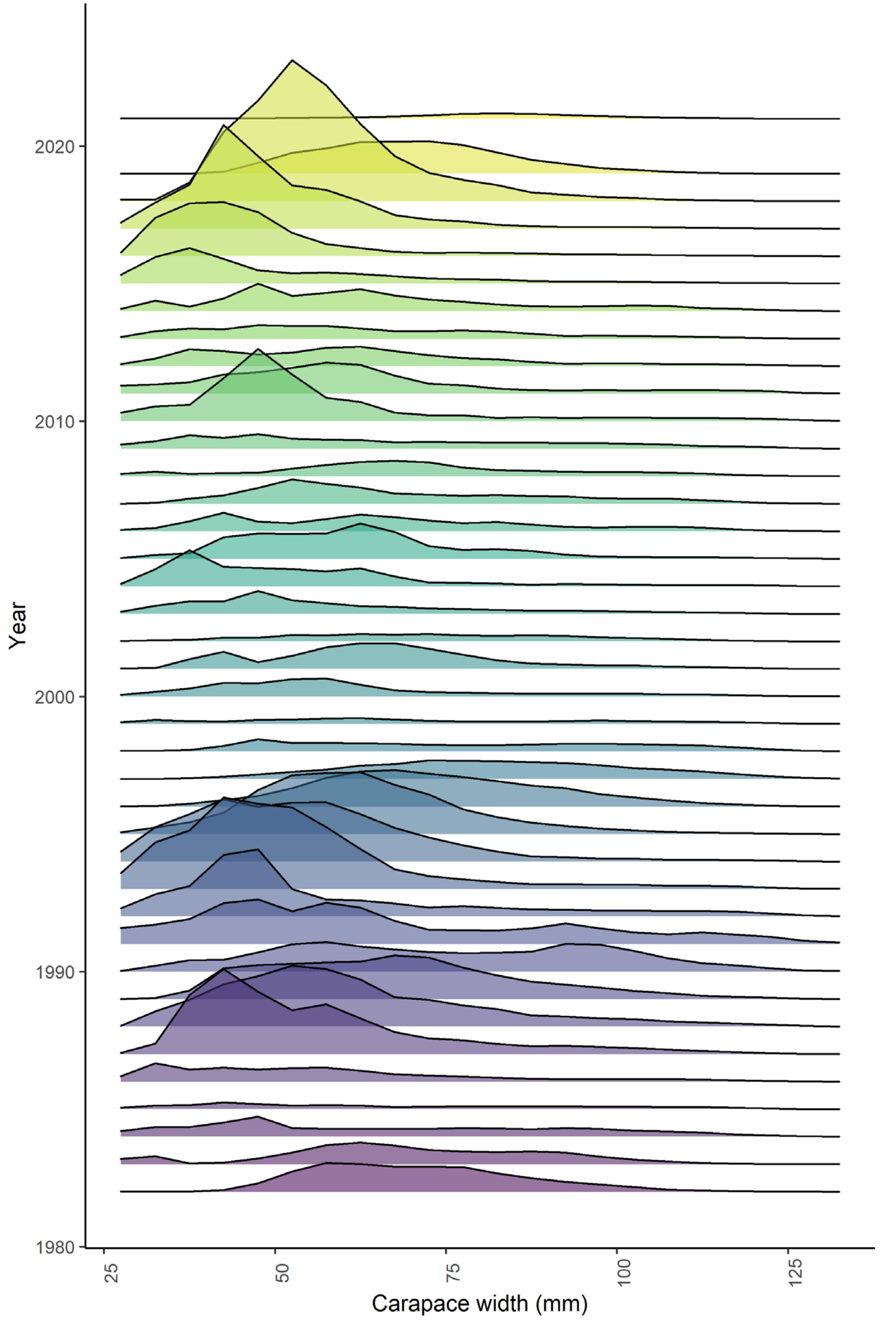
2021 assessment for eastern Bering Sea snow crab

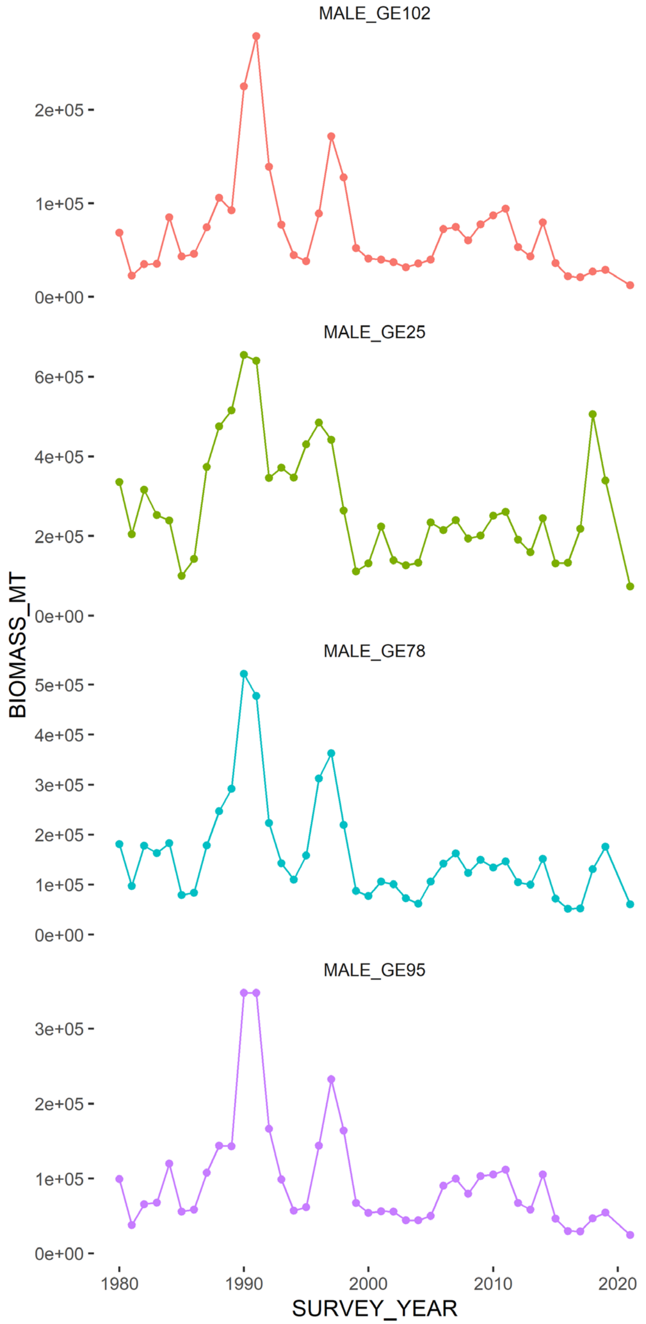
September 30, 2021

Record lows Maturity What happened?



The drop in observed numbers of male crab at size from 2018 to 2019 was even more severe in 2021.

Record lows



Maturity

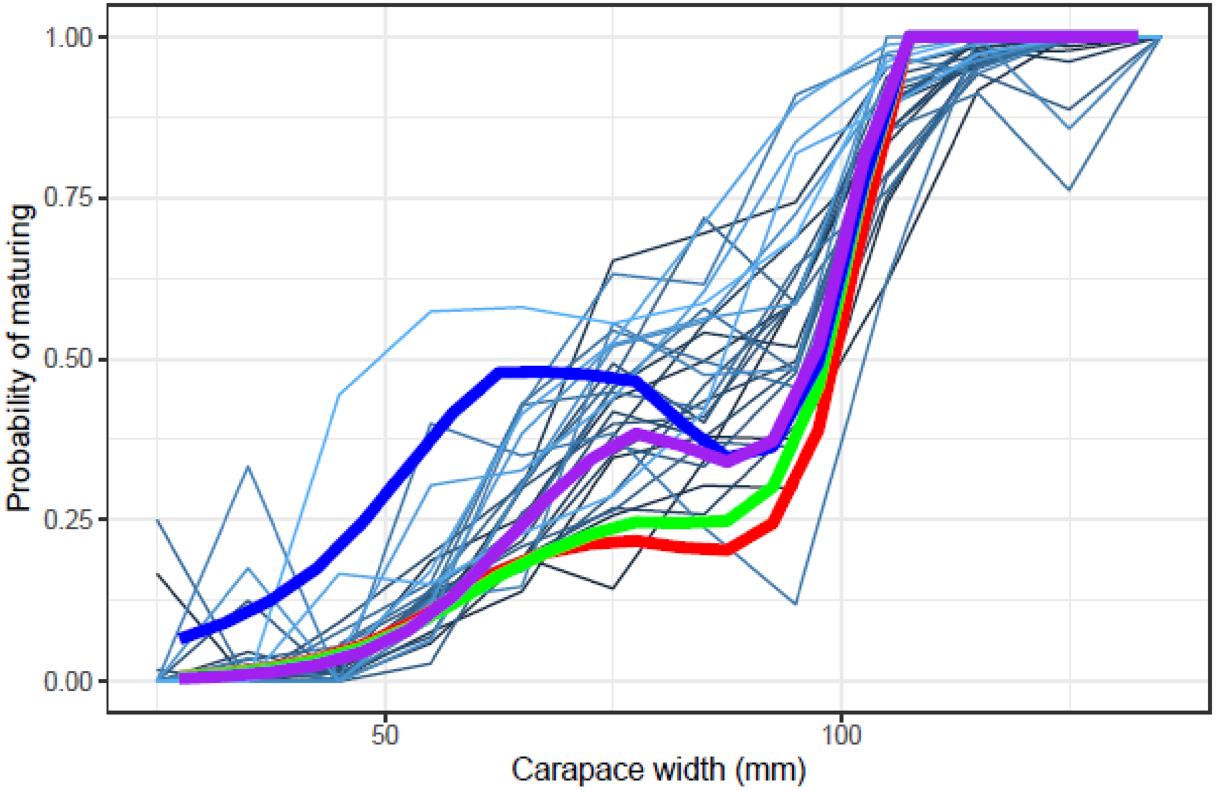
What happened?

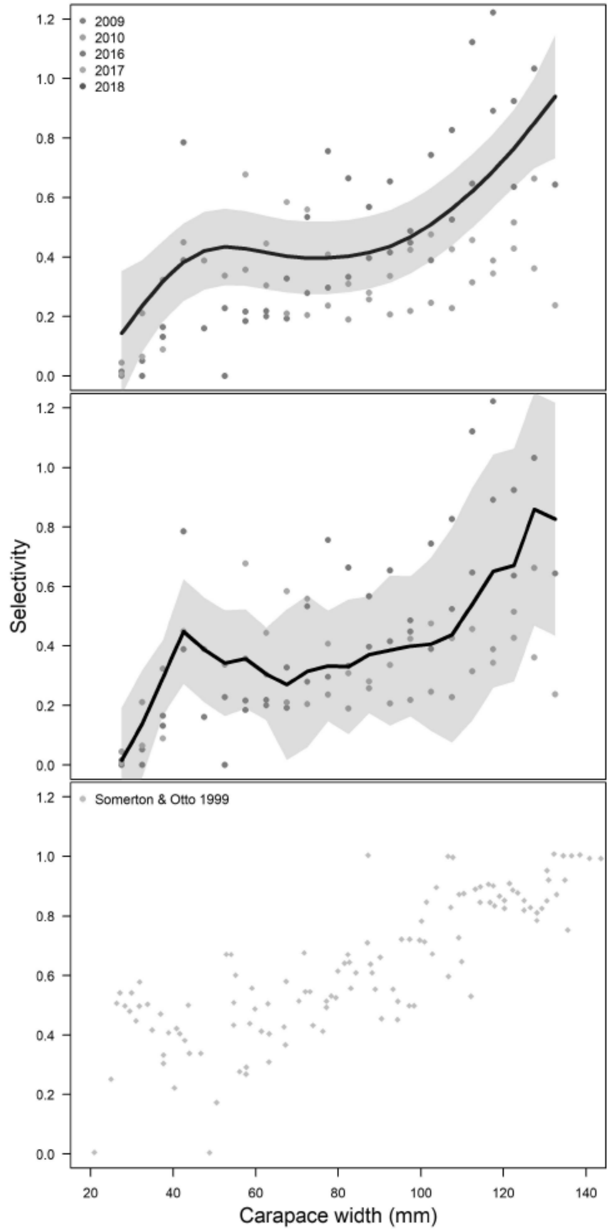
Nearly every size grouping is at all time lows.

Size group	Current biomass (kt)	Previous low (kt)	Overfished declaration (1999)
>101 mm	12.4	20.7 (2016)	52.0
>24 mm	73.5	99.8 (1985)	111.5
>77 mm	60.1	51.7 (2016)	87.1
>94 mm	24.4	29.4 (2016)	67.4

Record lows Maturity What happened?

Allowing for a more flexible survey selectivity produces probabilities of maturing more similar to observed…but reference points are impacted.

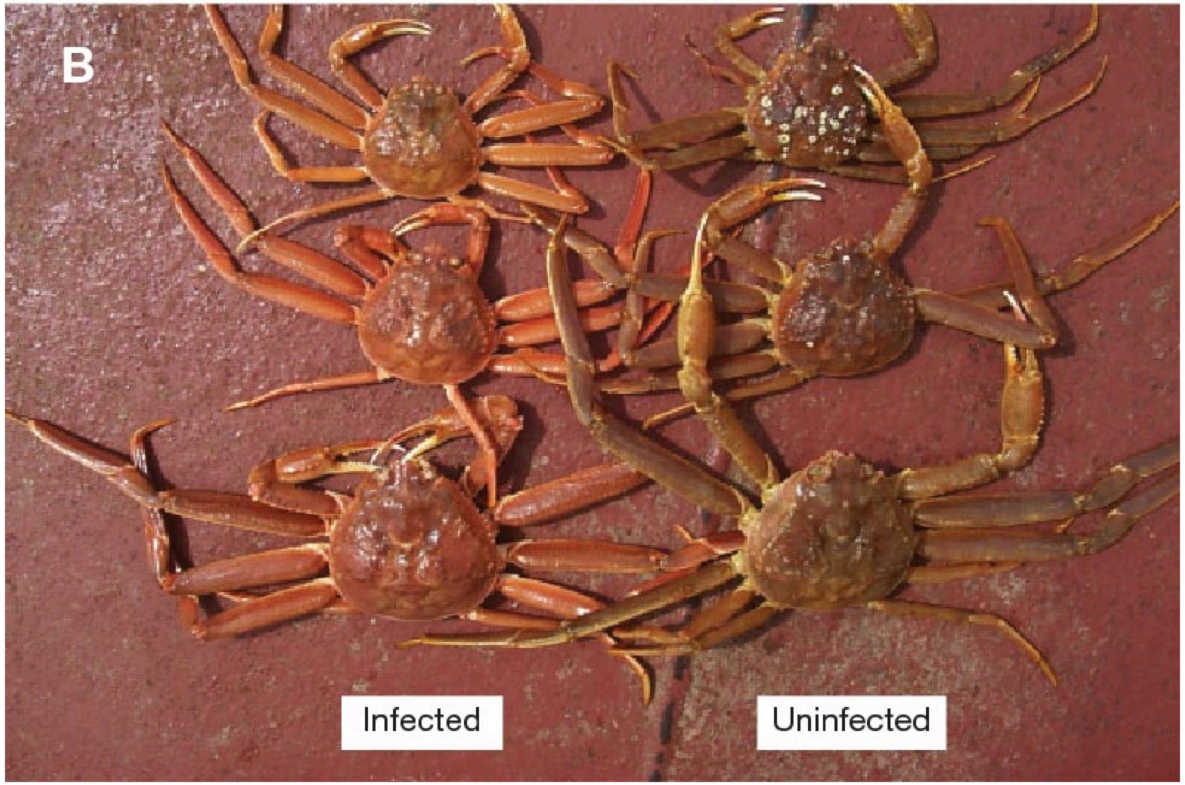


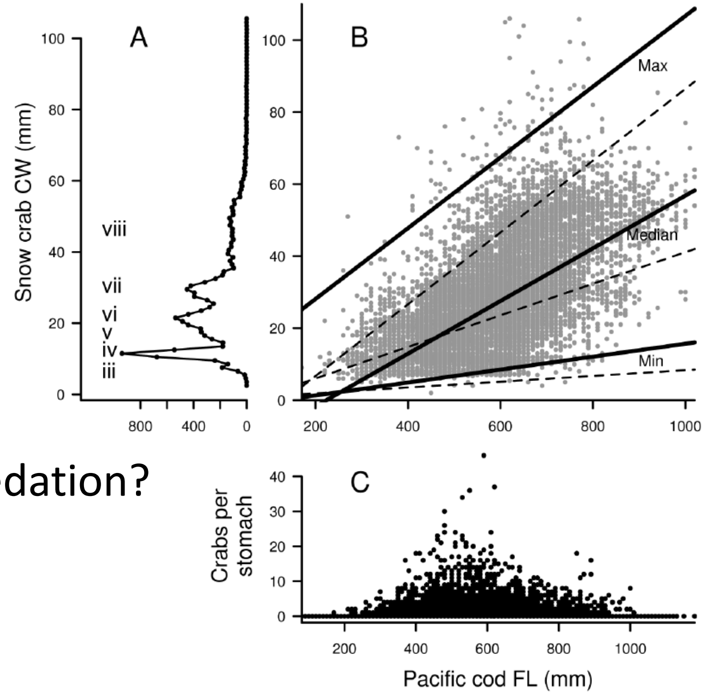


Record lows Maturity What happened?

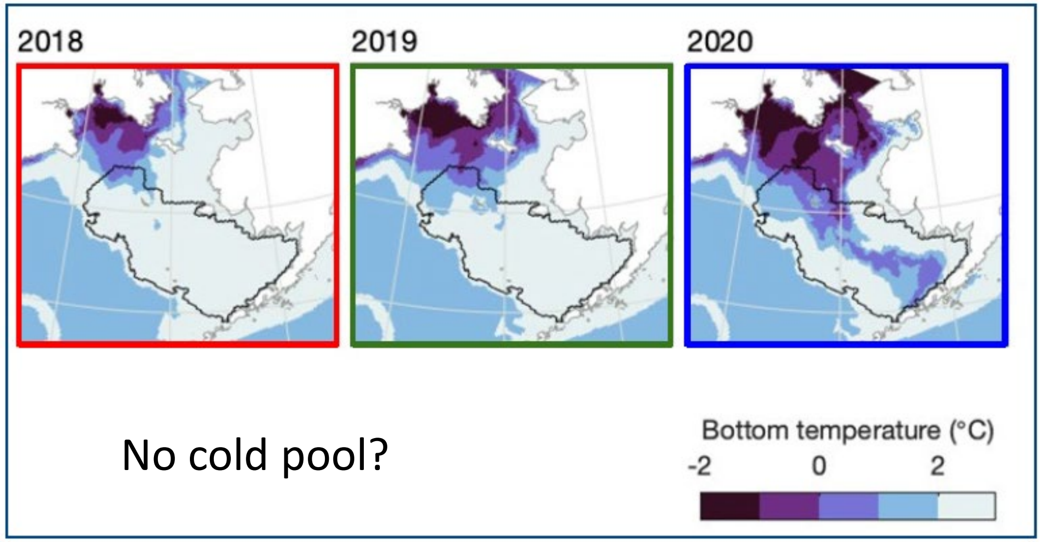
The best available information suggests a mortality event occurred.

Bitter crab syndrome?





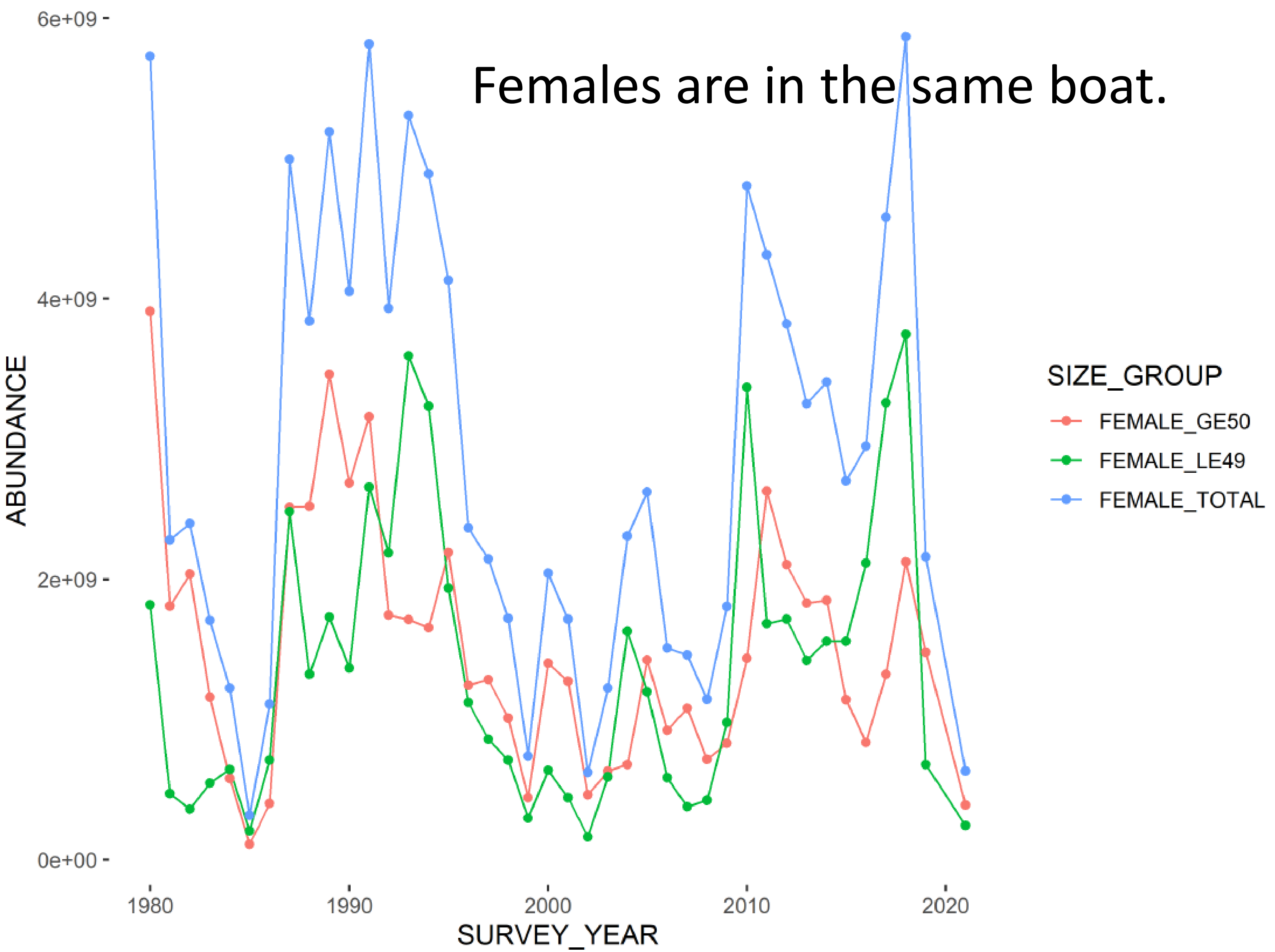
Cod predation?



No cold pool?

Record lows Maturity What happened?

Females are in the same boat.



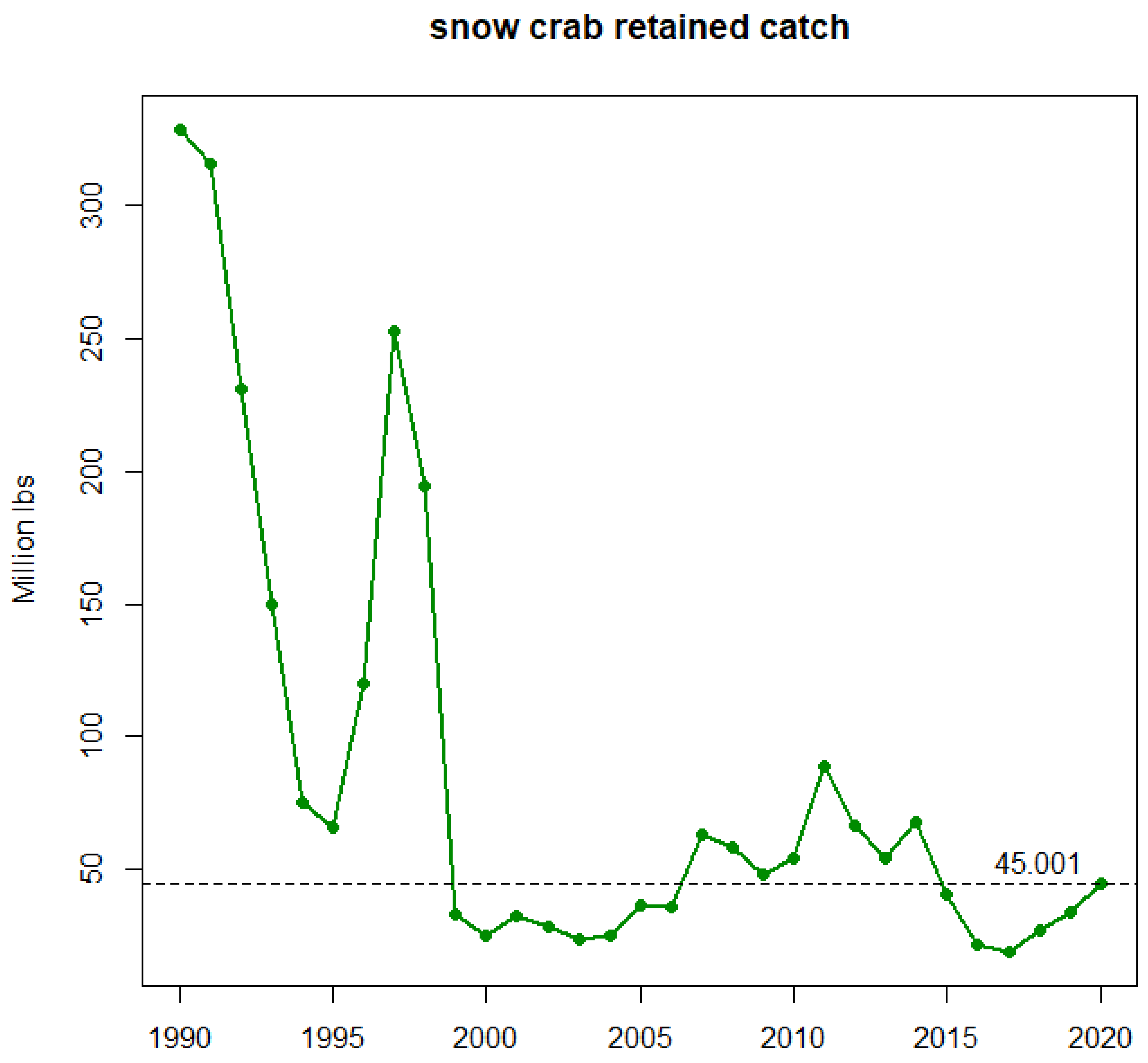
Fishery update

Hypotheses for missing crab

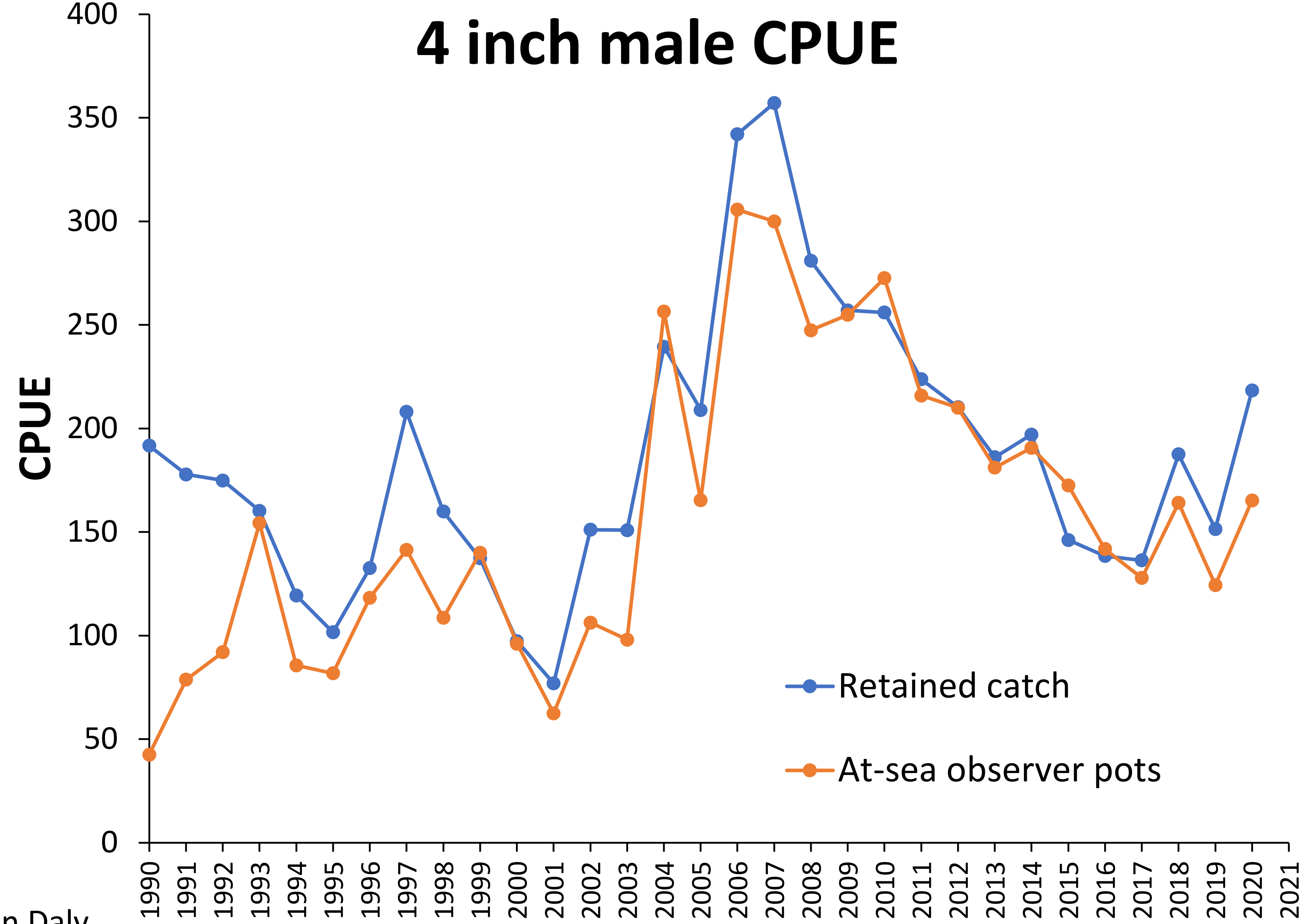
Assessment models and fits

Model selection

Fishery update

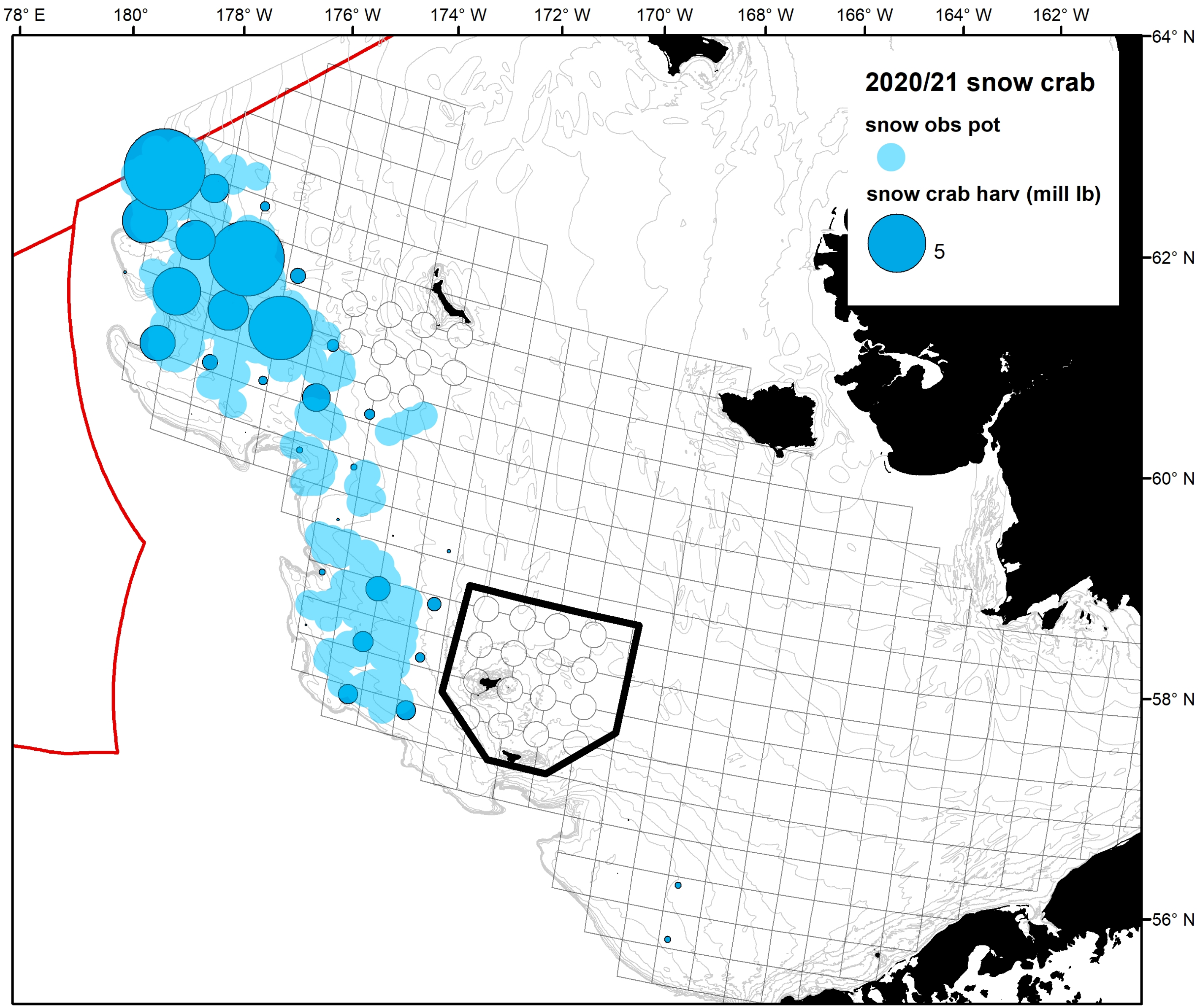


Contributed by Ben Daly



Contributed by Ben Daly

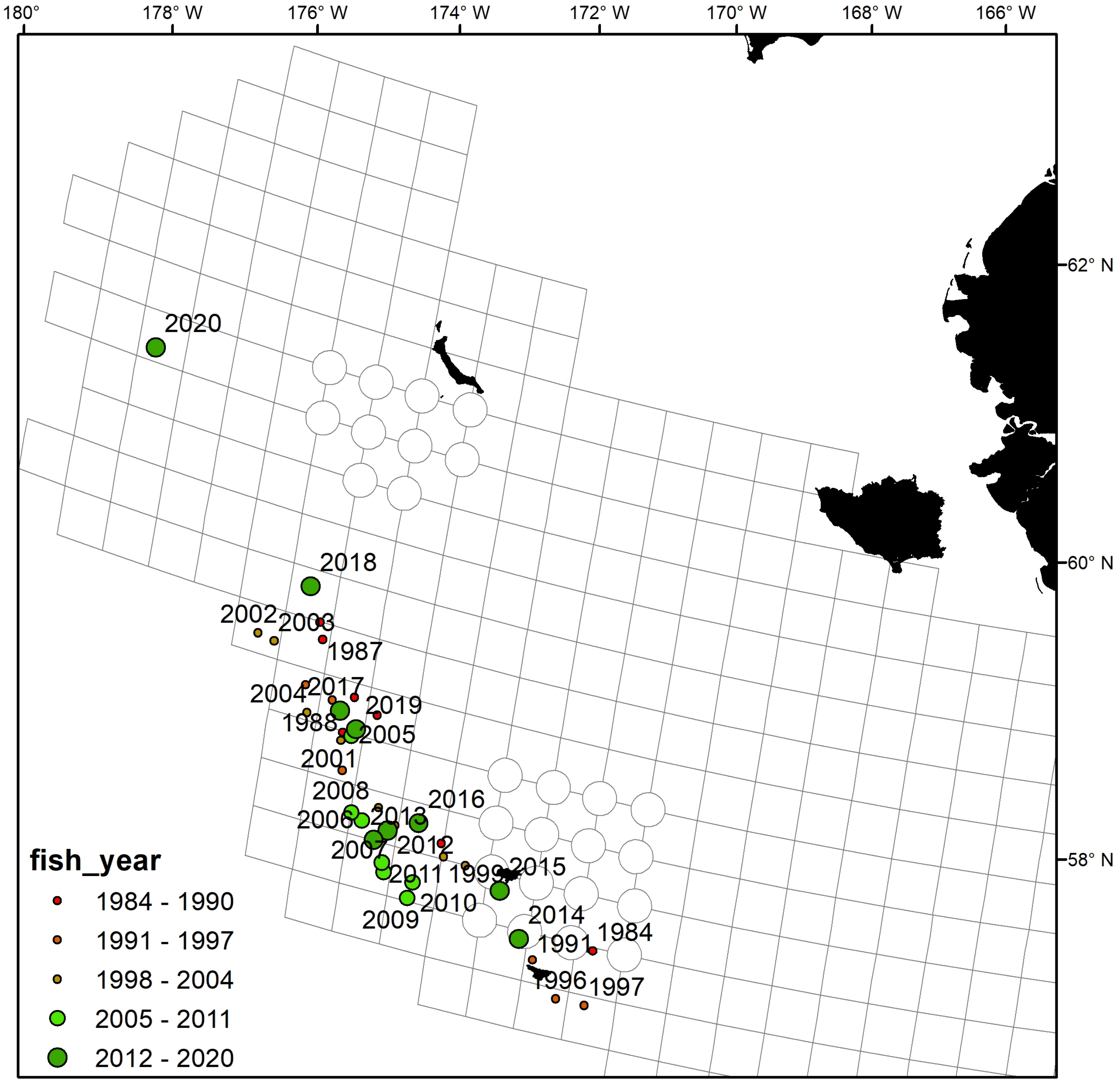
2020/21 snow crab retained catch



* Excludes stat areas with <3 vessels

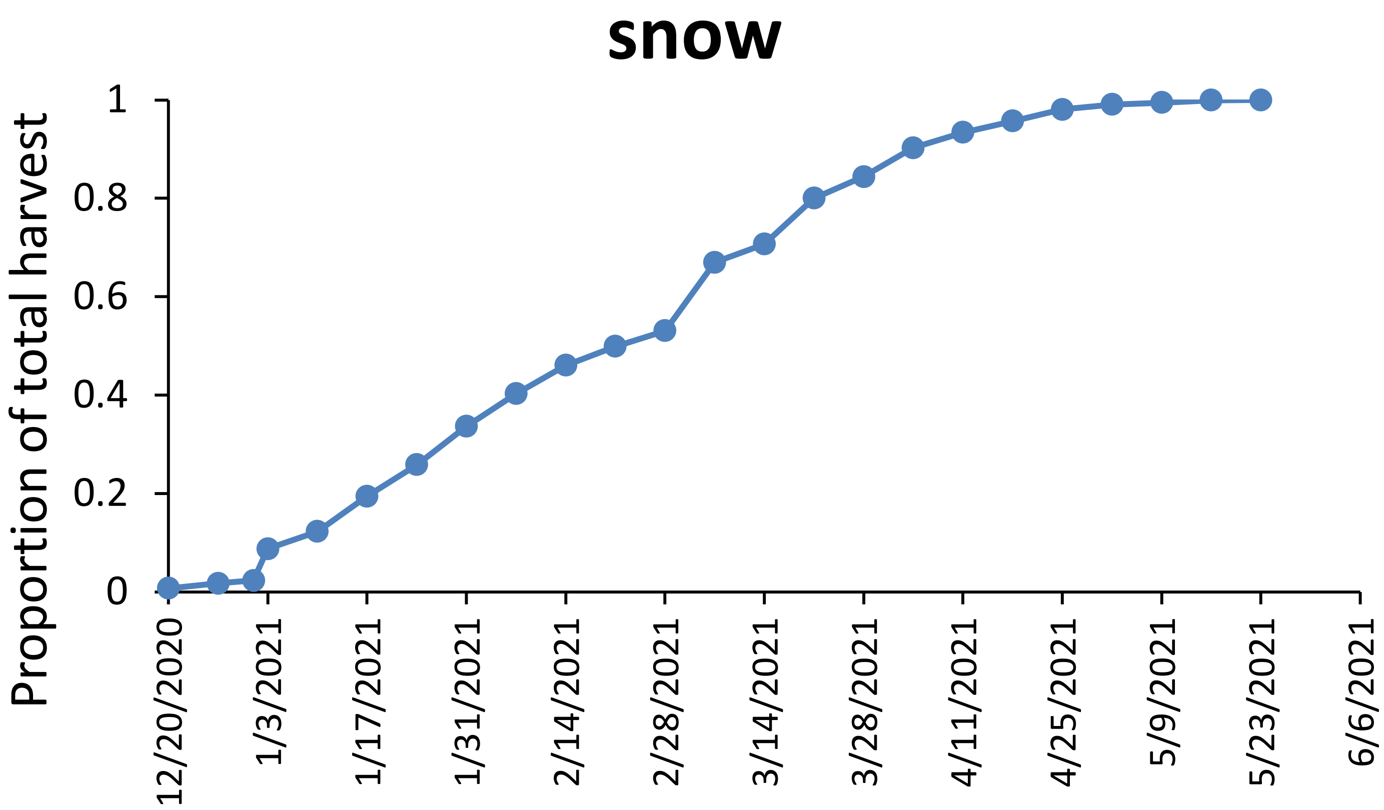
Contributed by Ben Daly

Snow crab weighted mean centers of catch



Contributed by Ben Daly

2020/21 snow crab



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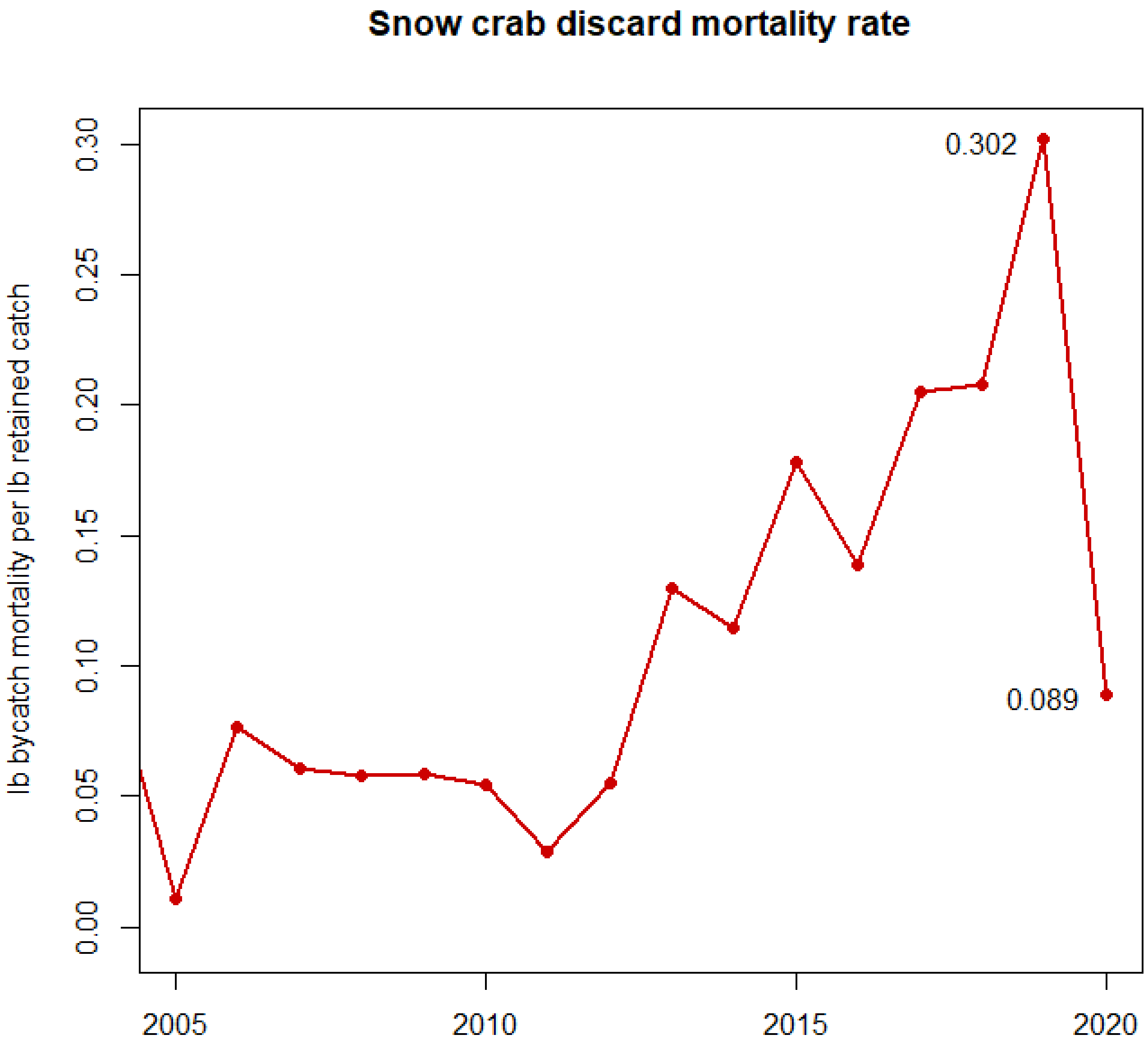

Contributed by Ben Daly

Assessment models

- Status quo model with updated data did not converge
- Availability and natural mortality parameters had large gradients
- Size composition re-weighting was recommended by CPT, SSC, CIE
  - Tried both McAllister-Ianelli (1998) and Francis (2011) reweighting for size composition, but neither produced viable models (for slightly different reasons)
- No GMACS model—time-varying M doesn't work with terminal molt yet

- 20.1 – Last year's accepted model (status quo) fit to last year's data
- 21.1 – Last year's accepted model (status quo) fit to this year's data
- 21.1a – 21.1 + empirical availability
- 21.1b – 21.1 + mortality events in 2018 and 2019
- 21.1c – 21.1a + McAllister-Ianelli re-weighting
- 21.2 – 21.1a + mortality events in 2018 and 2019 + tighter priors on M and maturity smoothness
- 21.3 – 21.1a + mortality events in 2018 and 2019 + empirical selectivity
- 21.3a – 21.3 + FMSY = natural mortality

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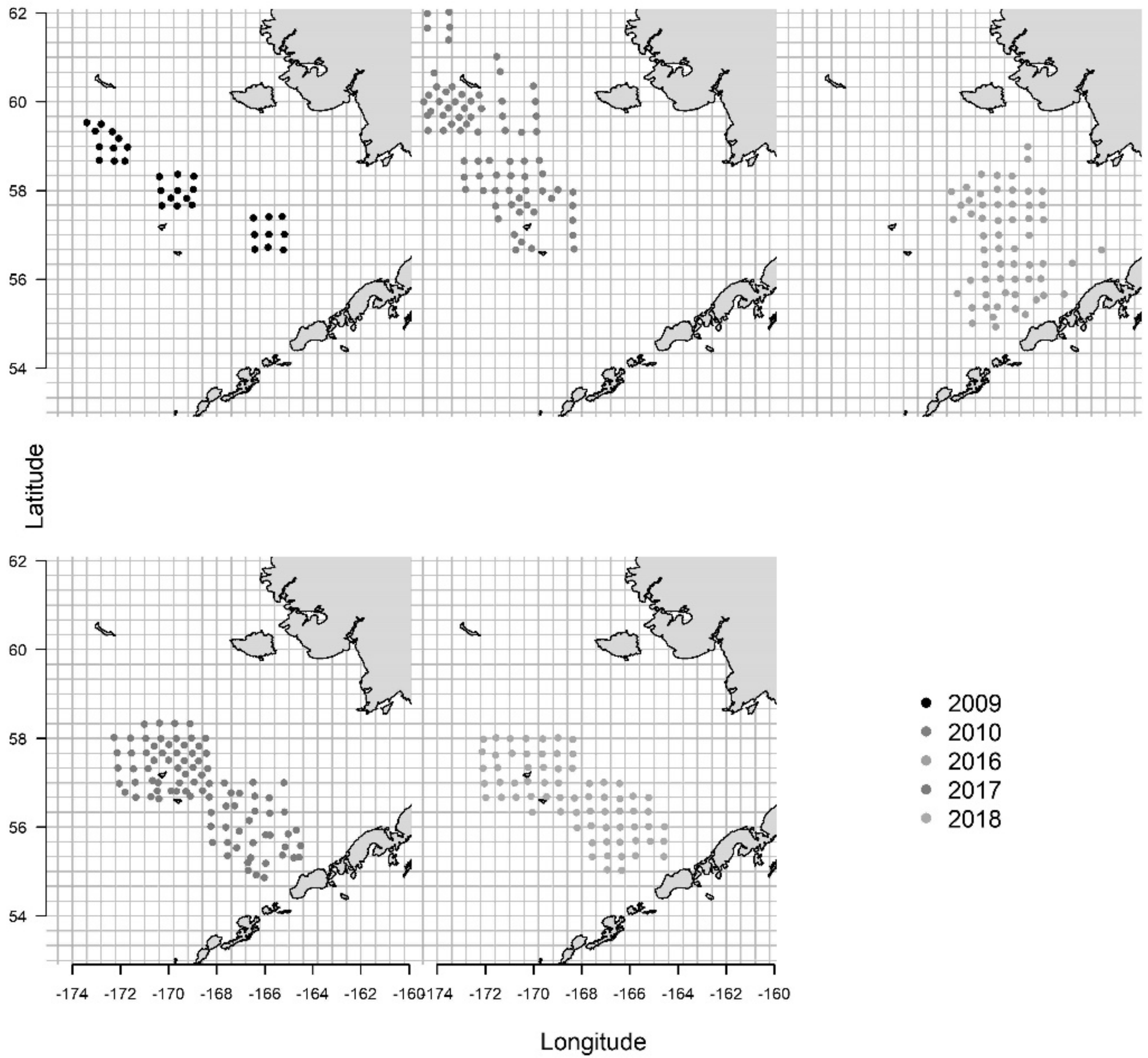
Empirical availability

To use the BSFRF data to inform survey selectivity, we need to know what portion of the NMFS survey data in the same year to compare it to—the ‘availability’ of the crab to the BSFRF surveys.

