Atlantic States Marine Fisheries Commission

Horseshoe Crab Management Board

October 21, 2023
3:00 – 5:00 p.m.

Draft Agenda

The times listed are approximate; the order in which these items will be taken is subject to change; other items may be added as necessary.

1. Welcome/Call to Order *(J. Davis)* 3:00 p.m.

2. Board Consent 3:00 p.m.
    - Approval of Agenda
    - Approval of Proceedings from April 2024

3. Public Comment 3:05 p.m.

4. Consider Stakeholder Workshop Report on Delaware Bay Management Objectives *(K. Weaver)* **Possible Action** 3:15 p.m.

5. Set 2025 Delaware Bay Bait Harvest Specifications **Final Action** 4:00 p.m.
    - Review Horseshoe Crab and Red Knot Abundance Estimates and Model Results from the Adaptive Resource Management Framework *(J. Sweka)*
    - Set 2025 Specifications *(C. Starks)*

6. Consider Approval of Fishery Management Plan Review and State Compliance for 2023 Fishing Year *(C. Starks)* **Action** 4:45 p.m.

7. Elect Vice-Chair **Action** 4:55 p.m.

8. Other Business/Adjourn 5:00 p.m.

The meeting will be held at The Westin Annapolis (100 Westgate Circle, Annapolis, Maryland; 888.627.8994) and via webinar; click here for details

Sustainable and Cooperative Management of Atlantic Coastal Fisheries

MEETING OVERVIEW

Horseshoe Crab Management Board
October 21, 2024
3:00 – 5:00 p.m.

Chair: Justin Davis (CT) Assumed Chairmanship: 02/24	Technical Committee Chair: Ethan Simpson (VA)	Law Enforcement Committee Rep: Nick Couch (DE)_
Vice Chair: Vacant	Advisory Panel Chair: Brett Hoffmeister (MA)	Previous Board Meeting: April 30, 2024
Voting Members: MA, RI, CT, NY, NJ, PA, DE, MD, DC, PRFC, VA, NC, SC, GA, FL, NMFS, USFWS (16 votes)		

2. Board Consent

- Approval of Agenda
- Approval of Proceedings from April 2024

3. Public Comment – At the beginning of the meeting, public comment will be taken on items not on the agenda. Individuals that wish to speak at this time must sign-in at the beginning of the meeting. For agenda items that have already gone out for public hearing and/or have had a public comment period that has closed, the Board Chair may determine that additional public comment will not provide additional information. In this circumstance, the Chair will not allow additional public comment on an issue. For agenda items that the public has not had a chance to provide input, the Board Chair may allow limited opportunity for comment. The Board Chair has the discretion to limit the number of speakers and/or the length of each comment.

4. Update on Horseshoe Crab Management Objectives Workshop (3:15-4:00 p.m.) Possible Action

Background

- As part of its ongoing discussions regarding how best to manage Delaware Bay-origin horseshoe crabs and in response to the 2023 Stakeholder Survey, a Horseshoe Crab Management Objectives Workshop was held in July 2024. The Workshop included a small group of managers, scientists, and stakeholders. The purpose of the workshop was to increase understanding of stakeholder perspectives and interests, current horseshoe crab modeling, and concerns, alternatives, and areas of common ground for HSC management.
- A report on the workshop discussions and recommendations was developed for the Board's consideration **(Briefing Materials)**.

Presentations

- Management Objectives Workshop Report by K. Weaver

Board actions for consideration at this meeting

- Consider implementing workshop recommendations for next steps

5. Set 2025 Delaware Bay Harvest Specifications (4:00-4:45) Final Action

Background

- In September 2024, the Delaware Bay Ecosystem TC (DBETC) and Adaptive Resource Management (ARM) Subcommittee met to review results of the horseshoe crab and red knot population abundance surveys in the Delaware Bay region **(Briefing Materials).**
- The ARM model was run using three fishery-independent surveys for horseshoe crabs, various sources of horseshoe crab removals, and the estimated population of red knots to provide a recommendation for harvest specifications for Delaware Bay states in 2025 **(Briefing Materials).**

Presentations

- Horseshoe Crab and Red Knot Abundance Estimates and 2024 ARM Model Results by J. Sweka

Board actions for consideration at this meeting

- Consider ARM harvest recommendations and set 2025 specifications for states in the Delaware Bay region

6. Consider Approval of Fishery Management Plan Review and State Compliance for the 2022 Fishing Year (4:45-4:55 p.m.) Action

Background

- State Compliance Reports were due July 1, 2024.
- The Plan Review Team reviewed each state report and compiled the annual FMP Review **(Briefing Materials).**
- South Carolina, Georgia, and Florida have requested and meet the requirements of *de minimis* status.

Presentations

- FMP Review of the 2023 Fishing Year by C. Starks

Board actions for consideration at this meeting

- Accept FMP Review and State Compliance Reports for the 2023 Fishing Year
- Approve de minimis requests

7. Elect Vice-Chair (4:55-5:00 p.m.) Action

Background

- The vice chair seat is empty since Justin Davis has assumed the role of chair.

Board actions for consideration at this meeting

- Elect Vice-Chair

8. Other Business/Adjourn (5:00 p.m.)

Horseshoe Crab

Activity level: Low

Committee Overlap Score: Low

Committee Task List

- TC – July 1st: Annual compliance reports due
- ARM & DBETC – Fall: Annual ARM model to set Delaware Bay specifications, review red knot and VT trawl survey results

TC Members: Katie Rodrigue (RI, Chair), Jeff Brunson (SC), Derek Perry (MA), Kelli Mosca (CT), Jennifer Lander (NY), Danielle Dyson (NJ), Jordan Zimmerman (DE), Steve Doctor (MD), Ingrid Braun (PRFC), Ethan Simpson (VA), Jeffrey Dobbs (NC), Eddie Leonard (GA), Claire Crowley (FL), Chris Wright (NMFS), Joanna Burger (Rutgers), Wendy Walsh (USFWS), Kristen Anstead (ASMFC), Caitlin Starks (ASMFC)

Delaware Bay Ecosystem TC Members: Wendy Walsh (USFWS, Chair), Danielle Dyson (NJ), Katherine Christie (DE), Jordan Zimmerman (DE), Steve Doctor (MD), Ethan Simpson (VA), Sarah Karpanty (VA Tech), Jim Fraser (VA Tech), Francesco Ferretti (VA Tech), Wendy Walsh (USFWS), Kristen Anstead (ASMFC), Caitlin Starks (ASMFC)

ARM Subcommittee Members: John Sweka (USFWS, Chair), Danielle Dyson (NJ), Katherine Christie (DE), Margaret Conroy (DE), Steve Doctor (MD), Sarah Karpanty (VA Tech), Wendy Walsh (USFWS), Conor McGowan (USGS/Auburn), David Smith (USGS), Jim Lyons (USGS, ARM Vice Chair), Jim Nichols (USGS), Kristen Anstead (ASMFC), Caitlin Starks (ASMFC)

DRAFT PROCEEDINGS OF THE

ATLANTIC STATES MARINE FISHERIES COMMISSION

HORSESHOE CRAB MANAGEMENT BOARD

The Westin Crystal City
Arlington, Virgina
Hybrid Meeting

April 30, 2024

These minutes are draft and subject to approval by the Horseshoe Crab Management Board.
The Board will review the minutes during its next meeting.

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INDEX OF MOTIONS

1. **Move to approve Agenda** by consent (Page 1).

2. **Move to approve Proceedings of October 16, 2023** by consent (Page 1).

3. **Move to accept the 2024 Horseshoe Crab Assessment Update for management use** (Page 10). Motion by Shanna Madsen; second by Conor McManus. Motion passes by unanimous consent (Page 10).

4. **Motion to adjourn** by consent (Page 18).

ATTENDANCE

Board Members

Dan McKiernan, MA (AA)
Raymond Kane, MA (GA)
Sarah Ferrara, MA, proxy for Rep. Peake (LA)
Conor McManus, RI, proxy for J. McNamee (AA)
Eric Reid, RI, proxy for Sen. Sosnowski (LA)
Justin Davis, CT (AA)
Bill Hyatt, CT (GA)
Marty Gary, NY (AA)
Scott Curatolo-Wagemann, NY, proxy for E. Hasbrouck (GA)
Jesse Hornstein, NY, proxy for Sen. Kaminsky (LA)
Joe Cimino, NJ (AA)
Jeff Kaelin, NJ (GA)
Adam Nowalsky, NY, proxy for Sen. Gopal (LA)
John Clark, DE (AA)
Roy Miller, DE (GA)
Craig Pugh, DE, proxy for Rep. Carson (LA)
Mike Luisi, MD, proxy for L. Fegley (AA Acting)
Russell Dize, MD (GA)
Shanna Madsen, VA, proxy for J. Green (AA)
Chris Batsavage, NC, proxy for K. Rawls (AA)
Chad Thomas, NC, proxy for Rep. Wray (LA)
Ben Dyar, SC, proxy for B. Keppler (AA)
Doug Haymans, GA (AA)
Spud Woodward, GA (GA)
Jeffrey Renchen, FL, proxy for J. McCawley (AA)
Gary Jennings, FL (GA)
Ron Owens, PRFC
Chris Wright, NMFS
Rick Jacobson, US FWS

(AA = Administrative Appointee; GA = Governor Appointee; LA = Legislative Appointee)

Ex-Officio Members

Brett Hoffmeister, Advisory Panel Chair
John Sweka, ARM Subcommittee Chair

Staff

Bob Beal
Toni Kerns
Tina Berger
Madeline Musante
Kristen Anstead
Katie Drew
Jeff Kipp
Jainita Patel
Tracey Bauer
James Boyle
Caitlin Stark
Chelsea Tuohy
Emilie Franke
Trevor Scheffel

Guests

Thad Altman, Florida House of Representatives
Mike Armstrong, MA DMF
Pat Augustine
Linda Barry, NJ DEP
Kendra Beaver, Save The Bay
Mel Bell
John Bello, Virginia Saltwater Sportfishing Assn
Colleen Bouffard, CT DEEP
Michael Bowen, Cornell University
Jeff Brunson, SC DNR
Jeffrey Brust, NJ DFW
Darlene Carpenter
Nicole Caudell, MD DNR
Michael Celestino, NJ DEP
Haley Clinton, NC DEQ
Margaret Conroy, DE DNREC
Danielle Contrada, FL FWC
James Cooper
Claire Crowley McIntyre, FL FWC
Caitlyn Czajkowski
Tanya Darden, SC DNR MRRI
Conor Davis, NJ DEP
Steve Doctor, MD DNR
Danielle Dyson, NJ DEP
Julie Evans, East Hampton Town Fisheries Advisory Cmte.
Delaney Farrell, FL FWC
Wenley Ferguson, Save The Bay
Anthony Friedrich, ASGA
Matthew Gates
Lewis Gillingham, VMRC
Angela Giuliano, MD DNR

Guests (Continued)

Laura Graziano, Jenkinson's Aquarium
Berlynna Heres, FL FWC
Harry Hornick, MD DNR
Derrek Hughes, NY DEC
Todd Janeski, VCU
Rachel Kalisperis, South Carolina Aquarium
TJ Karbowski, Rock & Roll Charters
Amy Karlnoski, NYS Assembly
Blaik Keppler, SC (AA)
Kris Kuhn
Robert LaCava, MD DNR
Jennifer Lander, NYS DEC
Christina Lecker, Fujifilm Wako Chemicals USA
Ben Levitan, Earthjustice
Susan Linder
John Maniscalco, NYS DEC
Victoria Melendez, FL FWC
Nichola Meserve, MA DMF
David Meservey
Steve Meyers
Chris Moore, Chesapeake Bay Foundation
Thomas Newman, North Carolina Fisheries Assn.
Scott Olszewski, RI DEM
Marina Owens, FL FWC
Danielle Palmer, NOAA
Cheri Patterson, NH (AA)
Derek Perry, MA DMF
Jill Ramsey, VMRC
Allen Reneau, Fujifilm Wako Chemicals USA
Sefatia Romeo Theken, MA DFG
James Rosato
Daniel Sasson, SC DNR
Chris Scott, NYS DEC
Ethan Simpson, VMRC
Somers Smott, VMRC
Renee St. Amand, CT DEEP
Benjie Swan
Yoshihiro Takasuga, Fujifilm Wako Chemicals USA
Kristen Thiebault, MA DMF
Laura Tomlinson, MA DMF
Kelly Whitmore, MA DMR
Kristoffer Whitney
Angel Willey, MD DNR
Travis Williams, NC DEQ
Steven Witthuhn, NY MRAC
Daniel Zapf, NC DEQ
Jordan Zimmerman, DE DNREC
Renee Zobel, NH FGD

The Horseshoe Crab Management Board of the Atlantic States Marine Fisheries Commission convened in the Jefferson Ballroom of the Westin Crystal City Hotel, Arlington, Virginia, a hybrid meeting, in-person and webinar; Tuesday, April 30, 2024, and was called to order at 3:00 p.m. by Chair Justin Davis.

CALL TO ORDER

CHAIR JUSTIN DAVIS: I'm going to go ahead and call to order this meeting of the Horseshoe Crab Management Board. My name is Justin Davis; I'm the Administrative Commissioner from Connecticut, and I have the pleasure of taking over as the Chair of this Board starting at this meeting. First order of business, I'll thank our outgoing chair, John Clark, for his excellent leadership of this Board over the last couple years, I think everyone would agree was pretty eventful for this Board.

I thank John for taking care of all that, so that we'll have relative peace and quiet for the next few years.

APPROVAL OF AGENDA

CHAIR DAVIS: As our first item on the agenda today, Approval of the Agenda. Does anyone have any additions or suggested changes to the agenda? Caitlin is reminding me that I have a change to the agenda that I'm supposed to tell everybody about.

We will not be electing a Vice-Chair today at today's Board meeting. That last item on the agenda is no longer on the agenda. Any other changes to the agenda? Okay, not seeing any, we'll consider the agenda approved by consent with that one change.

APPROVAL OF PROCEEDINGS

CHAIR DAVIS: Next item on the agenda is Approval of the Proceedings from the last meeting of this Board in October, 2023. Any suggested changes, additions, omissions from those meeting minutes? Okay, not seeing any hands, we'll consider the proceedings from the October, 2023 meeting approved by consent.

PUBLIC COMMENT

CHAIR DAVIS: Moving right along, next item on the agenda, Public Comment. As a reminder, this would be public comment on any items that are not on the agenda for today's Board meeting. Okay, I'm being told we didn't have anybody signed up for public comment. I see one hand in the back of the room. Sir, if you would like to go ahead and come up to the public microphone there on the corner.

MR. BRETT HOFFMEISTER: Great, thank you very much. My name is Brett Hoffmeister, I am the LAL Production Manager at Associates of Cape Cod. I just wanted to thank you for allowing me to comment today. It was in 1816 that Sir Walter Scott penned the phrase, "It is not the fish you are buying, but it's men's lives."

He couldn't have known just how relevant that statement would be over 200 years later. I cannot imagine he would have thought it relevant to the humble horseshoe crab either. But here we are. Human lives are now intertwined with those of the horseshoe crab on which we depend on for endotoxin testing. Testing that is so critical to our healthcare that is required by law in the U.S., 2024 marks 50 years of Associates of Cape Cod doing business. Our founder was the first to license LAL with the USFDA. Since then, LAL has functionally replaced the rabbit pyrogen test, it was viewed as the gold standard around the world for endotoxin testing.

We provide products, support, services to pharmaceutical and medical device manufacturers globally. We also provide clinical testing products and testing services for patients from or who are at risk of invasive fungal infections. This vital assay is used millions of times annually across the globe, to help ensure the safety of life saving, life enhancing medical devices, implants, hardware, IV fluid, drugs, vaccines and antibiotics.

This assay is so critical to our healthcare system that it is pretty safe to say that nearly every human being that you will meet in your entire life benefited from the products and services that this industry provides. The LAL test will be needed for many years to come, even as new technologies enter the market.

There are only four companies in the U.S. that are licensed to make LAL. Our facilities are scattered along the east coast of the U.S. We work closely with state and coastal fisheries managers, fishers, dealers, and regulatory agencies to provide the products and services so critical to an industry that not only extends human life, but helps to maintain and increase the quality of life for countless people around the world.

Our medical use of these animals is a low impact activity that is essential to our global healthcare system. It is amazing that LAL has a hundred percent safety record. It has never failed us when used correctly. It is within that context I would like to comment on the recent efforts to limit or prohibit collection of horseshoe crabs that defers business of LAL manufacturing.

While Associates of Cape Cod shares the concerns of many regarding conservation of these remarkable animals, it is vital to recognizes the role they play in human health. Conservation measures are working and data demonstrates the horseshoe crab populations are robust and healthy. Overall, fisheries related mortality over the past 15 or 20 years has been on a steady decline, and in many areas, populations appear to be growing substantially.

The well meaning for many efforts to list the horseshoe crabs as endangered or other means that will limit access to these animals, is reckless, and potentially dangerous, as it could limit the ability of the LAL industry to supply this essential assay to the companies that are required to test for endotoxins. This could have far-reaching and longstanding impacts on the healthcare system.

Alternative assays have been available for many years, and new products have recently been brought to market. Without a doubt they will have a role to play in the future. But allowing proper vetting takes time. Calls to ban fishing for crabs and force the use of alternatives are misconstrued and flawed approach that needlessly places at risk the people who are in need of medical intervention.

Simply put, there are no shortcuts around the barriers of the regulatory landscape, and this exists solely to protect human life. The political purses surrounding this fishery ignores the efforts of scientists and fisheries managers who have been tasked with managing our fisheries. Similarly, efforts are producing hundreds and in some cases thousands of electronically filled out letters and petitions to sway decision makers and adopting an agenda potentially undermines the system's that are put in place and been developed to allow experts, like you, to make decisions based on fact, science and data.

It is my hope and expectation that we can allow experts in a particular field to do their job and manage, regulate, or otherwise utilize the authority we have placed on their shoulders, unencumbered by misinformation, agendas and group sourcing. This goes for wildlife managers, fisheries managers, regulators, and those who contribute to human healthcare, management and safety. The impact of the decisions and the work that you do cannot be taken lightly, for indeed, it is not just fish you are selling.

CHAIR DAVIS: Brett, can I just ask that you wrap it up. We're over the three minutes.

MR. HOFFMEISTER: I'm done, thank you very much.

CHAIR DAVIS: Thank you for your comment. Any other public comment before we move on?

CONSIDER 2024 HORSESHOE CRAB STOCK ASSESSMENT UPDATE

CHAIR DAVIS: Okay, we're going to go ahead and move on to our next item on the agenda, which will be a presentation of the 2024 Horseshoe Crab Stock Assessment Update by Katie Rodrigue.

MS. KATHERINE RODRIGUE: To begin, I just want to go over the stock assessment schedule for horseshoe crab. The last coastwide assessment was the 2019 Benchmark Assessment, and the Peer Review Panel recommended a benchmark every 10 years with an update every 5, so now in 2024 we've completed the 5-year update assessment.

The next coastwide assessment will be the benchmark in 2029. There was also a revision the Delaware Bay ARM framework in 2022. The stock assessment update was developed by the SAS and approved by the TC, and it is a product of both committees. Here you can see that membership. There was no TC Chair or Vice-Chair for this update.

But going forward, we'll have Ethan Simpson from VMRC as Chair, and Ingrid Braun from PRFC as Vice-Chair. First, I'll go through the fishery dependent data. This is bait harvest coastwide from 1998 to 2022. The gray line on this figure is the coastwide bait harvest, and then the stacked bar charts underneath is showing the breakdown by sex.

The dotted orange line represents the coastwide quota. Since the 2019 benchmark, coastwide landings decrease in 2020 due to the COVID 19 pandemic, but then increased again in 2021 and 2022, the level similar to the recent year's preceding 2020. Landings have remained well below the coastwide quota since the implementation in 2000.

This is bait landings by management regions, so stock status is determined by four management regions for horseshoe crabs, there is the northeast region, the New York Region, Delaware Bay Region and the Southeast. These are based on tagging and genetic studies management and data availability. The assessment does recognize that there may be embayment specific populations or other nuances to these groupings. The majority of bait landings are harvested from the Delaware Bay region and are predominantly males, due to the harvest restrictions in the ARM framework. Historically the New York Region has had the next highest bait landings, but in recent years that has been the Northeast Region. Since 2004 ASMFC has required states to monitor the biomedical use of horseshoe crabs, and that is to determine the source of the crabs, track their total harvest, characterize pre and post bleeding mortality. In recent years sex data is also being provided.

The black line on this figure is showing the total number of crabs that are collected for the biomedical industry, and then the gray line is the number of crabs that were actually bled. The stacked bar chart below shows the breakdown of bled crabs by sex, and from a metanalysis of bleeding studies in the benchmark assessment, a mortality rate of 15 percent is applied to the number of bled crabs, to estimate the bleeding mortality.

That is added to the number of crabs that are actually observed during the biomedical process, to estimate total mortality from the biomed industry. That is shown on the orange line in this figure. The estimated mortality from the biomedical industry in 2022 was just under 146,000 crabs, which is the highest in the time series.

Dead discards are also provided from the Northeast Fisheries Science Center's Northeast Fisheries Observer Program. For horseshoe crab those discard estimates come specifically from Delaware Bay Region only, and that is due to the limited data on horseshoe crabs in the Observer Program, and also for its use in the Catch Survey Model.

While the methods used are the same from the benchmark, there was some improved data filtering from the 2022 ARM Revision, and so this is representing that update and analysis. The estimated number of dead horseshoe crabs is variable through time, with the highest values in 2016 and 2021, and the lowest in 2022.

Next, I'll move on to the fishery independent data and our indices of relative abundance. During the 2019 benchmark the SAS explored both nominal and standardized indices, and due to the high number of zeros in the data, used the Delta Distribution for the mean and variance for all indices. But in 2022, the Peer Review noted that fixed station surveys should be standardized, and so for this update any fixed station surveys, those indices were standardized, while the others used the delta mean.

I'll just briefly go through indices for each region from north to south. Here are the Northeast Region indices, on the upper left is the Massachusetts Trawl Survey north of Cape Cod. On the upper right the Massachusetts Trawl south of Cape Cod, and then on the bottom is the Rhode Island Trawl survey. For many surveys there are some data gaps due to reduced sampling during COVID, and this was the case in 2020 for the Massachusetts indices.

Spearman rank correlation coefficients were estimated between the indices within each region to see how these surveys are correlated with each other, and in the Northeast the Rhode Island index is negatively correlated with both Massachusetts indices, but the comparisons were not significant. Now moving on to the New York Region. Their indices are derived from five surveys. On the top left is the Connecticut/Long Island Sound Trawl Survey, on the upper right the New York/Peconic Trawl Survey, and on the bottom the Western Long Island Sound Seine Survey, with Jamaica Bay on the left and the Little Neck and Manhasset Bay is on the right. Again, there are some data gaps in these surveys in 2020 due to COVID. Then finally, the last survey for the New York Region is the New York Region of the NEAMAP Survey.

Again, we looked at correlation comparisons between the surveys. For the New York Region, all were positively correlated with 4 of the 10 being significant, and those are circled in red. Next on the left is the Delaware Bay Region. There are 14 indices for this region. First is the Delaware Bay Region of the NEAMAP Survey on the left, and Maryland Coastal Bay Survey on the right.

The New Jersey Ocean Trawl Survey has four different indices from the survey. On the top is the spring, with females on the left and males on the right, and on the bottom the fall survey. Again, females on the left and males on the right. No sampling was conducted in 2020 and 2021.

Next is the Delaware Bay Adult Trawl Survey, which is also separated out by sex and season, again with the spring survey on the top, fall survey on the bottom, and females on the left and males on the right there. Finally, the Virginia Tech Trawl Survey. This is separated out by sex and maturity stage. On the top here we have the newly mature crabs with females on the left and males on the right.

Then the bottom mature individuals, females on the left, males on the right. The data gap in the middle of the time series is due to a lack of funding for the survey during that time. For Delaware Bay there are 28 of the 91 comparisons were significant and positively correlated, and this is mostly between the Delaware Adult Trawl Survey, the New Jersey Ocean Trawl and the Virginia Tech Trawl Surveys, all of which are used in the Catch Survey Analysis and the ARM Framework.

Just those indices from the ARM framework were subset, and of those 28 comparisons 12 were significant and positively correlated. Lastly, the Southeast Region. On the upper left we've got the North Carolina Estuary and Gillnet Survey, on the upper right the South Carolina Crustacean Research and Monitoring Survey, which has since then renamed to the Estuarine Trawl Survey, but we're maintaining the old name here to be consistent with the benchmark, and that will be changed in the next assessment.

On the bottom left is the South Carolina Trammel Net Survey, and the bottom right the South Carolina section of the NEAMAP Survey. Both of these are marked with red stars, and that is to indicate that these surveys underwent changes in their sampling design in recent years. Trends post 2019 should be interpreted with caution, because we don' t know if those trends are representing true trends in abundance, or it it's more of an artifact of the change in the sampling design.

Typically, we would stop a time series if survey methods changed, so this is something that the SAS will revisit in the next benchmark assessment. Then the Georgia/Florida Region of the SEAMAP Survey on the left, again also subject to the sampling design changes, and then finally on the right is the Georgia Trawl Survey. For the Southeast, 4 of the 15 comparisons were significant. Most were positive, but one was negative, and that was between the Georgia/Florida Region of the SEAMAP Survey and the South Carolina Crustacean Research and Monitoring Survey. Next, I'll go through the tagging analysis. This data comes from the U.S. Fish and Wildlife Service's Horseshoe Crab tagging database, which also provides regional recapture rates.

This allows for mark-recapture analysis to derive survival estimates for each region. I do just want to note that the tagging analysis regions are slightly different from the management region, so you can see those on the screen. In this table, shows the survival estimates from that model, both with the 2019 benchmark and the 2024 update.

The highest survival rates were in Delaware Bay, and the lowest in the Southeast Region. All regions saw a decline in survival since the benchmark, with the exception of the Coastal New York/New Jersey Region. But though there was a decrease in survival for most regions, the error rate also increased quite a bit.

You can see the really wide confidence intervals in the 2024 update. This decrease in survival may be due to reduced tagging efforts in recent years, which I will show in more detail in a little bit. Then just to visually show between a benchmark and the update assessment estimates, those super wide confidence intervals.

With the exception of the Southeast, the update and benchmark confidence intervals full overlap. Just to illustrate the change in tagging effort. On the top table here is the number of tag releases, and the bottom the number of recaptures. The last three columns are how they deviate from the average within the last three years of the assessment.

You can see there was a decrease in both releases and recaptures in 2020, with some regions still remaining below average tagging effort in 2021 and 2022. Again, New York/New Jersey had the smallest reduction in tagging effort during COVID, and they are also the only region that did not see a decrease in their survival rate.

Just to kind of recap, the reduction of crabs in 2020 coupled with reductions in recapture reports in 2020 and 2021, would likely cause a tagging model to underestimate survival rates. This is because the tagging models rely on consistent reporting rates to produce reliable estimates, and the model will account for these missing tag-recaptures as mortalities or emigrants from the population, which will in turn reduce survival estimates.

From the tagging analysis, the survival rate from Delaware Bay is used to estimate natural mortality for the Catch Survey Model, and in 2019 in the benchmark assessment, that rate was 0.274, and the 2022 ARM revision it was 0.3, and for this update 0.4. I also just want to note that the calculation from survival to mortality may be more appropriately characterized as total mortality, rather than natural mortality. That will be reconsidered in the next benchmark.

Next, I'll talk about the Catch Multiple Survey Analysis. This is updated annually, as part of the ARM framework, to support harvest specification setting in the Delaware Bay Region. Use of quantifiable sources of mortality to estimate male and female horseshoe crab populations, it was developed for the 2019 benchmark, specifically for female horseshoe crabs, and then updated in the 2022 ARM revision, and the male model is also developed as part of that. Just to note, because of the Delaware Bay specific biomed data is confidential, population estimates for horseshoe crabs were made using the coastwide biomedical data or no biomedical data, to provide those upper and lower bounds.

I won't go through the analysis in too much detail, because this same version through 2022 was already presented to the Board in detail during the October 2023 meeting, as part of the ARM framework. As a reminder, there is no management action from the coastwide assessment that was based on this Catch Multiple Survey Analysis.

This is only used for management in the ARM framework. In 2022, the model estimated 16.1 to 16.2 million mature female horseshoe crabs in the Delaware Bay Region, and approximately 40.3 million mature male horseshoe crabs in 2022. Because of those data caveats that I spoke about with the tagging model for the 2024 update, the base run of the catch multiple survey analysis used the M of 0.3 from the 2022 ARM revision.

That is the gray line in these two figures here. But we did do a sensitivity run using the revised M of 0.4, and that is shown in the black line. Ultimately, the population estimates from each run varied pretty minimally, but in the sensitivity run, did result in slightly higher terminal year population estimates.

Next, I'll go over the ARIMAS, the Auto Regressive Integrated Moving Average Models. These are fit to the time series of horseshoe crab abundance indices that were shown before, and they estimate the probability that the terminal year in each index is less than certain reference points with 80 percent confidence intervals.

Those reference points are the lower quartile of the fitted index values, and also the 1998 for the index value. That year representing when harvest restrictions were implemented. Now I'll go through the results. Just to kind of orient you to this table here, the first column is the survey which the indices was derived from, and then I want to draw your attention to the columns with the percentages.

This fourth column here being the probability that the terminal year is below the 1998 reference point, and then in the third column from the right here, that is the probability that the terminal year was below the lower quartile reference point. Then the last two columns are the results of Mann-Kendall Test to detect trends in the data. That is since 2017, being the terminal year of the benchmark assessment, and also since 2012, which was the terminal year on the last update assessment. For the Northeast Region, there are mixed ARIMA model results.

For the Massachusetts Trawl Surveys they showed increasing of stable trends, with low probabilities of being less than either of those reference points, whereas the index from the Rhode Island Trawl Survey is showing a continued decrease, and has a high probability of being below both of those reference points. The New York Region has generally continued to show declining trends, which has been evident since the 2009 benchmark assessment. The Jamaica Bay, Little Neck and Manhasset Bay and Peconic Bay surveys all have high probabilities of the terminal year indices being below their 1998 reference points. But the Connecticut/Long Island Sound Survey has showed increasing trends since 2012, and the NEAMAP and the New York Peconic Trawl Surveys increased over the last 10 years.

The Delaware Bay Surveys generally all show increase in trends, and low probabilities of the terminal year being less than either or both reference points. This is the Virginia Tech Trawl Survey ARIMA results, and the only exception here is that the trawl survey for newly mature females has shown low abundance since 2019, and this has been discussed in the update report and also during previous Board meetings.

There are three possible hypotheses that have been discussed between SAS and TC members. The first being that there is a recruitment failure in recent years. But this seems the least likely hypothesis, because mature females have continued to increase, and there has not been a concurrent decrease in the newly mature male population.

The second hypothesis is a change the spatial distribution of newly mature females, which is resulting in lower catchability in the surveys or three, these individuals are being misclassified as mature individuals rather than newly mature. Both immature males and females are declining according to the Mann-Kendall Test, but have low probabilities of the terminal year value being less than the lower quartile reference point.

Finally for the Southeast, previous assessments have generally showed increasing or stable trends in abundance. But this update does indicate that there may now be some decline occurring. The South Carolina Trammel Net, Georgia Trawl and the Georgia/Florida portion of the SEAMAP Surveys showed declining trends in recent years, though the probabilities of being less than either the lower quartile in 1998 reference points are still low.

Then again, as previously stated, the trends in the Trammel Net Survey and the SEAMAP Survey should be interpreted with caution, due to the decreased sampling since 2020. As in the 2019 benchmark, stock status is based on the percentage of surveys having a greater than 50 percent probability of the terminal year fitted value being less than the 1998 reference point.

That is within each region and coastwide. Again, this 1998 reference point represents the point in time in which horseshoe crabs became actively managed by the ASMFC, and so status relative to this gives us some indication of the affects of management on the population. A region had poor status if greater than 66 percent of the surveys met these criteria, good if less than 33 percent of surveys met this, and then neutral if the status was between 34 and 65 percent of the surveys.

Here is the stock status over the last several assessments. The regional determinations effort that this update remains the same as in the 2019 benchmark, with the exception of the Delaware Bay Region, which improved from neutral to good status. The Northeast Region remains neutral, and New York remains poor, except for the 2019 benchmark, and the two hypotheses before then for the New York status is either one, that bait harvest remains at a level that is not sustainable in the New York Region, or the habitat has changed and simply cannot support the number of horseshoe crabs that it once did. Then again, although the status of the Southeast Region was determined to be good, this should be viewed with some caution, because it is only based on two surveys that extend back to 1998, one of which has showed recent declining trends, that being the South Carolina Trammel Net Survey, but again also subject to the sampling design changes.

Then the other surveys in the Southeast I would not use as part of stock status determination for the region, have shown some decreasing trends since 2012. But regardless, none of these surveys showed a high probability of the terminal year value being less than the reference points. Then lastly, the update assessment noted several research recommendations from the benchmark that have been either addressed or initiated.

That included collecting more information on horseshoe crab ecology and movement, as well as studies related to the biomedical industry. Then the use of the Catch Multiple Survey Analysis in the ARM Framework, and some additional recommendations from the 2024 update are addressing that reduced sampling in the Southern surveys.

Maintaining pre-pandemic levels of tagging effort, evaluating the use of Z instead of M, in the Catch Multiple Survey Analysis, and then reexamine the stock structure with more years of genetic and tagging data. With that I will be happy to take any questions.

CHAIR DAVIS: Okay, thank you, Katie, for that excellent presentation. I will look to the Board to see if there are any questions on the presentation on the stock assessment update. Mike Luisi.

MR. MICHAEL LUISI: Thank you, Katie, for the presentation. I wonder if you can clear something up for me. During your presentation you mentioned it a couple times, and you used the little red stars as a way to highlight areas to be, just taken with some caution. The first slide you mentioned that the surveys had changed.

Then I think later on you referred to, I believe it was in the Southeast, there just being low numbers of crabs being caught. Were they the same surveys where the methodologies have changed, and they're just catching low numbers? Just want to make sure I'm clear as to where that focus should be on that area of concern, or at least where to focus on, as far as being cautious about the results.

MS. RODRIGUE: Sure, so I believe that is true for the South Carolina Trammel Net Survey, and so that underlined the sampling design changes that lowered the number of samples that are conducted, and also saw declining trends. The other surveys that I spoke on that are showing declining trend, I don't believe they were part of the surveys that underwent those changes. But they are also not included in the stock status determination, because they don't go back to 1998. I would have to look back at specifically those surveys to let you know.

MS. LUISI: Just a quick follow up, Mr. Chairman. If the SAS takes a look at those surveys. Right now, it's kind of like apples to oranges, maybe. Would we anticipate that they would be brought together in some way to cut through a recalibration? Just trying to understand kind of where it went askew. I realize that if the sate wasn't able to conduct the number of surveys and the methodology has changed slightly. I don't have any problem with that. It is just that at some point we will have to figure out how to compare one time series with the other. Just looking, I have another interest in why this would be something outside of horseshoe crabs. But I'm just trying to get your thoughts on, how do you bring those two things in line, if that's the objective of the SAS?

MS. RODRIGUE: I think that standardization could help to an extent, but it may be that the change is too drastic for that to help. I think that typically a time series would not be used if nothing has changed so drastically. But I might look to Kristen if she has any other input on that.

DR. KRISTEN ANSTEAD: Yes, you're correct, Katie, and I'll just add that this was the case. There was a New Jersey Surf Clam Survey, and we have it now as just a shortened time series that we had in the benchmark, and then stopped using it. In the case of the SEAMAP or the trammel, we might either consider that now two indices, because I'm not clear on if there is going to be a calibration to correct the later time series. It might end up being broken or stopped at a terminal year, but it's still used, only through 2019.

CHAIR DAVIS: Okay, next I have Bill Hyatt.

MR. WILLIAM HYATT: In the 2019 assessment, in this assessment then in your presentation today. You referred to the poor condition of the New York area Region population, and speculated that either bait harvest is excessive, or habitat carrying capacity has declined. I was just wondering if you've had any conversations amongst your group, if you were able to speculate as to what type of habitat conditions might contribute to such a decline with horseshoe crabs.

I'm asking that sort of from the perspective of recognizing that within at least the Long Island Sound Portion of their range, the crab population that has made it through some pretty harsh environmental conditions and habitat changes in the past just fine. I'm just kind of at a loss as to what habitat changes might have occurred in the last 15 to 20 years that might be driving this.

MS. RODRIGUE: I don't know that I have an answer for you specifically. I can try and get back to you about it, or if anybody else has comments that might help.

MR. HYATT: No, I would appreciate that, and understand, I'm just looking for some thoughts and speculation. I'm sure there isn't anything concrete or it would have been in the report, so thank you.

CHAIR DAVIS: Next I have Shanna Madsen.

MS. SHANNA MADSEN: My comments are related to Mike Luisi's. First of all, thank you, Katie for a wonderful presentation. I think my question is probably going to be more directed at ASMFC staff, but I find it concerning that the South Carolina Trammel Net Survey portion of SEAMAP has reduced sampling. I'm wondering if that is a permanent change, and if it is a permanent change, why that is happening and what other species might be affected by this, because it is the first time I'm kind of seeing it come up. Thank you.

DR ANSTEAD: Yes, so there were a couple of things going on with the SEAMAP Survey, one was, one of the years there were some storms, and so that was a legitimate not being able to sample during the times they normally. It's also my understanding that SEAMAP has changed their seasons from three seasons to two seasons. I believe that is a permanent change from the previous three seasons, now two that kind of straddle the three. That is one reason why we're not going to be able to go back in time and make these consistent time series. I believe that is permanent.

CHAIR DAVIS: Next I have Conor McManus.

DR. CONOR McMANUS: Really nice presentation, Katie. I know that it is an update assessment, and TOR 1 specific to updating last assessments entities. I'm just kind of curious for food for thought on future assessments, if the group discussed other surveys that exist that are not currently used for individual regions that may also provide insight into relative abundance trends for horseshoe crab.

Just kind of curious if in your meetings there was discussions about other state surveys from other gear types or other seasons that might be of use, particularly in some of the stock units where there may be two, three indices currently being used. It's okay if the answer is, we didn't talk about it. But just kind of curious.

MS. RODRIGUE: Yes, and unfortunately that might be my answer, Conor. But yes, I don't know if Kristen again has anything to add to that.

DR. ANSTEAD: Yes, we didn't re-pole the states for like new data, because it's an update. But certainly, that is something we will do for the next benchmark, and I'm hopeful that there will be some other datasets that play out, especially in those regions that we have fewer.

CHAIR DAVIS: Next I have Ben Dyar.

MR. BEN DYAR: Yes, just to kind of give a little more clarification on some of those sampling methods and changes in South Carolina. The Trammel Net Survey went from monthly sampling down to two months out of every three months for each quarter, and that is just due to logistics. All the methods are the same, the methodologies did not change.

Gear, everything, it's still a random stratified sampling design, so it's just a change in those. Then the SEAMAP is unfortunately, due to funding. But with a new vessel coming online soon, hopefully they will still be standardized methodologies as well with the new gear type for the new vessel.

CHAIR DAVIS: Next on the list I have Dan McKiernan.

MR. DANIEL McKIERNAN: Yes, Katie, great presentation, and I'm not sure you're the person to ask this question, but I need to bring it to the Policy Board. Given the last couple of slides about recommended future studies. Do you folks ponder like where we could find some of that money, because the public interest in the species is just enormous, and yet you can't go to S-K for it or it's not a federally managed species.

It tends to be the poor child among our advantaged species. You don't even have to answer it, but I guess to my colleagues on the Board. I wonder if we can put our heads together to find funding sources for a lot of these questions that you've identified that will help us manage going forward.

MS. RODRIGUE: Thank you, and I will just say, at least in Rhode Island we do take advantage of the State Wildlife Grant for species like horseshoe crab that aren't covered by say the Sport Fish Restoration Fund. But in terms of all their funding sources, I'm not really sure.

DR. DAVIS: John, go ahead, John Clark.

MR. JOHN CLARK: Thank you for the presentation, Katie. Just curious, I know the issue with the primiparous and the Virginia Tech Trawl was kind of an oddity there. I know this went through 2022, the assessment. Did you get 2023 data? Did that still continue where they are still not seeing primiparous females in the Virginia Tech Trawl for last year?

MS. RODRIGUE: I have not seen the 2023 data, so I'm not sure about that.

