year's model (Model 19.1)

- Rerun of 2019 model with up-to-date data included



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Removal of ϕ link on K makes little to no difference in model results



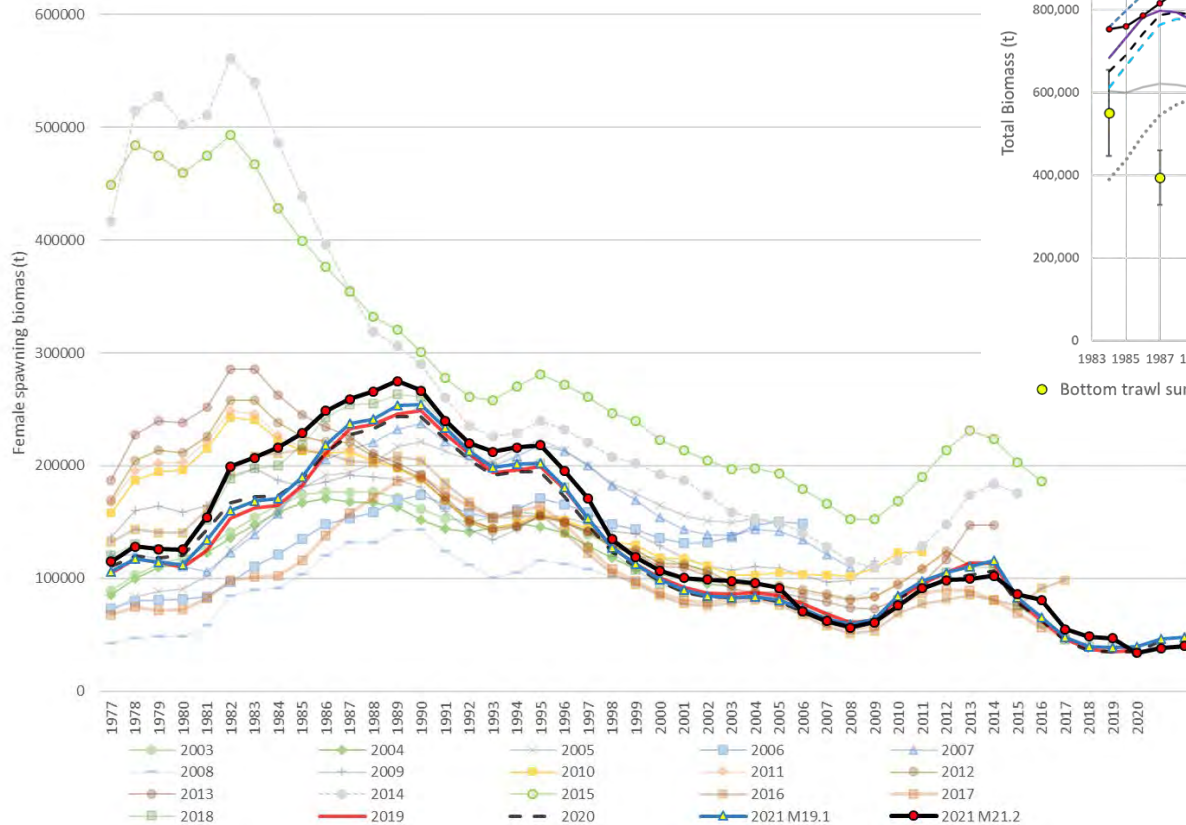
Model 21.2 without K link parameter

- Model 21.2 retains K link parameter

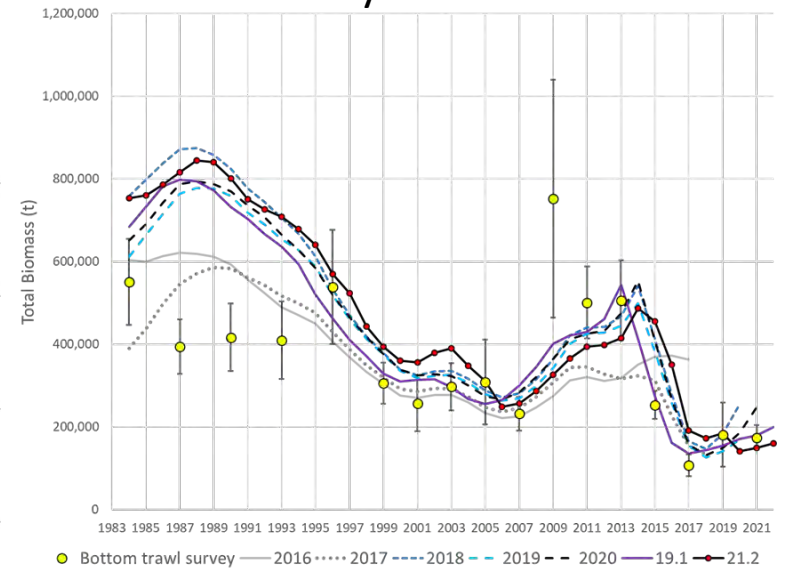


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Female spawning biomass