The status quo model estimated availabilities for males and females in 2009 and 2010.

However, we have the information to calculate the availabilities—the size compositions from the total NMFS survey and the size compositions from the NMFS survey that occurred in the BSFRF study areas in a given year.

$$Q_{l,y} = \frac{N_{l,y,NMFS\_s}}{N_{l,y,NMFS\_tot}}$$

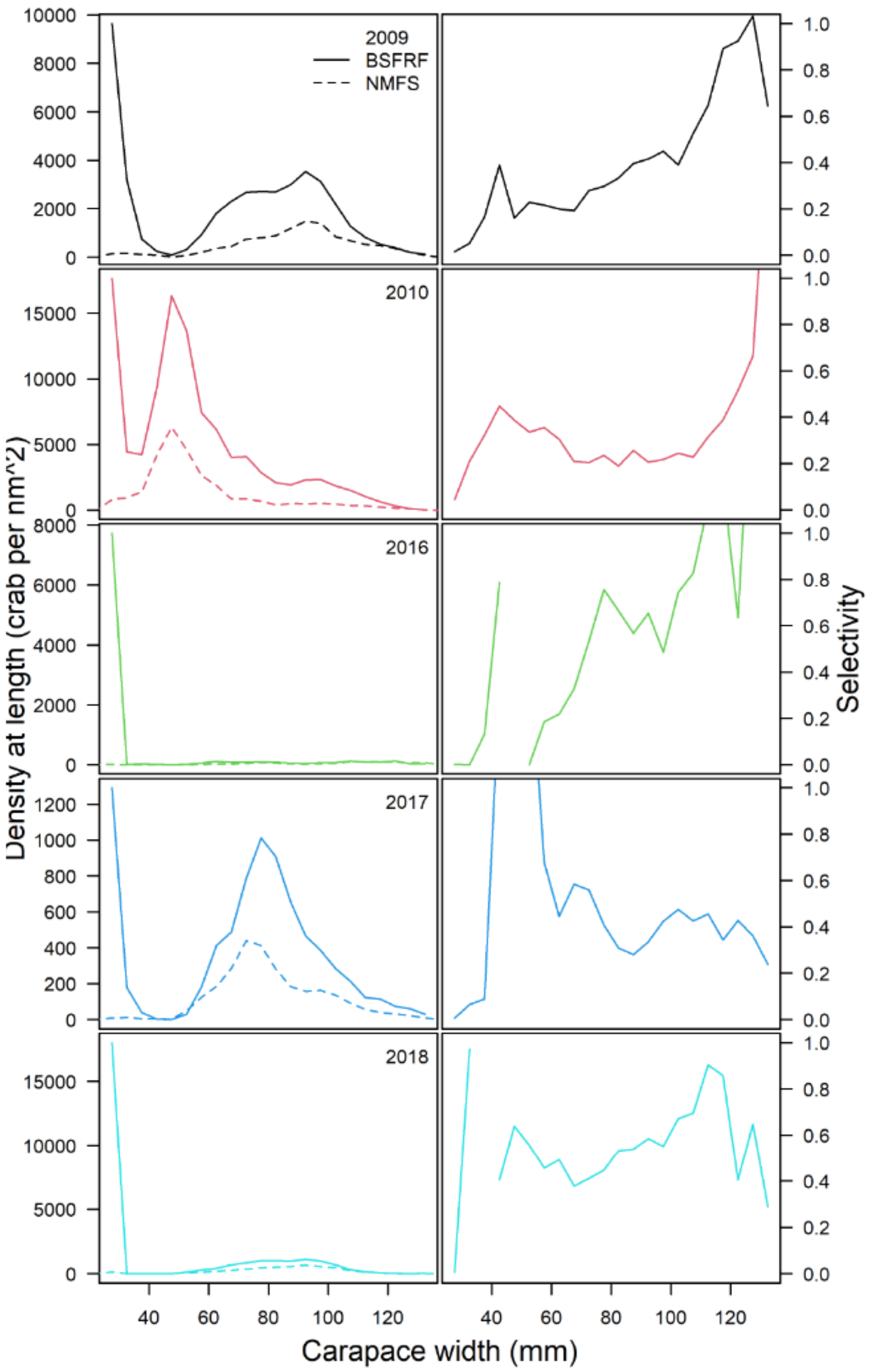


Empirical selectivity

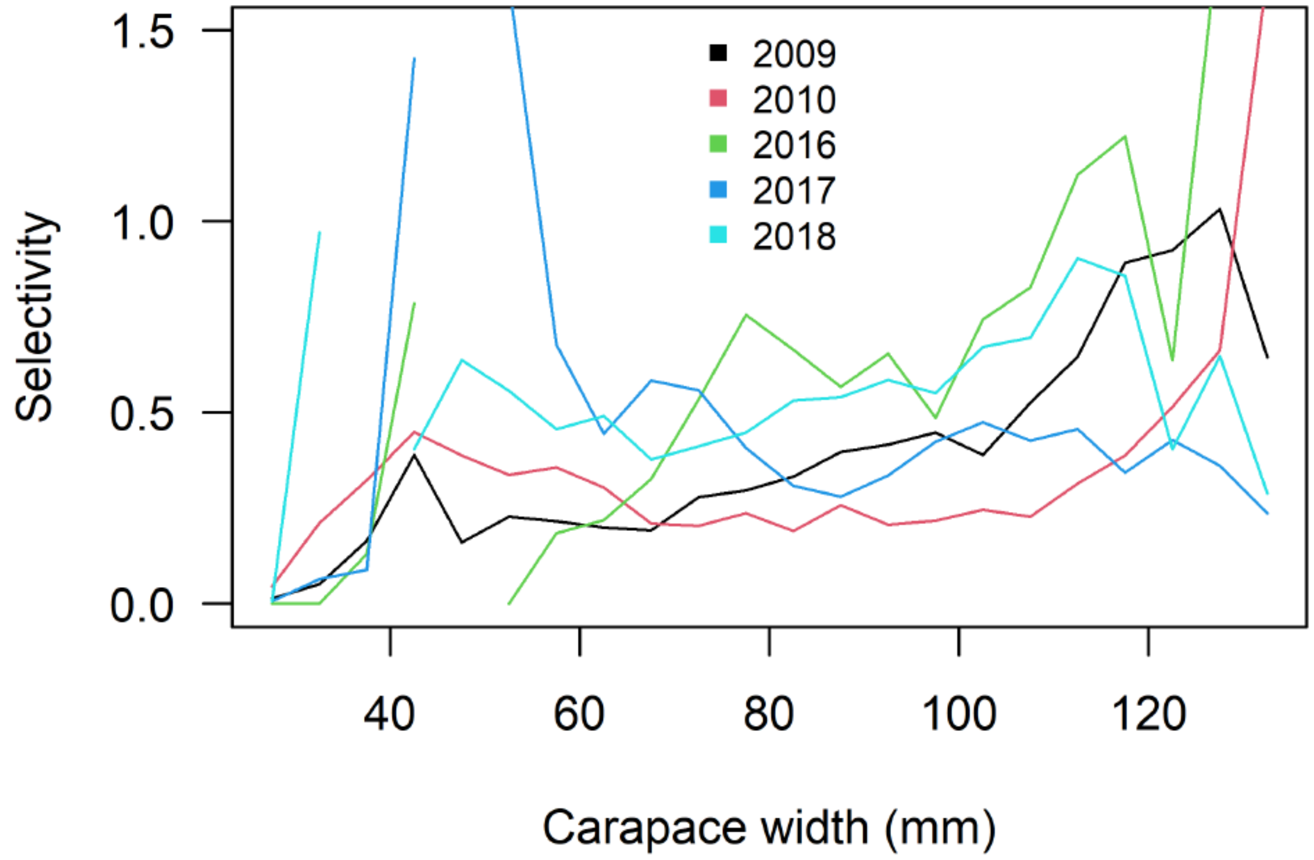
- "Empirical selectivity" is the estimate of the proportion of crab caught in the BSFRF study area in a given year, based on estimates of numbers at size in both surveys

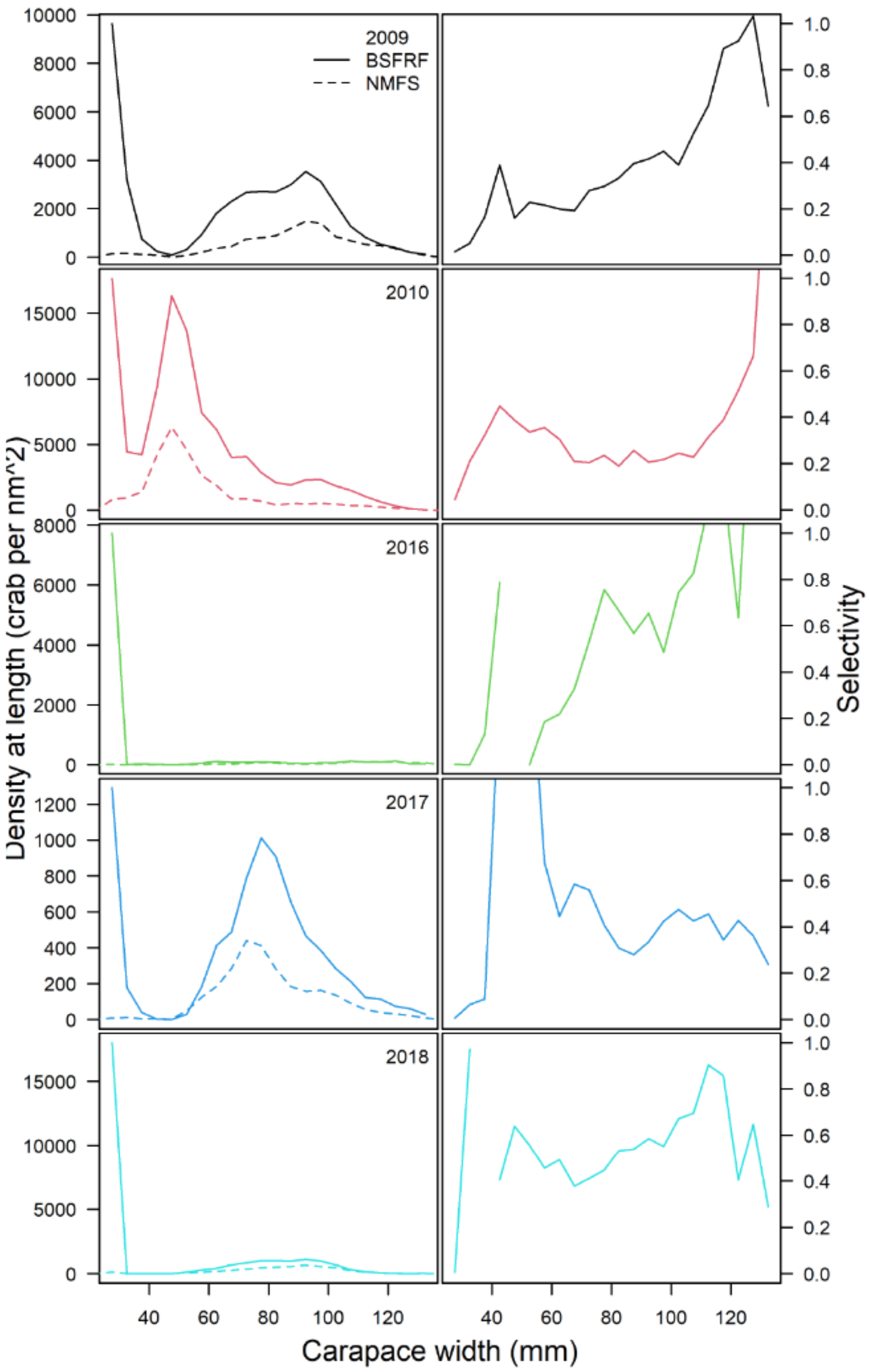
$$S_{l,y} = \frac{N_{l,y,NMFS\_s}}{N_{l,y,BSFRF}}$$

- $S_{l,y}$ was used as a prior for non-parametric selectivity in some models.



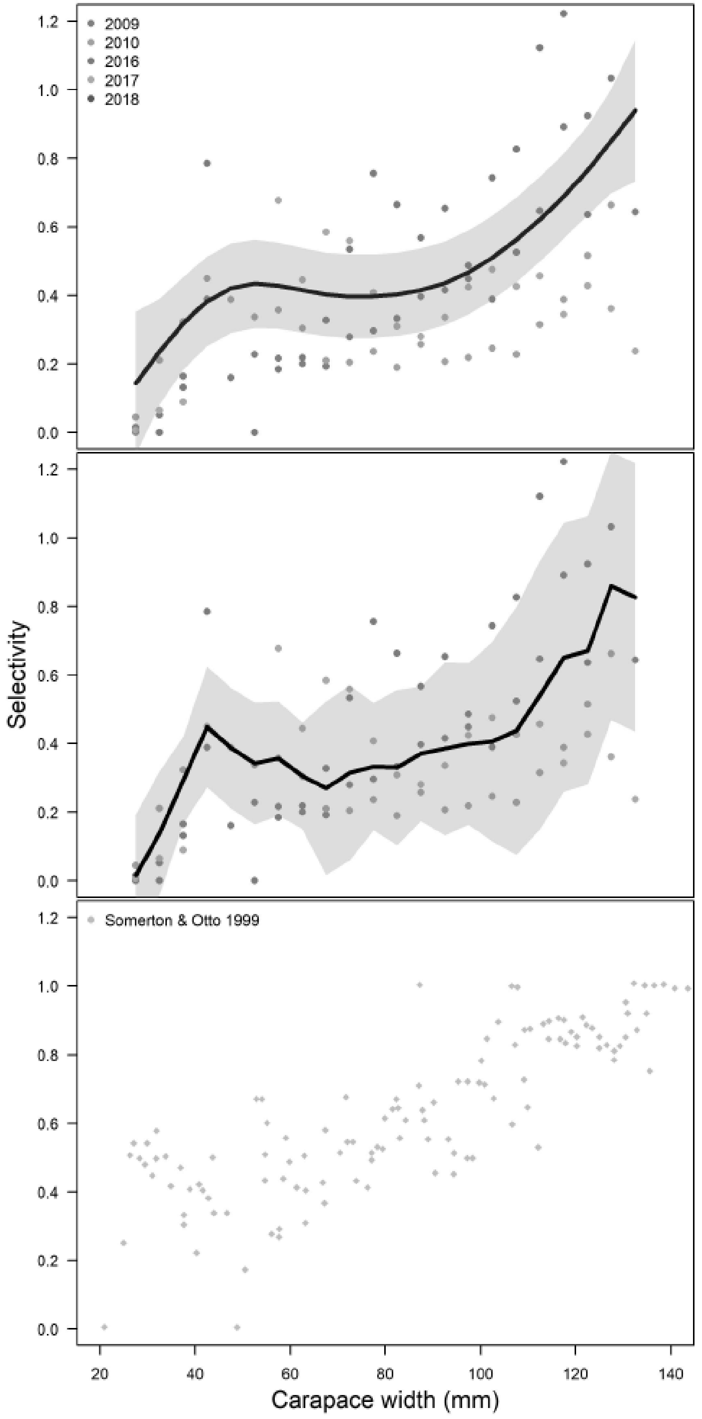
Empirical selectivity





Empirical selectivity

- Consistency across experiments
- Methods for developing a prior:
    - Mean of $S_{l,y}$ across 2009, 2010, 2016, 2017, 2018, weighted by sample size
    - Fit a generalized additive model to data, use predicted $S_{l,y}$ and estimated SE
- Outcomes are similar, but not identical
- Additional exploration needed



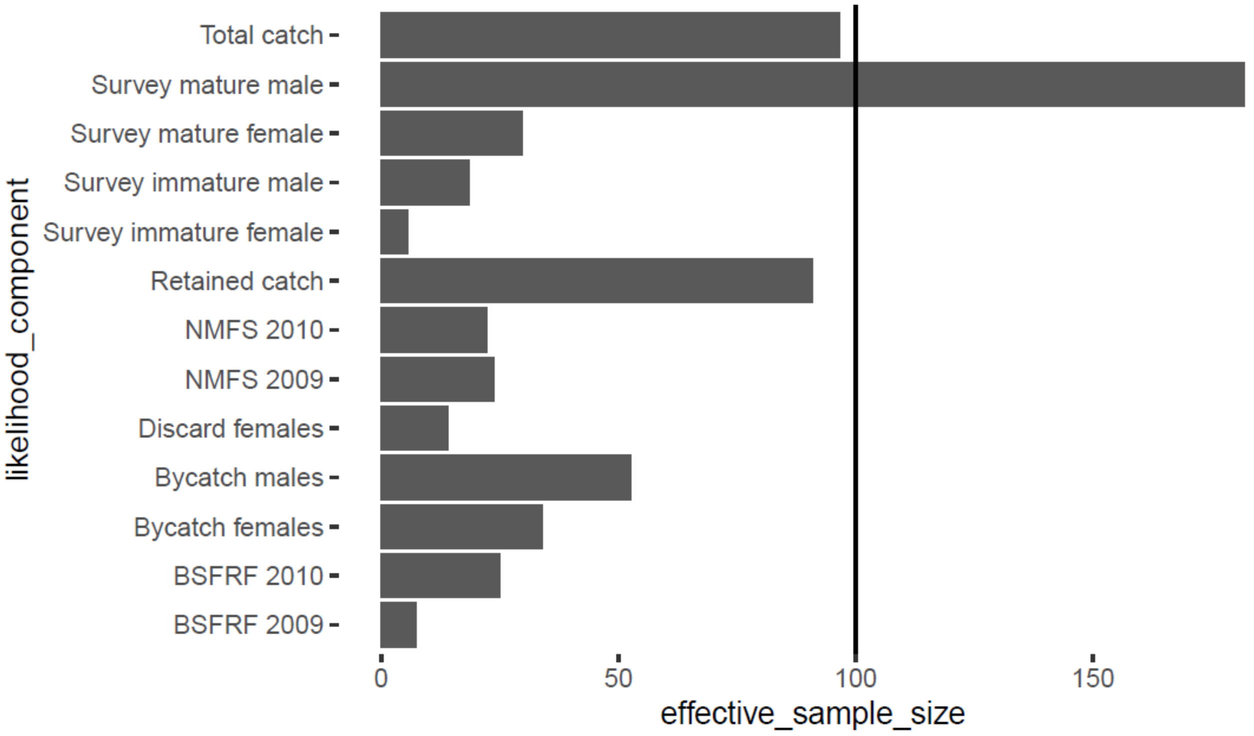
Size composition reweighting

Size composition reweighting ‘balances’ the contribution of size composition data in the model.

Francis and McAllister-Ianelli methods attempted

M-I converged to stable weightings, but the models ran with those weights did not converge (max gradient >>0.01)

Francis did not converge to stable weightings, the size composition data were essentially removed from the objective function.



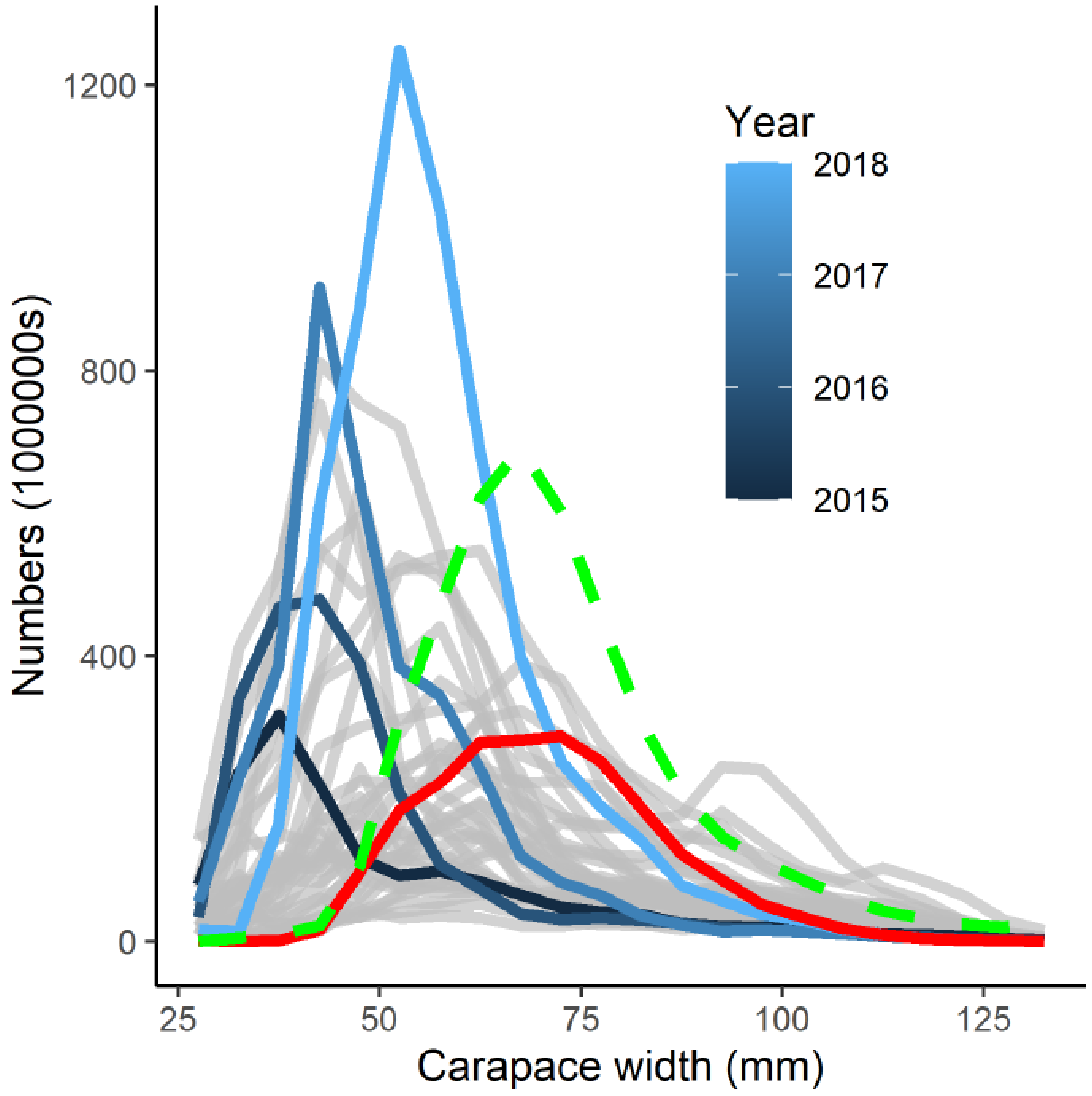
Mortality events

- Transformed M to an array with dimensions for sex, maturity, and year
- Specify years for mortality (2018, 2019)
- All classes of M allow additional mortality in those year
  - Immature
  - Mature female
  - Mature male
- Estimated as bounded numbers between 0 and 4

```
#################################
## time-varying natural mortality specs
#################################
# use_extra_m_imm : extra immature mortality added?
1
# extra_m_phase_imm : phase
5
# extra_m_len_imm_n : number of years of extra imm
2
# extra_m_yr_imm : what years have extra mortality?
2018 2019
# use_extra_m_mat : extra mature mortality added?
1
# extra_m_phase_mat : phase
5
# extra_m_len_mat_n : number of years of extra mature m
2
# extra_m_yr_mat : what years have extra mortality?
2018 2019
```

Why 2018 and 2019?

- Big decline from 2018 to 2019
- 2020 bycatch was very low, suggesting whatever mortality occurred happened before 2020
- Estimating additional M in 2020 would have been difficult with no survey data



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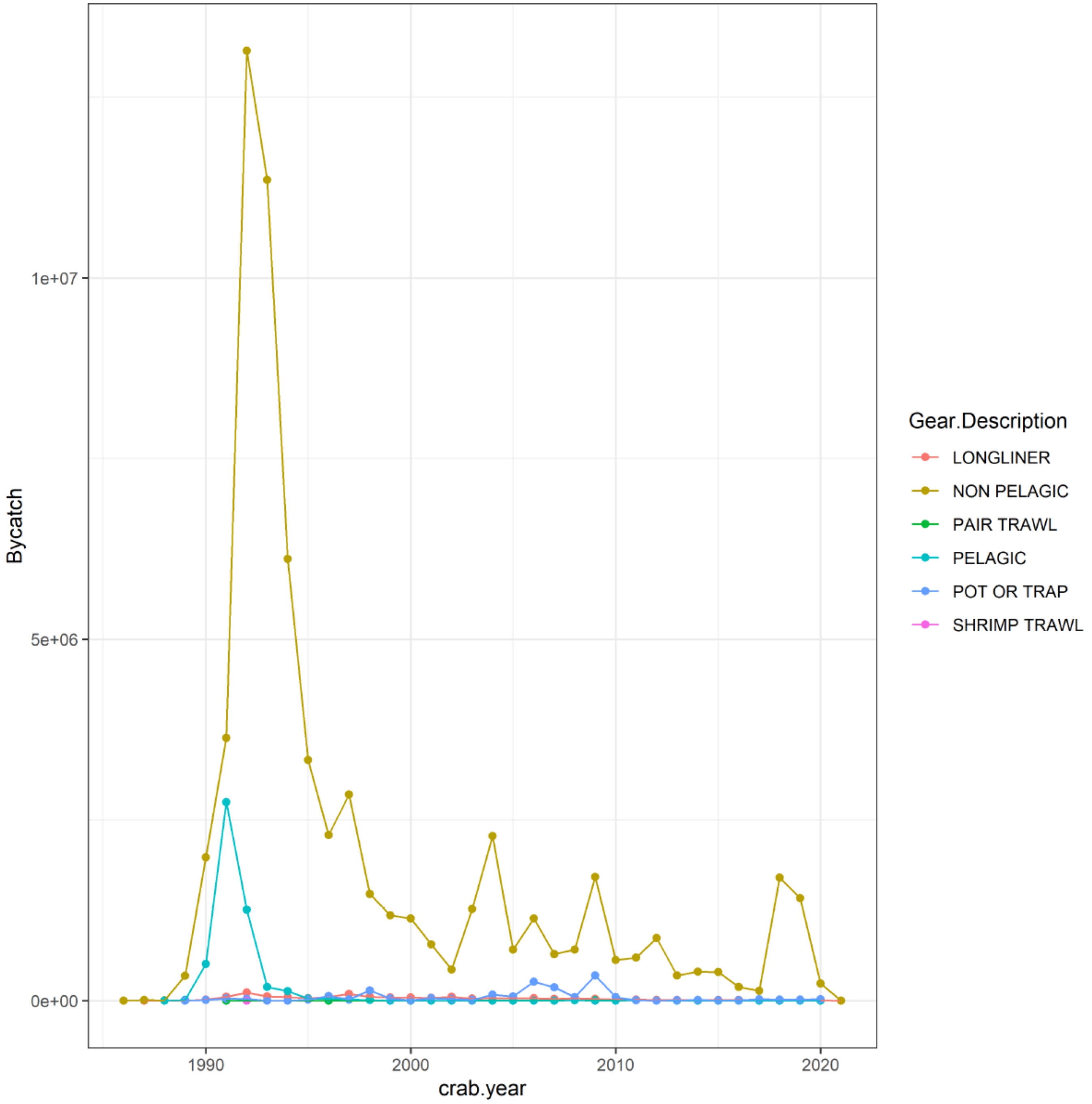

Hypotheses for the decline

Possibilities

- The crab are alive:
  - Crab moved into the northern Bering Sea
  - Crab are in the eastern Bering Sea, but the survey didn't see them
  - Crab moved off of the shelf
  - Crab moved into Russian waters

- The crab are dead:
  - Predation
  - Disease
  - Temperature effects
  - Fishery effects
  - Cannibalism

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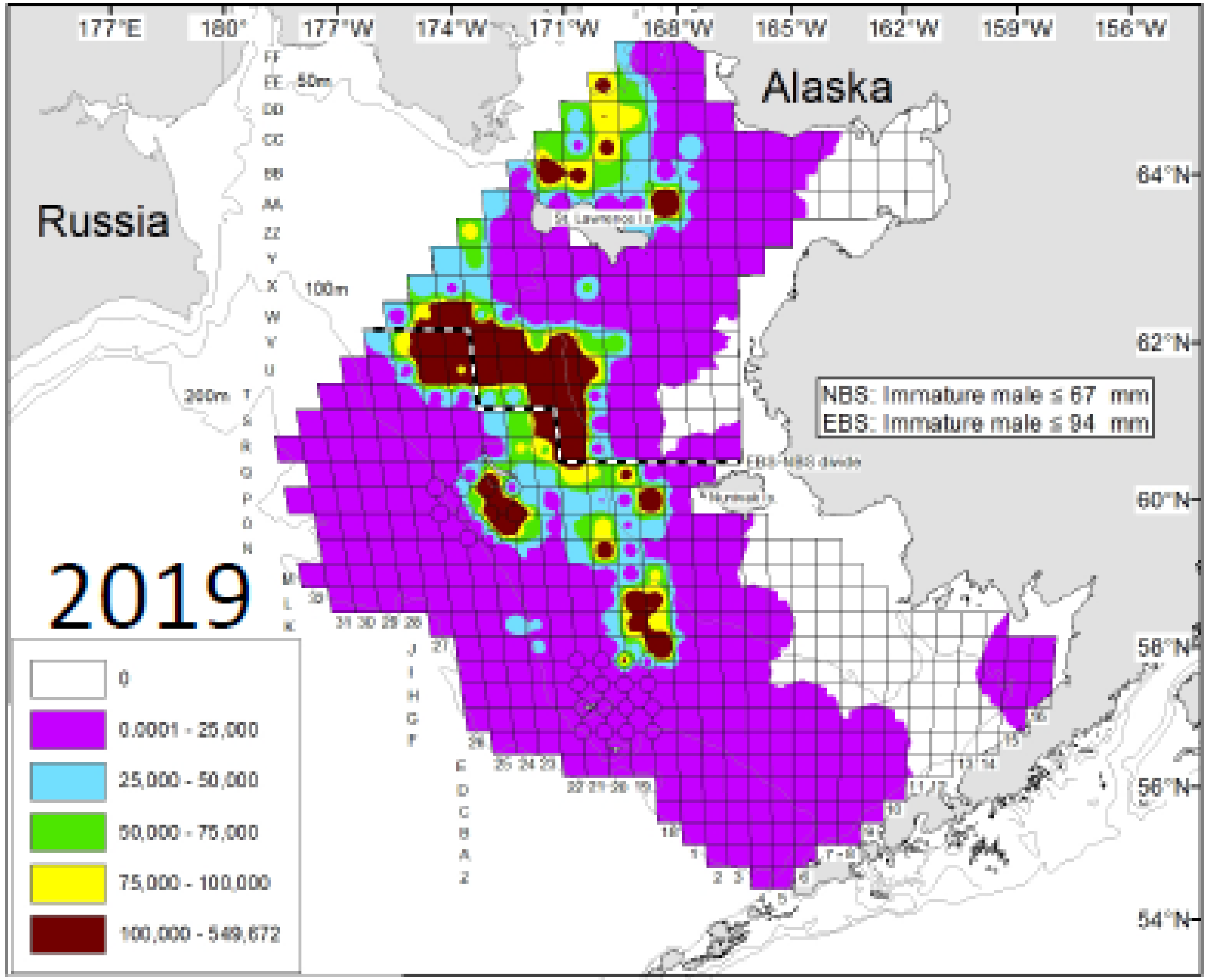
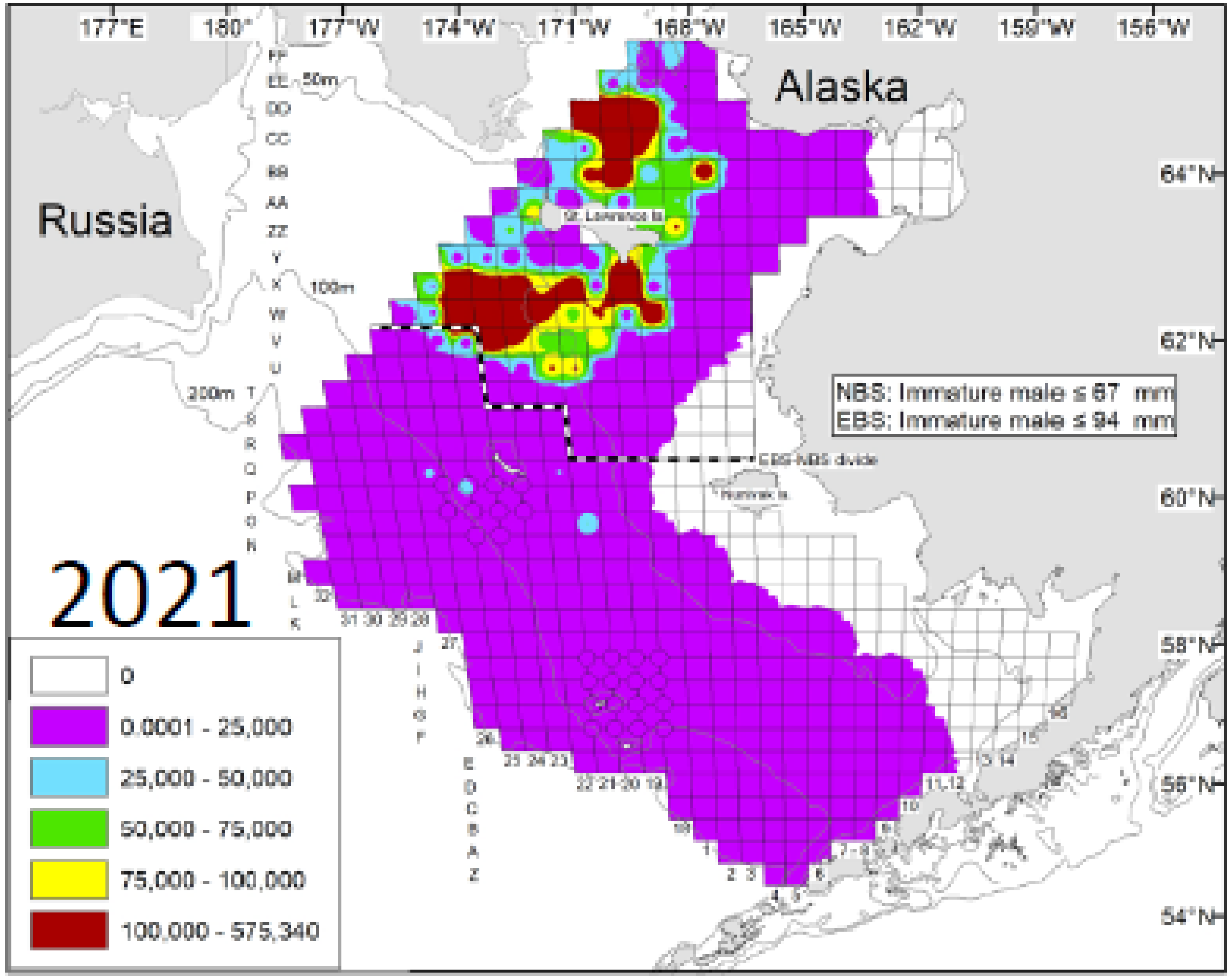
Immature males





Crab are still present in the NBS, but the densities at size ranges that are missing from the EBS are not sufficiently high to suggest crab from the EBS moved into the NBS.

From Mike Litzow et al.

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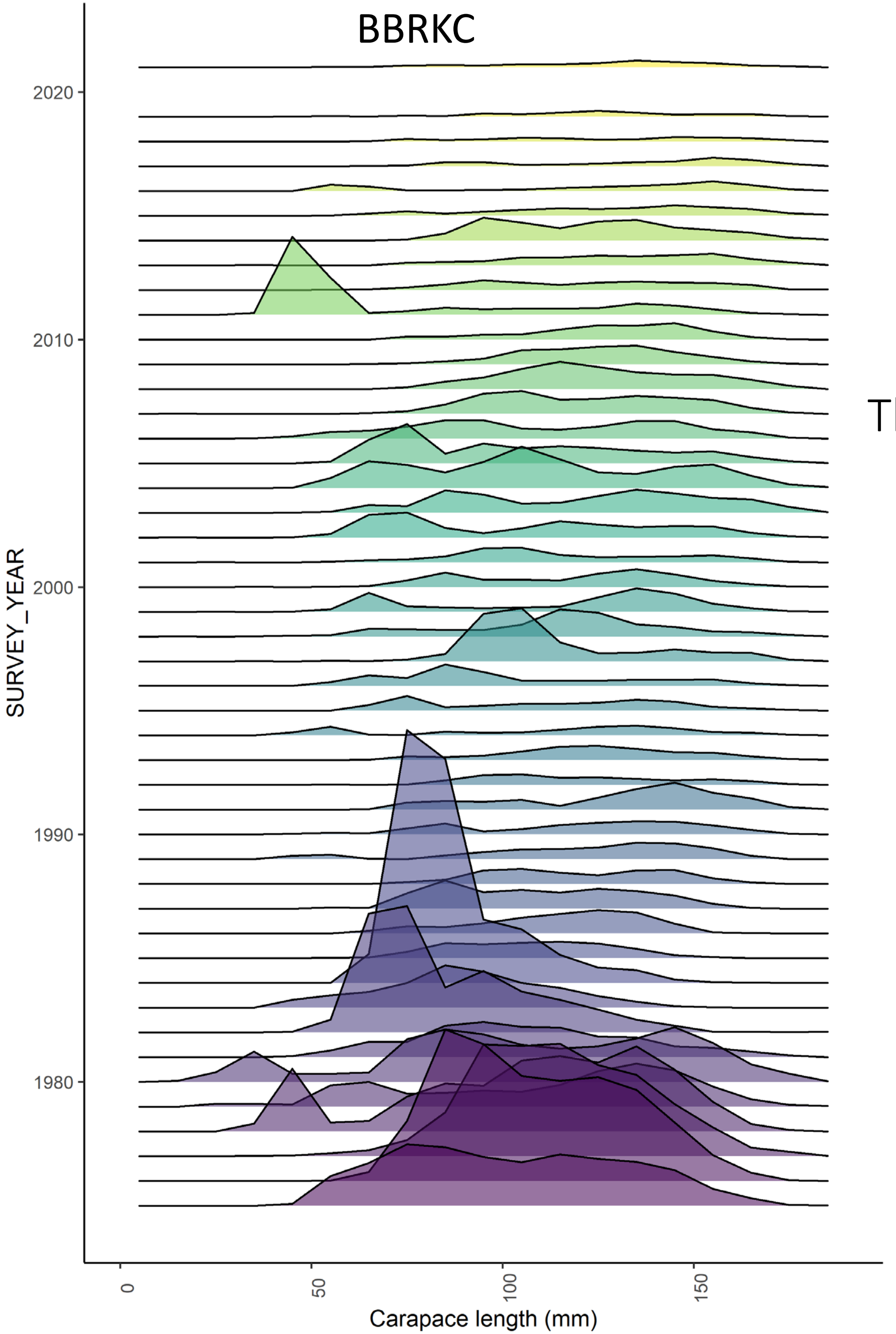
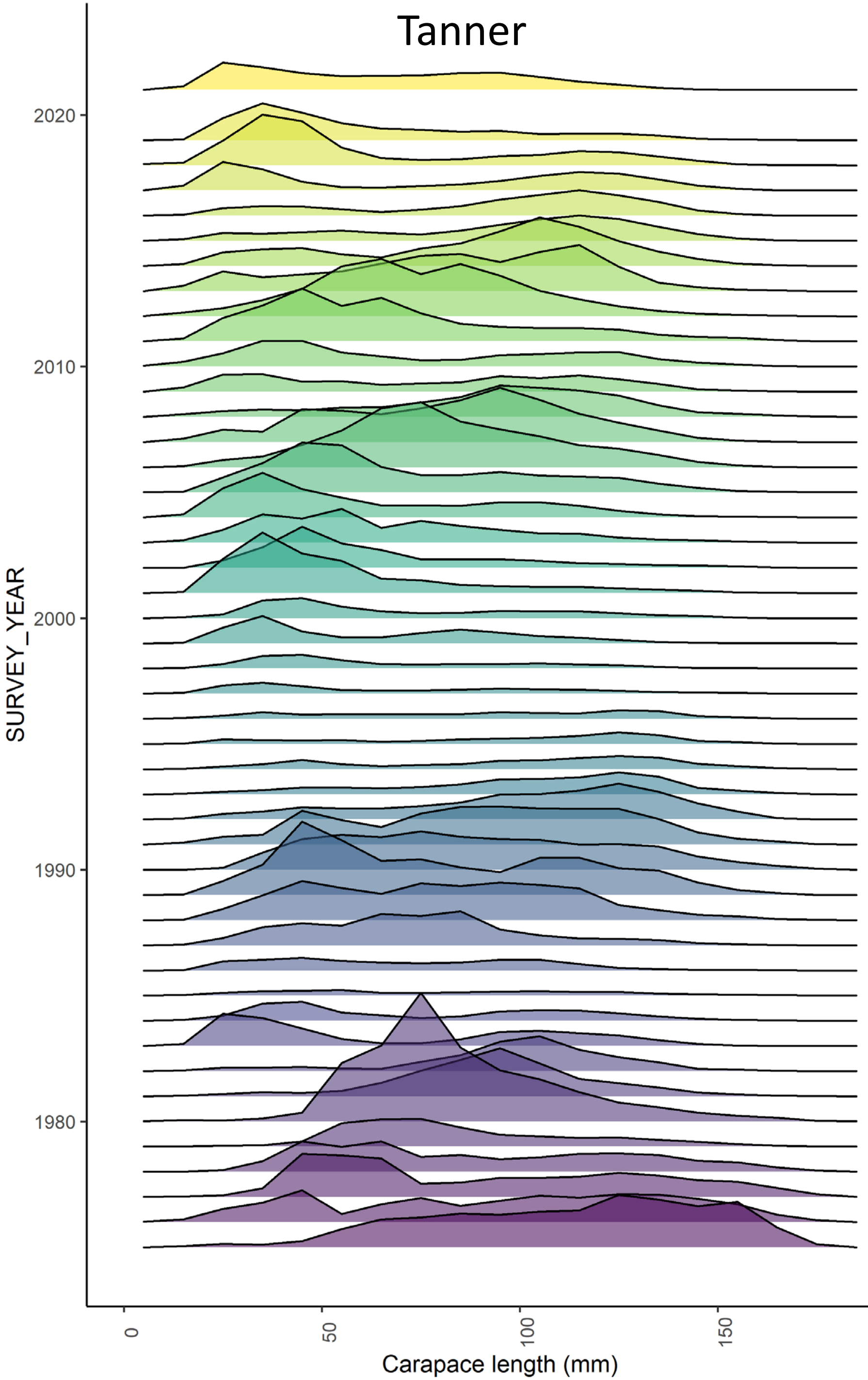


The survey worked as expected for Tanner and BBRKC.