DR. ANSTEAD: John, we did hear from Virginia Tech after the 2023 season, and they did see primiparous this past year. We won't get that data for a couple more months, and I have just queried for all of the data to support the ARM that you will see in the fall. But there were primiparous again.

CHAIR DAVIS: Okay, I don't have anybody else on the list. Last call here for questions on the presentation. Any hands online? Okay, I think at this point, as a next step, we would want a motion to approve the stock assessment for management use. I'll look to the Board to see if anybody is inclined to make that motion. Shanna Madsen.

MS. MADSEN: **Move to accept the 2024 Horseshoe Crab Assessment Update for management use.**

CHAIR DAVIS: I'll look for a second. Conor McManus. Shanna, would you like to provide some rationale for the motion? Okay, you're going to pass, Conor, as the seconder of the motion?

DR. McMANUS: Just nice work and thank you, really good stuff.

CHAIR DAVIS: Okay, any discussion on the motion? Let's see if we can do this the easy way**. Are there any objections to the motion? Any abstentions for the record? Okay, seeing no hands the motion passes by unanimous consent.** I believe that concludes that item on the agenda. I'll look to Caitlin to see if I'm forgetting anything.

DISCUSS HORSESHOE CRAB BAIT DEMAND

CHAIR DAVIS: We're good, all right, so we'll move on to our next item on the agenda, which is a Discussion of Horseshoe Crab Bait Demand, and we're going to have a presentation from Caitlin Starks.

MS. CAITLIN STARKS: At the last Horseshoe Crab Board meeting there was a brief discussion about differences in state regulations concerning horseshoe crab bait harvest along the coast and how restrictions in some states might impact other states.

POSSIBLE IMPACT OF STATE HARVEST REGULATIONS ON BAIT DEMAND

MS. STARKS: The Board requested that staff gather some information from the states with horseshoe crab bait fisheries, as well as states with fisheries that use horseshoe crab as bait, to better understand these dynamics.

Some questions were sent out to the State Administrative Commissioners, and these were, what commercial pot fisheries in your state are using horseshoe crab as bait? Has a survey been conducted of the trap or pot fishermen in your state that use horseshoe crab as bait about their use and alternative bait, and are data for these fisheries collected that could reveal trends and effort? For example, number of active permits or traps fished or trap hauls.

If those data are being collected, what are the trends that are being seen? Then if the state bans or severely restricts the bait harvest of horseshoe crab, has it also considered restrictions on the use of horseshoe crab as bait by pot fishermen? Then lastly, does the state collect any data that would allow us to quantify the origin of horseshoe crab imported from other states, and how much?

I'll just go over the summary of responses that I received. First, the two pot fisheries that were identified as using horseshoe crab as bait are eel and whelk or conch. Most states have at least one of these fisheries, and as you can see at the bottom, there were some blanks where I'm missing some information.

Then as for the state survey, none of the states indicated that they've conducted their own surveys of the pot or trap fishermen in their states about their bait use. The only survey that has been conducted relevant to this topic was the ASMFC survey on eel fishing practices in 2017, and that survey found that about 22 percent of the eelers that responded used horseshoe crab as bait.

Then some but not all of the states have data that can show trends in effort in the eel and whelk fisheries. Generally, the states have landings data as well as permit data, or number of participants. Then there are a few states like Connecticut, Delaware and Virginia that do have trip level effort data for eel and whelk.

Then in terms of the trends that these states have been seeing. Massachusetts reported that effort and landing in the whelk fishery have been declining. Connecticut indicated there has been low but steady effort for eel, while the whelk there show effort decline from the mid-2000s to mid-2010s, and then has stabilized at a lower level.

New York data don't show significant trends for eel, but for whelk the pot landings trips and number of fishers reporting landings have all increased since 2014. The number of permits also increased from 2000 to 2023 by 24 percent, but it has been declining since 2009. Then New Jersey indicated they have seen increases in the last couple years for both of these fisheries. Maryland has seen declines in both the number of eel potters and landings since 2012, but for whelk the number of potters decreased, while the whelk landing increased. Then in Delaware there has been a significant decrease in eel effort since the female horseshoe crab harvest ban. Then for whelk the number of participants has decreased, but soak days and landings have increased.

Then lastly, Virginia data show that there has been declining effort for the eel fishery, but a shift in the effort trends for whelk, where it increased and then was followed by a decrease in the more recent years of the time series. Regarding the question on whether states with bans or significantly restrictive regs for horseshoe crab harvest have also implemented restrictions on bait use; the answer is generally no. None of the states have implemented or considered such measures at this point. Then the last question that was asked is whether the states collect any data that would show the quantity and origin of horseshoe crabs imported from other states. Again, the answer across the board here was generally that the states so not collect any such data. I know that was a quick summary, but I'm happy to take any questions.

CHAIR DAVIS: Thank you, Caitlin, I'll look to the Board to see if there are any questions. Dan McKiernan.

MR. McKIERNAN: Thank you, Caitlin, for compiling that. I know I brought that up at the last meeting, and I really appreciate you compiling all that information.

CHAIR DAVIS: Thank you, Dan. Any other members of the Board with questions or comments? Do we have any hands online? Okay, no hands online. Okay, if there are no further comments, we'll move along to our next item on the agenda.

ADAPTIVE RESOURCE MANAGEMENT SUBCOMMITTEE (ARM) REPORT

CHAIR DAVIS: Okay, so the next item on our agenda is a report from the Adaptive Resource Management Subcommittee. John Sweka.

DR. JOHN SWEKA: Just a little history about how we got here and the source of this presentation. The original Adaptive Resource Management Framework was adopted for management use back in 2012, and it began setting harvest levels for horseshoe crabs in the Delaware Bay region beginning in 2013.

From 2013 through 2022, the ARM Framework consistently recommended 500,000 males and 0 female harvest. The ARM Revision then was ultimately adopted in 2022, had many changes to the modeling. This was because we gained much, much, more data in the Delaware Bay specific both to horseshoe crabs and red knots, and our methodologies for modeling both species greatly improved.

However, with the new ARM Revision there was potential for female harvest, and this created a lot of controversy among various stakeholder groups, and resulted in extensive public comment prior to the October 2022 and 2023 Board meetings. The Board decided then to still set female harvest at 0 after both of those meetings.

TECHNICAL RESPONSE TO EXTERNAL REVIEW OF ARM FRAMEWORK REVISION

DR. SWEKA: Earthjustice contracted outside experts to review the ARM Revision Report, and they supplied public comments in September, 2022, which contained the views and critique by Dr. Kevin Shoemaker of the University of Nevada, Reno, and Dr. Romauld Lipcius from VIMS. Then again in September, 2023, Earthjustice supplied more public comment, which contained an additional review and analyses by Dr. Shoemaker. During the Board meetings last October, the Board tasked the ARM Subcommittee with responding to the 2023 review by Dr. Shoemaker.

What I'll present today here are responses to six major topical criticisms by Dr. Shoemaker, from his 2023 review of the ARM Framework, and then also provide some brief responses to additional items that were contained in his 2022 review, as well as those from Dr. Lipcius from VIMS.

A much greater detail on my response is provided in the report, the ARM Subcommittee generated report. Jumping into it. Criticism 1, the major topic here was that estimates of red knot survival used in the ARM appear to be artificially inflated, resulting in falsely optimistic estimates of population resilience.

Well, there is high survival and long lifespan, which is commonly known for red knots and other shorebirds of similar size and similar life histories. Our estimates of survival are not out of the realm of possibility, and are similar to others. The survival rates that were used in the ARM are calculated from tagging data for red knots in the Delaware Bay, and are comparable to other public studies.

We critically reviewed the tagging information to represent the best available data and all of those caveats were addressed in the data in our survival estimates, and they are provided in our 2022 report. The analysis of the tagging data and its use in modeling was commended also by the Peer Review Panel.

One of the more specific claims in Dr. Shoemaker's review was that survival estimates are biased by individual misidentification of or flagged misreads. While the Delaware Bay misread error is probably between 0.38 percent and 4.5 percent. The way we figure this is there were records of 702 impossible flag observations. These are data entry errors, or data recording errors in the field, where a flag number was written down, but it never occurred when you go back to the historic data. That particular number was never actually applied to a bird.

Also, there was approximately 8,500 single observations of birds. In a given year, there always is a possibility that you misidentify the flag on a bird. We looked at those data and you can remove single observations of a bird within a season. Obviously, if you see a bird more than once, you are more confident that that flag reading is right.

However, some additional modeling by Anna Tucker showed that this level of possible error would have very minimal impact on our survival estimates. I'm moving on to Criticism 2, and that was the trawl-based indices of horseshoe crab abundance are inadequate for modeling the biotic interaction between red knots and horseshoe crabs.

While the inclusion of trawl surveys as indices of horseshoe crab abundance may be imperfect, but it is the best available science that we have, and it has been used for horseshoe crab stock assessment for a long time, and has gone through several independent peer reviews. Most of the criticisms that we received on the trawl surveys would also apply to egg densities or bird count data. All surveys suffer from the same sorts of catchability problem.

There is also consensus among all the trawl surveys for an increasing trend in horseshoe crab abundance since 2010. It's not like we only have one survey that shows an increase, all of them are showing an increase. Ultimately, trawl surveys are the standard method of sampling for bottom dwelling organisms such as horseshoe crabs, and are used for many other species as well.

Within this criticism, we were criticized for not using a general linear model or a general additive model in calculating indices of abundance for horseshoe crab. While the Delaware Trawl Survey actually does use a GLM approach, and this is because it is fixed station survey, and this was pointed out during the peer review of the ARM Revision.

We went back and changed it and recalculated that index. Also, the Virginia Tech Trawl Survey follows a stratified sampling design, and those sorts of things that would affect trawl catchability are taken into account by the sampling strata. Also, the New Jersey Trawl Survey, we had attempted to do a GLM standardization in the 2019 benchmark stock assessment, and found that it didn't really improve the data or the error on the data very much.

There has also been a lot of criticism for a lack of correlation between the trawl surveys. Well, it depends on what sort of correlation analysis you do, and at the end of the day each trawl survey still shows an increasing trend. It's the consensus among these trends that is important, not exactly how closely they match one another.

There is always going to be some mismatch, you know a trawl being in the right place at the right time gets crabs. I'll have more on this correlation criticism in the next point. Criticism 3 was that red knot survival is strongly sensitive to horseshoe crab egg density, indicating that persistent degradation of the horseshoe crab resource could have dire consequences for the red knot population.

Well, we've been criticized for not using egg density data. The egg density data were requested by the ARM Subcommittee, but they were never provided. Therefore, we couldn't consider them as a data input to the models. When we look at the egg density data, which was finally supplied in a publication by Smith et al in 2022, after we had finished up the ARM Revision.

We look at the trends in egg density data, and low and behold they are correlated with other data inputs from the years included in the ARM Model. Thus, we think even if we would have had the egg density data ahead of time, it's unlikely that they would result in any meaningful difference from current ARM Framework, in terms of harvest recommendations, because they showed similar trends.

Again, the Smith et al paper that documented the egg densities in recent years, showed general increasing trend in horseshoe crab eggs. They were very similar to the horseshoe crab abundance, and consistent with the findings of the ARM revision. Here we have the correlations of the egg density data that was extracted from Smith et al. The population estimates from the Catch Multiple Survey Analysis, the New Jersey Trawl, Delaware Trawl, and Virginia Tech Trawl, and here we have a correlation coefficient, and those that are circled are statistically significant at the 0.05 or 0.10 level. Also on this graph, we just compare our catch multiple survey analysis estimates of female horseshoe crab abundance with egg density data that we digitized from Figure 2 in Smith et al, 2022.

As you can see, both of them show interannual variations, some ups and downs, which could be due to sampling effects, or just random sampling error. But overall, there is an increasing trend over both time periods for the egg density data, as well as female crab abundance from the Catch Multiple Survey Analysis. Dr. Shoemaker also reanalyzed the egg density data from Smit et al, to try to account for differences in survey methodologies through time.

Once he reanalyzed those data, contrary to Smith et al, he found no increasing trend. Well, there is not a whole lot we can say about this, because again, we weren't provided the egg density data. But it is interesting that Dr. Shoemaker reanalyzed their data to account for differences in survey methodology, which was one of the reasons why we've always been reluctant to use egg density data, because of the consistently changing survey methodologies through the years.

Dr. Shoemaker also conducted an analysis then to determine the effect of egg density on red knot survival, and he found that survival was positively correlated with egg density. But the methods that he described in his report weren't documented in great detail, and only included the New Jersey side of the Bay, so egg density and also bird data just from the New Jersey side.

It is somewhat questionable whether that analysis is applicable to the entire Bay. If Dr. Shoemaker's analyses are correct, we would have a positive relationship between egg density and red knot survival, but no trend in egg density. But all of our analyses and our Catch Multiple Survey Analysis shows an increasing trend in female abundance.

It begs the question, how do we then link harvest, which affects crab abundance, which then obviously crab abundance should affect egg density, not only red knot survival. How do we then model each one of those steps in the entire process? Unfortunately, Dr. Shoemaker in his criticisms and review doesn't propose a parameterized model to do so.

Moving on to Criticism 4, the ARM exaggerates evidence for an increasing trend in the number of females horseshoe crabs in the Delaware Bay. Well, the analyses that were provided in Dr. Shoemaker's report had some errors, including the use of incorrect data sub-setting for some of the indices that he was provided data, and applications of an analysis that we feel is inappropriate for the data. The trawl-based indices were early considered by the ARM modelers. Katie just presented them to you here today as part of our stock assessment update.

They represent the best available science for tracking horseshoe crab abundance, been through several peer reviews by this point. The goal of the ARM modelers is not to find an increasing trend, but to develop the data in the most statistically sound way possible, regardless of what the answer may be. When Dr. Shoemaker was provided the data, he reanalyzed the New Jersey Ocean Trawl Survey using a GLM approach. The ARM Subcommittee, we have no issue at all with using a GLM approach, and like I said, we attempted this during the 2019 benchmark assessment, but found that it didn't really improve the data much. As we collect more data, perhaps we can better derive the effect of covariates upon catchability, and a GLM would be more useful. As I said, however, Dr. Shoemaker subset the data in an inappropriate manner, and this was discovered in an initial review of his report by staff at New Jersey.

Dr. Shoemaker made a questionable analytical choice when conducting a trend analysis. Here on these figures the two figures on the left are from Dr. Shoemaker's trend analysis approach, where he fit a linear model to both his raw and also adjusted index values, adjusted using the general linear model.

Well, Dr. Shoemaker ran this trend analysis on the entire time series of the data, and obviously early on we did have a decrease in horseshoe crab abundance. You know the Delaware Trawl Survey went back to 1990, and there was a decline in abundance, and a decline up through 2000, and this was part of the reason it spurred on the development of the fisheries management plan for horseshoe crab.

What we have here is a time series of data from the three trawl surveys that shows a U shape. Well, if you fit a linear model to U-shaped time series, of course the slope is going to be close to zero over that entire time series. What should be done is either, you know you can see clearly in the surveys here that around 2010 is when we seem to hit a low point in abundance from all the surveys.

If we looked at just the information in the time series coming from 2010 with just a simple linear model from that point to the present. You know we have a significant increase in female crab. Another possible approach, if you wanted to look at the entire time series, would have been to use a segmented regression approach, and that would show you a decreasing trend, and then again even with the segmented regression approach, it turns out that around 2010 we have a change in the slope, where it changed from decreasing to an increasing trend.

Looking at Criticism 5, this focused on our red knot model, and it's the integrated population model used for estimating red knot population parameters is overparameterized and likely yields spurious results. Dr. Shoemaker's criticism of the red knot model is really unsubstantiated, and misrepresents the models used in the ARM Framework.

Much like the trawl surveys, I mean red knot data are imperfect, but they are the best available data that we have. They are also subject to catchability issues or detection error from one year to the next or from one trip to another to another out in the field. Dr. Shoemaker assumes that too many parameters will produce incorrect results, when the relationship between overparameterization and bias models is really more nuance than that.

I would like to remind everybody, the Integrated Population Model that was used for red knots is actually three different models all put together, and each one of them feed into one another. You know first we have a life cycle model; this is your typical stage structured model that advances juveniles to recruits to adults, and those adults then produce these juveniles. Typical sort of model used in all population biology. We also have the open robust model, which is used to estimate survival from the tagging data on the bird, and a state space model, which accounts for the observed counts and those aerial surveys and ground count surveys of birds from one year to the next. If all three of these models are essentially ran simultaneously, and they feed into one another in the estimation of those vital parameters, such as survival and recruitment for red knot. This is something I think Dr. Shoemaker failed to recognize is that structural linkage between the sub models. His claims for overparameterization may be valid for traditional applications of singular models, but it is much more nuanced for an integrated population model.

At least at this point in time there is no hard and fast rules as to what overparameterization may be. One thing you always keep in mind is that overparameterization does not necessarily mean biased results. Under-parameterization can too. The next criticism is that the Integrated Population Model exhibits poor fit to the available data.

In this critique, Dr. Shoemaker provided some conflicting arguments from the use of goodness and fit test to the red knot model. Goodness and fit test applied to the red knot model indicated poor fit in one model component, but the proportion of the model including the survival probability did not fail that goodness of fit test.

There are certainly some more details than that in the report if you would like to read them. Moving on to Criticism 7 through 11. These were a few major topical things that we as the ARM Subcommittee thought we should bring forward to the Board, and these are from the 2020 reviews by Dr. Shoemaker and Dr. Lipcius, and some additional items from a supplemental section in Dr. Shoemaker's 2023 report.

On Criticism Number 7, this is a big one in the first comments we got from Dr. Shoemaker and Earthjustice. This is the estimate of mean horseshoe crab recruitment and propagation of error within the horseshoe crab population dynamics model is inappropriate. Do you remember, we had those years of Virginia Tech Survey when it did not operate. Admittedly, those years of our estimates of recruitment coming from our Catch Multiple Survey Analysis, those are poor years.

But the estimate of mean horseshoe crab recruitment used by our Subcommittee is still really the most biologically realistic. If mean recruitment were lower, as Dr. Shoemaker suggests, then as we project our population forward, the current population estimate of horseshoe crabs will be well, well above any predicted "carrying capacity" of the Delaware Bay, and certainly we expect the crab population to decline due to that carrying capacity.

Now Dr Shoemaker's proposed method for air propagation is something that is worth considering by the ARM Subcommittee in the next revision of the ARM. But when we make some comparisons between his population projections and those of our current models, they are nearly identical, and this was shown in this slide.

The graphs on the left are from Dr. Shoemaker's 2020 review, where he recalculated the Catch Multiple Survey Analysis, used his method for air propagation, and it's more of a Bayesian model and predicted that forward. Then on the right are predictions from our current ARM model for horseshoe crab. The top graphs are under a situation of no female harvest ever, and also a 210,000 female harvest, you know the maximum allowable. If you just did that and held that constant each year. As you can see, I tried to scale these graphs as best I could, so that the scales match up, and essentially, for all of the concern over our air propagation and mean recruitment, in the end the projections from both Dr. Shoemaker's model and that of the ARM Subcommittee are essentially the same, you know the same number of multiparous and primiparous crabs, so the N and the R.

The next criticism was that the ARM model would not predict a decline in red knot under a total collapse of the horseshoe crab population, and that is evidence that the model is fatally flawed. Well, Dr. Shoemaker is incorrect that the ARM model would not predict a decline in red knot if the horseshoe crab population collapsed.

His assertion that red knots would continue to increase in the absence of horseshoe crabs is just mathematically impossible in the model. Red knot survival in our model is a function of the log of female crab abundance. Obviously as survival declines to zero as crab abundance decreases. Also, we should keep in mind that a complete collapse of a horseshoe crab population is a sensationalized and extreme scenario.

If that should happen, nobody would argue either at the ARM Subcommittee level, the TC level or this management board, that if our abundance of horseshoe crabs would dip to low levels that are lower than what we've seen or used to build our models, you know we wouldn't advocate for additional harvest of horseshoe crabs.

You know certainly, we're trying to make predictions on a model based on data that is well outside the range of a model. Criticism 9 deals with demographic data that indicate a declining horseshoe crab population. These comments came from Dr. Lipcius with VIMS in the 2022 comment.

During his comment, one of the things he looked at was this declining size of mature horseshoe crabs in the Virginia Tech Trawl Survey. That decline started in 2008. He used that as an argument that it could indicate overfishing is occurring. Now we certainly agree that in a typical finfish fishery, if you have declining mean size at age, that is indicative of overfishing, because a fishery will select for faster growing individuals, and those faster growing individuals are plucked out of the fishery the sooner, and then therefore your mean length at age would decline.

However, application of that rule of thumb to horseshoe crabs is a bit uncertain, because horseshoe crabs will grow, have a terminal molt, and then stop growing afterwards. It's pretty uncertain whether you can apply that same general rule of overfishing to the species like horseshoe crabs.

Now along with that declining size at age, the smaller the horseshoe crab size the fewer eggs you would expect to be laid by that crab. Dr. Lipcius assumed that we would also have declining recruitment or egg deposition in recruitment. But assuming the natural mortality is not changed, and we've seen the increase in abundance of horseshoe crab, abundance of horseshoe crabs could not have increased if egg deposition and hatch also had not increased over that same time period.

Recent low estimates of the other thing is recent low estimates of female newly mature crabs, as seen in the Virginia Tech Survey. We've discussed this problem over the past few Board meetings, Katie mentioned it earlier. Again, male newly mature crabs did not decrease over the same time period. Although it really doesn't seem that overfishing is occurring with horseshoe crabs in the Delaware Bay, and we have no evidence to suggest that. Criticism 10 was specific to the bird population model again, and that is that there is an incorrect specification of the "pi" parameter in the red knot IPM model.

The "pi" parameter is the probability of being present in Delaware Bay in the occasion t of year j. Is the bird present or not as the Integrated Population Model is looking at, you know different time periods within a year, could the birds be present or not in Delaware Bay? This is a criticism that does warrant some further consideration by the ARM Workgroup.

We should look into this a bit further, and our folks that were experts in bird modeling are considering this in any future revisions. Finally, the last criticism is that there is an overrepresentation of Mispillion Harbor in red knot resighting data. While use of data from Mispillion Harbor does not result in bias inferences, it is very true that the bulk of red knots are seen in Mispillion Harbor.

But when we start to look at the number of birds and the proportion of birds that are seen just in Mispillion versus other sites, this really is not like it's overwhelming or the overwhelming amount of data comes solely from Mispillion Harbor. As we can see here, this is the proportion of birds that are seen in Mispillion Harbor only, other non-Mispillion Harbor sights and then sighted at both Mispillion and other sights.

You can see they are almost the same across the board, and it varies a bit from year to year. It's not like data from one site is overwhelming the model. Just to conclude our rebuttal to a lot of the comments we've received. You know continued scientific review is always welcome. That is how science progresses, so we welcome that. The ARM Revision really represented some great advances in our understanding of population dynamics for both species, and methods to optimize the harvest.

The ARM Subcommittee, we are left wondering, with all the advances we made in our modeling, why was the original ARM not criticized nearly as much, and we can't help but ask, is the real problem with the final answer and not necessarily the data methods or the process? The benefit of the ARM Framework is the ability to make decisions with imperfect data. That is why we went down the Adaptive Management Route from the beginning, way back in 2008.

We strived to design a modeling framework with routine monitoring to allow rapid learning. This is a critical feature that wasn't addressed by Dr. Shoemaker in his reviews. You know our models are based on the data that we get from routine modeling. Easily updated, and easily changed from year to year as more data is added.

A lot of the criticisms really stem from the belief that there had to be a strong relationship between horseshoe crab, egg density, horseshoe crab abundance, and red knot survival. Dr. Shoemaker postulated that the collection of additional data may show the relationship between horseshoe crab abundance and red knot survival could either disappear or become negative with a collection as we move forward. He states in his '22 review, this outcome would pose an existential problem for the ARM Framework, decoupling the two-species framework and rendering the red knot model unusable in the context of management. Our question then is, well, would we not expect the relationship between horseshoe crab abundance and red knot survival to disappear if horseshoe crab abundance were high enough, such that it did not limit red knot survival.

That is something we should expect would happen. There is no question that Dr. Shoemaker is very knowledgeable in quantitative ecology, however, his criticisms focused on specific model components of why each might be wrong. He doesn't provide any recommendations for how to then take all of these individual pieces that he added comments to, and put them back into place and bring them all together again in one unifying decision-making framework.

He also failed to recognizes how uncertainty is handled in the optimization, the approximate dynamic programming. We found it very interesting that throughout all of the comments we received that there were no criticisms about the approximate dynamic programming, no criticism about the utility functions for horseshoe crabs or red knots, and no criticisms about ultimately the Harvest Policy Function that are solved for, and that is really what tells you how many crabs you can harvest, given the number of birds or horseshoe crabs.

There will always be some room for improvement in the ARM Framework, and it is designed to do exactly that through the double-loop learning process. Every few years we add more data. We go back, we rerun our models, rerun the optimization, tweak our models as need be. The critique by Dr. Shoemaker and Earthjustice failed to really make any real recommendations for improvement on that front.

The ARM Subcommittee stands firm in our belief that our work currently provides the best approach to addressing the problem statement, if that problem statement is still valid today. At this point I certainly, myself and the ARM Subcommittee, we really thank the Board for allowing us this opportunity to respond publicly to a lot of the criticism that we received. Thank you.

CHAIR DAVIS: Thank you, John for that excellent presentation, and on behalf of the Board I want to thank the ARM Subcommittee for putting together such a thorough and thoughtful response to the external criticisms of the ARM Revision. It is obvious a tremendous amount of work went into that report, but certainly a worthwhile effort. At this point, I'll look to the Board to see if there are any questions or comments on John's presentation or the report. Bill Hyatt.

MR. HYATT: John, thank you, and I'll echo what Justin just said that to you and all your team that was a tremendous amount of work, tremendous report, and I think it's going to be useful to us as Board members on many fronts. I have a question, and I hope it is not an eye roller. I hope I didn't miss something.

But in the report, itself, I believe there is a research recommendation in the text to examine the horseshoe crab abundance egg density estimates, to begin to establish that longer chain that you were talking about. I guess I'm wondering, is the data that is being collected currently, provided you have access to all the data. Is the data that is being collected currently sufficient to begin that process, or is there additional data that needs to be collected and additional work that needs to be done, just to get it started?

DR. SWEKA: That is a difficult one to answer. I think the egg collection data has gotten better in New Jersey through the years, you know at least with what we have been given in the final report for publication. I mean it does sound better than it was. If you remember back in 2013, that was when Delaware was questioning whether or not they needed to collect egg density data anymore.

You know at that point in time it seemed, you know the methodologies seemed to constantly be changing, and when asked whether or not they should collect it, the TC and the SAS, that no, we don't need to, because the methodologies are constantly changing. Since then, I think it has improved. Is it adequate enough? Well, I guess we would have to see it to really know.

CHAIR DAVIS: John Clark.

MR. CLARK: Thank you, John, and the Committee. This is phenomenal. It is great that it is out, and of course the problem is that the damage was done over a year ago, when all this came out and I still see the Shoemaker criticisms in newspaper articles and of course we're still seeing a lot of push from some of the more extreme groups to ban horseshoe crab harvesting total. I still don't understand the connection between male horseshoe crabs and eggs on the beach.

One of the criticisms, I mean Bill brought up the egg density, and that keeps coming up, and yet we have this great data showing that as the population of females is increased, obviously it is not a limitation here. I don't see how they cannot make the connection between the horseshoe crabs and greater egg density out there.

It just seems to be something that just keeps coming up. As you said, the egg density study was terminated on the Delaware side, and it is not something we look forward to, but that question just stays out there. We've heard from some NGOs that are asking us for permits to do their own egg density work and all.

It's obviously a concern, I mean there just doesn't seem to be, when people that have agendas out there want to do this work, it's just a little off-putting to us. Phenomenal work, but don't know if it is really going to cure the problem. But I hope this does get the type of publicity it should get from the many criticisms that we've seen about the ARM since the ARM came out.

CHAIR DAVIS: I have Mike Luisi next on the list.

MR. LUISI: Thank you, John, for your presentation. I just wanted to make a general comment. As someone who has dedicated the past 25 years in a natural resource management career, I find a lot of comfort in what just happened between the report, the work to develop a response in a very articulate way, in a professional way, to confront the critics that we often get to the survey work that we do, the results that we put forth, the modeling exercises that we go through. I'm often challenged, as well as my colleagues in Maryland about when the results are what the stakeholders are looking for, they are often challenging the work that we do. I was actually, I wanted more. I wanted there to be more criticisms. It was the first time in a while I've been disappointed that one of his presentations wasn't getting to wrapping up. But I thought you did an excellent job, and I think that the work that, I would love to give you credit, Mr. Chairman, but I think maybe this might have been John's work as a former Chair, working to allow the ARM Subcommittee to put forth this report in the way that they did.

I hope we can use this as a process in the future, not just for horseshoe crabs but for other species, when we as a management board are criticized about the work we're doing. We have some of the world's greatest scientists working right with us every day, and I just found it refreshing, and I hope that we can take this in and consider using this type of process down the road when we have other hurdles that we have to get over. Thank you.

CHAIR DAVIS: Next I have Rick Jacobson.

MR. RICK JACOBSON: John, I want to echo what everyone else said, fantastic work on your part and on the work of the entire Subcommittee. The ARM Model is really a remarkable step forward, so thank you for that. I actually have two questions, and the first question hearkens back to your response to Criticism Number 4.

If I understood your description correctly, there is actually a recognition of a changing trend in horseshoe crab abundance based on the survey data that that occurs before 2010, and that that occurs after 2010, a shift from declining abundance to increasing abundance. I wonder if there is anything in particular you can point to that would suggest that inflection point, and where there was a change.

What was forcing that change or causing that change? Then the second question builds on Mr. Hyatt's question earlier about egg abundance data. If we were to start anew. You know we make substantial investments today in the various survey techniques for adults and immature horseshoe crabs.

If we were to reinvest those dollars in some way, with a very structured and thoughtful approach to egg abundance surveys, where we had confidence in the data that was being collected. Is there any reason to think that we would be further ahead reinvesting in that direction, or would we be further ahead staying with our investments, looking at immature and mature horseshoe crabs?

DR. SWEKA: Thanks, Rick. To your first question, why the change in 2010. You know it really makes sense when you think about the life history of horseshoe crab. They don't mature until they are 9. 1-0 years old, and the first FMP came online in 1998, you know by the time the harvest was curtailed greatly after that.

It would really take a good decade, and we said this all along, even from early on in the horseshoe crab management. It's going to take a while to see an effect. After 10 years, you started to get all of the age classes that were protected and had less fishing pressure on them, they all matured. It made perfect sense that around 2010 is why we would see the increase. You know I think the Commission should be proud, you know this is certainly an example where management has worked, you know decreased harvest. We kind of knew as scientists it is going to take a while to see a change, and eventually it did change and we can detect that. As far s the egg abundance, certainly we've never been opposed to using egg density data, it is very difficult to use, because not only do you have year to year variations, you've got day to day, you know beach variation.

Could another survey be developed and consistent methodology be put forth to develop a good egg density survey that we're all confident in? Yes, I think we can. I think it would be expensive, you know take a great deal of effort on people's part, not only collecting the samples, but then processing the samples and enumerating eggs in a core sample of eggs or a core sample of sand.

Is it worth doing? You know that is something I think we could discuss more on the SAS or the ARM Subcommittee. You know we do have the empirical relationship between horseshoe crab abundance and survival now. By adding the step of eggs into our model, I mean it is going to increase some uncertainty.

Even if we could find a good relationship between crab numbers and egg density, that is still one more step and a bit more uncertainty that we add into our model. Those confidence intervals on the population may get bigger. Yes, I'm not sure if it's really, really worth it. I don't know, we might have to do another exercise where we look at what is known as the evaluation of perfect information, you know would it really change a decision if we had that additional step in there, you know an exercise we could do?

CHAIR DAVIS: Next I have Rob Lafrance.

MR. ROBERT LAFRANCE: I think that was a really great explanation of the egg density. That was kind of the way I was going, in terms of the question. One of the things I think happened, when you think about red knots, that is what they are looking at, but that is the egg density issue. I really appreciate what you said, in terms of understanding it.

Is it your sense though that the protocols are actually getting better? Are we getting any better consistency in how we would look at it, or is that still something that needs additional work before we could come up with something that may be used for management?

DR. SWEKA: I think it needs more critical review. Like I said, we see what is in their latest publication, and that sounds good, but we haven't seen the real data. If the generators of the egg density data would conform to typical processes within ASMFC, to provide data when a stock assessment starts, just like every other entity. We get information from the state, from academia, from other federal agencies. You know we would certainly treat them the same with the same critical rigor, but also the same fairness.

CHAIR DAVIS: Shanna Madsen.

MS. MADSEN: Thank you, Dr. Sweka and Dr. Anstead and the rest of the ARM Team. I can see the amount of work that this represents, and I, like Mr. Luisi, think that this was a really important step, and something that was needed to be done. It's really important when we're criticized scientifically that we are allowed the space to respond scientifically as well. I appreciated seeing that. This isn't really a question, but more of a comment. I think that it would behoove us to have this on the management website for horseshoe crabs, maybe go out as a press release or something along those lines, because again, this sort of information really needs to get out there. These are the legs that we stand on, and I think that needs to be out.

CHAIR DAVIS: Thanks for that, Shanna, and I'm sure there can be some follow-on conversations after the meeting deciding the best way to publicize this report. I agree. I have exhausted the list of hands I have on this topic, and I don't believe we have anybody online, so I'll just issue one last call for questions or comments on this topic before we move on. Not seeing anyone, thank you, John.

UPDATE ON HORSESHOE CRAB MANAGEMENT OBJECTIVES WORKSHOP

CHAIR DAVIS: We'll move on to our final scheduled bit of business on the agenda today, which is an Update on the Horseshoe Crab Management Objective Workshop from Caitlin.

MS. STARKS: Sorry, I was trying to get out of this. But the first week update where we are with this workshop. We've sent out invitations to a list of participants that cover the stakeholder groups with an interest in horseshoe crab management in the Delaware Bay. We have participants who are shorebird biologists, horseshoe crab biologists, state managers, representatives of environmental organizations, and bird advocacy organizations as well, as well as some biomedical representatives.

I think this will be a really good group to get all of their heads together and have some productive discussion. The workshop has been scheduled for July, mid-July, 15th and 16th. The location is still to be determined, but we are aiming for the Delaware/Maryland coast area, to try to make it more assessable for some of the folks coming from those coastal areas that this fishery takes place in.

That is our next step is to hold that workshop, and then coming out of that workshop we won't have quite enough time to get a report back to the Board in August, so the expectation is that we will have a report, including recommendations from that group, and things for the Board to consider for future management at the October meeting.

In case I didn't mention it previously, we have contracted with Dr. Kristina Weaver, who helped with the Menhaden Workshop in Virginia, and came highly recommended, and so we have full faith in her abilities to help us get at some of these difficult questions about horseshoe carab management.

CHAIR DAVIS: Dan McKiernan.

MR. McKIERNAN: Quick question, Caitlin. Will there be an opportunity for folks from other states to listen in to the conversation?

MS. TONI KERNS: Dan, we're going to try to. But I'm not going to make a promise just yet.

MS. STARKS: The workshop will be open to the public, if folks want to attend and listen in, in person.

ADJOURNMENT

CHAIR DAVIS: Okay, any other questions on the Horseshoe Crab Management Objectives Workshop? Okay, not seeing any hands, that brings us to the end of our scheduled agenda today. I'll ask if there is any other business to come before this Board. Not seeing any hands; this Board stands adjourned.

(Whereupon the meeting adjourned at 4:30 p.m. on Tuesday, April 30, 2024.)

Report on the July 2024

Horseshoe Crab Management Objectives Workshop

Prepared by
Atlantic States Marine Fisheries Commission (ASMFC) Staff
& Weaver Strategies LLC

Prepared for
ASMFC Horseshoe Crab Management Board

Submitted on
October 7, 2024

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I. Acknowledgements

Funding for the Horseshoe Crab Management Workshop was provided by the Atlantic States Marine Fisheries Commission (ASMFC). Toni Kerns, Caitlin Starks, and James Boyle led ASMFC staff efforts to design the workshop, communicate with stakeholders, and develop this report. They were assisted in these efforts by public policy mediator Kristina Weaver (Weaver Strategies LLC), who consulted on process design, facilitated the workshop, and assisted with developing the report. Shanna Madsen (Virginia Marine Resource Commission [MRC]), Joe Cimino (New Jersey Department of Environmental Protection [DEP]), John Clark (Delaware Department of Natural Resources and Environmental Control [DNREC]), and Michael Luisi (Maryland Department of Natural Resources [DNR]) provided guidance on process design. Delaware DNREC provided facility space to conduct the meeting at the Lewes Field Office.

We are grateful for the assistance of Kristina Weaver, PhD, of Weaver Strategies LLC, who served as the workshop's impartial facilitator. Bringing more than 15 years of experience as an environmental mediator and professional facilitator, including a career with the Institute for Engagement & Negotiation at the University of Virginia, Dr. Weaver had previously facilitated a workshop with similar objectives around menhaden management convened in 2023 by the Virginia Institute for Marine Science. In addition to working closely with the ASMFC convening team, Dr. Weaver conducted stakeholder interviews to solicit input on workshop design.

We especially thank all workshop participants for contributing to candid, collegial, and productive dialogue that generated many insights and several areas of common ground. We also thank members of the public who attended and made comments in person, as well as members of the public who observed the live feed and submitted comments.

Workshop Participants

Henrietta Bellman
Nora Blair
Allen Burgenson
Tim Dillingham
Jeff Eustler
Craig Pugh
Sam Martin
Kim Abplanalp
Lisa Ferguson
John Sweka
Wendy Walsh
Jordan Zimmerman

ASMFC Staff and State Managers

Bob Beal, Executive Director, ASMFC
Toni Kerns, ASMFC
Kristen Anstead, ASMFC
Caitlin Starks, ASMFC
Joe Cimino, New Jersey DEP
John Clark, Delaware DNREC
Michael Luisi, Maryland DNR
Shanna Madsen, Virginia MRC

II. Executive Summary

Horseshoe crab is an important resource in the Delaware Bay region, where multiple stakeholder groups and members of the public have expressed perspectives regarding how the resource should be used and managed. One critical issue of contention is the extent to which the horseshoe crab population abundance and harvest levels are directly linked to the population health of red knot shorebirds (at the species level).

In response to significant stakeholder input following a 2021 revision of its Adaptive Resource Modeling (ARM) Framework for horseshoe crab modeling and regulation, the ASMFC convened professionally facilitated multi-stakeholder workshop aimed at fostering open, deep, and productive dialogue in Lewes, Delaware on July 15 and 16, 2024. The workshop convened stakeholders representing environmental NGO, fishing, biomedical, bird and horseshoe crab scientists, and management perspectives. The workshop adopted a consensus building process designed to surface core issues and concerns, gauge existing areas of common ground, and probe the extent to which new areas of agreement could be developed. Among the more important findings of the workshop were three fundamental areas where common ground was achieved:

- A consensus that there has been an increase in the horseshoe crab population in the Delaware Bay since 2010.

- Universal disapproval with the idea of using a harvest control rule regulatory framework, and an implicit affirmation of a preference for the Adaptive Resource Management Framework (ARM) as the most appropriate modeling and regulatory paradigm.

- A consensus agreement that the ASMFC should continue running the ARM but pause female harvest while several additional recommendations are considered and implemented, including: an investment in better science communication to build understanding among stakeholder groups and to educate the public about all existing channels for input; additional and focused stakeholder outreach to garner "essential concerns" (especially from members of the environmental NGO community that have registered significant disagreement with the ARM Revision); and a process to garner stakeholder input on refining the ARM reward and utility functions towards improving the model and strengthening its credibility.

Beyond these areas of consensus, additional comments, ideas, and proposals were shared and documented. In their closing remarks, participants affirmed that the workshop was highly productive and collaborative, and that important gains had been made around the stated meeting purposes (i.e., increasing understanding of stakeholder perspectives; increasing understanding of current modeling; and identifying concerns, alternatives, and areas of common ground for management). This report provides additional detail on background for the workshop and a summary of dialogue and consensus proposals. A more complete recording of input is included in Appendix 1, with workshop materials enclosed in Appendix 2.

