Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation

Presentation to the ASMFC Horseshoe Crab Management Board

January 26, 2022

Management History

- 1998 – Fisheries Management Plan approved
- 2007 – Effort began to develop a multi-species management approach
- 2009 – Original version of the Adaptive Resource Management (ARM) Framework was peer-reviewed
- 2012 – Addendum VII approved and the ARM instituted for the DE Bay states.
- 2013 – Coast wide stock assessment update
- 2019 – Coast wide benchmark stock assessment and beginning of an ARM Revision.

Original ARM Framework

Problem Statement:

Manage harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also maintain ecosystem integrity and provide adequate stopover habitat for migrating shorebirds.

Original ARM Framework

- Three possible red knot population dynamics models with differing model weights
  - No effect of HSC
  - HSC affects red knot fecundity
  - HSC affects red knot survival and fecundity
- Horseshoe crab model based largely on literature values
  - Theoretical age-structured model (Sweka et al. 2007) converted to a stage-structured model

Original ARM Framework

Selection of 5 possible optimal harvest packages depending on abundance of horseshoe crabs and red knots

Package	Males	Females
1	0	0
2	250,000	0
3	**500,000**	**0**
4	280,000	140,000
5	420,000	210,000

Why should we revise the ARM?

- It's time!
  - Address critiques from the original peer-review
  - Decade more of data for both species
  - Previously used software (ASDP) is obsolete
  - Evolution of modeling techniques and experience
  - Management Board request biomedical data

- Previous knife edge utility functions act as an "all or nothing" harvest control rule

Overview of Changes

Revised Problem Statement

Manage harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also to maintain ecosystem integrity, provide adequate stopover habitat for migrating shorebirds, and ensure that the abundance of horseshoe crabs is not limiting the red knot stopover population or slowing recovery.

Overview of Changes

- Revised HSC population dynamics model
- Revised red knot population dynamics model
- Revised reward function
- Abandonment of ASDP software
- Adoption of Approximate Dynamic Programing (ADP) for optimization
- Harvest recommendations on a continuous scale
- Easier model updating

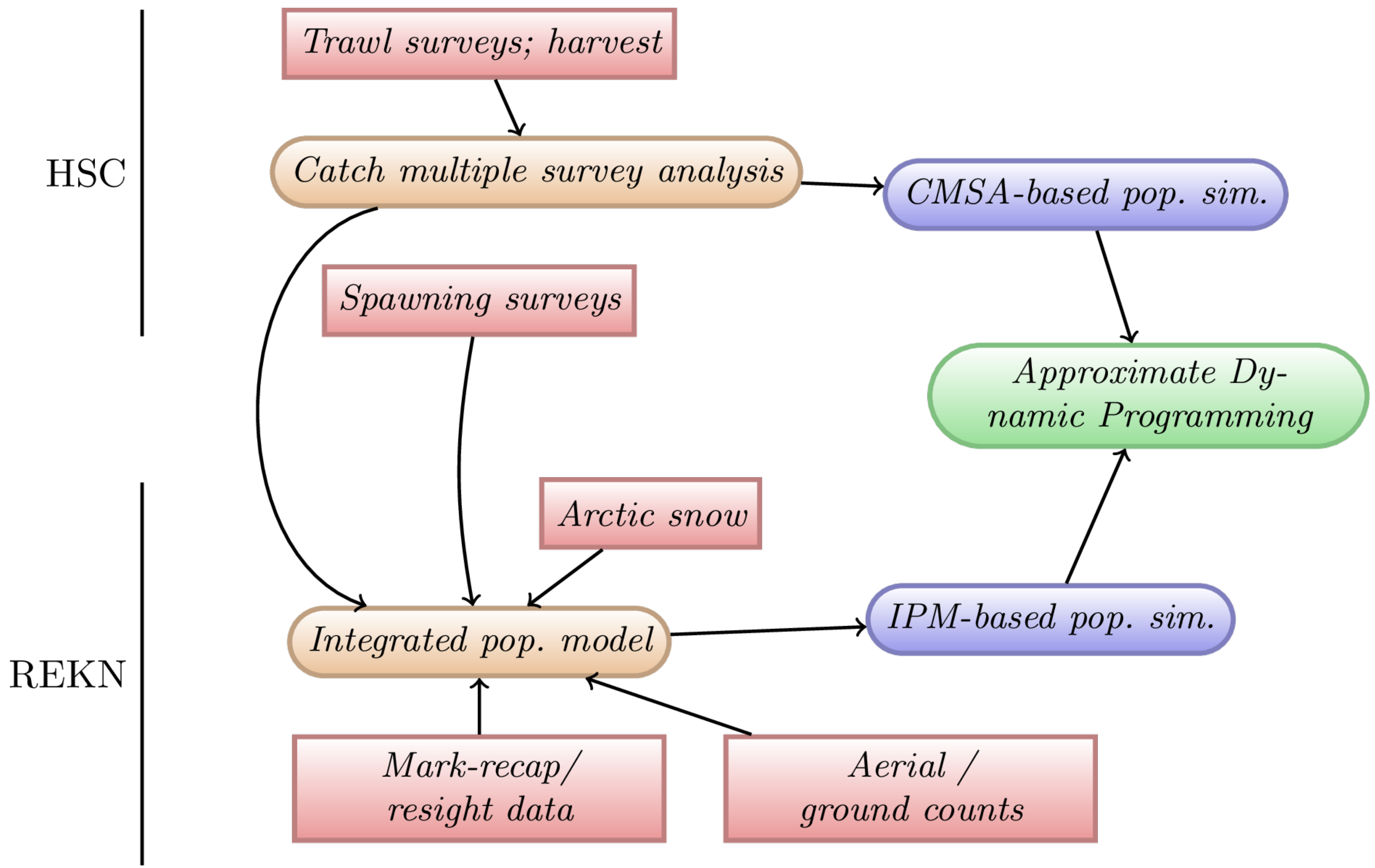
Overview of Changes

NOTE: The conceptual model of horseshoe crab abundance influencing red knot survival and reproduction remains intact with the intent of insuring that the abundance of horseshoe crabs does not become a factor limiting the population growth of red knots.

Delaware Bay Origin Crabs

- "Crabs that spawn at least once in DE Bay"
- Genetics data indicate crabs from Cape Cod to Cape Hatteras are related
- Tagging data indicate there is movement of crabs along the coast
- Recent genetic evidence (Hallerman et al. *in review*) was used to estimate the proportion of states' landings, discards, and biomedical harvest that were DE Bay origin.
- Updated values from previous assessments: DE = 1.0; NJ = 1.0, MD = 0.45, VA = 0.20

Revised ARM Conceptual Model



Catch Multiple Survey Analysis (CMSA)

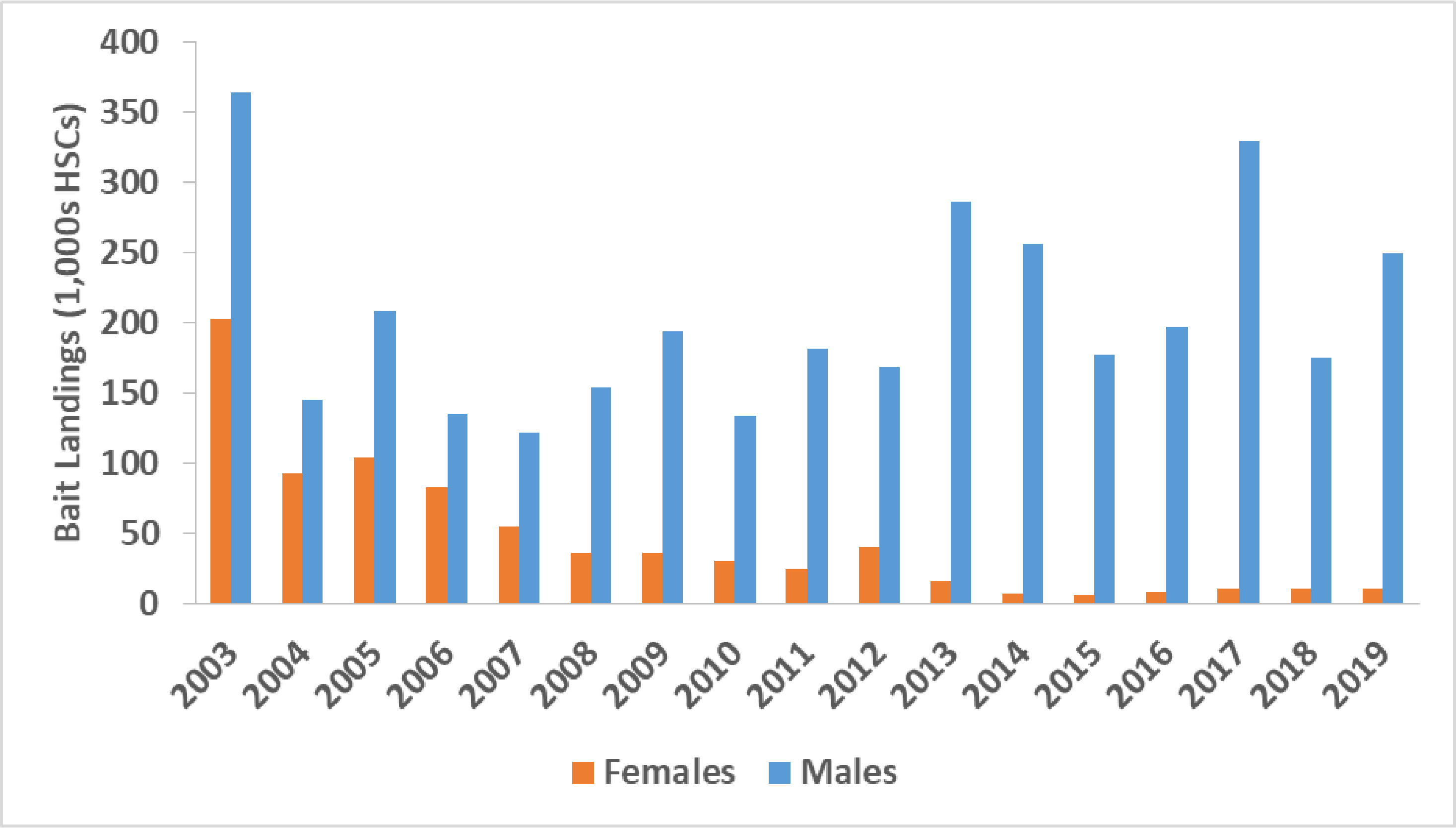
- Approved during the 2019 benchmark stock assessment for use as the best estimate of HSC abundance in the DE Bay area

$$N_{y+1} = \left(\left(N_y + R_y\right)e^{-Mt} - C_y\right)e^{-M(1-t)}$$

y = year
N = multiparous crabs
R = primiparous crabs
C = catch (bait + biomedical + dead discards)
M = natural mortality (0.30)
t = fraction of the year of harvest midpoint

CMSA: Catch (C)

DB-Origin Bait Landings



CMSA: Catch (C)