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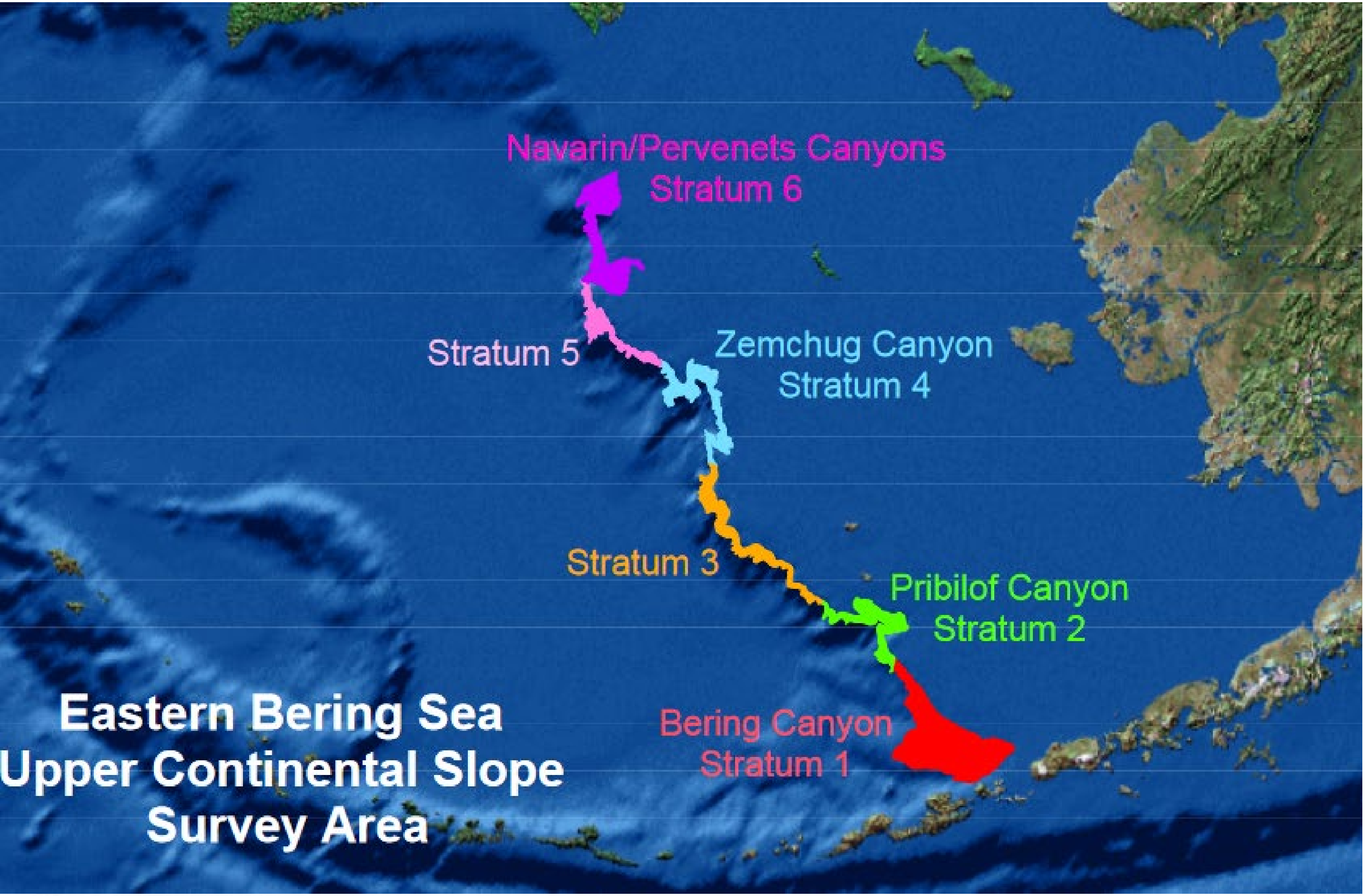
Bering Sea slope surveys



- Not sampled since 2016
- < 10% of EBS shelf area
- Maximum estimated biomass = 738 t (2012)
- < 0.1% of estimated EBS biomass in 2018

From Mike Litzow et al.

Seasonal migrations of morphometrically mature male snow crab (*Chionoecetes opilio*) in the eastern Bering Sea in relation to mating dynamics

Daniel G. Nichol (contact author)
David A. Somerton

- 33 mature males tagged
- Commercial size males predominantly stayed on outer shelf
- Some moved more than 100 km in one direction

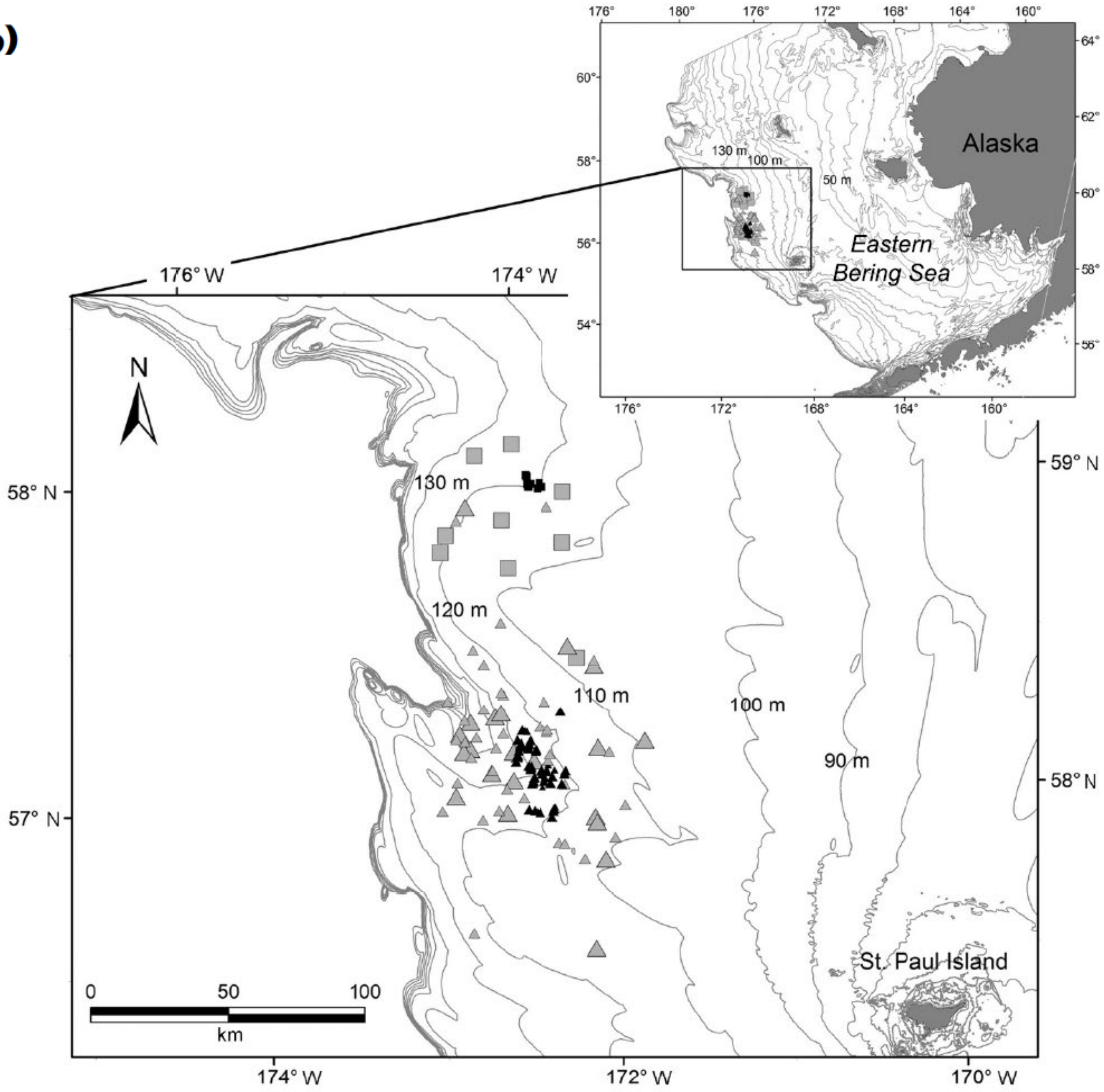


Figure 1

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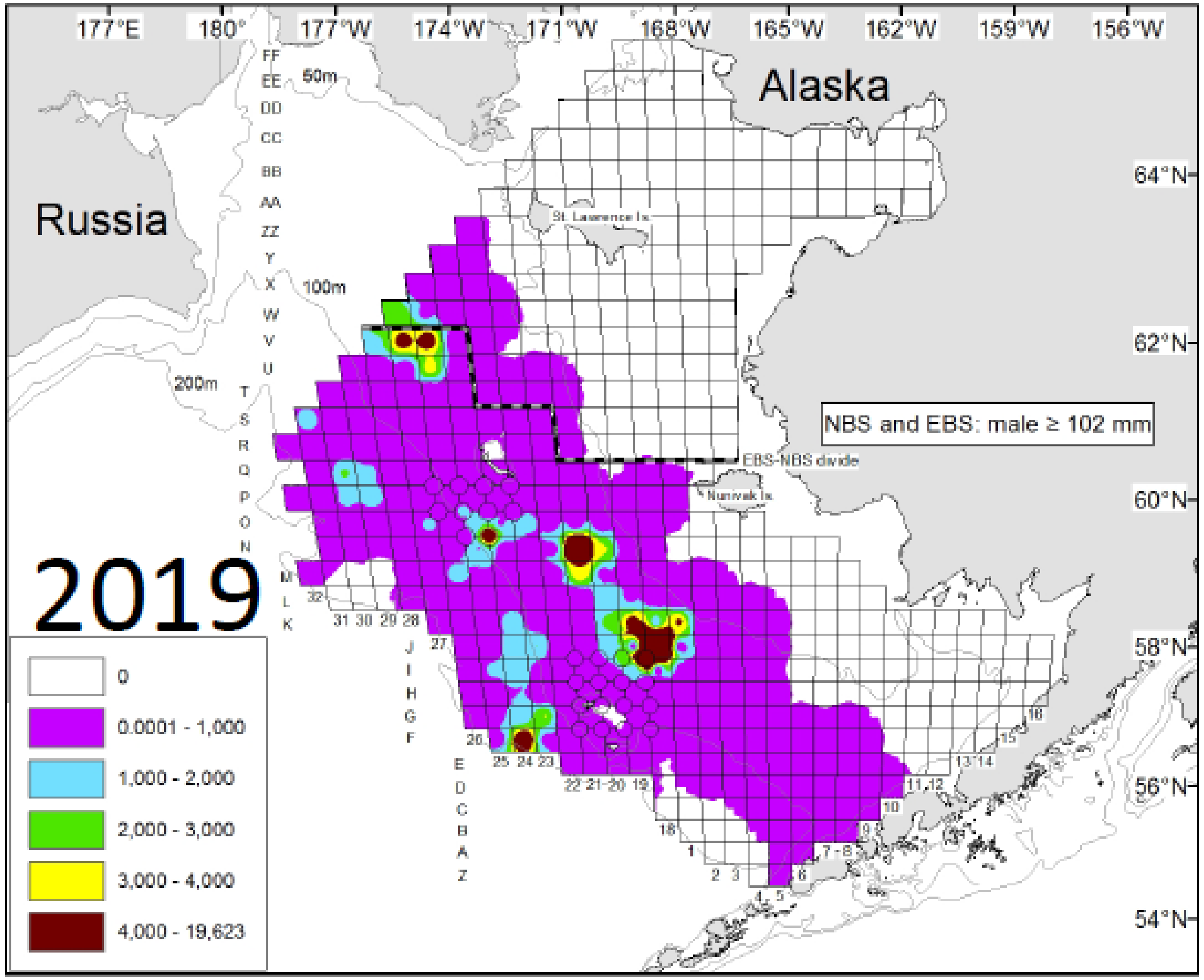
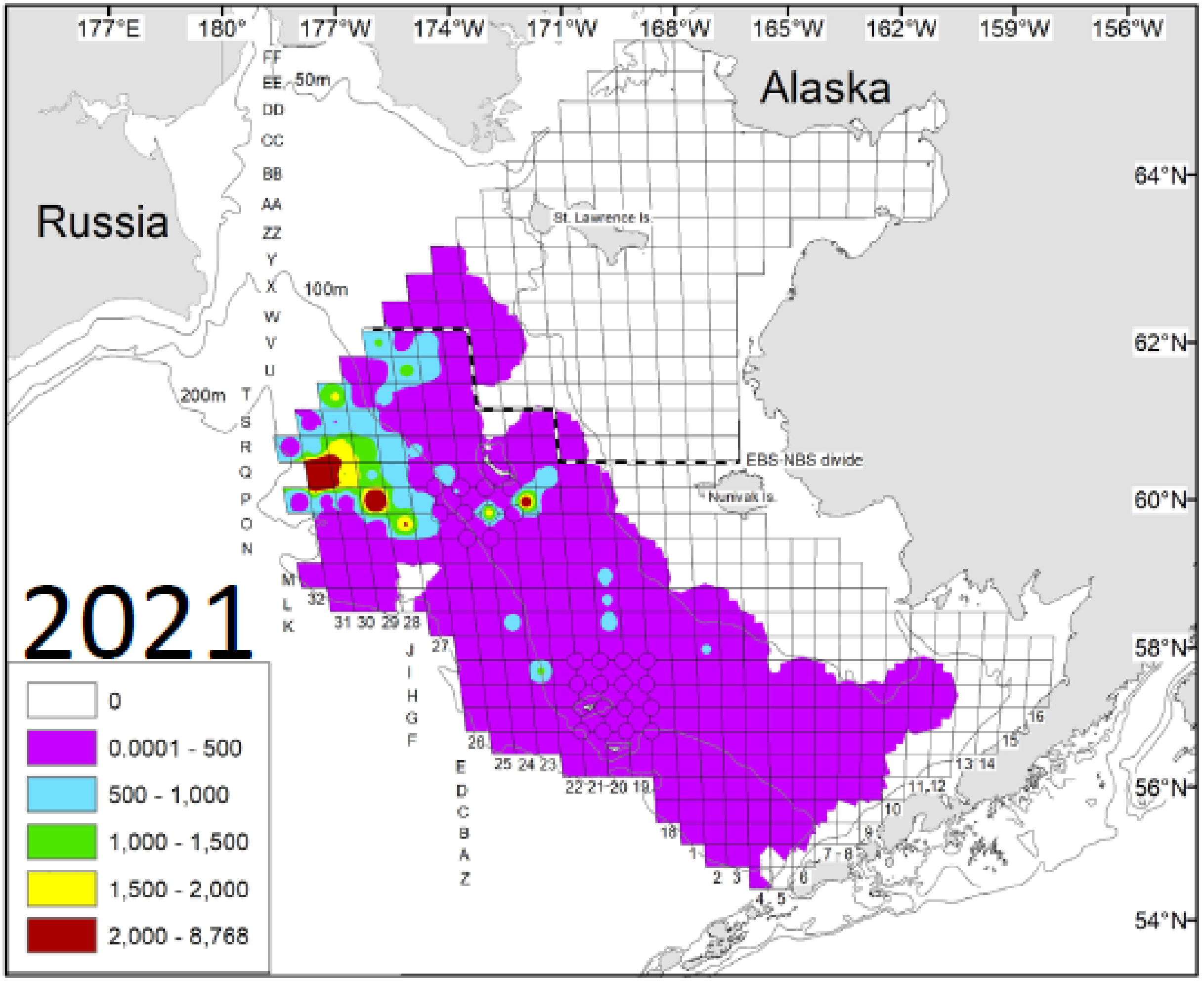
Industry preferred males





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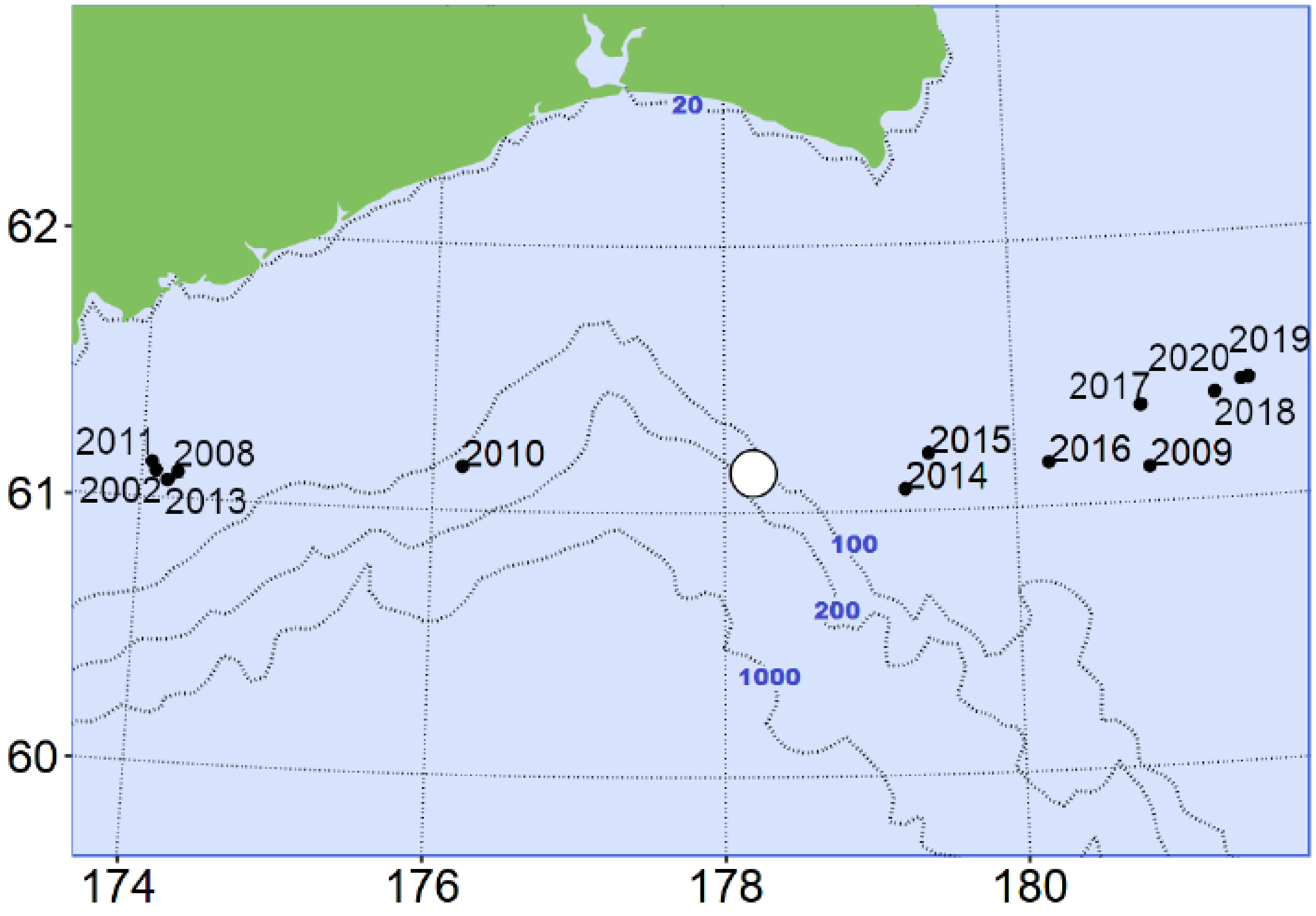

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СТАНДАРТИЗАЦИЯ ПРОИЗВОДИТЕЛЬНОСТИ ПРОМЫСЛА КРАБА-СТРИГУНА ОПИЛИО ЗАПАДНОЙ ЧАСТИ БЕРИНГОВА МОРЯ С ИСПОЛЬЗОВАНИЕМ АДДИТИВНЫХ ЛИНЕЙНЫХ МОДЕЛЕЙ

Рис. 1. Медианы позиций промысловых судов в Западно-Беринговоморской зоне по годам промысла. *Белая точка* — медиана за весь период

Fig. 1. Medians of the fishing vessels position in the West Bering Sea fishery zone, by years (the median for entire period is shown by *white point*)

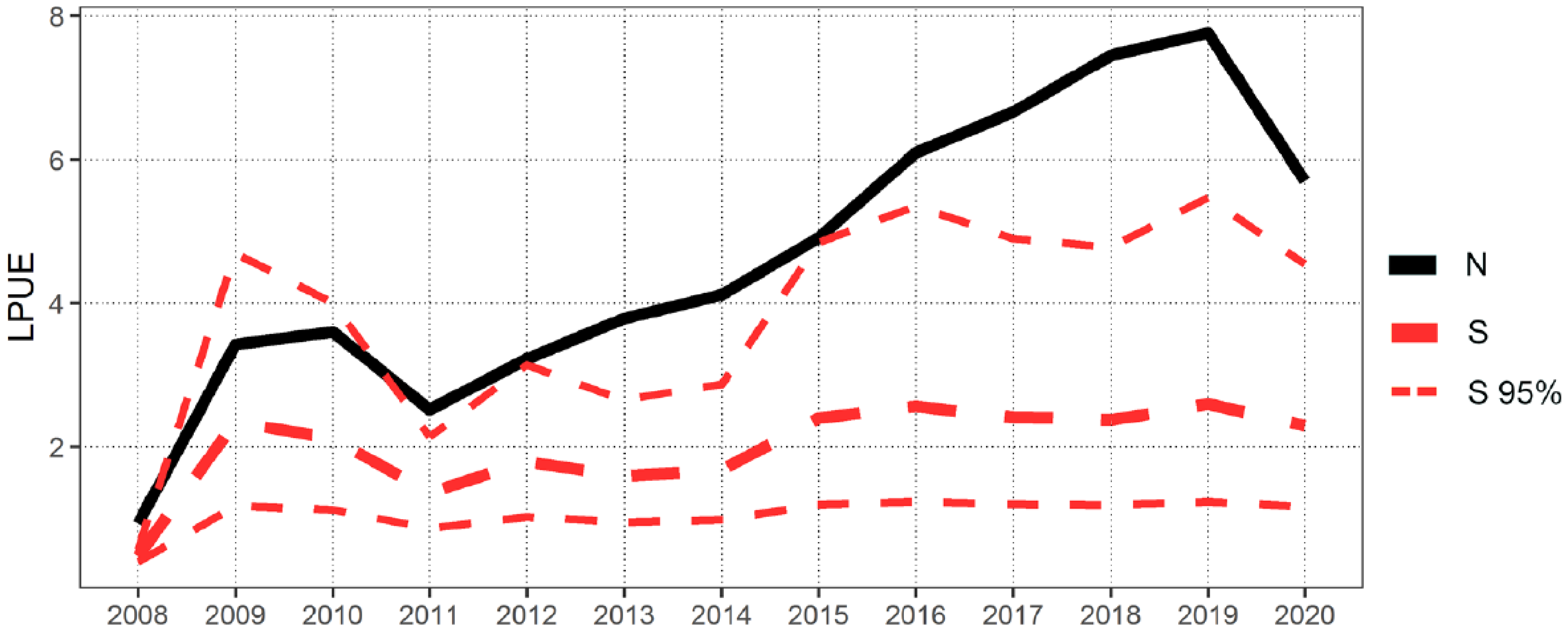

Рис. 7. Номинальные и стандартизованные значения уловов на судо-сутки: *N* — номинальные значения; *S* — стандартизованные; *S 95%* — доверительные интервалы

Fig. 7. Nominal and standardized values of landing per vessel per day: *N* — nominal values; *S* — standardized values; *S 95%* — confidence intervals

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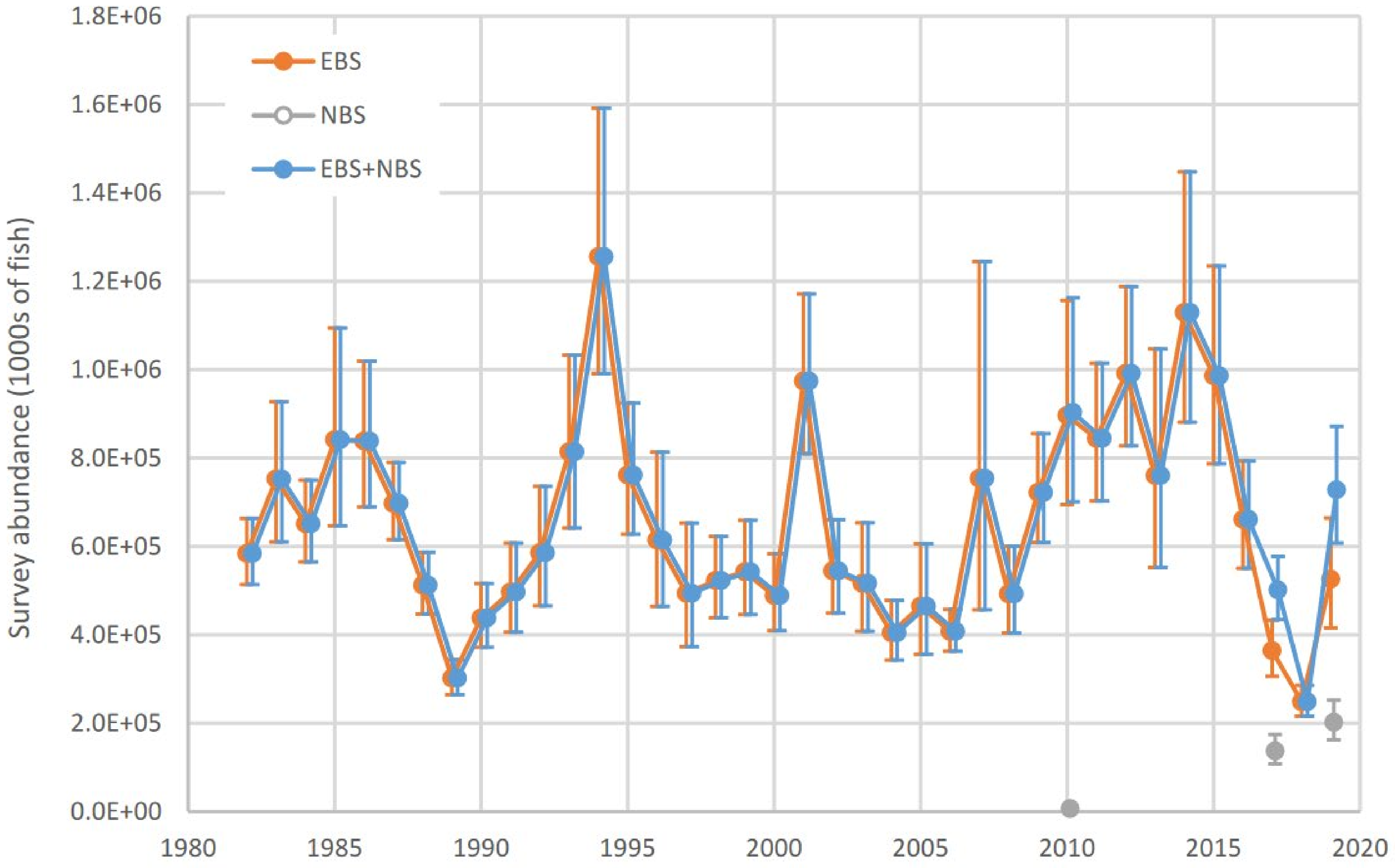
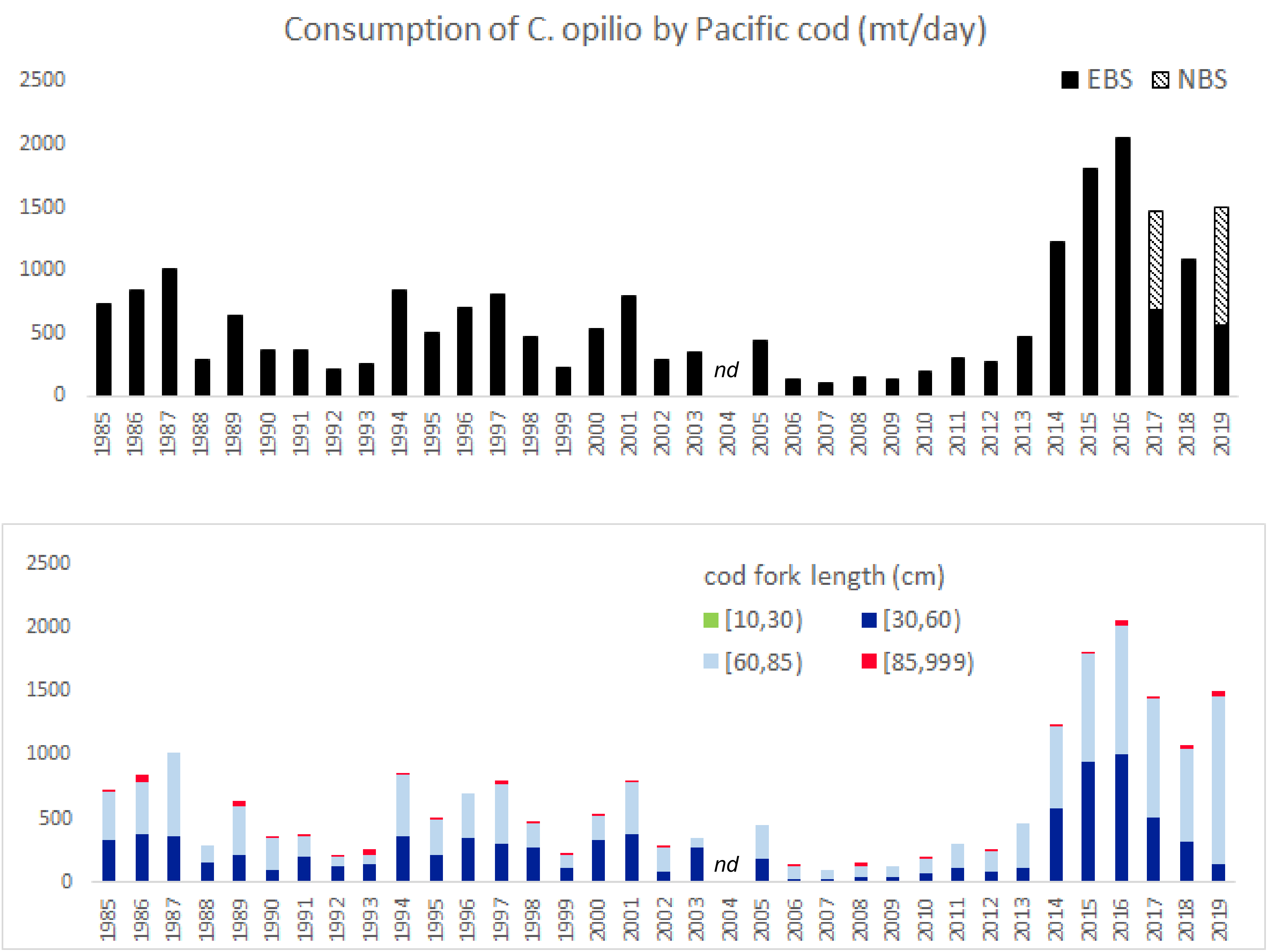
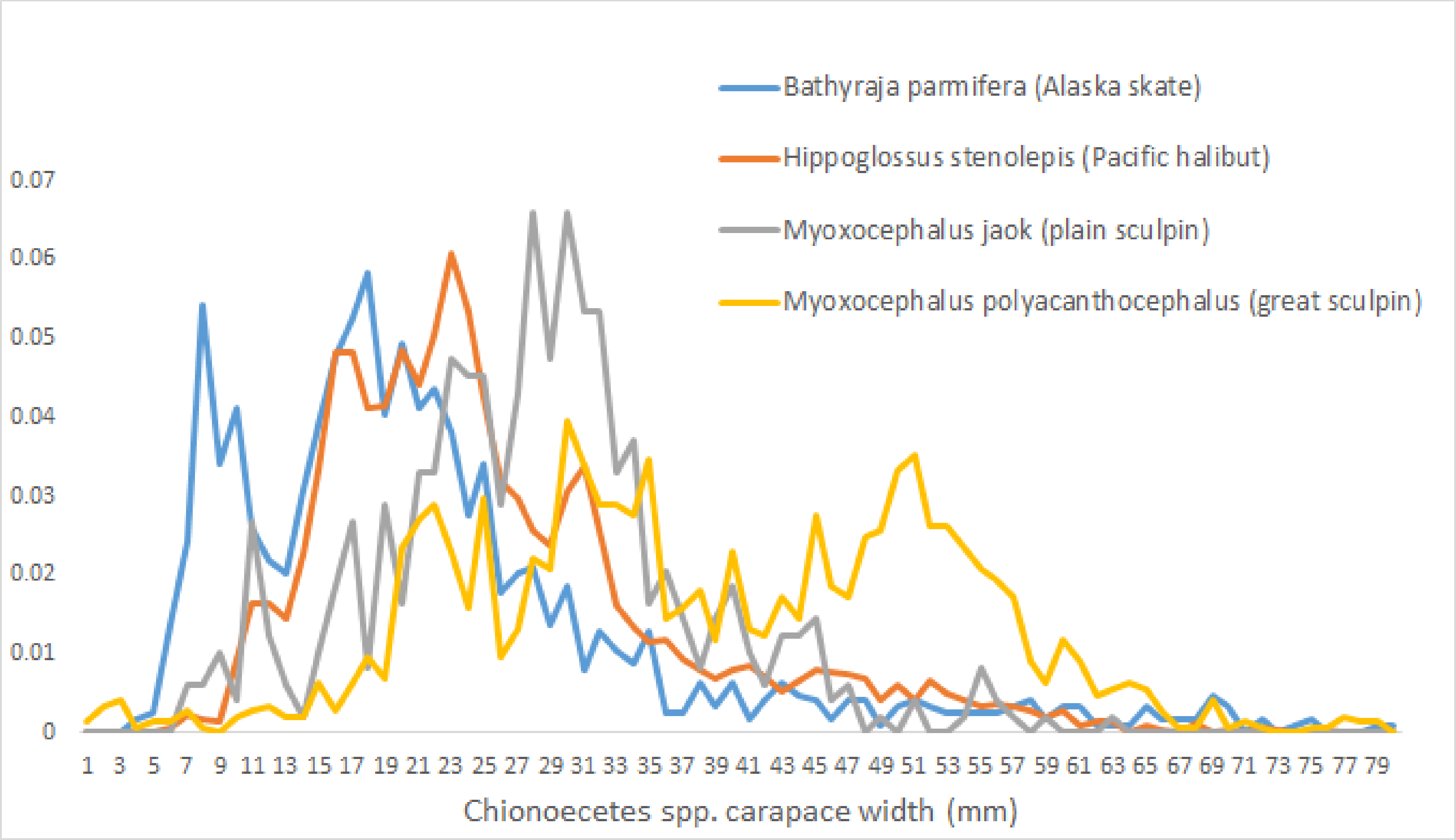


From Grant Thompson



From Kerim Aydin

Other predators to consider



Many other predators (smallmouth flatfish, eelpouts, pollock) eat crab <20mm CW

From Kerim Aydin

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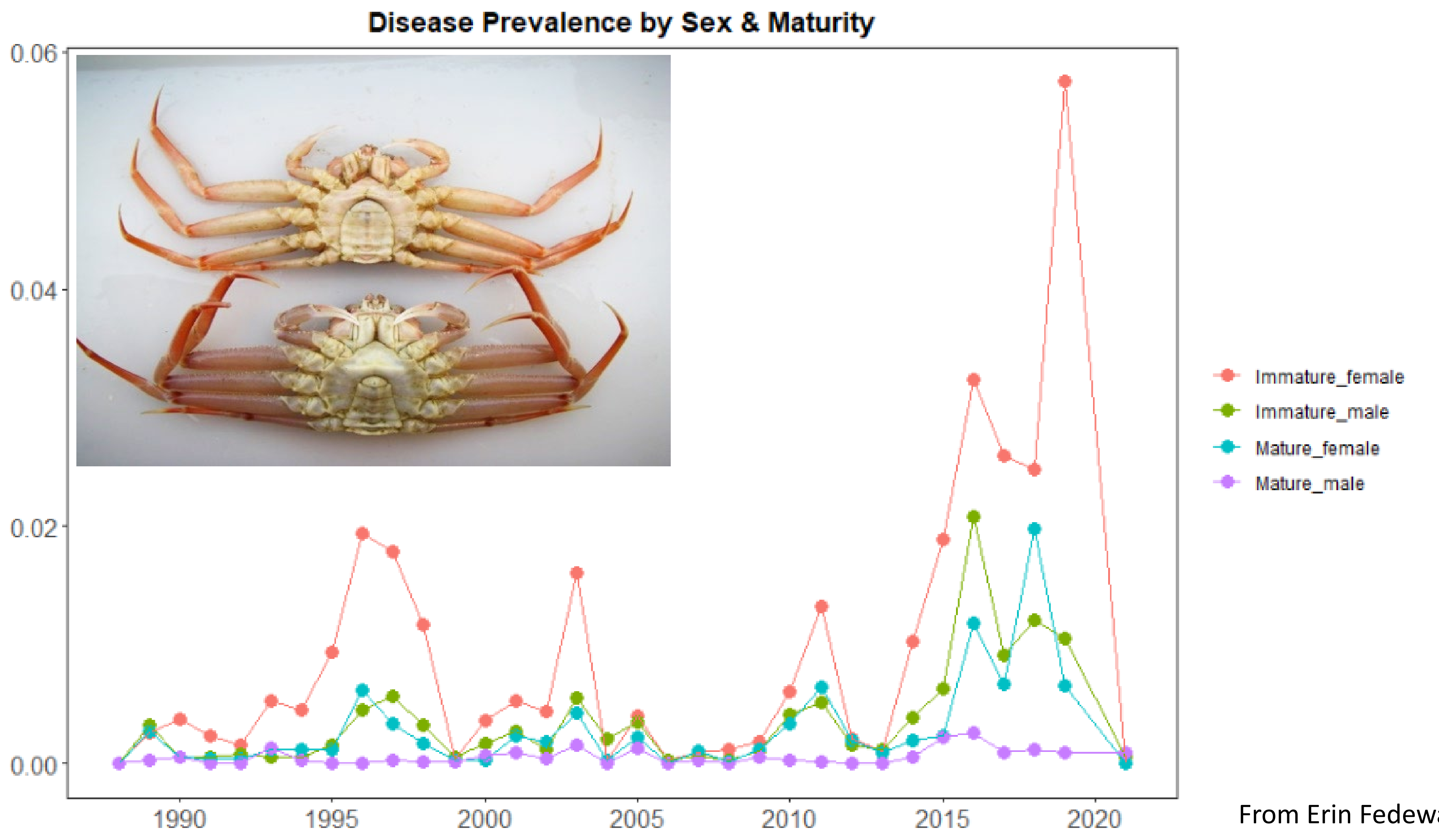
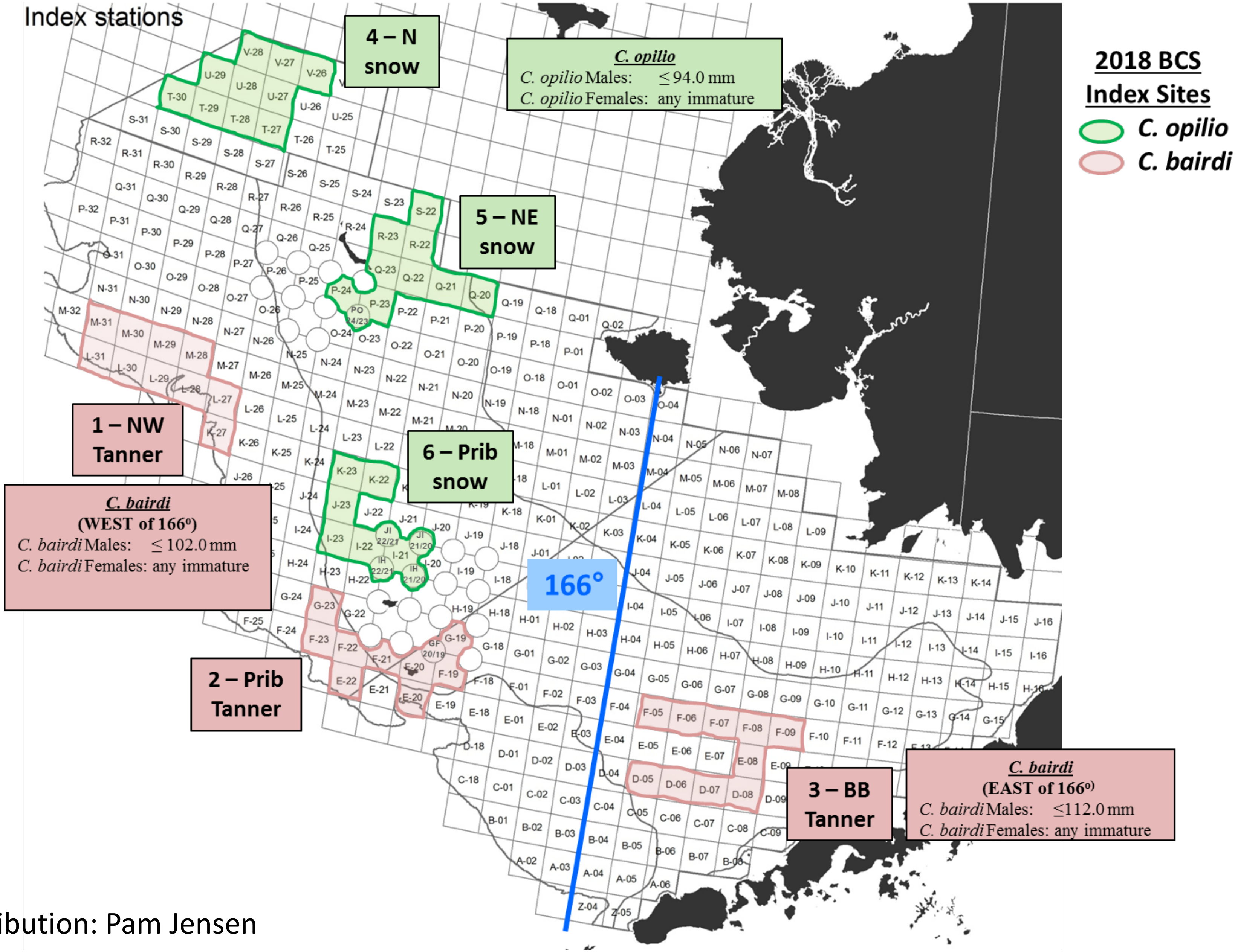