BT survey vs. Total biomass



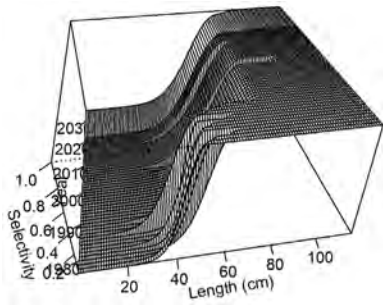
Summary model selection

- All three models within the realm of models considered previously
- Relative catchability (survey biomass/total biomass) is 1.0 for all three models considered.

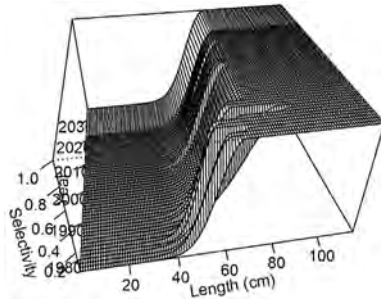


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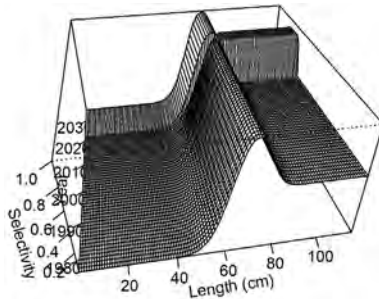
Trawl Fishery