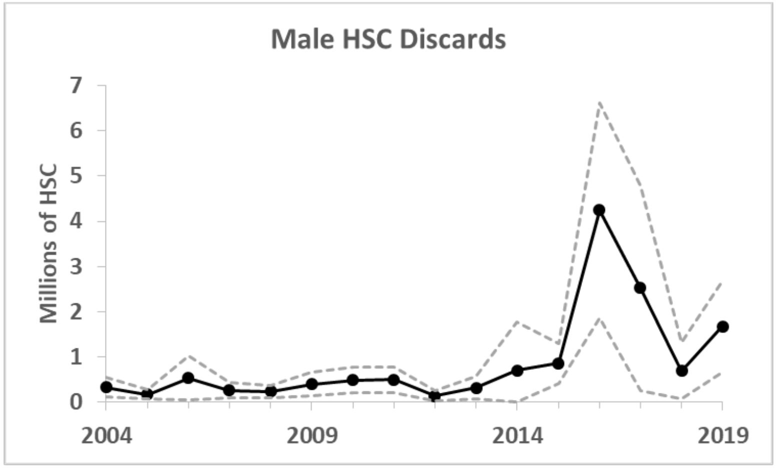
Biomedical Mortality

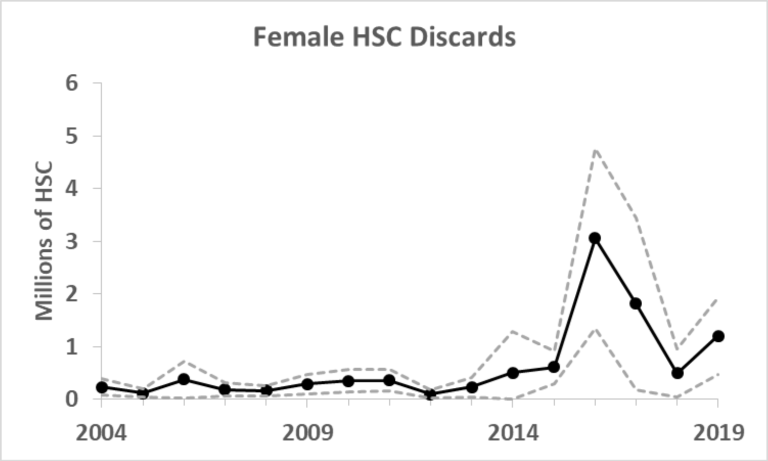
- Six facilities coastwide, four in DB
- Used coastwide estimates in this report
- DB-specific will be used when actually setting harvest recommendations

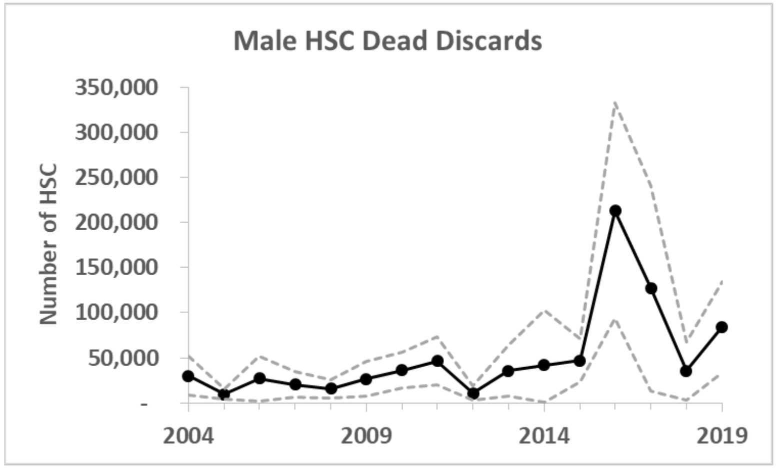
CMSA: Catch (C)