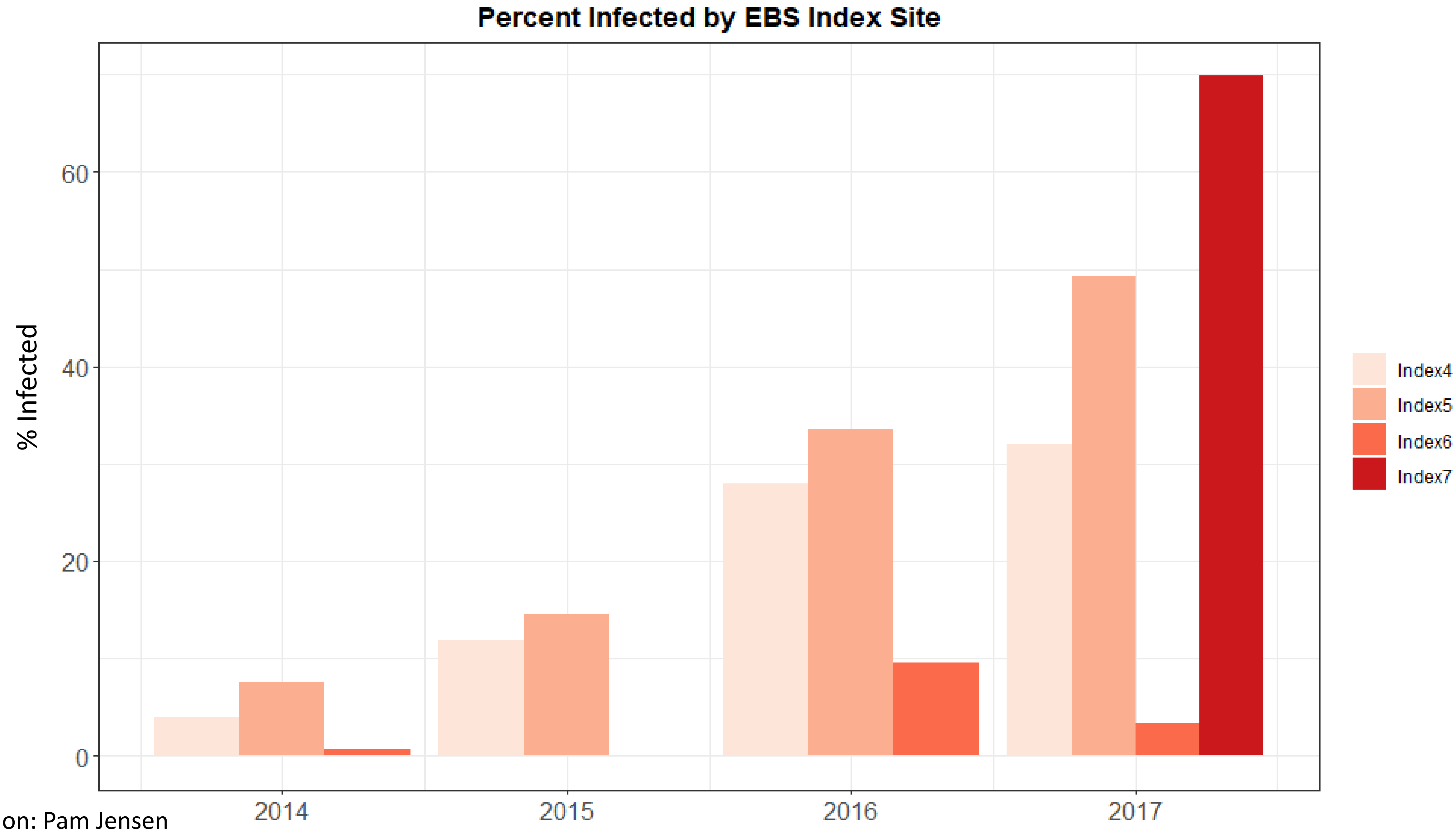
From Erin Fedewa

Blood samples have been collected at 6 index sites in the EBS (2014-2019) for DNA tests to detect the presence of the parasite *Hematodinium* sp., the causative agent of Bitter Crab Syndrome



Contribution: Pam Jensen

Overall, prevalence of bitter crab syndrome at index sites increased annually from 2014-2017



Contribution: Pam Jensen

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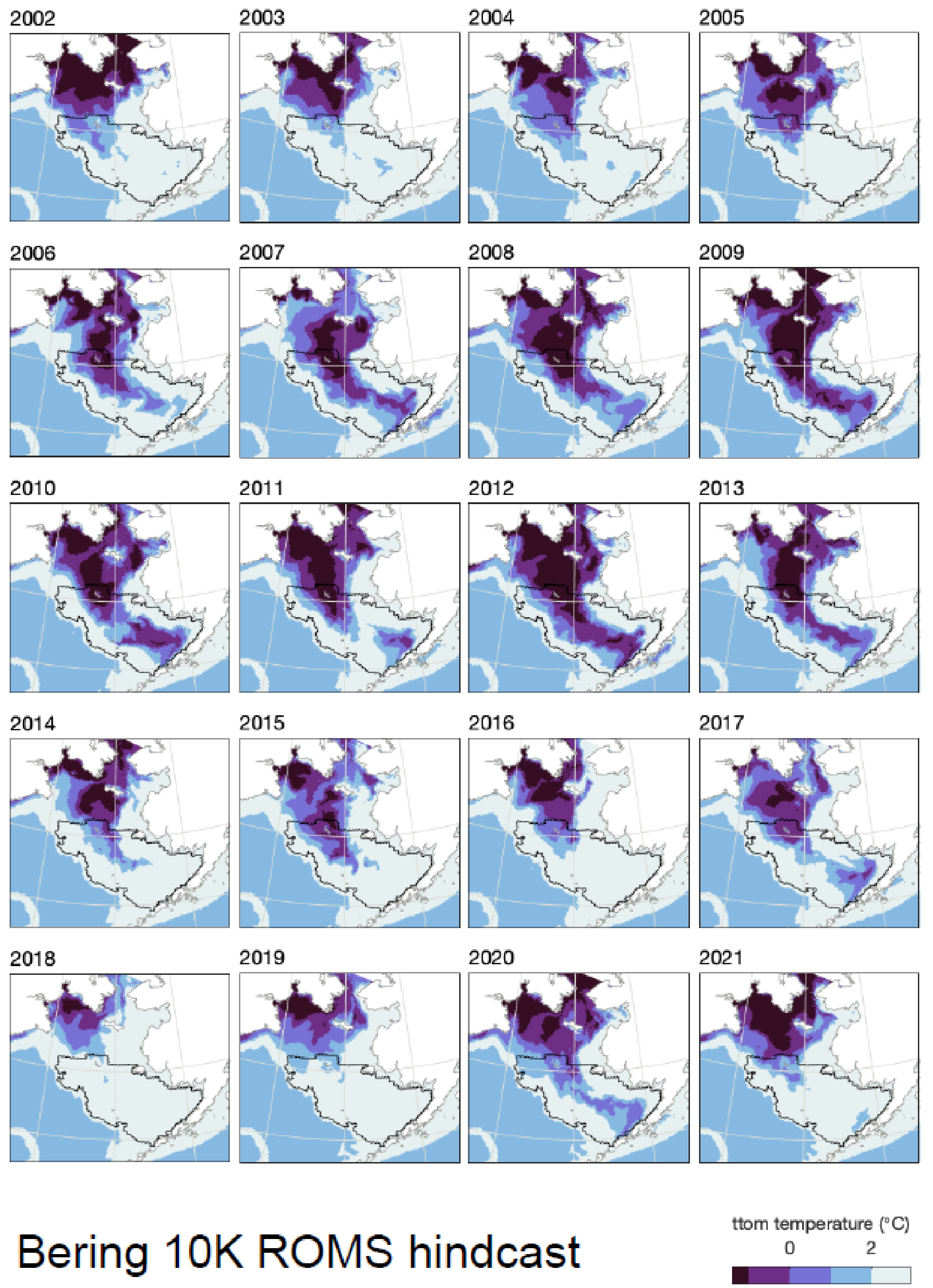

Cold pool in 2018 and 2019 were the smallest since 2003.

Negative effects on metabolic processes are not apparent in mature snow crab until temperatures exceed 6-7 degrees C (Foyle et al, 1989; Siidavuopio, S.I. et al., 2017)

Routine oxygen demand can be met even at lethal temperatures of 18 degrees C (Foyle et al., 1989)

Food consumption increases to 6 degrees C, then falls (Foyle et al., 1989)

Figure from Kelly Kearney

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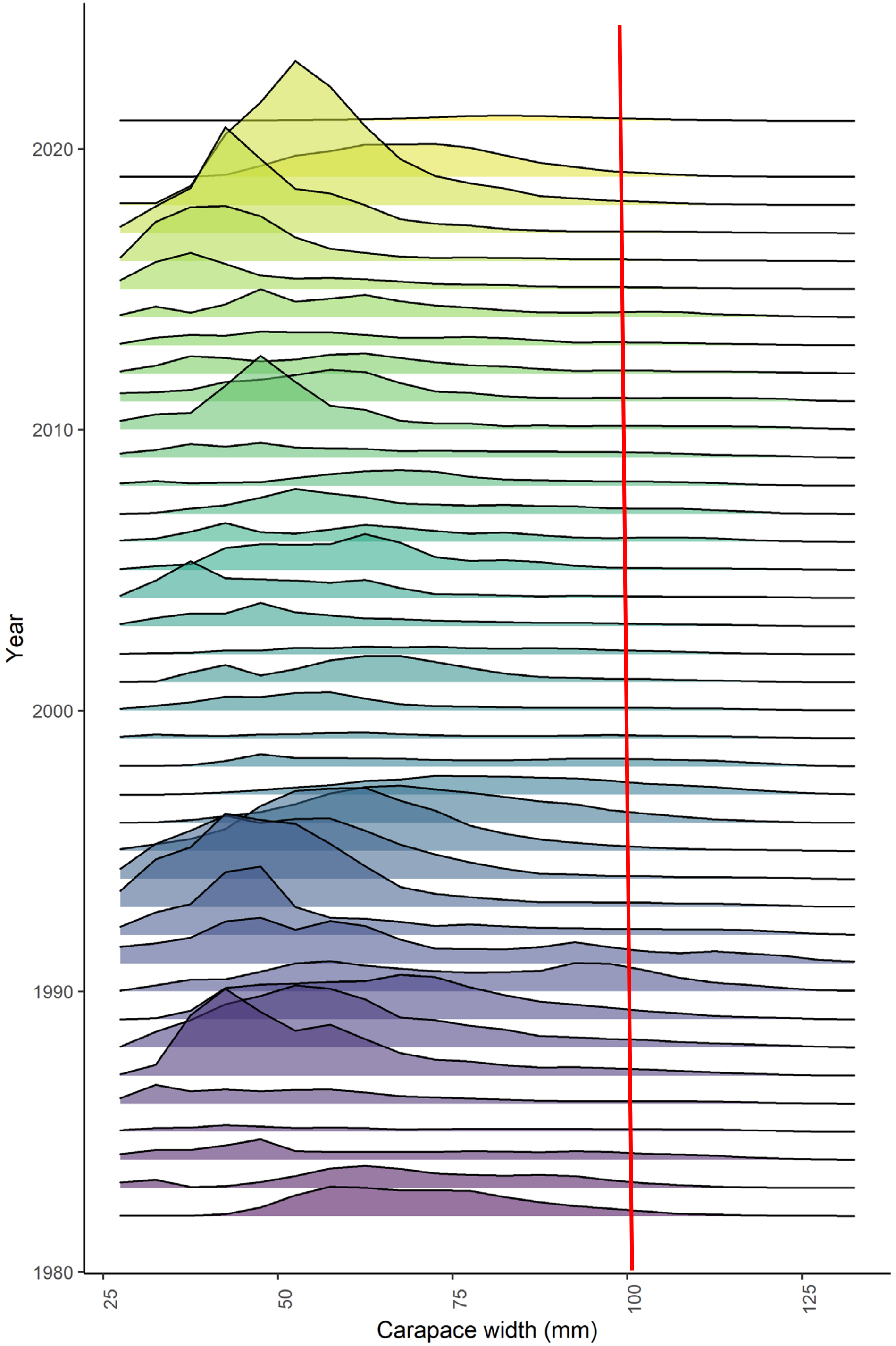
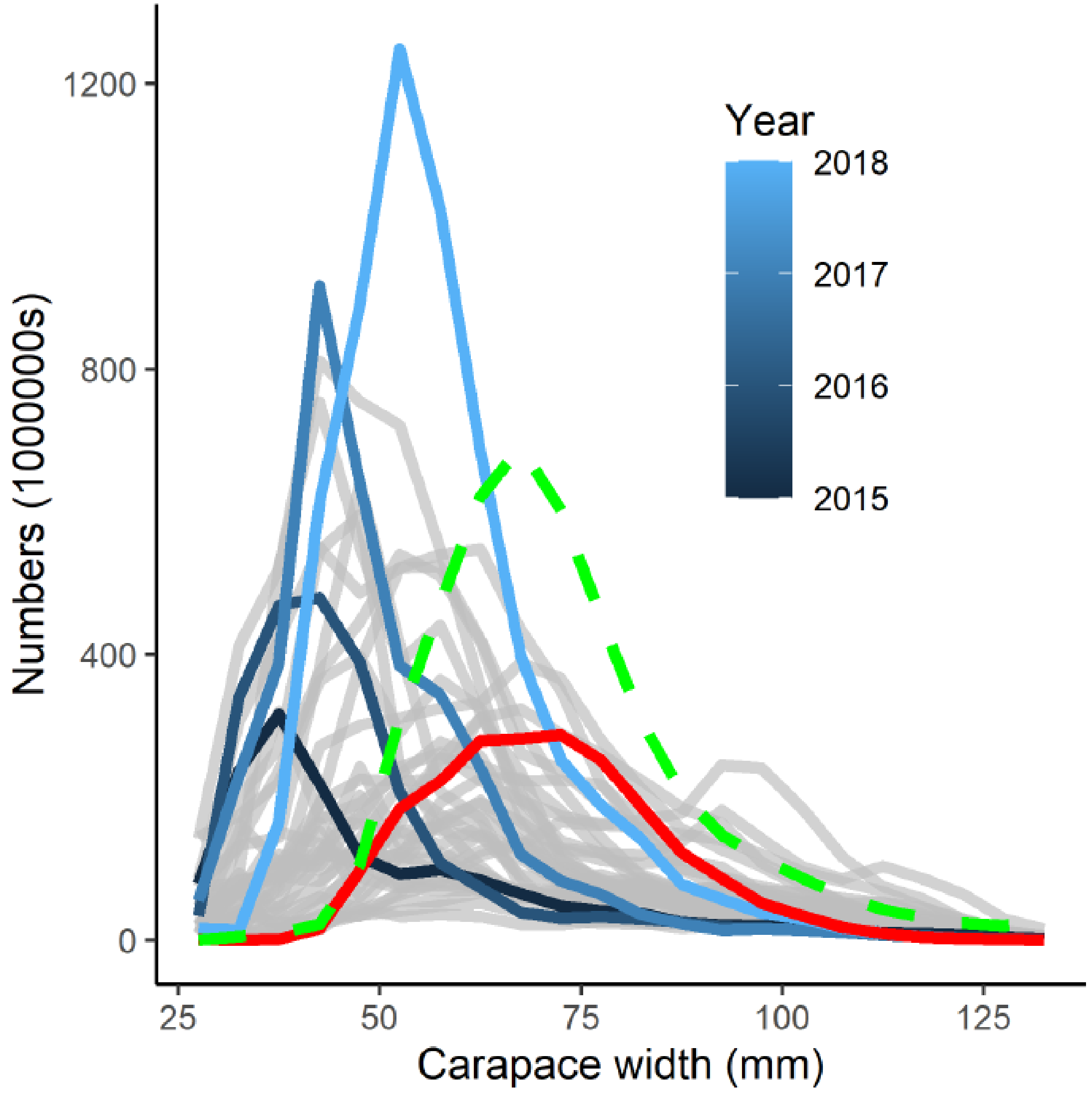
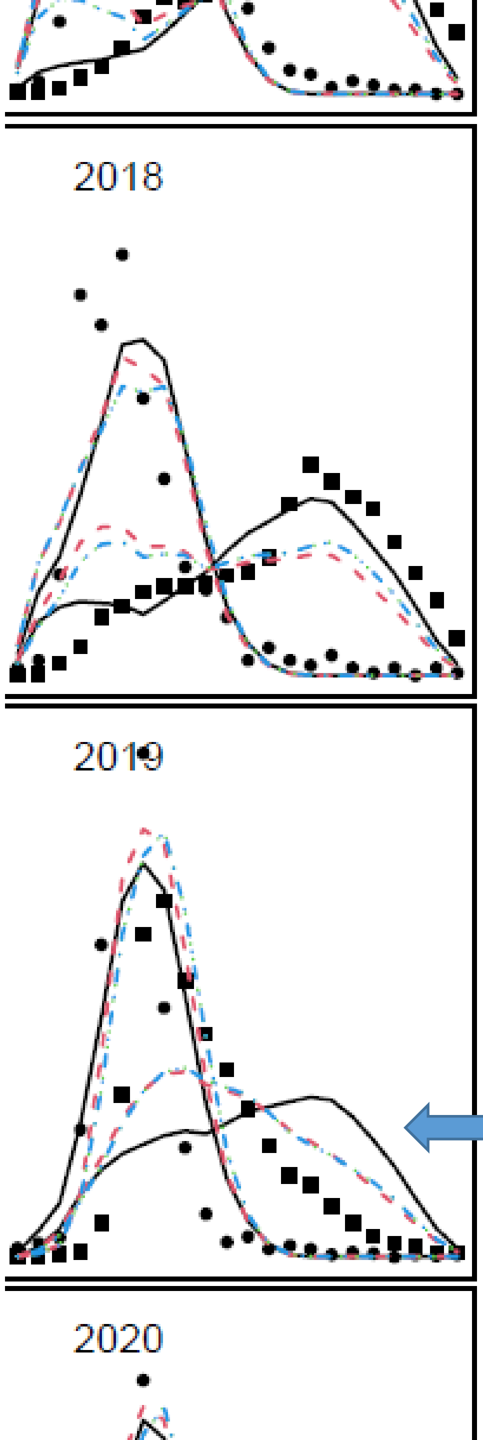
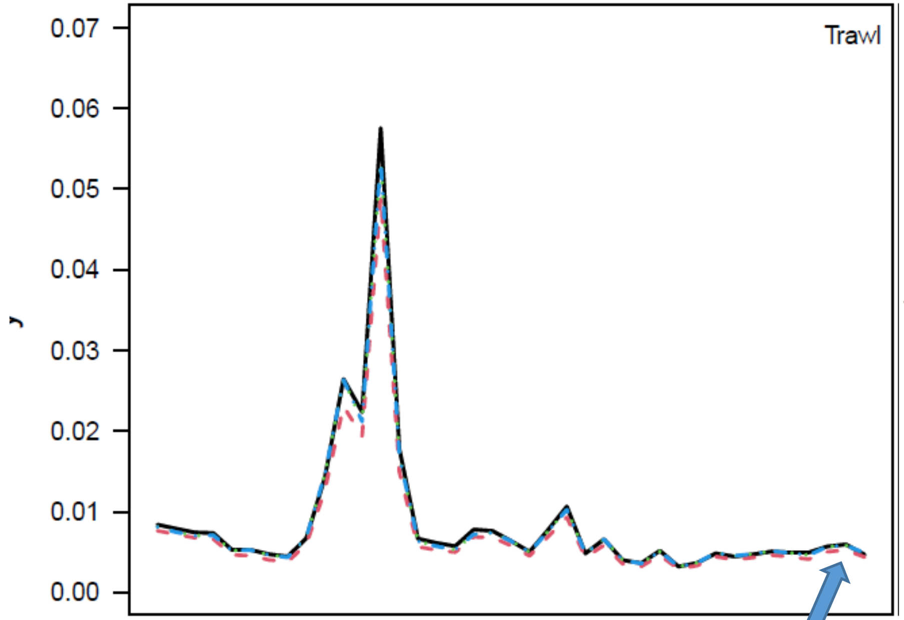


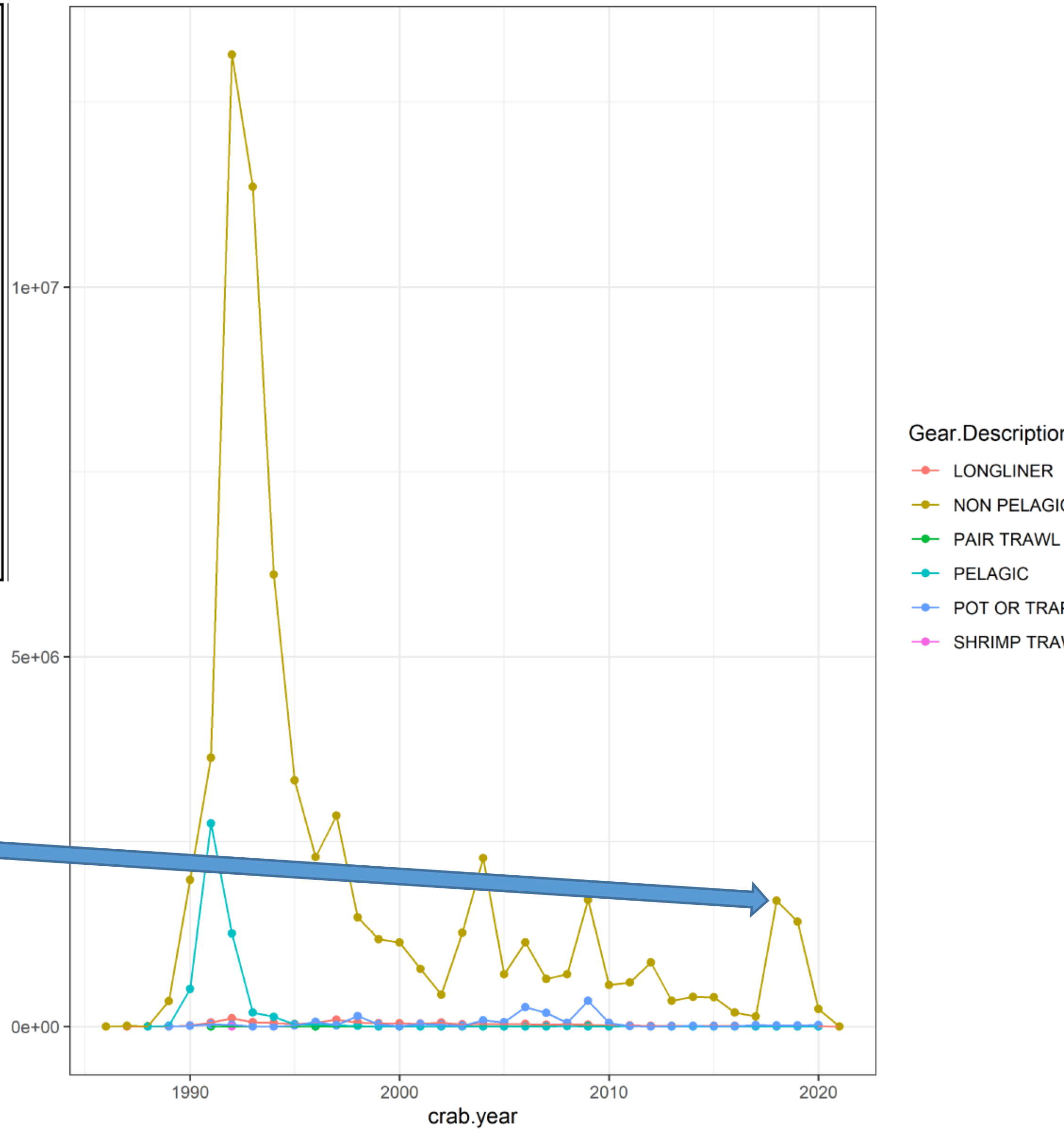
Missing crab were largely not vulnerable to the directed fishery







- Estimated exploitation rate was less than 1%.
- Trawl bycatch spiked in 2018 and 2019, but nowhere near historical levels.
- Size composition in 2019 was different for males.



Quantification and reduction of unobserved mortality rates for snow, southern Tanner, and red king crabs (*Chionoecetes opilio, C. bairdi,* and *Paralithodes camtschaticus*) after encounters with trawls on the seafloor

Craig S. Rose (contact author)[1]
Carwyn F. Hammond[1]
Allan W. Stoner[2]
J. Eric Munk[3]
John R. Gauvin[4]

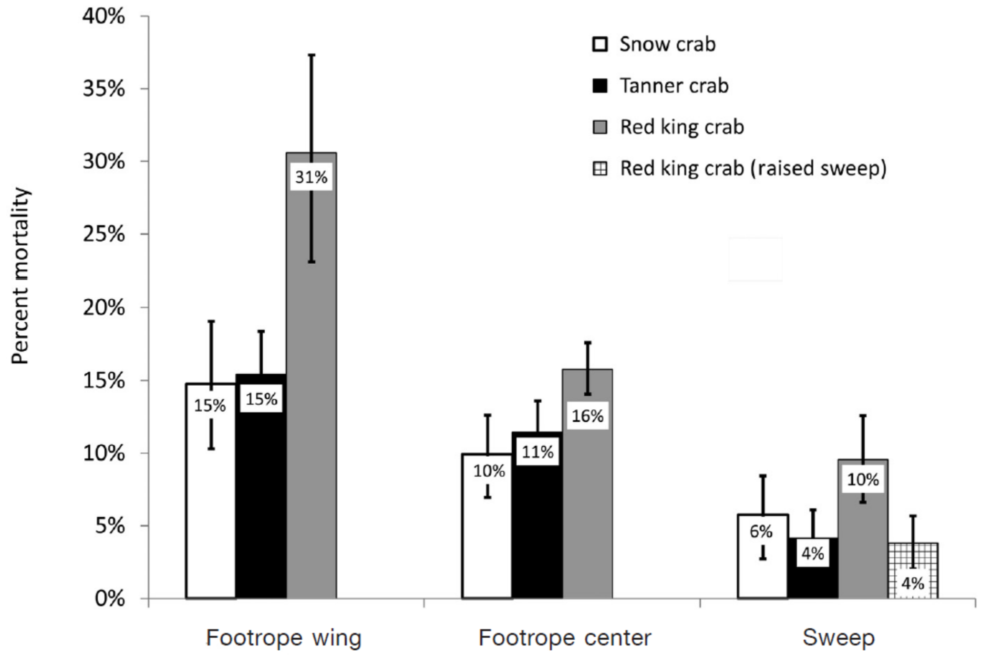


Figure 4

Estimates and 95% confidence intervals of rates of mortality for snow crab (*Chionoecetes opilio*), southern Tanner crab (*C. bairdi*), and red king crab (*Paralithodes camtschaticus* that resulted from contact with 1 of 3 different components of a bottom trawl representative of the gear used bottom trawl fisheries in the Bering Sea—the footrope wings or extensions, the center of the footrope, or the sweep—and, for red king crab only, a sweep raised off of the seafloor (Rose et al., 2010).

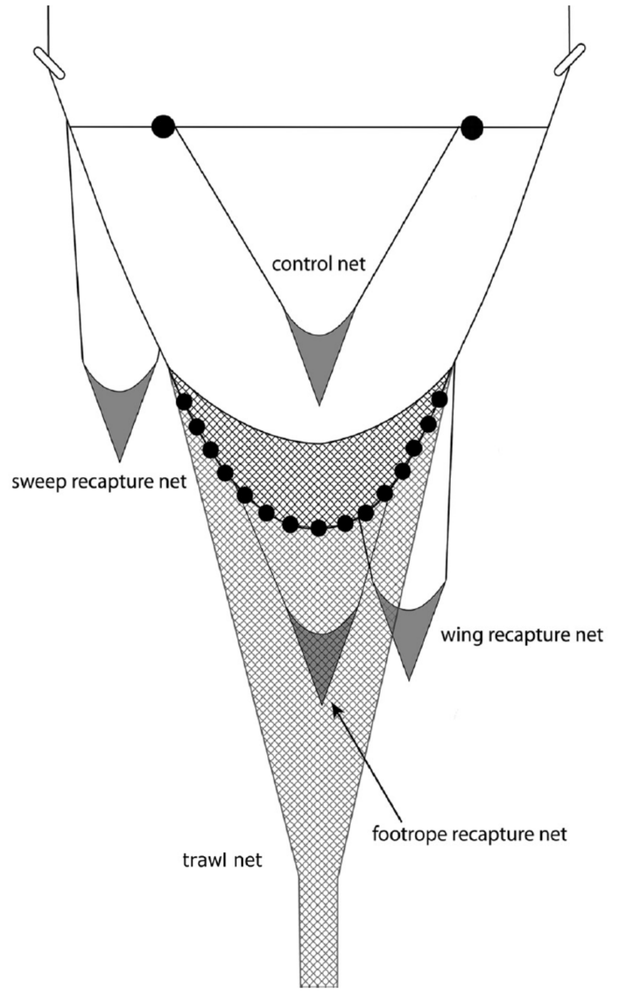
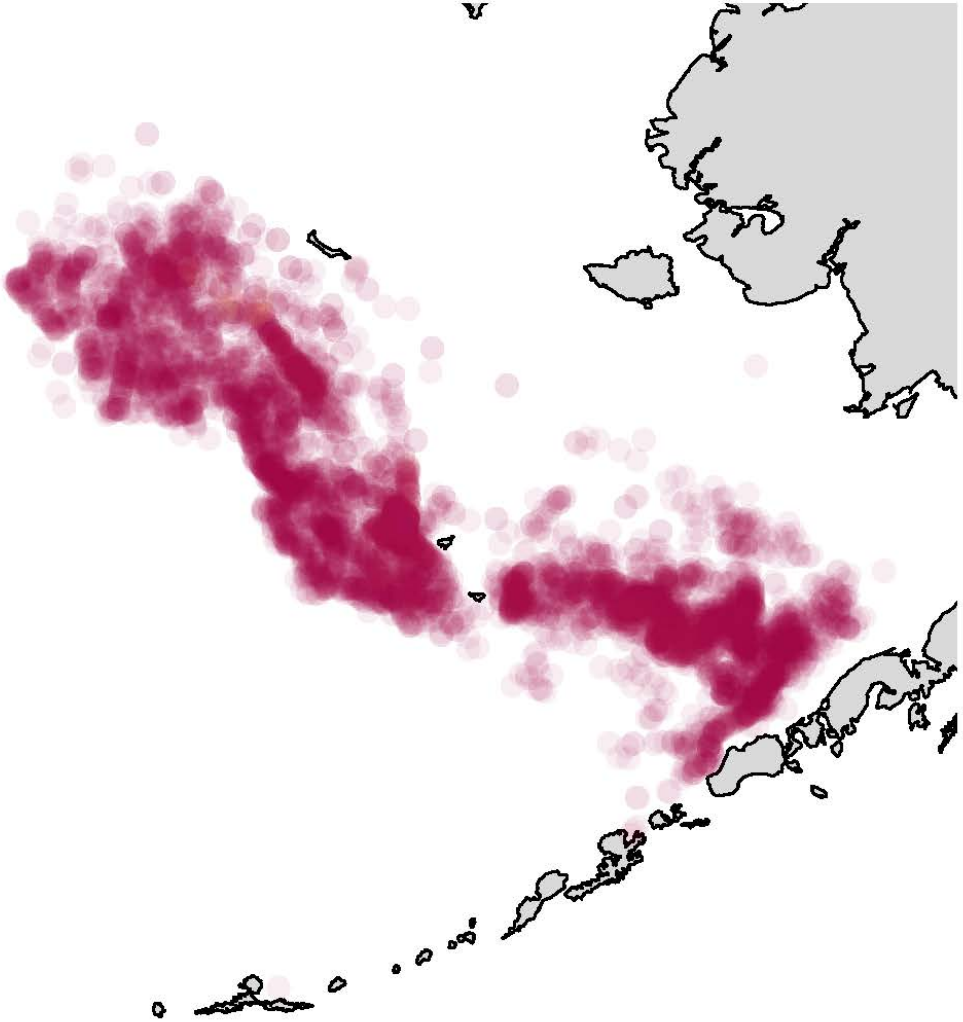


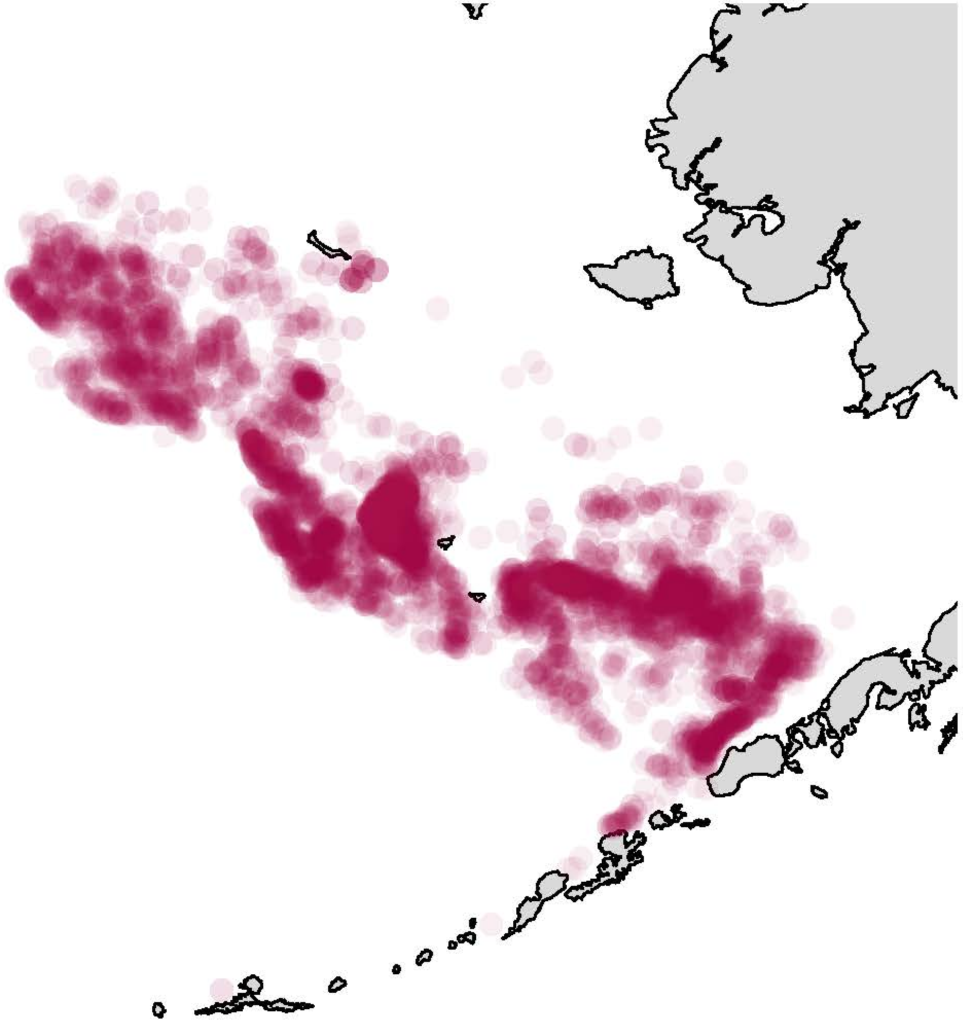
Figure 2

Diagram of the trawl net (not to scale) used in our study of unobserved mortality rates for snow crab (*Chionoecetes opilio*), southern Tanner crab (*C. bairdi*), and red king crab (*Paralithodes camtschaticus*), showing positions of recapture nets designed to retain crabs after contact with various trawl components. No more than 2 of these nets were fished during the same tow, and the control net always was fished separately. Illustration by Karna McKinney.