III. Brief Background / Context

a) Horseshoe Crab Ecology, Fishery, and Management

Horseshoe crab, (*Limulus polyphemus*) is an important resource, with diverse values for coastal ecosystems, Atlantic coast fisheries, and human health. Horseshoe crabs play an important ecological role in the food web for migrating shorebirds. The Delaware Bay population of horseshoe crabs is the largest along the Atlantic coast, and this region is also the largest staging area for shorebirds in the Atlantic Flyway. Millions of migrating shorebirds stopover in the Delaware Bay region during their annual migration to feed and rebuild energy reserves prior to completing their journey northward. Horseshoe crab eggs, laid on beaches, are one of the most important food sources for these birds. In addition to their role as a food source for birds, horseshoe crabs provide bait for commercial American eel and conch fisheries along the coast. With their unique blood, horseshoe crabs are also an important resource for human health. Horseshoe crabs are collected by the biomedical industry to support the production Limulus Amoebocyte Lysate (LAL), a clotting agent that is used worldwide to detect of human pathogens in patients, drugs, and intravenous devices. The challenge of fisheries managers is to ensure that horseshoe crabs are managed to meet all these diverse needs, while conserving the resource for future generations.

b) ARM Framework Revision

ASMFC has maintained primary management authority for horseshoe crabs in state and federal waters since it adopted the Interstate Fishery Management Plan for Horseshoe Crabs (FMP) in 1998. Since 2012, the Delaware Bay population of horseshoe crabs has been managed under the ARM Framework[1] in recognition of its ecological role in the Delaware Bay. The Framework considers the abundance levels of horseshoe crabs and shorebirds in determining the optimal harvest level for the Delaware Bay states of New Jersey, Delaware, Maryland, and Virginia (east of the COLREGS) to achieve multi-species objectives for horseshoe crabs and red knots. It was developed with the guidance of the Horseshoe Crab and Shorebird Technical Committees, which defined management objectives and values associated with horseshoe crab harvest. Since 2013, the Horseshoe Crab Management Board (Board) has annually reviewed recommended harvest levels from the ARM model, and specified harvest levels for the following year in the four Delaware Bay states.

In 2021, a revision to the ARM Framework was completed. The revision updated and improved the ARM model with an additional decade of data on shorebirds and horseshoe crabs in the Delaware Bay region, and advancements in modeling software and techniques, including recommendations from the original peer review. Changes to the ARM Framework are described in detail in the 2021 Revision to the Adaptive Resource Management Framework and Peer Review Report. The ARM Framework Revision was evaluated by an independent peer review

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[1] https://asmfc.org/uploads/file/2009DelawareBayARMReport.pdf

panel, which endorsed it as the best and most current scientific information for the management of Delaware Bay horseshoe crabs. Consequently, the Board adopted the revised ARM Framework for setting harvest specifications for the Delaware Bay region under Addendum VIII[2] in November 2022.

c) Stakeholder Survey

During the public comment period on Addendum VIII over 30,000 comments were submitted by the public opposing the adoption of the ARM Revision in large part due to the fact that the results of the revised model run for the 2023 fishing year allowed for a limited amount of female horseshoe crab by the bait fishery for the first time. In response to the widespread concern, the Board elected to implement zero female horseshoe crab harvest for the 2023 season, despite the ARM model output. Given the apparent differences in stakeholder opinions on female harvest, in 2023 the Board conducted a survey of stakeholders including bait harvesters and dealers, biomedical fishery and industry participants, and environmental groups to better understand their diverse perspectives and values, and whether changes to horseshoe crab management for the Delaware Bay region should be considered.

The results of the survey[3] confirmed that the various stakeholder groups hold divergent values and perspectives. Commercial industry participants indicated they still value the harvest of female horseshoe crabs, though it has not been permitted in the Delaware Bay region since 2012. Researchers and environmental groups tended to value the protection of female horseshoe crabs and the ecological role of horseshoe crabs as a food source for shorebirds over the fishery. Considering these conflicting values, the ASMFC held a stakeholder workshop in July 2024 with participants from all stakeholder groups to generate recommendations for Board consideration regarding horseshoe crab management in the Delaware Bay region.

IV. Summary of Dialogue and Key Findings

a) Overview of the Workshop Process

Following the substantial public input regarding the ARM Framework Revision, and the results of the survey described above, ASMFC recognized both an urgent need and timely opportunity for multi-stakeholder dialogue to explore potential future objectives and management approaches for the Delaware Bay horseshoe crab fishery. Working with an external facilitator (Weaver Strategies LLC, see below for additional information), ASMFC convening team refined the meeting purposes:

1. Increase understanding of various stakeholder perspectives and interests.
2. Increase understanding of current horseshoe crab modeling.
3. Identify concerns, alternatives, and areas of common ground for HSC management.

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[2] https://asmfc.org/uploads/file/63d2e8afHSC_AddendumVIII_November2022.pdf

[3] https://asmfc.org/uploads/file/653932c4DB_HorseshoeCrab_ManagementSurveyReport.pdf

Stakeholder Groups Represented at the Workshop

The workshop included representation from the environmental NGO and advocacy communities, the biomedical industry, the fishing industry (including the harvest and biomedical dealer sectors), and biologists (including expertise in shorebirds and in horseshoe crabs). The workshop also included state managers from New Jersey, Delaware Maryland, and Virginia. ASMFC staff provided technical assistance. A list of stakeholders with affiliations is included in Appendix 2 of this report.

The workshop design was informed by insights from a subset of participants interviewed by the facilitator ahead of finalizing the agenda. Open-ended interviews were conducted with a member of the environmental NGO community, a member of the biomedical community, a horseshoe crab scientist, and a shorebird scientist. A member of the fishing community was also invited to participate but an interview was not successfully scheduled.

Dialogue Process

The workshop featured a presentation on the ARM Framework including a brief overview of the history of adaptive management of the species, a summary of known stakeholder perspectives, and an explanation of current modeling. Additional baseline knowledge and understanding was developed through an opportunity for each stakeholder community to share their primary concerns and perspectives. Prior to and during the workshop, participants were reminded to share not only their own perspectives but to do their best to represent their understanding of the broader stakeholder interests and concerns they represented.

The workshop facilitator introduced a consensus-building process aimed at encouraging participants to register their level of support for ideas along a three-scale gradient (where ‘3’ indicates full support; ‘2’ indicates support but with questions and concerns; and ‘1’ indicates that one cannot support an idea given too many questions and concerns). Using this approach, participants with concerns were asked to share ideas that might shift their position towards support. As concrete ideas emerged through dialogue, the facilitator supported participants in developing proposals, consensus testing, openly sharing their questions and concerns, and working creatively towards refined ideas and solutions. Participants agreed (by consensus) to adopt this process as a strategy for focusing dialogue towards potential recommendations, with an understanding that this input *would not* be binding but *would be* weighed as valued input by the Board. Participants devoted the bulk of workshop time to revisiting core aspects of horseshoe crab management, testing for consensus, and developing new ideas (detailed below). The workshop agenda is included in Appendix 2.

Opportunities for Public Engagement with the Workshop

The workshop was open to members of the public, and several observed in person. At the end of each day, time was reserved for public comment (see Appendix 1 for summaries of comments). A live recording of the workshop was also broadcast for observing members of the public; despite best efforts to incorporate technology designed for better including remote observers/listeners, there were technical difficulties with the acoustics of the space and several observers noted difficulty hearing all of the dialogue.

Overall, the Horseshoe Crab Management Workshop was highly collaborative and productive, with participants generally assessing, in their concluding remarks, that the three facets of the meeting's purpose were substantially advanced. Participants developed several recommendations around which to gauge and build consensus. Key areas are summarized below.

b) Consensus Proposals

As part of the consensus-building process, participants were guided to introduce proposed ideas/recommendations to the group and to then note their level of agreement using the previously described three tier gradient system. Where all participants registered a '3' or '2,' consensus was technically achieved, with a larger portion of '3s' indicating a stronger consensus. Where any participant registered a '1,' consensus was not technically achieved and participants were prompted to engage in further dialogue, time permitting, to try and address concerns through refined proposals. Please note that participants were not required to indicate their level of support for each proposal. In many cases, there were abstentions, particularly from scientists or managers who wanted to defer to the perspectives of other stakeholders.

Participants were also asked by ASMFC staff to consider three "reality testing" questions when developing ideas to propose for consensus testing:

(1) Does the idea shift us way from adaptive resource management and, if so, is that desired?
(2) Are there resources available to implement the idea?
(3) What information about the idea would help ASMFC make management decisions?

Consensus was achieved on five proposals/statements, as detailed below. Each statement is briefly explained and annotated with the number of participants who registered a '3' and '2' level of support. For all five of these, no participants registered a '1' (indicating cannot support, too many questions and concerns). Note that some of these statements are slightly elaborated for clarity relative to the documented versions developed with flip chart notetaking during the workshop.

- ***The horseshoe crab population has increased in the Delaware Bay since 2010.***

  Participants used consensus to gauge the extent to which the group supported the above statement.

  - 11-12 participants registered a '3' (full support)
  - 2 participants registered a '2' (will support, but with some questions and concerns)

- ***ASMFC should conduct outreach to gather the 'essential concerns' of key stakeholders.***

Participants had considerable dialogue around the best way for ASMFC to gain a deeper understanding of the most significant concerns about the ARM, especially from some representatives of the environmental NGO community. Several ideas emerged and are more fully captured in Appendix 1. Participants were ultimately able to achieve consensus on the idea that there should be an outreach effort by the ASMFC to gather "essential concerns." The precise method and timing for this outreach is to be determined.

    - 8 participants registered a '3' (full support)
    - 2 participants registered a '2' (will support, but with some questions and concerns)

- ***Using current ASMFC processes, refine the ARM reward and utility functions with stakeholder input.***

Having affirmed a preference for adaptive management over other approaches, participants agreed the reward and utility functions component of the ARM framework represent relatively "low-hanging fruit" for concerned stakeholders to provide input to improve the model and, by extension, to strengthen its credibility. While the group considered a variety of stakeholder engagement process options, consensus was ultimately reached around the suggestion to use existing ASMFC channels.

    - 7 participants registered a '3' (full support)
    - 5 participants registered a '2' (will support, but with some questions and concerns)

- ***ASMFC should improve science communication about the ARM, including optimizing existing channels for engaging with the public.***

Participants frequently spoke to the difficulty of adequately explaining and understanding the science underpinning the ARM Framework and saw an important opportunity for the ASMFC to invest in science communications efforts. Related to this, there was an acknowledgement that existing channels for the public to engage with the ASMFC may not be fully understood or utilized, and could be better explained and disseminated.

    - 11 participants registered a '3' (full support)
    - 1 participant registered a '2' (will support, but with some questions and concerns)

- ***ASMFC should continue to run the ARM by default with a recommendation to pause female harvest in the meantime (i.e., while the other recommendations listed are implemented and stakeholder input is further considered).***

Participants considered a variety of alternatives to the ARM Framework, ultimately affirming a preference to continue running the ARM but with a need to pause female harvest while the above ideas are considered and implemented.

    - 11 participants registered a '3' (full support)
    - 2 participants registered a '2' (will support, but with some questions and concerns)

c) Proposals where Consensus was Tested but Not Reached

In working to identify and build areas of common ground, participants considered several ideas and proposals where consensus was not technically achieved. As part of the consensus-testing process, each participant registering a '1' was asked to explain their questions/concerns and offer any ideas that might shift them towards a '2' or '3', time permitting. For proposals where any participant indicated a '1' (even despite further dialogue on the idea), consensus was not achieved (see list below). In some cases, subsequent dialogue led to the consensus proposals listed above.

- ***Female harvest is appropriate under some circumstances.***

  Participants used consensus to gauge the extent to which the group supported the above statement. Questions/concerns noted by the participants registering a '1' included not seeing a justification for female harvest, and that there are still too many questions about the impact of female horseshoe crab harvest given their role as a food source for red knots.
    - 11 participants registered a '3' (full support)
    - 2 participants registered a '2' (will support, but with some questions and concerns)
    - **2 participants registered a '1' (cannot support, too many questions and concerns).** Concerns shared included:
        - *The case for expanding to female harvest has not been adequately justified.*
        - *There are remaining concerns with the model itself.*
        - *An understanding that red knots need a "superabundance" of eggs that may exceed what would be deemed as a sustainable level for horseshoe crabs.*
        - *A desire to represent the interests of Audubon members who believe female horseshoe crabs should not be harvested until red knot are delisted or there is more robust evidence about the link between eggs and red knots. This participant acknowledged the challenge and opportunity may be largely about information sharing and improving the accessibility of existing scientific knowledge.*
        - *A concern that more time is needed to fully assess data about female horseshoe crab abundance and red knot population trends, and should exercise caution having only recently "turned a corner."*

- ***The ASMFC should revert to a Harvest Control Rule (and not use Adaptive Resource Management).***

  Participants universally affirmed they did not support returning to the earlier modeling approach, thus implying a strong preference for adaptive management. It should be noted that while the earlier modeling approach was not intended as a harvest control rule, it would essentially function as such under realistic horseshoe crab and red knot population conditions.
    - 0 participants registered a '3' (full support)

    - 0 participants registered a ‘2’ (will support, but with some questions and concerns)
    - **12 participants registered a ‘1’ (cannot support, too many questions and concerns)**.
        - *Given the level of objection to the idea of a harvest control rule, dialogue advanced from this topic expediently without itemizing all concerns. It was clear that the group prefers to find a way to stay within an Adaptive Resource Management framework.*

- ***Pause running the ARM to focus on modeling for male-only harvest based in science.***

This idea was proposed as an alternative to devoting resources to run the ARM annually while not following the output around female harvest, which some viewed as a poor use of the modelers’ time and resources.

    - 1 participant registered a ‘3’ (full support)
    - 3 participants registered a ‘2’ (will support, but with some questions and concerns)
    - **7 participants registered a ‘1’ (cannot support, too many questions and concerns).**
        - *This proposal was introduced by a participant who was concerned that running the ARM annually without following its outputs would amount to a waste of resources with negative impacts on the staff who administer the model, and that the proposal would be a preferred solution to doing that. While participants did not elaborate on their specific concerns, it was clear from this consensus test that there would not be agreement on advancing this idea and dialogue quickly moved beyond it.*

- ***Work on a conflict resolution process with NGOs.***

Some participants raised the concern that those environmental NGOs with the most significant objectives to the ARM revision were not present at the workshop, and that the ASMFC should devise a way to directly work through the most serious disagreements with the environmental NGO community. Ideas discussed for this concept ranged from face-to-face meetings, to listening sessions, to independent review of the ARM by a small group of (3-4) external experts.

    - 7 participants registered a ‘3’ (full support)
    - 2 participants registered a ‘2’ (will support, but with some questions and concerns)
    - **3 participants registered a ‘1’ (cannot support, too many questions and concerns).**
        - *The primary concerns shared were that it would be unfair for ASMFC to hold private meetings with some but not all stakeholder groups or communities, and that it would discredit and undermine the rigorous external peer review process in place to evaluate the science of the ARM Framework.*

- ***Pause the ARM via an ASMFC addendum while stakeholder engagement on reward and utility functions and conflict resolution with environmental NGOs are implemented.***

  This proposal was an attempt to assemble several ideas that emerged through dialogue. When consensus was not achieved, focus shifted to teasing out areas of agreement towards developing the consensus-based proposals listed above.
    - 4 participants registered a '3' (full support)
    - 3 participants registered a '2' (will support, but with some questions and concerns)
    - **3 participants registered a '1' (cannot support, too many questions and concerns)**
        - *Participants who did not support this proposal expressed concerns about creating additional controversy and losing important information as a result of pausing the ARM, and that any pause should have a time limit.*

As time permitted, there was participant dialogue around all of the above proposals. Appendix 1 provides a more complete overview of the ideas and comments raised.

d) Recommended Next Steps

In developing consensus-based proposals, participants understood the recommendations would not be binding, neither in relation to participant adherence nor ASMFC adoption. Rather, workshop conveners emphasized that the meeting presented an opportunity to gauge where there could be areas of common ground, with an expectation that participant ideas would be seriously considered by the Horseshoe Crab Board. As was explained by ASMFC staff at multiple points, participants also understood that any further recommendations by the Board regarding the ARM would in turn be subject to public notice and opportunity to comment.

Beyond the proposal to continue running the ARM but pause female harvest for the time being, there are several recommendations the ASMFC could begin exploring and implementing using existing resources and avenues. In fact, consensus-based proposals reflect a sensitivity to resource constraints and the opportunity to optimize channels for engagement that are already available but may not be fully accessed. In light of these and other suggestions emerging from the workshop, three potential next steps for the Board to consider are described below.

1. **Initiate an addendum to establish a concrete interim solution (multi-year specifications)**

   While the workshop participants all agreed the ARM should continue to be run while additional recommendations are addressed, they expressed a desire for more certainty around harvest specifications. Specifically, the participants agreed it would be preferable to set female harvest quota to zero for the time needed to address other recommendations. An addendum that allows the Board to set specifications for multiple years at a time would provide greater predictability about future harvest levels, but would not abandon use of the ARM Framework. An addendum could be developed and implemented before the Board needs to set harvest specifications in the fall of 2025.

2. **Begin a dialogue with key stakeholders to identify 'essential concerns'**
   Workshop participants discussed the need for ASMFC to gain a deeper understanding of the most significant concerns about the ARM, especially from some representatives of the environmental NGO community that were not participants. ASMFC could begin such a dialogue through a series of webinar meetings with key stakeholders, with the purpose of allowing concerns or questions about the ARM Framework data and models to be raised and addressed. This could build greater collective understanding of the ARM, provide ASMFC with a list of critical concerns regarding the ARM Framework, and allow proposals of alternative methods to be considered. It could also provide preliminary direction for the next step. Depending on the format of these meetings, additional resources could be needed.

3. **Initiate a process to develop alternative reward and utility functions with stakeholder engagement**
   Participants affirmed a preference for adaptive management over other approaches, but suggested the reward and utility functions component of the ARM Framework could be evaluated and modified to better address stakeholder concerns and values. The workshop discussions suggested that the process of reevaluating the reward and utility functions should engage stakeholders using existing ASMFC channels (e.g., committee meetings). It should be noted that this type of process will take time, similar to the 2021 ARM Framework Revision, and ultimately management action would be needed to implement any changes. Under the new process identified in Addendum VIII, the next ARM Framework revision would begin 2028 or 2029 but the Board can take action to start this process sooner. If this is pursued, additional resources would be needed including staff time. Depending on the timing of this process, other Commission assessments may need to be reprioritized.

Additional recommendations were developed at the workshop that could be considered as medium to longer-term goals. The first is to evaluate the Horseshoe Crab Advisory Panel (AP) to determine if it has adequate representation across stakeholder groups. This may require adding seats to the panel for non-traditional stakeholders (i.e., environmental NGOs). The states can work with ASMFC to review and modify AP membership as needed. The second is to take steps to improve science communication about the ARM, including optimizing existing channels for engaging with the public. Participants agreed that adequately explaining and understanding the science underpinning the ARM Framework is an ongoing challenge. They acknowledged the general public may not fully understand or utilize existing channels for engaging with the ASMFC, so this information needs to be better explained and disseminated. Working toward improving science communication on the ARM could be an opportunity to collaborate with key NGO stakeholders in developing outreach content and programs related to this topic and disseminating information to a wider audience. These stakeholders could provide valuable feedback on where improvements in communication could be made.

V. Appendix 1: Additional Comments and Ideas

The notes in Appendix 1 capture public comment and additional participant comments and ideas shared across the one and one-half days of dialogue. Notes on the dialogue were captured on flipcharts (by the facilitator) and via laptop recording (by ASMFC staff). Raw notes have been edited, re-organized, and consolidated for clarity. Some acronyms are used in these notes (e.g., "HSC" means "horseshoe crab). Bullets represent distinct comments by a participant; sub-bullets indicate direct follow-up comments in response to points made.

a) Public Comment

The notes below capture comments by members of the public who attended the workshop in person. Public comment was invited at the end of each day.

- Framing of Science vs. Politics - We are all looking for the best science and lack of answers drives a precautionary approach
- Stakeholder engagement suggestions:
    - Make information publicly available as quickly as possible and consider timing for input
    - A previous offer to field questions about registered concerns was not taken up
    - Technical committees do not allow for meaningful engagement
- There is a great deal we do not know about red knots
    - We have to govern horseshoe crabs with management tools that can be improved
    - Disagrees with not harvesting females; request that ASMFC not give up on the ARM
    - Cannot understand opposition to collection for Limulus amebocyte lysate (LAL) given the interests human health and lack of adequate replacement
    - Political avenues are wrong - decisions should be made in rooms like this
- Everyone here is an expert and if we listen to each other discuss facts in our area of expertise it would be easier to get past the idea of "misinformation"
    - Would love to see egg density data included in ARM
    - Fish also consume HSC eggs
    - What's the carrying capacity of the ecosystem?
- Education is very important. Some groups ignore the facts
    - Media coverage is upsetting; data are not placed in context
- Importance of public input in the process
    - Dialogue today advanced when it became more specific re: concerns
    - Take public comment seriously (i.e., 34,000 submitted comments)
    - Even technical comments were ignored initially by the Horseshoe Crab Board and the process was difficult for the public to engage in
    - Concerned about red knot decline and trajectory

b) Participant Hopes for the Workshop

These hopes were recorded during the initial round of introductions on Day 1. While closing comments were not recorded, participants largely affirmed that their hopes for the workshop had been substantially realized.

- Get along
- Get an idea of how much science we can put in this
- Increase understanding of the science
- “We’ll see how this works out.”
- Clarify misconceptions / misinformation
- Build relationships and consensus
- Find common ground
- Good science and strong protections for HSC
- Discuss what adaptive management mean
- Learn and gain understanding
- Consensus
- Feel heard
- Gain understanding
- Learn
- Hearing from everyone and finding a way forward
- Share perspectives and listen
- Increase common understanding about the ARM
- Consensus
- Come out with Objectives
- Better shared understanding of facts and science
- Support restoration and protection of both species

c) Fundamental Interests of Stakeholder Groups

Prior to shifting into consensus building, participants were asked to help refine the collective understanding of the ecosystem of issues and concerns across all stakeholder groups. Participants were reminded that they should speak not only about their own perspectives, but try to capture the concerns of the broader network of stakeholders they represented. Each cluster of stakeholders broke into small group discussion then reported back to the large group.

“Fundamental Interests” of Each Stakeholder Group (report back of small group discussion on key areas of concern)

Biomedical Community - Fundamental Interests

- We are collectors not harvesters
- Ubiquity and magnitude of LAL medical applications in terms of safety and success
- Human health
- Products, processes, procedures have evolved over time
- State legislatures getting involved – concern about the topic being taken away from scientists

- Misinformation – Is biomedical really a top risk for horseshoe crab?
- LAL regulation is very complex
- Health risks of synthetics currently – we are trying to get to synthetics but LAL remains the gold standard now

Red Knot Scientists - Fundamental Interests

- Recovering the red knot is a requirement of our work
- Best available science to optimize recovery resources
- Risk aversion given uncertainty - avoid overshoot
- Consensus would advance recovery
- Improve science communication across all data sets
- Link between horseshoe crab and red knot still valid - lots going on across life cycle
- Need consensus in collection methods for surveying horseshoe crab egg data

HSC Scientists - Fundamental Interests

- Questioning of scientific integrity of HSC scientists has been really difficult
- Scientists are NOT in “back pocket” of industry
- Context is very important. Especially in the media, there is a need to look at population size and mortality data together (not in isolation)
- Media spin has been a major problem
- Clarification on timing of the VT survey - spring / fall / summer

Managers - Fundamental Interests

- Strong reaction to ARM outcome was concerning because the ARM uses best available science and includes red knot considerations
- Fear of continued misinformation given that HSC is actually one of the better communicated models. Sense that no matter what comes out, misinformation will seek to overcome it
- No matter what, people won’t be happy – polarization
- Alternative hypotheses for red knot trends seem to be unwelcome
- We manage on science, not “vibes”
- Is misinformation intentional bias or about education / misunderstanding?
- Best available science doesn’t mean “great” science – err on abundance of caution
- Prefer to leave politics out of it BUT options become political and HSC is very politically charged
- Can’t lose sight of human health
- Haven’t harvested females since 2012, so what IS harming red knot?
- Wants to get out of a position of fear

Fishermen - Fundamental Interests

- HSC quotas are important
- Demand market fluctuates mainly on conch
- Females - it’s not the commercial harvesters impacting them currently, but this used to be an important market

- Presence of females in harvest can help sell males too, even if there are limited numbers of females; “something is better than nothing”
- Issue of misinformation, not relying on best available science, overreacting
- Want to uncover the real problems for red knot
- Long term, generational view – a lot is invested over generations and fishermen take a generational perspective
- Regulation has been a battle through the lifetime of a fisherman, and is not always logical
- Faced with an argument that we “protect a dinosaur” given public perceptions
- Female is commercially 10X better than a male at market in terms of size and effectiveness
- 2022 ARM is good news and an improvement
- Younger generations haven’t experienced female harvest
- Water quality supports good larvae recruitment on all levels. Plastics are a big issue we can all get behind
- Fishermen are stewards and keep good records

Environmental NGOs - Fundamental Interests

- Biological indicators are still very fragile re: red knot
- There is a very real link and we are in a crisis
- Does ARM adequately capture fluctuations?
- Why is there a need for female harvest?

d) Discussion of the 2022 ARM Objective Statement

Participants were prompted to consider the 2022 ARM Objective Statement and to discuss the extent to which it still reflected their interests and concerns.

2022 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 HSCs is not limiting the red knot stopover population or slowing recovery.

- Note that the consensus reached in this room may be higher than what would be reached outside of this room
- Note that for biomedical the word to use is “collect” not “harvest”
- Could be strengthened with more specificity, measurability, inclusion of criteria
    - Conversely, more specific numbers could lead us back to a threshold approach and away from the ARM
- Need to clarify how limitation is defined and whether it’s an appropriate measure
- Shorebird communities dislike “maximize harvest”
    - Optimal vs. Maximum?
    - Manage?
    - Add “sustainable”?

  - "Adaptive"? Element of time could signal the ability to incorporate data over time
- Replace "stopover habitat" with "food habitat"
- Edit to avoid use of "but"
- How to define "adequate"?
- Caution that wordsmithing could be perceived as "lipstick on a pig"
- Alternate verbiage:
  - "Provide sustainable harvest opportunity while also maintaining ecosystem integrity…"
  - "Accommodate sustainable harvest…"

A participant then developed a ***"strawman" Objective Statement revision****, in light of this input, and provided the revision to the facilitator ahead of Day 2. The workshop facilitator shared with the group that this had been provided and could be discussed. Ultimately the group did not have time to consider this revision given time constraints, but it is included here:*

"Through adaptive management based on best available science, optimize harvest of horseshoe crabs in the Delaware Bay Region to maintain ecosystem integrity, provide adequate food resources for migrating shorebirds, and ensure that the abundance of horseshoe crabs is not limiting the red knot stopover population or slowing recovery, while also accommodating sustainable harvest."

e) Additional Participant Comments

The facilitator and ASMFC staff worked to record participant comments, questions, concerns, and ideas across the 1.5 days of dialogue. While recording could not capture every comment at a transcript level, a robust list of issues that were surfaced is included here:

- It was a mistake not to include some of the NGOs with the greatest concerns at the workshop
- What is ASMFC's long-term plan?
- "Threatened with Extinction" is misinformation in the media and is frustrating; NGOs may have differences but are operating from an umbrella group that is spreading misinformation
- We need to celebrate successes also re: HSC population gains, hatchery operations
  - Hatcheries are not really successful
- HSC recovery has had a lag
  - There may be a lag for red knot too; other factors could be impacting the link
- Why was there such a strong response to the ARM?
  - Timing of ARM revisions came up against uncertainty in the field recently and raised questions about translation of datasets
  - Trust issues
- Question: Why does the NGO community call to ban any harvest?
  - Don't group all NGOs together
  - Issue of enforcement capacity

- Don’t call views that disagree with you “misinformation”
- Bias on Managers’ side as reaction to other extreme
- If ARM is best available science, then (a) why ignore it? (b) what signal does ignoring it send?
    - “best available” is not necessarily great but can become better
    - Ways to make science better?
- Difference between current ARM and “adaptive management”?
- Science, even if great, will always have uncertainty
- Board should be open to additional stakeholder input around functions
- Public is extremely risk averse given decline in red knot
- Science is also political
- Re-evaluate how model reflects public sentiment
- Need more communication with stakeholders on existing channels to provide input to ASMFC
- No reason to go away from the current modeling approach
    - Issue is female harvest
    - Need ability to be flexible
- If we don’t harvest females for now, why run the ARM every year?
    - Don’t run ARM until a future point?
    - Find a model for male harvest?
- ARM incorporates uncertainty already and is revised over time
    - Male only harvest could be a large number if based in science
    - Reward and Utility Function is where stakeholder input is most valuable (i.e., economic value of females, probability of red knot extinction)
- Give ARM time and see how it goes
- Re: Utility and Reward Functions, new ARM doesn’t have a real option for no female harvest
    - Are we more concerned when red knot are high or low? Issues with abundance
    - Incorporate switch somehow
- Watermen perspective re: “following the science” - Trust
- Proposed female harvest would be so small couldn’t detect effect
- You can’t just turn the ARM off - inputs will be lost in reality
- Could be outcry with either option - “which do you want to defend”
- Can current ARM be adjusted so no females is an option?
    - Unclear
    - Could re-weight Reward Function
- No one wants to back away from “best available science” including the environmental community
- Useful from a Scientist perspective: Task ARM subcommittee with identifying alternative Reward and Utility Functions for stakeholder consideration through a consensus process

VI. Appendix 2: Workshop Materials

The following pages include these workshop materials:

- Workshop Agenda
- Slide Deck – Presentation on "Adaptive Resource Management (ARM) Framework Overview"
- Terminology Handout

Atlantic States Marine Fisheries Commission

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MEMORANDUM

TO: **Horseshoe Crab Management Board**

FROM: **Delaware Bay Ecosystem Technical Committee and Adaptive Resource Management Subcommittee**

DATE: **September 23, 2024**

RE: **Delaware Bay Horseshoe Crab Harvest Recommendation for 2025**

This memo describes the 2025 harvest recommendation for Delaware Bay Region horseshoe crabs using the methods from the Adaptive Resource Management (ARM) Framework (ASMFC 2022a). Since 2013, the horseshoe crab bait fisheries in the Delaware Bay Region (New Jersey, Delaware, Maryland, and Virginia) have been managed under the ARM Framework to set harvest levels with consideration of the needs of migratory shorebirds. The ARM was developed jointly by the Commission, US Fish and Wildlife Service, and US Geological Survey in recognition of the importance of horseshoe crab eggs to migratory shorebirds stopping over in the Delaware Bay Region. In particular, horseshoe crab eggs are an important food source for the *rufa* red knot, which is listed as threatened under the Endangered Species Act.

Under Addendum VIII (ASMFC 2022b), the 2022 ARM Revision is used to annually produce bait harvest recommendations for male and female horseshoe crabs of Delaware Bay-origin based on the abundance of horseshoe crabs and red knots. The maximum number of male and female horseshoe crabs the ARM Framework can recommend is 500,000 males and 210,000 females.

1. Objective 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.

2. Population estimates

Red knot abundance estimates used to make harvest recommendations under the ARM Revision are based on mark-resight total stopover population estimates (Figure 1; Lyons 2024). The 2024 red knot population estimate was 46,127 (95% CI: 39,286 – 57,799), an increase from the 2023 estimate. However, to align the red knot population estimates with the horseshoe crab population estimates, the 2023 red knot population estimate of 39,361 (95% CI: 33,724 -47,556) was used in making harvest recommendations for the 2025 harvest season.

In the ARM Revision, all quantifiable sources of mortality (i.e., bait harvest, coastwide biomedical mortality, and commercial dead discards; Figure 2 - Figure 3) were used in the catch multiple survey analysis (CMSA) to estimate male and female horseshoe crab population estimates. The Virginia Tech (VT) Trawl Survey estimates are used in the CMSA along with the New Jersey Ocean Trawl and the Delaware Fish and Wildlife Adult Trawl Surveys (ASMFC 2022a; Jiao et al. 2024; Figure 4 -Figure 5).

Since 2019, the VT Trawl Survey has recorded very low numbers or zero newly mature female horseshoe crabs. Newly mature males have not shown the same decline. Horseshoe crabs are estimated in the Delaware Bay using a two-stage model (the catch multiple survey analysis) which requires estimates of newly mature and mature horseshoe crabs by sex from the VT Trawl Survey. The model cannot run with a zero data point for newly mature horseshoe crabs. For the last two years, the modeling team, in discussion with the Delaware Bay Ecosystem Technical Committee (DBETC) and ARM Subcommittee, has been reproportioning the *mature* female horseshoe crab numbers into newly mature and mature female horseshoe crabs using a ~20% ratio of newly mature to mature horseshoe crabs based on previous years of data from the VT and Delaware Adult Trawl Surveys. Following the Horseshoe Crab Stakeholder Workshop in July 2024 and through discussions with the VT Trawl team, it was determined that newly mature females are being misclassified during sampling as *immature*, not mature. Simply, due to increased population numbers in the coastal Delaware Bay Region, the crew of the VT Trawl Survey have been overwhelmed with the large numbers of horseshoe crabs in the tows during the sampling season. As a result, the sampling of non-mature females (those that could be immature or newly mature) to determine if eggs are present (indicating that they are newly mature) has been inconsistently applied between tows. Distinguishing the stages in male horseshoe crabs is straight-forward compared to female horseshoe crabs. Therefore, the modeling team should reconsider the method for calculating newly mature female horseshoe crabs for use in the model.

To re-calculate newly mature females for 2019-2023, the modeling team proposed using a linear regression of newly mature males and females where females were lagged by one year to acknowledge that newly mature males are typically 9-years-old and newly mature females are 10-years-old. There was a strong positive relationship between these two population estimates (Figure 6), so the linear regression method can predict newly mature female population estimates for the years of 2019-2023 when newly mature female horseshoe crabs were not sampled as rigorously in the survey. The DBETC and ARM committees agreed with using the new method this year, while recognizing that the priority is return to using the VT Trawl data as provided when sampling issues have been resolved. However, for the Board's awareness, a correction will need to be made again next year when making 2026 harvest recommendations because the VT Trawl Survey estimated 0 newly mature females in the fall of 2023.

No adjustments had to be made for the male horseshoe crab model.

Using the adjusted newly mature female populations methods in the CMSA model, there were approximately 30.4 million (95% CI: 22.0-41.9) mature male and 16.6 million (95% CI: 13.0-21.1) mature female horseshoe crabs in the Delaware Bay Region in 2023 (Figure 7 - Figure 8).

3. Harvest Recommendation

Harvest recommendations for the 2025 fishing year made using the ARM Revision are based on CMSA estimates of horseshoe crab abundance and the red knot mark-resight abundance estimates. ARM harvest recommendations are based on a continuous scale rather than the discrete harvest packages in the previous ARM Framework. Therefore, a harvest number up to the maximum allowable harvest could be recommended, not just the fixed harvest packages. Harvest of females is decoupled from the harvest of males so that each is determined separately. The maximum possible harvests for both females and males are maintained from the previous ARM Framework at 210,000 and 500,000, respectively.

The annual recommendation of allowable Delaware Bay horseshoe crab harvest is based on current state of the system (abundances of both species in the previous calendar year) and the optimal harvest policy functions from the ARM Revision. Annual estimates of horseshoe crab and red knot abundances are used as input to the harvest policy functions, which then output the optimal horseshoe crab harvest to be implemented. As per Addendum VIII, if the optimal recommended harvest is less than the maximum, it is rounded down to the nearest 25,000 crabs to uphold biomedical data confidentiality.

The harvest recommendation for 2025 based on the ARM Framework is 175,000 female and 500,000 male horseshoe crabs.

4. Quota Allocation

Allocation of allowable harvest was conducted in accordance with the methodology in Addendum VIII (Table 1). Note that the total quotas for Maryland and Virginia are capped under Addendum VIII based on the female harvest recommendation.

Table 1. Delaware Bay-origin and total horseshoe crab quota for 2025 by state. Virginia total quota only refers to the amount that can be harvested east of the COLREGS line.