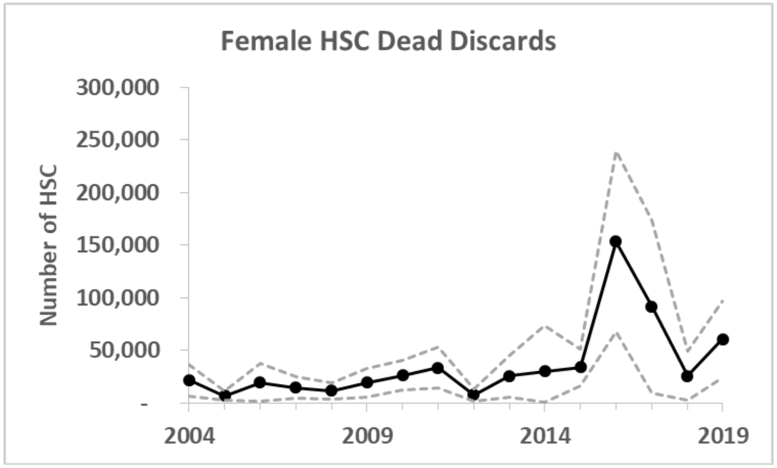
Dead discards

- NEFOP data
- Revised methods from 2019 benchmark assessment

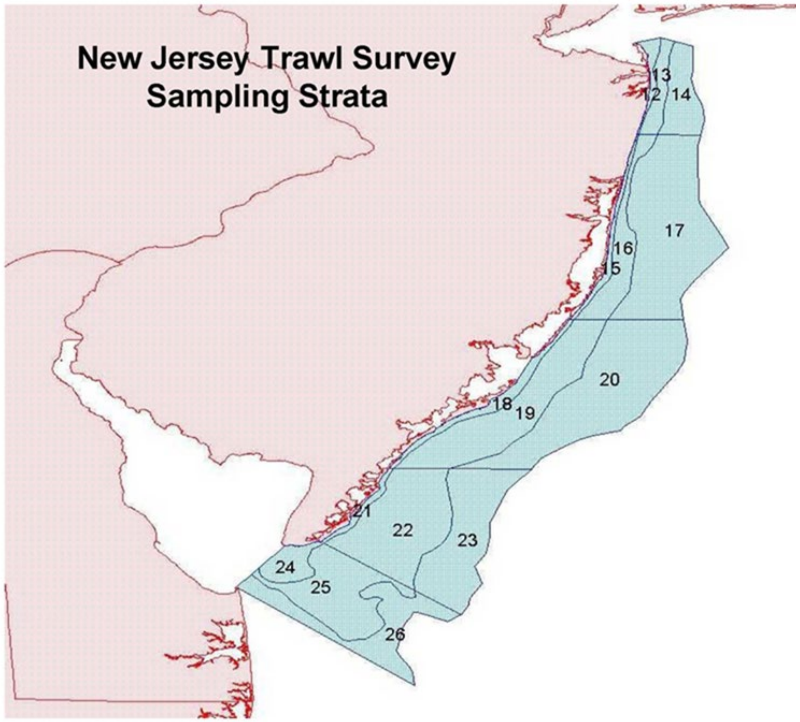


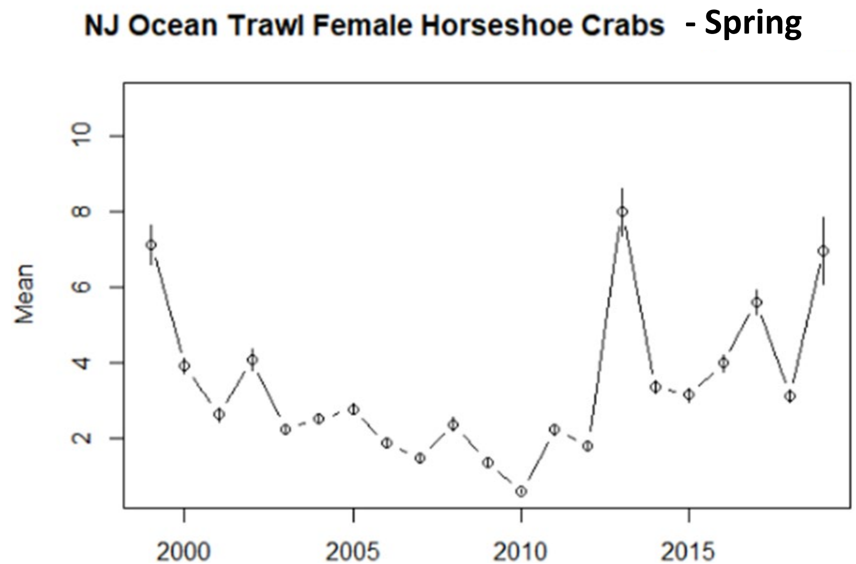


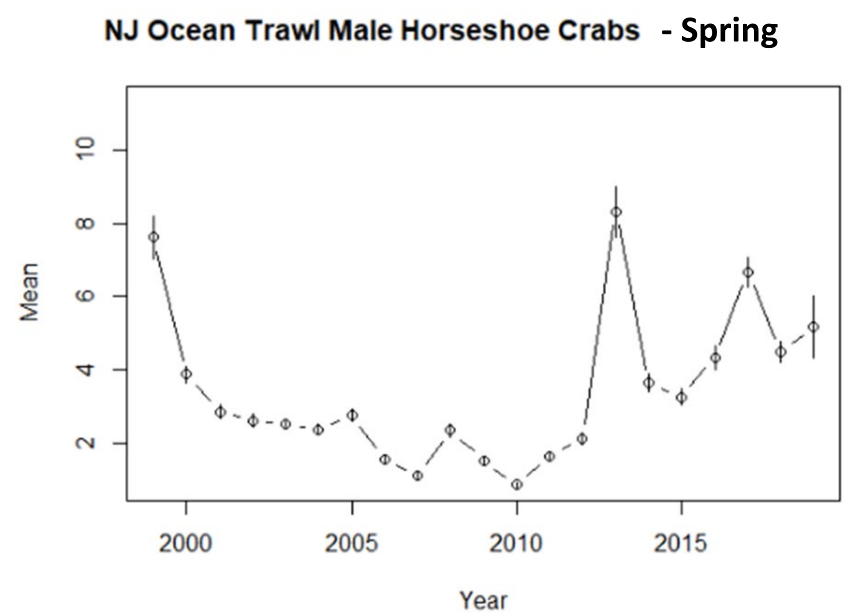




Fishery Independent Surveys







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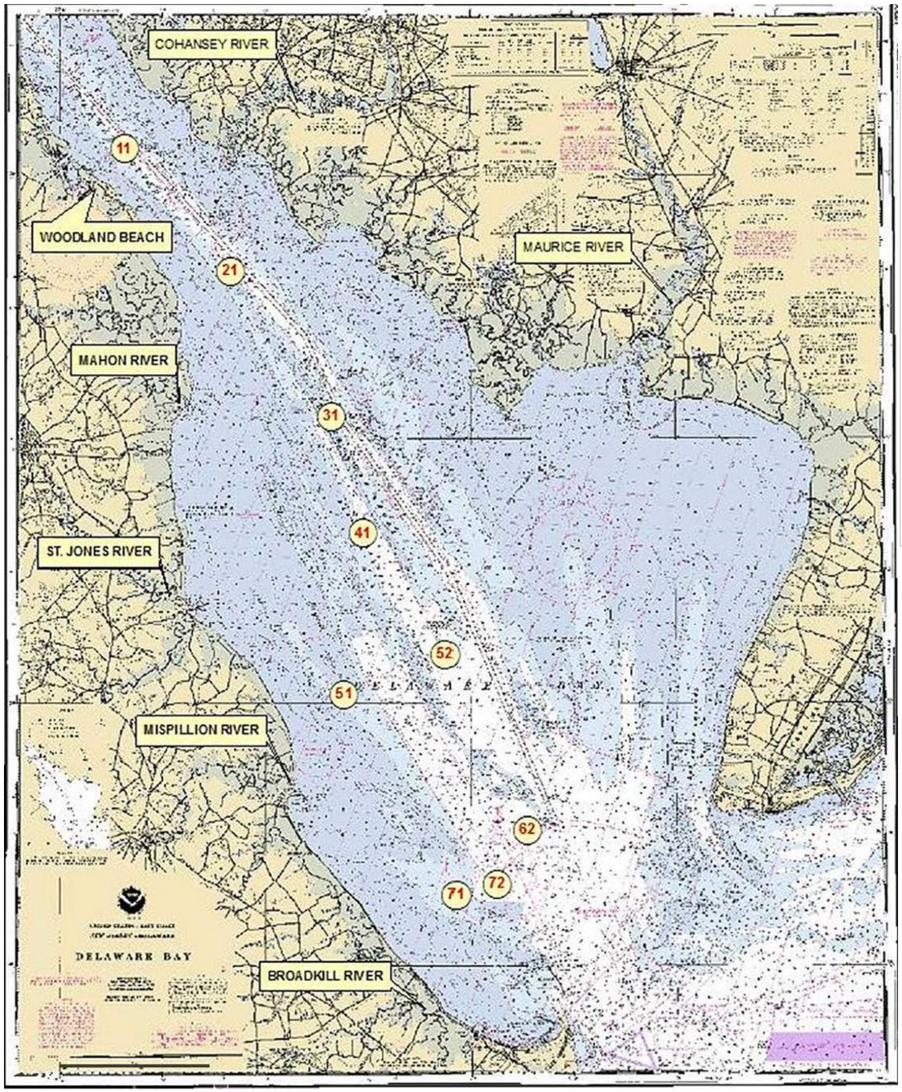
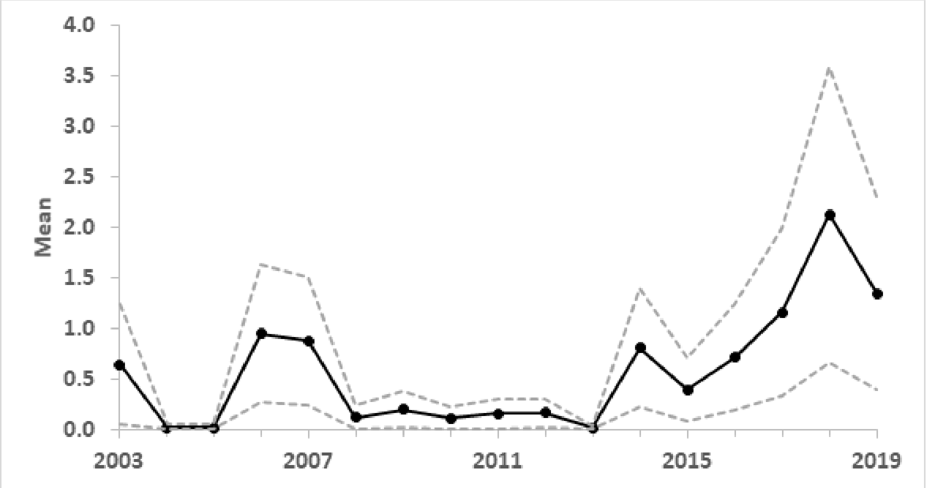
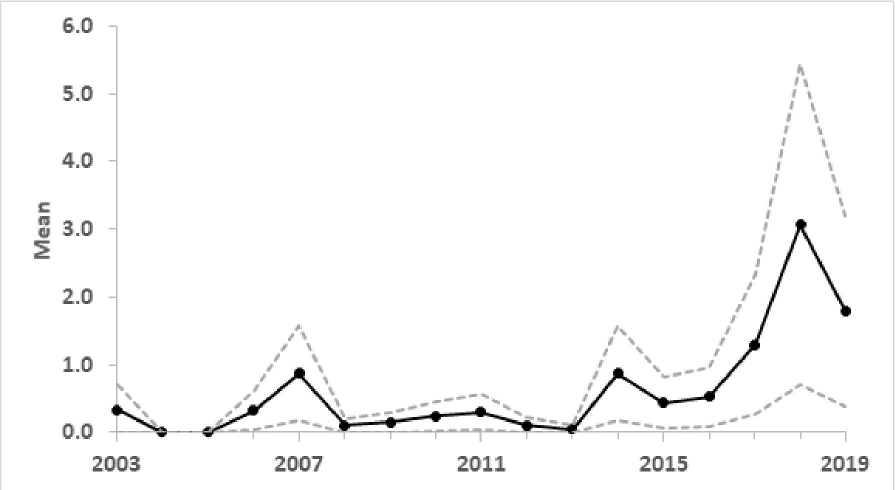