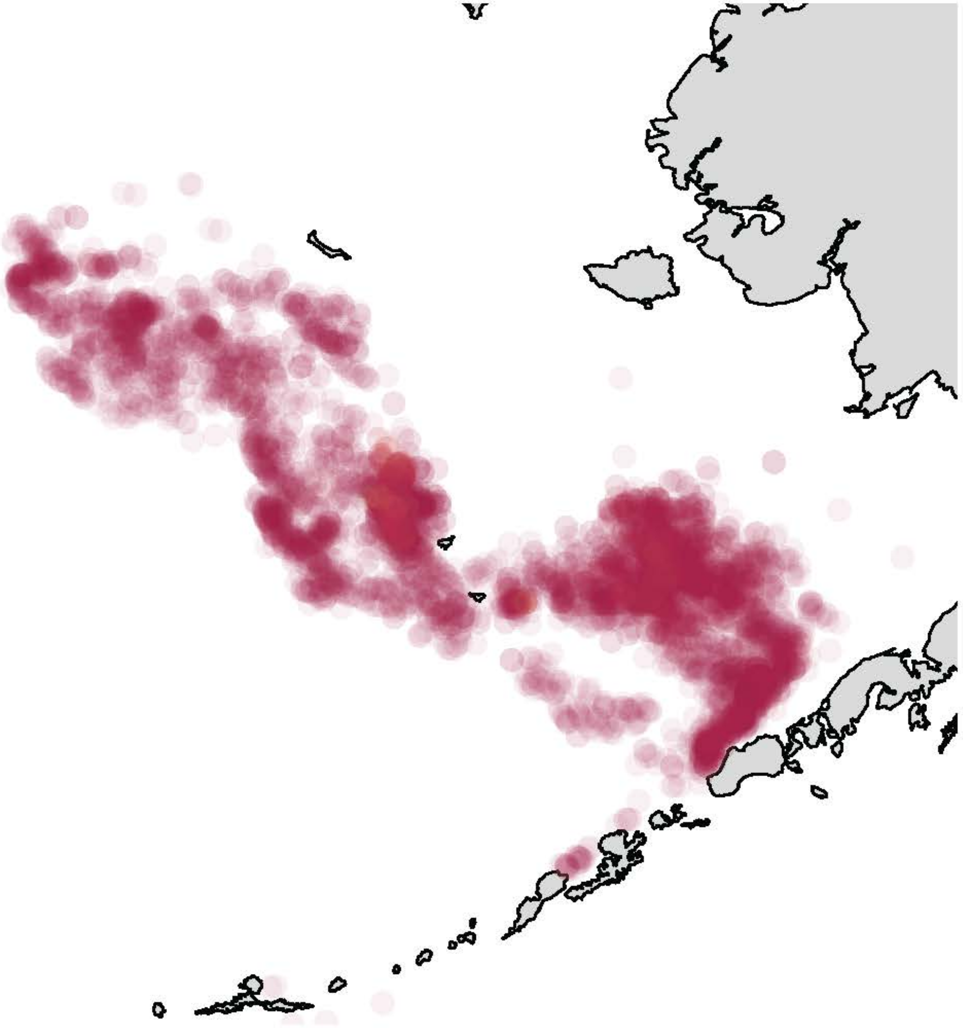
2009



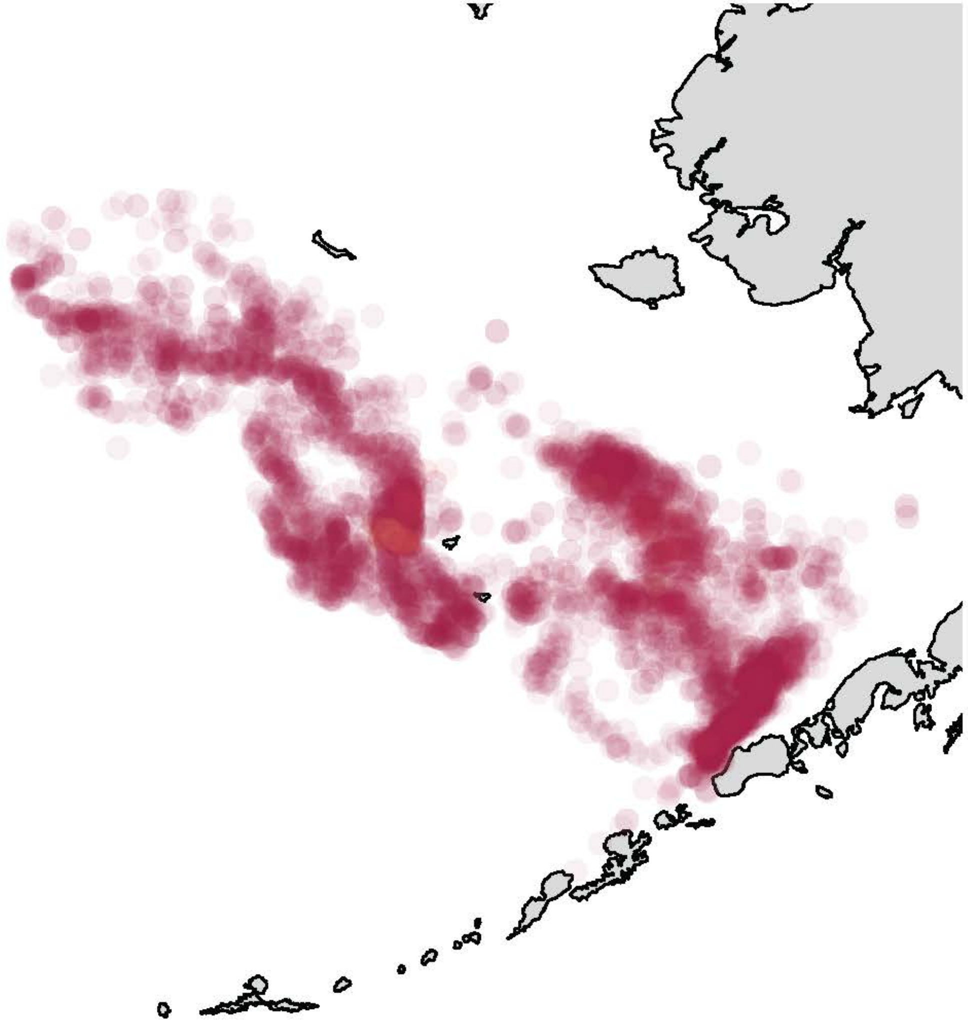
2010



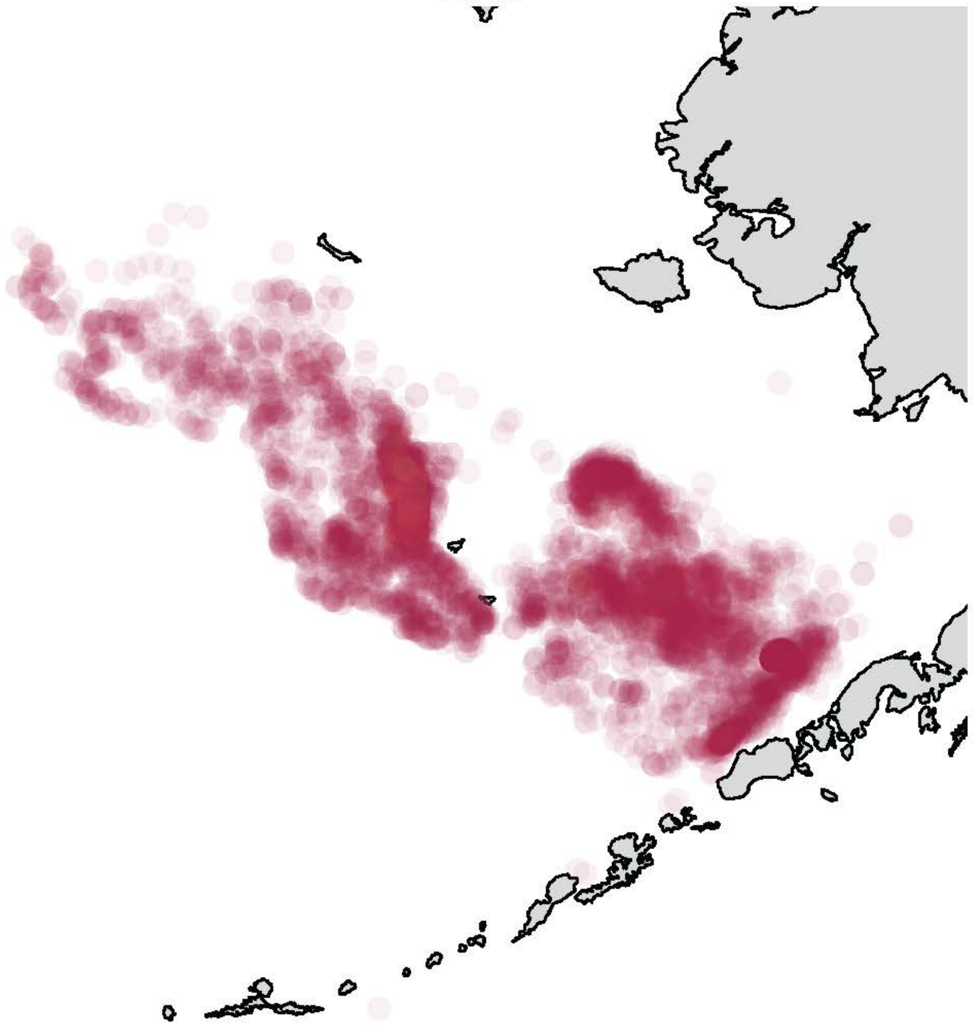
2011



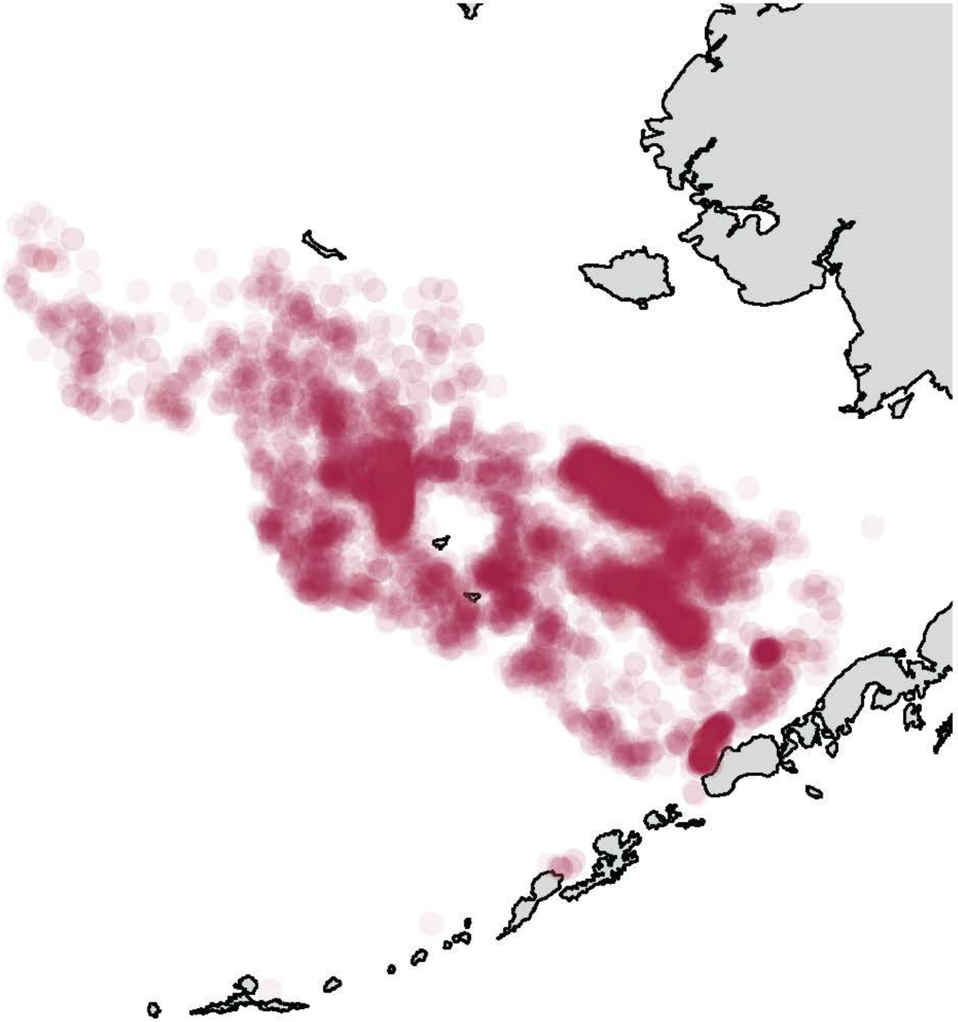
2012



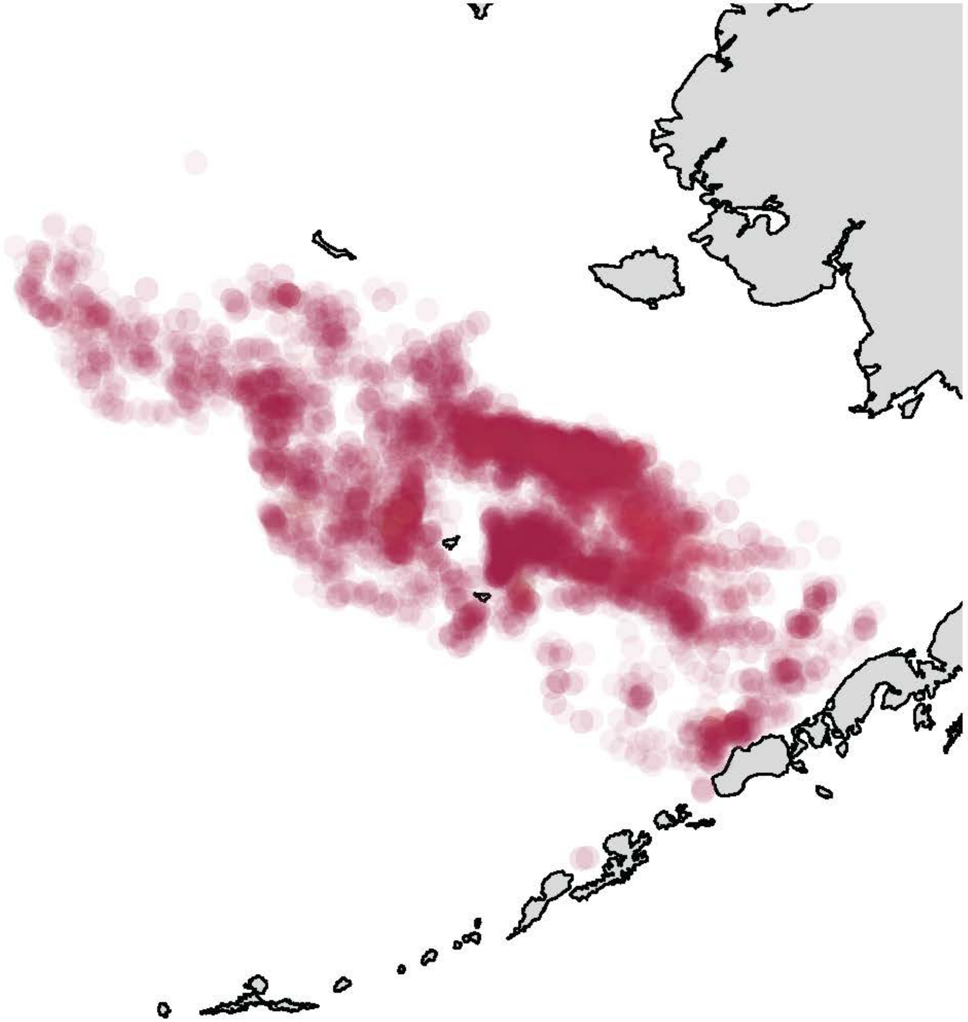
2013



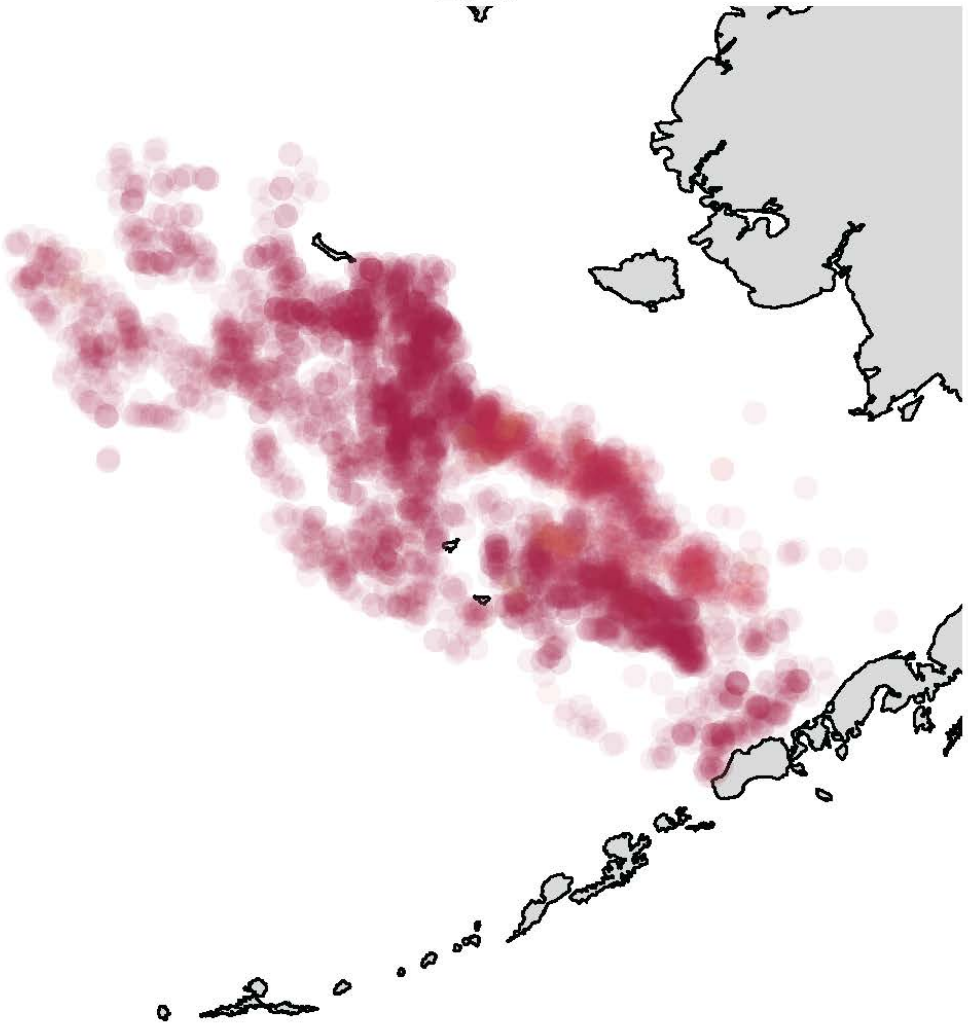
2014



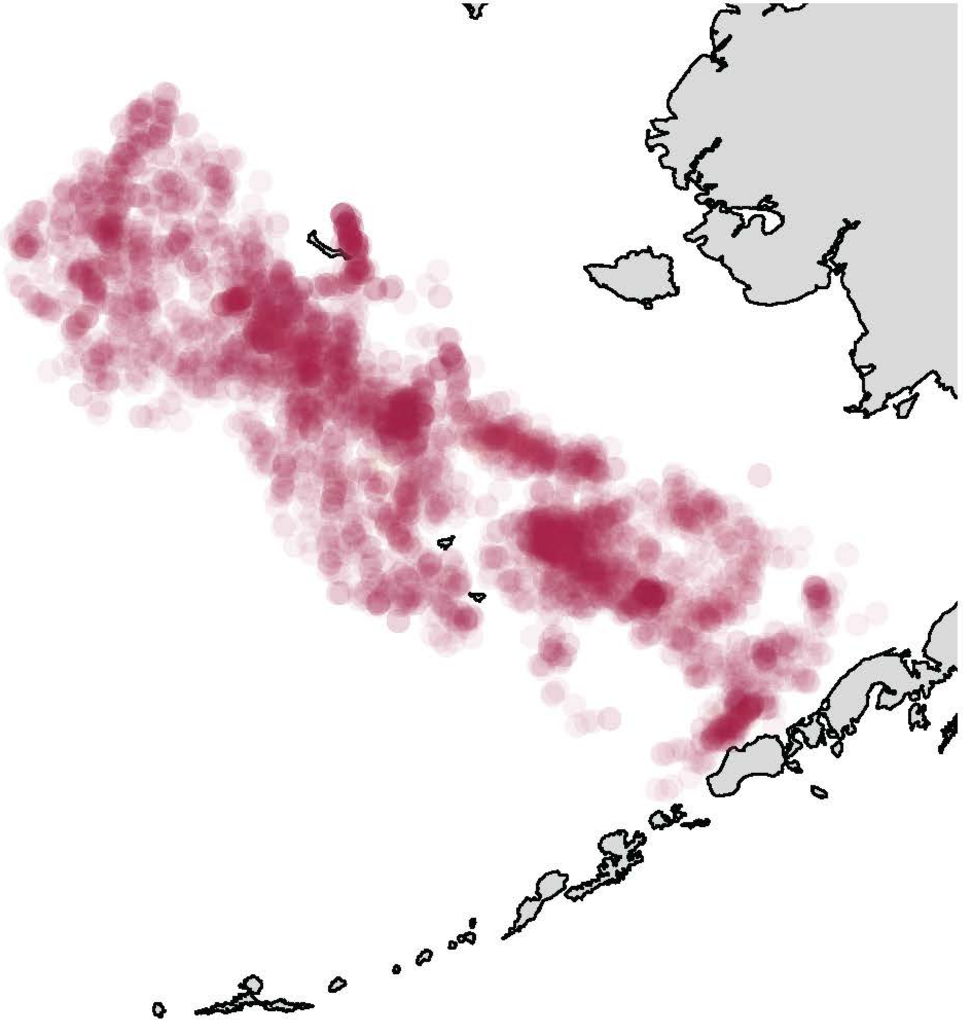
2015

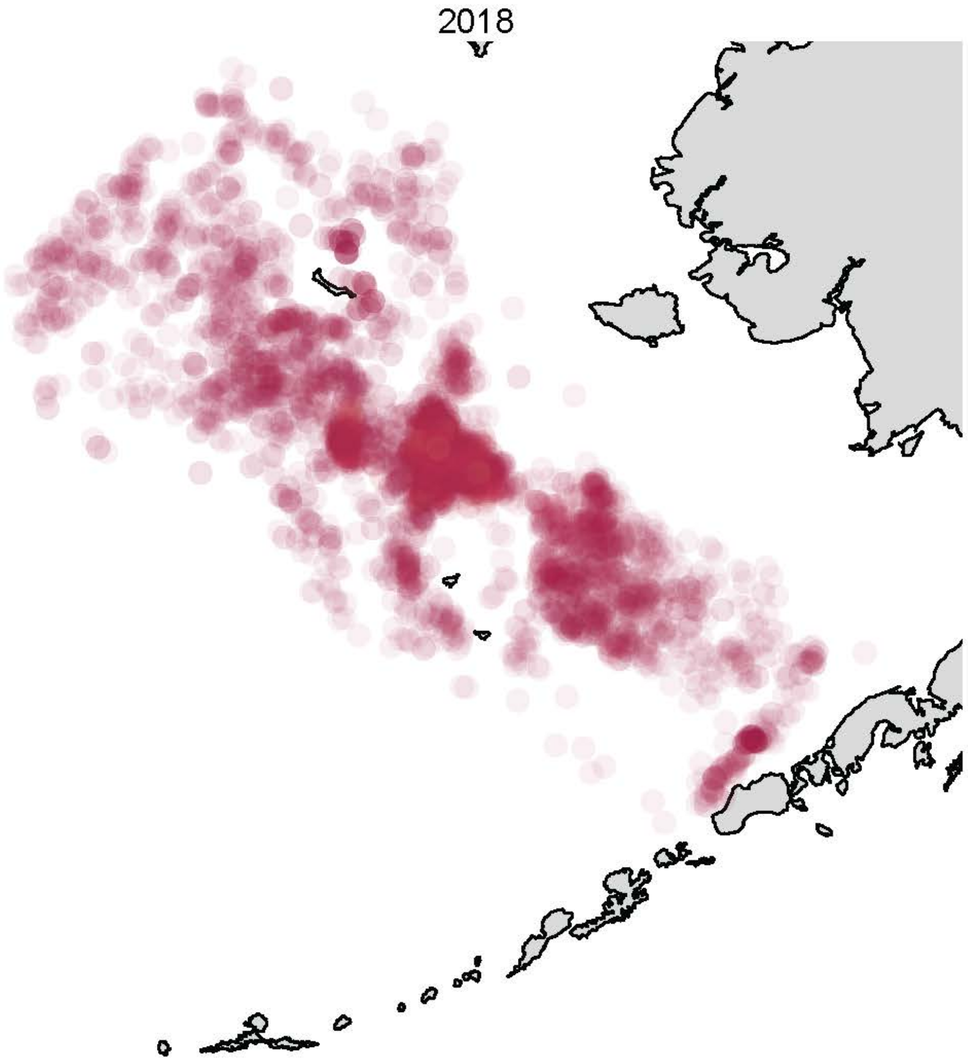


2016

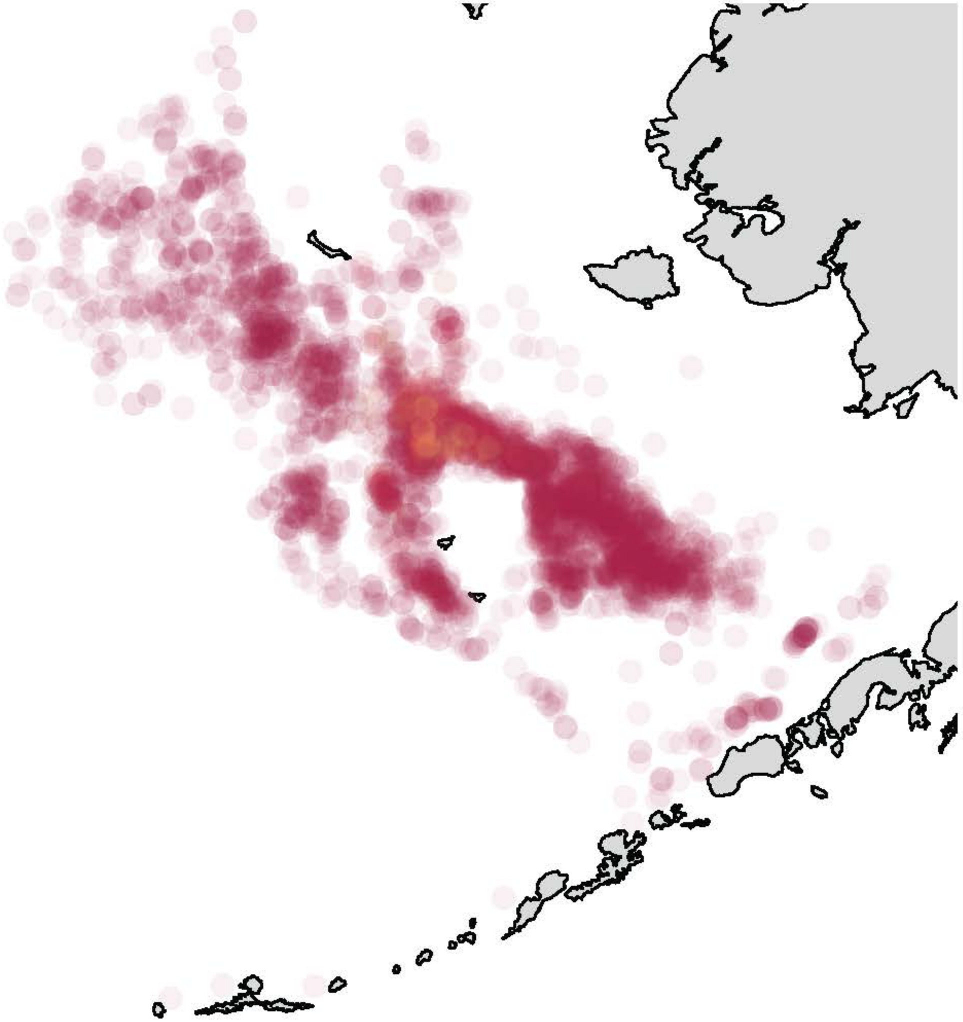


2017

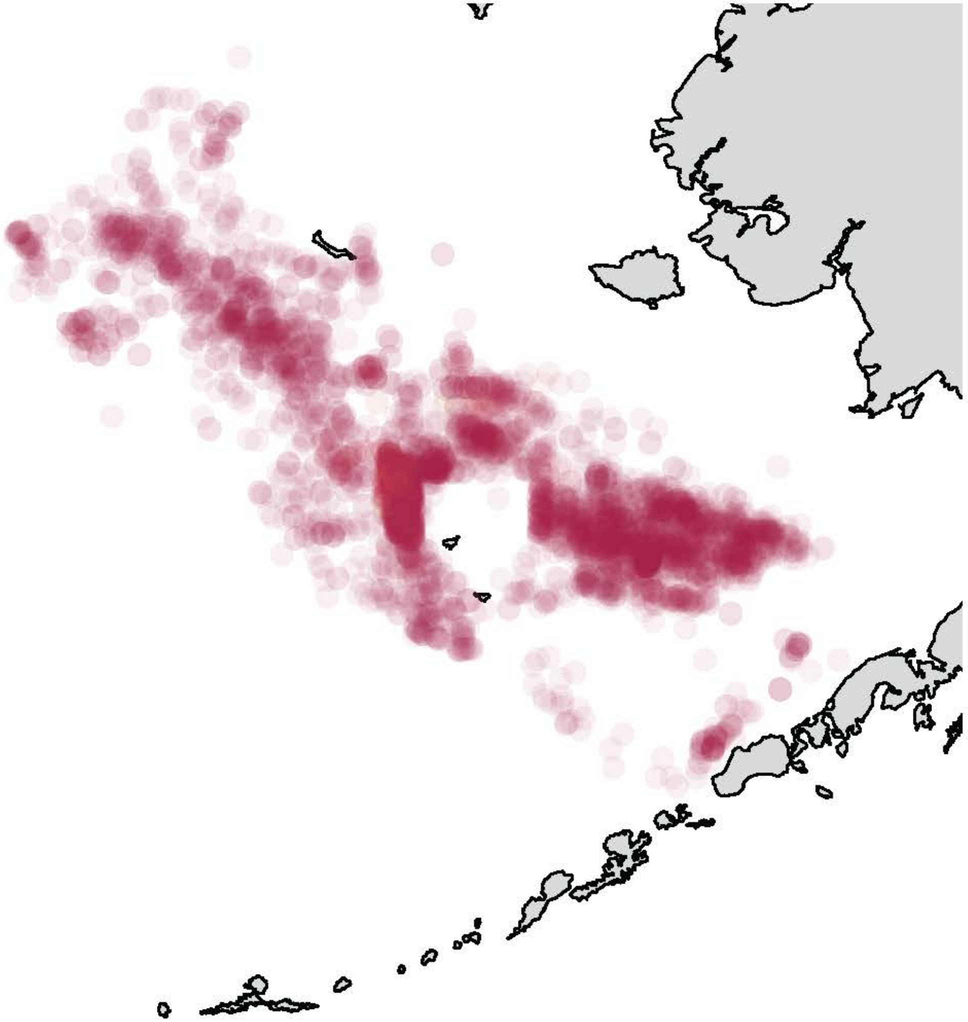



2018

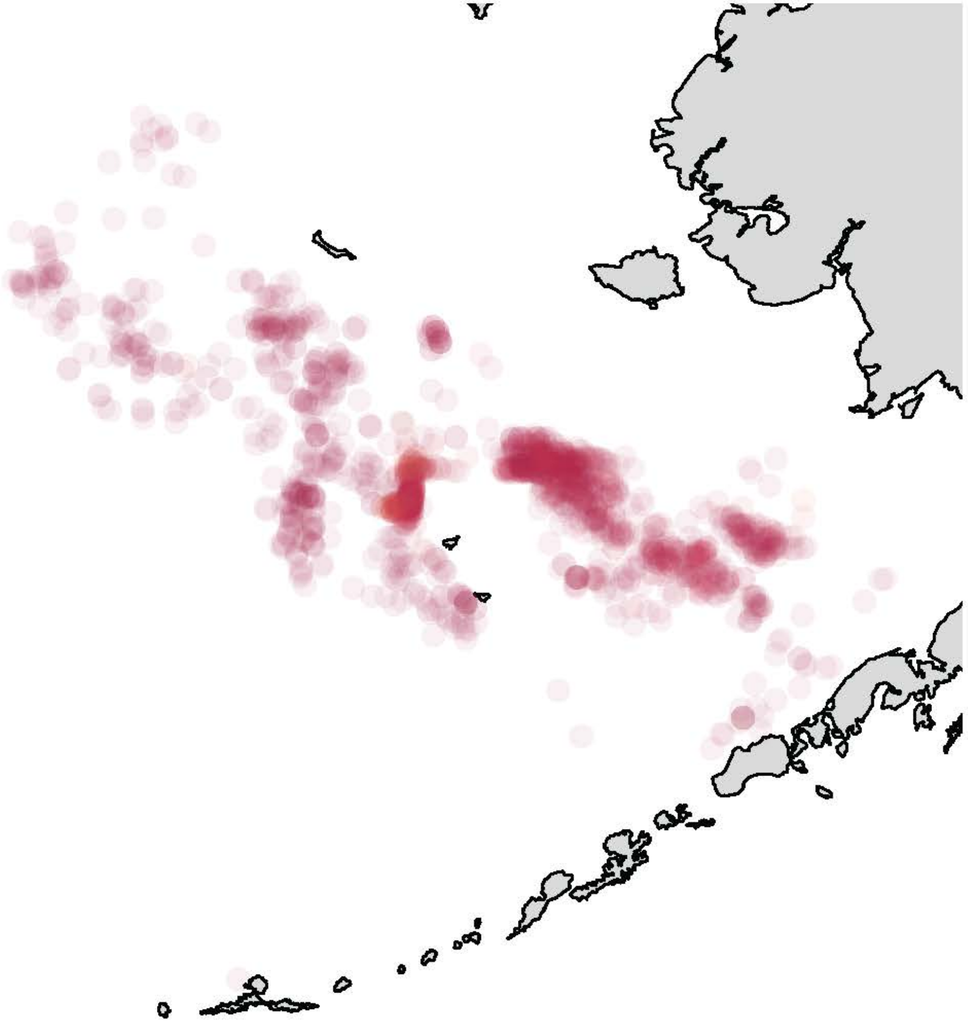
2019



2020



2021



Possibilities

- The crab are alive:
  - Crab moved into the northern Bering Sea
  - Crab are in the eastern Bering Sea, but the survey didn't see them
  - Crab moved off of the shelf
  - Crab moved into Russian waters

- The crab are dead:
  - Predation
  - Disease
  - Temperature effects
  - Fishery effects
  - **Cannibalism?? (Spatial analysis to come)**

Summary

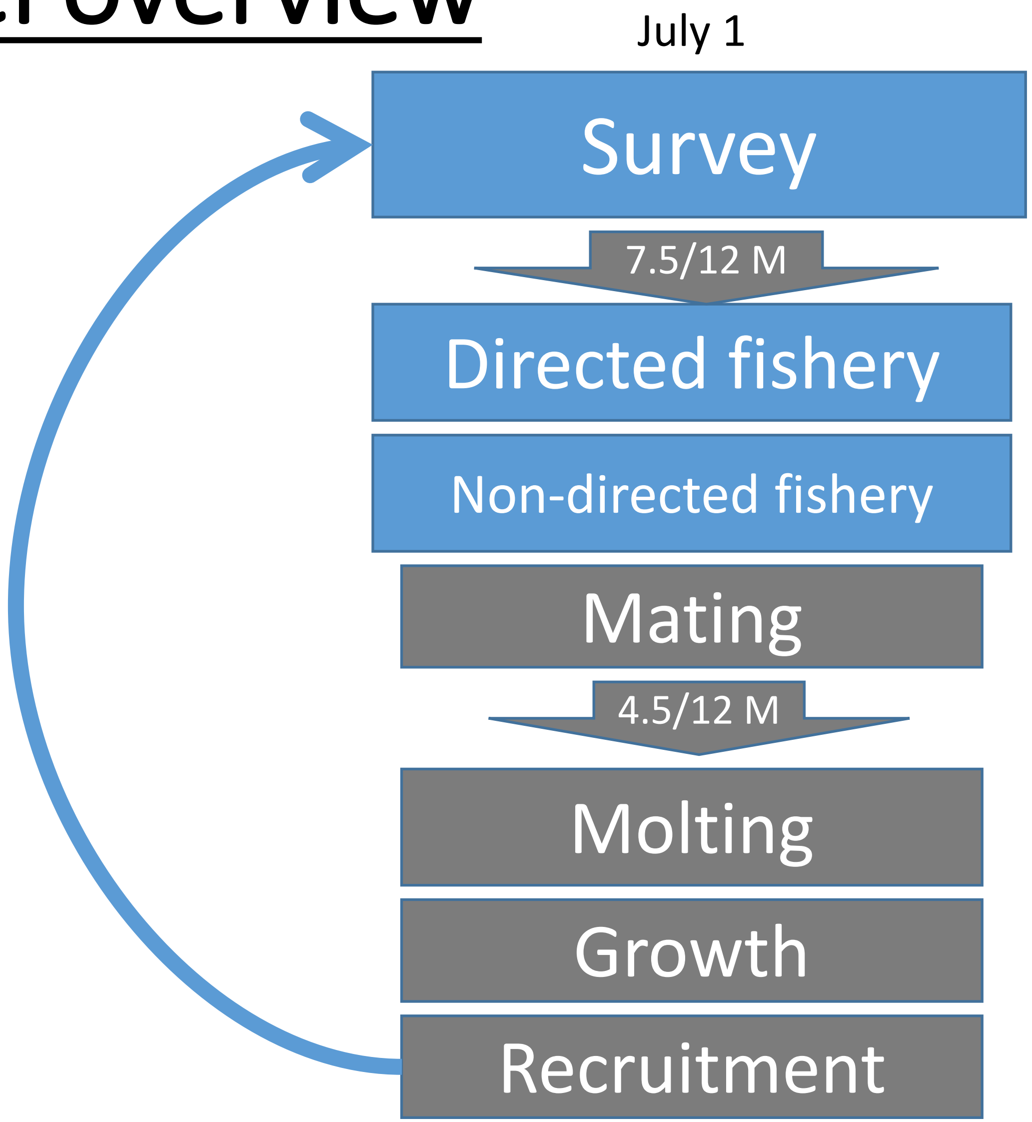
- Missing crab were not in the NBS
- Survey worked as expected for Tanner crab
- Slope area is tiny compared to the area occupied by the animals on the shelf, particularly in the north
- Russian nominal CPUE dropped in 2020 while fishing the line

- Cod consumption was at all time highs in past several year
- Visually identified infections of bitter crab were at all time highs recently
- Bitter crab infections known to be more severe than visually identified based on focused PCR work during 2014-2017
- Bottom temperatures very high in 2018 and 2019—no cold pool
- Bycatch increased in 2018 and 2019, spatial foot print was expanded, but estimated fishing mortality very small
- Unobserved bycatch mortality add <15% additional mortality

Given the available information,
a **mortality event** likely contributed at least in part
to observed declines.

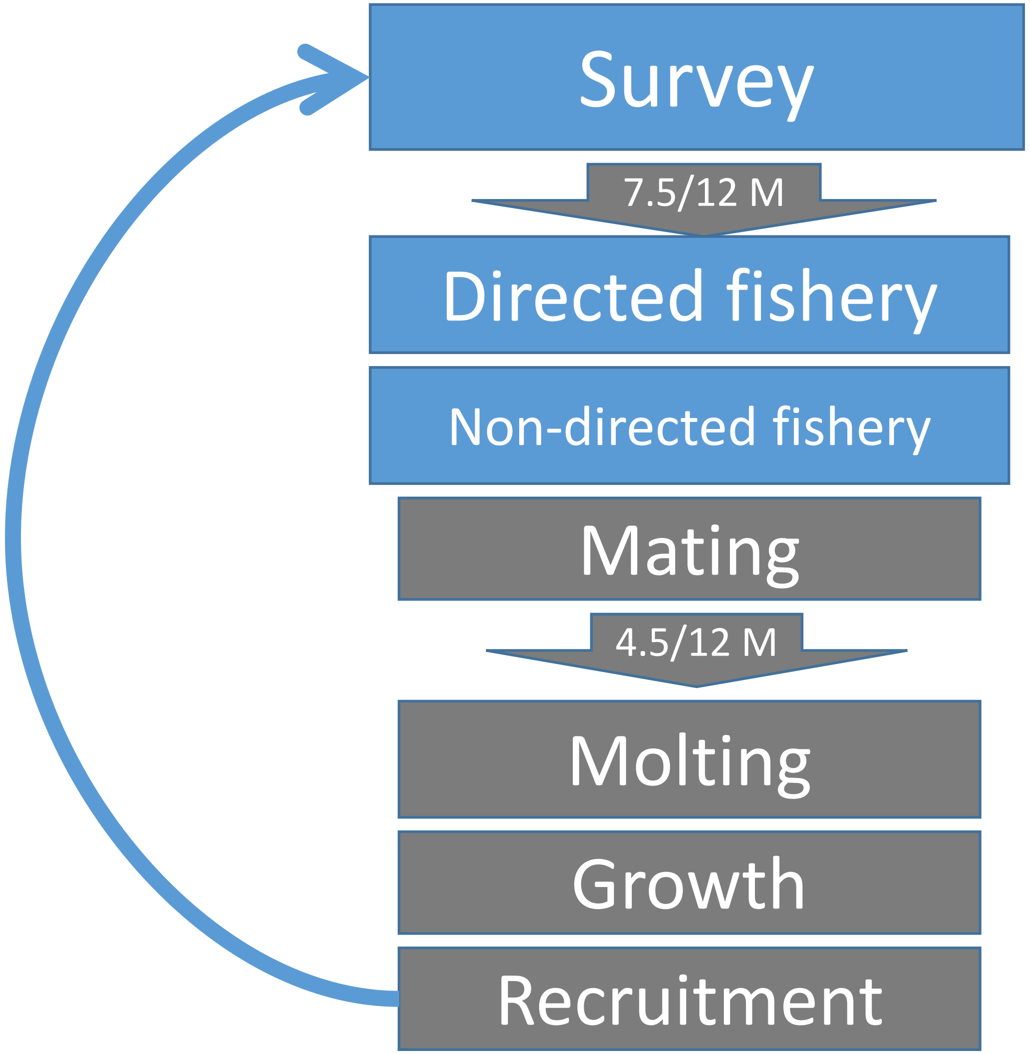
- 20.1 – Last year's accepted model (status quo) fit to last year's data
- 21.1 – Last year's accepted model (status quo) fit to this year's data
- 21.1a – 21.1 + empirical availability
- 21.1b – 21.1 + mortality events in 2018 and 2019
- 21.1c – 21.1a + McAllister-Ianelli re-weighting
- 21.2 – 21.1a + mortality events in 2018 and 2019 + tighter priors on M and maturity smoothness
- 21.3 – 21.1a + mortality events in 2018 and 2019 + empirical selectivity
- 21.3a – 21.3 + FMSY = natural mortality

Model overview



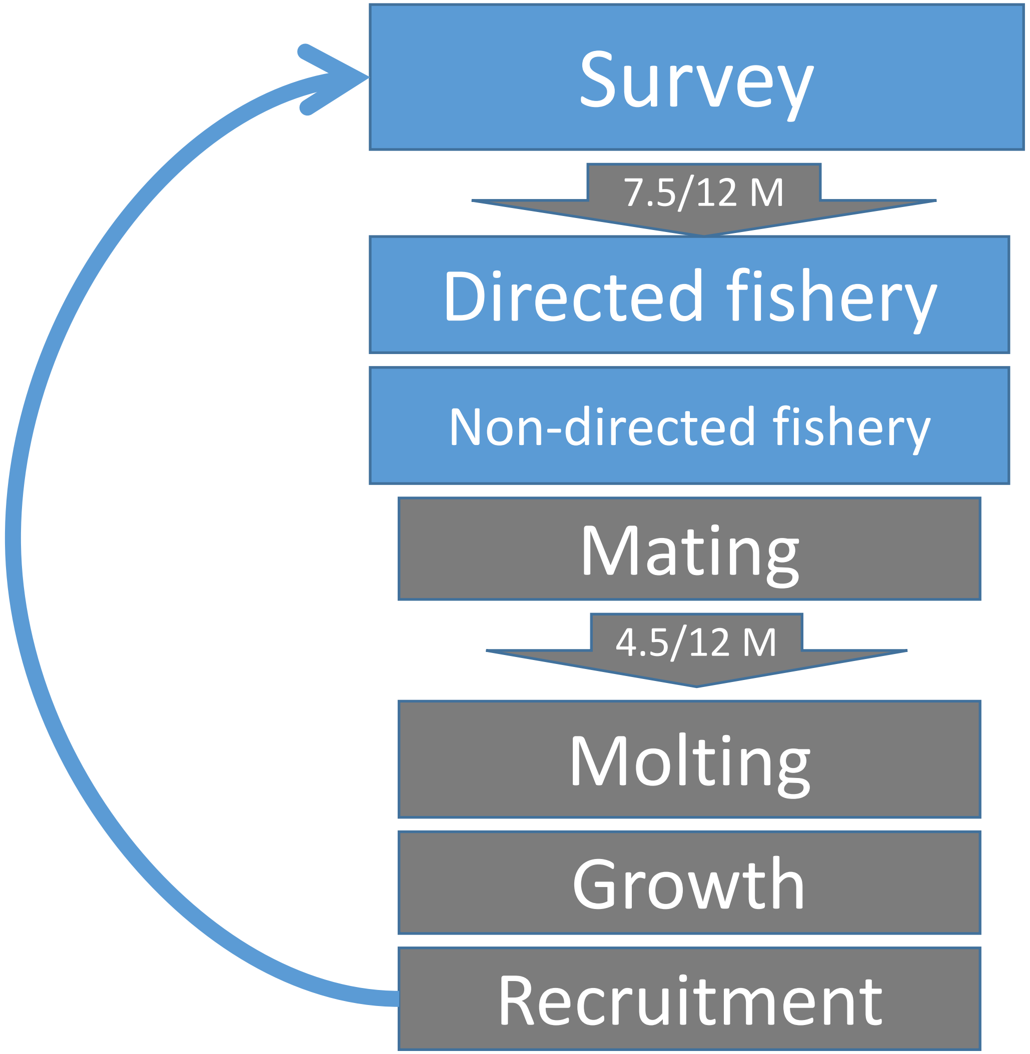
1. Logistic selectivity in 2 ‘eras’
2. Linked to BSFRF data
3. Size composition and biomass index

Model overview



1. Mature males, immature for both sexes, mature females
2. Estimated with a prior

Model overview

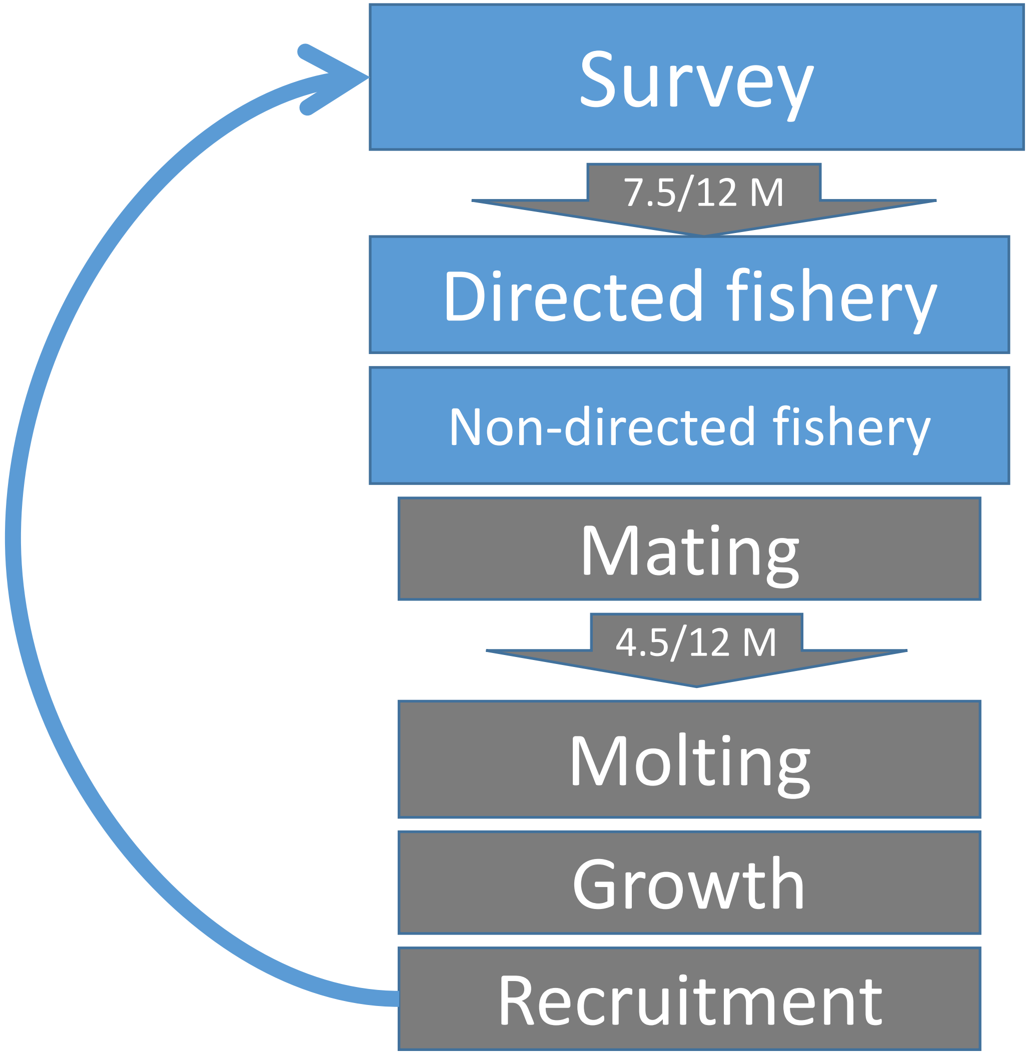


1. Logistic selectivity
2. Retention selectivity
3. Discard mortality equal to 30%

Fit to:

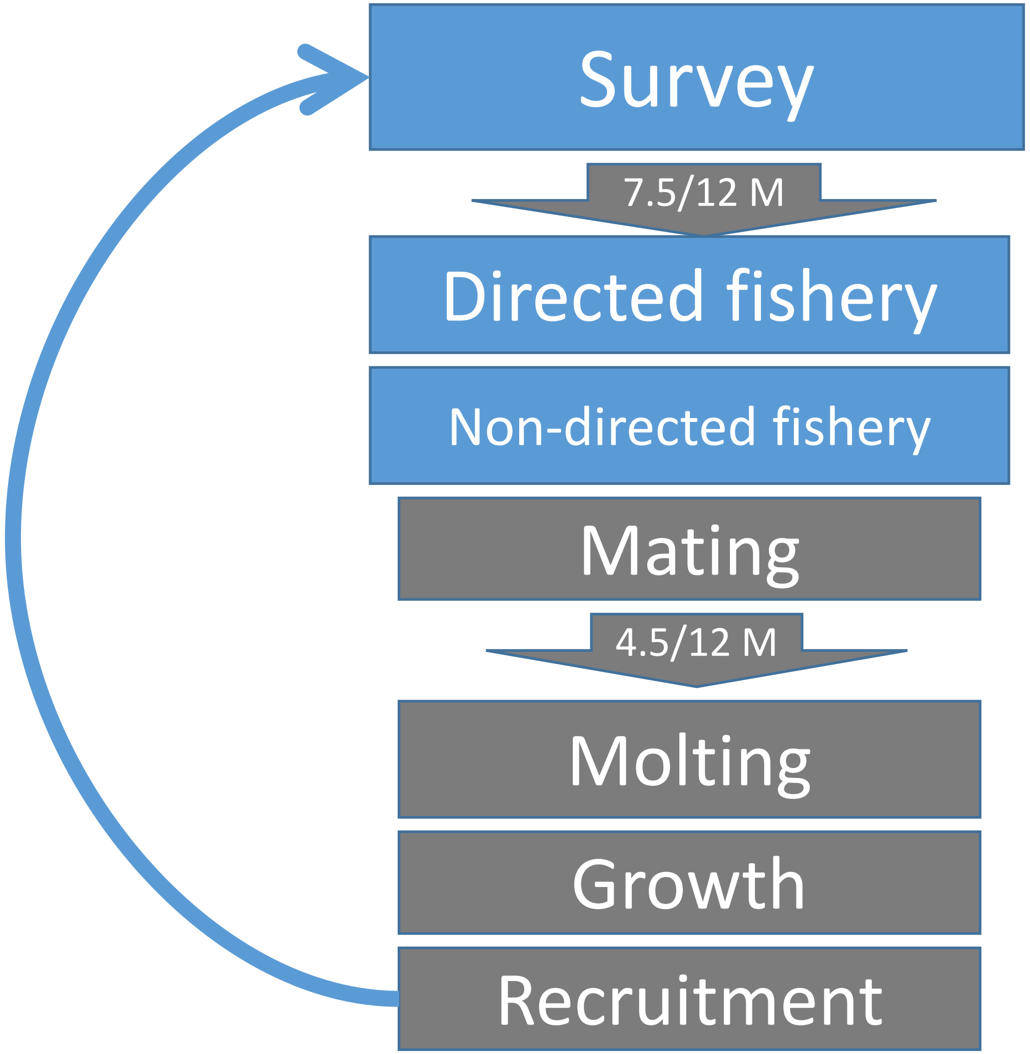
Retained length comps
Total length comps
Retained biomass
Male and female discard biomass

Model overview



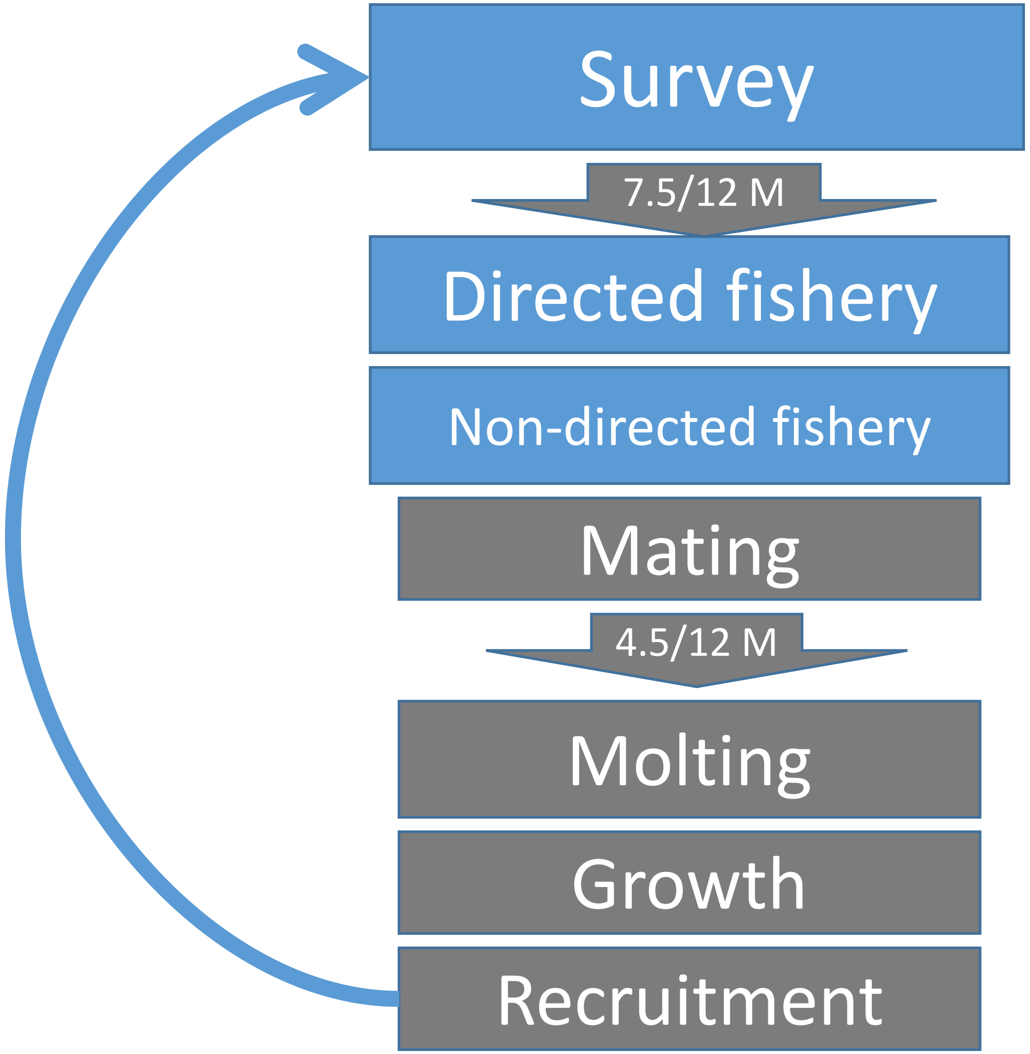
1. Logistic selectivity
2. Discard mortality equal to 80%