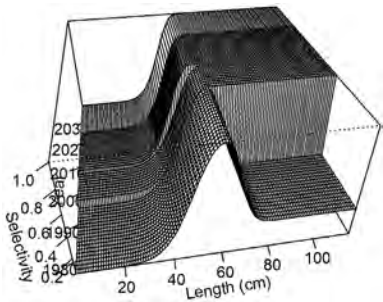
Longline Fishery



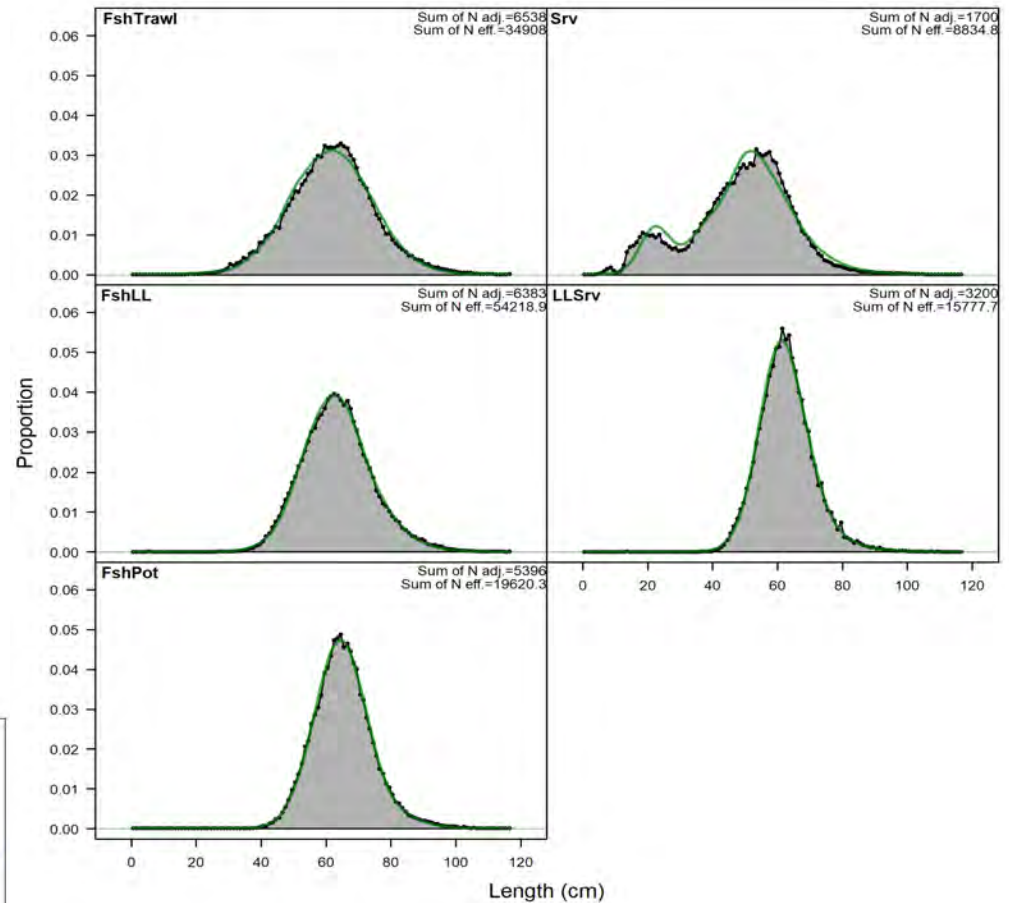
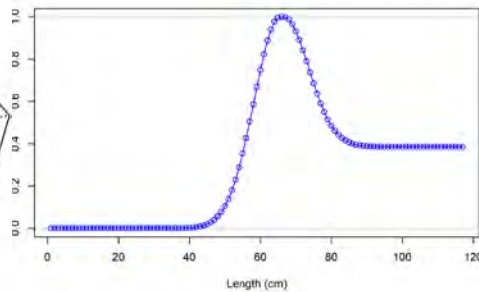
Pot Fishery