DE Adult Trawl Survey – Adult Females

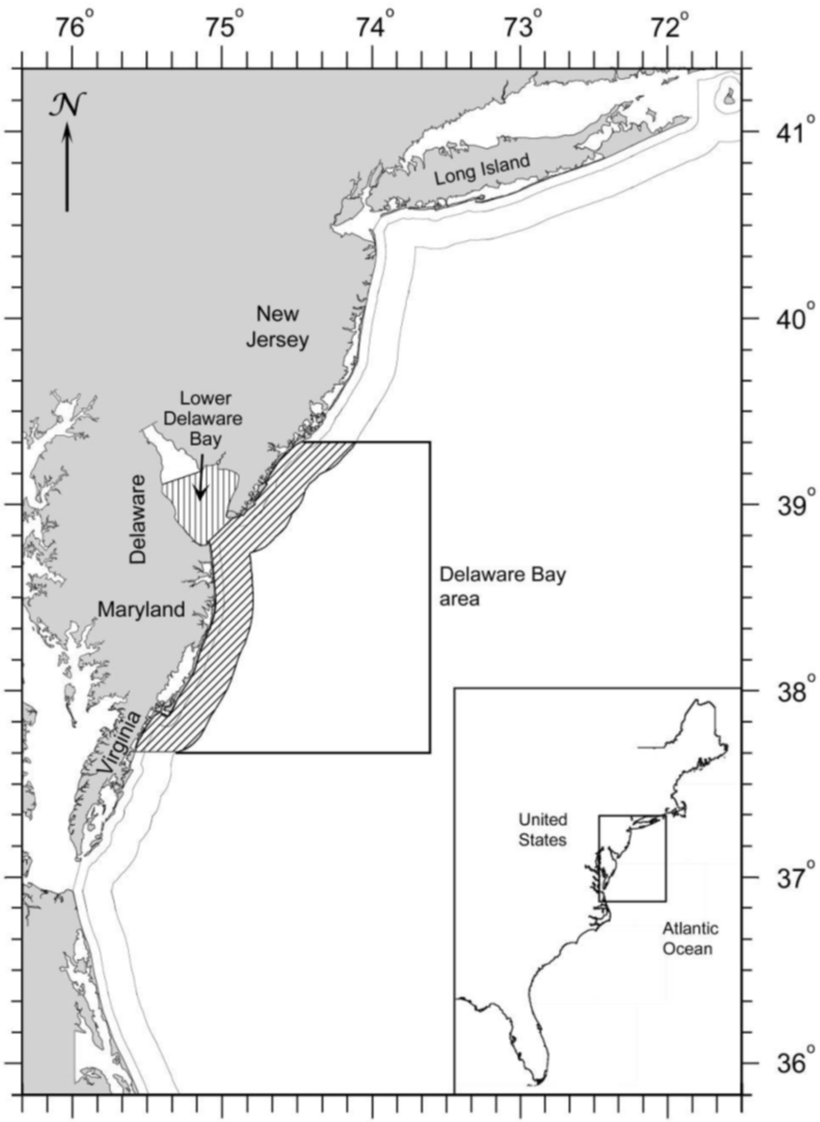


DE Adult Trawl Survey – Adult Males

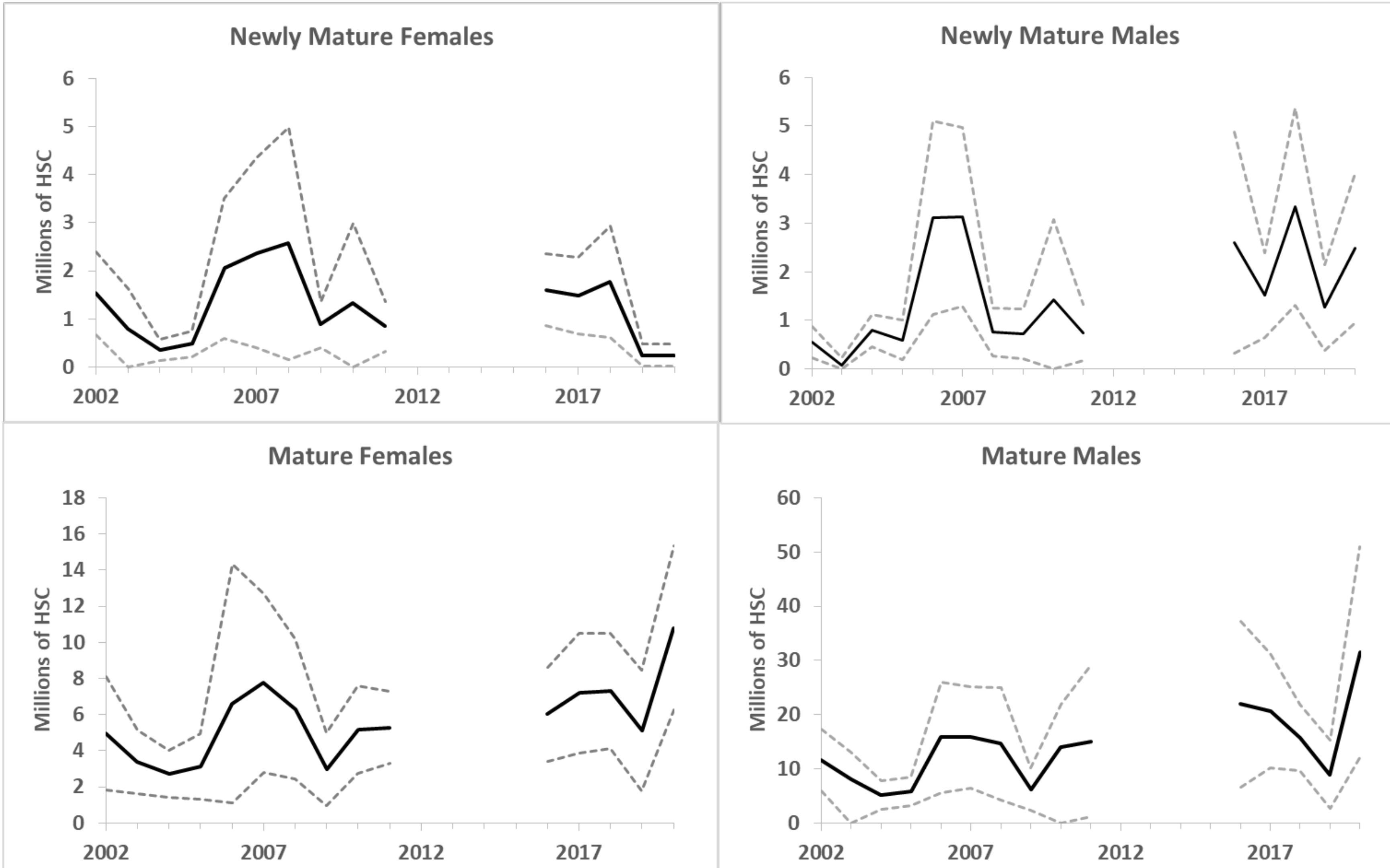


Fishery Independent Surveys

Virginia Tech Trawl Survey



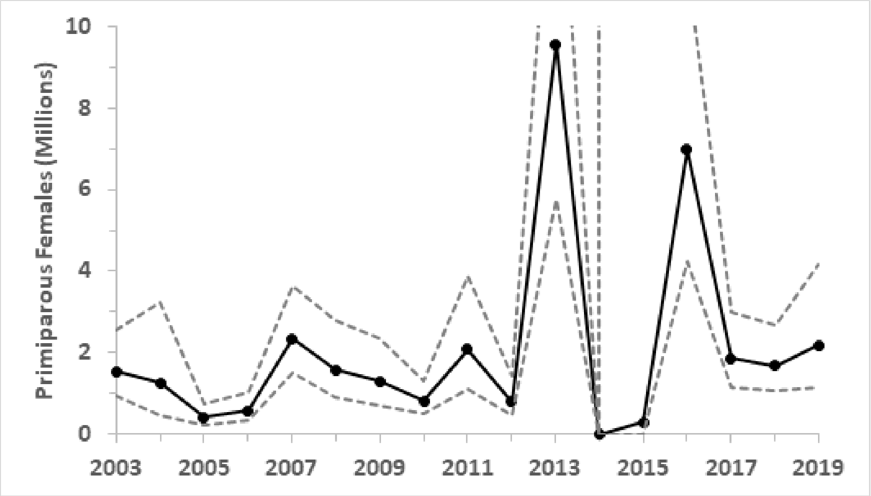
Fishery Independent Surveys



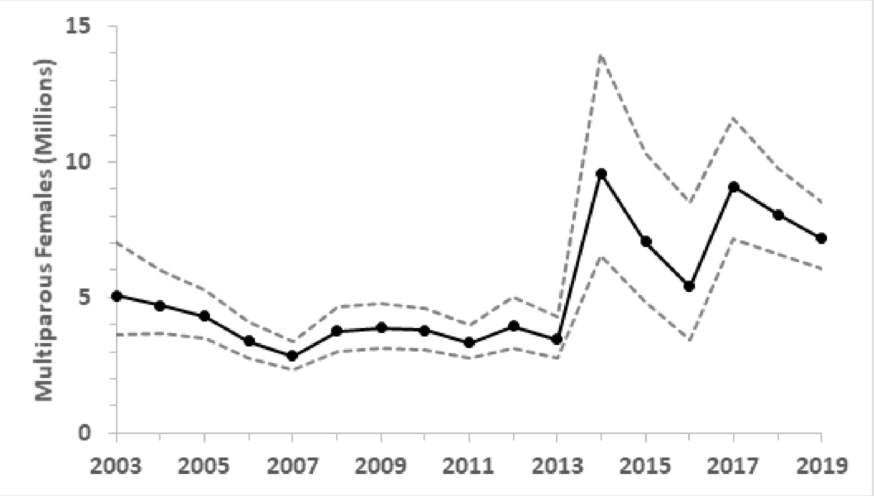
CMSA Results - Females

Year	R	N	R+N	F
2003	1,544,190	5,061,010	6,605,200	0.041
2004	1,254,290	4,695,600	5,949,890	0.027
2005	415,565	4,291,810	4,707,375	0.032
2006	584,244	3,375,510	3,959,754	0.035
2007	2,337,530	2,832,230	5,169,760	0.021
2008	1,573,060	3,751,750	5,324,810	0.015
2009	1,292,980	3,884,420	5,177,400	0.017
2010	822,549	3,772,200	4,594,749	0.019
2011	2,074,450	3,339,270	5,413,720	0.018
2012	802,266	3,940,520	4,742,786	0.020
2013	9,569,380	3,442,890	13,012,270	0.005
2014	2	9,588,260	9,588,262	0.007
2015	299,411	7,056,410	7,355,821	0.008
2016	6,977,790	5,404,420	12,382,210	0.008
2017	1,867,980	9,099,120	10,967,100	0.008
2018	1,672,230	8,063,460	9,735,690	0.006
2019	2,189,510	7,167,890	9,357,400	
q_DE	7.41E-08			
q_NJ	3.77E-07			

Primiparous (R)



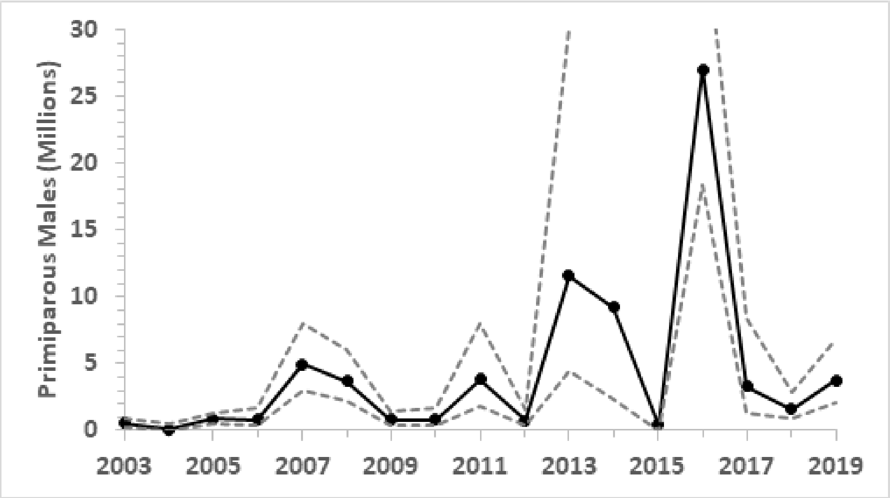
Multiparous (N)



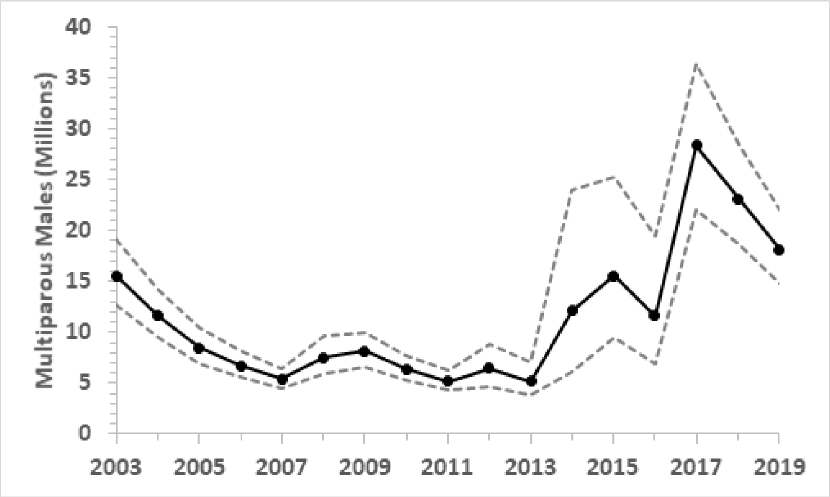
CMSA Results - Males

Year	R	N	R+N	F
2003	555,967	15,597,600	16,153,567	0.029
2004	83,631	11,625,800	11,709,431	0.019
2005	880,457	8,509,190	9,389,647	0.031
2006	798,084	6,745,350	7,543,434	0.028
2007	4,929,030	5,435,810	10,364,840	0.020
2008	3,681,160	7,526,320	11,207,480	0.021
2009	788,876	8,132,640	8,921,516	0.032
2010	834,793	6,401,670	7,236,463	0.030
2011	3,822,740	5,200,980	9,023,720	0.034
2012	768,416	6,462,870	7,231,286	0.036
2013	11,581,300	5,167,790	16,749,090	0.024
2014	9,233,350	12,114,500	21,347,850	0.017
2015	436,065	15,540,500	15,976,565	0.017
2016	26,978,600	11,631,500	38,610,100	0.009
2017	3,312,030	28,352,400	31,664,430	0.015
2018	1,615,990	23,099,300	24,715,290	0.011
2019	3,789,120	18,108,800	21,897,920	
q_DE	3.17E-08			
q_NJ	1.89E-07			

Primiparous (R)



Multiparous (N)



CMSA Sensitivity Analyses

- Several sensitivity analyses conducted
  - Discard mortality rates
  - Natural mortality (benchmark M and this assessment M)
  - Survey weights
  - Coastwide biomedical mortality included/excluded

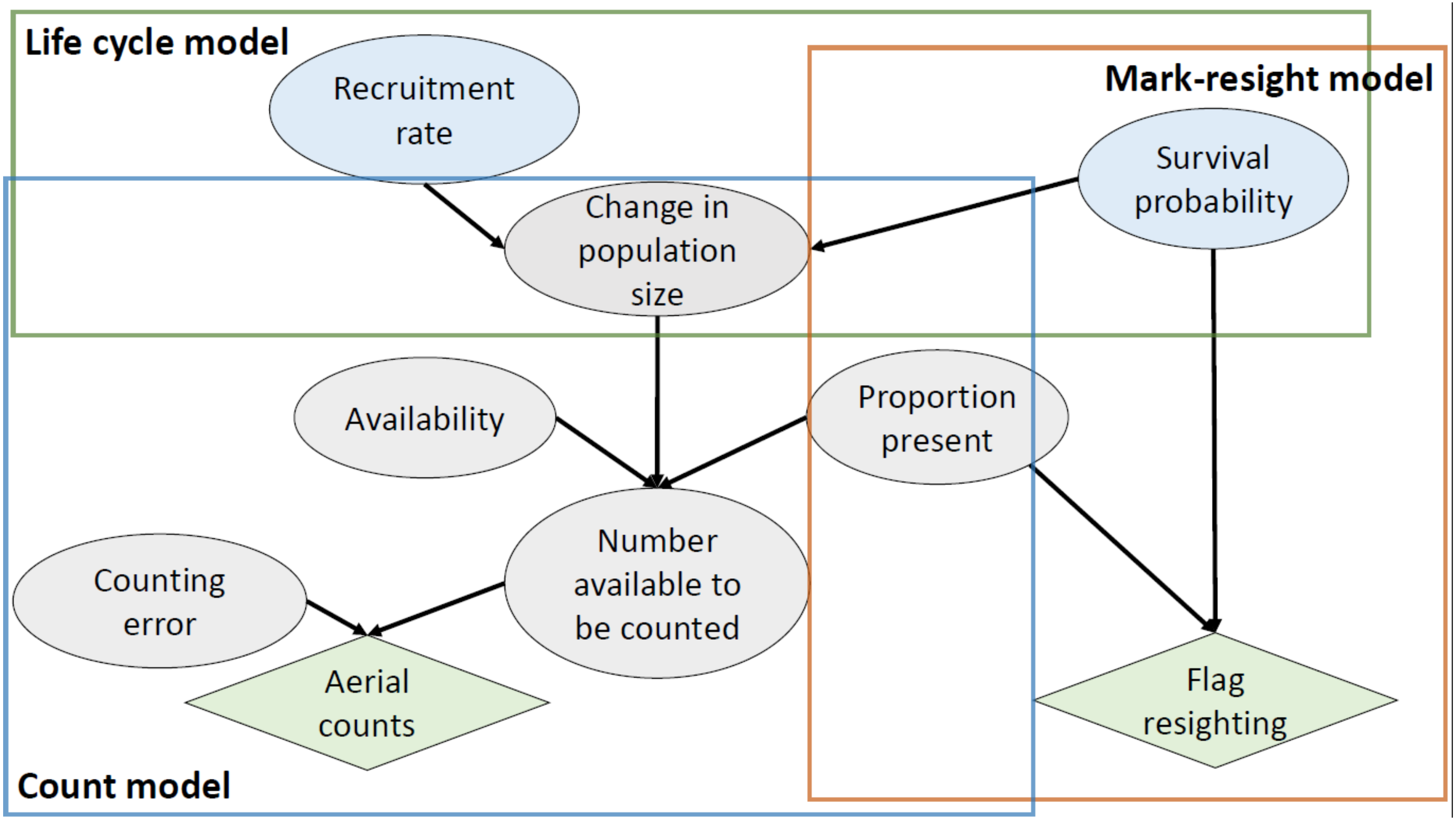
- CMSA output (total population size) was robust
  - Female deviations from base model ranged from -7% to +7%
  - Male deviations from base model ranged from -12% to +4%