Model overview



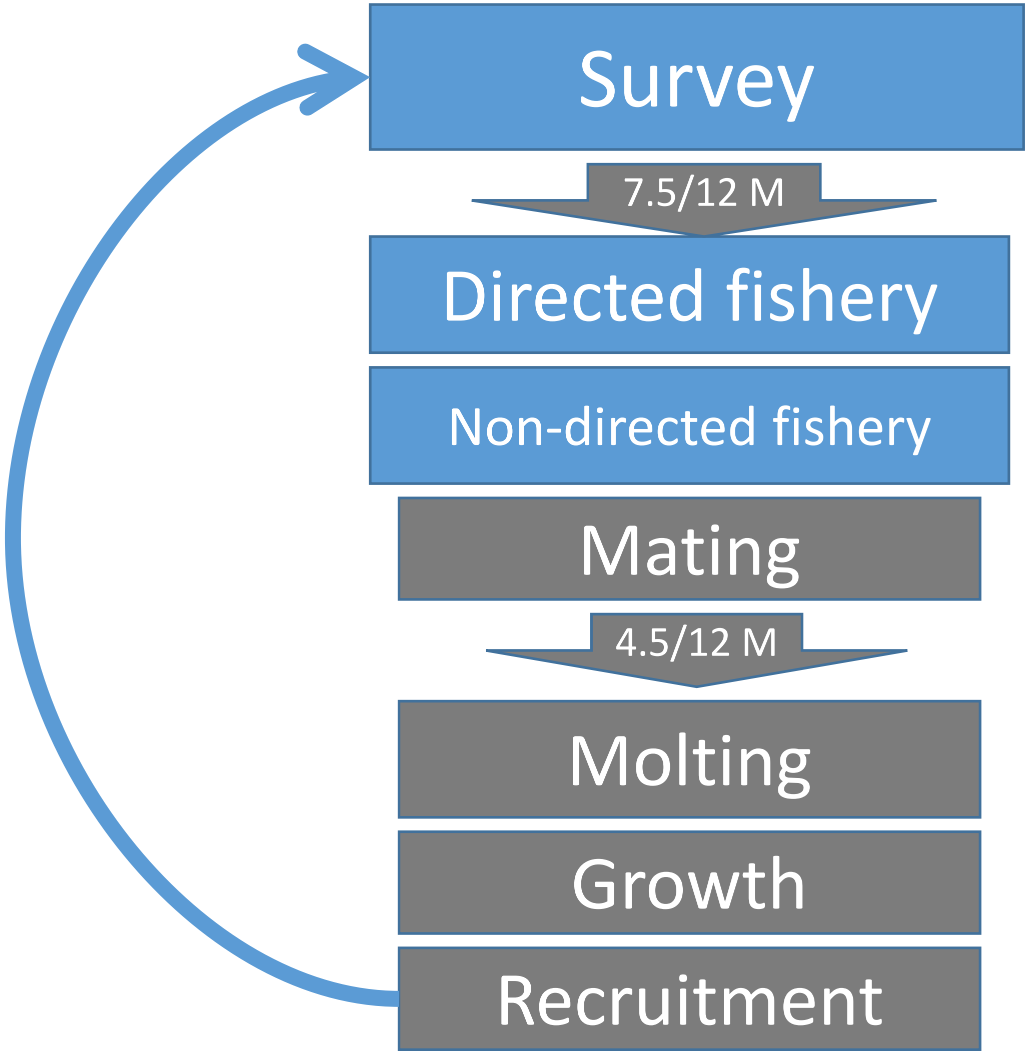
1. Freely estimated maturity curves
2. February 15

Model overview



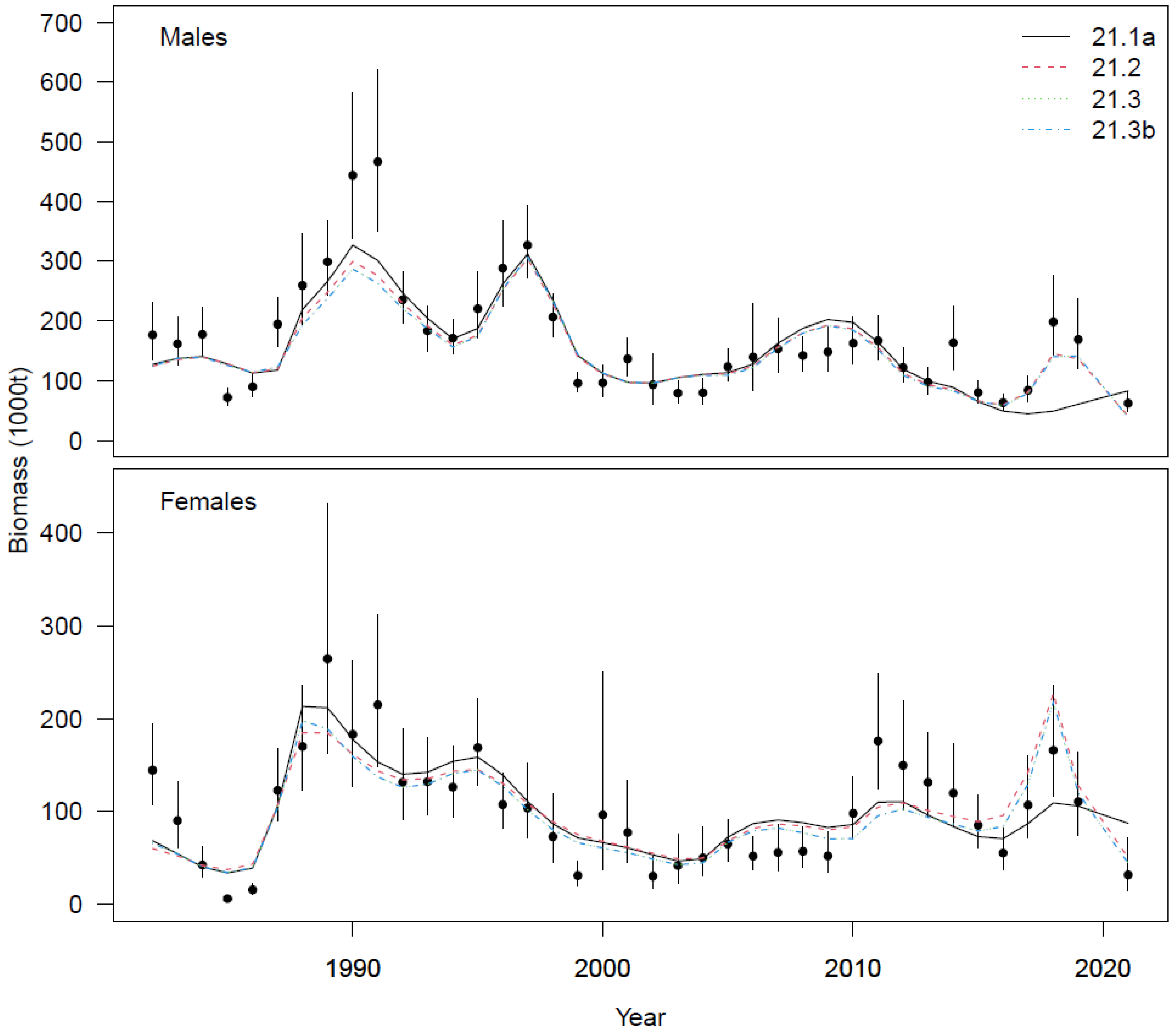
1. All immature crab assumed to molt
2. Terminal molt to maturity

Model overview



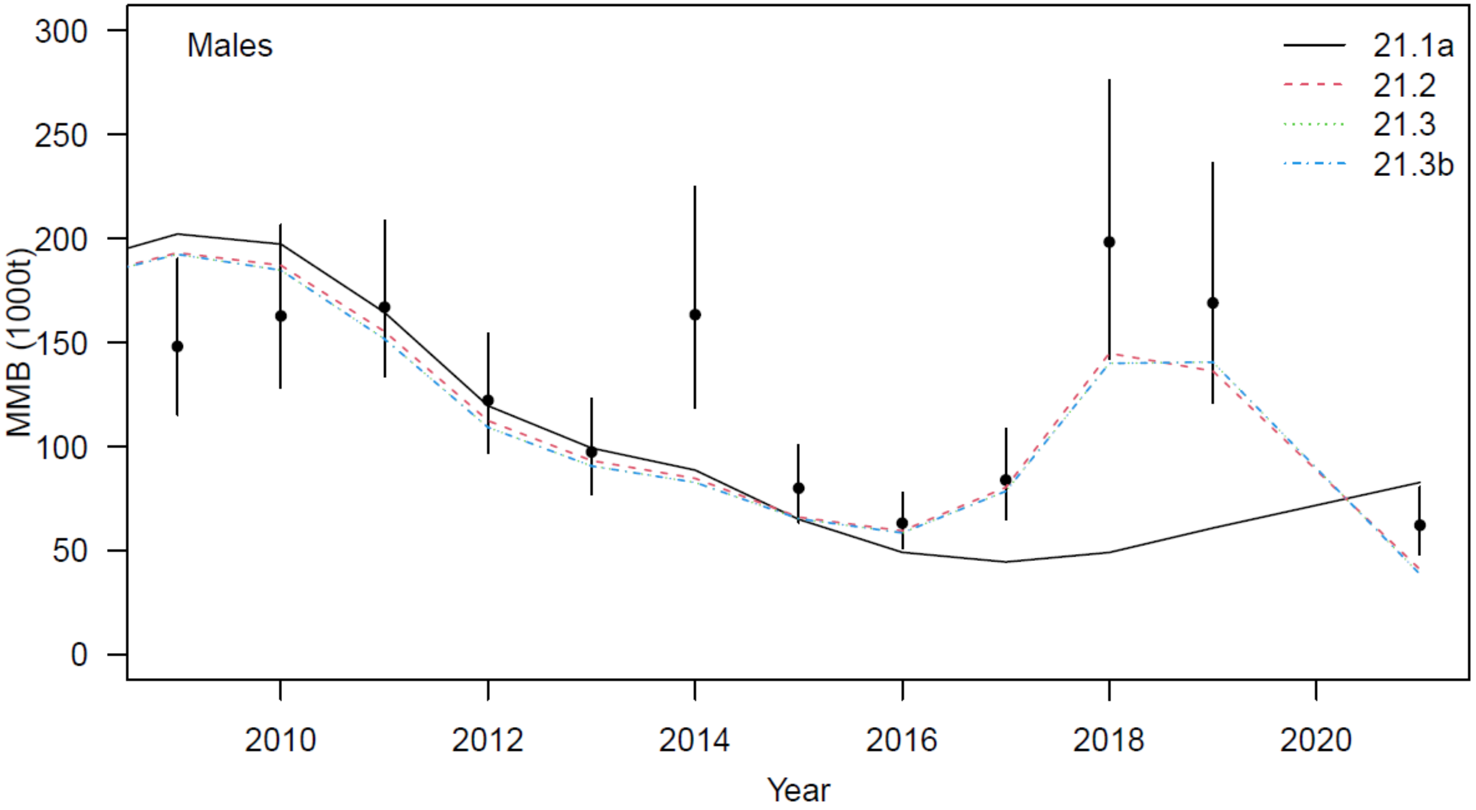
1. Linear growth estimated outside of the model for both sexes

Fits to data



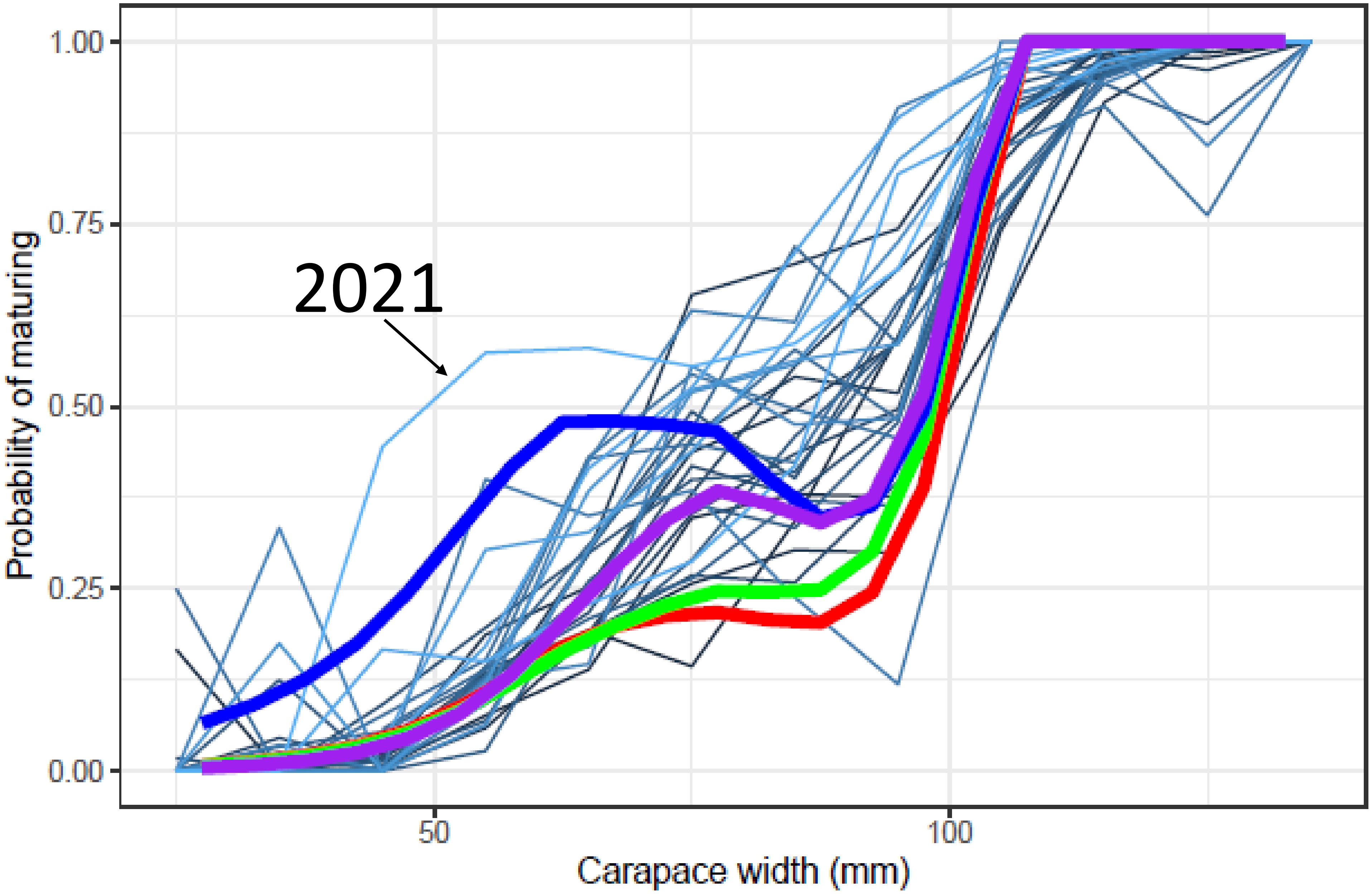
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth			
Catch			
Retained size comp			
Total size comp			
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data

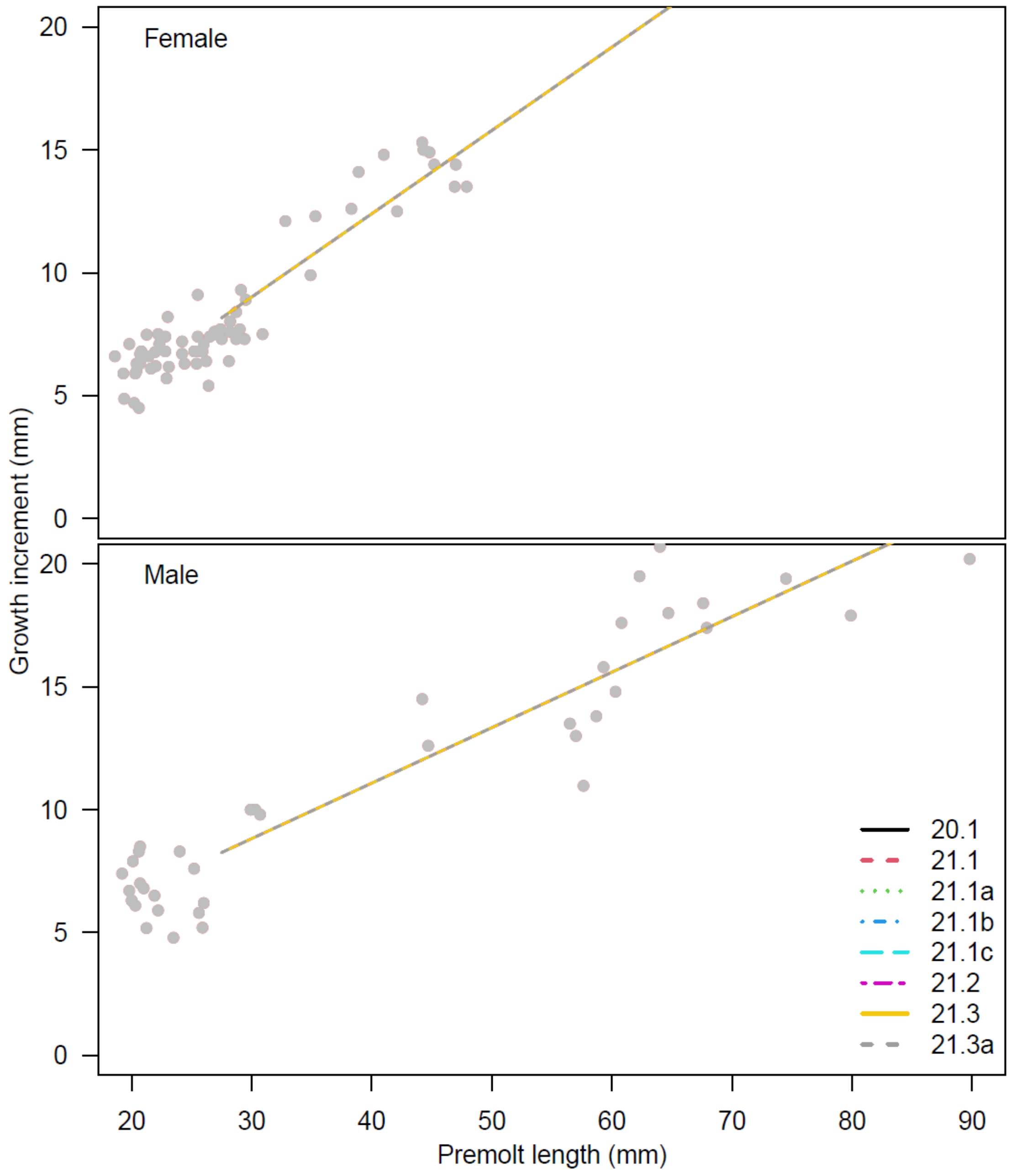


Model estimates of MMB are lower than the observed…why is that?

Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth			
Catch			
Retained size comp			
Total size comp			
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

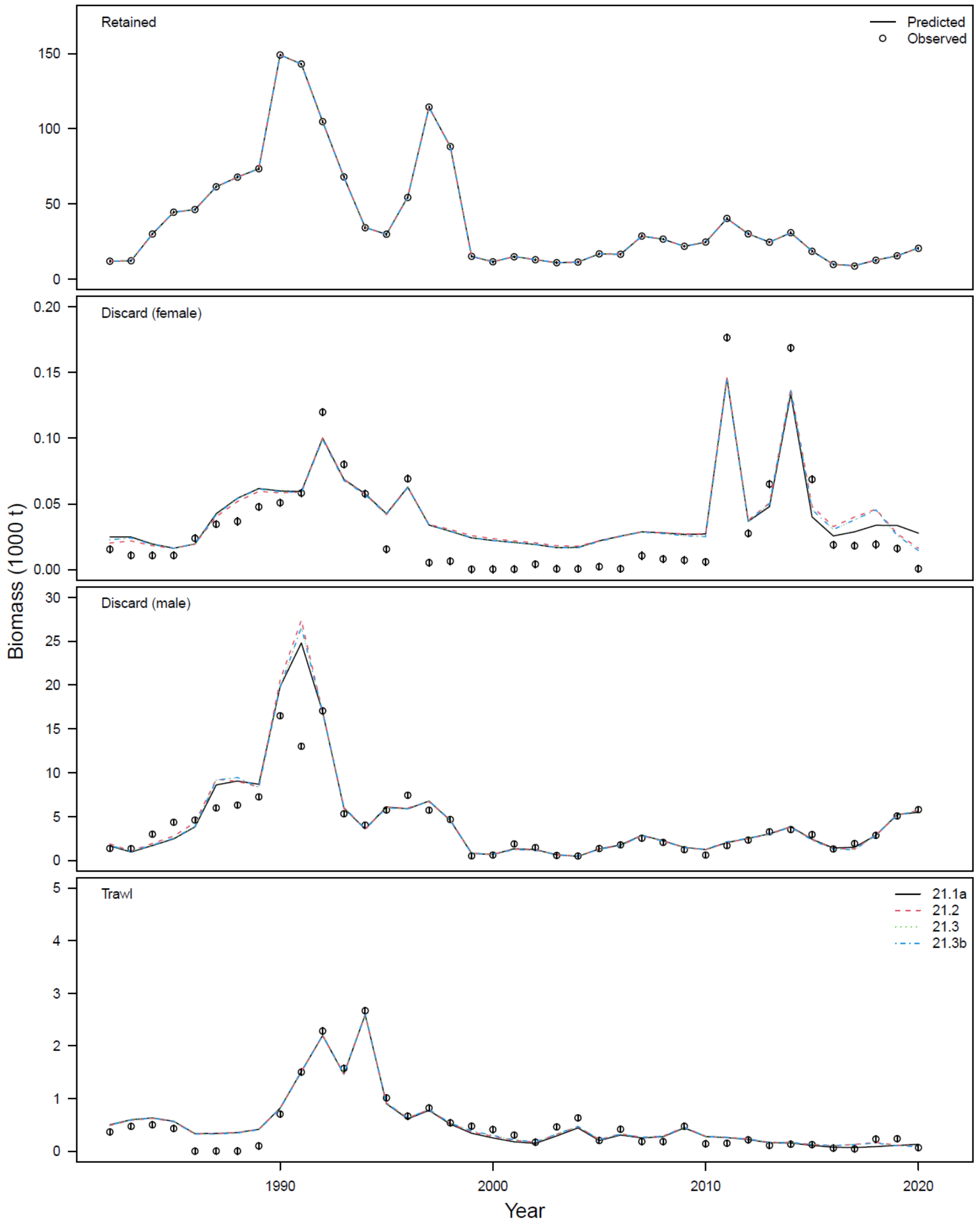

2021
Probability of maturing
1.00
0.75
0.50
0.25
0.00
50
100
Carapace width (mm)

Fits to data



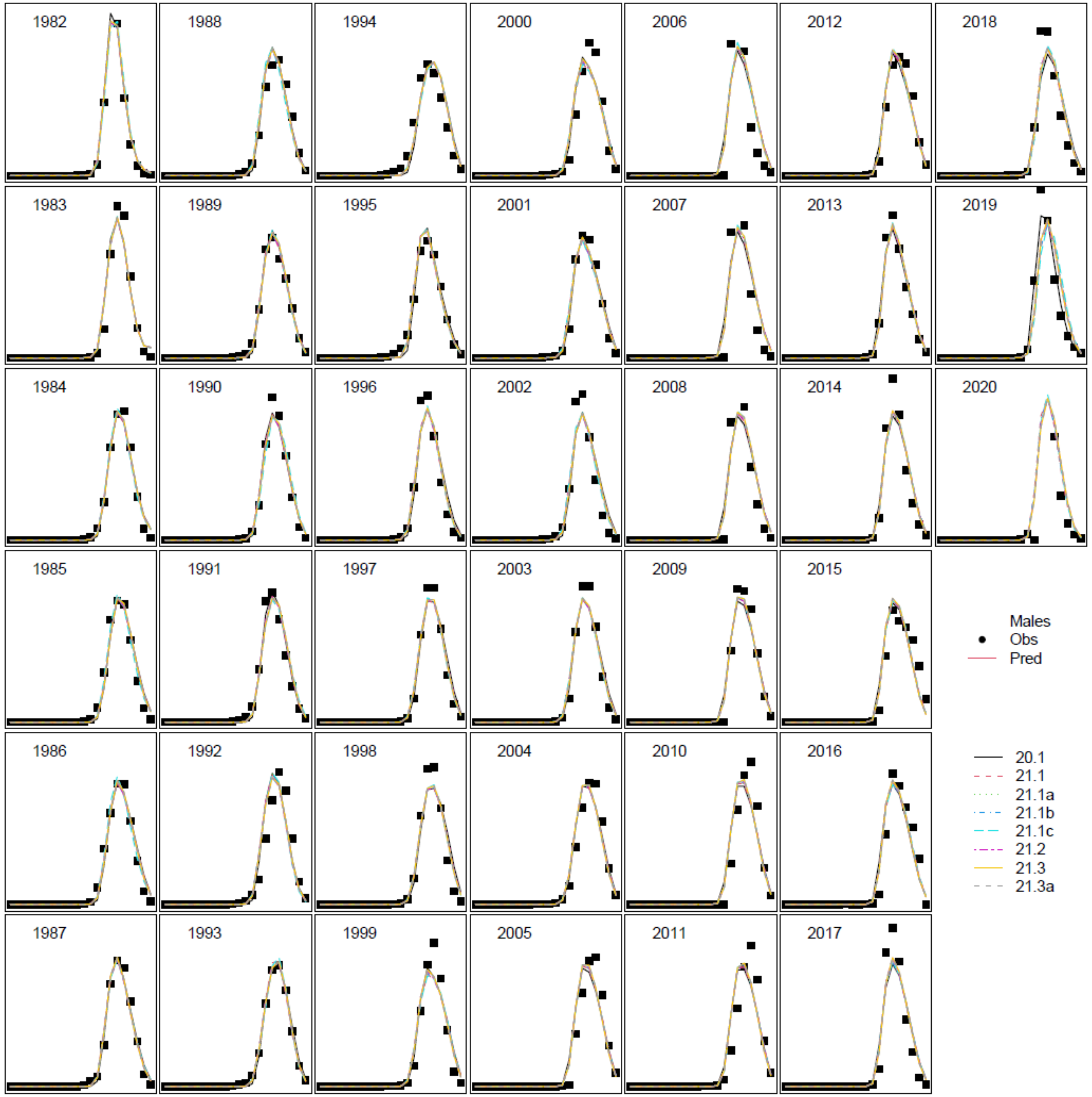
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch			
Retained size comp			
Total size comp			
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



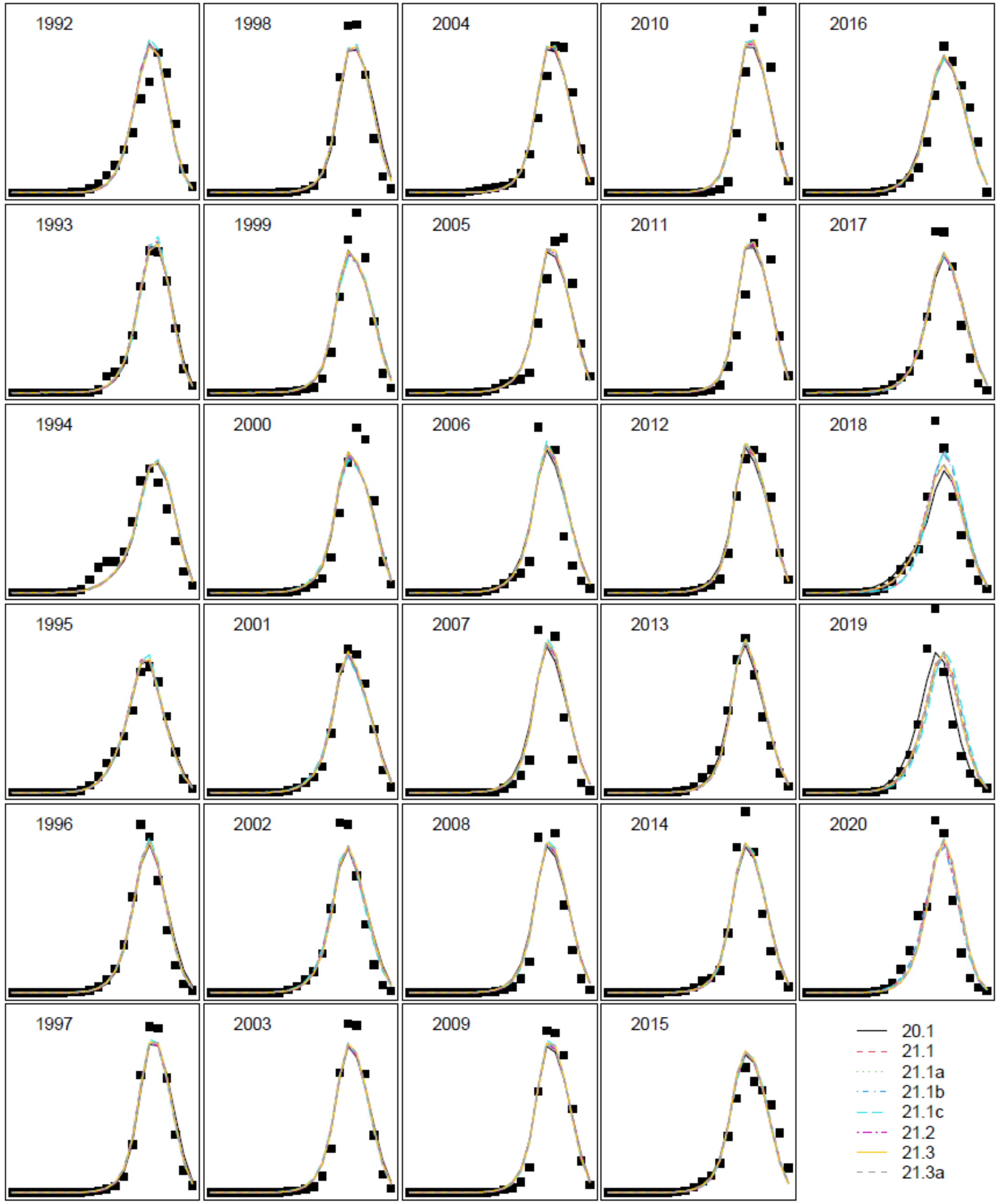
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp			
Total size comp			
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



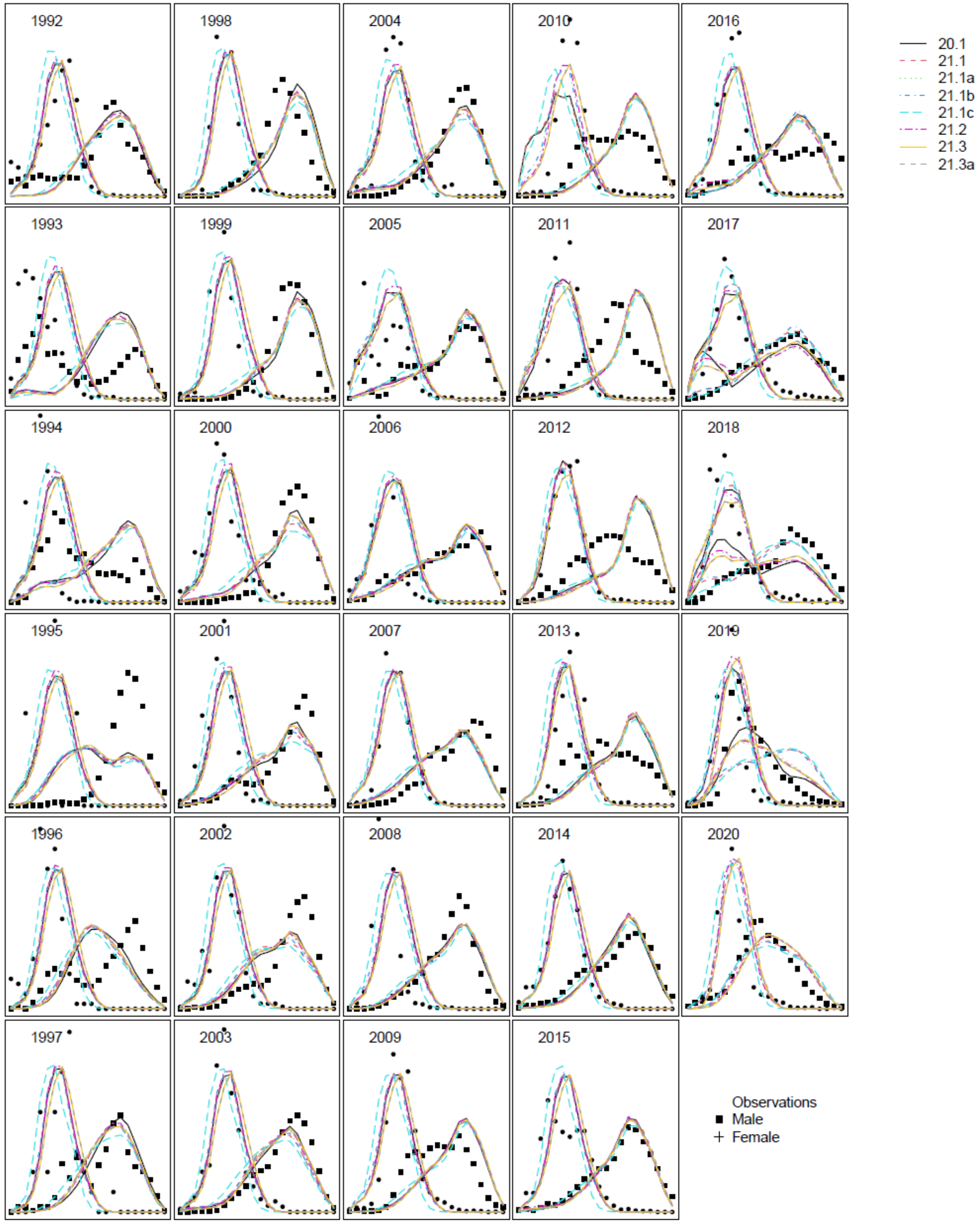
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp			
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



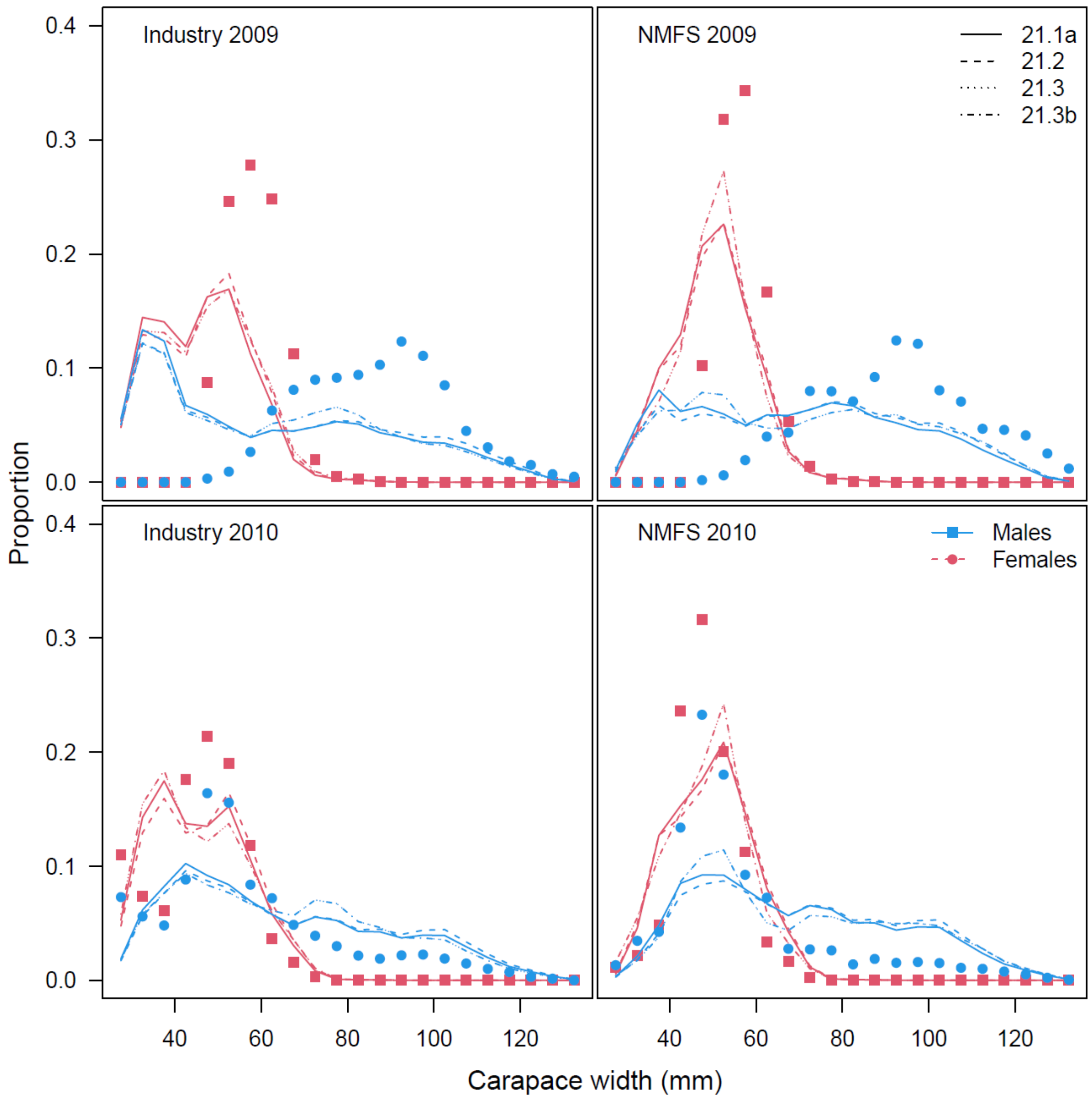
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp			
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



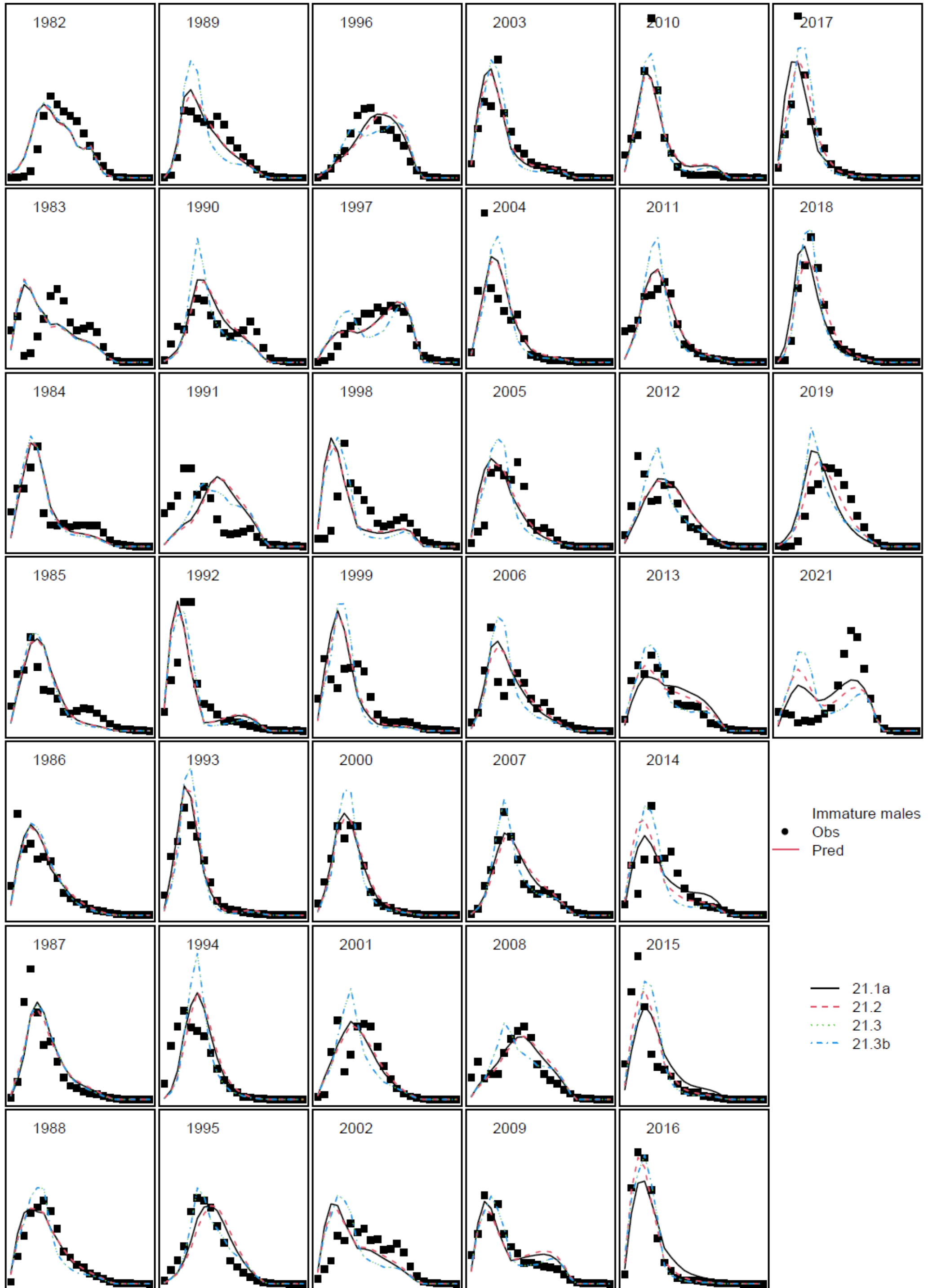
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp			
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



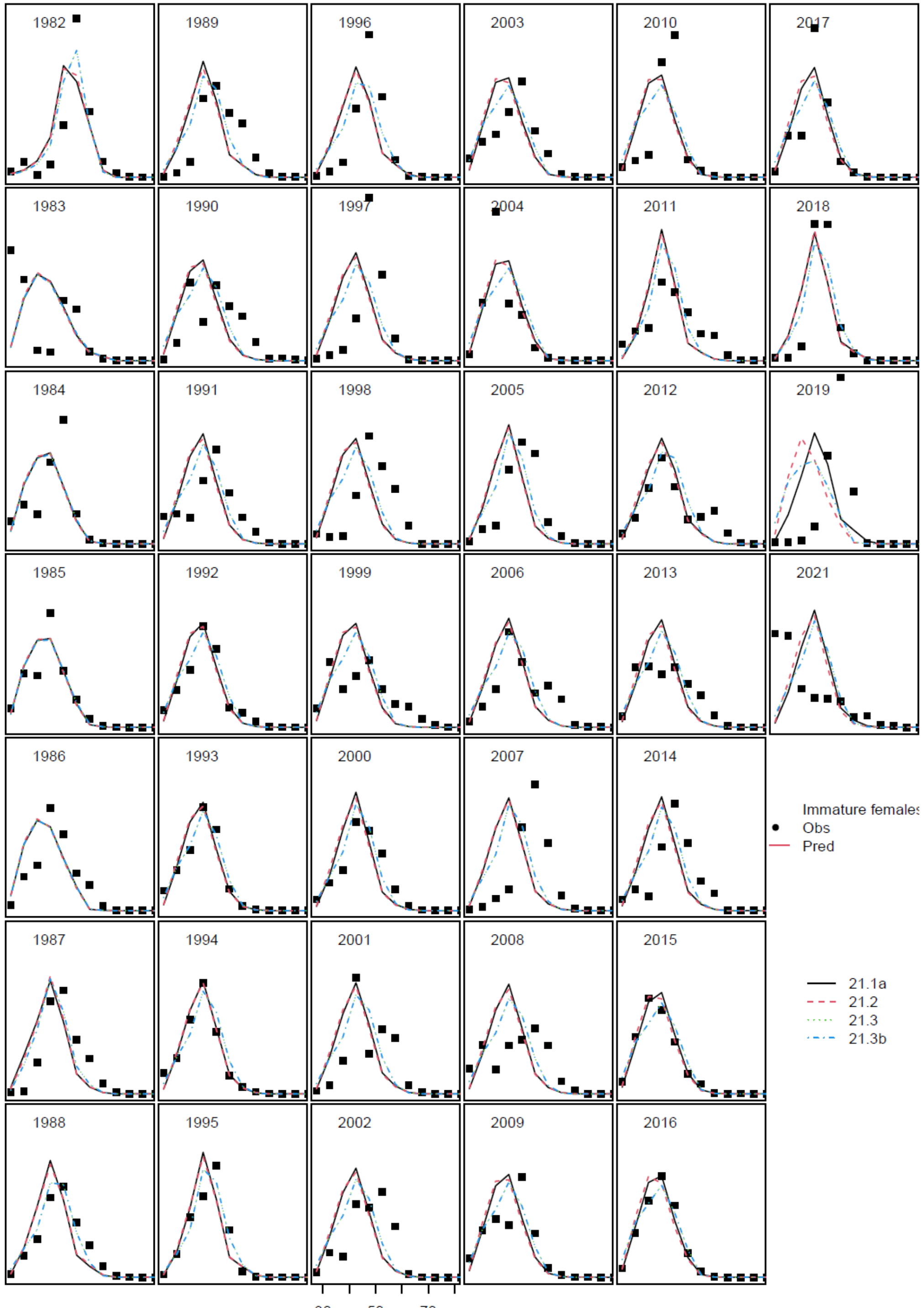
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