Bottom Trawl Survey



Longline Survey

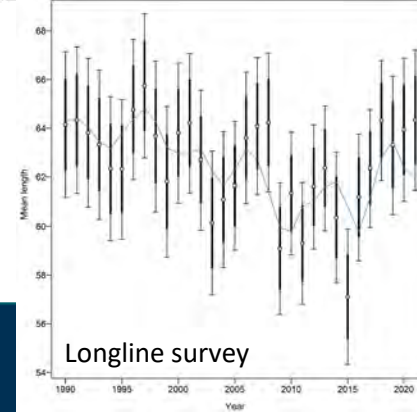
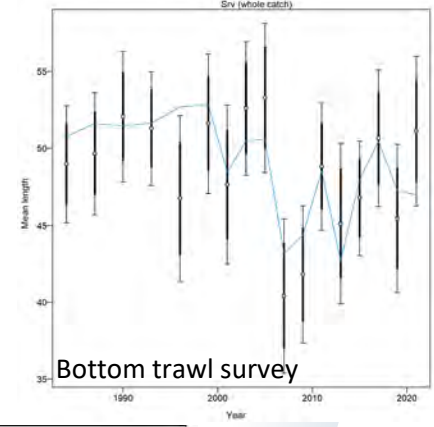
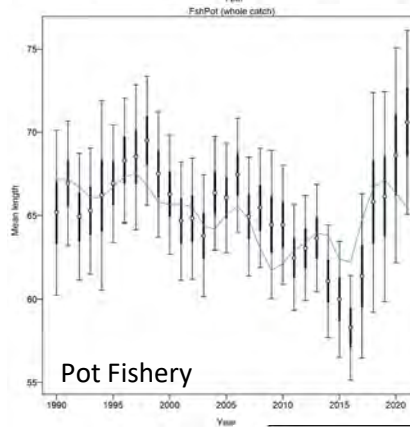
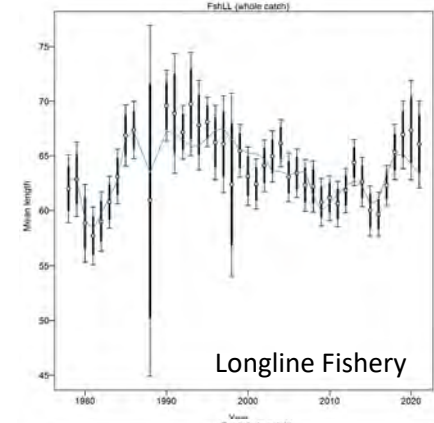
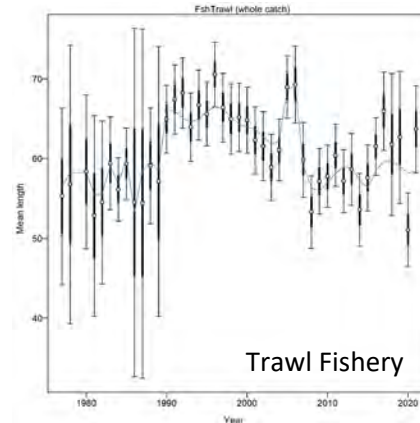
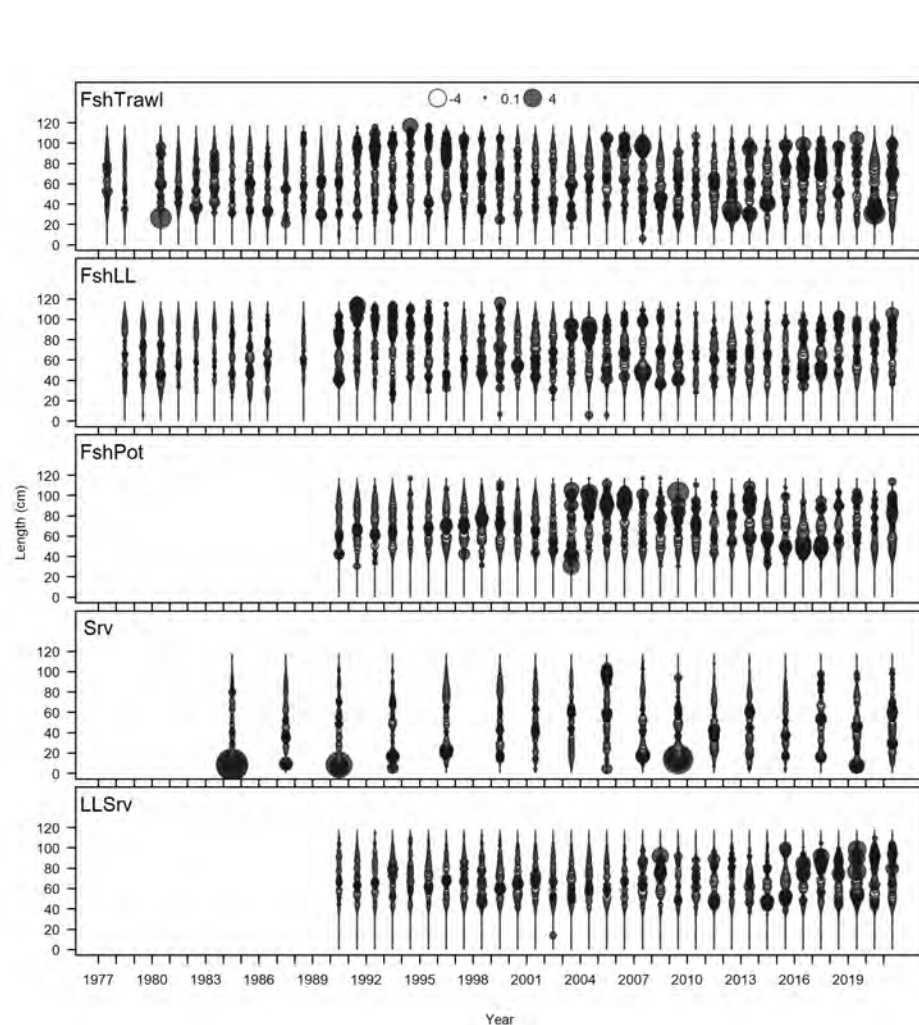