Red Knot Integrated Population Model (IPM)

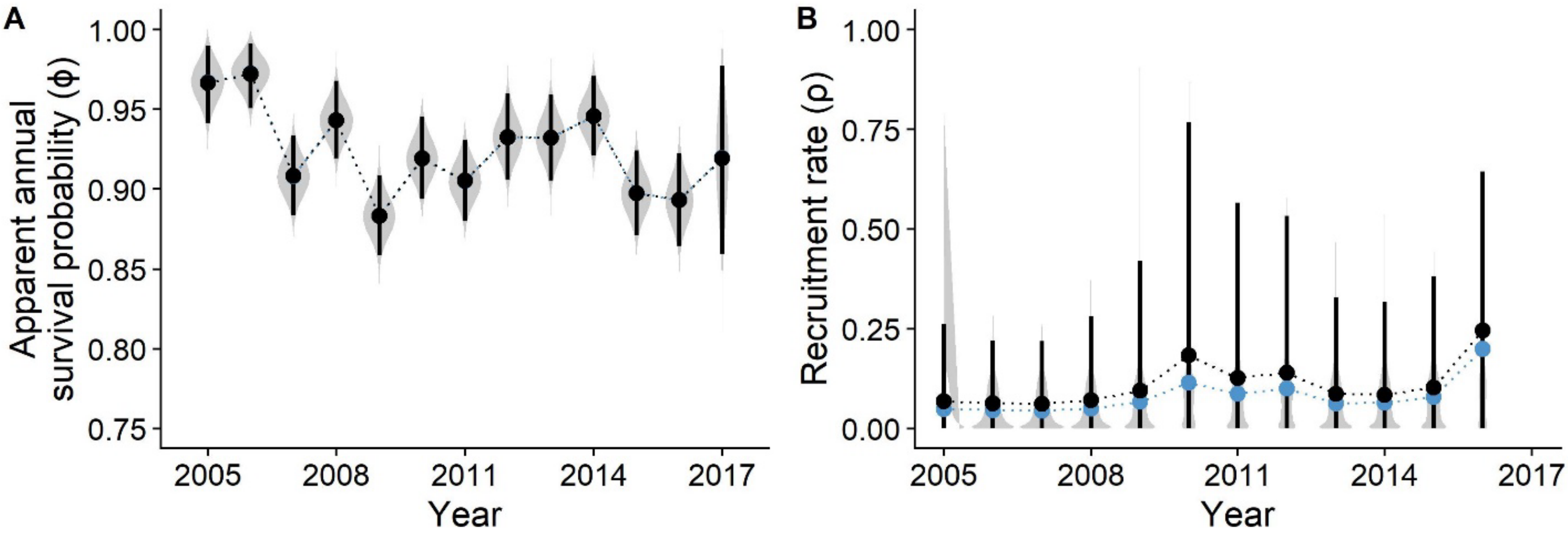
Three components to the IPM:

- Mark-resight model *(open robust design model)*–estimates survival probability and site use while accounting for imperfect detection (2005-2018 data)
- Count model *(state-space model)*–estimates change in population size among years Aerial count data (2005-2018 data)
- Life cycle model (*matrix population model)*–describes the underlying population dynamics that link survival and recruitment to change in population size

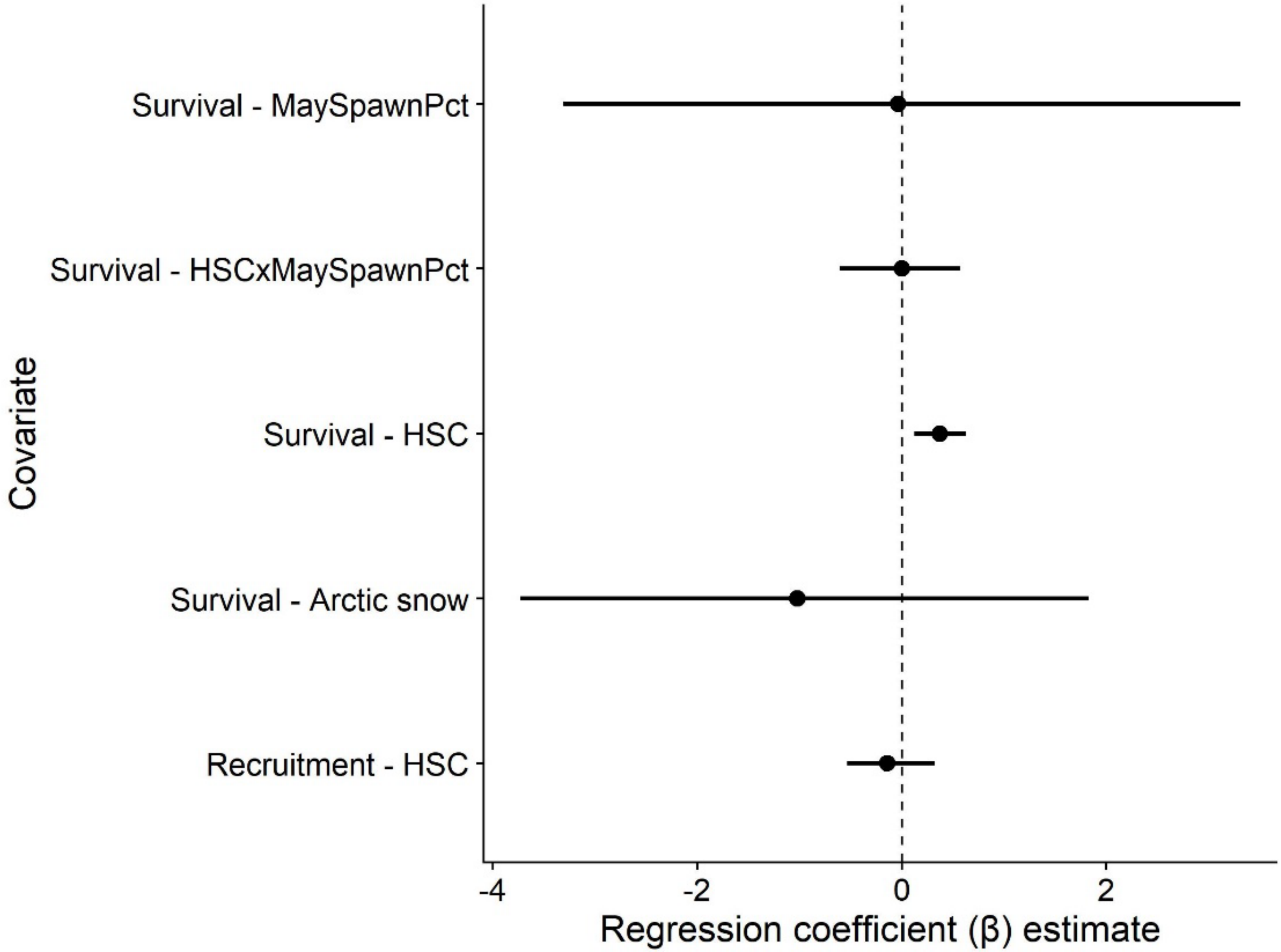
Red Knot Integrated Population Model (IPM)



Red Knot IPM – Survival and Recruitment



Red Knot IPM – Covariate Effects



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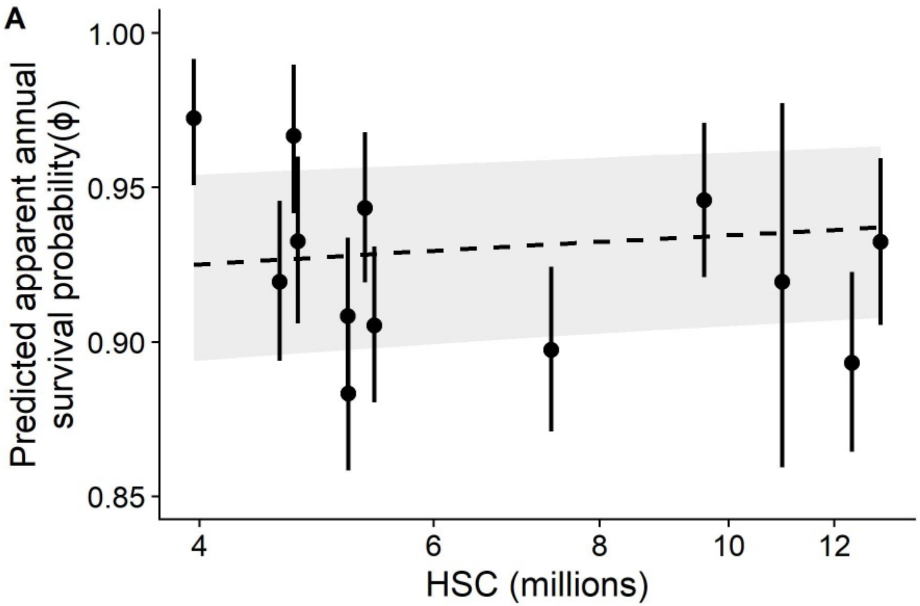
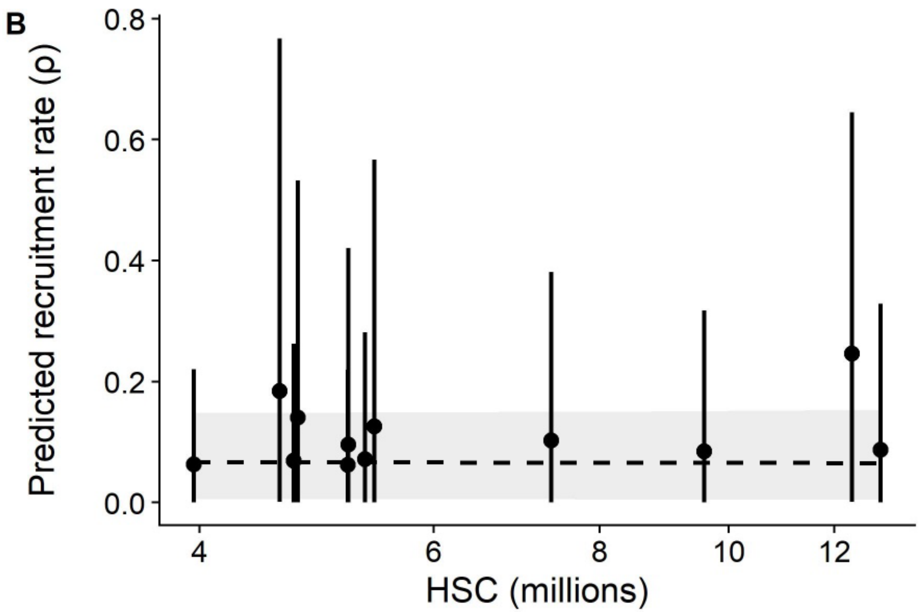


Mean = 0.93
(95% CRI: 0.90, 0.95)



Mean = 0.063
(95% CRI: 0.005, 0.149)

Population Projection Models

- Horseshoe Crabs
  - Based on CMSA
  - Mean recruitment of 1.7 million primiparous females and 2.2 million primiparous males
  - Recruitment decreases when total females <3.75 million
- Red Knots
  - Based on the IPM using MCMC output
- Models were then linked and simulated together for the optimization of harvest policy functions in Approximate Dynamic Programing (ADP)

Reward Function

Annual reward: $r_y = u_y^h + u_y^k + u_y^h u_y^k$

- Multiple Criteria Decision Analysis: The ideal situation is when we harvest the maximum allowed and red knots abundance ≥81,900 (Everybody is happy!)