State	Delaware Bay-Origin Quota		Total Quota	
	Male	Female	Male	Female
Delaware	173,014	60,555	173,014	60,555
New Jersey	173,014	60,555	173,014	60,555
Maryland	132,865	46,503	126,410	44,243
Virginia	21,107	7,387	40,667	20,331
TOTAL	500,000	175,000	513,106	185,684

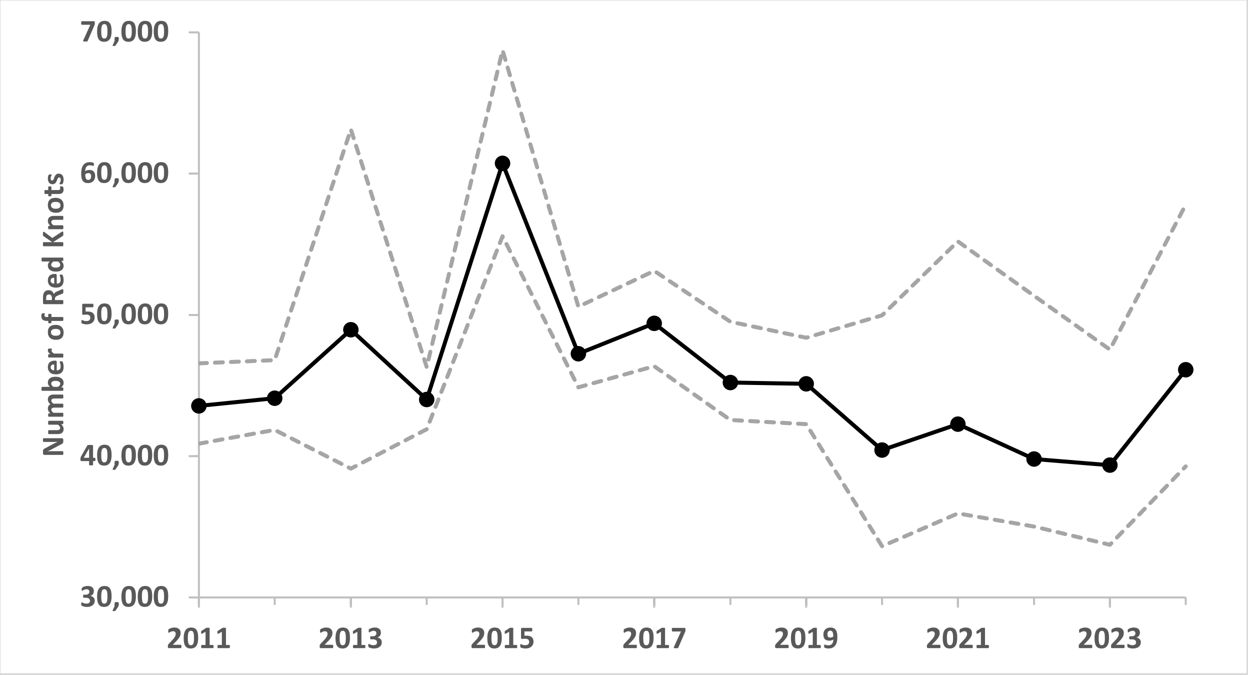

Figure 1. **Mark-resight abundance estimates for the red knot stopover population with 95% confidence intervals, 2011-2024.**

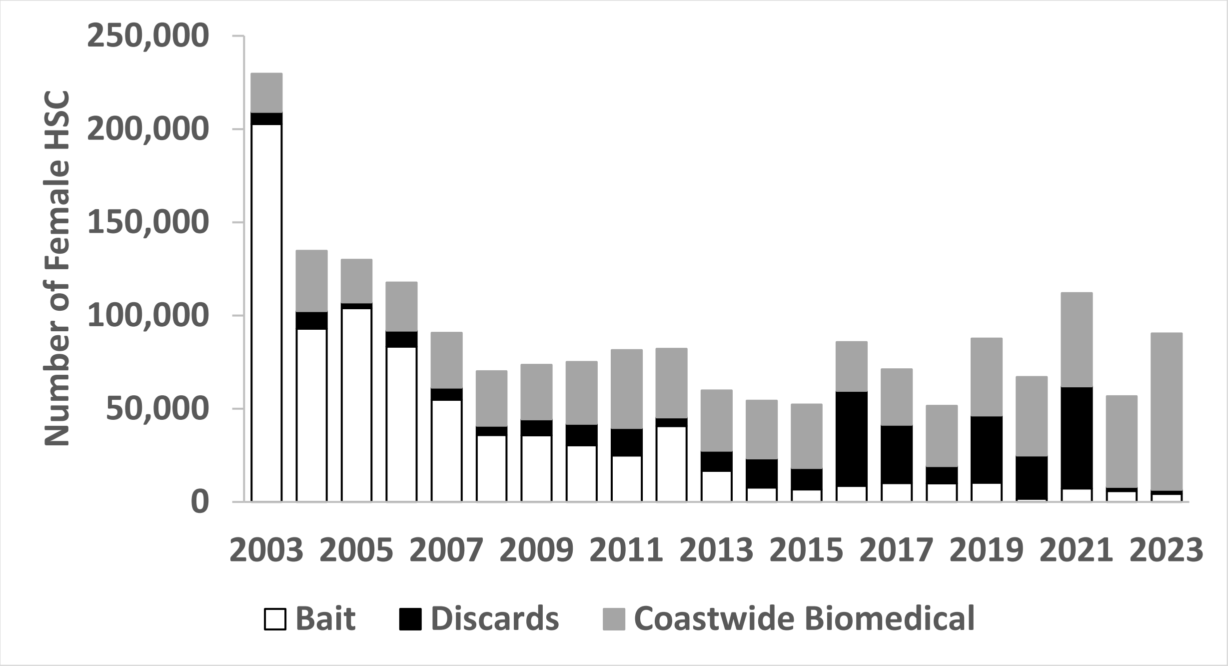

Figure 2. **Total female horseshoe crab harvest by source in the Delaware Bay, 2003-2023.**

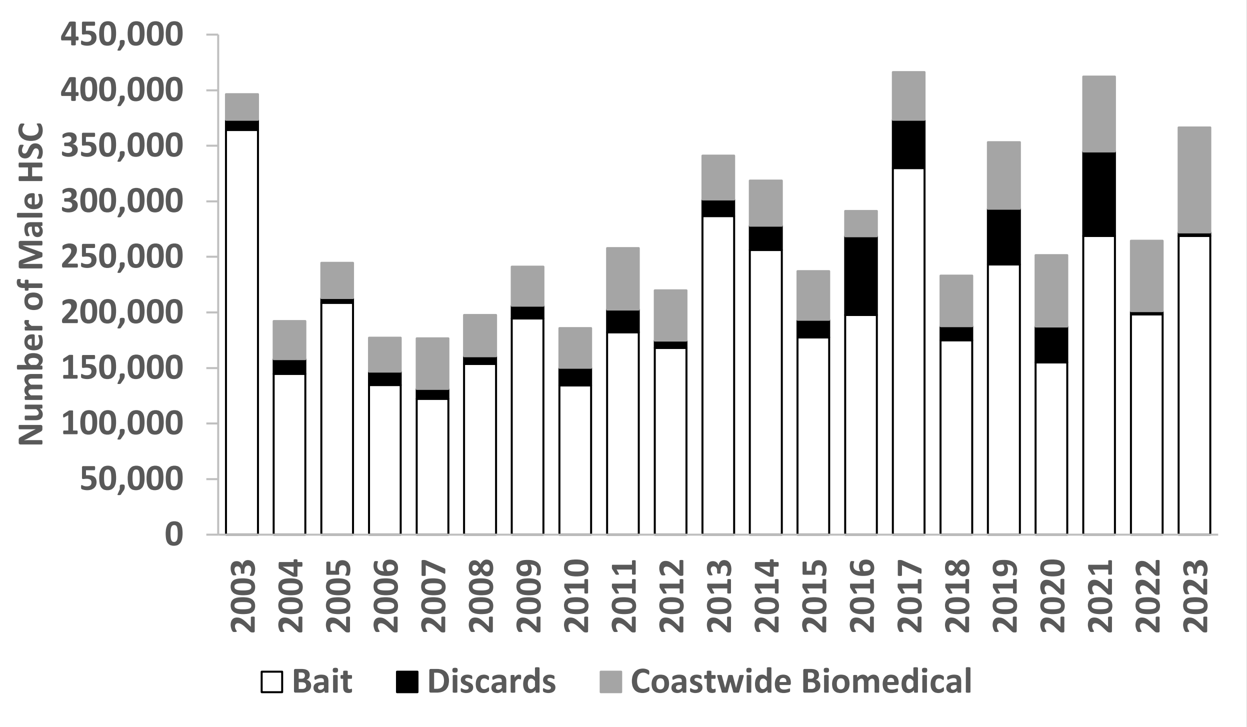

Figure 3. **Total male horseshoe crab harvest by source in the Delaware Bay, 2003-2023.**

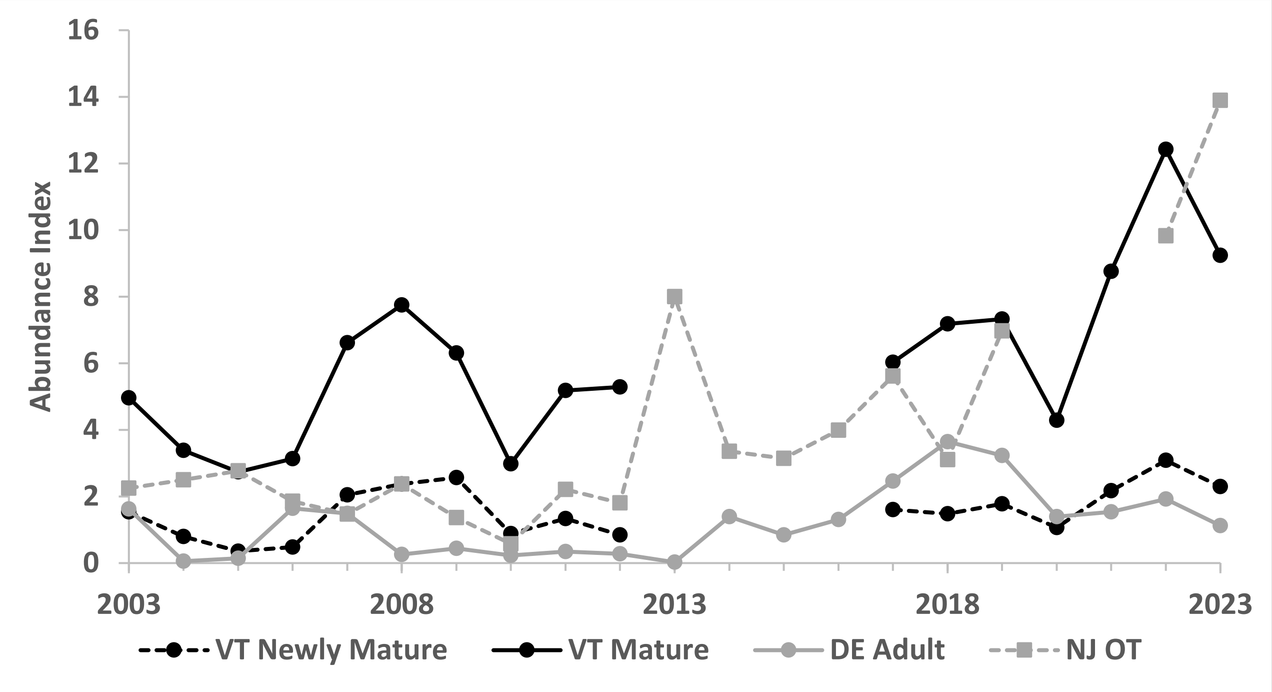

Figure 4. **Female horseshoe crab abundance indices used in the CMSA. The Virginia Tech (VT) indices are in millions of newly mature and mature crabs while the Delaware Adult (DE Adult) and New Jersey Ocean Trawl (NJ OT) are in catch-per-tow.**

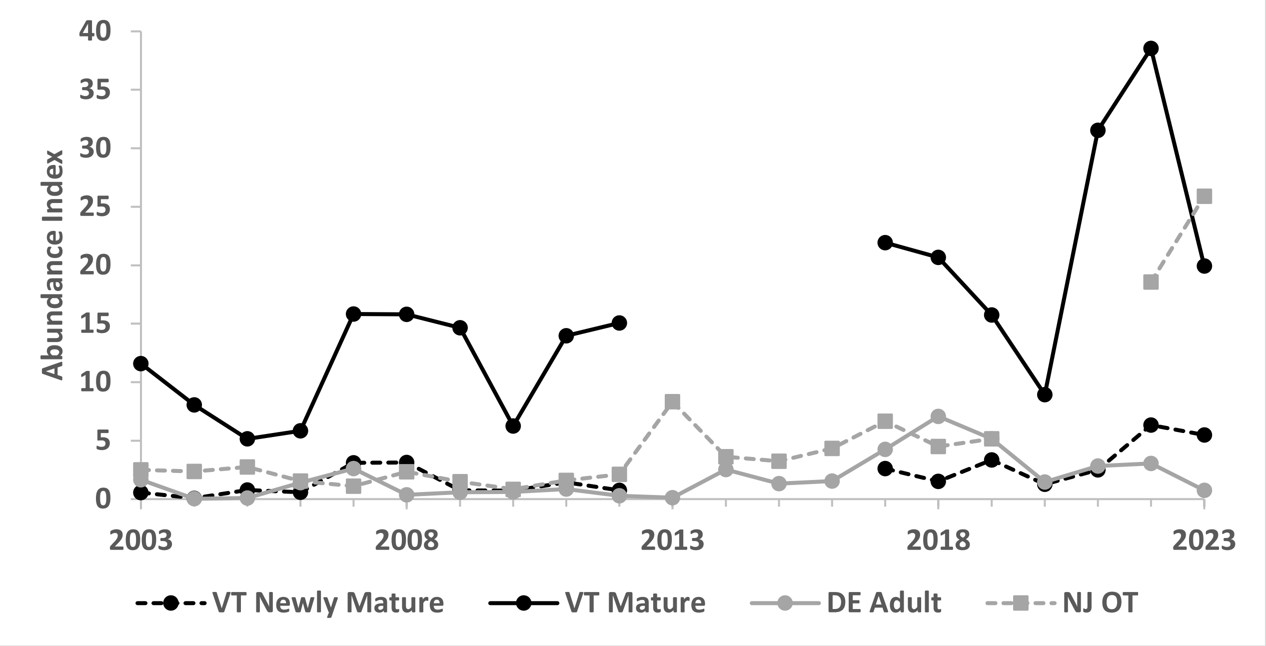

Figure 5. Male horseshoe crab abundance indices used in the CMSA. The Virginia Tech (VT) indices are in millions of newly mature and mature crabs while the Delaware Adult (DE Adult) and New Jersey Ocean Trawl (NJ OT) are in catch-per-tow.

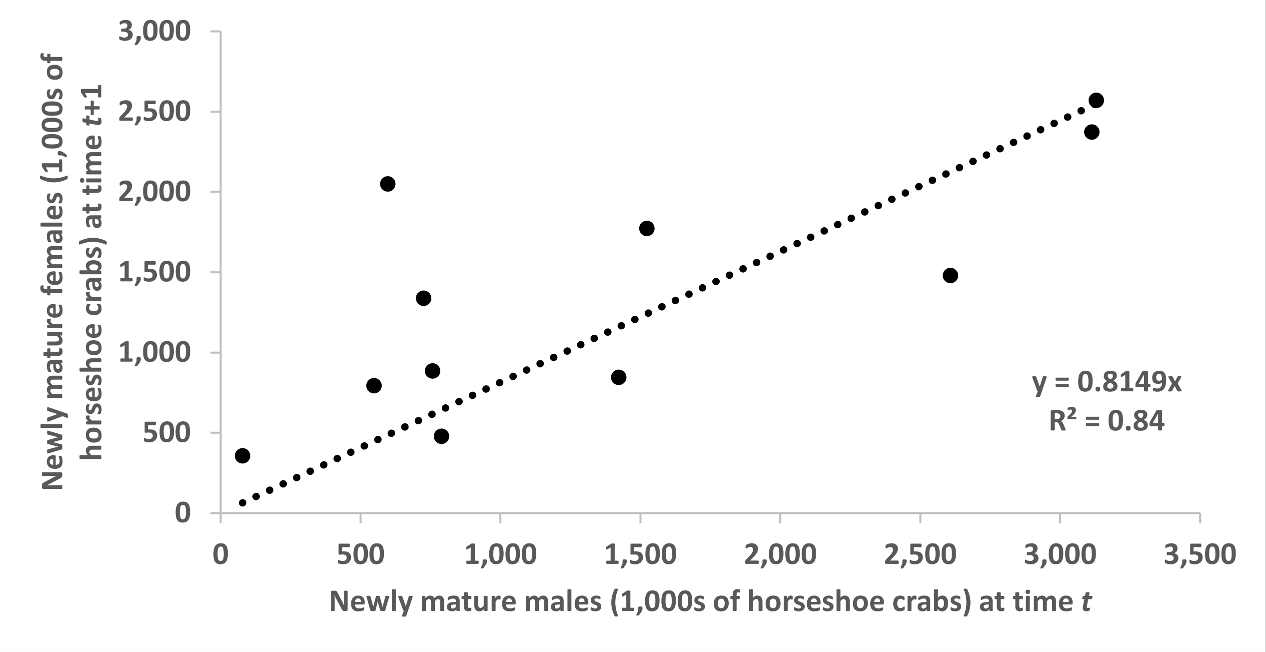

Figure 6. Linear regression between the population estimates of newly mature male to female horseshoe crabs, 2002-2018. The intercept has been fixed at 0.

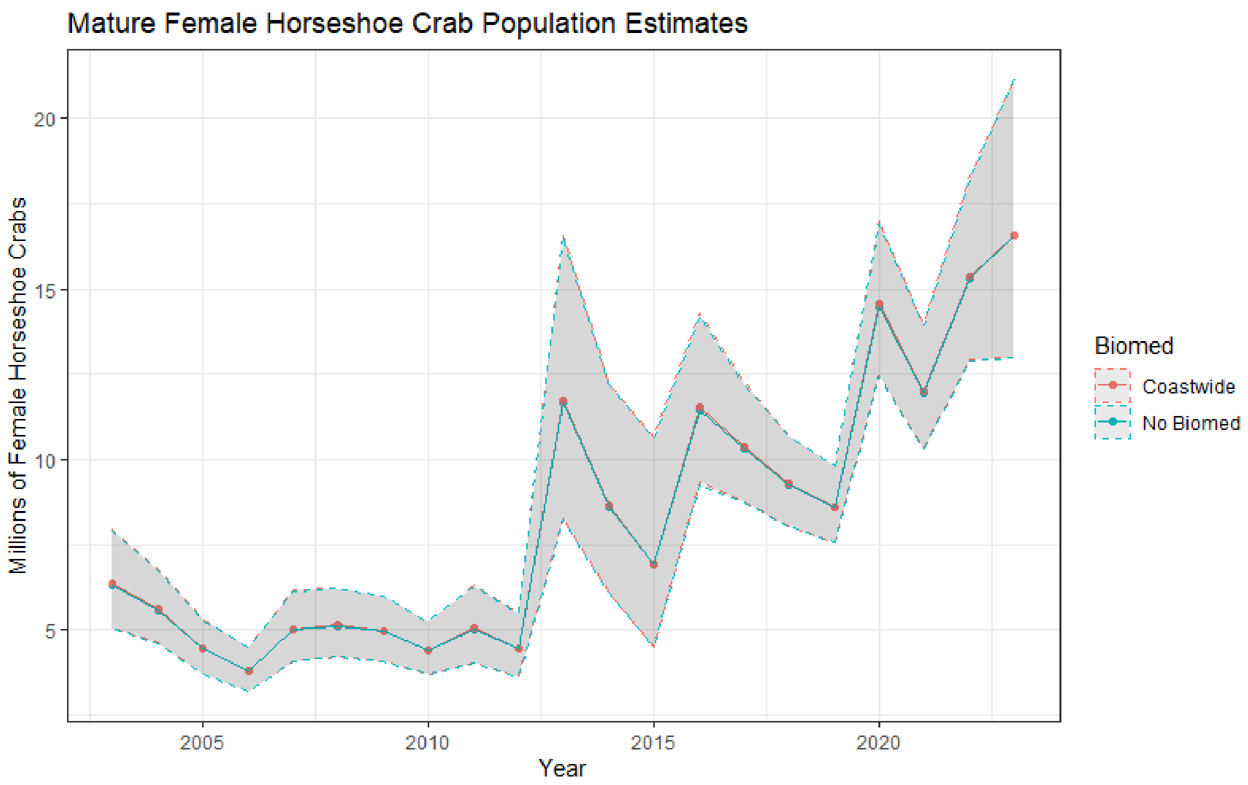

Figure 7. Population estimates from the CMSA for mature female horseshoe crabs with 95% confidence intervals. Delaware Bay biomedical data is confidential so population estimates using coastwide and zero biomedical data provide upper and lower bounds, although there is very little difference between the two and the time series overlap on the figures.

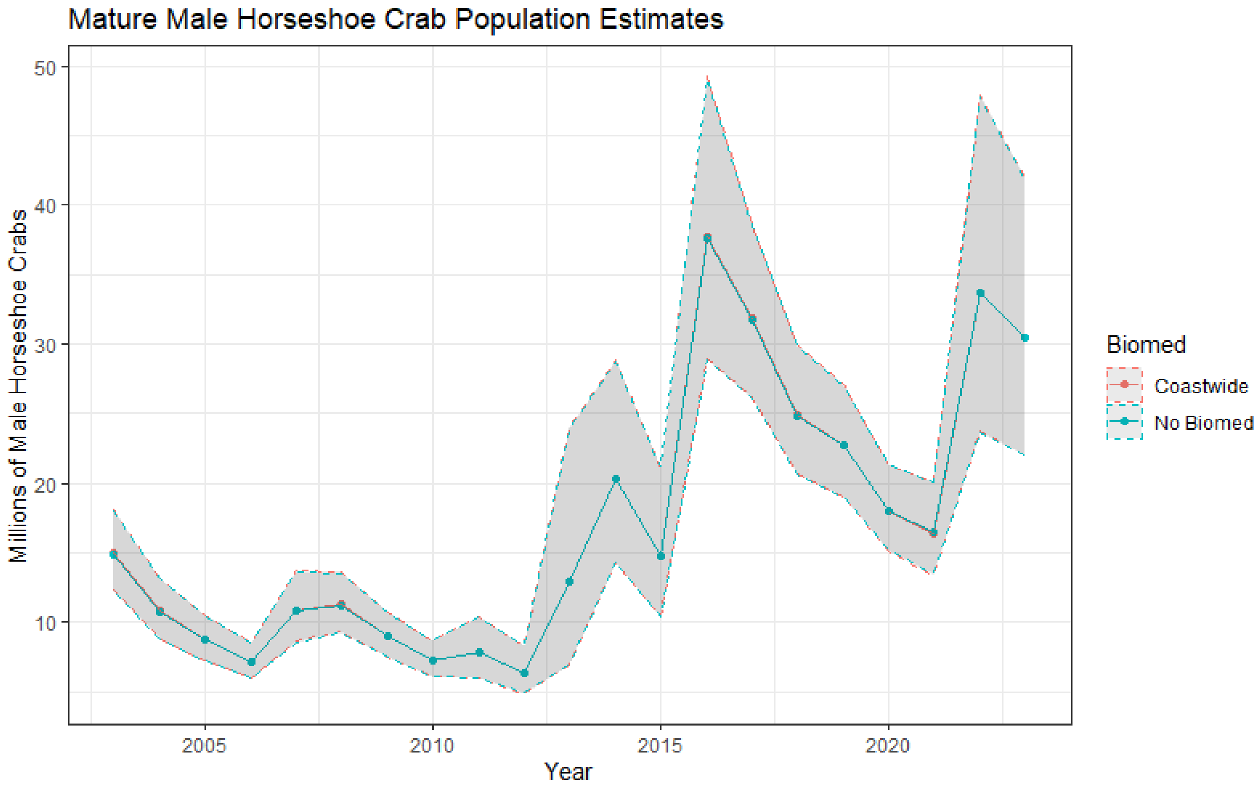

Figure 8. **Population estimates from the CMSA for male horseshoe crabs with 95% confidence intervals. Delaware Bay biomedical data is confidential so population estimates using coastwide and zero biomedical data provide upper and lower bounds, although there is very little difference between the two and the time series overlap on the figures.**

5. References

ASMFC. 2022a. Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation and Peer Review Report. Arlington, VA. 302 pp.

ASMFC. 2022b. Addendum VIII to the Fishery Management Plan for Horseshoe Crab. Washington D.C. 12pp.

Lyons, J.E. 2024. Red Knot Stopover Population Size and Migration Ecology at Delaware Bay, USA, 2024. Memorandum to the Delaware Bay ARM Working Group. U.S. Geological Survey Patuxent Wildlife Research Center, Laurel, Maryland. 18 pp.

Jiao, Y., F. Ferretti, and E. Hallerman. 2024. Results of the 2023 Horseshoe Crab Trawl Survey: Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees. 30 pp.

Results of the 2023 Horseshoe Crab Trawl Survey:

Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees

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Abstract

Annual analyses of the population dynamics of key demographic groups are essential for appropriate management of the mid-Atlantic horseshoe crab (*Limulus polyphemus*) fishery. We conducted a trawl survey along the coast of the Delaware Bay area (DBA, Virginia to New Jersey), quantified mean catch per 15-minute tow, and compared the relative abundance of demographic groups with those of prior years. Due to time constraints, no trawls were performed in the lower Delaware Bay this year. Mean catch-per-tow across all demographic groups was similar to last year's analysis, except for the newly mature males, which were relatively high in the previous two years of surveys. Mean stratified catch-per-tow across all demographic groups remains highly variable, although mature females show a positive trend over the study period. Newly mature males also have an increasing trend in recent years, although their relative abundance was low in 2023. Prosomal widths of all demographic groups, except immature individuals, show decreasing trends over the time-series in the DBA. Our findings will be used to parameterize the Adaptive Resource Management model used to set annual harvest levels for horseshoe crabs.

Introduction

To effectively manage the mid-Atlantic horseshoe crab (*Limulus polyphemus*) fishery, accurate information on relative abundance levels and trends is needed. The Adaptive Resource Management (ARM) model (McGowan et al. 2011) adopted by the ASMFC requires annual, fishery-independent indices of newly mature recruit and adult abundances. The purpose of this project was to conduct a horseshoe crab trawl survey along the Mid-Atlantic coast in order to: (1) determine horseshoe crab relative abundance, (2) describe horseshoe crab population demographics, and (3) track inter-annual changes in horseshoe crab relative abundance and demographics. Here, we report our cumulative results through the fall 2023 trawl survey.

We have provided the ARM Subcommittee relative abundance estimates of horseshoe crabs in the Delaware Bay area (DBA) and lower Delaware Bay (LDB) surveys to inform the ARM model runs. Herein, we present the population estimates through the 2023 survey. Gear catchability has not been evaluated for these estimates, so they should be considered conservative.

Methods

The Virginia Polytechnic Institute and State University horseshoe crab trawl survey is traditionally conducted in two areas (Figure 1). The coastal DBA survey extended in the Atlantic Ocean from shore out to 22.2 km (12 nautical miles), and from 39º 20' N (Atlantic City, NJ) to 37º 40' N (slightly north of Wachapreague, VA). This area was previously sampled from 2002 to 2011, and again from 2016 to 2023. Due to time constraints, the LDB survey area, which extends from the Bay mouth to a line between Egg Island Point, New Jersey, and Kitts Hummock, Delaware, was not sampled this year. The LDB was previously sampled from 2010 to 2012 and 2016 to 2021. The surveys were conducted between 6 September to 30 October 2023.

The DBA survey area was stratified by distance from shore (0-3 nm, 3-12 nm) and bottom topography (trough, non-trough) as in previous years. The LDB survey area was stratified by bottom topography only, as in previous years. Sampling was conducted aboard a 16.8-m chartered commercial fishing vessel operated out of Ocean City, MD. We used a two-seam flounder trawl with an 18.3-m headrope and 24.4-m footrope, rigged with a Texas Sweep of 13-mm link chain and a tickler chain. The net body consisted of 15.2-cm (6-in) stretched mesh, and the bag consisted of 14.3-cm (5 5/8-in) stretched mesh. Tows were usually 15 minutes bottom time, but were occasionally shorter to avoid fishing gear (e.g., gill nets, crab and whelk pots) or vessel traffic. The start and end positions of each tow were recorded when the winches were stopped and when retrieval began, respectively. The bottom water temperature was recorded for each tow. We sampled 53 stations in the DBA survey. Two of these trawls were either shorter or longer in duration than average, one being a five-minute tow within our inshore/non-trough stratum and the other being a 25-minute trawl in the offshore/trough stratum. Both were included in our data analysis as no malfunctions were reported. Additionally, due to the high variance in CPUE and density of HSCs in each stratum (Figure 2), a larger sample size will help better explain variability.

Horseshoe crabs were culled from the catch, and either all individuals or a subsample were examined for prosomal width (PW, millimeters) and identified for sex and maturity. Maturity classifications were immature, newly mature (those that are capable of spawning but have not yet spawned), and mature (those that have previously spawned). Newly mature and mature males are morphologically distinct and are believed to be classifiable without error. However, some error is associated with distinguishing newly mature from immature females. Females that were not obviously mature (females with no rub marks) or immature (too small or soft-shelled) were probed with an awl to determine the presence or absence of eggs. Females with eggs but without rub marks were considered newly mature. Females with both eggs and rub marks were considered mature. Initial sorting classifications were presumed adult males (newly mature and mature), presumed adult females, and all immature. Up to 25 adult males, 25 adult females, and 50 immatures were retained for examination (sometimes catches were lower than these target sample sizes). The remainder were counted separately by classification and released. Characteristics of the examined subsamples were then extrapolated to the counted portions of the catch. According to a recent discussion with the vessel, in the last three years, not all subsampled ambiguous newly mature females were probed with an awl to test whether they had eggs. These tests occurred only when onboard logistic conditions allowed, i.e., when the crew had sufficient time between one tow and the next. When such a test could not be performed, we classified these cases as female immatures.

In each stratum, the mean catch per 15-minute tow and associated variance were calculated using two methods, i.e., either assuming a normal distribution model or a delta-lognormal distribution model (Pennington, 1983). Stratum mean and variance estimates were combined using formulas for a stratified random sampling design (Cochran, 1977). The approximate 95% confidence intervals were calculated using the effective degrees of freedom (Cochran, 1977). Annual means were considered significantly different if 95% confidence limits did not overlap. Stratified means calculated using the delta-lognormal distribution model are not additive - i.e., means calculated for each demographic group do not sum to the mean calculated using all crabs. Means calculated using the normal-distribution model are additive, within rounding errors.

Annual size-frequency distributions, in intervals of 10-mm prosomal width, were calculated for each sex/maturity category by pooling size-frequency distributions of all stations (adjusted for tow duration if necessary) in a stratum in a year to determine the relative proportions for each size interval. Those proportions were then multiplied by the stratum mean catch-per-tow that year to produce a stratum size-frequency distribution. Stratum size-frequency distributions then were multiplied by the stratum weights and added in the same manner as calculating the stratified mean catch per tow. Areas under the distribution curves represent the stratified mean catch per tow at each size interval.

Within the DBA, excluding the one shorter trawl, the average tow distance for a 15-min tow was 1.06 kilometers at a speed of 4.25 KPH. No net-spread measurement device was used during sampling. Instead, the net-spread was calculated using the net-spread regression relationship, *net spread (S, in meters)/tow speed (C, in KPH)*, developed from previous trawl *surveys* $(S = 13.84 - 0.858 \times C)$. From our combined 53 tows, the average net-spread was 10.19 meters.

For each tow, catch density (catch/km^2) was calculated from the product of tow distance (in km) and estimated net-spread (converted from meters to km), assuming that all fishing was done only by the net, and that there was no herding effect from the ground gear (sweeps):

$$\text{catch/km}^2 = \text{catch}/[\text{tow distance (km)} \times \text{net-spread (km)}].$$

Within each stratum, the mean catch per square kilometer and associated variance were calculated assuming a normal-distribution model and a lognormal delta-distribution model. Stratum mean densities and variance estimates were combined to produce a stratified mean density ($\bar{X}_{st}$) using formulas for a stratified random sampling design as with the catch-per-tow estimates described above. Population totals were estimated by multiplying stratified mean density ($\bar{X}_{st}$) by survey area (DBA = 5127.1 km^2 ; LDB = 528.4 km^2):

$$\text{Population total} = \bar{X}_{st} \text{ x } (5127.1 \text{ or } 528.4 \text{ km}^2)$$

A model-based approach was also used to standardize the HSC CPUE using hurdle models (Wong, 2023). The hurdle model framework used in this study is a generalized linear model that models the probability of HSC observations and the observed positive counts using two separate models combined for each of the six HSC demographic groups. Such analysis aims to remove the catchability effect of external factors on our observed CPUE when estimating relative abundance. A Binomial distribution was used in the probability submodel, and a lognormal distribution was used for the positive counts submodel. The factors considered include year, latitude, longitude, depth strata (inshore, offshore), topography strata (trough, non-trough), average trawl depth, time of day, month, bottom temperature, bottom salinity, and distance from shore. Factors like month, time of day, and average depth had major effects on the observed CPUE of all demographic groups. Detailed analysis based on data by 2022 can be found in Wong (2023).

Results

Delaware Bay Area

For all demographic groups other than newly mature males, mean stratified catch-per-tow values have remained relatively consistent between 2016 and 2018. Since then, there has been a substantial increase in variation over the past four years among newly mature and mature individuals (Tables 1 and 2; Figure 3). The mean stratified catches-per-tow for mature males and females increased substantially. The number of newly mature females continued to be low; the number of newly mature males was much lower than in the past two years. Immature individuals decreased, but have been relatively stable since 2016. Newly mature females' relative abundance has been low since 2019, and none were caught this year.

There is a significant correlation between stratified mean catches of mature males and mature females ($r = 0.96$; $p < 0.001$; $T = 14.04$; $n = 18$) when considering all data since 2002. This is also true for immature males and females ($r = 0.99$; $p < 0.001$; $T = 33.42$; $n = 18$), but not for newly mature individuals. Previously, there was a significant positive correlation between newly mature individuals between 2002 – 2018. However, this correlation was lost with the addition of data from 2019 and 2022, likely due to the low number of newly mature females trawled in recent years compared to newly mature males.

Historically, the design-based approach has been used to estimate the stratified mean catches per 15-minute tow of horseshoe crabs in the coastal Delaware Bay area by demographic group (Hata and Hallerman 2017, 2019; Hallerman and Jiao 2020; Wong et al. 2022). Comparison between the design-based and model-based approaches shows that the standardized CPUE from a hurdle model with delta-lognormal distribution generally showed similar trends with variations to different degrees among different demographic groups (Figure S1, Table S1). The large increase in 2023 mature males and females estimated from the model-based approach is less apparent than in the design-based approach. There were two high tows in 2023, both in September and in non-trough strata, and most tows were in September, which tends to have a higher cate rate (Wong et al. 2022, and Figure S2).

Lower Delaware Bay

No samples were collected within Delaware Bay in 2022 and 2023 due to rising costs and limited time. Stratified mean catches of immature female and male crabs and newly mature female crabs in 2019 and 2020 were the lowest for the time series (Tables 3 and 4; Figure 4). The number of both males and females in all three maturity groups was low in 2020 and 2021. The mean catches of mature males are significantly correlated with the mean catches of mature females ($r = 0.919$; $T = 5.71$; $p = 0.001$; $n = 8$).

Size distributions

Like the results in last year's report, size-frequency distributions remained highly variable (Figure 5). There were no distinct modal groups simultaneously in both sexes other than in 2009 with immature individuals. However, this modal group did not continue into the following years and was not found within the previous year of sampling in the lower Delaware Bay (Figure 6).

We had previously reported that mean prosomal widths of crabs in the DBA survey displayed slight, but detectable, decreases over time (Table 5, Figure 7) (Hata and Hallerman 2017, 2019, Hallerman and Jiao 2020). This trend appears to have continued this year within the Delaware Bay area. The negative correlation between years and mean prosomal width of newly mature and mature individuals remained statistically significant. The LDB portion of the table has been retained for comparison, but has not changed from our previous analysis, as no new data were added. A similar trend is present within the LDB amongst newly mature females and mature individuals.

Sex ratios

Overall, mature males were generally twice as common as mature females throughout the sampling period. Sex ratios (M:F) from mean catch-per-tow within the DBA ranged from 1.72 in 2019 to 3.64 in 2016, with an average of 2.27 over the time series. Male-to-female sex ratios in newly mature individuals have been highly variable, ranging from 0.11 in 2003 to 47.7 in 2022, with a new overall average of 5.67 over the time series. This may reflect sampling effects, temporal variability in recruitment to the newly mature class relative to the survey period, or differences in year-class abundance because females are believed to mature a year later than males.

Compared to the coast, the lower Delaware Bay has had a much higher male-to-female sex ratio in mature individuals. These values for mature individuals have ranged from 2.60 in 2018 to 20.5 in 2020, with an average of 5.98. This relationship between the coast and bay has been historically similar for newly mature individuals, with a minimum of 0.45 in 2010 and a maximum of 6.10 in 2012. Excluding 2019 and 2020 — where newly mature males were caught, but no newly mature females — this led to an average of 3.09. The higher sex ratios within Delaware Bay may reflect a tendency for male horseshoe crabs to remain near the spawning beaches.

Population estimates

Annual population estimates of immature crabs in the DBA survey mirror trends observed in the catch-per-tow estimates and have been variable over time, with a large peak in 2009 (Tables 6 and 7). Compared to the previous year, the estimated mean population total decreased for mature individuals and newly mature males, while newly mature females and immature individuals increased. Assuming the normal distribution, the significance found in catch-per-tow estimates is mirrored in total population estimates. These mean total population estimates are similar to those seen since 2016 for immature individuals. Newly mature males and mature individuals appear to have a recent increasing trend, while newly mature females appear to show a recent decreasing trend. There is a significant correlation between population estimates for mature males and females and immature males and females, as observed in mean catches per tow reported above. There is no significant correlation among newly mature individuals in the DBA.

Without new data, population estimates for immature crabs in lower Delaware Bay in 2022 and 2023 are unavailable. The estimates in 2021 have been consistent with coastal estimates since the LDB survey began in 2010 (Tables 8 and 9). On average, 15.6% of the total number of immature females and 19.7% of immature males occurred within Delaware Bay, although the LDB sampling area comprises only 9.3% of the total combined area. In 2020, both immature and mature crabs occurring within the Bay were the lowest among the survey years. Over the whole time series, about 5% of the combined population of newly mature females occurred within the Bay, while 9% of newly mature males were in the Bay. In 2020, 0 and 0.2% of newly mature females and males, respectively, occurred within Delaware Bay, with the percentage of immature males being the lowest in the history of the survey. About 21% of mature females and 28% of mature males occurred within the Bay on average, with 0.3 and 5%, respectively, occurring within the Bay in 2020. Within the combined survey population, the sex ratio of mature males:females ranged from 2.24 to 4.07 between 2010 and 2020, and averaged 3.02, with a ratio of 2.93 in 2020.

Effects of the sampling period

Sampling in the Delaware Bay Area occurred primarily during September and October, with the last trawls occurring on October 30th. This time frame is similar to those in sampling years prior to 2019, as trawls between 2019 and 2021 were performed earlier in August and September. Although the water temperature was lower than last year, it was similar to the higher average water temperature seen in the past six years compared to sampling prior to 2016 (Table 10; Figure 8). This more consistent temperature within the Delaware Bay is in contrast to the lower Delaware Bay, where the average water temperature is more directly inversely proportional to the ordinal date.

When comparing water temperature and the time of our sampling period, there appears to be a correlation within the DBA of mean catches-per-tow of immature males and females with both water temperature ($p = 0.021$, $p = 0.018$) and ordinal date ($p = 0.015$, $p = 0.012$) (Table 11). CPUE of newly mature females significantly correlates with ordinal date, and CPUE of mature females significantly correlates with water temperature.

Key Findings

1. Mean catch-per-tows of mature males and females are much higher than in the past, with high variances.
2. Mean catch-per-tow of immature male and female horseshoe crabs in the DBA have remained variable since 2002 and have no apparent trend.
3. Mean catch-per-tow of newly mature male horseshoe crabs in the DBA remained highly variable, and were relatively higher in 2016-2022, while newly mature females have remained relatively low since 2019.
4. Mean catch-per-tow of immature demographic groups in the DBA may be correlated with the ordinal date. Mean catch-per-tow of immature and mature individuals may be correlated with temperature.
5. Annual mean prosomal width appears to still be decreasing in mature and newly mature males and females in the DBA.

Literature Cited

Cochran, W. G. 1977. Sampling Techniques, 3rd ed. John Wiley and Sons, Inc., New York. 428 p.

Hata, D. and E. Hallerman. 2017. Results of the 2016 Horseshoe Crab Trawl Survey: Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees.

Hata, D. and E. Hallerman. 2019. Results of the 2018 Horseshoe Crab Trawl Survey: Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees.

Hallerman, E. and Y. Jiao. 2021. Results of the 2020 Horseshoe Crab Trawl Survey: Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees.

McGowan, C.P., D. R. Smith, J. A. Sweka, J. Martin, J. D. Nichols, R. Wong, J. E. Lyons, L. J. Niles, K. Kalasz, J. Brust, and M. Klopfer. 2011. Multispecies modeling for adaptive management of horseshoe crabs and red knots in the Delaware Bay. Natural Resource Modeling 24:117-156.

Pennington, M. 1983. Efficient estimators of abundance, for fish and plankton surveys. Biometrics 39:281-286.

Wong, C.C, Y. Jiao, and Hallerman, E. 2021. Results of the 2022 Horseshoe Crab Trawl Survey: Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab and Delaware Bay Ecology Technical Committees.

Wong, C.C. 2023. Design- and model-based approaches for estimating abundance of American horseshoe crab. M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

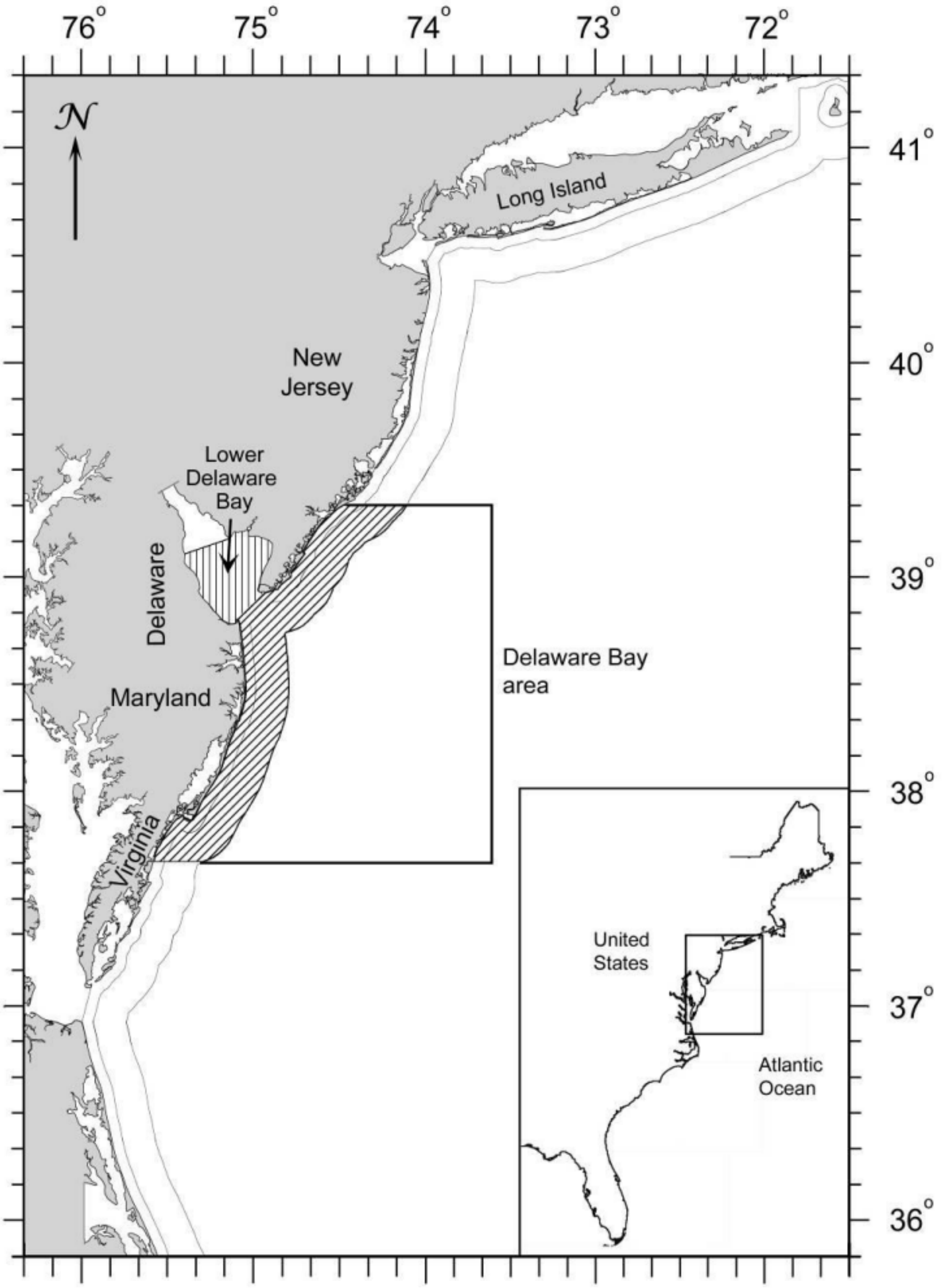


Figure 1. Fall 2023 horseshoe crab trawl survey sampling area. The coastal Delaware Bay area (DBA) and Lower Delaware Bay (LDB) survey areas are indicated. Mean catches between years were compared using stations within the shaded portions of the survey areas.