Model 21.2 Length composition fits

- Good overall fit to the length composition data
- Bottom trawl survey may underfit some small size classes

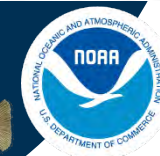


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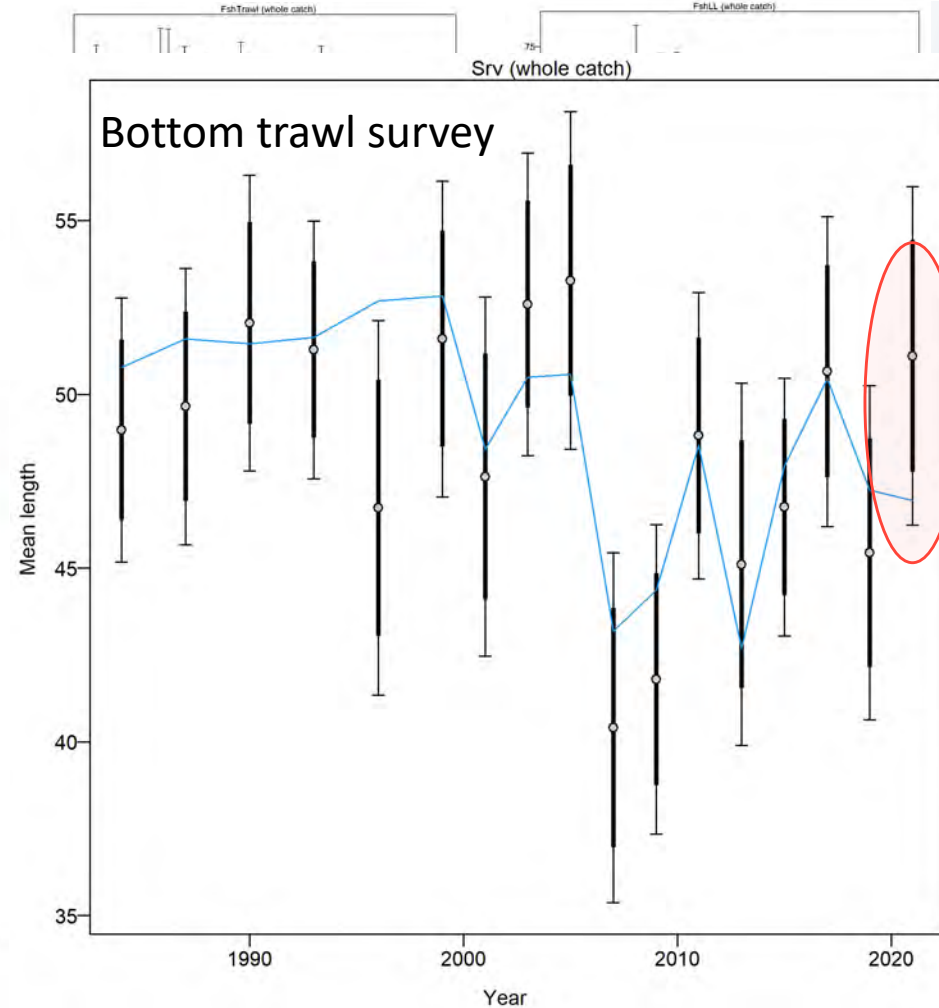
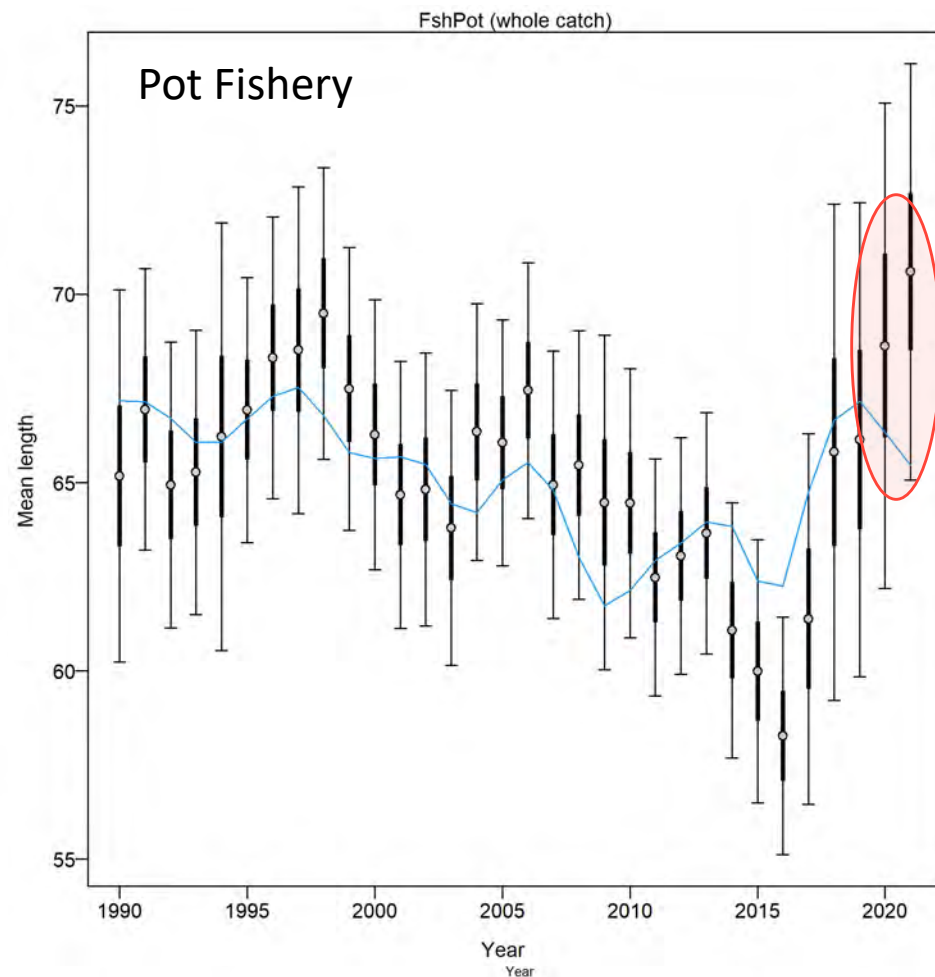