- Values of u can range from 0 to 1; therefore $r_y = (0\ ,\ 3)$

- r_y = 1 + 1 + 1x1 = 3 (Everybody is happy!)

- This formulation of the reward function prevents getting all the reward from only horseshoe crab harvest (e.g., r_y = 1 + 0 + 1x0 = 1)

Reward Function

$$r_y = u_y^h + u_y^k + u_y^h u_y^k$$

		Red Knot Utility										
		0.0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
Horseshoe Crab Harvest Utility	**0.0**	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	0.1	0.1	[illegible]	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.1	1.2
	0.2	0.2	0.3	[illegible]	0.6	0.7	0.8	0.9	1.0	1.2	1.3	1.4
	0.3	0.3	0.4	0.6	[illegible]	0.8	1.0	1.1	1.2	1.3	1.5	1.6
	0.4	0.4	0.5	0.7	0.8	[illegible]	1.1	1.2	1.4	1.5	1.7	1.8
	0.5	0.5	0.7	0.8	1.0	1.1	[illegible]	1.4	1.6	1.7	1.9	2.0
	0.6	0.6	0.8	0.9	1.1	1.2	1.4	[illegible]	1.7	1.9	2.0	2.2
	0.7	0.7	0.9	1.0	1.2	1.4	1.6	1.7	[illegible]	2.1	2.2	2.4
	0.8	0.8	1.0	1.2	1.3	1.5	1.7	1.9	2.1	[illegible]	2.4	2.6
	0.9	0.9	1.1	1.3	1.5	1.7	1.9	2.0	2.2	2.4	[illegible]	2.8
	1.0	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0

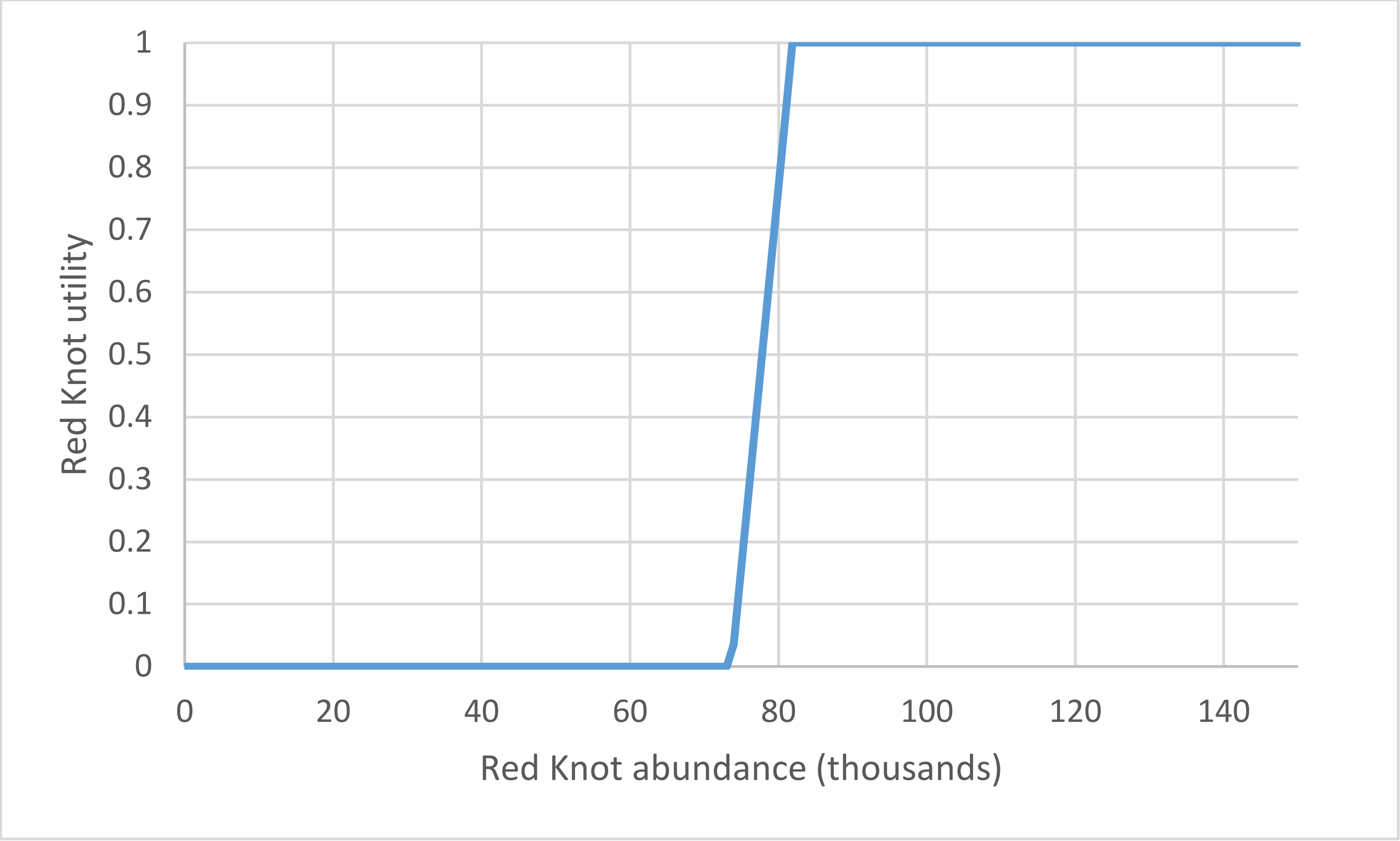
Optimization

Maximize the average total reward over some time horizon (e.g. 100 years)

Red Knot Utility

A values based decision

$$r_y = u_y^h + u_y^k + u_y^h u_y^k$$



Horseshoe Crab Utility

An economics decision, proportion of maximum economic value

$$r_y = u_y^h + u_y^k + u_y^h u_y^k$$

$$u_y^h = \frac{2H_y^f + H_y^m}{2H_{max}^f + H_{max}^m}$$

$$H_{max}^f = 210{,}000 \text{ and } H_{max}^m = 500{,}000$$

H_y^f and H_y^m are the actual harvest of females and males

Harvest Policy Functions

Harvest factor = $\eta(s) = \frac{1}{1+e^{\alpha(\beta-s)}}$

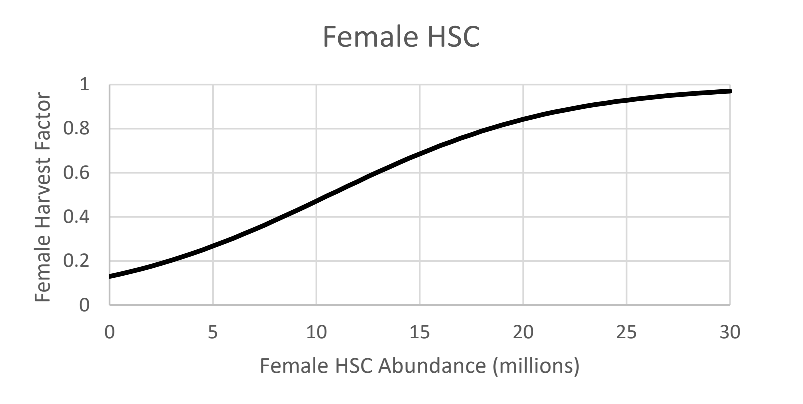
α and β for each of these 3 functions is optimized

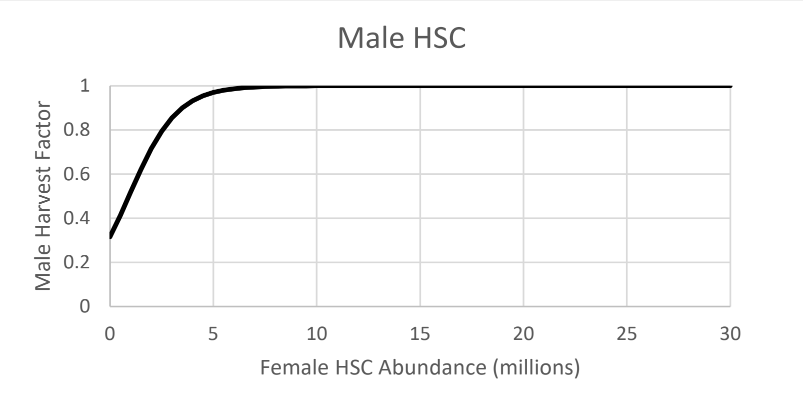
Harvest factors get multiplied by maximum allowable harvest of each sex