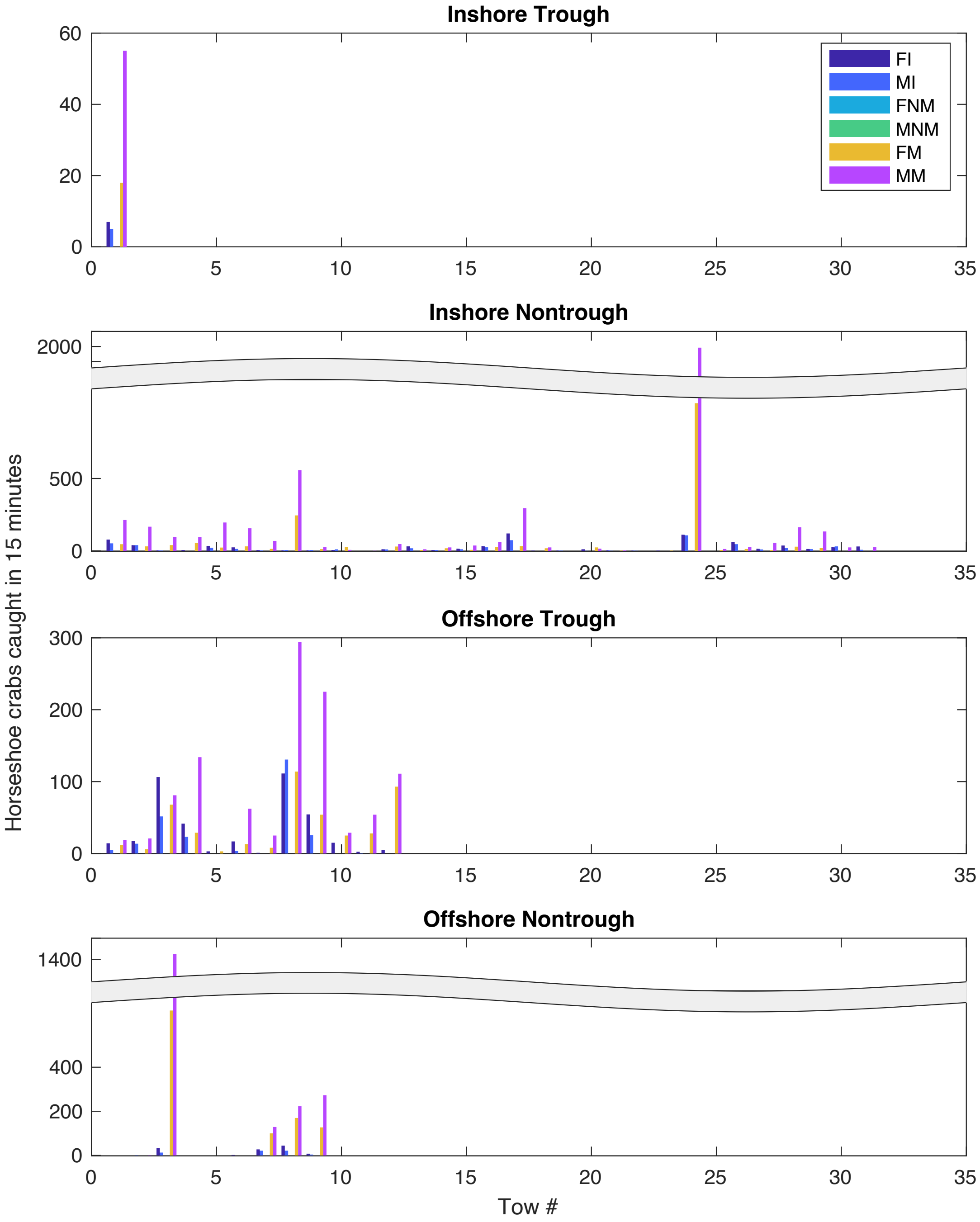


Figure 2. Plots showing high variability of relative abundances of horseshoe crabs of different demographic groups caught within the same strata in fifteen-minute tows in 2023.

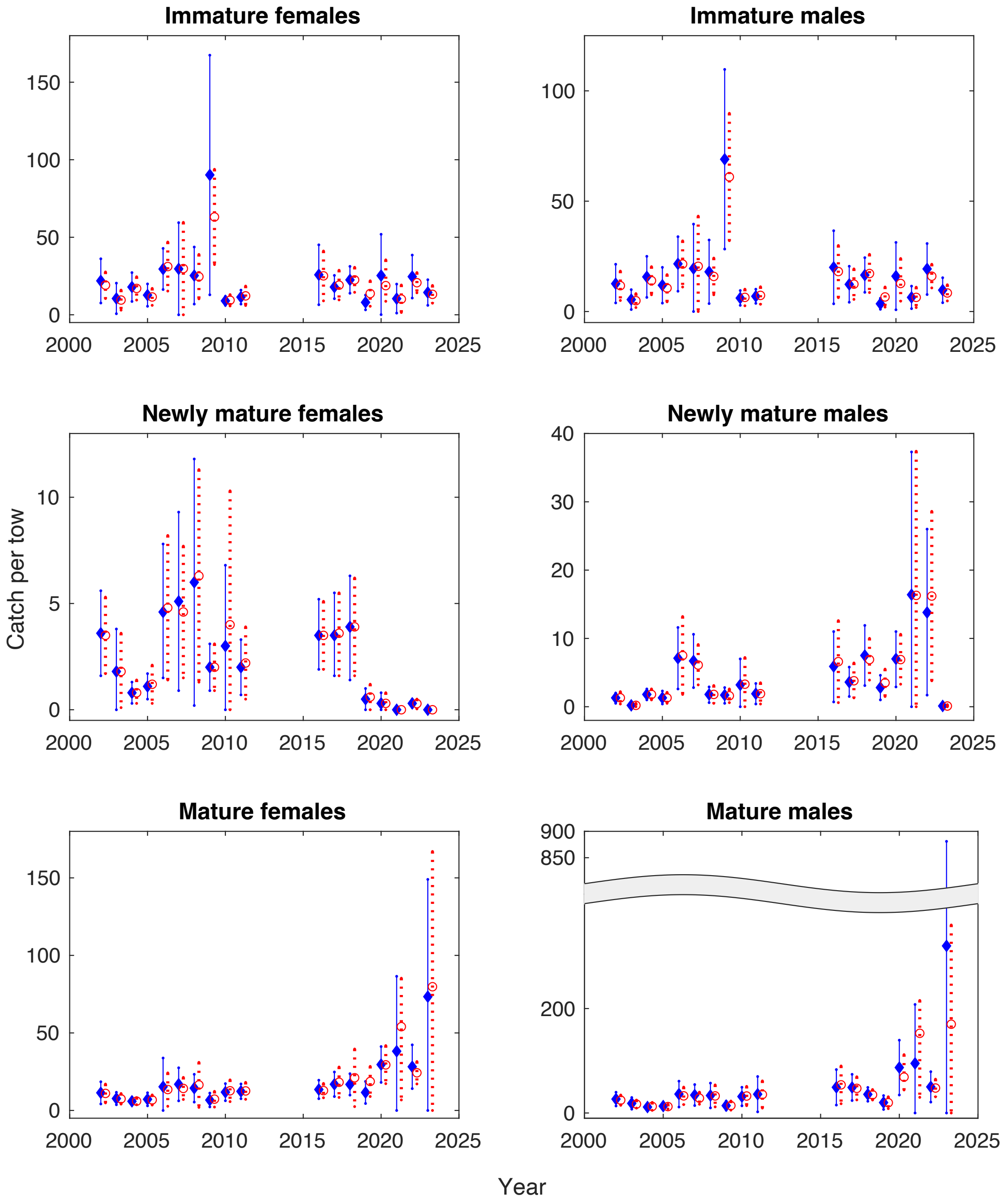


Figure 3. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the coastal **Delaware Bay area** survey by demographic group. Vertical lines indicate 95% confidence intervals. Solid blue symbols and lines indicate the **delta distribution** model. Open red symbols and dashed lines indicate the **normal distribution** model. Data are from Tables 1 and 2. Note the differences in the *y*-axis scales.

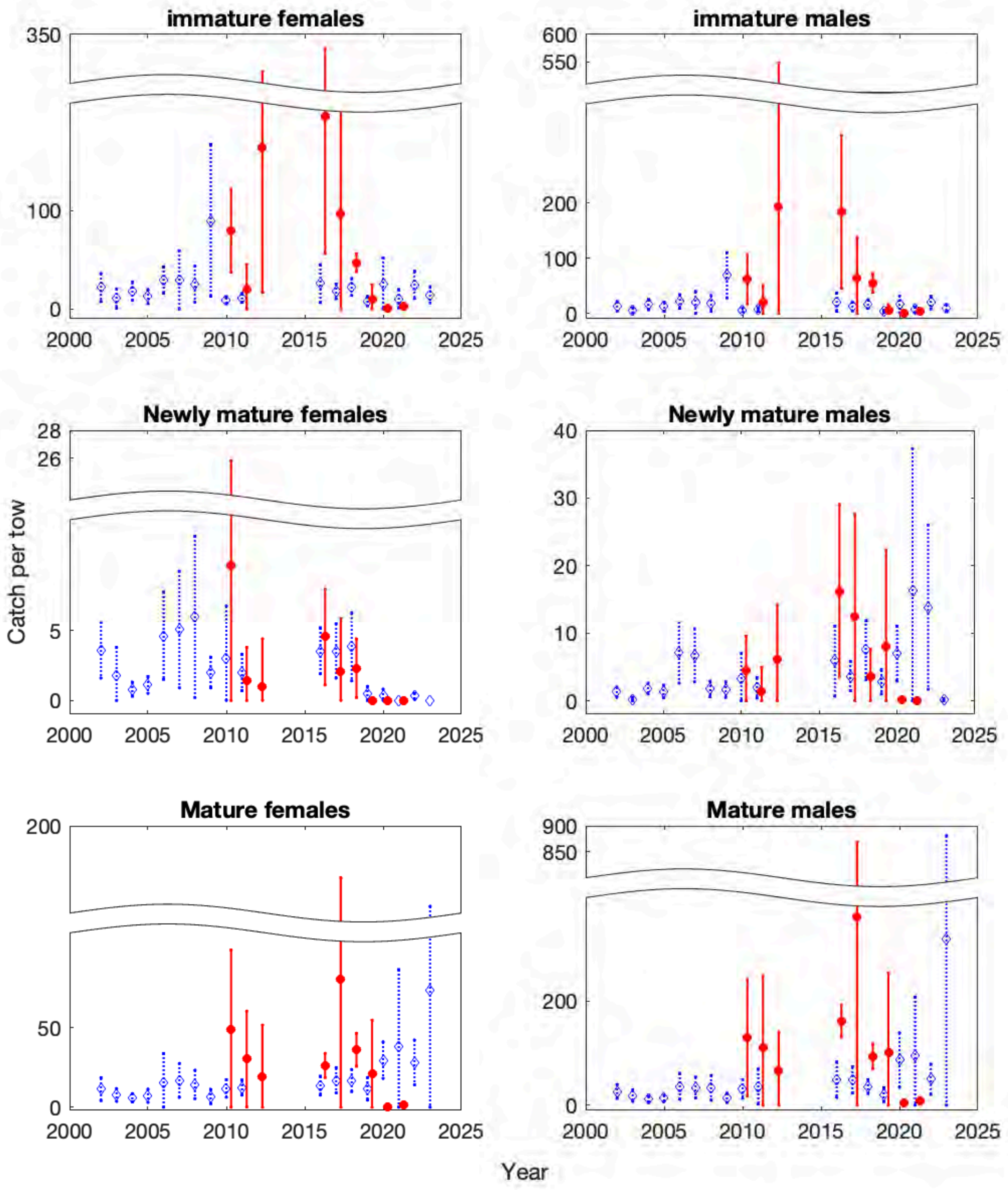


Figure 4. Plots of stratified mean catch per 15-minute tow of horseshoe crabs in the **lower Delaware Bay** survey by demographic group, with coastal **Delaware Bay area** survey means for comparison. Vertical lines indicate 95% confidence limits. Only the **delta distribution** model means are presented for clarity. Solid symbols and lines indicate **the lower Delaware Bay survey**. Open symbols and dashed lines indicate the coastal **Delaware Bay area** survey. Note differences in *y*-axis scales.

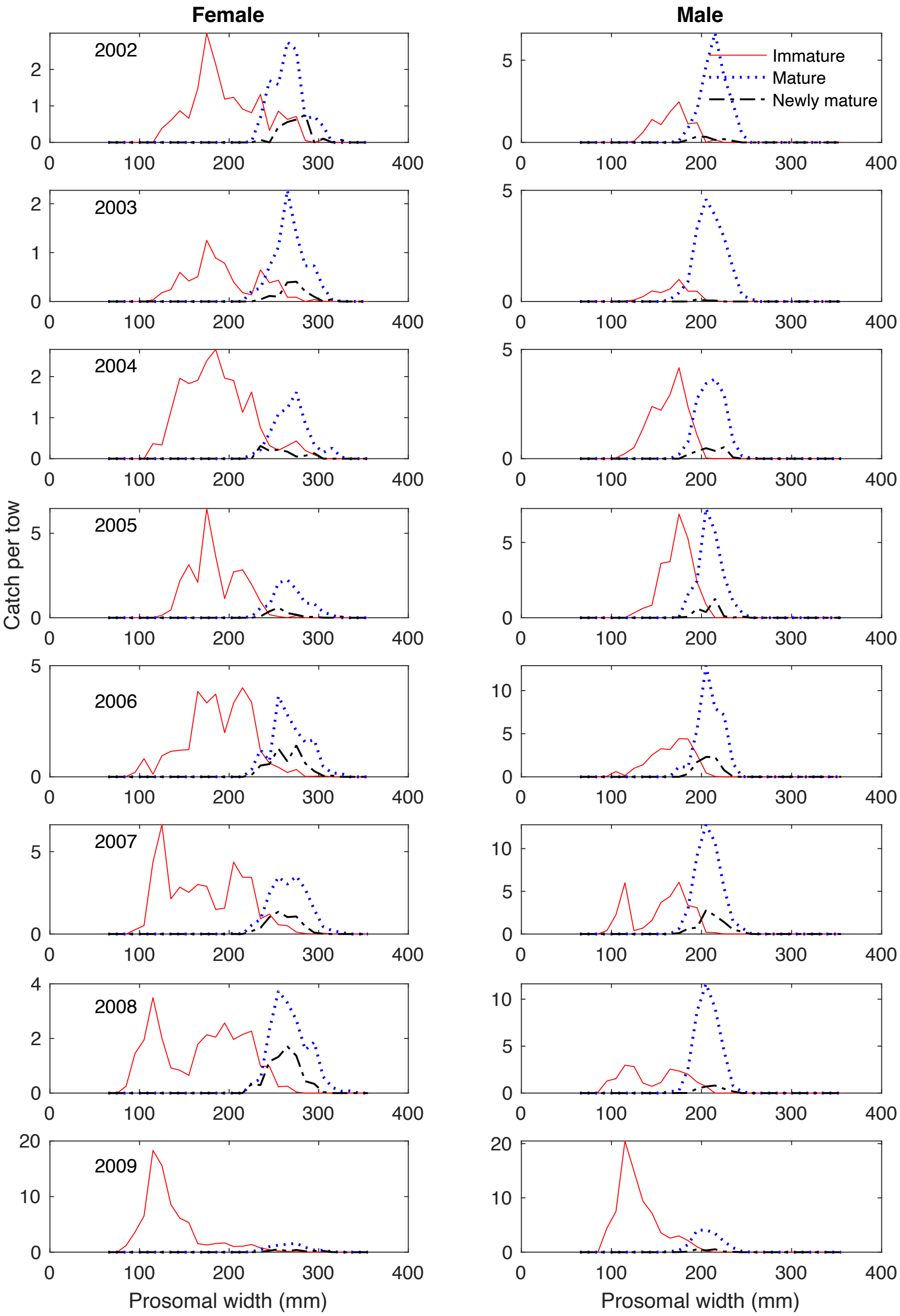
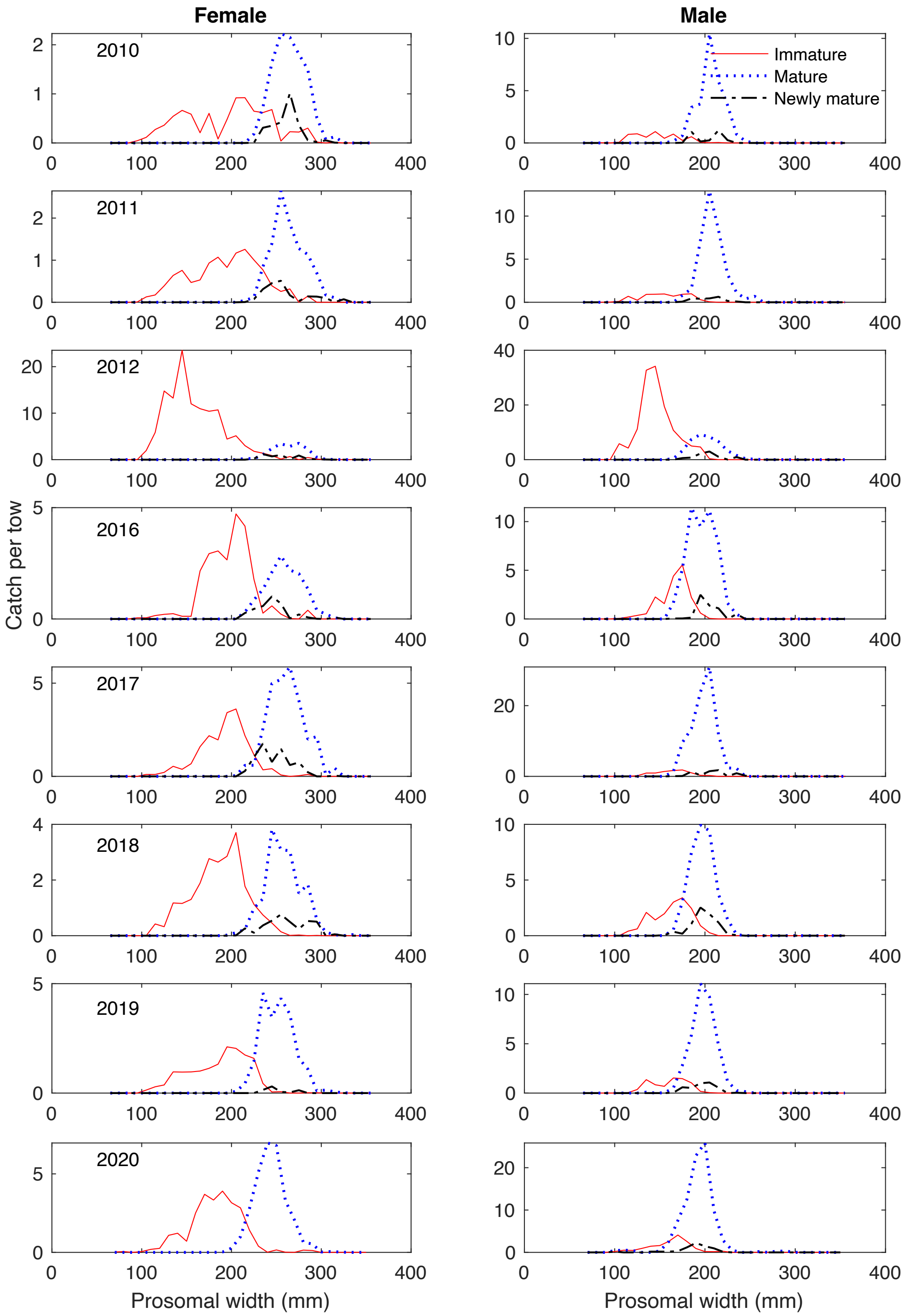


Figure 5. Size-frequency distributions of horseshoe crabs by demographic group and year in the coastal **Delaware Bay area** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 1.



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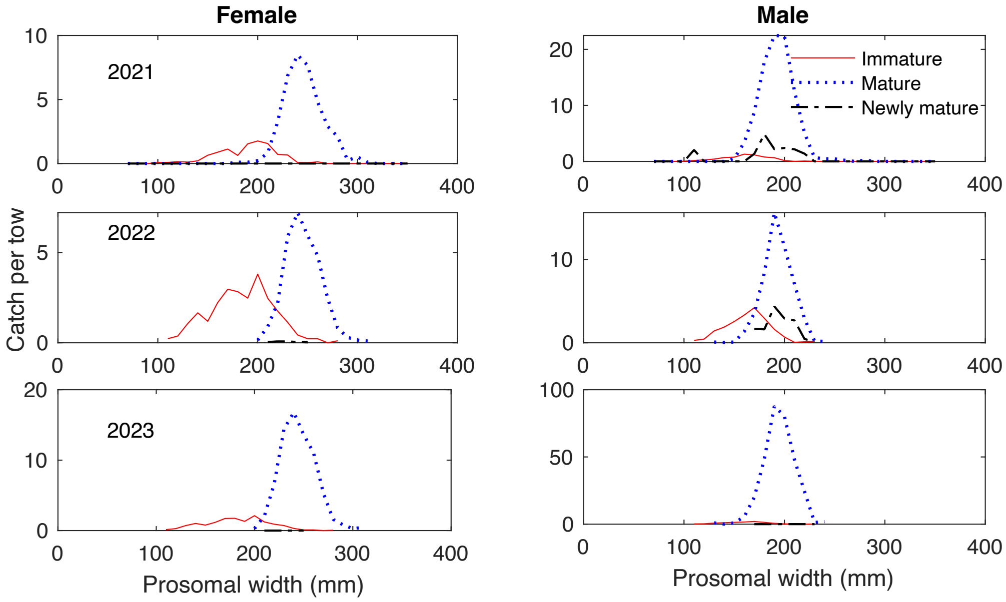

Figure 5. continued.

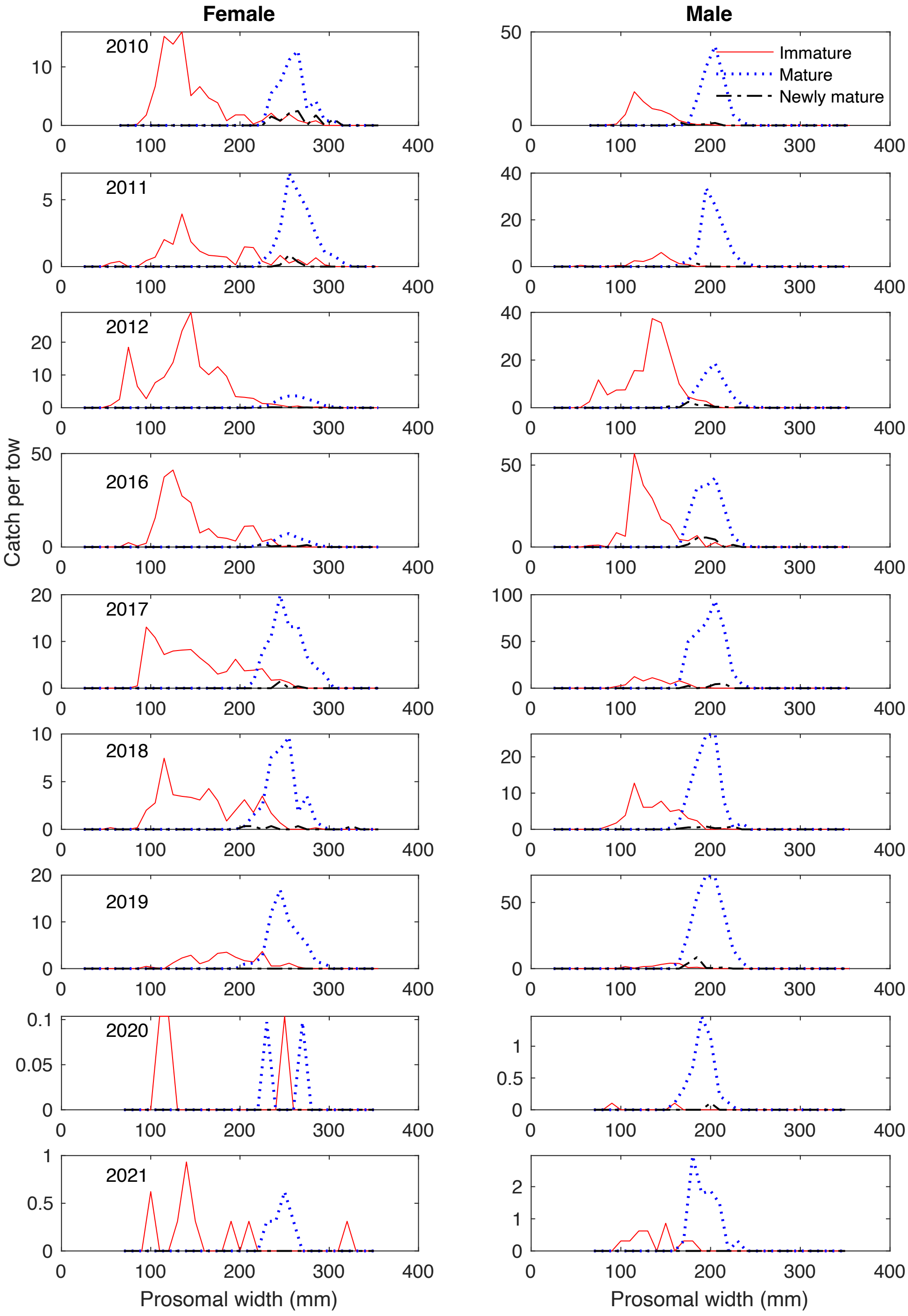

Figure 6. Relative size-frequency distributions of horseshoe crabs by demographic group and year in the **lower Delaware Bay** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 3.

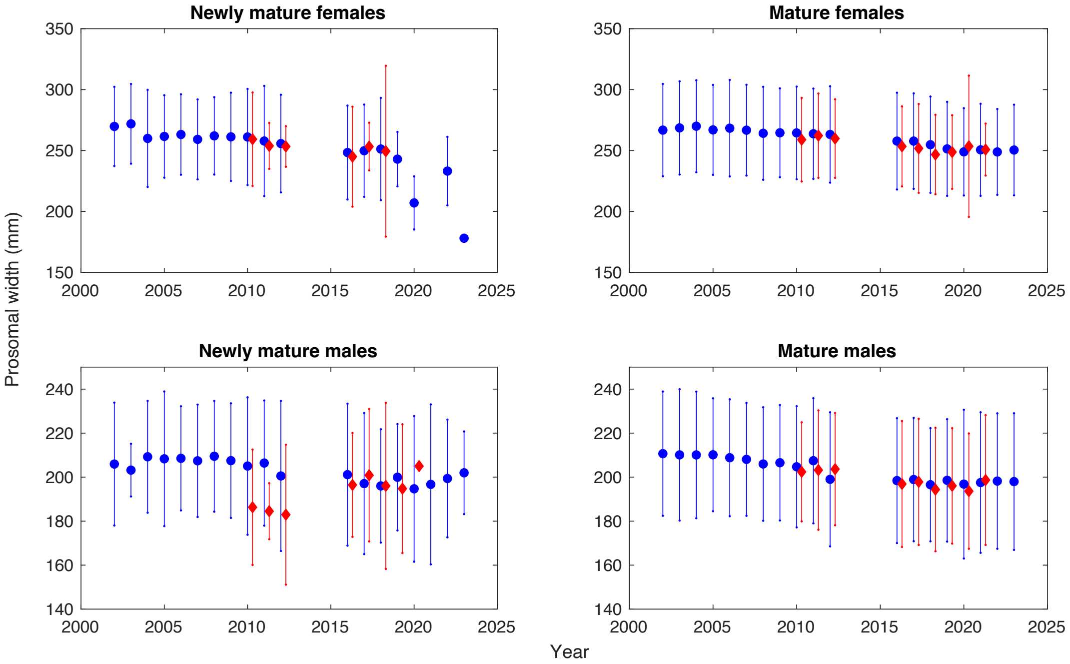

Figure 7. Mean prosomal widths (mm) (± 2 standard deviations) of mature and newly mature female and male horseshoe crabs in the Delaware Bay area (blue symbols and lines) and lower Delaware Bay (red symbols and lines) surveys.

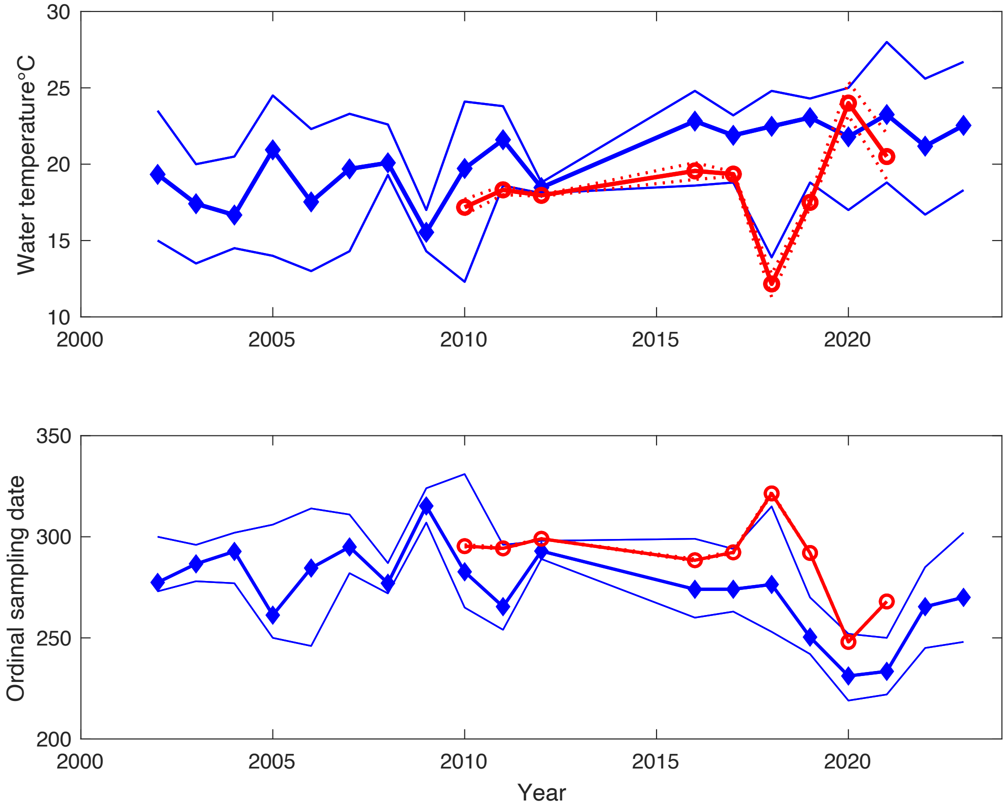

Figure 8. Plots of bottom water temperatures and ordinal sampling dates (days since 1 January) in the coastal Delaware Bay area and lower Delaware Bay trawl surveys. Solid symbols and blue lines indicate coastal Delaware Bay area. Open symbols and red lines indicate lower Delaware Bay. Points indicate mean values. Thinner lines indicate maximum and minimum values.

Table 1. Stratified mean catch-per-tow of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **delta distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2002	21.9	36.1	7.6	0.31	6.8	2002	12.6	21.4	3.9	0.33	4.2
2003	10.5	20.4	0.7	0.43	4.6	2003	5.4	9.9	0.9	0.39	2.1
2004	17.9	27.2	8.6	0.25	4.5	2004	15.7	25.0	6.4	0.29	4.5
2005	12.7	19.9	5.5	0.28	3.5	2005	11.9	20.0	3.8	0.33	3.9
2006	29.5	42.8	16.3	0.21	6.3	2006	21.6	33.9	9.2	0.25	5.4
2007	29.6	59.4	0.0	0.41	12.2	2007	19.5	39.6	0.0	0.42	8.2
2008	25.3	43.7	6.9	0.33	8.3	2008	18.0	32.4	3.6	0.35	6.3
2009	90.2	167.4	12.9	0.39	35.5	2009	69.0	109.7	28.3	0.29	19.8
2010	9.0	11.9	6.1	0.16	1.4	2010	6.1	9.5	2.8	0.27	1.6
2011	11.4	15.9	6.9	0.19	2.2	2011	6.9	10.1	3.7	0.23	1.6
2016	25.8	45.1	6.5	0.36	9.2	2016	20.0	36.6	3.5	0.39	7.9
2017	17.9	25.4	10.4	0.19	3.4	2017	12.3	20.5	4.2	0.27	3.3
2018	22.5	31.2	13.9	0.18	4.1	2018	16.5	24.4	8.7	0.22	3.7
2019	8.0	12.7	3.2	0.3	2.4	2019	3.5	6.0	1.0	0.35	1.2
2020	25.3	51.9	0.1	0.6	15.2	2020	16.0	31.3	0.8	0.56	9.1
2021	10.4	19.8	1.1	0.52	5.5	2021	6.4	11.5	1.3	0.46	3.0
2022	24.6	38.5	10.8	0.33	8.1	2022	19.3	30.8	7.7	0.36	6.9
2023	14.4	22.6	6.1	0.31	4.5	2023	9.7	15.3	4.0	0.32	3.1
Mature Females						Mature Males					
2002	11.4	18.5	4.2	0.3	3.4	2002	26.6	39.7	13.4	0.24	6.3
2003	7.7	11.7	3.7	0.25	1.9	2003	18.4	29.6	7.3	0.28	5.2
2004	5.9	8.6	3.3	0.21	1.3	2004	11.4	17.1	5.7	0.24	2.8
2005	7.2	11.4	3.0	0.27	2.0	2005	13.2	19.1	7.3	0.21	2.8
2006	15.3	33.8	0.0	0.44	6.7	2006	36.2	60.9	11.4	0.28	10.1
2007	16.9	27.5	6.2	0.3	5.1	2007	34.3	54.4	14.3	0.28	9.7
2008	14.4	23.3	5.4	0.29	4.2	2008	33.5	57.2	9.8	0.33	11.2
2009	6.7	11.2	2.3	0.32	2.1	2009	14.1	22.8	5.3	0.30	4.2
2010	11.8	17.3	6.3	0.22	2.6	2010	31.5	49.2	13.8	0.27	8.6
2011	12.3	17.1	7.6	0.18	2.2	2011	36.0	69.8	2.2	0.41	14.7
2016	13.5	19.5	7.6	0.21	2.9	2016	49.2	83.1	15.2	0.29	14.3
2017	16.9	24.8	9.0	0.23	3.9	2017	48.9	74.0	23.9	0.25	12.2
2018	16.8	23.7	9.9	0.2	3.3	2018	35.7	48.9	22.5	0.17	6.2
2019	11.6	18.7	4.5	0.3	3.5	2019	20.0	33.3	6.8	0.33	6.6
2020	29.6	41.2	18.1	0.23	6.9	2020	87.0	139.4	34.5	0.36	31.1
2021	38.2	86.5	0.0	0.72	27.4	2021	95.0	207.8	0.0	0.67	64.1
2022	28.2	42.3	14.1	0.29	8.3	2022	50.0	79.1	20.9	0.34	17.2
2023	73.4	149.0	0.0	0.56	41.3	2023	320.0	881.0	0.0	0.95	302.0
Newly Mature Females						Newly Mature Males					
2002	3.6	5.6	1.6	0.26	0.9	2002	1.3	2	0.5	0.28	0.4
2003	1.8	3.8	0.0	0.49	0.9	2003	0.2	0.5	0.0	0.84	0.2
2004	0.8	1.3	0.3	0.3	0.2	2004	1.8	2.6	1	0.21	0.4
2005	1.1	1.7	0.5	0.28	0.3	2005	1.3	2.3	0.4	0.33	0.4
2006	4.6	7.8	1.5	0.3	1.4	2006	7.1	11.6	2.6	0.36	2.7
2007	5.1	9.3	0.9	0.39	2.0	2007	6.7	10.6	2.8	0.28	1.9
2008	6.0	11.8	0.2	0.44	2.7	2008	1.8	2.9	0.6	0.32	0.6
2009	2.0	3.1	0.9	0.26	0.5	2009	1.7	2.8	0.5	0.34	0.6
2010	3.0	6.8	0.0	0.59	1.8	2010	3.2	7.0	0.0	0.55	1.8
2011	2.0	3.3	0.7	0.31	0.6	2011	1.9	3.4	0.4	0.37	0.7
2016	3.5	5.2	1.9	0.23	0.8	2016	5.9	11	0.7	0.42	2.5
2017	3.5	5.5	1.6	0.27	0.9	2017	3.6	5.8	1.5	0.29	1.0
2018	3.9	6.3	1.4	0.3	1.2	2018	7.5	11.9	3.1	0.27	2.1
2019	0.5	1.0	0.0	0.46	0.2	2019	2.8	4.6	1.0	0.32	0.9
2020	0.3	0.8	0.0	0.85	0.3	2020	7.0	11.0	2.9	0.35	2.4
2021	0.0	NA	NA	NA	NA	2021	16.4	37.3	0.0	0.69	11.3
2022	0.3	0.5	0.1	0.5	0.1	2022	13.8	26.0	1.7	0.52	7.2
2023	0.0	NA	NA	NA	NA	2023	0.1	0.3	0.0	0.76	0.1