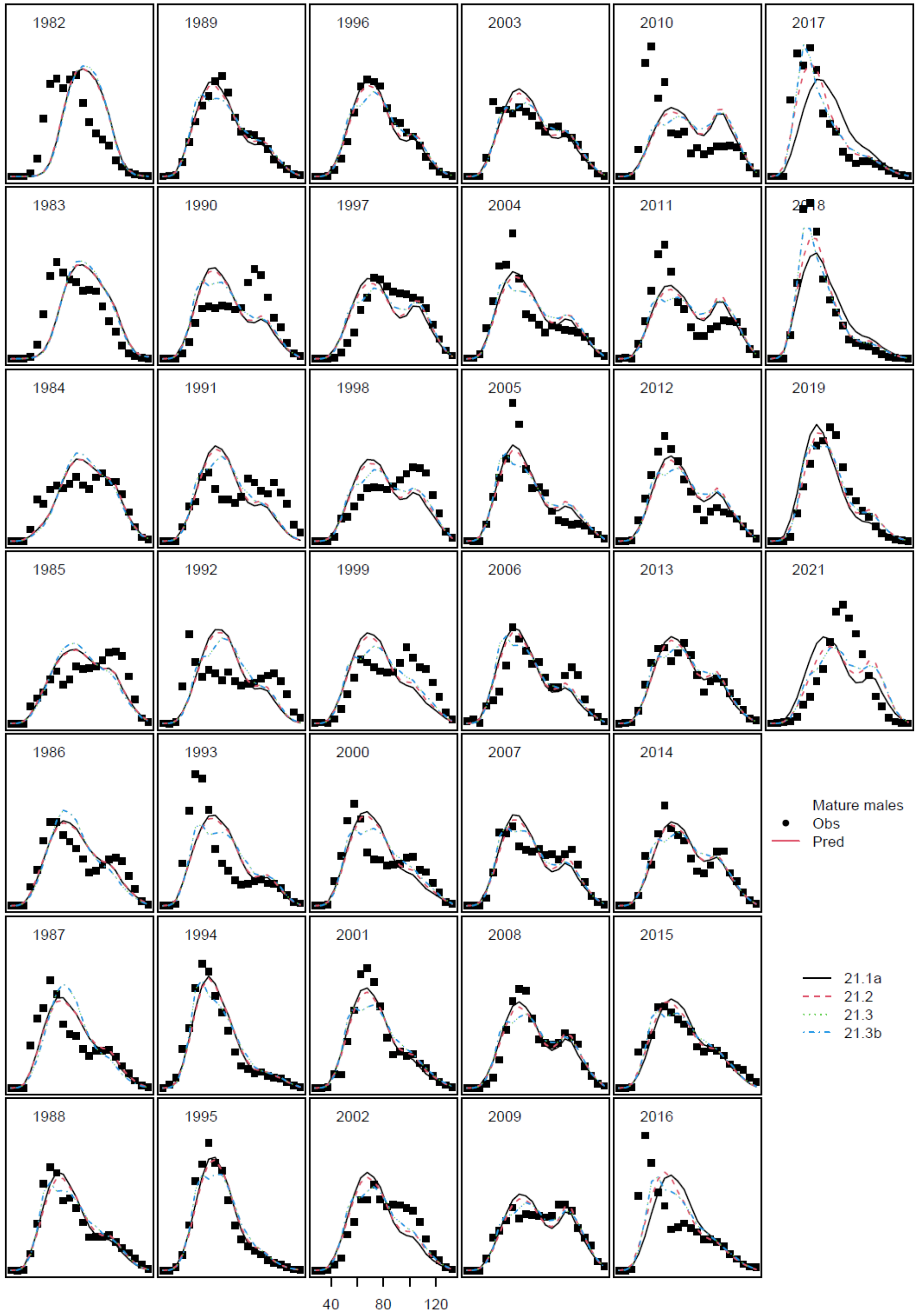
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data



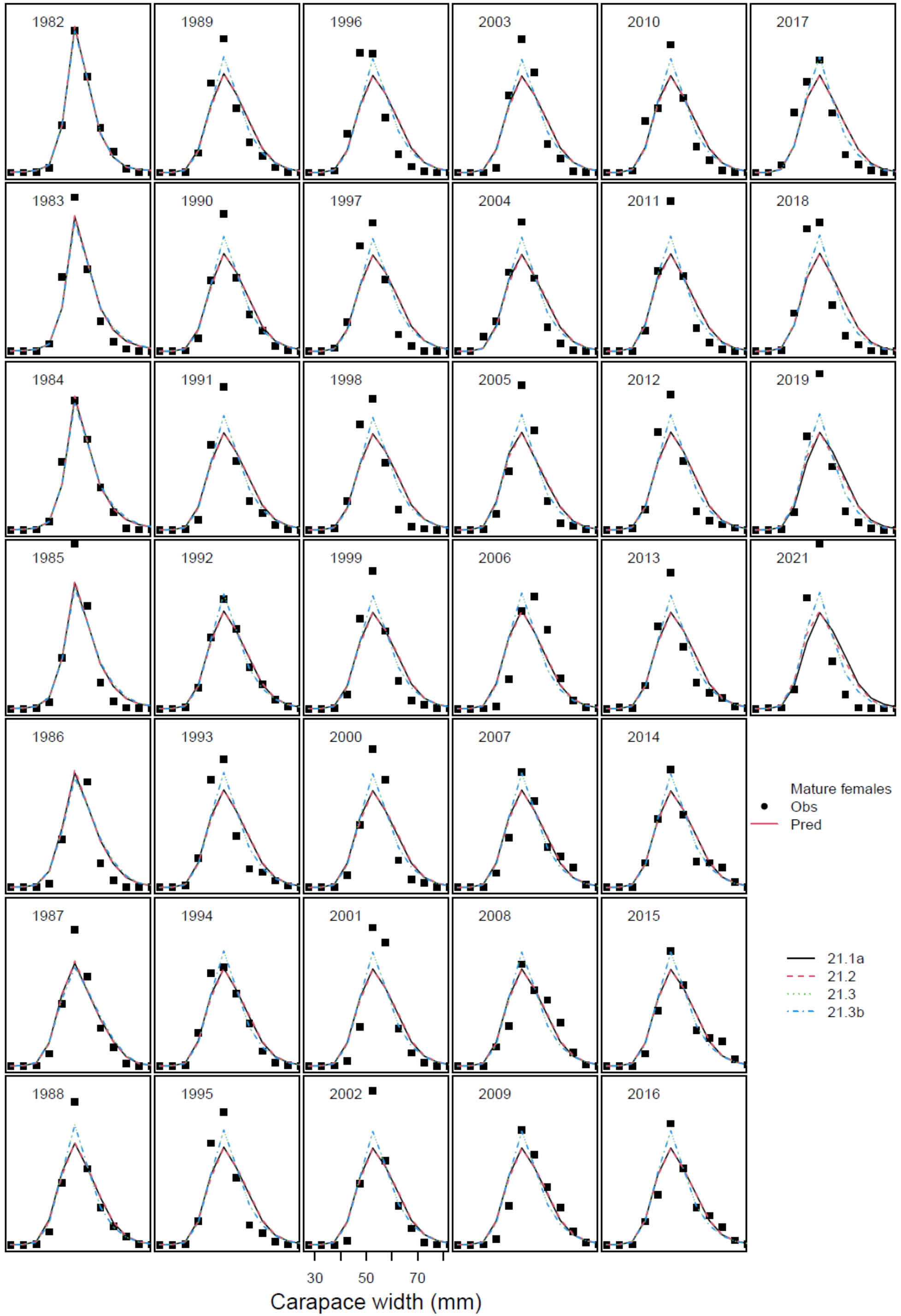
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			
Survey size comp (mat M)			
Survey size comp (mat F)			

Fits to data

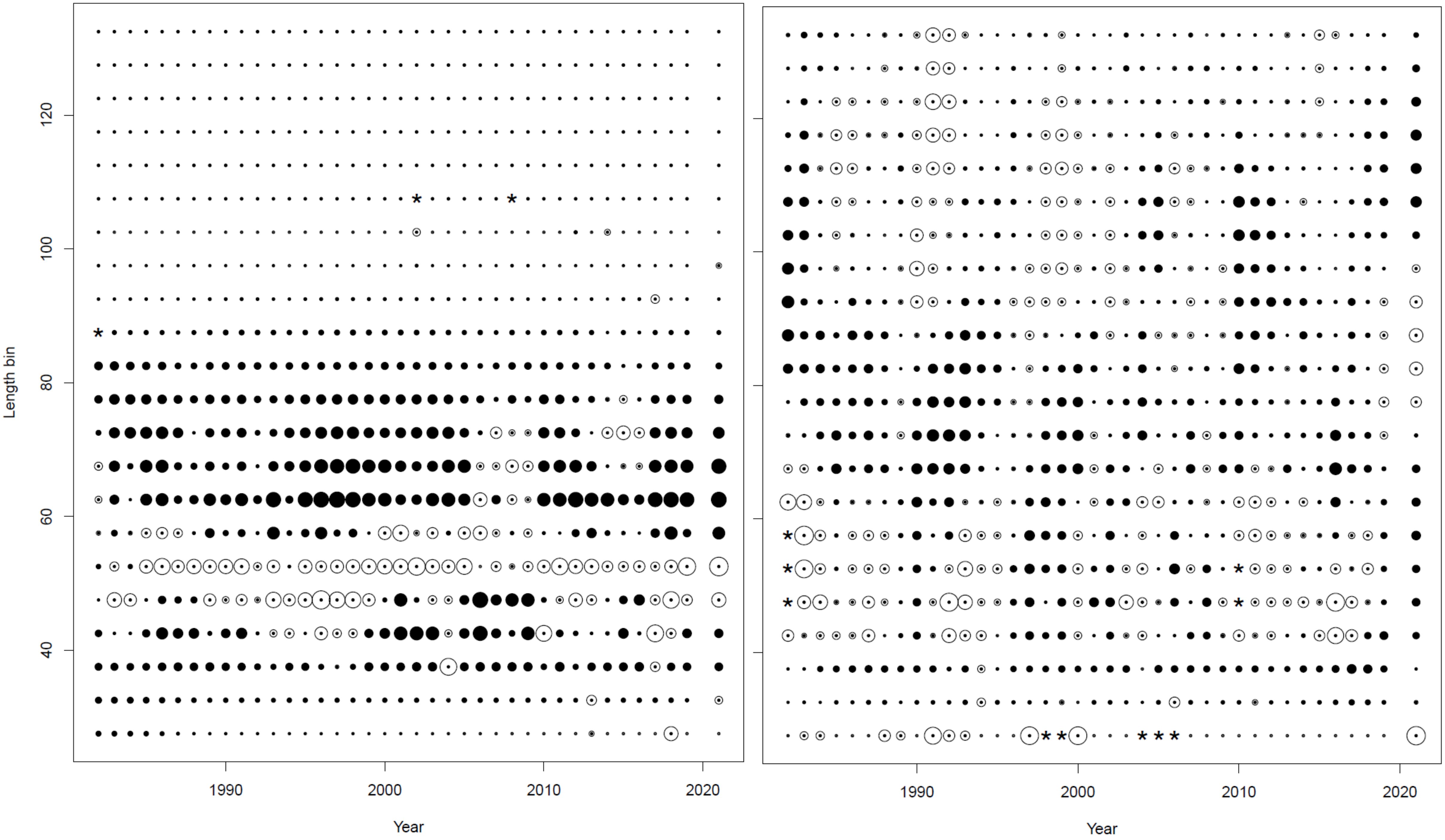


Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			~
Survey size comp (mat M)			
Survey size comp (mat F)			

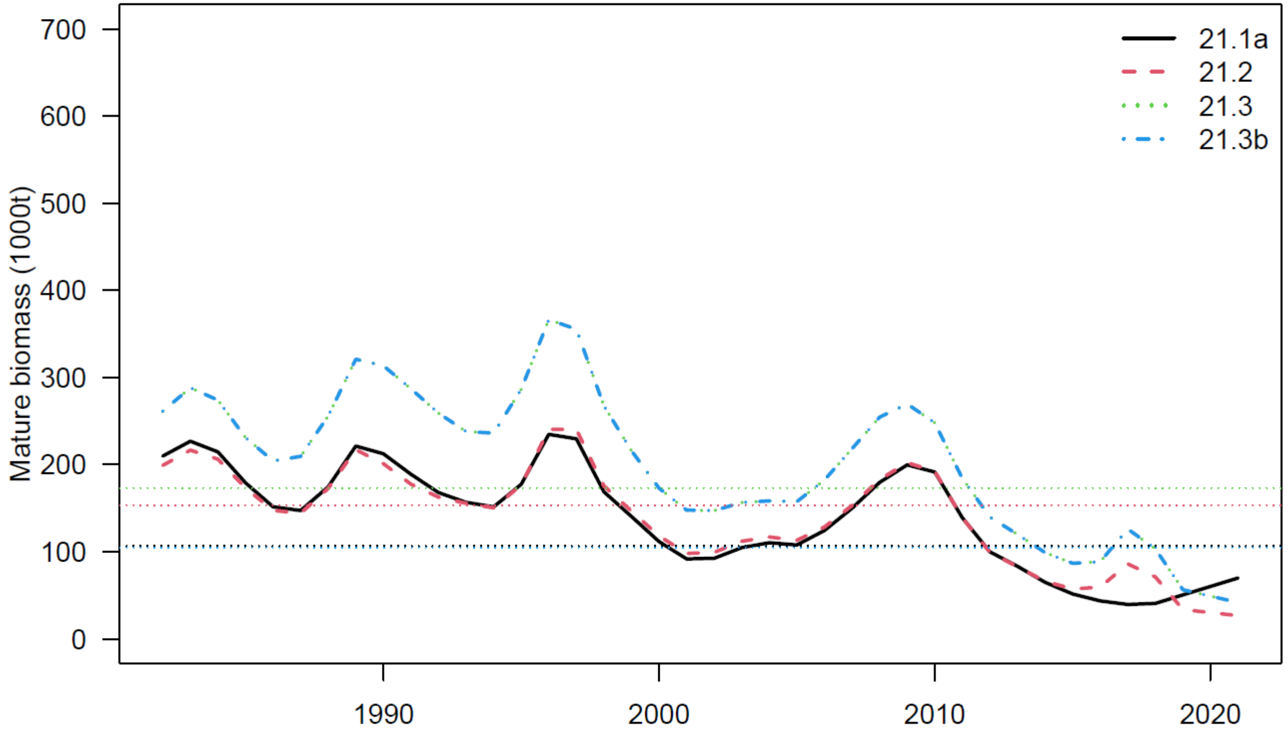
Fits to data



Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			~
Survey size comp (mat M)			
Survey size comp (mat F)			~

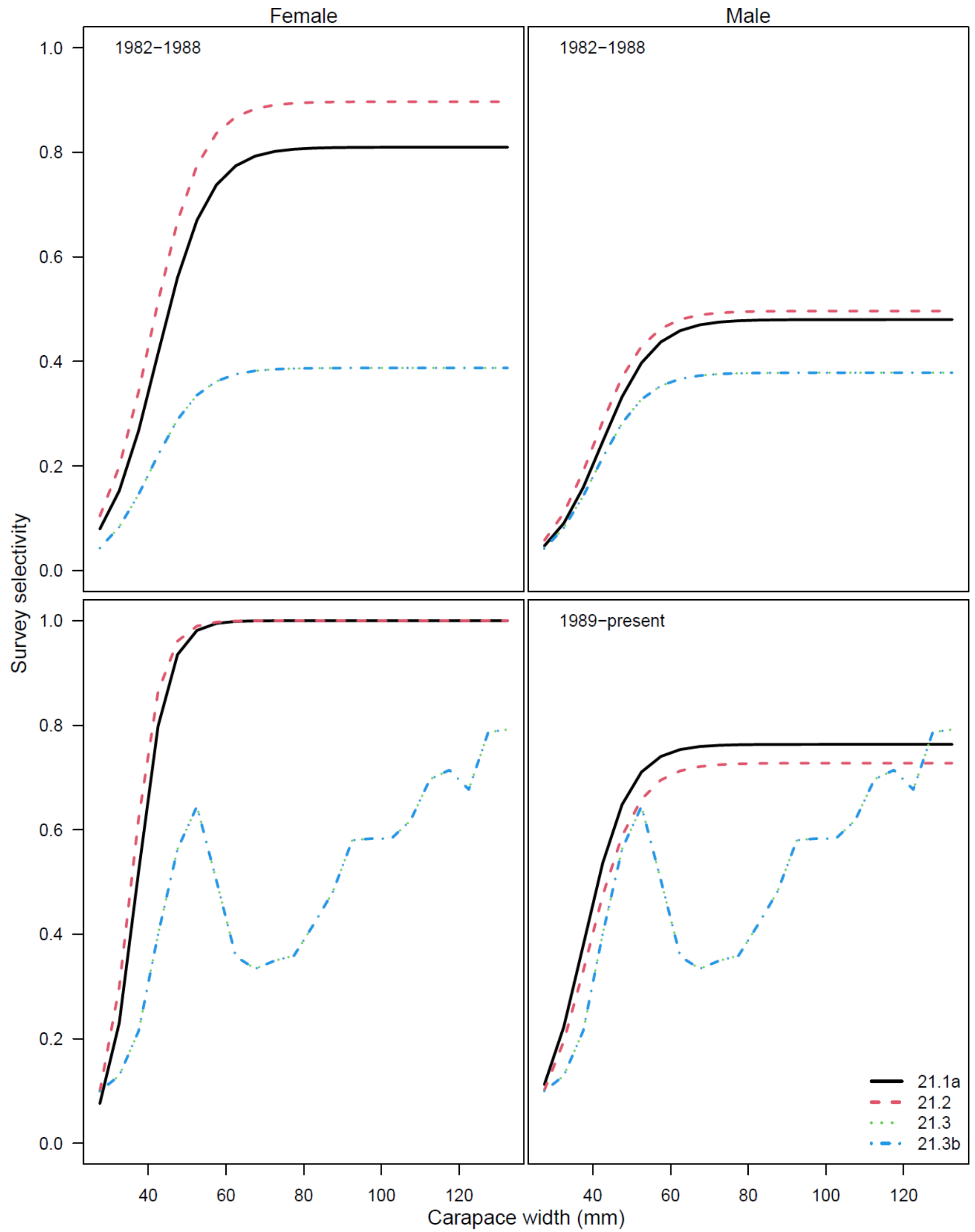

Length bin
40
60
80
100
120
1990
2000
2010
2020
Year
1990
2000
2010
2020
Year

Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			
Probability of maturing			
Fishing mortality			
Recruitment			
Natural mortality			
Status			

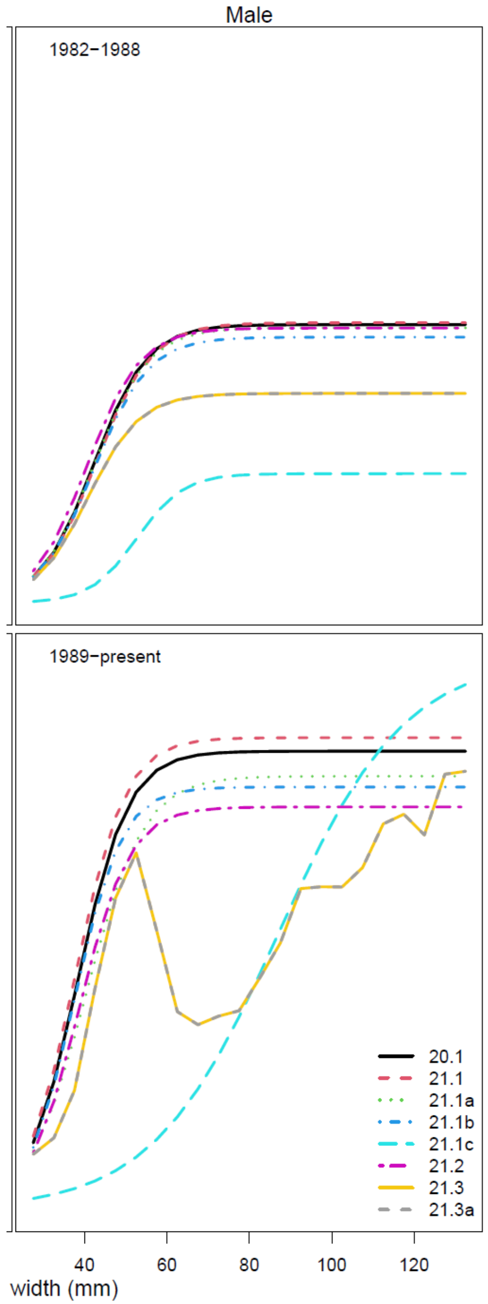
Estimated population processes

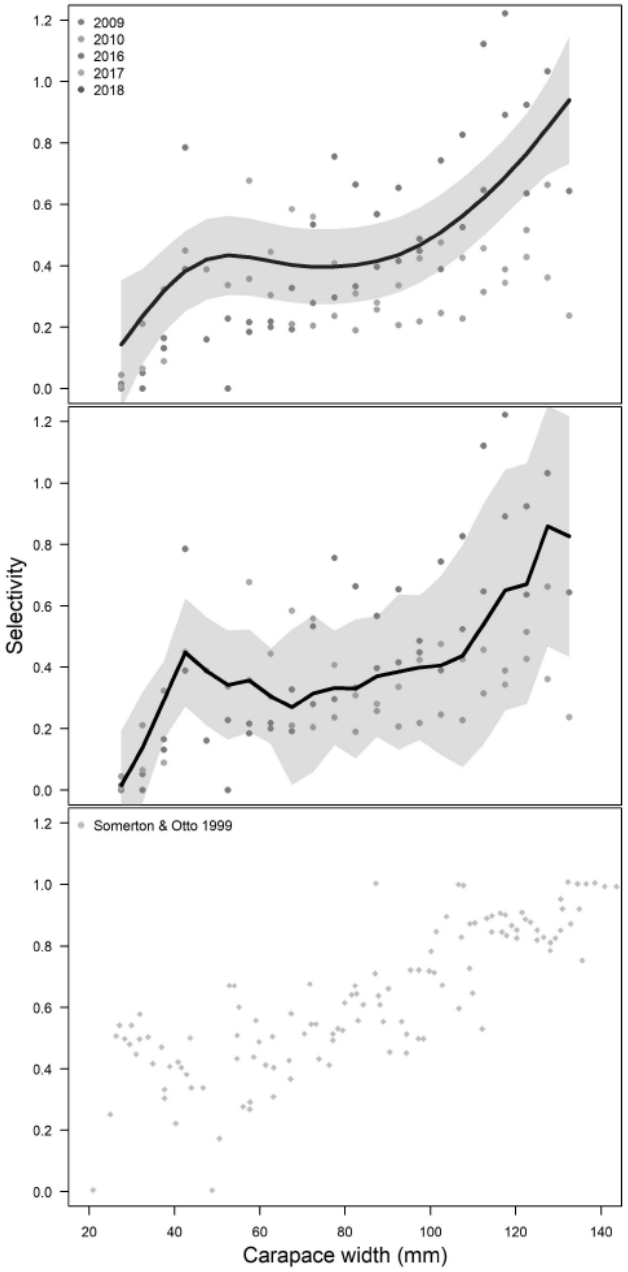


Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			
Fishing mortality			
Recruitment			
Natural mortality			
Status			

- Next cycle, exclude the first era (this was done in the GMACS models prepared for this cycle…which then couldn’t be used because of the lack of time-variation in M)

Estimated population processes

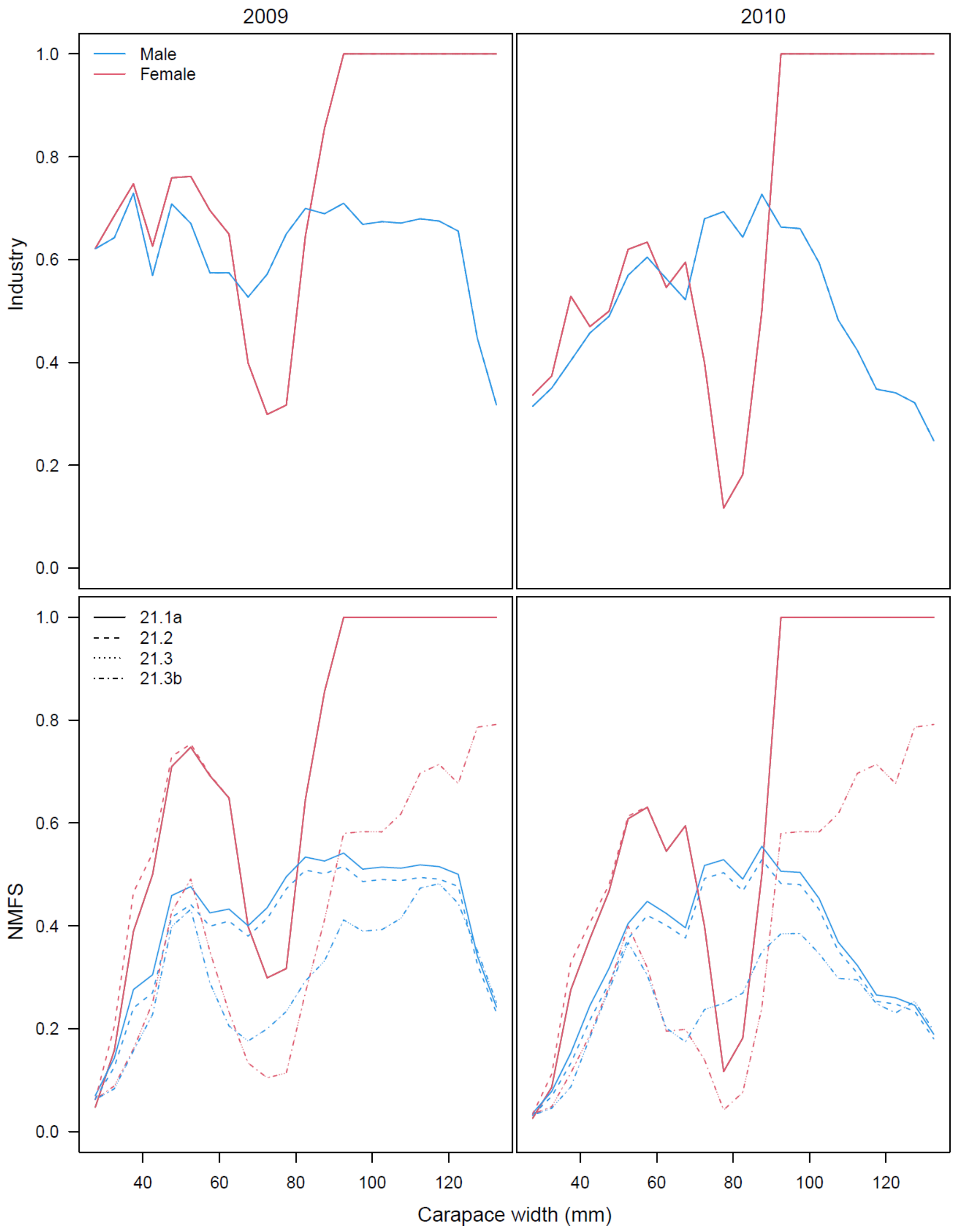




Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			
Fishing mortality			
Recruitment			
Natural mortality			
Status			

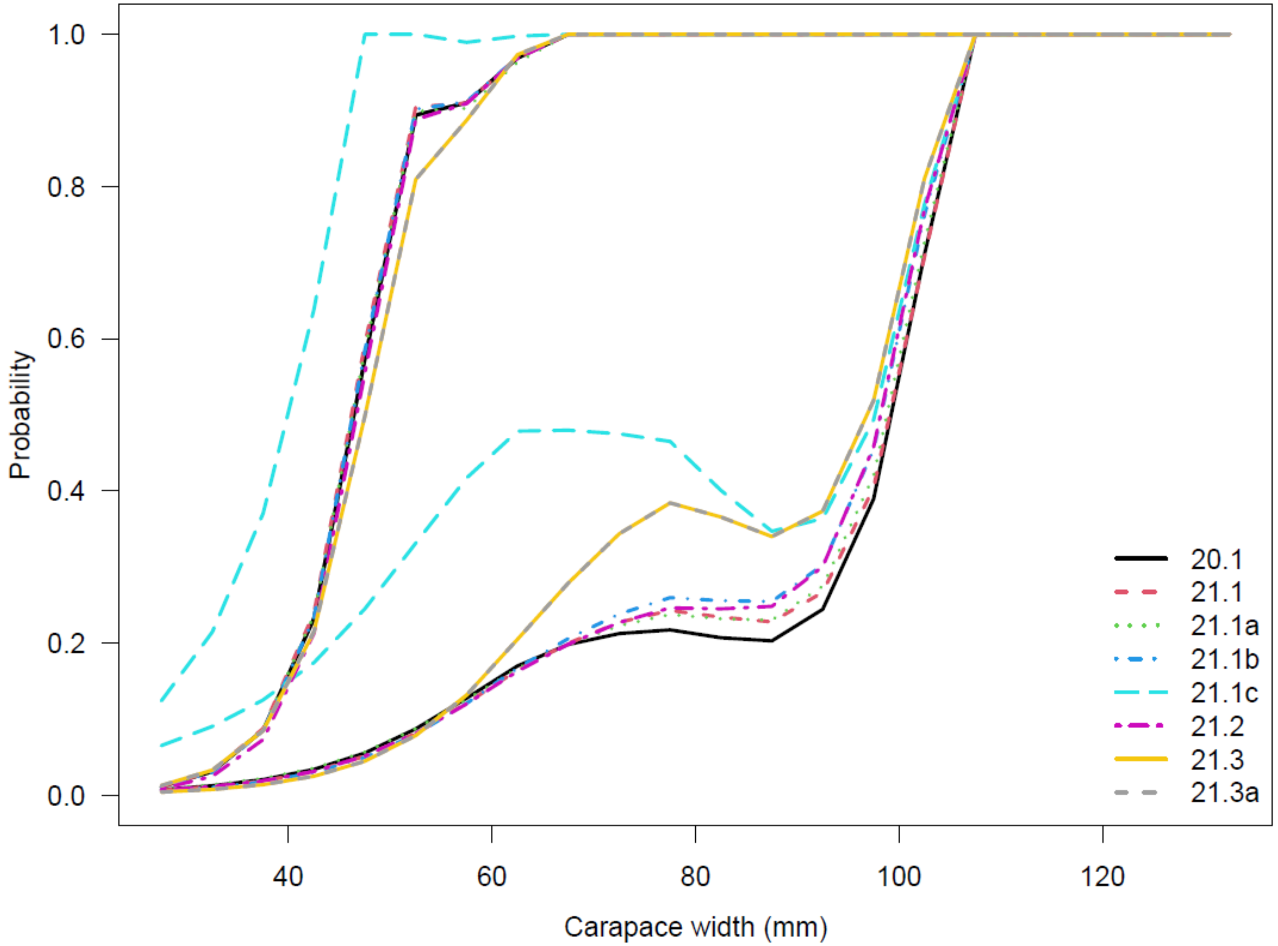
- Size-comp reweighting gives fits similar to the logistic curve estimated in Somerton and Otto (1998)
- Free selectivity ‘wants’ higher selection around 50 mm carapace width than in the BSFRF data
- Remarkably consistent pattern in experimental data

Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment			
Natural mortality			
Status			

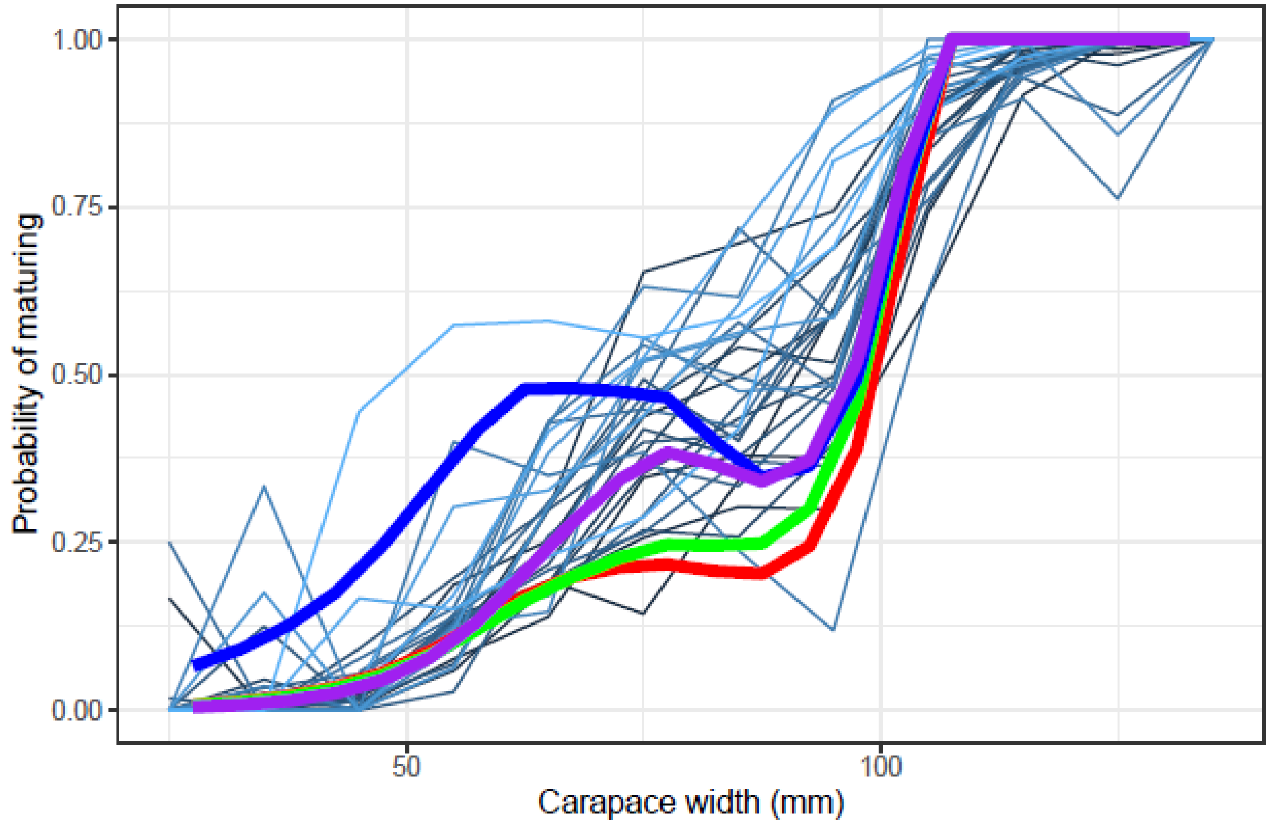
Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment			
Natural mortality			
Status			

- Reweighting the size composition data produced much higher probabilities of terminal molt than all other models.

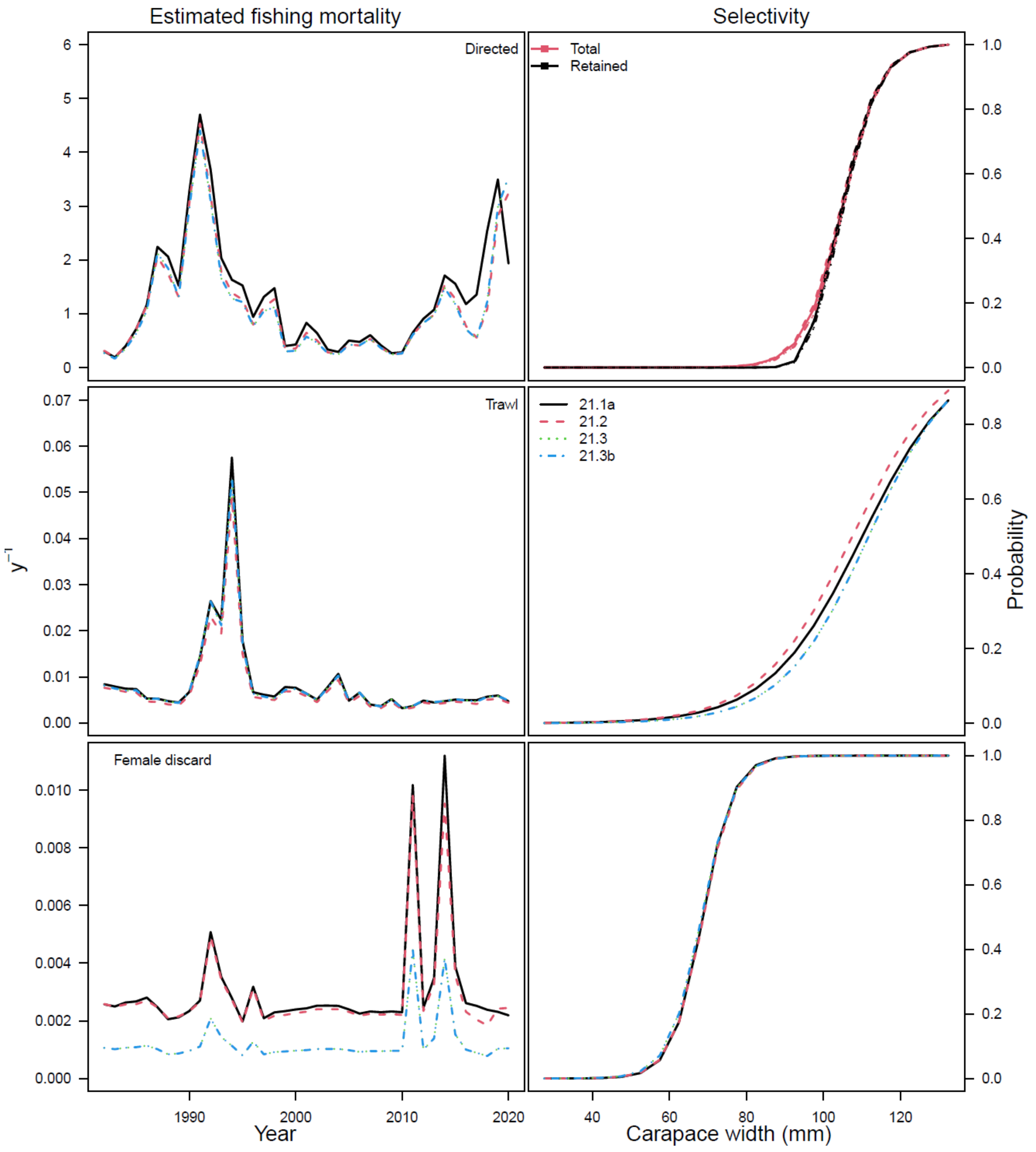
Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment			
Natural mortality			
Status			

- Bold blue is size composition reweighting
- Purple is 21.3; green is 21.2, red is 21.1

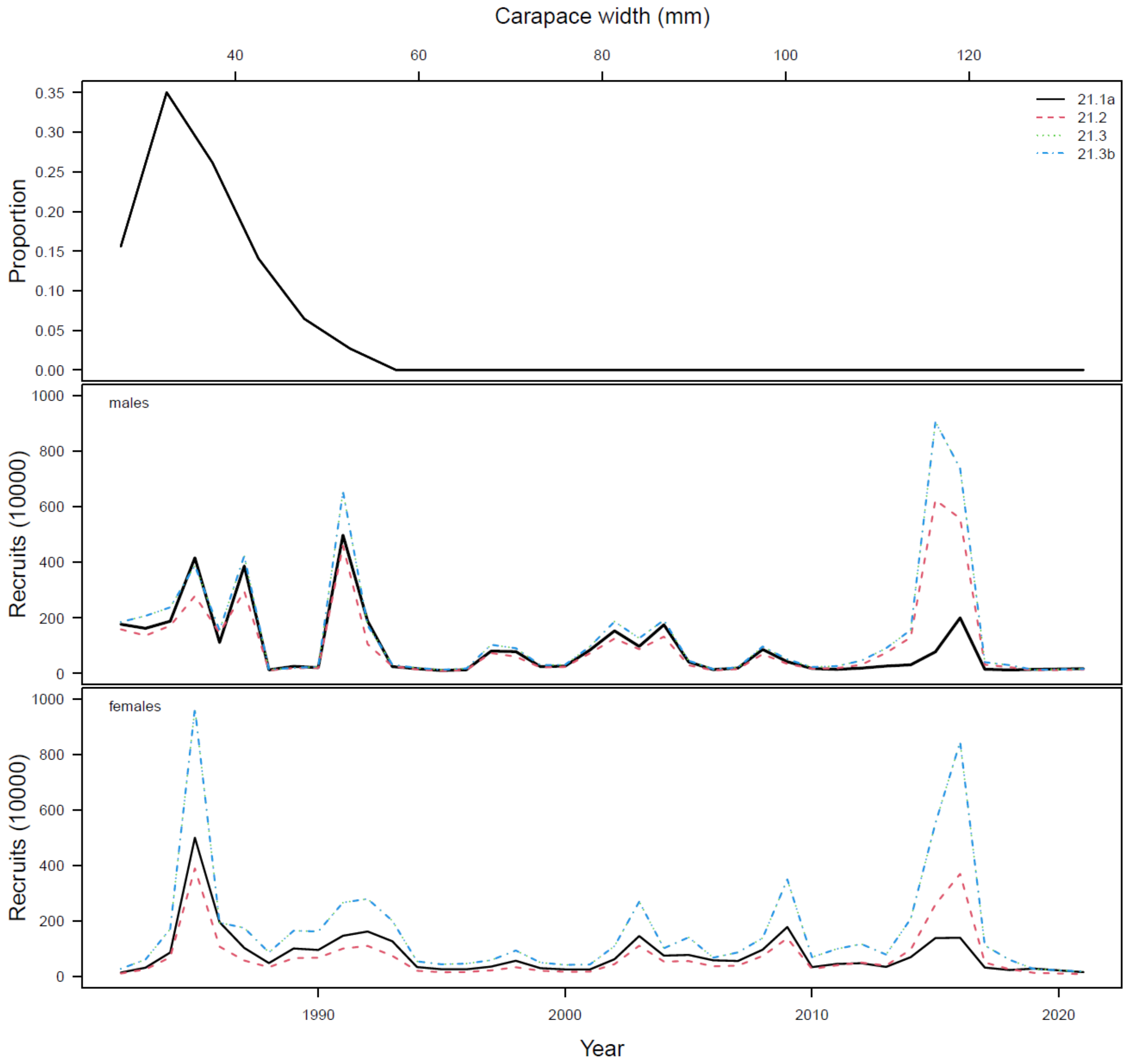
Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment			
Natural mortality			
Status			