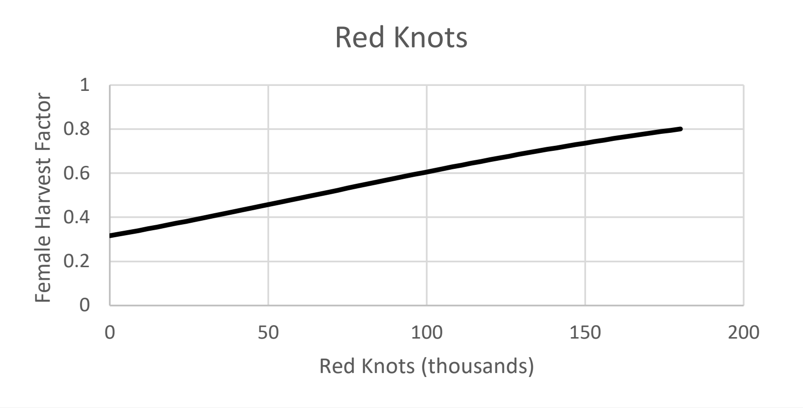
$$H^m = \eta^m H^m_{max}$$

$$H^f = H^f_{max} \times (\eta^f + \eta^k - \eta^f \eta^k)$$

$H^f_{max} = 210{,}000$; H^m_{max} = 500,000



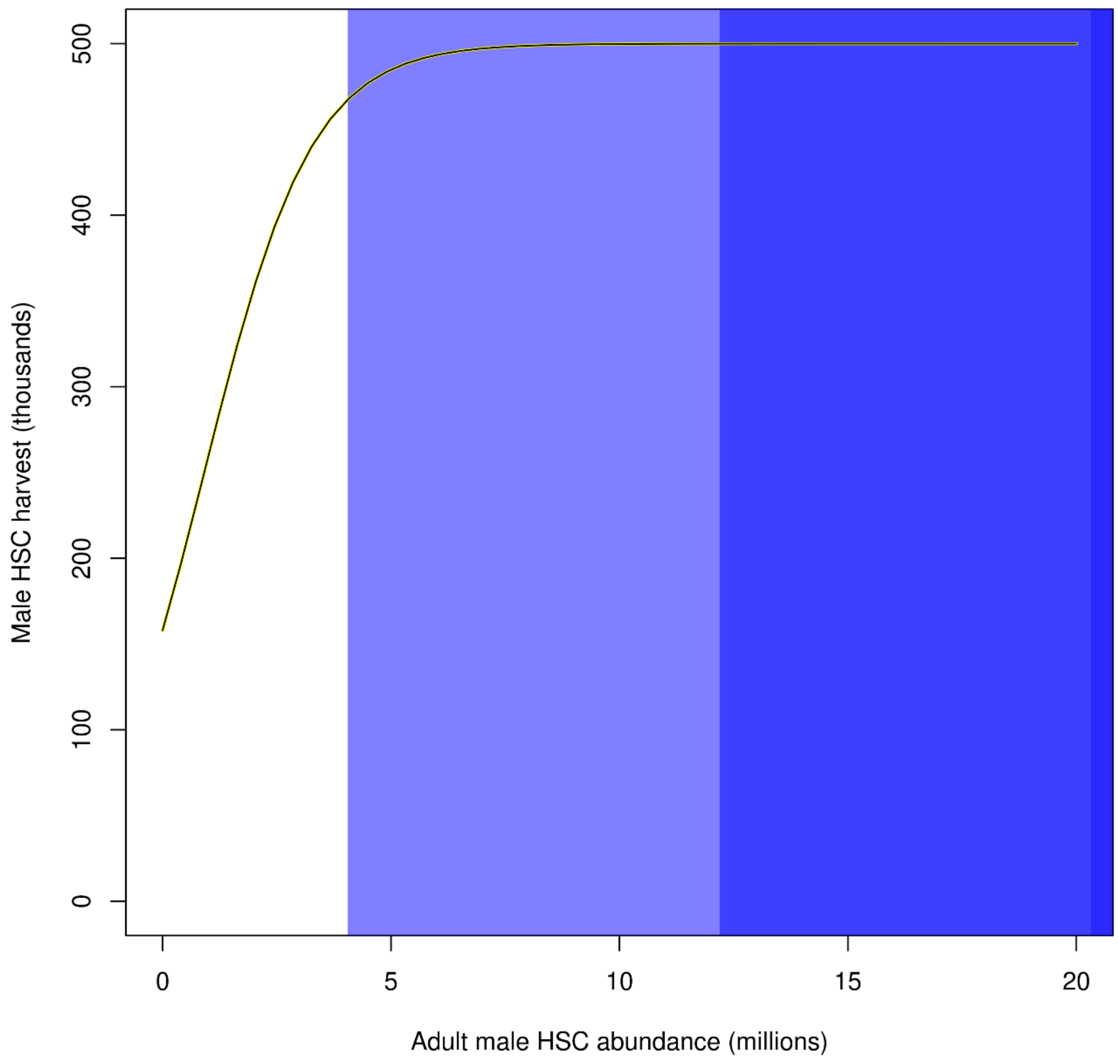




Optimization routine for α and β parameters

- Randomly select α and β for each harvest policy function
- In a simulation, apply the recommended harvest specified by a suite of α and β for a given level of HSC and RKT abundance
- Calculate reward for a year of a population projection iteration
- Project the population forward with the harvest based on the selected α and β parameters, and repeat over and over
- Sum the yearly rewards over a long time horizon (e.g. 100 years)
- Search for α and β parameters that maximize the average total reward over 10,000 simulations

Results: Optimal Harvest Policy Functions



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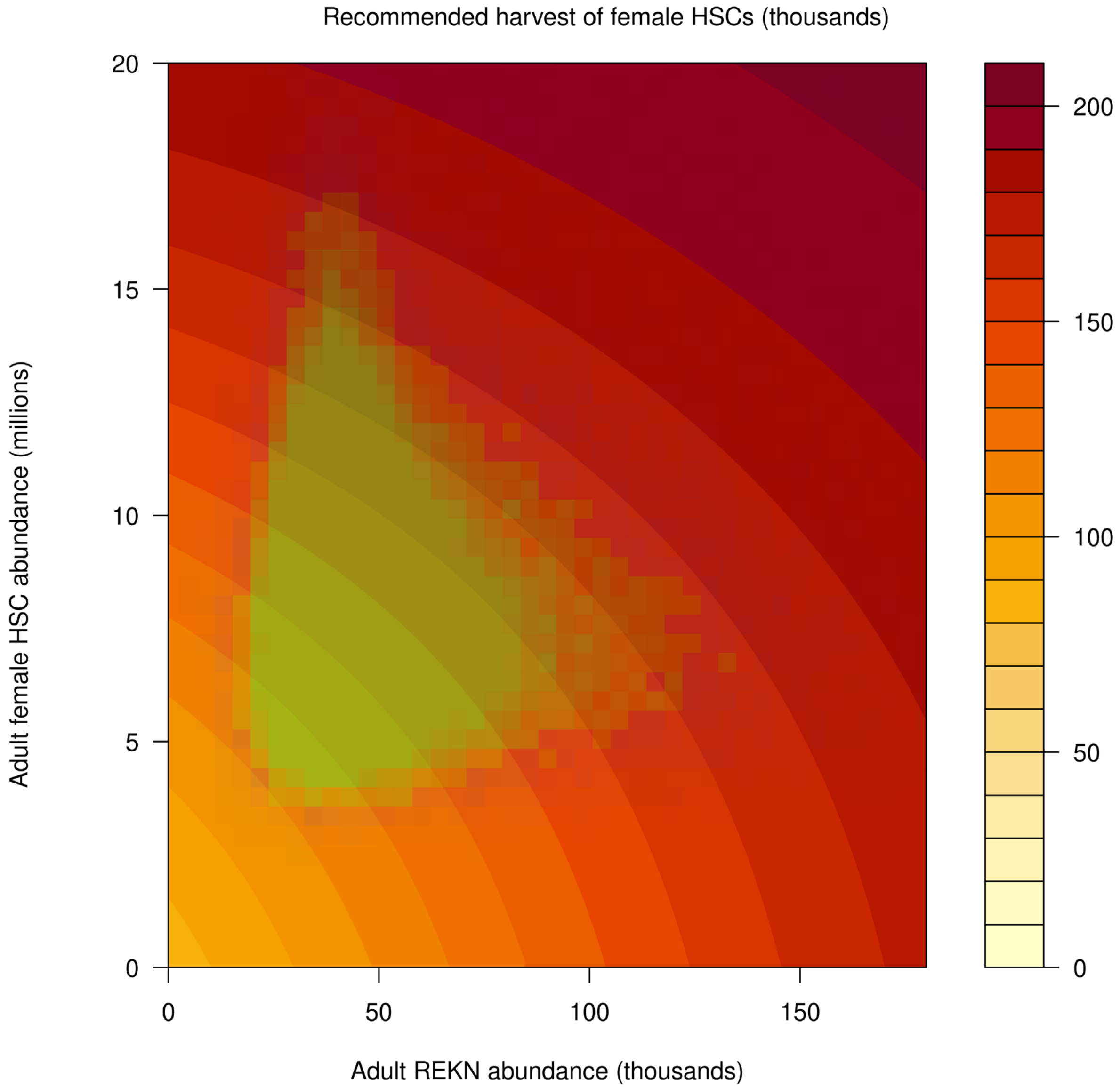
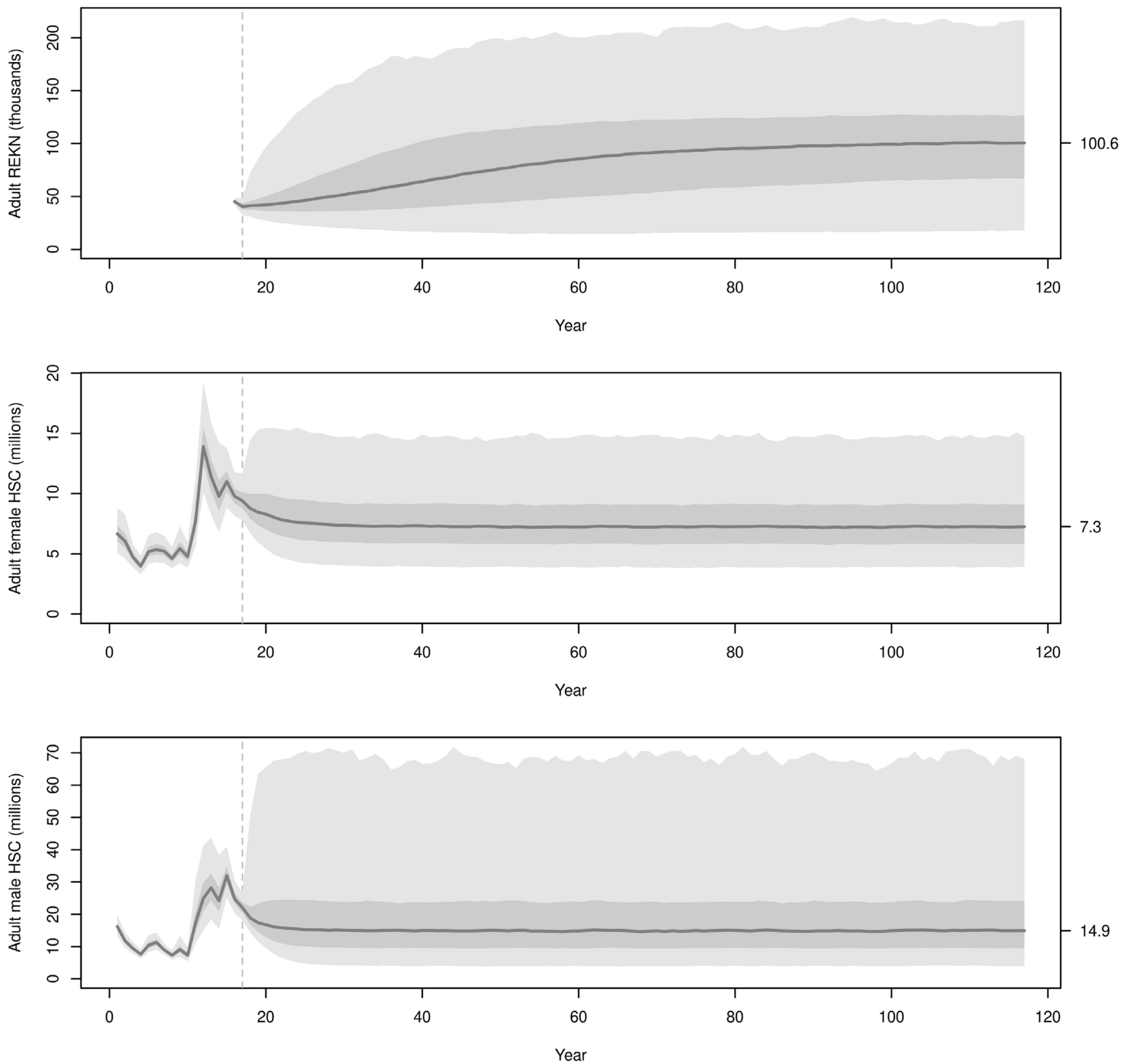
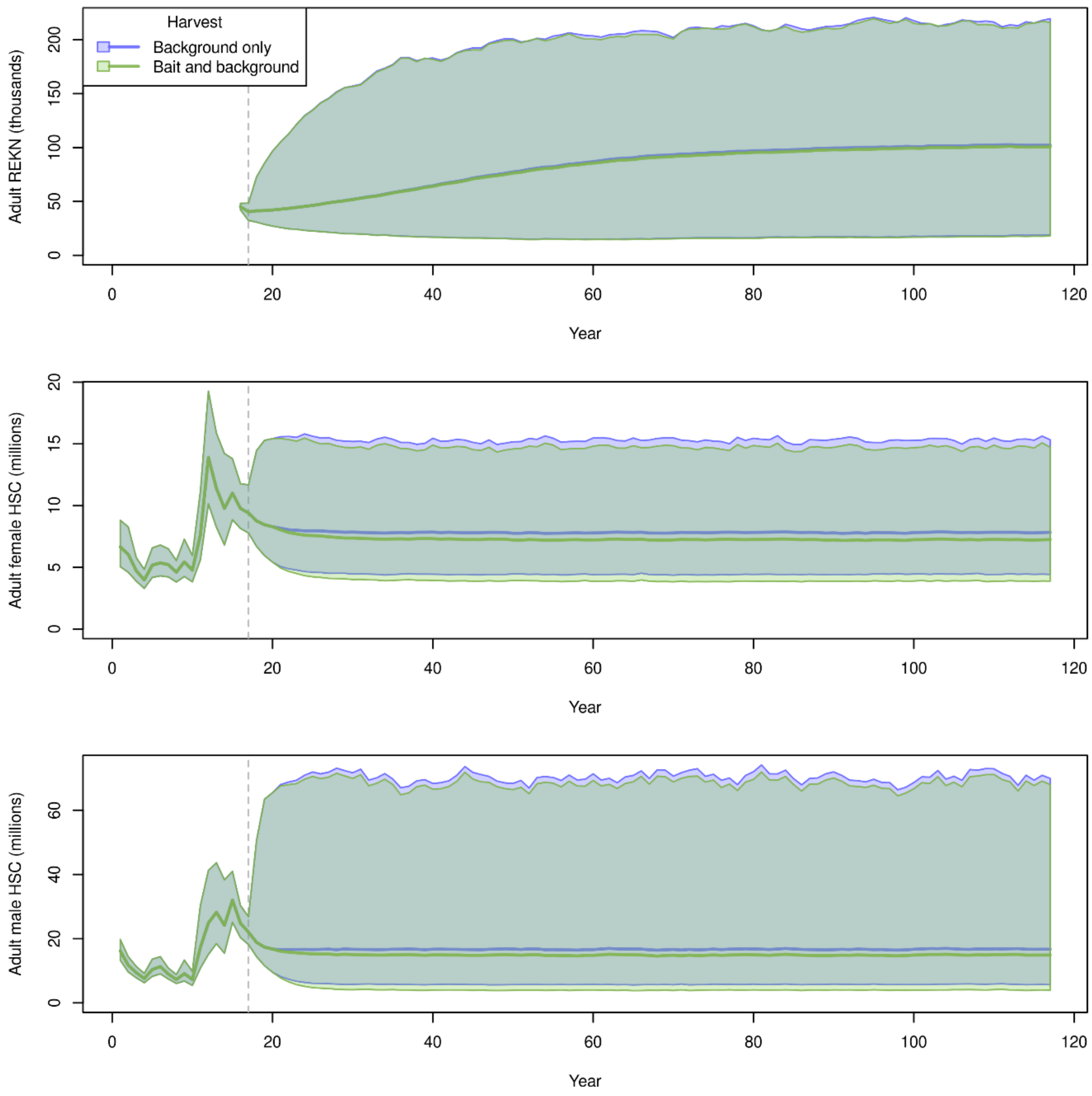