Table 2. Stratified mean catch-per-tow of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **normal distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2002	19.1	27.6	10.5	0.22	4.1	2002	11.7	18.3	5.0	0.27	3.2
2003	9.5	15.9	3.0	0.32	3.1	2003	4.9	8.1	1.8	0.30	1.5
2004	17.0	24.5	9.5	0.21	3.6	2004	14.0	20.3	7.6	0.22	3.1
2005	11.5	17.0	6.1	0.23	2.6	2005	10.6	16.7	4.4	0.28	2.9
2006	31.1	46.9	15.3	0.24	7.5	2006	21.5	32.0	11.1	0.23	5.0
2007	29.8	59.6	0.0	0.41	12.2	2007	20.5	43.2	0.0	0.45	9.3
2008	24.6	38.9	10.3	0.27	6.6	2008	15.9	24.2	7.6	0.24	3.8
2009	63.1	93.8	32.4	0.24	14.9	2009	61.0	89.8	32.1	0.23	14.0
2010	9.4	13.0	5.7	0.19	1.8	2010	6.4	10.1	2.6	0.29	1.8
2011	12.2	18.5	6.0	0.25	3.0	2011	7.3	11.2	3.3	0.26	1.9
2016	25.1	41.1	9.0	0.31	7.7	2016	18.1	29.9	6.3	0.31	5.7
2017	19.1	28.7	9.6	0.24	4.6	2017	12.4	19.3	5.5	0.26	3.3
2018	22.5	30.6	14.5	0.17	3.8	2018	17.2	25.9	8.6	0.24	4.1
2019	13.7	21.9	5.5	0.3	4.1	2019	6.6	11.1	2.0	0.34	2.2
2020	18.8	35.4	8.7	0.32	6.0	2020	12.7	24.0	4.7	0.37	4.8
2021	10.1	19.2	1.5	0.50	5.1	2021	6.4	11.0	1.8	0.42	2.7
2022	20.7	27.2	14.2	0.18	3.8	2022	16.0	21.4	10.7	0.20	3.2
2023	13.2	18.9	7.5	0.24	3.2	2023	8.4	12.1	4.8	0.25	2.1
Mature Females						Mature Males					
2002	11.0	17.0	4.9	0.26	2.8	2002	24.6	34.4	14.8	0.19	4.7
2003	7.5	10.9	4.1	0.22	1.6	2003	17.0	24.7	9.4	0.21	3.6
2004	6.0	8.3	3.7	0.19	1.1	2004	12.6	20.2	5.1	0.29	3.6
2005	6.8	10.0	3.5	0.22	1.5	2005	12.3	16.7	7.8	0.17	2.1
2006	13.5	24.2	2.7	0.31	4.2	2006	32.8	49.5	16.1	0.22	7.4
2007	14.2	21.3	7.1	0.24	3.4	2007	28.4	39.9	16.8	0.20	5.6
2008	16.5	31.0	2.0	0.41	6.8	2008	32.7	53.7	11.7	0.31	10.0
2009	7.3	12.3	2.2	0.33	2.4	2009	14.2	22.9	5.5	0.29	4.1
2010	12.7	19.7	5.7	0.26	3.3	2010	32.5	50.9	14.1	0.27	8.8
2011	12.6	18.1	7.2	0.2	2.6	2011	35.4	61.4	9.5	0.32	11.5
2016	12.8	17.4	8.2	0.17	2.2	2016	53.9	90.0	17.8	0.30	16.2
2017	18.2	28.0	8.4	0.26	4.8	2017	47.2	69.3	25.1	0.23	10.8
2018	21.1	39.6	2.5	0.41	8.7	2018	34.9	44.9	24.9	0.14	4.8
2019	18.7	28.4	9.0	0.26	4.8	2019	19.7	31.0	8.4	0.28	5.6
2020	29.4	41.8	17.3	0.25	7.2	2020	68.8	111.7	44.1	0.21	14.7
2021	54.0	85.3	6.8	0.50	26.8	2021	152.6	215.5	30.0	0.46	69.7
2022	24.3	31.5	17.1	0.18	4.3	2022	47.8	64.7	31.0	0.21	9.9
2023	79.8	167.0	0.0	0.59	47.2	2023	170.0	360.0	0.0	0.60	102.0
Newly Mature Females						Newly Mature Males					
2002	3.5	5.3	1.7	0.24	0.9	2002	1.3	2.2	0.4	0.31	0.4
2003	1.8	3.6	0.1	0.45	0.8	2003	0.2	0.5	0.0	0.84	0.2
2004	0.8	1.4	0.3	0.33	0.3	2004	1.8	2.6	1.0	0.21	0.4
2005	1.2	2.1	0.3	0.35	0.4	2005	1.3	2.1	0.5	0.29	0.4
2006	4.8	8.2	1.4	0.33	1.6	2006	7.5	13.2	1.8	0.36	2.7
2007	4.6	7.7	1.5	0.32	1.5	2007	6.1	9.1	3.2	0.23	1.4
2008	6.3	11.3	1.3	0.37	2.3	2008	1.8	3.1	0.5	0.34	0.6
2009	2.0	3.1	0.9	0.26	0.5	2009	1.6	2.6	0.6	0.30	0.5
2010	4.0	10.3	0.0	0.74	3.0	2010	3.3	7.2	0.0	0.56	1.9
2011	2.2	3.9	0.5	0.38	0.8	2011	1.9	3.5	0.4	0.38	0.7
2016	3.5	5.1	1.9	0.22	0.8	2016	6.6	12.6	0.6	0.43	2.9
2017	3.6	5.5	1.6	0.27	1.0	2017	3.8	6.4	1.3	0.32	1.2
2018	3.9	6.2	1.6	0.28	1.1	2018	6.9	10.0	3.9	0.21	1.5
2019	0.6	1.2	0.0	0.48	0.3	2019	3.5	5.5	1.5	0.29	1.0
2020	0.3	0.8	0.0	0.84	0.3	2020	6.9	10.6	3.3	0.31	2.1
2021	0.0	NA	NA	NA	0.0	2021	16.3	37.4	0.0	0.69	11.3
2022	0.3	0.5	0.04	0.46	0.1	2022	16.2	28.6	3.8	0.45	7.2
2023	0.0	NA	NA	NA	NA	2023	0.1	0.3	0.0	0.76	0.1

Table 3. Stratified mean catch–per-tow of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **delta distribution** model, by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2010	79.7	122.2	37.3	0.21	16.5	2010	61.2	105.5	16.9	0.30	18.1
2011	19.7	45.2	0.0	0.47	9.2	2011	20.2	50.7	0.0	0.55	11.0
2012	164.3	311.8	16.9	0.32	53.1	2012	192.6	548.4	0.0	0.43	82.7
2016	196	335.5	56.6	0.29	57.0	2016	184.2	322.9	45.5	0.32	58.7
2017	96.7	210.0	0.0	0.46	44.1	2017	62.9	137.6	0.0	0.46	29.0
2018	47.2	56.2	38.1	0.08	3.8	2018	55.1	71.8	38.4	0.12	6.8
2019	9.5	24.3	0.0	0.60	5.7	2019	5.7	15.8	0.0	0.70	4.0
2020	0.3	0.8	0.0	0.97	0.3	2020	0.2	0.6	0	0.97	0.2
2021	3.1	NA	NA	0.99	3.1	2021	3.3	NA	NA	0.78	2.6
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA
Mature Females						Mature Males					
2010	48.8	98.9	0.0	0.4	19.5	2010	130.3	242.6	18.1	0.34	43.7
2011	30.3	60.4	0.2	0.36	10.8	2011	110.2	249	0.0	0.45	50.0
2012	19.1	51.6	0.0	0.4	7.6	2012	66.8	141.1	0.0	0.35	23.3
2016	26.3	33.9	18.7	0.12	3.2	2016	161.7	192.5	131.0	0.08	13.3
2017	80.6	167.1	0.0	0.39	31.1	2017	362.7	868.5	0.0	0.50	182.2
2018	36.2	46.6	25.8	0.12	4.3	2018	94.3	117.9	70.7	0.11	10.0
2019	20.8	54.7	0.0	0.63	13.2	2019	100.4	254	0.0	0.59	59.7
2020	0.2	0.5	0.0	0.97	0.2	2020	4.1	8.8	0.0	0.67	2.7
2021	1.6	NA	NA	0.99	1.5	2021	8.7	NA	NA	0.72	6.3
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA
Newly Mature Females						Newly Mature Males					
2010	9.7	25.8	0.0	0.64	6.2	2010	4.4	9.5	0.0	0.46	2.0
2011	1.4	3.8	0.0	0.58	0.8	2011	1.4	4.9	0.0	0.94	1.3
2012	1.0	4.4	0.0	0.76	0.8	2012	6.1	14.2	0.0	0.48	2.9
2016	4.6	8.0	1.1	0.31	1.4	2016	16.2	29.0	3.5	0.3	5.0
2017	2.1	5.9	0.0	0.65	1.4	2017	12.4	27.6	0.0	0.44	5.4
2018	2.3	4.4	0.2	0.35	0.8	2018	3.6	7.6	0.0	0.44	1.6
2019	0	0	0	NA	0	2019	8.0	22.3	0.0	0.7	5.6
2020	0	0	0	NA	0	2020	0.1	0.3	0.0	0.97	0.1
2021	0	NA	NA	NA	0	2021	0.0	NA	NA	NA	0.0
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA

Table 4. Stratified mean catch-per-tow of horseshoe crabs in **the lower Delaware Bay** survey area in 2010-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **normal distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

	YEAR	MEAN	UCL	LCL	CV	SD		YEAR	MEAN	UCL	LCL	CV	SD
Immature Females							Immature Males						
	2010	79.5	116.5	42.6	0.19	15.1		2010	60.4	95.7	25.1	0.25	15.3
	2011	21.3	54.2	0.0	0.55	11.8		2011	21.5	57.2	0.0	0.60	12.9
	2012	165.5	287.6	43.4	0.30	49.9		2012	183.9	360.1	7.8	0.34	63.4
	2016	186.5	284.7	88.3	0.22	40.1		2016	167.9	249.7	86.0	0.21	34.6
	2017	90.8	176.0	5.6	0.37	33.2		2017	58.2	109	7.5	0.36	20.7
	2018	47.1	55.6	38.6	0.08	3.6		2018	54.9	69.6	40.2	0.11	6.2
	2019	16.0	30.4	1.5	0.35	5.6		2019	10.7	21.7	0.0	0.40	4.3
	2020	0.3	0.8	0.0	0.97	0.3		2020	0.2	0.6	0.0	0.97	0.2
	2021	3.1	NA	NA	NA	NA		2021	3.3	NA	NA	NA	NA
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2023	NA	NA	NA	NA	NA
Mature Females							Mature Males						
	2010	49.1	99.8	0.0	0.40	19.7		2010	128.0	227.9	28.2	0.3	38.9
	2011	28.6	49.9	7.4	0.27	7.7		2011	100.3	187.7	13.0	0.31	31.5
	2012	18.7	46.2	0.0	0.34	6.4		2012	65.3	111.7	18.8	0.28	18.1
	2016	26.2	33.4	19.0	0.11	3.0		2016	161.8	192.4	131.1	0.08	13.3
	2017	80.5	165	0.0	0.38	30.4		2017	303.4	531.7	75.2	0.27	82.2
	2018	36.2	47.2	25.1	0.12	4.3		2018	94.7	120.3	69.0	0.11	10.8
	2019	29.3	54.8	3.8	0.34	9.9		2019	49.9	90	9.9	0.31	15.6
	2020	0.2	0.5	0.0	0.97	0.2		2020	4.1	8.8	0.0	0.67	2.7
	2021	1.6	NA	NA	NA	NA		2021	8.7	NA	NA	NA	NA
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2023	NA	NA	NA	NA	NA
Newly Mature Females							Newly Mature Males						
	2010	9.6	24.9	0.0	0.62	5.9		2010	4.3	9.1	0.0	0.43	1.9
	2011	1.4	3.8	0.0	0.58	0.8		2011	1.4	4.9	0.0	0.94	1.3
	2012	1.0	4.4	0.0	0.76	0.8		2012	6.1	14.1	0.0	0.47	2.9
	2016	4.5	8.0	1.1	0.3	1.3		2016	16	27.2	4.9	0.27	4.3
	2017	2.1	5.9	0.0	0.65	1.4		2017	12.4	25.7	0.0	0.42	5.2
	2018	2.3	4.3	0.3	0.34	0.8		2018	3.6	7.6	0.0	0.44	1.6
	2019	0.0	0.0	0.0	NA	0.0		2019	8.5	22.9	0.0	0.66	5.6
	2020	0.0	0.0	0.0	NA	0.0		2020	0.1	0.3	0.0	0.97	0.1
	2021	0.0	NA	NA	NA	0.0		2021	0.0	NA	NA	NA	0.0
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2023	NA	NA	NA	NA	NA

Table 5. Results of correlation analyses of mean prosomal width (mm) and survey year for mature and newly mature males and females from the Delaware Bay area and lower Delaware Bay surveys. Statistics presented are number of years included: *n*; *T-score*; probability, *p*; and correlation coefficient, *r*. A negative correlation coefficient indicates a decreasing regression slope.

Maturity Group	**n**	**T**	**p**	**r**
Delaware Bay Area 2002 - 2023				**p**
Mature females	19	-15.40	<0.001	-0.966
Newly mature females	19	-5.21	0.001	-0.793
Mature males	19	-11.74	<0.001	-0.943
Newly mature males	19	-5.63	<0.001	-0. 807
Lower Delaware Bay 2010 - 2021				
Mature females	9	-6.78	<0.001	-0.932
Newly mature females	9	-3.98	0.016	-0.894
Mature males	9	-6.32	<0.001	-0.922
Newly mature males	9	2.28	0.063	0.681

Table 6. Estimated population (in thousands) of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **delta distribution model** by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2002	9470	15665	3275	0.31	2936	2002	5483	9284	1683	0.33	1809
2003	4585	8848	321	0.43	1972	2003	2303	4217	390	0.39	898
2004	7774	11770	3778	0.25	1944	2004	6810	10895	2725	0.29	1975
2005	5630	8856	2404	0.28	1576	2005	5260	8839	1681	0.33	1736
2006	12928	18691	7164	0.21	2715	2006	9327	14554	4100	0.24	2238
2007	13684	27486	0	0.41	5610	2007	8966	18246	0	0.42	3766
2008	10933	18650	3216	0.32	3499	2008	7841	13917	1766	0.35	2744
2009	39032	72868	5197	0.39	15222	2009	29864	47269	12460	0.28	8362
2010	3954	5220	2688	0.16	633	2010	2686	4144	1229	0.26	698
2011	4965	6945	2985	0.2	993	2011	3092	4547	1637	0.23	711
2016	11699	20462	2935	0.36	4212	2016	9102	16649	1555	0.39	3550
2017	7505	10708	4302	0.19	1426	2017	5091	8465	1717	0.27	1375
2018	10173	14285	6061	0.19	1933	2018	7507	11173	3842	0.23	1727
2019	3397	5516	1279	0.31	1053	2019	1487	2614	360	0.38	565
2020	9475	19779	0	0.65	6159	2020	5925	11967	0	0.61	3614
2021	4174	7947	400	0.53	2218	2021	2574	4634	513	0.47	1199
2022	9930	15493	4366	0.33	3282	2022	7652	12192	3112	0.35	2686
2023	8228	14206	2250	0.39	3238	2023	5313	8835	1792	0.36	1910
Mature Females						Mature Males					
2002	4959	8084	1834	0.3	1488	2002	11584	17335	5834	0.24	2780
2003	3379	5160	1599	0.25	845	2003	8069	13029	3110	0.29	2340
2004	2735	4043	1426	0.23	629	2004	5150	7788	2511	0.25	1288
2005	3138	4942	1333	0.27	847	2005	5844	8461	3228	0.22	1286
2006	6611	14330	0	0.42	2777	2006	15825	26060	5589	0.27	4273
2007	7746	12704	2789	0.31	2401	2007	15795	25104	6487	0.28	4423
2008	6311	10202	2419	0.29	1830	2008	14647	24995	4299	0.33	4834
2009	2975	4971	979	0.32	952	2009	6240	10197	2283	0.3	1872
2010	5178	7616	2740	0.23	1191	2010	13963	21910	6015	0.28	3910
2011	5290	7282	3297	0.18	952	2011	15060	29000	1120	0.4	6024
2016	6024	8635	3413	0.21	1265	2016	21941	37216	6665	0.29	6363
2017	7185	10525	3844	0.23	1653	2017	20664	31208	10119	0.25	5166
2018	7326	10520	4131	0.21	1538	2018	15749	21880	9619	0.18	2835
2019	5110	8454	1767	0.32	1635	2019	8924	15202	2646	0.35	3108
2020	10803	15359	6247	0.25	2706	2020	31546	51050	12042	0.36	11583
2021	15498	35873	0	0.75	11,568	2021	38538	85949	0	0.7	26925
2022	11421	17179	5662	0.30	3380	2022	19921	31447	8395	0.34	6806
2023	59866	138341	0	0.71	42480	2023	245346	716731	0	1.03	253925
Newly Mature Females						Newly Mature Males					
2002	1537	2400	675	0.26	400	2002	548	869	227	0.28	153
2003	794	1633	0	0.49	389	2003	78	221	0	0.84	66
2004	358	575	141	0.29	104	2004	789	1127	451	0.21	166
2005	479	753	206	0.27	129	2005	597	1002	191	0.33	197
2006	2051	3509	594	0.31	636	2006	3113	5113	1113	0.31	965
2007	2373	4339	408	0.4	949	2007	3129	4972	1287	0.28	876
2008	2571	4984	158	0.43	1106	2008	757	1254	261	0.31	235
2009	885	1361	410	0.26	230	2009	725	1240	210	0.34	247
2010	1338	2990	0	0.59	789	2010	1422	3070	0	0.55	782
2011	845	1360	331	0.3	254	2011	749	1335	164	0.36	270
2016	1608	2357	860	0.23	370	2016	2608	4884	331	0.42	1095
2017	1480	2274	687	0.26	385	2017	1523	2392	654	0.28	426
2018	1773	2923	622	0.31	550	2018	3341	5367	1316	0.29	969
2019	242	472	12	0.47	114	2019	1271	2154	389	0.34	437
2020	133	330	0	0.87	117	2020	2492	4030	953	0.37	914
2021	0	NA	NA	NA	NA	2021	6333	14328	0	0.68	4309
2022	115	207	23	0.46	53	2022	5487	10293	681	0.52	2,835
2023	0	NA	NA	NA	NA	2023	55	131	0	0.77	42

Table 7. Estimated population (in thousands) of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **normal distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2002	8222	11875	4568	0.21	1727	2002	5076	7998	2155	0.28	1421
2003	4089	6860	1317	0.32	1308	2003	2114	3462	766	0.3	634
2004	7376	10616	4135	0.21	1549	2004	6033	8786	3281	0.22	1327
2005	5104	7521	2687	0.23	1174	2005	4673	7414	1932	0.28	1308
2006	13714	20988	6439	0.25	3429	2006	9378	13971	4786	0.23	2157
2007	13692	27335	48	0.41	5614	2007	9350	19735	0	0.45	4208
2008	10595	16578	4612	0.26	2755	2008	6897	10443	3350	0.23	1586
2009	27375	40519	14232	0.23	6296	2009	26435	38730	14140	0.23	6080
2010	4102	5706	2497	0.19	779	2010	2781	4423	1139	0.29	806
2011	5426	8433	2420	0.27	1465	2011	3301	5219	1382	0.28	924
2016	11292	18441	4144	0.3	3388	2016	8185	13512	2858	0.31	2537
2017	7948	11818	4077	0.23	1828	2017	5082	7829	2335	0.26	1321
2018	10115	13839	6391	0.18	1821	2018	7768	11653	3882	0.24	1864
2019	14855	15027	14682	0.33	4902	2019	66	236	0	1.27	84
2020	6832	10559	3106	0.32	2213	2020	4610	7540	1679	0.38	1740
2021	4053	7670	436	0.51	2064	2021	2548	4389	707	0.42	1074
2022	8328	11016	5639	0.19	1580	2022	6359	8461	4257	0.20	1243
2023	7702	12775	2629	0.36	2770	2023	4510	6819	2202	0.29	1296
Mature Females						Mature Males					
2002	4779	7431	2128	0.26	1243	2002	10711	14972	6450	0.19	2035
2003	3308	4851	1764	0.22	728	2003	7454	10827	4082	0.21	1565
2004	2767	3919	1615	0.20	553	2004	5586	8875	2297	0.28	1564
2005	2957	4323	1592	0.22	651	2005	5408	7322	3494	0.17	919
2006	5867	10517	1218	0.31	1819	2006	14461	21734	7188	0.23	3326
2007	6553	9864	3243	0.25	1638	2007	13100	18506	7694	0.20	2620
2008	7172	13336	1008	0.4	2869	2008	14244	23240	5247	0.30	4273
2009	3230	5523	936	0.33	1066	2009	6319	10255	2383	0.29	1833
2010	5588	8698	2478	0.26	1453	2010	14396	22600	6192	0.27	3887
2011	5388	7629	3147	0.20	1078	2011	14858	25890	3825	0.33	4903
2016	5735	7770	3700	0.17	975	2016	24017	40197	7837	0.30	7205
2017	7785	12033	3537	0.27	2102	2017	19985	29245	10724	0.23	4597
2018	9463	18463	464	0.44	4164	2018	15264	19849	10680	0.15	2290
2019	6420	6506	6334	0.32	2054	2019	11660	11824	11497	0.37	4314
2020	10927	16014	5840	0.28	3021	2020	25200	34983	15416	0.23	5810
2021	21766	40665	2867	0.49	10750	2021	61879	109880	13877	0.45	27576
2022	9839	12836	6842	0.18	1770	2022	19032	25588	12475	0.20	3859
2023	69076	167547	29396	0.77	52,990	2023	148824	362850	0	0.77	115167
Newly Mature Females						Newly Mature Males					
2002	1509	2278	741	0.24	362	2002	561	925	196	0.31	174
2003	787	1547	26	0.45	354	2003	78	222	0	0.84	66
2004	367	613	120	0.32	117	2004	786	1120	452	0.20	157
2005	531	908	154	0.34	181	2005	580	927	233	0.29	168
2006	2122	3705	540	0.33	700	2006	3377	6076	678	0.38	1283
2007	2129	3584	674	0.33	703	2007	2841	4214	1468	0.23	653
2008	2697	4780	613	0.36	971	2008	776	1315	237	0.33	256
2009	883	1366	399	0.26	230	2009	708	1157	259	0.31	219
2010	1770	4532	0	0.74	1310	2010	1464	3180	0	0.56	820
2011	882	1495	269	0.34	300	2011	766	1343	190	0.36	276
2016	1583	2304	863	0.22	348	2016	2939	5588	290	0.43	1264
2017	0.00	NA	NA	NA	NA	2017	1590	2623	557	0.32	509
2018	1780	2866	695	0.29	516	2018	3064	4466	1663	0.22	674
2019	77	225	0	0.94	73	2019	112	267	0	0.68	77
2020	134	330	0	0.87	117	2020	2430	3676	1184	0.30	740
2021	0	NA	NA	NA	NA	2021	6308	14299	0	0.68	4307
2022	115	212	18	0.46	53	2022	6,370	11143	1597	0.44	2795
2023	0	NA	NA	NA	NA	2023	55	131	0	0.77	42

Table 8. Estimated population (in thousands) of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **delta distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

	YEAR	MEAN	UCL	LCL	CV	SD		YEAR	MEAN	UCL	LCL	CV	SD
Immature Females							Immature Males						
	2010	3510	5199	1822	0.2	702		2010	2632	4476	788	0.29	763
	2011	870	1931	0	0.44	383		2011	881	2160	0	0.52	458
	2012	8021	15084	958	0.32	2567		2012	9381	21965	0	0.42	3940
	2016	9046	15558	2534	0.29	2623		2016	8429	14813	2044	0.32	2697
	2017	4536	10029	0	0.47	2132		2017	2920	6458	0	0.47	1372
	2018	2211	2803	1619	0.1	221		2018	2597	3516	1678	0.15	390
	2019	525	1278	0	0.56	294		2019	308	816	0	0.64	197
	2020	12	33	0	0.97	12		2020	8	22	0	0.97	8
	2021	130	NA	NA	0.99	129		2021	140	NA	NA	0.78	109
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
Mature Females							Mature Males						
	2010	2117	4260	0	0.39	826		2010	5657	10247	1067	0.32	1810
	2011	1348	2599	96	0.33	445		2011	4829	10570	0	0.43	2076
	2012	938	2522	0	0.39	366		2012	3263	6864	0	0.35	1142
	2016	1274	1710	837	0.15	191		2016	7735	9709	5761	0.1	774
	2017	3674	7501	0	0.38	1396		2017	16794	40517	0	0.51	8565
	2018	1771	2588	953	0.18	319		2018	4616	6600	2631	0.18	831
	2019	1148	3011	0	0.63	723		2019	5746	14583	0	0.6	3448
	2020	7	19	0	0.97	7		2020	152	332	0	0.68	103
	2021	65	NA	NA	0.99	64		2021	365	NA	NA	0.72	262
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
Newly Mature Females							Newly Mature Males						
	2010	414	1087	0	0.63	261		2010	187	409	0	0.46	86
	2011	65	170	0	0.58	38		2011	58	208	0	0.94	55
	2012	50	214	0	0.76	38		2012	301	710	0	0.49	147
	2016	206	357	55	0.3	62		2016	727	1268	186	0.29	211
	2017	88	249	0	0.66	58		2017	542	1100	0	0.40	217
	2018	115	220	9	0.36	41		2018	148	290	7	0.40	59
	2019	0	0	0	NA	0		2019	361	1022	0	0.71	257
	2020	0	0	0	NA	0		2020	4	11	0	0.97	4
	2021	0	NA	NA	NA	NA		2021	0	NA	NA	NA	NA
	2022	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA
	2023	NA	NA	NA	NA	NA		2022	NA	NA	NA	NA	NA

Table 9. Estimated population (in thousands) of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2023, with the mean, standard deviation (sd), and coefficient of variation (CV), calculated using the **normal distribution** model by demographic group. Also included are the estimated upper and lower 95% confidence limits (UCL, LCL).

YEAR	MEAN	UCL	LCL	CV	SD	YEAR	MEAN	UCL	LCL	CV	SD
Immature Females						Immature Males					
2010	3503	5155	1851	0.18	631	2010	2588	4056	1120	0.24	621
2011	938	2311	0	0.53	497	2011	935	2437	0	0.58	542
2012	8125	14222	2027	0.31	2519	2012	9023	17690	356	0.35	3158
2016	8618	13190	4046	0.22	1896	2016	7725	11638	3812	0.21	1622
2017	4325	8829	0	0.41	1773	2017	2731	5408	53	0.38	1038
2018	2209	2780	1638	0.10	221	2018	2595	3529	1661	0.15	389
2019	852	868	836	0.01	9	2019	566	566	566	0.00	0
2020	12	33	0	0.97	12	2020	8	22	0	0.97	8
2021	130	NA	NA	0	0	2021	140	NA	NA	0.00	0
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA
Mature Females						Mature Males					
2010	2124	4340	0	0.41	871	2010	5600	9916	1285	0.30	1680
2011	1290	2239	340	0.27	348	2011	4479	8332	625	0.31	1388
2012	915	2242	0	0.34	311	2012	3188	5456	921	0.28	893
2016	1264	1647	880	0.13	164	2016	7727	9570	5883	0.10	773
2017	3654	7307	2	0.36	1315	2017	13805	23702	3908	0.26	3589
2018	1782	2666	898	0.19	339	2018	4647	6901	2393	0.19	883
2019	1932	1948	1916	0	0	2019	8356	8356	8356	0.00	0
2020	7	19	0	0.97	7	2020	152	332	0	0.68	103
2021	65	NA	NA	0	0	2021	365	NA	NA	0.00	0
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA
Newly Mature Females						Newly Mature Males					
2010	418	1097	0	0.63	263	2010	185	391	0	0.43	80
2011	65	170	0	0.58	38	2011	58	208	0	0.94	55
2012	50	214	0	0.76	38	2012	302	719	0	0.50	151
2016	205	355	55	0.28	57	2016	716	1176	256	0.25	179
2017	88	249	0	0.66	58	2017	541	1090	0	0.40	216
2018	114	226	3	0.35	40	2018	149	296	1	0.41	61
2019	0	0	0	NA	0	2019	401	408	394	0.00	3
2020	0	0	0	NA	0	2020	4	11	0	0.97	4
2021	0	NA	NA	NA	NA	2021	0	NA	NA	NA	NA
2022	NA	NA	NA	NA	NA	2022	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	2023	NA	NA	NA	NA	NA

Table 10. Mean, minimum (min), and maximum (max) bottom water temperature (C°) and ordinal sampling date (numerical calendar date from 1 January) for survey collections in the Delaware Bay area and Lower Delaware Bay. For reference, 1 September is ordinal date 243 in non-leap years.

	Water Temperature			Ordinal Date		
	mean	max	min	mean	max	min
Delaware Bay Area						
2002	19.33	15	23.5	277.41	273	300
2003	17.41	13.5	20	286.60	278	296
2004	16.67	14.5	20.5	292.74	277	302
2005	20.94	14	24.5	261.23	250	306
2006	17.53	13	22.3	284.53	246	314
2007	19.69	14.3	23.3	294.96	282	311
2008	20.09	19.3	22.6	277.02	272	287
2009	15.54	14.3	17	315.24	307	324
2010	19.72	12.3	24.1	282.68	265	331
2011	21.60	18.6	23.8	265.44	254	296
2012	18.47	18.1	18.8	292.92	289	298
2016	22.82	18.6	24.8	274.02	260	299
2017	21.89	18.8	23.2	274.05	263	294
2018	22.48	13.9	24.8	276.41	253	315
2019	23.05	18.8	24.3	250.38	242	270
2020	21.79	17	25	231.15	219	252
2021	23.25	18.8	28	233.44	222	250
2022	21.18	16.7	25.6	265.42	245	285
2023	22.54	18.3	26.7	270.02	248	302
Lower Delaware Bay						
2010	17.18	16.7	17.7	295.36	295	296
2011	18.32	18	18.6	294.27	294	295
2012	17.96	17.9	18	299.00	299	299
2016	19.56	19	20.1	288.40	288	289
2017	19.35	19.2	19.5	292.30	292	293
2018	12.16	11.3	12.8	321.44	321	322
2019	17.50	17.2	17.8	292.00	292	292
2020	24.00	23.2	25.4	248.00	248	248
2021	20.50	19	22	268.00	268	268
2022	NA	NA	NA	NA	NA	NA
2023	NA	NA	NA	NA	NA	NA

Table 11. Correlations between annual mean catches-per-tow of horseshoe crabs with mean bottom water temperature and ordinal sampling date in the Delaware Bay area survey and the lower Delaware Bay survey, by demographic group. The Delaware Bay area surveys included 15 years, and the lower Delaware Bay surveys included 8 years. Statistics presented include correlation coefficient, *r*; *T-score*; and probability, *p*. Data are from Tables 1, 3, and 10.

	Water Temperature			**Ordinal Date**		
Delaware Bay Area 2002 - 2023	***r***	***T***	***p***	***r***	***T***	***p***
Immature females	-0.540	-2.56	0.021	0.563	2.72	0.015
Immature males	-0.547	-2.61	0.018	0.577	2.83	0.012
Mature females	0.479	2.18	0.044	-0.397	-1.73	0.103
Mature males	0.397	1.73	0.103	-0.265	-1.10	0.288
Newly mature females	-0.222	0.91	0.377	0.498	2.29	0.036
Newly mature males	0.370	1.59	0.130	-0.451	-2.02	0.060
Lower Delaware Bay 2010 - 2021						
Immature females	-0.116	-0.31	0.767	0.346	0.98	0.362
Immature males	-0.154	-0.41	0.692	0.36	1.02	0.341
Mature females	-0.371	-1.06	0.325	0.537	1.69	0.136
Mature males	-0.153	-0.41	0.694	0.37	1.05	0.327
Newly mature females	-0.273	-0.75	0.477	0.318	0.89	0.405
Newly mature males	-0.086	-0.23	0.826	0.303	0.84	0.428

Appendix:

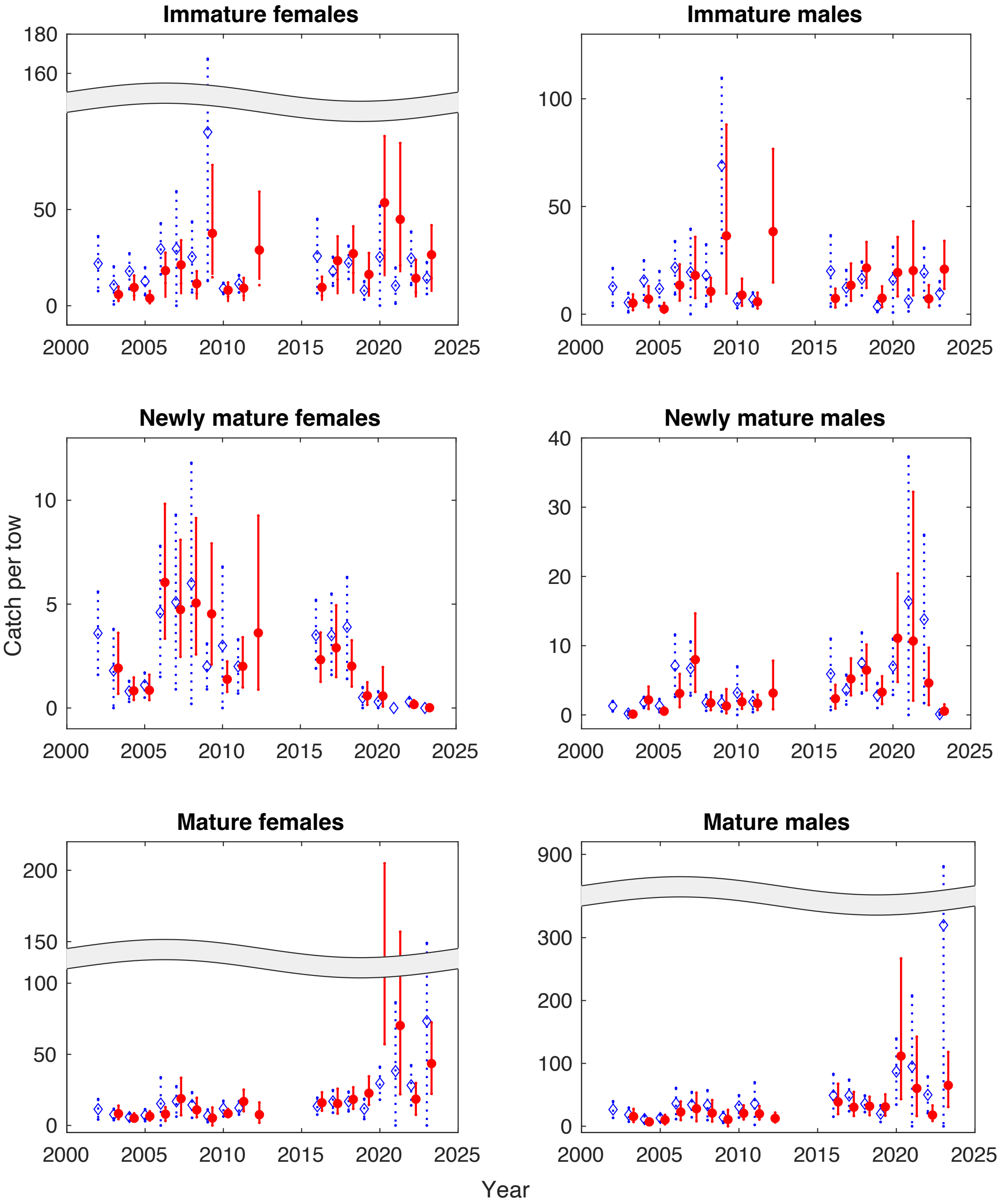

Figure S1. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the coastal **Delaware Bay area** survey by demographic group, compared with the standardized CPUE from a delta-lognormal model. Vertical lines indicate 95% confidence intervals. Open blue symbols and lines indicate the **delta distribution** model. Solid red symbols and dashed lines indicate results from the **hurdle model with delta-lognormal distribution**.

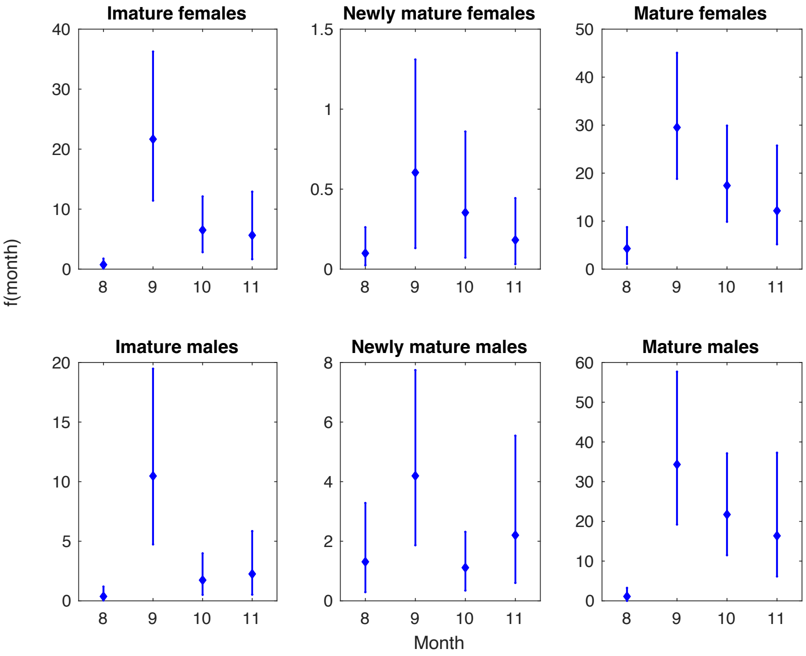

Figure S2: Effect of month on the relative abundance of horseshoe crab from the hurdle model with delta-lognormal distribution.

Table S1: Standardized CPUE (mean catches per 15-minute tow) of horseshoe crabs in the coastal Delaware Bay area from the model-based approach, i.e., hurdle models with delta-lognormal distribution.

	FI				**FN**				**FM**			
Year	**Mean**	**Median**	**LCL**	**UCL**	**Mean**	**Median**	**LCL**	**UCL**	**Mean**	**Median**	**LCL**	**UCL**
2003	5.82	5.60	2.82	9.90	1.92	1.83	0.69	3.61	8.30	8.04	4.45	13.87
2004	9.48	9.18	5.25	15.69	0.83	0.80	0.39	1.47	5.08	4.81	2.80	8.50
2005	3.90	3.70	1.34	7.63	0.85	0.81	0.38	1.60	6.46	6.33	3.46	9.95
2006	18.24	17.61	11.77	27.54	6.05	5.90	3.34	9.83	7.96	7.84	3.19	12.87
2007	21.24	20.33	11.64	33.98	4.74	4.53	2.47	8.09	18.87	17.71	7.18	33.46
2008	11.42	11.12	6.32	17.91	5.05	4.84	2.58	9.14	10.96	10.52	5.77	19.42
2009	37.61	34.21	14.83	73.15	4.53	4.28	2.10	7.92	5.19	4.85	0.00	12.58
2010	8.07	7.95	4.76	12.07	1.38	1.32	0.78	2.24	8.34	8.22	5.84	11.54
2011	9.12	8.85	5.12	14.43	2.00	1.93	0.99	3.40	16.80	16.56	9.99	25.13
2012	28.92	26.64	10.68	59.25	3.61	3.29	0.89	9.26	7.56	7.18	1.93	16.15
2016	9.52	9.32	5.20	15.07	2.32	2.24	1.26	3.63	15.94	15.51	10.37	23.28
2017	23.38	22.73	13.64	36.02	2.90	2.88	1.49	4.94	15.37	14.99	8.36	25.77
2018	27.06	26.06	17.07	41.23	2.01	1.96	1.03	3.26	18.36	18.07	11.70	26.79
2019	16.26	15.89	8.61	27.38	0.59	0.54	0.15	1.24	22.66	22.14	14.54	34.46
2020	53.53	51.98	28.81	88.12	0.58	0.44	0.07	1.96	111.36	104.77	57.16	204.82
2021	44.86	42.02	21.00	84.50					70.27	62.86	21.99	156.92
2022	14.25	13.92	6.96	23.84	0.17	0.15	0.04	0.37	18.49	18.34	7.55	29.79
2023	26.55	25.94	14.29	41.80	0.01	0.01	0.00	0.04	43.52	42.49	22.29	72.45

	MI				**MN**				**MM**			
Year	**Mean**	**Median**	**LCL**	**UCL**	**Mean**	**Median**	**LCL**	**UCL**	**Mean**	**Median**	**LCL**	**UCL**
2003	5.14	4.92	1.90	9.19	0.11	0.09	0.01	0.29	15.52	15.11	6.78	27.56
2004	7.04	6.64	3.25	13.00	2.17	2.06	0.86	4.08	7.01	6.75	3.35	11.96
2005	2.42	2.25	0.69	5.24	0.54	0.49	0.17	1.09	10.13	9.85	3.24	18.02
2006	13.50	12.83	6.34	23.10	3.10	2.93	1.12	5.91	22.74	22.59	9.86	39.34
2007	18.00	16.90	7.55	35.86	7.98	7.54	3.34	14.65	27.92	27.25	8.08	53.26
2008	10.56	10.21	5.96	16.87	1.73	1.63	0.69	3.32	20.99	19.92	7.58	41.57
2009	36.38	31.13	9.60	88.01	1.29	1.02	0.24	3.73	10.67	10.26	0.00	25.97
2010	8.90	8.38	3.95	16.48	1.88	1.84	0.89	3.06	20.47	19.97	10.87	33.16
2011	5.75	5.56	2.67	9.98	1.66	1.57	0.71	2.91	19.82	19.15	10.75	32.08
2012	38.34	35.59	14.78	76.72	3.15	2.66	0.82	7.82	12.57	12.20	6.27	21.71
2016	7.31	7.09	3.14	11.85	2.34	2.23	0.92	4.34	38.74	36.22	19.39	67.57
2017	13.43	12.85	6.21	23.52	5.20	5.18	2.83	8.17	30.33	28.91	16.44	54.44
2018	21.46	20.69	12.22	33.52	6.47	6.35	3.56	10.16	31.90	31.83	17.65	46.93
2019	7.44	7.22	3.29	12.92	3.29	3.17	1.57	5.57	30.89	30.00	16.87	50.73
2020	19.38	18.28	8.29	35.83	11.08	10.74	4.77	20.42	111.69	99.11	43.22	266.93
2021	20.24	18.63	8.75	43.06	10.68	8.77	2.07	32.21	60.23	52.01	16.36	142.35
2022	7.16	6.75	3.21	13.49	4.61	4.17	1.42	9.70	17.85	16.88	8.51	33.12
2023	20.94	20.25	11.84	33.98	0.54	0.48	0.09	1.52	65.11	62.58	30.80	117.85

Red Knot Stopover Population Size and Migration Ecology at Delaware Bay, USA, 2024

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Abstract

Red Knots (*Calidris canutus rufa*) stop at Delaware Bay on the mid-Atlantic coast of North America during northward migration to feed on eggs of horseshoe crabs (*Limulus polyphemus*). Horseshoe crabs have been harvested for use as bait in eel (*Anguilla rostrata*) and whelk (*Busycon* sp.) fisheries since at least 1990. In the late 1990s and early 2000s, the number of Red Knots counted during aerial surveys at Delaware Bay declined, leading to conservation concern for Red Knots and shorebirds at Delaware Bay. In 2013, the Atlantic States Marine Fisheries Commission began using an Adaptive Resource Management (ARM) framework to manage the harvest of horseshoe crabs in the Delaware Bay region. The objective of the ARM framework is to manage sustainable harvest of Delaware Bay horseshoe crabs while maintaining ecosystem integrity and supporting Red Knot recovery with adequate stopover habitat. The ARM framework thus requires annual estimates of horseshoe crab population size and Red Knot stopover population size to recommend annual harvest quotas. We estimated the passage population of Red Knots at Delaware Bay in 2024 using a mark-recapture-resight investigation. We used a Bayesian analysis of a Jolly-Seber model, which accounts for turnover in the population and the probability of detection during surveys. The 2024 passage population size estimate was 46,127 (95% credible interval: 39,286–57,799), an increase from 2023 (39,361 [33,724–47,556]). Since 2019, the stopver population has fluctuated between approximately 39,000 and 46,000, and appears stable given the broad overlap in the confidence intervals of the annual population estimates. The 2024 Red Knot stopover population size estimate will inform decision making in the next horseshoe crab management cycle of the Atlantic States Marine Fisheries Commission.