- Considerable jumps in estimated F in recent years with the updated data

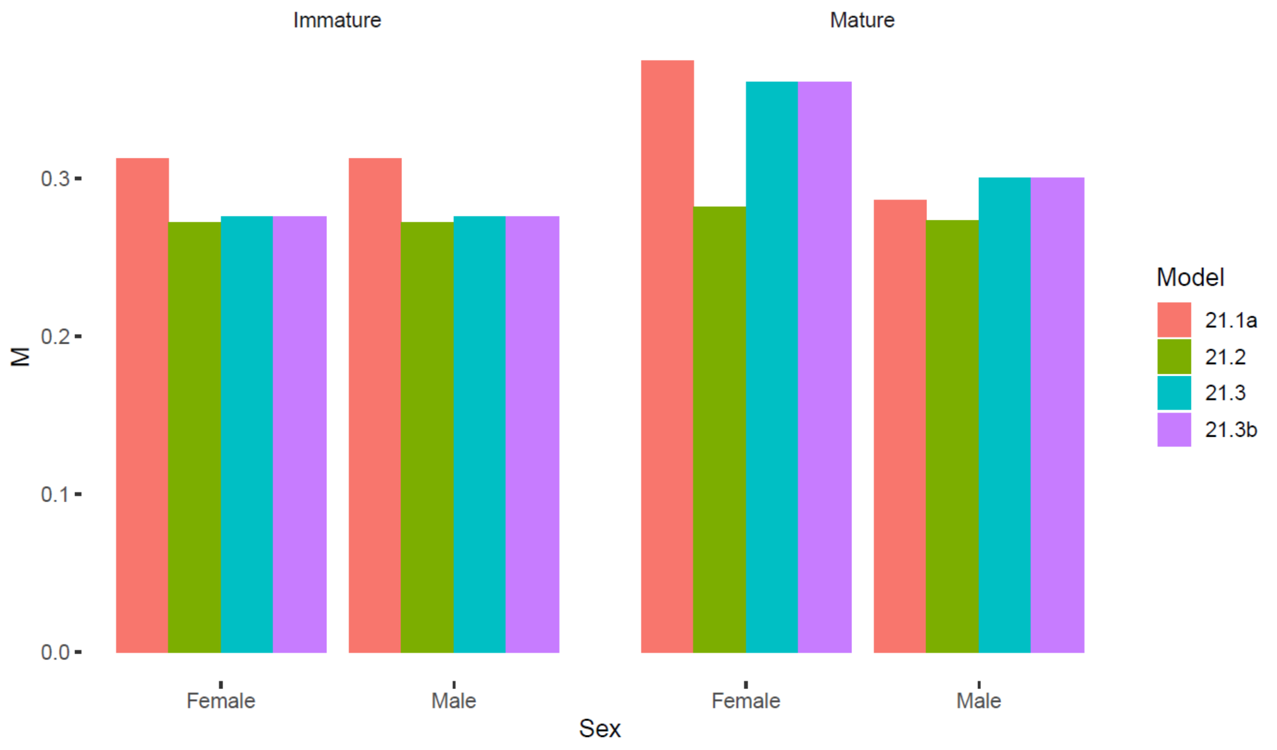
Estimated population processes



Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment		~	~
Natural mortality			
Status			

- Model 21.2 and 21.3 were able to estimate the large recruitment pulse in 2015, 21.1a was not

Estimated population processes



Model	Immature males		Immature females		Mature males		Mature females	
	'18	'19	'18	'19	'18	'19	'18	'19
21.2	0.45	1.69	4	4	1.14	1.87	0.31	0.65
21.3	0.35	1.85	4	4	1.22	1.96	0.25	0.63

Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment		~	~
Natural mortality		~	~
Status			

M	0.5	1.0	1.5	2.0	4
Survival	60%	36%	22%	13%	2%

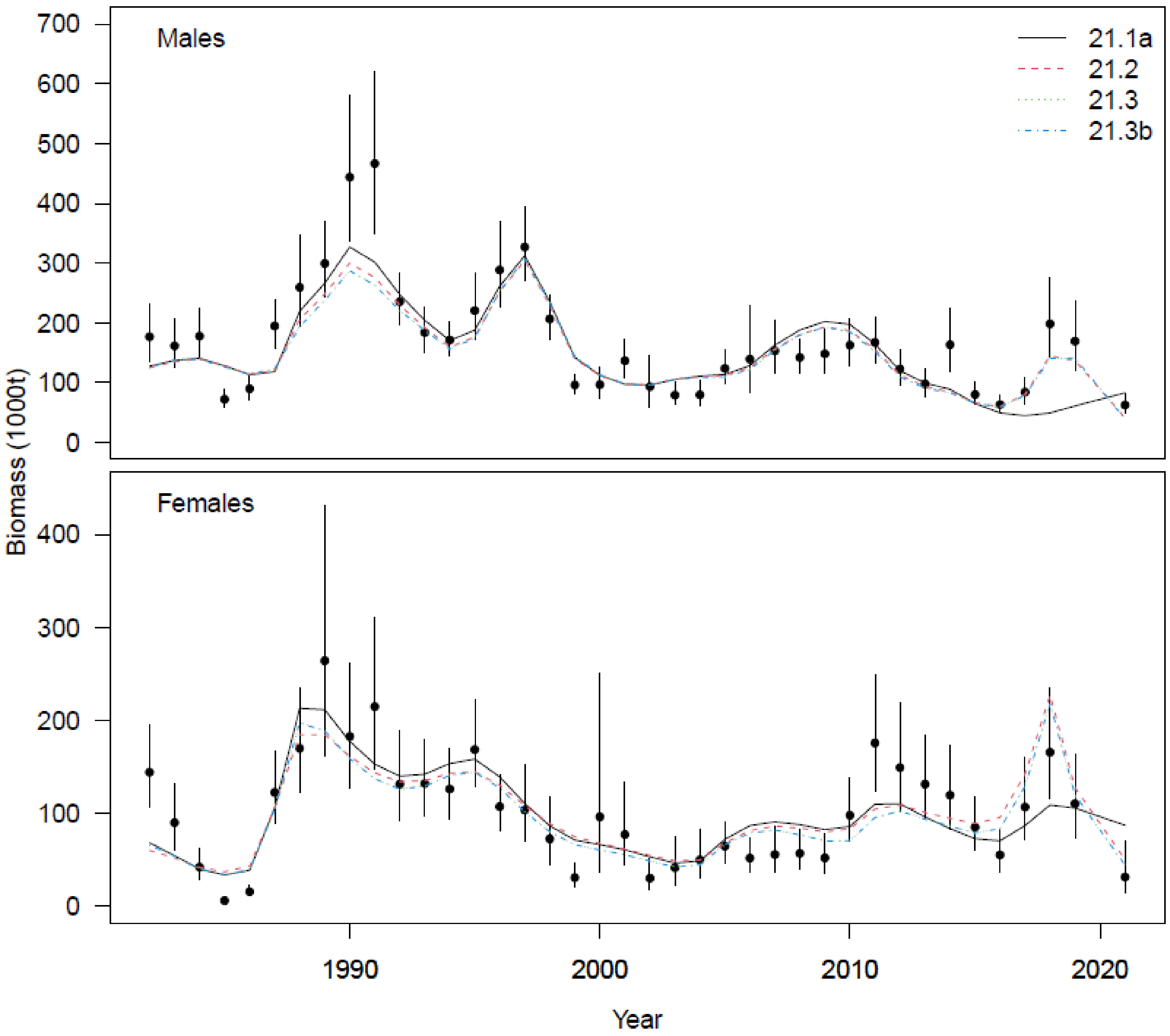
Model selection

Population process	21.1a	21.2	21.3
Mature male biomass			
Survey selectivity			~
Probability of maturing			~
Fishing mortality			
Recruitment		~	~
Natural mortality		~	~
Status			

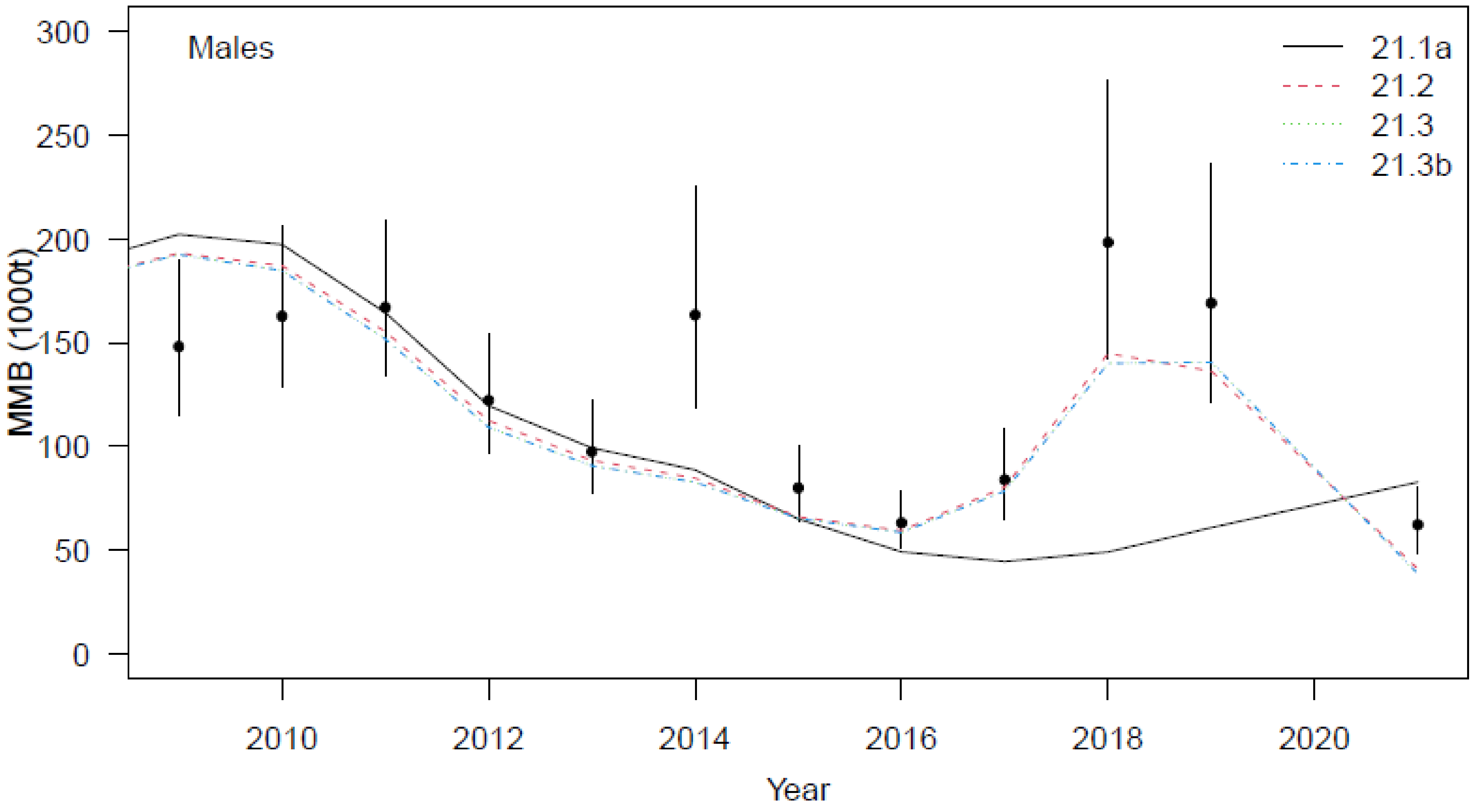
Data source	21.1a	21.2	21.3
Survey biomass		X	X
Growth	~	~	~
Catch	~	~	~
Retained size comp	~	~	~
Total size comp	~	~	~
Bycatch size comp	~	~	~
BSFRF size comp	~		
Survey size comp (imm M)			
Survey size comp (imm F)			~
Survey size comp (mat M)			
Survey size comp (mat F)			~

In terms of fits to data and population processes, model 21.3 is a clear winner in my opinion.

	Model 21.1a		Model 21.2		Model 21.3	
	Pro	Con	Pro	Con	Pro	Con
Fits to survey MMB		Does not fit last years	Fits terminal years		Fits terminal years	
Estimates of >101mm males		>triple observed				
Probability of terminally molting		Does not reproduce observed		Does not reproduce observed	Closer to observed	
Survey selectivity		Does not reproduce observed		Does not reproduce observed	Closer to observed	
Reference points	Target exploitation rates <100%		Target exploitation rates <100%			Target exploitation rates ~100%
Survey size comp fit					~90 likelihood units better	
Retrospective patterns		Double the other models				



- If the model is not allowed to reach to the 2018 2019 data points and decline via mortality event, it will 'split the difference' between 2021 and 2018-2019 to some degree.
- This model mis-specification will pull up the estimate of the final year of MMB, which would result in an overly optimistic estimate of exploitable biomass (and giant retrospective patterns).



Males
21.1a
21.2
21.3
21.3b
MMB (1000t)
300
250
200
150
100
50
0
2010
2012
2014
2016
2018
2020
Year

	Model 21.1a		Model 21.2		Model 21.3	
	Pro	**Con**	**Pro**	**Con**	**Pro**	**Con**
Fits to survey MMB		Does not fit last years	Fits terminal years		Fits terminal years	
Estimates of >101mm males		>triple observed				
Probability of terminally molting		Does not reproduce observed		Does not reproduce observed	Closer to observed	
Survey selectivity		Does not reproduce observed		Does not reproduce observed	Closer to observed	
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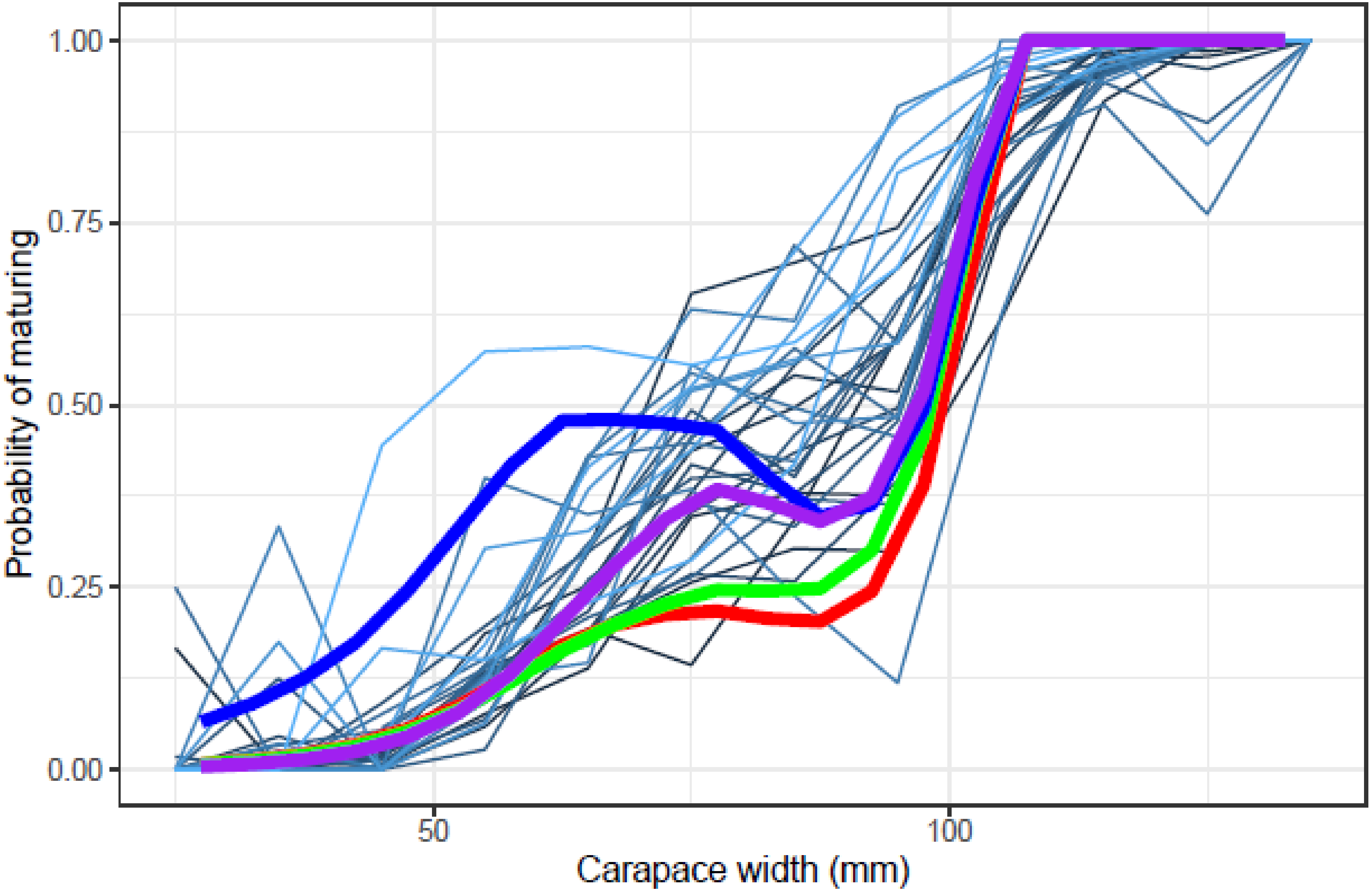
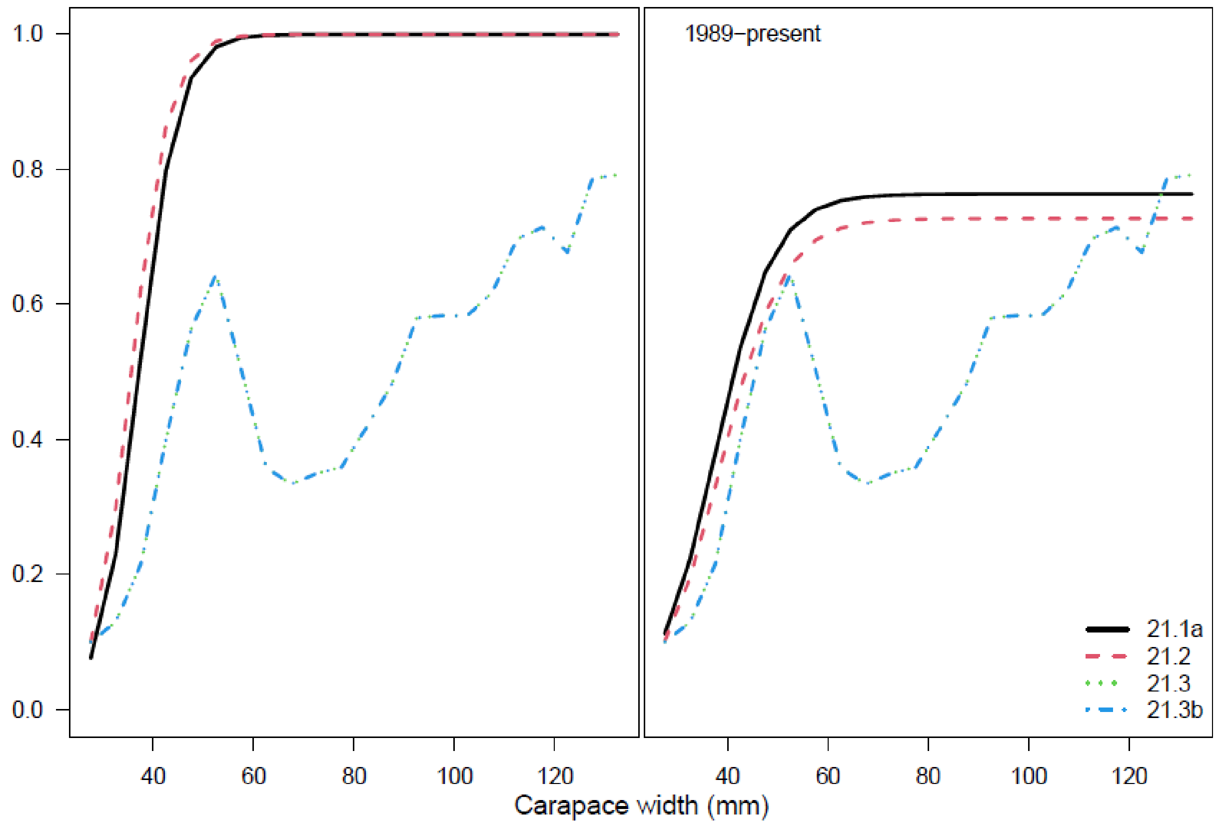
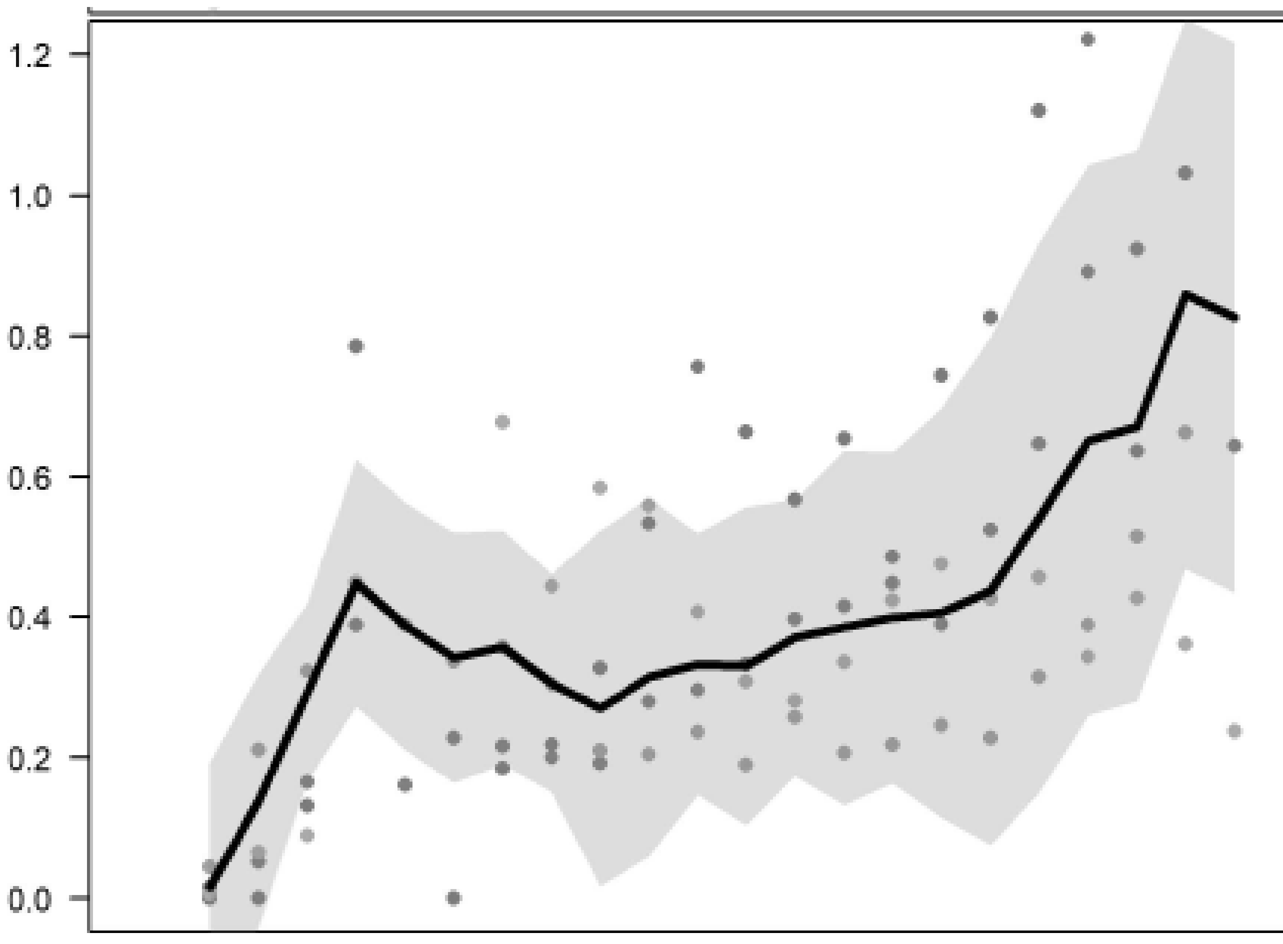
Retrospective patterns		Double the other models				



Probability of maturing
1.00
0.75
0.50
0.25
0.00
50
100
Carapace width (mm)


1.0
0.8
0.6
0.4
0.2
0.0
1989–present
21.1a
21.2
21.3
21.3b
40
60
80
100
120
Carapace width (mm)


1.2
1.0
0.8
0.6
0.4
0.2
0.0

	Model 21.1a		Model 21.2		Model 21.3	
	Pro	**Con**	**Pro**	**Con**	**Pro**	**Con**
Fits to survey MMB		Does not fit last years	Fits terminal years		Fits terminal years	
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Reference points	Target exploitation rates <100%		Target exploitation rates <100%			Target exploitation rates ~100%
Survey size comp fit					~90 likelihood units better	
Retrospective patterns		Double the other models				

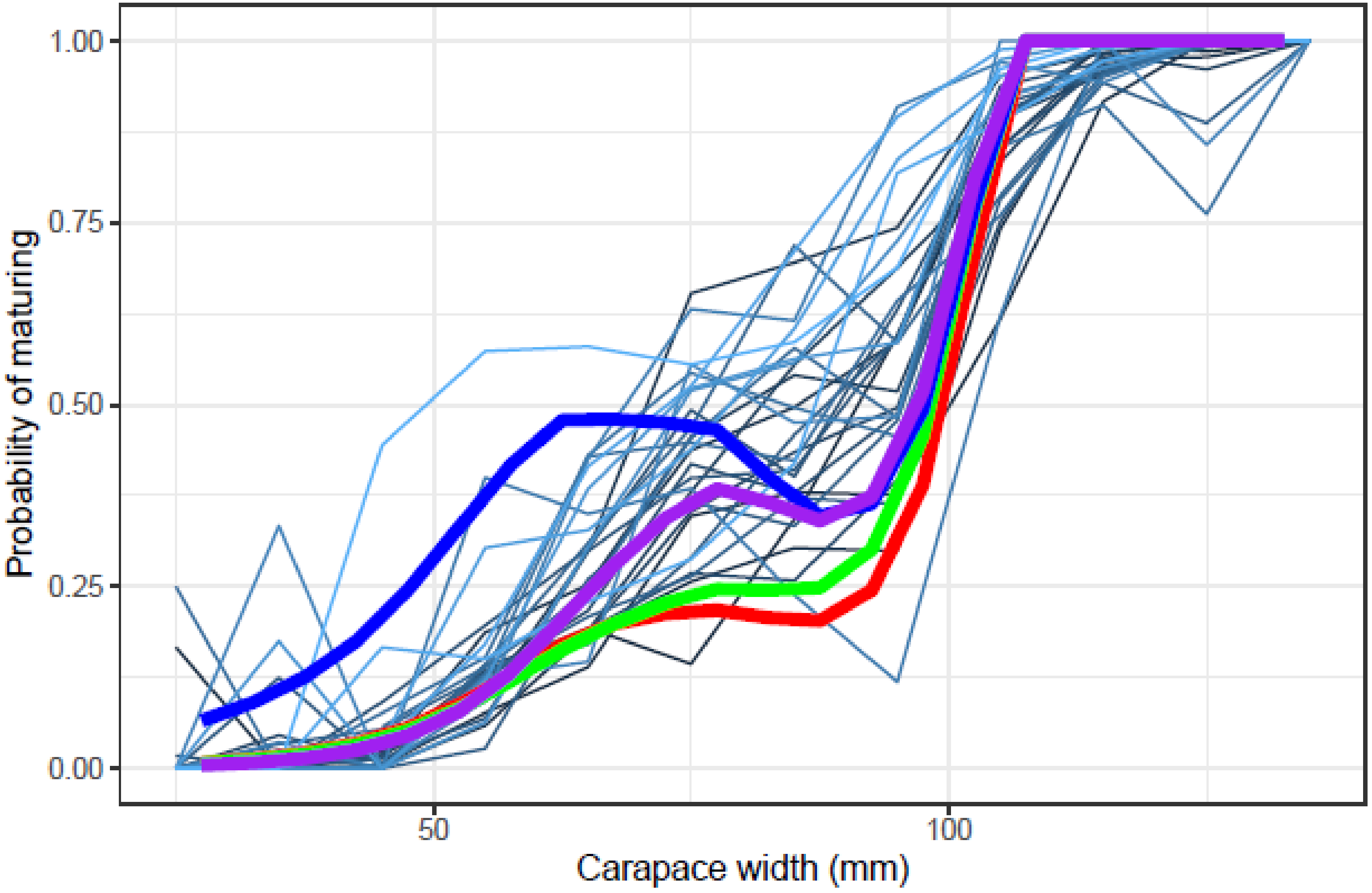
Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
20.1	133.51	121.47	1.23	1.23	88.90	0.29	103.91	1.10
21.1	58.55	101.73	1.46	1.06	27.55	0.28	91.44	0.58
21.1a	69.93	106.87	1.79	1.40	35.70	0.29	92.51	0.65
21.1b	24.63	137.98	1.43	0.38	7.82	0.29	119.43	0.18
21.1c	171.58	183.36	165.67	105.22	51.92	0.27	158.00	0.94
21.2	26.74	153.42	1.43	0.37	7.50	0.27	106.14	0.17
21.3	41.82	173.36	4.76	1.15	17.03	0.30	146.83	0.24
21.3a	41.82	173.36	0.30	0.10	2.27	0.30	146.83	0.24

Target fishing mortality (F35) of 4.76 translates to an exploitation rate of 99.2%

(F35 = 1.43 is 76%)

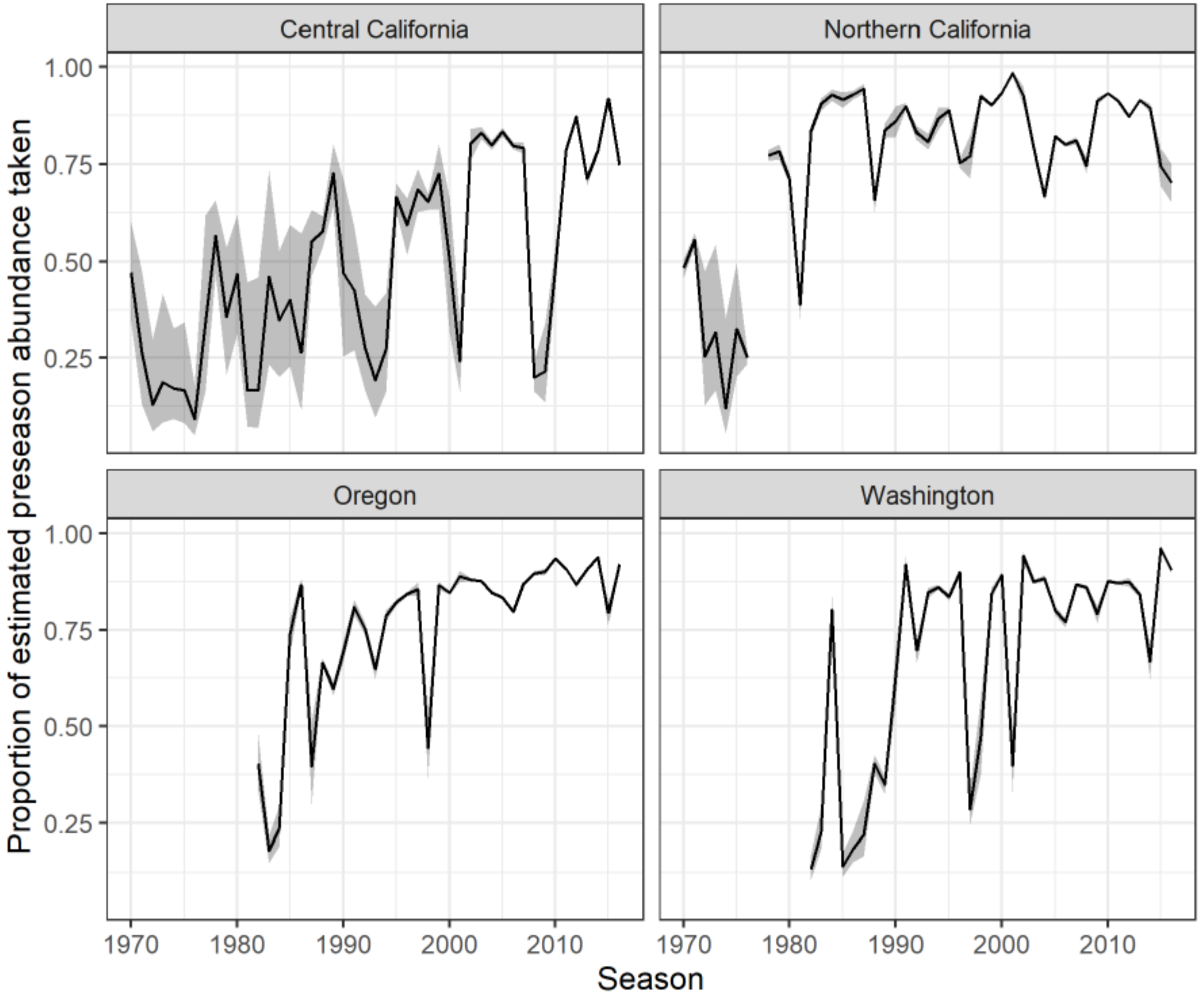
This means that almost all males >101mm could be harvested in a given year.

Morphometric maturity as currency of management



Maybe a high F35% is appropriate?

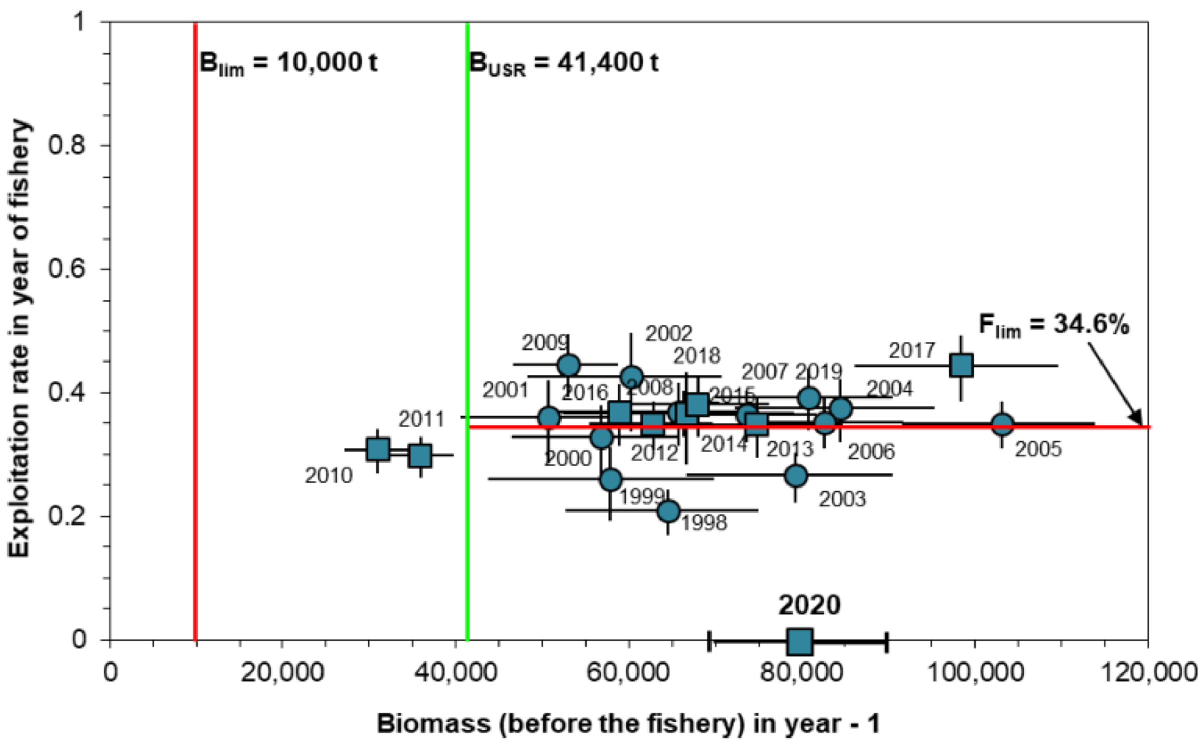
- Dungeness crab seem to do ok with high Fs, given size limits and seasons are appropriate (Richardson, 2020)
- Laboratory studies show small males can fertilize females (e.g. Watson, 1972 in which a 61 mm male successfully mated with a female that molted from 64 mm to 74 mm).



Richerson, K. et al. 2020. Nearly half a century of high but sustainable exploitation in the Dungeness crab fishery.

Maybe F35% isn't appropriate?

- Other productive snow crab fisheries have lower Fs (see Gulf of St Lawrence →)
- Functional maturity in situ appears to be >95mm carapace width (Conan and Comeau, 1986; Ennis et al., 1988)



	Model 21.1a		Model 21.2		Model 21.3	
	Pro	**Con**	**Pro**	**Con**	**Pro**	**Con**
Fits to survey MMB		Does not fit last years	Fits terminal years		Fits terminal years	
Estimates of >101mm males		>triple observed				
Probability of terminally molting		Does not reproduce observed		Does not reproduce observed	Closer to observed	
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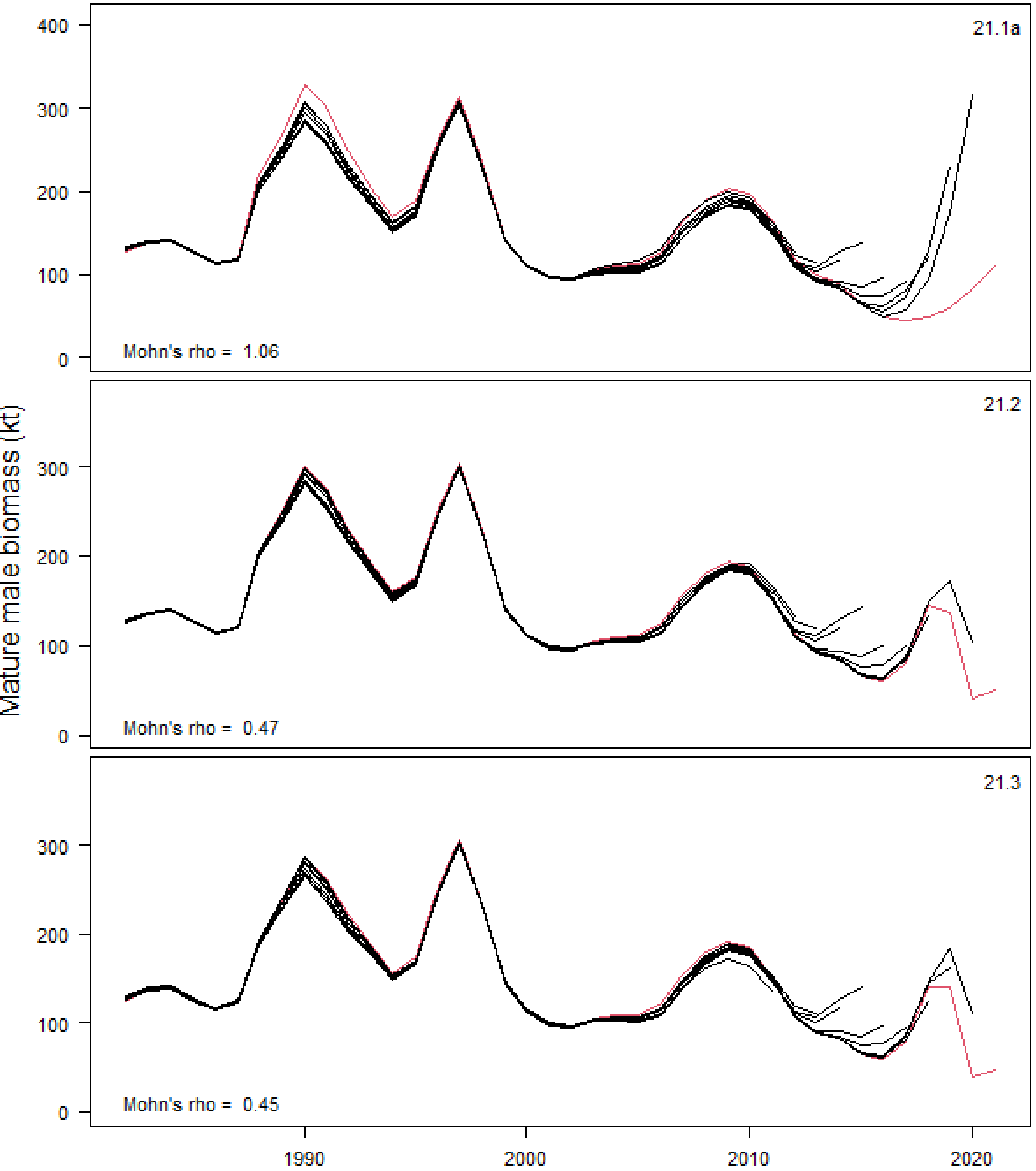
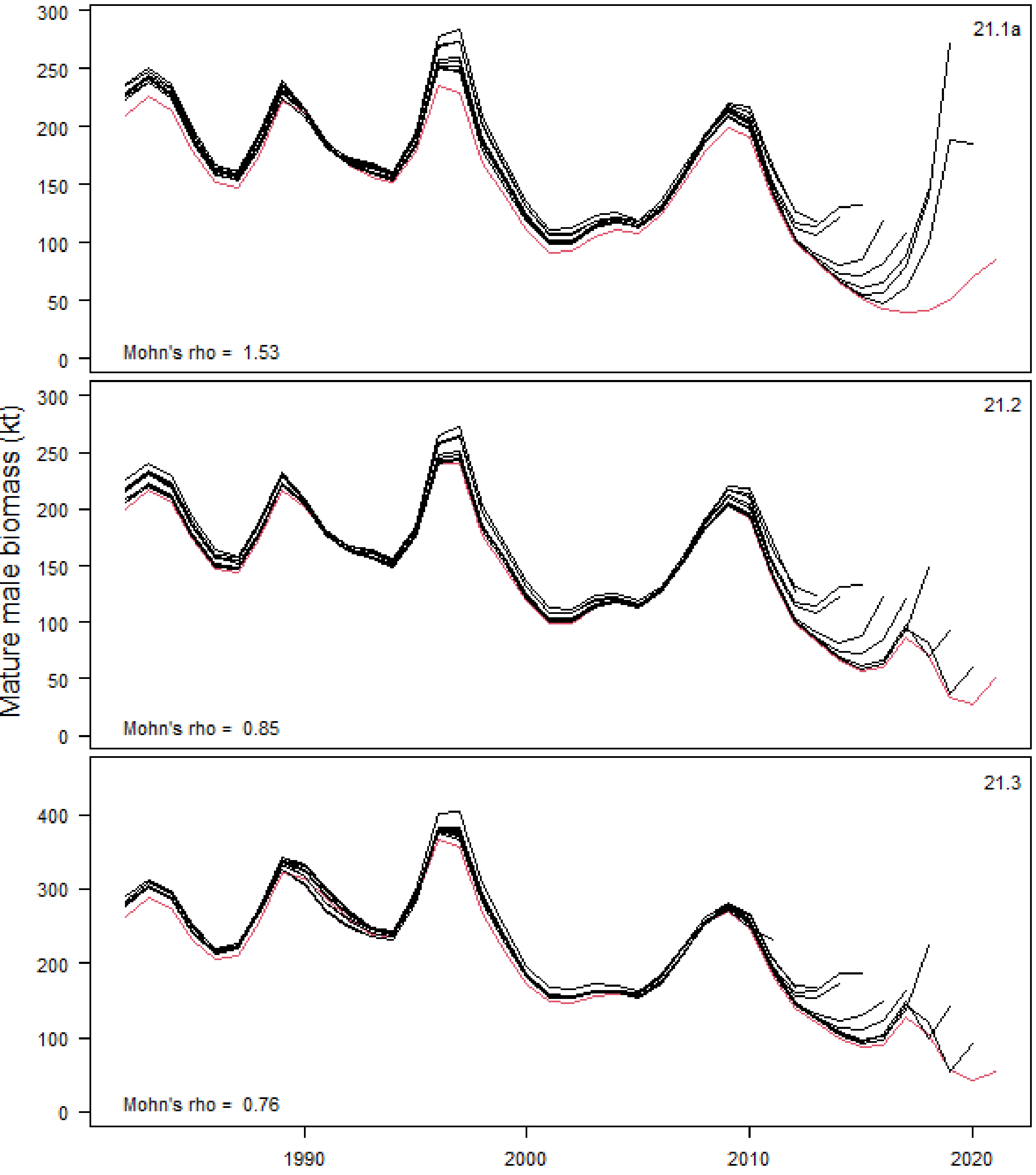
Reference points	Target exploitation rates <100%		Target exploitation rates <100%			Target exploitation rates ~100%
Survey size comp fit					~90 likelihood units better	
Retrospective patterns		Double the other models				



Mature male biomass at the time of survey

Model	Mohn's rho
21.1a	1.06
21.2	0.47
21.3	0.45



Mature male biomass at the time of mating

Model	Mohn's rho
21.1a	1.53
21.2	0.85
21.3	0.76

	Model 21.1a		Model 21.2		Model 21.3	
	Pro	**Con**	**Pro**	**Con**	**Pro**	**Con**
Fits to survey MMB		Does not fit last years	Fits terminal years		Fits terminal years	
Estimates of >101mm males		>triple observed				
Probability of terminally molting		Does not reproduce observed		Does not reproduce observed	Closer to observed	
Survey selectivity		Does not reproduce observed		Does not reproduce observed	Closer to observed	
Reference points	Target exploitation rates <100%		Target exploitation rates <100%			Target exploitation rates ~100%
Survey size comp fit					~90 likelihood units better	
Retrospective patterns		Double the other models				

Model	MMB	B35	F35	FOFL	OFL	M	avg_rec	Status
21.1a	69.93	106.87	1.79	1.40	35.70	0.29	92.51	0.65
21.2	26.74	153.42	1.43	0.37	7.50	0.27	106.14	0.17
21.2a	26.74	153.42	0.27	0.08	1.96	0.27	106.14	0.17
21.3	41.82	173.36	4.76	1.15	17.03	0.30	146.83	0.24
21.3a	41.82	173.36	0.30	0.10	2.27	0.30	146.83	0.24

Model 21.2a and 21.3a substitute estimated M for the FMSY proxy, similar to tier 4 stocks, but use the population dynamics model from the status quo model to estimate MMB and status.

21.3b	**32.42**	**105.01**	**0.63**	**0.146**	**3.14**	**0.30**	**146.83**	**0.30**

Model 21.3b used >95 mm carapace width as the definition of 'maturity' in reference point calculations instead of morphometric maturity.

A model similar to 21.3 should be the goal, but given the knock-on effects, the methodology should be considered further before adoption.

The CPT preferred model 21.2.

If model 21.2 is adopted, the stock is overfished.