Results: Predicted population sizes



Results: Predicted population sizes



Results: Example Harvest Recommendation

Year	VA Tech Swept Area Estimates		Red knots	Optimal HSC Harvest (previous ARM)	
	Female HSC	Male HSC		Female	Male
2017	6,654,877	21,405,997	49,405	0	500,000
2018	7,555,622	19,346,403	45,221	0	500,000
2019	7,934,057	16,645,912	45,133	0	500,000

Year	CMSA Estimates		Red knots	Optimal HSC Harvest (revised ARM)	
	Female HSC	Male HSC		Female	Male
2017	10,967,100	31,664,430	49,405	154,483	500,000
2018	9,735,690	24,715,290	45,221	146,792	500,000
2019	9,357,400	21,897,920	45,133	144,803	500,000

Stock Status and Conclusions

- No overfished/overfishing definitions for DE Bay horseshoe crab populations
- Optimal harvest given the states of horseshoe crabs and red knots
- Dependent on underlying population dynamics of both species
- THE major source of uncertainty for both species is recruitment

Stock Status and Conclusions

Advantages of the ARM Revision

- Models for both species are based on empirical data from DE Bay
  - Incorporation of additional HSC mortality sources
- Model updating easily conducted with routine monitoring data (perhaps annually)
- No capacity limitations of ASDP – all uncertainty is carried through the optimization
- Reward function now values both HSC harvest and RKT abundance (can’t get full reward from one only)
- Continuous scale harvest recommendations (could be truncated to maintain yearly consistency in management)

Research Recommendations

Many research recommendations from the ARM Subcommittee and the peer review panel

Complete list in the supplemental report

- Future Research (e.g., climate change, observed egg density versus HSC abundance)

- Data Collection (e.g., VA Tech trawl analyses, sex and stage info from DE and NJ trawls, tagging efforts for both species)

- Data analysis and modeling (e.g., tagging analysis, regular model updating, use of EVPI)

Minority Opinion: Niles

Key issue	Majority Response
Apparent lack of trend in egg density data	• Removed from consideration early on in the process • Direct link between HSC abundance estimates and red knot survival • Direct comparison to early egg density estimates (Botton et al. 1994) is inappropriate
Apparent lack of trend in VA Tech trawl survey	• There is an increasing trend in swept area population estimates that are used as input into the CMSA
Inclusion of NJ and DE trawls in CMSA	• NJ and DE trawls have long been used as an index of abundance for HSC • Included in 2004, 2009, 2013, and 2019 stock assessments/updates.

Minority Opinion: Walsh

Key issue	Majority Response
Utility functions	• Previous utility functions were technically flawed and resulted in "all or nothing" harvest.
Stakeholder input	• Diversity of expertise on ARM Subcommittee, DBETC, Advisory Panel • There will be a comment period on any draft addendum process
CMSA survey weights	• Not clear on what the appropriate weighting should be • Consensus was reached early in the ARM Revision process for equal weighting
Model uncertainty	• This is exactly why we do adaptive management modeling

Questions ?????

ARM Framework Revision
Peer Review Report

Horseshoe Crab Fishery Management Board

January 26, 2022

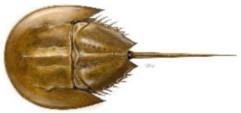
Stock Assessment Peer Review Process

- Horseshoe Crab Technical Committee and ARM Subcommittee developed new ARM Revision

- ARM Revision Review Workshop November 16-18, 2021

- Scientific review focused on data inputs, models, results, sensitivities, and overall quality of new ARM framework

Products
- ASMFC ARM Revision and Peer Review Report
- www.asmfc.org/species/horseshoe-crab



Peer Review Process

Scientific Peer Review Panel

- Chair + 3 additional Technical Reviewers, with expertise in
  - Horseshoe Crab and Migratory Shorebird Ecology
  - Population Dynamics and Statistics
  - Stock Assessment Modeling
  - Adaptive Resource Management, Structured Decision Making

Dr. Yong Chen (Chair), SUNY-Stony Brook

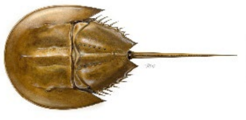
Stony Brook University

Dr. Erica Nol, Trent University

Dr. Kelly Robinson and Dr. Justin Bopp, Michigan State University

Review Panel Overall Findings

- The WG completed their TORs, and the ARM Revision is significantly improved over the previous ARM
- The ARM Revision represents the best available science and is appropriate for providing management advice.
  - Project sex-specific HSC abundance with the stock assessment model (Catch Multiple Survey Analysis, CMSA)
  - Develop an integrated population model for red knot population dynamics
  - Change reward function
  - Shift to Approximate Dynamic Programming



Review Findings

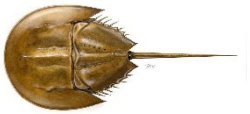
✓ **ToR 1:** Evaluate the models for estimating horseshoe crab population dynamics for use in the ARM Framework

<u>Panel Conclusions</u>

- The proposed CMSA model and projection model are appropriate for use in the ARM
- The CMSA-estimated DB HSC stock dynamics is robust and appropriate for use in the ARM

Recommendation 1: *Better define DB HSC stock*

Recommendation 2: *Use full-time period (2003-2019) of recruitment estimates in the projection model*



Review Findings

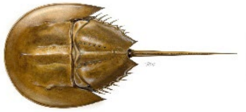
✓ **ToR 2:** Evaluate proposed changes to red knot population dynamics model

<u>Panel Conclusions</u>

- The proposed Integrated Population Model for REKN is a significant improvement over the previous model
- The analyses are appropriate for use in the ARM

Recommendation 1: *Continue exploring the multi-state model*

Recommendation 2: *Update the model parameters frequently, particularly in the short term, to reduce uncertainty in the model and decision for HSC harvest*



Review Findings

✓ **ToR 3:** Evaluate the data used in the ARM Framework revision

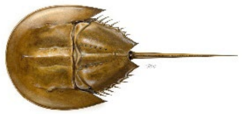
Panel Conclusions

- Data used are adequate for the ARM Revision to provide HSC management recommendation

Recommendation 1: *Determine how changes in environments and sampling time may influence HSC survey catchability*

Recommendation 2: *Evaluate apparent lack of relationship between HSC egg densities by beach surveys and REKN survival*

Recommendation 3: *Update the assessment models with new data for both species on an annual basis in the near term*



Review Findings

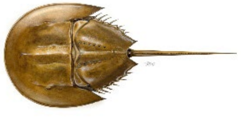
✓ **ToR 4:** Develop recommendations for improving assessment methodology and data collection

Recommendation 1: *Revisit ARM Framework every 5-10 years*

Recommendation 2: *Continue funding the VT HSC survey*

Recommendation 3: *Evaluate whether the new utility and harvest functions represent stakeholders values*

Recommendation 4: *Use expected value of perfect information (EVPI) to evaluate effects of uncertainties in REKN and HSC dynamics on harvest decision*



Review Findings

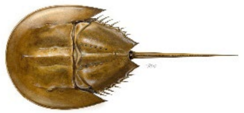
✓ **ToR 5:** Review minority opinions and associated analyses

Panel Conclusions

- Agreed with the majority response in survey effectiveness;
- Agreed with the majority responses in reformulating utility and harvest functions for fast updates to reduce the uncertainty

Recommendation 1: *Explore the mismatch between egg sampling and HSC spawning abundance*

Recommendation 3*: Consider uncertainty in HSC management and ensure current functions to adequately represent stakeholder concerns*




Questions?
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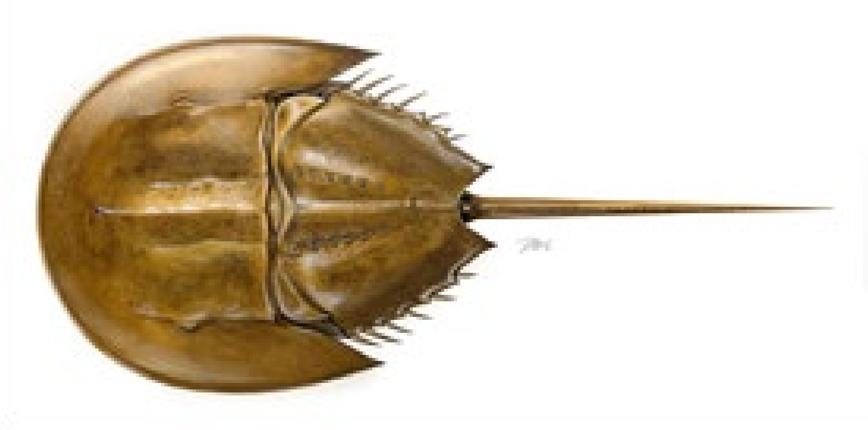
Management Response to ARM Framework Revision



Management Action

- ARM Framework implemented through Addendum VII in 2012
- Addendum required to implement ARM revisions
  - Consider initiating an addendum to consider implementing changes to the ARM Framework as recommended by the ARM subcommittee and Peer Review

Potential Changes

- Double-loop process definition
- Harvest packages
- Revised Delaware-bay % of state harvest
- State allocations
- Adaptive management
- Other issues as desired by the Board