1 Introduction

The northward migration of Red Knots (*Calidris canutus rufa*) in the mid-Atlantic region coincides with the onset of spawning of horseshoe crabs (*Limulus polyphemus*). Red Knots stop at Delaware Bay to feed on horseshoe crabs eggs, which are an important food resource for Red Knots and other shorebirds because they have a high energy content and are easily digestible (Karpanty et al. 2006, Haramis et al. 2007).

Horseshoe crabs have been harvested since at least 1990 for use as bait in American eel (*Anguilla rostrata*) and whelk (*Busycon* sp.) fisheries (Kreamer and Michels 2009). In the 1990s and early 2000s the estimated number of Red Knots counted at Delaware Bay during aerial surveys declined from ~50,000 to ~13,000 (Niles et al. 2008). The number of horseshoe crabs harvested began to increase around 1990, peaked in the late 1990s, and then declined in the early 2000s. Avian conservation biologists hypothesized that unregulated harvest of horseshoe crabs from Delaware Bay in the 1990s prevented sufficient refueling during stopover for successful migration to the breeding grounds, nesting, and survival for the remainder of the annual cycle (Baker et al. 2004, McGowan et al. 2011).

The Atlantic States Marine Fisheries Commission (ASMFC) has managed the horseshoe crabs in the Delaware Bay region since 1998 and in 2012 adopted an Adaptive Resource Management (ARM) framework, which explicitly incorporates shorebird objectives in horseshoe crab (hereafter “crab” or “crabs”) harvest regulation (McGowan et al. 2015b). The ARM framework was designed to constrain the harvest so that the number of spawning crabs would not limit the number of Red Knots stopping at Delaware Bay during migration. To achieve multiple objectives simultaneously, the ARM framework requires an estimate each year of both the crab population and the Red Knot stopover population size to inform harvest recommendations (McGowan et al. 2015a). Therefore, we estimated the stopover population size in 2024, as we have each year since 2011, using mark-resight data on individually-marked birds and a Jolly-Seber model for open populations.

2 Methods

Red Knots have been individually marked at Delaware Bay and other locations in the Western Hemisphere (e.g., Argentina, Brazil, Canada, Chile) with engraved leg flags since 2003. Each leg flag is engraved with a unique, field-readable 3-character alphanumeric code (Clark et al. 2005). Mark-resight data (i.e., sight records of individually-marked birds and counts of marked and unmarked birds) were collected on the Delaware and New Jersey shores of Delaware Bay in 2024 according to the methods for mark-resight investigations of Red Knots at Delaware Bay (Lyons 2016). This protocol has been used at Delaware Bay since 2011.

Surveys to locate leg-flagged birds were conducted on 20 beaches (Appendix 1) in 2024 according to the sampling plan, i.e., every three days in May and early June (Table 1). During these resighting surveys, agency staff and volunteers surveyed the beach and recorded the field- readable alphanumeric combinations detected on leg-flagged birds.

As in previous years (Lyons 2023), all flag resightings were validated with physical capture and banding data available in the data repository at http://www.bandedbirds.org/. Resightings without a corresponding record of physical capture and banding (i.e., “misread” errors) were discarded and not included in the analysis. However, banding data from Argentina are not available for validation purposes in bandedbirds.org; therefore, all resightings of orange engraved flags were included in the analysis without validation using banding data. We also omitted resightings of 12 flagged individuals in 2024 whose flag codes were accidentally deployed in both New Jersey and South Carolina (Amanda Dey, New Jersey Division of Fish and Wildlife, pers. comm., 31 May 2017) because it is not possible to confirm individual identity in this case. Section 3 “Summary of Mark-resight Data Collected in 2024” describes additional quality control procedures and the potential for other types of errors in the mark- resight dataset.

While searching for birds marked with engraved leg flags, observers also periodically used a scan sampling technique to count marked and unmarked birds in randomly selected portions of Red Knot flocks (Lyons 2016). As part of the scan sampling protocol to estimate the marked-unmarked ratio (Lyons 2016), observers checked a random sample of birds for marks (leg flags) and recorded 1) the number of individually-marked birds, and 2) the number of birds checked for marks in each sample.

To estimate stopover population size, we used the methods of Lyons et al. (2016) to analyze 1) the mark-resight data (flag codes), and 2) data from the scan samples of the marked-unmarked ratio. Lyons et al. (2016) relied on the "superpopulation" approach developed by Crosbie and Manly (1985) and Schwarz and Arnason (1996). The superpopulation is defined as the total number of birds present in the study area on at least one of the sampling occasions over the entire study, i.e., the total number of birds present in the study area at any time between the first and last sampling occasions (Nichols and Kaiser 1999). In this superpopulation approach, passage population size is estimated each year using the Jolly-Seber model for open populations, which accounts for the flow-through nature of migration areas and probability of detection during surveys.

In our analyses for Delaware Bay, the days of the migration season were aggregated into 3-day sampling periods (a total of 10 sample periods possible each season, Table 1). Data were aggregated to 3-day periods because this is the amount of time necessary to complete mark-resight surveys on all beaches in the study (a summary of the mark-resight data from 2023 is provided in Appendix 2).

With the mark-resight superpopulation approach, we first estimated the number of birds that were carrying leg flags, and then adjusted this number using the estimated proportion of the population with flags to account for unmarked birds. The estimated proportion with leg flags is thus an important statistic. We used the scan sample data (i.e., the counts of marked birds and the number checked for marks) and a binomial model to estimate the proportion of the population that is marked. To account for the random nature of arrival of marked birds at the study area and the addition of new marks during the season, we implemented the binomial model as a generalized linear mixed model with a random effect for the sampling period. More detailed methods are provided in Lyons et al. (2016) and Appendix 3.

3 Summary of Mark-resight and Marked Ratio Data Collected in 2024

3.1 Mark-resight encounter data

The 2024 Red Knot mark-resight dataset included a total of 1,413 individual birds that were recorded at least once during mark-resight surveys at Delaware Bay between 1 May and 6 June 2024; these birds were originally captured and banded with leg flags in five to seven different countries (Fig. 1). The number of individuals in 2024 was greater than 2023 (1,091) but similar to the number of individuals detected during 2020 – 2022 (1,546 – 1,591; Table 2).

The 10 sampling periods of this mark-resight study include 8 May to 6 June (Table 1). In 2024, there were sufficient data for analysis in only 7 of the 10 sampling periods. At the beginning of the season in 2024, there was very little data collected during 8 – 13 May (i.e., periods 1 and 2). At the end of the season, there was little data available from 4 – 6 June (i.e., period 10), so this period was also discarded and not included in the 2024 analysis. It is not unusual to have sparse data from 4 – 6 June because most birds have departed Delaware Bay by this time in most years. After discarding periods 1, 2, and 10, there were 1,389 flagged individuals that were included in the 2024 analysis.

One assumption of the mark-resight approach is that individual identity of marked birds is recorded without error (see Lyons 2016 for discussion of all model assumptions). As noted above, some field-recording errors are evident when sight records are compared to physical capture record available from bandedbirds.org. Again, any engraved flag reported by observers that did not have a corresponding record of physical capture was omitted. Field observers submitted 2,396 resightings in 2024; 82 were not valid (i.e., no corresponding banding data), for an overall misread read of 3.4 %. These invalid resightings were removed before analysis, but a second type of "false positive" is still possible, i.e., false positive detection of flags that were deployed prior to 2024 but were not in fact present at Delaware Bay in 2024. It is not possible to identify this second type of false positive with banding data validation or other quality assurance/quality control methods (Tucker et al. 2019).

3.2 Marked ratio data ("scan samples" in Appendix 3)

In 2024, 495 marked ratio scan samples were collected: 334 and 161 samples in Delaware and New Jersey, respectively (Appendix 4). In 2020, 2021, 2022, and 2023, there were 734, 564, 541, and 504 marked-ratio scan samples collected, respectively.

In 2024, 5.8% of the stopover population carried engraved leg flags (95% CI: 4.3%–7.4%; Appendix 5 Fig. A5). This is lower than the percentage in 2023 (6.8% [95% CI: 5.9%–7.9%]) and continues a declining trend in the percentage of the population with leg flags. Historically, the percentage of the population that has leg flags has been close to 10% and was as high as 9.6% (95% CI: 8.8%–10.3%) in 2020 (Lyons 2020).

4 Summary of 2024 Migration

Approximately 25% of the stopover population was present during 14 – 16 May (Fig. 2a, period 3); these birds likely arrived during 8 – 13 May (periods 1 and 2), or even earlier, but there was not enough mark-resight data during 8 – 13 May for analysis. Another 30% of the stopover population arrived during 17 – 19 May (period 4, Fig. 2a). Thus, approximately 55% of the stopover population had arrived by approximately 18 May. The peak in arrivals was approximately 18 May, which is consistent with long-term pattern in the peak of arrival times (J. Lyons, personal observation, 2023-09-23).

Stopover departure probability is the probability that a bird present at Delaware Bay during sampling period *i* departs before sampling period *i* + 1. In 2024, departure probability was low (~7%) during 14 – 16 May (Fig. 2b). Departure probability increased and was closer to 30% during 17 – 22 May indicating turnover in the population beginning approximately 17 May. Departures peaked around 24 May, but then decreased during the next two sample periods, 26 – 28 May and 29 – 31 May. The decreasing departure probability at the end of the season is unusual because in most years, departures increase steadily after approximately 24 May (J. Lyons, personal observation, 2024-09-04).

Following Lyons et al. (2016), we used the Jolly-Seber model to estimate stopover duration. Stopover duration in 2024 was approximately 9.0 days (95% CI: 8.0, 10.0), which similar to 2023 (9.2 days [95% CI: 8.2 – 10.4 days]). The stopover duration in 2023 and 2024 was slightly lower than during 2019 – 2021, however, when stopovers ranged from 10.3 to 12.1 days (Lyons 2023). This method of estimating stopover duration provides a coarse measure in our Delaware Bay study, however, because it is derived from the estimated number of sampling periods (i.e., the time step in the mark-recapture model) that birds remained in the study area. Each sampling period in this analysis is 3 consecutive days in which the data are aggregated (Table 1). To estimate stopover duration in number of days at Delaware Bay with this method, we first estimate the number of sampling periods that each bird remained in the study area and then multiply this by 3 (the number of days in each period). The resolution of the stopover duration estimate is thus limited by the resolution of the sampling periods.

Probability of resighting in 2024 was constant for much of the season, remaining between 0.30 and 0.40 from about 15 – 27 May (Fig. 2c), before decreasing to about 0.06 at the end of the season.

5 Stopover Population Estimate

The passage population size estimate for 2024 was 46,127 (95% CI: 39,286 – 57,799; Table 3), which is an increase from 2023 (39,361 [95% CI: 33,724 – 47,556]). Since 2019, the stopver population has fluctuated between approximately 39,000 and 46,000, and appears stable given the broad overlap in the confidence intervals of the annual population estimates.

The time-specific stopover population estimate was approximately 13,600 at 15 May and increased to approximately 20,000 – 23,000 during about 18 – 24 May. The populaiton size estimates then decreased to about 10,000 during 27 May to 2 June. In many years, the population declines to ≤ 5,000 at the end of the season, so the number at the end of the season in 2024 was unusual. The estimate of the number of birds remaining at the season reflects late arrivals and low departure probability at the end of the season (Fig. 2a and 2b). The uncertainty in the estimates for number of birds remaining, and wide confidence intervals, reflect the low probability of resighting at the end of the season.

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References

Baker, A. J., P. M. González, T. Piersma, L. J. Niles, I. de Lima Serrano do Nascimento, P. W. Atkinson, N. A. Clark, C. D. T. Minton, M. K. Peck, and G. Aarts. 2004. Rapid population decline in Red Knots: fitness consequences of decreased refuelling rates and late arrival in Delaware Bay. Proceedings of the Royal Society of London. Series B: Biological Sciences 271:875–882.

Clark, N.A., S. Gillings, A.J. Baker, P.M. González, and R. Porter. 2005. The production and use of permanently inscribed leg flags for waders. Wader Study Group Bull. 108: 38–41.

Crosbie, S. F., and B. F. J. Manly. 1985. Parsimonious modelling of capture-mark-recapture studies. Biometrics 41:385–398.

Haramis, G. M., W. A. Link, P. C. Osenton, D. B. Carter, R. G. Weber, N. A. Clark, M. A. Teece, and D. S. Mizrahi. 2007. Stable isotope and pen feeding trial studies confirm the value of horseshoe crab Limulus polyphemus eggs to spring migrant shorebirds in Delaware Bay. Journal of Avian Biology 38:367–376.

Howes, L.-A., S. Béraud, and V. Drolet-Gratton. 2016. Pan American Shorebird Program shorebird marking protocol. Canadian Wildlife Service, Environment and Climate Change Canada, Ottawa, ON, Canada. https://www.shorebirdplan.org/wp-content/uploads/2016/08/PASP-Marking-Protocol-April-2016.pdf

Jolly, G. M. 1965. Explicit estimates from capture-recapture data with both death and immigration-stochastic model. Biometrika 52:225–248.

Karpanty, S. M., J. D. Fraser, J. Berkson, L. J. Niles, A. Dey, and E. P. Smith. 2006. Horseshoe crab eggs determine red knot distribution in Delaware Bay. Journal of Wildlife Management 70:1704–1710.

Kéry, M., and M. Schaub. 2012. Bayesian population analysis using WinBUGS: a hierarchical perspective. 1st ed. Academic Press, Boston.

Lyons, J.E. 2016. Study design guidelines for mark-resight investigations of Red Knots in Delaware Bay. Unpublished report. U.S. Fish and Wildlife Service Division of Migratory Bird Management, Laurel, MD. 13 pp.

Lyons, J.E., W.P. Kendall, J.A. Royle, S.J. Converse, B.A. Andres, and J.B. Buchanan. 2016. Population size and stopover duration estimation using mark-resight data and Bayesian analysis of a superpopulation model. Biometrics 72:262-271.

Lyons, J. E. 2020. Red Knot stopover population estimate for 2020. Unpublished report submitted to the Atlantic States Marine Fisheries Commission, Arlington, VA. 12 pp.

Lyons, J. E. 2023. Red Knot stopover population size and migration ecology at Delaware Bay, USA, 2023. Delaware Division of Fish and Wildlife, Dover, DE. 15 pp. Available at: https://dnrec.alpha.delaware.gov/fish-wildlife/conservation/shorebirds/research/

McGowan, C. P., J. E. Hines, J. D. Nichols, J. E. Lyons, D. R. Smith, K. S. Kalasz, L. J. Niles, A. D. Dey, N. A. Clark, P. W. Atkinson, C. D. T. Minton, and W. L. Kendall. 2011. Demographic consequences of migratory stopover: linking Red Knot survival to horseshoe crab spawning abundance. Ecosphere 2:Article 69.

McGowan, C. P., J. E. Lyons, and D. R. Smith. 2015a. Developing objectives with multiple stakeholders: Adaptive management of horseshoe crabs and red knots in the Delaware Bay. Environmental Management 55:972–982.

McGowan, C. P., D. R. Smith, J. D. Nichols, J. E. Lyons, J. Sweka, K. Kalasz, L. J. Niles, R. Wong, J. Brust, M. Davis, and B. Spear. 2015b. Implementation of a framework for multi-species, multi-objective adaptive management in Delaware Bay. Biological Conservation 191:759–769.

Kreamer, G., and S. Michels. 2009. History of horseshoe crab harvest on Delaware Bay. Pages 299–313 in J. T. Tanacredi, M. L. Botton, and D. R. Smith, editors. Biology and Conservation of Horseshoe Crabs. Springer, New York, NY.

Nichols, J. D., and A. Kaiser. 1999. Quantitative studies of bird movement: a methodological review. Bird Study 46:S289–S298.

Niles, L. J., H. P. Sitters, A. D. Dey, P. W. Atkinson, A. J. Baker, K. A. Bennett, R. Carmona, K. E. Clark, N. A. Clark, C. Espoz, P. M. González, B. A. Harrington, D. E. Hernández, K. S. Kalasz, R. G. Lathrop, R. N. Matus, C. D. T. Minton, R. I. G. Morrison, M. K. Peck, W. Pitts, R. A. Robinson, and I. L. Serrano. 2008. Status of the red knot (Calidris canutus rufa) in the Western Hemisphere. Studies in Avian Biology 36:xviii+185.

Royle, J. A., and R. M. Dorazio. 2008. Hierarchical modeling and inference in ecology: the analysis of data from populations, metapopulations and communities. Academic Press, Amsterdam.

Royle, J. A., and R. M. Dorazio. 2012. Parameter-expanded data augmentation for Bayesian analysis of capture–recapture models. Journal of Ornithology 152:521–537.

Schwarz, C. J., and A. N. Arnason. 1996. A general methodology for the analysis of capture- recapture experiments in open populations. Biometrics 52:860–873.

Seber, G. A. F. 1965. A note on the multiple-recapture census. Biometrika 52:249–259.

Tucker, A. M., C. P. McGowan, R. A. Robinson, J. A. Clark, J. E. Lyons, A. DeRose-Wilson, R. du Feu, G. E. Austin, P. W. Atkinson, and N. A. Clark. 2019. Effects of individual misidentification on estimates of survival in long-term mark–resight studies. The Condor: Ornithological Applications 121:1-13.

Table 1. Dates for mark-resight survey periods (3-day sampling occasions) for Red Knot (C. c. rufa) population analysis at Delaware Bay in 2024. The same sampling periods have been used at Delaware Bay since 2011. In 2024, there were few resightings of Red Knots in survey periods 1, 2, and 10; these periods were not used in the 2024 analysis because the data were insufficient.

Survey period	Dates	Survey period	Dates
1	8–10 May	6	23–25 May
2	11–13 May	7	26–28 May
3	14–16 May	8	29–31 May
4	17–19 May	9	1–3 June
5	20–22 May	10	4–6 June

Table 2. Number of leg-flagged Red Knot (C. c. rufa) detected at Delaware Bay from 2019–2023 by banding country (flag color). Flag colors were designated by country by the Pan American Shorebird Program (Howes et al. 2016). USA uses both light green and dark green leg flags.

	Leg-flagged individuals detected by year					
Banding country (flag color)	2019	2020	2021	2022	2023	2024
USA (light green)	2,368	1,255	1,292	1,281	843	991
USA (dark green)	351	161	118	118	141	294
Argentina/Uruguay (orange)	216	89	81	66	48	44
Canada (white)	156	52	78	62	41	69
Brazil/Paraguay (dark blue)	35	21	17	14	14	13
Chile (red)	10	9	5	5	4	2
Total	3,136	1,587	1,591	1,546	1,091	1,413

Table 3. Red Knot (C. c. rufa) stopover (passage) population estimate using mark-resight methods compared to a peak-count index using aerial- or ground-survey methods at Delaware Bay. The mark-resight estimate of stopover (passage) population, *N**, accounts for population turnover during migration. The peak-count index, a single count on a single day, does not account for turnover in the population. “AG” indicates a combination of aerial and ground counts used to formulate the peak-count index. CI = credible interval. The peak-count index is provided by NJ Department of Environmental Protection.

Year	Stopover population[a] (mark-resight *N**)	95% CI *N**	Peak-count index (aerial [A]; ground [G])
2011	43,570	(40,880 – 46,570)	12,804 (A)[b]
2012	44,100	(41,860 – 46,790)	25,458 (G)[c]
2013	48,955	(39,119 – 63,130)	25,596 (A)[d]
2014	44,010	(41,900 – 46,310)	24,980 (A)[c]
2015	60,727	(55,568 – 68,732)	24,890 (A)[c]
2016	47,254	(44,873 – 50,574)	21,128 (A)[b]
2017	49,405[e]	(46,368 – 53,109)	17,969 (A)[f]
2018	45,221	(42,568 – 49,508)	32,930 (A)[b]
2019	45,133	(42,269 – 48,393)	30,880 (A)[g]
2020	40,444	(33,627 – 49,966)	19,397 (G)[c]
2021	42,271	(35,948 – 55,210)	6,880 (AG)[h]
2022	39,800	(35,013 – 51,355)	12,114 (AG)[g]
2023	39,361	(33,724 – 47,556)	22,266 (G)[g]
2024	46,127	(39,286 – 57,799)	14,225 (A)[g]

[a] passage population estimate for entire season, including population turnover

[b] 23 May

[c] 24 May

[d] 28 May

[e] Data management procedures to reduce bias from recording errors in the field; data from observers with greater than average misread rate were not included in the analysis.

[f] 26 May

[g] 22 May

[h] 27 May

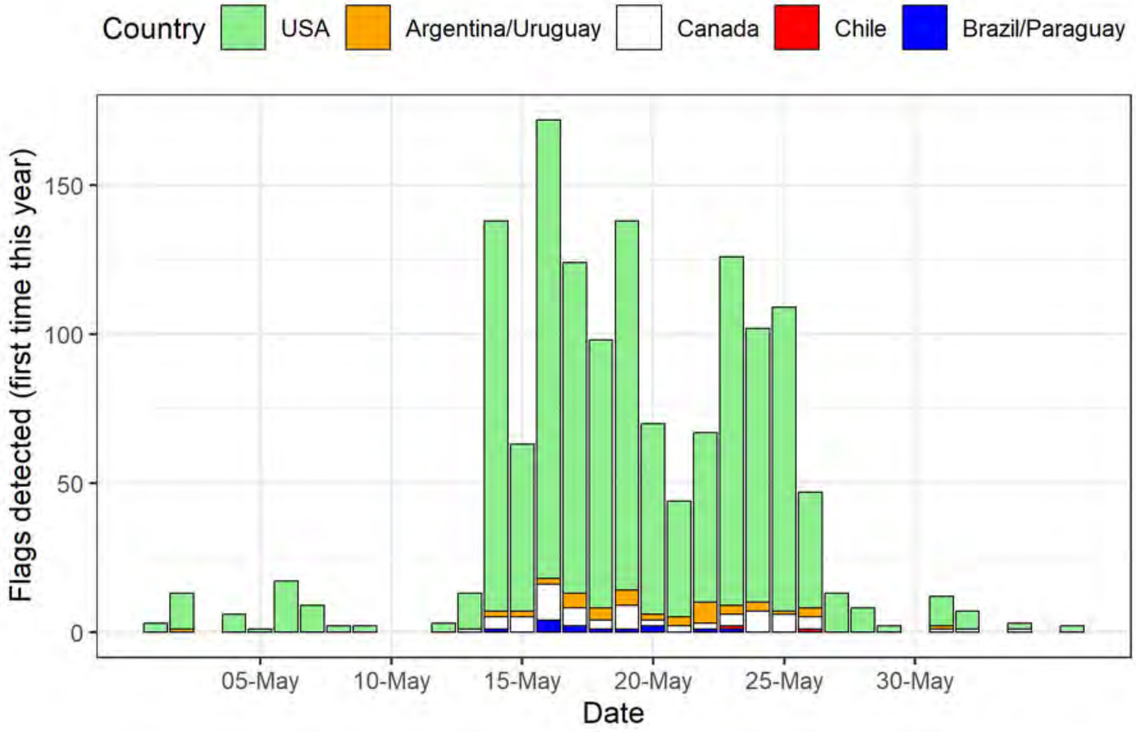

Figure 1 Number of birds detected for the first time (in 2024) by banding country (flag color). Colors correspond to leg-flag colors assigned to countrys in the Pan American Shorebird Program (Howes et al. 2016). USA includes both light and dark green flags.

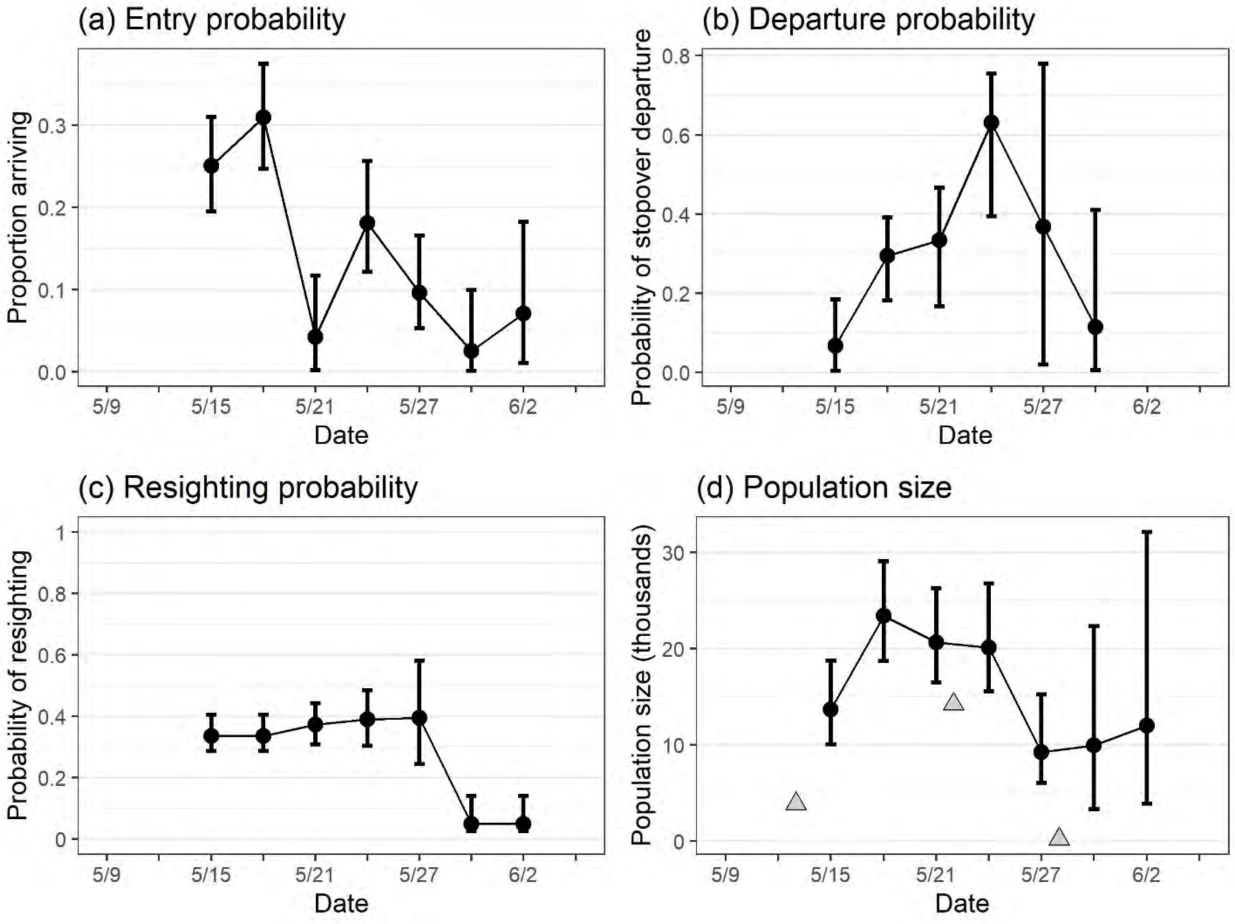

Figure 2 Estimated Jolly-Seber (JS) model parameters from a mark-resight study of Red Knots (C. c. rufa) at Delaware Bay in 2024: (a) proportion of stopover population arriving at Delaware Bay, (b) stopover departure probability, (c) probability of resighting, and (d) time-specific population size. Dates on the x-axis indicate the mid-point of 3-day sampling occasions (i.e., 3-day survey periods, Table 1). Triangles in (d) are aerial survey results provided by W. Pitts, NJ Department of Environmental Protection.

Appendix 1. Locations around Delaware Bay, USA, where mark-resight surveys were conducted to estimate Red Knot (*C. c. rufa*) stopover population size in 2023. DE = Delaware and NJ = New Jersey.

State	Beach	Longitude	Latitude
DE	Port Mahon	-75.4021	39.1831
DE	Pickering Beach	-75.4087	39.1377
DE	Kitts Hummock	-75.4048	39.1130
DE	Ted Harvey Wildlife Area	-75.4019	39.0864
DE	North Bowers	-75.3973	39.0630
DE	South Bowers	-75.3860	39.0498
DE	Brockenbridge	-75.3638	39.0359
DE	Mispillion	-75.3131	38.9519
DE	Slaughter Beach	-75.3146	38.9282
DE	Fowlers Beach	-75.2633	38.8766
DE	Prime Hook Beach	-75.2467	38.8604
NJ	Gandys/Money Island	-75.2417	39.2767
NJ	Fortescue	-75.1675	39.2233
NJ	North Reeds	-74.8908	39.1228
NJ	South Reeds	-74.8922	39.1138
NJ	Cooks	-74.8941	39.1082
NJ	Kimbles	-74.8948	39.1049
NJ	Bay Cove	-74.8965	39.1008
NJ	Pierces Point	-74.9013	39.0897
NJ	Villas and Norburys	-74.9298	39.0449

Appendix 2. Summary (“m-array”) of Red Knot (C. c. rufa) mark-resight data from Delaware Bay, USA, 2023. NR = never resighted.

			Next resighted at sample						
Sample	Dates	Releases	4	5	6	7	8	9	NR
1	8-10 May	0							
2	11-13 May	0							
3	14-16 May	222	69	40	16	3	0	0	94
4	17-19 May	483		126	54	14	0	1	288
5	20-22 May	422			111	23	1	2	285
6	23-25 May	479				71	3	3	402
7	26-28 May	281					8	9	264
8	29-31 May	22						2	20
9	1-3 June	36							
10	4-6 June	0							

Appendix 3. Statistical Methods to Estimate Stopover Population Size of Red Knots (*C. c. rufa*) Using Mark-Resight Data and Counts of Marked Birds

We converted the observations of marked Red Knots into encounter histories, one for each bird, and analyzed the encounter histories with a Jolly-Seber (JS) model (Jolly 1965, Seber 1965, Crosbie and Manly 1985, Schwarz and Arnason 1996). The JS model includes parameters for recruitment (β), survival (ϕ), and capture (*p*) probabilities; in the context of a mark-resight study at a migration stopover site, these parameters are interpreted as probability of arrival to the study area, stopover persistence, and resighting, respectively. Stopover persistence is defined as the probability that a bird present at time *t* remains at the study area until time *t* + 1. The Crosbie and Manley (1985) and Schwarz and Arnason (1996) formulation of the JS model also includes a parameter for superpopulation size, which in our approach to mark-resight inferences for stopover populations is an estimate of the marked (leg-flagged) population size.

We chose to use 3-day periods, rather than days, as the sampling interval for the JS model given logistical constraints on complete sampling of the study area; multiple observations of the same individual in a given 3-day period were combined for analysis. A summary (m-array) of the mark-resight data is presented in Appendix 2.

We made inference from a fully-time dependent model; arrival, persistence, and resight probabilities were allowed to vary with sampling period [β_t ϕ_t p_t]. In this model, we set $p_1 = p_2$ and $p_{K-1} = p_K$ (where *K* is the number of samples) because not all parameters are estimable in the fully-time dependent model (Jolly 1965, Seber 1965, Crosbie and Manly 1985, Schwarz and Arnason 1996).

We followed the methods of Royle and Dorazio (2008) and Kéry and Schaub (2012, Chapter 10) to fit the JS model using the restricted occupancy formulation. Royle and Dorazio (2008) use a state-space formulation of the JS model with parameter-expanded data augmentation. For parameter-expanded data augmentation, we augmented the observed encounter histories with all-zero encounter histories (n = 2000) representing potential recruits that were not detected (Royle and Dorazio 2012). We followed Lyons et al. (2016) to combine the JS model with a binomial model for the counts of marked and unmarked birds in an integrated Bayesian analysis. Briefly, the counts of marked birds (m_s) in the scan samples are modeled as a binomial random variable:

$$m_s \sim Bin(C_s, \pi), \tag{1}$$

where m_s is the number of marked birds in scan sample *s*, C_s is the number of birds checked for marks in scan sample *s*, and π is the proportion of the population that is marked. Total stopover population size $\widehat{N^*}$ is estimated by

$$\widehat{N^*} = \widehat{M^*}/\hat{\pi} \tag{2}$$

where $\widehat{M^*}$ is the estimate of marked birds from the J-S model and $\hat{\pi}$ is the proportion of the population that is marked (from Eq. 1). Estimates of marked subpopulation sizes at each resighting occasion *t* $\left(\widehat{M_t^*}\right)$ are available as derived parameters in the analysis. We calculated an estimate of population size at each mark-resight sampling occasion $\widehat{N_t^*}$ using $\widehat{M_t^*}$ and $\hat{\pi}$ as in equation 2.

To better account for the random nature of the arrival of marked birds and addition of new marks during the season, we used a time-specific model for proportion with marks in place of equation 1 above:

$$m_{s,t} \sim Binomial\left(C_{s,t}, \pi_t\right) \tag{3}$$

$$for\ s\ in\ 1, \ldots, n_{samples}\ and\ t\ in\ 1, \ldots, n_{occasions}$$

$$logit(\pi_t) = \alpha + \delta_t$$

$$\delta_t \sim Normal\left(0, \sigma^2_{occasions}\right)$$

where m_s is the number of marked birds in scan sample s, C_s is the number of birds checked for marks in scan sample s, δ_t is a random effect time of sample s, and π_t is the time-specific proportion of the population that is marked. Total stopover population size $\widehat{N^*}$ was estimated by summing time-specific arrivals of marked birds to the stopover (B_t) and expanding to include unmarked birds using estimates of proportion marked:

$$\widehat{N^*} = \sum \widehat{B_t} / \pi_t$$

Time-specific arrivals of marked birds are estimated from the Jolly-Seber model using $\widehat{B_t} = \widehat{\beta}_t \widehat{M^*}$ where $\widehat{M^*}$ is the estimate of the number of marked birds and $\widehat{\beta_t}$ is the fraction of the population arriving at time t.

Appendix 4. Marked-ratio scan samples of Red Knots (*C. c. rufa*).

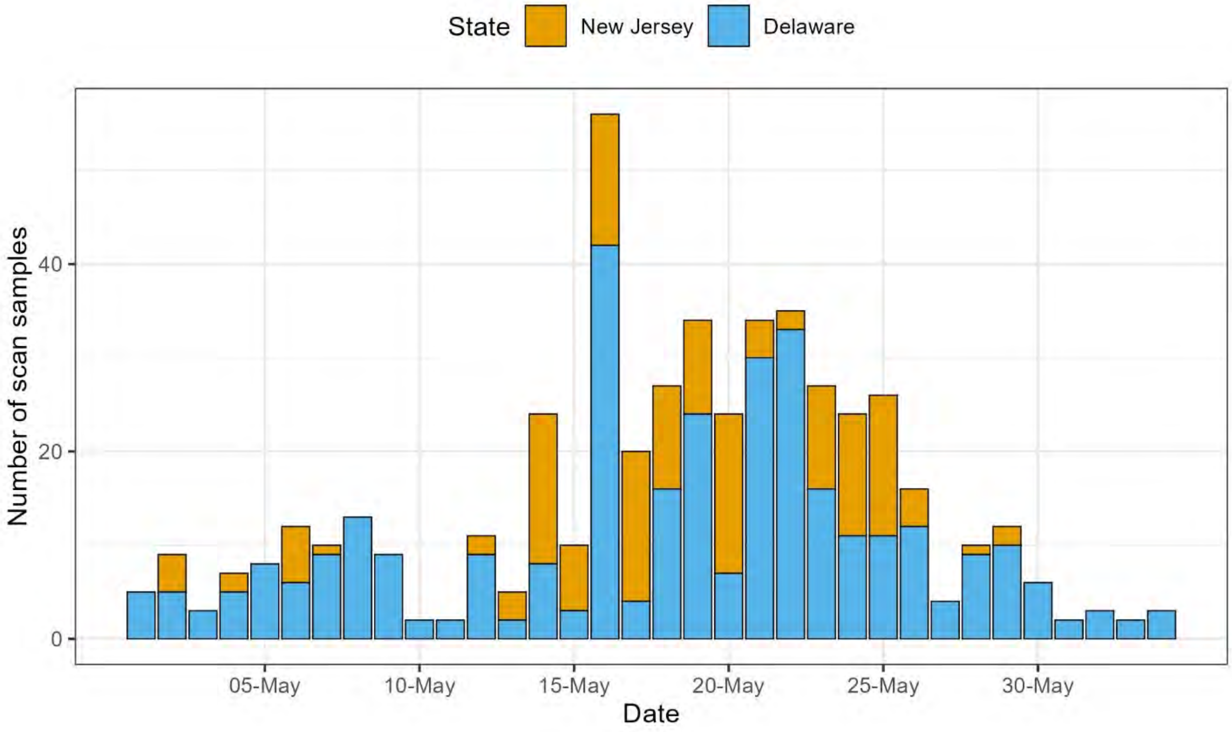

Figure A4. Number of Red Knot (*C. c. rufa*) marked-ratio scan samples (n = 495) collected in Delaware Bay in 2024 by field crews in Delaware (blue, n = 334 scan samples) and New Jersey (orange, n = 161 scan samples) and date.

Appendix 5. Marked proportion.