Model 21.2 Length composition fits

- Good overall fit to length composition data
- Bottom trawl survey may underfit some small size classes
- 2021 projected mean sizes are smaller than observed in all fisheries and surveys



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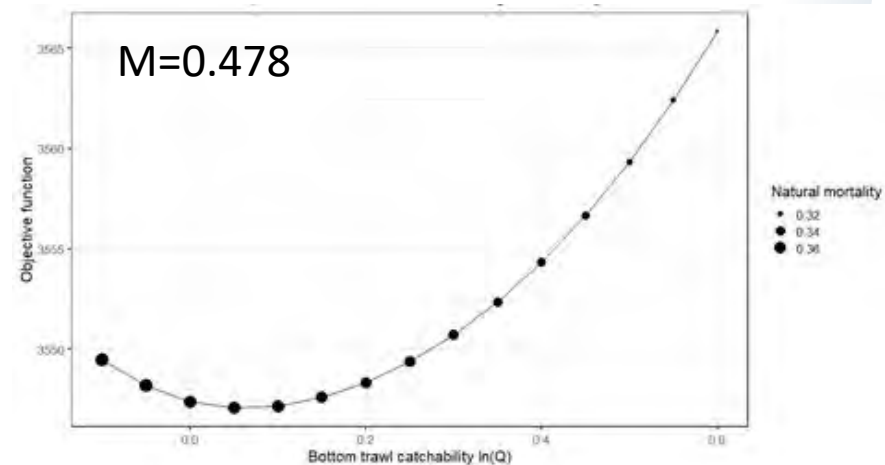
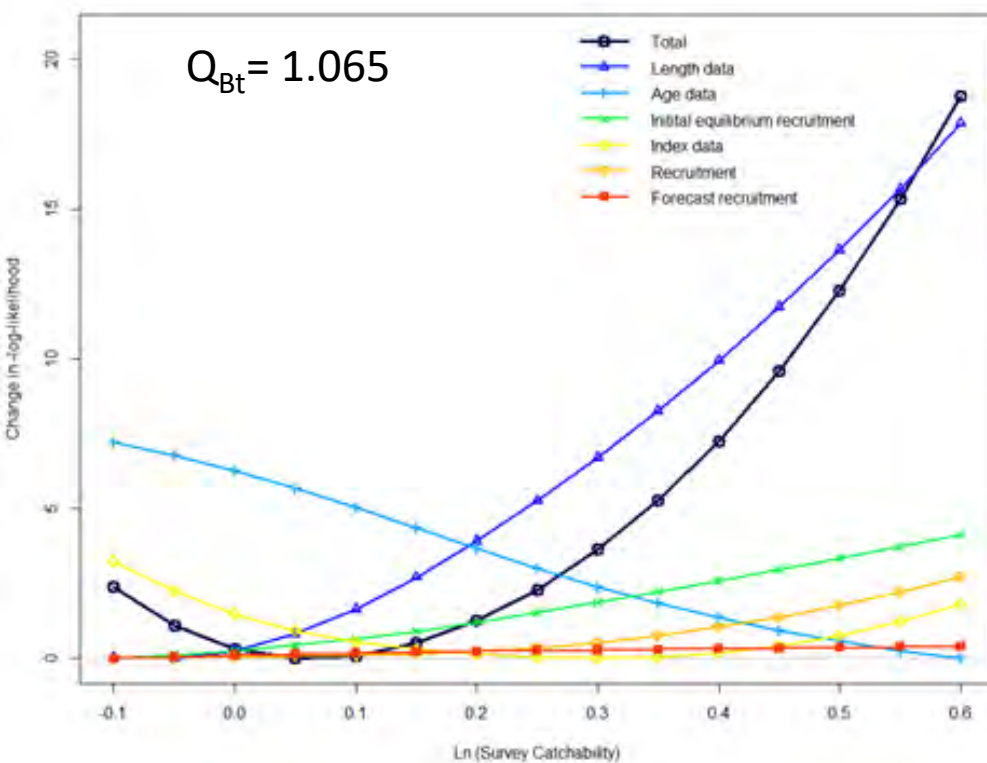


Model 21.2 Length composition fits

- 2021 projected mean sizes are smaller than observed in all fisheries and surveys



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Model 21.2 Catchability and natural mortality

- Q is well fit in Model 21.2
- Q and M are inversely correlated.



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Assessment-related considerations	Population dynamics considerations	Environmental/ecosystem considerations	Fishery Performance
Level 1: Normal	Level 1: Normal	Level 1: Normal	Level 1: Normal

- **Assessment related** – Still some uncertainty on pre-1985 population, but improved over last year's model
- **Population dynamics** – Still low spawning biomass, but appears to be improving, signs of good recruitment in 2020 and average in 2021.
- **Environmental/ecosystem** – Cooling in 2021 to average or below and overall better conditions.
- **Fishery performance** – Mixed results as normal, EM adds some uncertainty in how to measure performance.

Risk table

- Level 1: Normal for all components