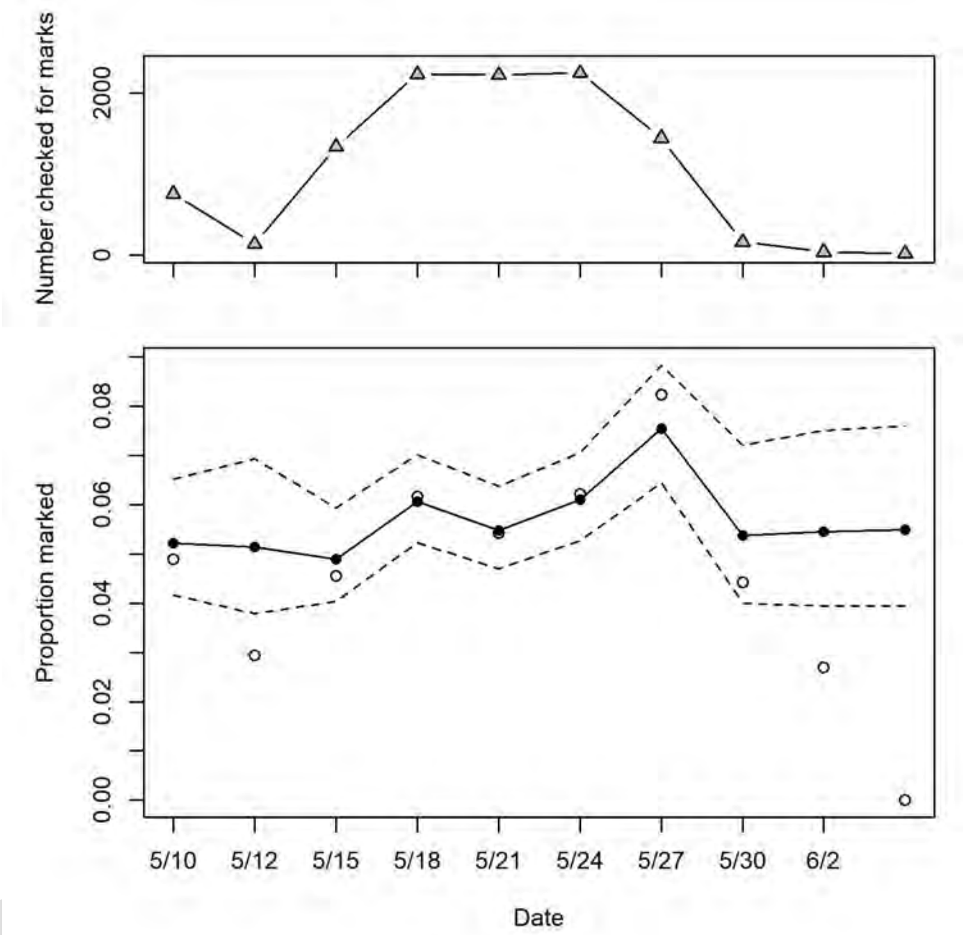

Figure A5. Estimated proportion of the Delaware Bay stopover population of Red Knots (*C. c. rufa*) carrying leg flags in 2024 (overall average and 95% credible interval: 0.058 [0.043, 0.074]). The marked proportion was estimated from marked-ratio scan samples for each 3-day sampling period (Table 1). The upper panel shows the sample size (number scanned, i.e., checked for marks) for each sample period. The bottom panel shows the estimated proportion marked for each sample occasion, which was estimated with the generalized linear mixed model described in Appendix 2. Solid and dashed lines are estimated median proportion marked and 95% credible interval, respectively; open circles show (number with marks/number scanned).

ATLANTIC STATES MARINE FISHERIES COMMISSION

REVIEW OF THE INTERSTATE FISHERY MANAGEMENT PLAN

HORSESHOE CRAB
(*Limulus polyphemus*)

2023 Fishing Year

Prepared by the Plan Review Team

October 2024

Sustainable and Cooperative Management of Atlantic Coastal Fisheries

Table of Contents

I. Status of the Fishery Management Plan

Date of FMP Approval: December 1998

Amendments None

Addenda Addendum I (April 2000)
Addendum II (May 2001)
Addendum III (May 2004)
Addendum IV (June 2006)
Addendum V (September 2008)
Addendum VI (August 2010)
Addendum VII (February 2012)

Management Unit: Entire coastwide distribution of the resource from the estuaries eastward to the inshore boundary of the EEZ

States with Declared Interest: Massachusetts – Florida, Potomac River Fisheries Commission

Active Boards/Committees: Horseshoe Crab Management Board, Advisory Panel, Technical Committee, and Plan Review Team; Delaware Bay Ecosystem Technical Committee; Adaptive Resource Management Subcommittee

Goals and Objectives

The Interstate Fishery Management Plan for Horseshoe Crabs (FMP) established the following goals and objectives.

2.0. Goals and Objectives

The goal of this Plan is to conserve and protect the horseshoe crab resource to maintain sustainable levels of spawning stock biomass to ensure its continued role in the ecology of the coastal ecosystem, while providing for continued use over time. Specifically, the goal includes management of horseshoe crab populations for continued use by:

1) *current and future generations of the fishing and non-fishing public (including the biomedical industry, scientific and educational research);*
2) *migrating shorebirds; and,*
3) *other dependent fish and wildlife, including federally listed (threatened) sea turtles.*

To achieve this goal, the following objectives must be met:

(a) prevent overfishing and establish a sustainable population;
(b) achieve compatible and equitable management measures among jurisdictions throughout the fishery management unit;

(c) establish the appropriate target mortality rates that prevent overfishing and maintain adequate spawning stocks to supply the needs of migratory shorebirds;
(d) coordinate and promote cooperative interstate research, monitoring, and law enforcement;
(e) identify and protect, to the extent practicable, critical habitats and environmental factors that limit long-term productivity of horseshoe crabs;
(f) adopt and promote standards of environmental quality necessary for the long-term maintenance and productivity of horseshoe crabs throughout their range; and,
(g) establish standards and procedures for implementing the Plan and criteria for determining compliance with Plan provisions.

Fishery Management Plan Summary

The framework for managing horseshoe crabs along the Atlantic coast was approved in October 1998 with the adoption of the Interstate Fishery Management Plan (FMP) for Horseshoe Crabs. The goal of this plan is to conserve and protect the horseshoe crab resource to maintain sustainable levels of spawning stock biomass to ensure its continued role in the ecology of coastal ecosystems while providing for continued use over time.

In 2000, the Horseshoe Crab Management Board approved Addendum I to the FMP. Addendum I established a state-by-state cap on horseshoe crab bait landings at 25 percent below the reference period landings (RPL's), and *de minimis* criteria for those states with a limited horseshoe crab fishery. Those states with more restrictive harvest levels (Maryland and New Jersey) were encouraged to maintain those restrictions to provide further protection to the Delaware Bay horseshoe crab population, recognizing its importance to migratory shorebirds. Addendum I also recommended that the National Marine Fisheries Service (NMFS) prohibit the harvest of horseshoe crabs in federal waters (3-200 miles offshore) within a 30 nautical mile radius of the mouth of Delaware Bay, as well as prohibit the transfer of horseshoe crabs in federal waters. A horseshoe crab reserve was established on March 7, 2001, by NMFS in the area recommended by ASMFC. This area is now known as the Carl N. Shuster Jr. Horseshoe Crab Reserve (Figure 1).

In 2001, the Horseshoe Crab Management Board approved Addendum II to the FMP. The purpose of Addendum II was to allow the voluntary transfer of harvest quotas between states to alleviate concerns over potential bait shortages on a biologically responsible basis. Voluntary quota transfers require Technical Committee review and Management Board approval.

In 2004, the Board approved Addendum III to the FMP. The addendum sought to further the conservation of horseshoe crab and migratory shorebird populations in and around the Delaware Bay. It reduced harvest quotas and implemented seasonal bait harvest closures in New Jersey, Delaware, and Maryland, and revised monitoring components for all jurisdictions.

Addendum IV was approved in 2006. It further limited bait harvest in New Jersey and Delaware to 100,000 crabs (male only) and required a delayed harvest in Maryland and Virginia.

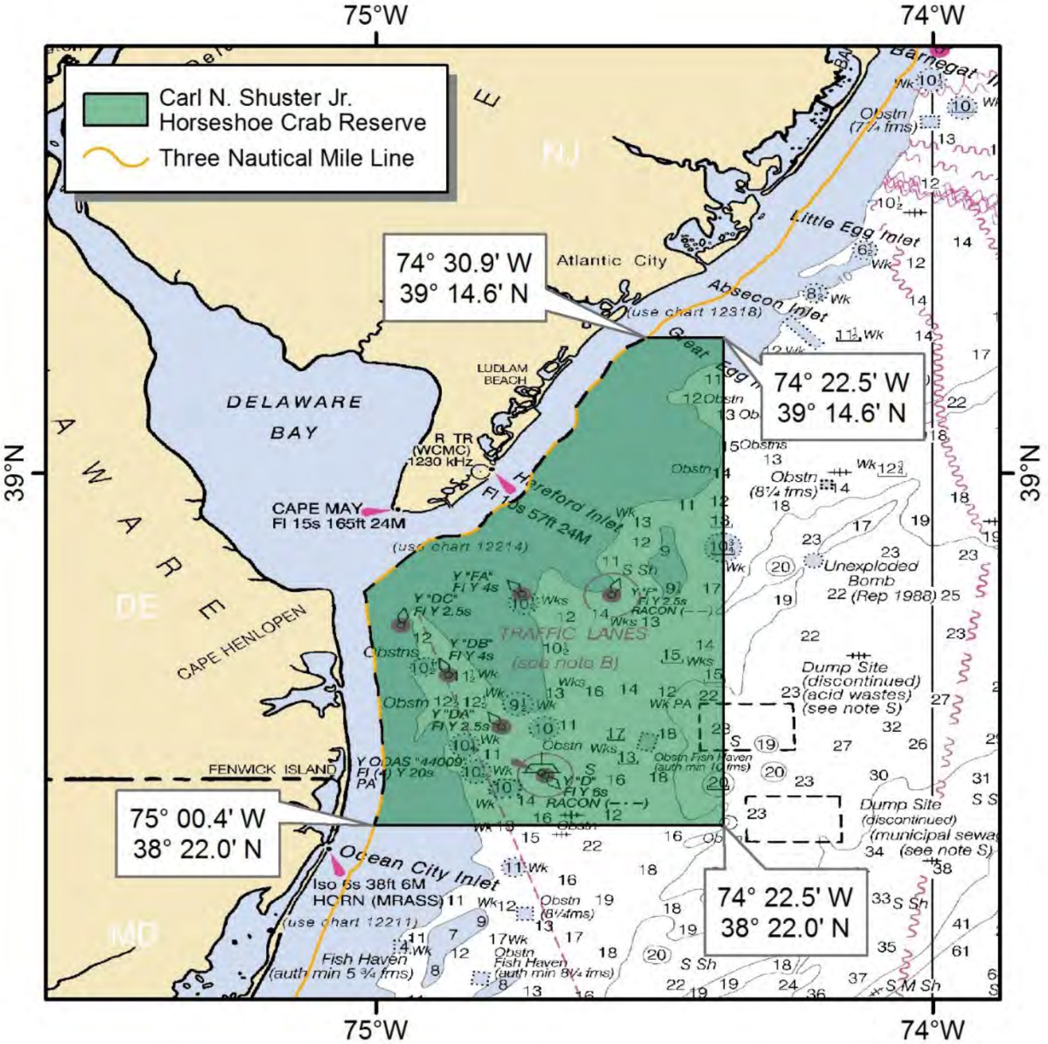

Figure 1. Carl N. Shuster Jr Horseshoe Crab Reserve.

Addendum V, adopted in 2008, extended the provisions of Addendum IV through October 31, 2010.

In early 2010, the Board initiated Draft Addendum VI to consider management options that would follow expiration of Addendum V. The Board voted in August 2010 to extend the Addendum V provisions, via Addendum VI, through April 30, 2013. The Board also chose to include language allowing them to replace Addendum VI with another Addendum during that time, in anticipation of implementing an Adaptive Resource Management (ARM) Framework.

The Board approved Addendum VII in February 2012. This addendum implemented an ARM framework for use during the 2013 fishing season and beyond. The framework considers the abundance levels of horseshoe crabs and shorebirds in determining the optimized bait harvest level for the Delaware Bay states of New Jersey, Delaware, Maryland, and Virginia (east of the COLREGS).

The ARM Framework underwent a revision process in 2021 to incorporate more available data and update the software platform. Several improvements were made to the ARM Framework during this revision. The ARM Revision improves the population models for horseshoe crabs and red knots by incorporating Delaware Bay region-specific data collected over the past few decades. Horseshoe crab population estimates from the Catch Multiple Survey Analysis (CMSA) model used in the 2019 Benchmark Stock Assessment were incorporated into the ARM Revision. Additionally, the ARM Revision includes more sources of horseshoe crab removals than the previous version, adding mortality in the biomedical industry and commercial discards from other fisheries. The maximum number of male and female horseshoe crabs the ARM Revision can recommend remains the same at 210,000 females and 500,000 males. However, harvest recommendations under the ARM Revision are now based on a continuous scale rather than the fixed harvest packages in the previous Framework. Also, the harvest of females is decoupled from the harvest of males so that each are determined separately. While additional data and model improvements are used in the ARM Revision, the conceptual model of horseshoe crab abundance influencing red knot survival and reproduction remains intact with the intent of ensuring the abundance of horseshoe crabs does not become a limiting factor in the population growth of red knots. The Board accepted the ARM Revision and Peer Review for management use in January 2022.

Addendum VIII was approved in November 2022. Addendum VIII adopts the changes to the ARM Framework as recommended in the peer-reviewed 2021 ARM Framework for use in setting annual specifications for horseshoe crabs of Delaware Bay-origin.

II. Status of the Stock and Assessment Advice

A benchmark stock assessment was completed and approved for management use in 2019[1]. This assessment was the first to successfully apply a stock assessment model to a component of the horseshoe crab stock. A Catch Multiple Survey Analysis (CMSA) model, a stage-based model that tracks progression of crab abundances from pre-recruits to full recruits to the fishery, was applied to female crabs in the Delaware (DE) Bay region (New Jersey-Virginia). This model estimated regional female crab abundance using relative abundance information from the Virginia Tech Benthic Trawl Survey, New Jersey Ocean Trawl Survey, and Delaware Adult Trawl Survey, and estimates of mortality including natural mortality, commercial bait harvest, commercial discard mortality, and mortality associated with biomedical use. While reference points were not approved to determine stock status, the CMSA population estimates were recommended as the best estimates for female horseshoe crab abundance in the DE Bay region.

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[1] The 2019 benchmark stock assessment report is available at: http://www.asmfc.org/uploads/file/5cd5d6f1HSCAssessment_PeerReviewReport_May2019.pdf

Autoregressive Integrated Moving Average (ARIMA) models, similar to those used in previous assessments, were applied to all regions. ARIMA models were fit to fishery-independent survey indices trends of abundance in each of the regional horseshoe crab populations: Northeast (Massachusetts-Rhode Island), New York (Connecticut-New York), DE Bay, and Southeast (North Carolina-Florida). No definitions for overfishing or overfished status have been adopted by the Management Board. However, the assessment characterized the status of each regional and the coastwide population based on the percentage of surveys within a region (or coastwide) having a >50% probability of the terminal year being below the ARIMA reference point. The ARIMA reference point was the 1998 index for each survey. "Poor" status was defined as >66% of surveys meeting this criterion, "Good" status was defined as <33% of surveys, and "Neutral" status was defined as 34–65% of surveys.

An assessment update was completed in May 2024[2]. The updated CMSA model estimates were approximately 40 million mature male and 16 million mature female horseshoe crabs in the Delaware Bay region in 2022. The CMSA model results indicate that mature female horseshoe crabs have been steadily increasing in the region since the implementation of the initial ARM Framework in 2012. The ARIMA models used to determine stock status for the four regional and the coastwide horseshoe crab populations were also updated. The current stock status indicates that the Northeast region is in a neutral state and the New York region continues to be in a poor state, with three out of four surveys being below 1998 reference points. Based on the ARIMA results, the Delaware Bay, Southeast, and coastwide populations are in good condition, an improvement since the 2019 benchmark.

III. Status of the Fishery

Bait Fishery

For most states, the bait fishery is open year-round. However, because of seasonal horseshoe crab movements (to the beaches in the spring; deeper waters and offshore in the winter), the fishery operates at different times along the coast. New Jersey has prohibited commercial harvest of horseshoe crabs in state waters since 2006. State waters of Delaware are closed to horseshoe crab harvest and landing from January 1st through June 7th each year, and other state horseshoe crab fisheries are regulated with various season/area closures.

The total reported bait landings in 2023 totaled 738,789 crabs. This is well below the ASMFC coastwide quota of 1,591,730 crabs (Table 1, Figure 2) and represents a 29% increase from 2022 landings of 570,988 crabs. Landings increased in all states with commercial harvest.

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[2] The 2024 stock assessment update can be found here: http://www.asmfc.org/uploads/file/663d0fcdHorseshoeCrabStockAssessmentUpdate_April2024.pdf

Reported coastwide landings since 1998 show more male than female horseshoe crabs were harvested annually. Several states presently have sex-specific restrictions in place which limit or ban the harvest of females. The American eel pot fishery prefers female horseshoe crabs as bait, while the whelk (conch) pot fishery is less dependent on females. States with greater than 5% of coastal landings are required to report sex for at least a portion of their bait harvest; for 2023 these states include Massachusetts, New York, Delaware, Maryland, and Virginia. Within these states, 64% of reported bait landings were male, 6% were female, and 29% were unclassified in 2023.

The hand, trawl, and dredge fisheries accounted for the majority of reported commercial horseshoe crab bait landings in 2023. Other gears that account for the remainder of the harvest include rakes, hoes, and tongs, fixed nets, and gill nets.

Table 1. Reported commercial horseshoe crab bait landings by jurisdiction. "C" indicates confidential landings.

	MA	RI	CT	NY	NJ*	DE*	MD*	PRFC	VA**	NC	SC	GA	FL	TOTAL
ASMFC Quota 2023	330,377	26,053	48,689	366,272	164,364	164,364	255,980	0	172,828	24,036	0	29,312	9,455	1,591,730
State Quota 2023	140,000	8,398	48,689	150,000	0	164,364	255,980	-	172,828	24,036	0	29,312	9,455	1,003,062
Landings by Year														
2015	117,611	7,867	19,632	145,324	0	151,262	27,494	0	102,235	24,839	0	0	264	596,528
2016	110,399	20,676	21,945	176,632	0	109,836	157,013	0	128,848	25,197	0	0	689	751,235
2019	172,664	C	17,588	167,181	0	164,225	145,907	0	151,727	13,463	0	0	0	832,755
2020	163,695	C	15,942	63,367	0	124,803	61,165	0	24,031	3,672	0	0	0	456,675
2021	156,013	1,706	17,492	97,860	0	172,927	181,044	0	112,497	2,145	0	0	C	741,684
2022	135,731	C	1,343	111,481	0	147,558	84,627	0	89,748	500	0	0	C	570,988
2023	139,746	2,314	3,297	130,658	0	168,208	186,466	0	107,166	934	0	0	C	738,789

*Male-only harvest

**Virginia harvest east of the COLREGS line is limited to 81,331 male-only crabs. Virginia harvest east of the COLREGS in 2023 was confidential.

Biomedical Use

The horseshoe crab is an important resource for research and manufacture of materials used for human health. In 2023 there were six companies along the Atlantic Coast that process horseshoe crab blood for use in manufacturing Limulus Amebocyte Lysate (LAL), and biomedical collections occurred in six states: Associates of Cape Cod (MA, RI); Charles River Laboratories (MA, SC, VA), FUJIFILM Wako (MD); Lonza (MD); Limuli Laboratories (NJ); and Martin Fish Company LLC (MD). Addendum III requires states where horseshoe crabs are collected for biomedical purposes to collect and report total collection numbers, crabs rejected, crabs bled (by sex) and to characterize mortality.

The Plan Review Team (PRT) annually calculates total coastwide collections and estimates mortality associated with biomedical use. In 2023, 1,113,644 crabs were collected coastwide solely for biomedical purposes[3] (Table 2). This represents a 22% increase from 2022. Of the total biomedical collections in 2023, males accounted for 52.9%, and females comprised 42.1%. Some crabs were rejected prior to bleeding due to mortality, injuries, slow movement, and size (mortality observed while crabs were going through the biomedical process is included under 'Observed Mortality' in Table 2). Approximately 2% of crabs collected solely for biomedical purposes were observed and reported as dead from the time of collection up to the point of release.

During the 2019 benchmark stock assessment, a meta-analysis of literature estimates was performed to estimate post-bleeding mortality of horseshoe crabs. Although many of these studies did not implement biomedical best practices, these values are the only available estimates of mortality experienced after bleeding. Based on the literature review, post-bleeding mortality is estimated at 15%. Tagging data was used in the assessment to compare survivorship between crabs that were and were not bled. These results indicated some decrease in short-term survivorship, but greater long-term survivorship for bled crabs. These results are likely attributable to the culling process used by biomedical facilities to select healthy crabs for bleeding.

Post-bleeding mortality, calculated as 15% of the number of bled biomedical-only crabs (not from the bait market), for 2023 was estimated to be 155,801 crabs. Total mortality (observed mortality plus post-bleeding mortality) of biomedical crabs for 2023 was estimated at 178,232 crabs. The total estimated mortality from biomedical collections represents approximately 19.4% of the 2023 total directed use mortality (917,021 crabs), which includes both total biomedical mortality and removals for bait.

In 2023, a work group appointed by the Board reviewed and updated the *Best Management Practices for Handling Horseshoe Crabs for Biomedical Purposes*[4]. The work group included technical committee and advisory panel members with expertise in horseshoe crab biology, ecology, and biomedical processing. The purpose of the BMPs is to recommend broadly

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[3] This does not include bait crabs borrowed for bleeding and then returned to the bait market; these are counted against state bait quotas. The dual use of horseshoe crabs harvested for bait is encouraged as a conservation tool. Facilities that bleed horseshoe crabs to manufacture LAL can utilize crabs from the bait market in what is often referred to as the "rent a crab" program. Permitted bait harvesters and/or dealers can "rent" crabs caught for the bait industry to the bleeding facility; these crabs are returned to the bait vendor after bleeding. These crabs are caught under bait permits, are counted against the bait quota of the state of origin, and must comply with that state's regulations for bait harvest. The dual use of crabs in this program can reduce overall harvest, may decrease overall mortality, can provide the LAL manufacturers with an additional source of raw material, and may offer harvesters and dealers opportunity within this secondary market.

[4] Best Management Practices for Handling Horseshoe Crabs for Biomedical Purposes can be found here: https://asmfc.org/uploads/file/645bf065HSC_Biomedical_BMPs_2023.pdf

applicable industry standards that are expected to minimize mortality and injury of horseshoe crabs associated with the biomedical process.

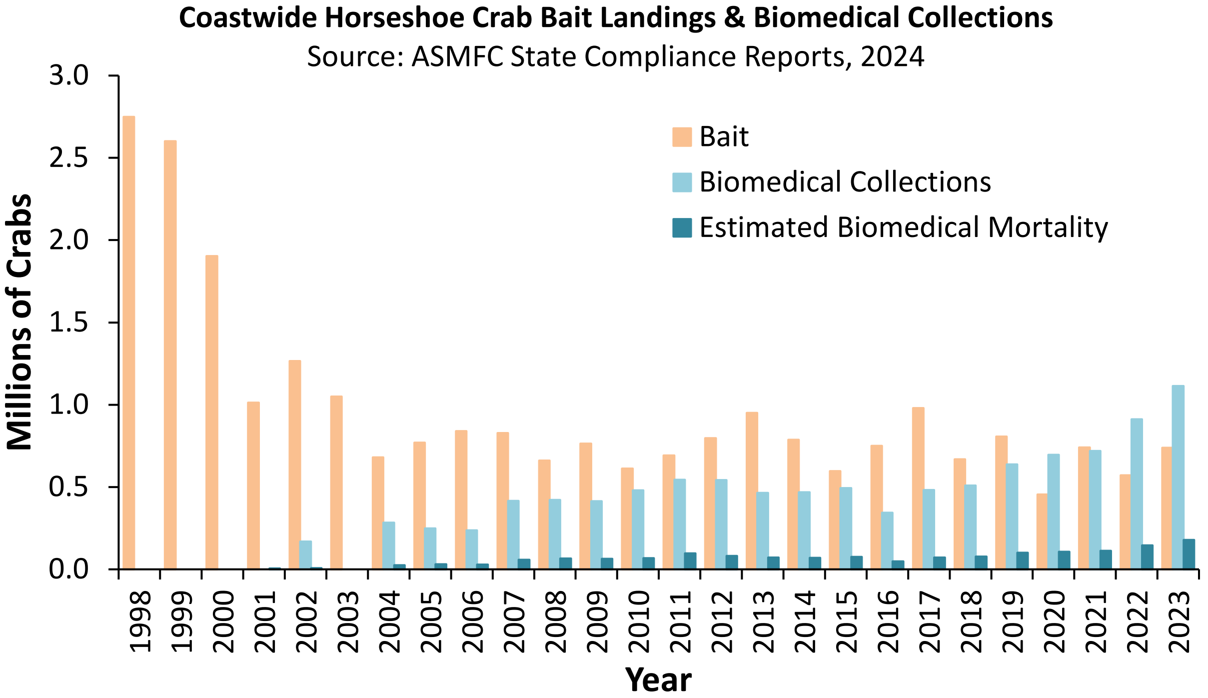

Figure 2. Number of horseshoe crabs harvested for bait and collected for biomedical purposes, 1998-2023.

*Biomedical collections are annually reported to the Commission and include all horseshoe crabs brought to bleeding facilities except those that were harvested as bait, “rented” by biomedical facilities and counted against state bait quotas.

*Crabs collected solely for biomedical crabs are returned to the water after bleeding; a 15% mortality rate is assumed for all bled crabs that are released. This number plus observed mortality reported annually by bleeding facilities via state compliance reports equals the 'Estimated Biomedical Mortality.'

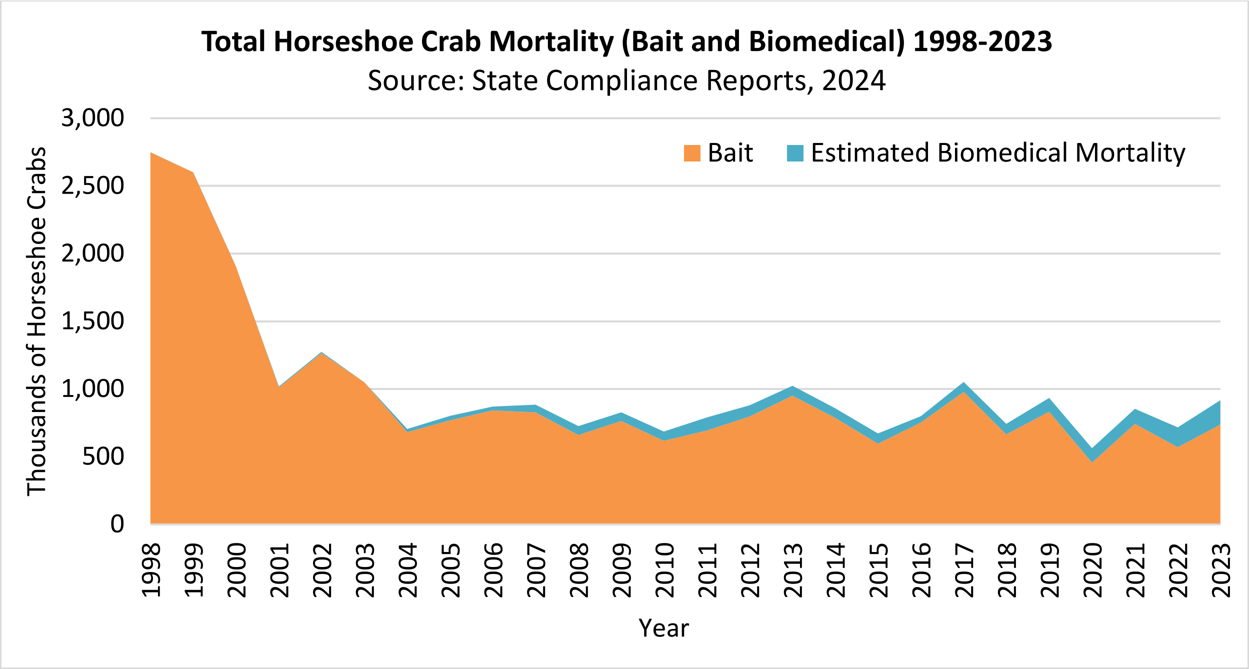

Figure 3. Total Horseshoe Crab Mortality from Bait and Estimated Biomedical Mortality, 1998-2023.

Table 2. Numbers of horseshoe crabs collected, bled, and estimated mortality for the biomedical industry. Numbers shown are for crabs collected solely for biomedical use. Mortality of bled crabs that later enter the bait industry is included in bait harvest.

Year	Crabs Collected	Crabs Bled	Post-Bleeding Mortality	Observed Mortality	Total Mortality
2010	480,914	412,781	61,917	6,829	68,746
2011	545,164	486,850	73,028	24,139	97,166
2012	541,956	497,956	74,693	7,370	82,063
2013	464,657	440,402	66,060	5,447	71,507
2014	467,897	432,340	64,851	5,658	70,509
2015	494,123	464,506	69,676	5,362	75,038
2016	344,495	318,523	47,778	1,004	48,782
2017	483,245	444,115	66,617	6,056	72,674
2018	510,407	479,142	71,871	5,588	77,459
2019	637,029	589,361	88,404	12,789	101,193
2020	697,025	649,546	97,432	8,907	106,339
2021	718,809	667,951	100,193	11,911	112,104
2022	911,826	828,181	124,227	21,693	145,920
2023	1,113,644	1,038,673	155,801	22,431	178,232

**Some biomedical collections were reduced in 2016 due to temporary changes in production.*

IV. Status of Research and Monitoring

The Horseshoe Crab FMP set forth an ambitious research and monitoring strategy in 1999 and again in 2004 to inform future management decisions. Despite limited time and funding there are many accomplishments since 1999. These accomplishments were largely made possible by forming partnerships between state, federal and private organizations, and the support of hundreds of public volunteers.

Addendum III Monitoring Program

Addendum III requires affected states to carry out three monitoring components:

1. All states who do not qualify for *de minimis* status report monthly harvest numbers and subsample a portion of the catch for sex and harvest method. In addition, those states with annual landings above 5% of the coastwide harvest report all landings by sex and harvest method. Although states with annual landings less than 5% of annual coastwide harvest are not required to report landings by sex, the PRT recommends all states require sex-specific reporting for horseshoe crab harvest.
2. States with biomedical collections are required to monitor and report collection numbers and mortality associated with the transportation and bleeding of the crabs.
3. States must identify spawning and nursery habitat along their coasts. All states have completed this requirement, and a few continue active monitoring programs.

Virginia Tech Research Projects

The Virginia Tech Horseshoe Crab Trawl Survey (VT Survey) has been sampling horseshoe crab to estimate relative abundance since 2002, except for the years 2013-2015, due to a lack of funding. The survey conducted in 2023, and is in progress for 2024. Funding sources beyond 2024 continue to be explored. The 2023 surveys were conducted between September 6 and October 30. The lower Delaware Bay area of the survey was not sampled in 2022 and 2023 as increased operational costs resulted in limitations to time on the water.

For the Delaware Bay Area (DBA), the 2023 survey results indicate that mean stratified catches-per-tow for mature males and females increased substantially. The number of newly mature females continued to be low, and the number of newly mature males was much lower than in the past two years. Immature individuals decreased, but have been relatively stable since 2016. Newly mature females' relative abundance has been low since 2019, and none were caught this year. Prosomal widths of mature and newly mature males and females show decreasing trends over the time series in the DBA.

The indices from this survey, along with the New Jersey Ocean Trawl and Delaware Fish and Wildlife Adult Trawl Survey indices, are used to estimate horseshoe crab abundance in the ARM Framework to produce optimal harvest limits for the upcoming year.

Spawning Surveys

The Delaware Bay spawning survey was completed for the twenty-fifth consecutive year in 2023. Ten beaches in Delaware and ten beaches in New Jersey were sampled. Peak spawning occurred during the second lunar period in May (17-21) in New Jersey and in the first lunar period in June (1-5) in Delaware. Baywide female and male spawning activity has exhibited a statistically significant increasing trend since 2010.

Tagging Studies

The USFWS continues to maintain a toll-free telephone number and a website for reporting horseshoe crab tag returns and assists interested parties in obtaining tags. Tagging work continues to be conducted by biomedical companies, research organizations, and other parties involved in outreach and spawning surveys. Beginning with the 2013 tagging season, additional efforts were implemented to ensure that current tagging programs are providing data that benefits the management of the coastwide horseshoe crab population. All existing and new tagging efforts are required to submit an annual application to be considered for the USFWS tagging program and all participants must submit an annual report along with their tagging and resighting data to indicate how their tagging program addresses at least one of the following objectives: determine horseshoe crab sub-population structure, estimate horseshoe crab movement and migration rates, and/or estimate survival and mortality of horseshoe crabs. The PRT recommends all tagging programs approved by the states coordinate with the USFWS tagging program, in order to ensure a consistent coastwide program to support management.

From 1999 through 2023, 428,553 horseshoe crabs have been tagged and released through the USFWS tagging program along the Atlantic coast, and 67,210 unique crabs have been recaptured. Horseshoe crabs have been tagged and released from every state on the Atlantic Coast from Florida to New Hampshire. In the early years of the program, tagging was centered around Delaware Bay; however, tagging has expanded and increased in Long Island Sound and the Southeast. Tagging information from this database has been used in the 2019 Benchmark Stock Assessment to define stock structure, estimate total mortality, and characterize impacts of biomedical use on horseshoe crab mortality.

New York Region Monitoring

Following the 2019 Benchmark Stock Assessment, which characterized the status of the horseshoe crab population in the New York region as “Poor”, the Board directed the PRT to monitor fishery-independent surveys in this area to track progress of state management actions toward improving this regional population. During the assessment, five surveys were included in the ARIMA model to characterize this population. One of these, the Northeast Area Monitoring and Assessment Program (NEAMAP), includes sample areas outside of the New York region, making it too data-intensive to specify the regional index on an annual basis. The most recent information from the state-conducted surveys used in the assessment is summarized below, but can be viewed in greater detail in the Connecticut and New York state compliance reports. The Western Long Island (WLI) Little Neck Bay and Manhasset Bay seine surveys were combined in the assessment to form a single index, but are shown below separately. None of these beach seine surveys were completed in 2020 due to the COVID-19 pandemic but resumed in 2021. Figures 5-8 show the annual index for each survey over the time series until 2023.

Connecticut

- Long Island Sound Trawl (LISTS) (Fall) – 2023 index – The 2022 and 2023 surveys were limited in April and June due to staff limitations and in June because of mechanical issues with the research vessel. The LISTS indices for 2023 were above average in both the spring and fall, though the spring index has been decreasing over the last few years.

The fall index has been increasing in recent years, with the 2023 index being the highest in the time series.

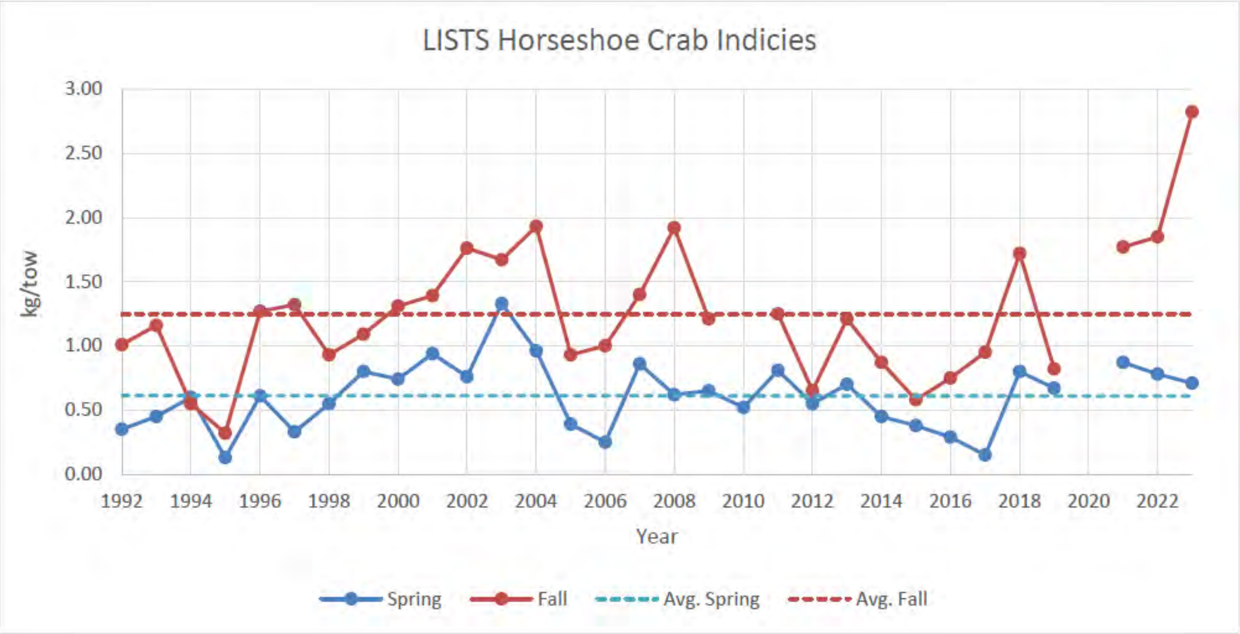

Figure 4. LISTS Horseshoe Crab Indices, 1992-2023.

New York

- Peconic Trawl – 2023 index = 0.26 (delta distribution average catch per unit effort [CPUE]), increase from 2022.
- WLI Jamaica Bay Seine (all horseshoe crabs) – 2023 index = 0.32 (geometric mean), increase from 2022.
- WLI Little Neck Bay Seine (all) – 2023 index = 1.80 (geometric mean), increase from 2022.
- WLI Manhasset Bay Seine (all) – 2023 index = 0.59 (geometric mean), decrease from 2022.

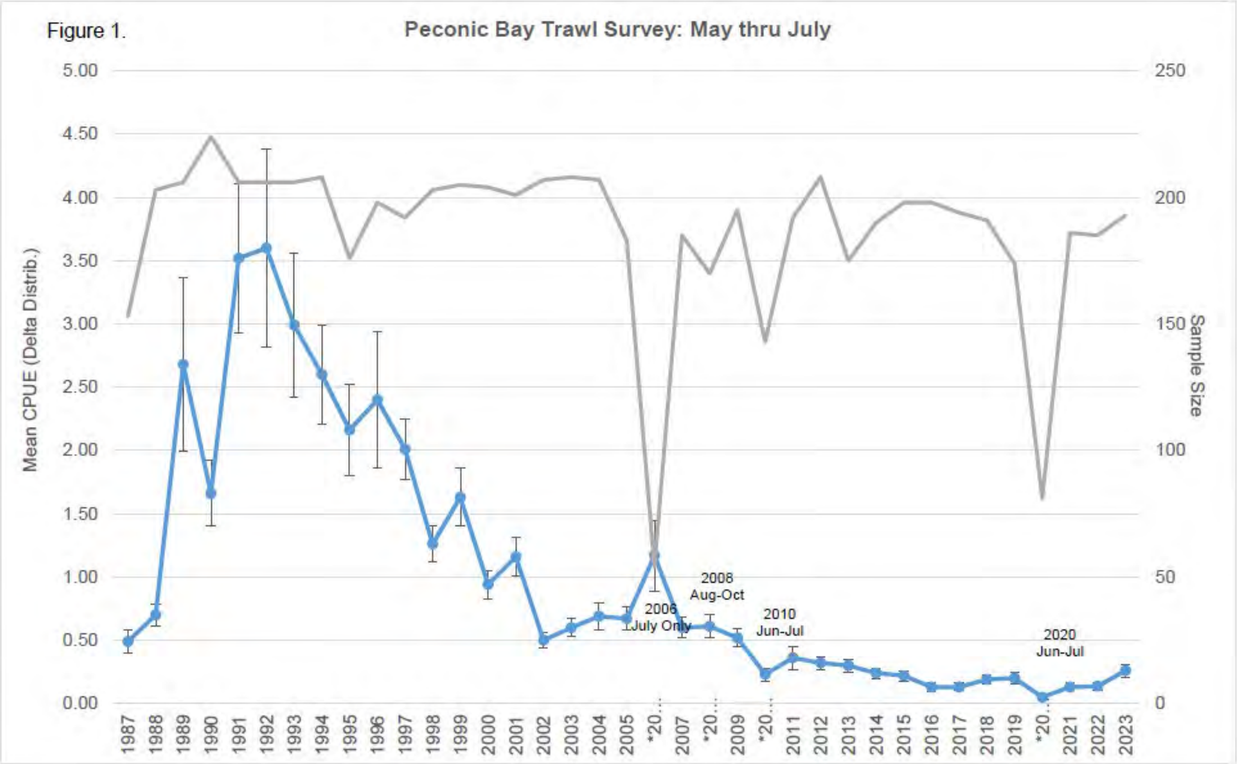

Figure 5. Peconic Bay Trawl Survey: May through July, 1987-2023. (Gray line=sample size, blue line=mean CPUE).

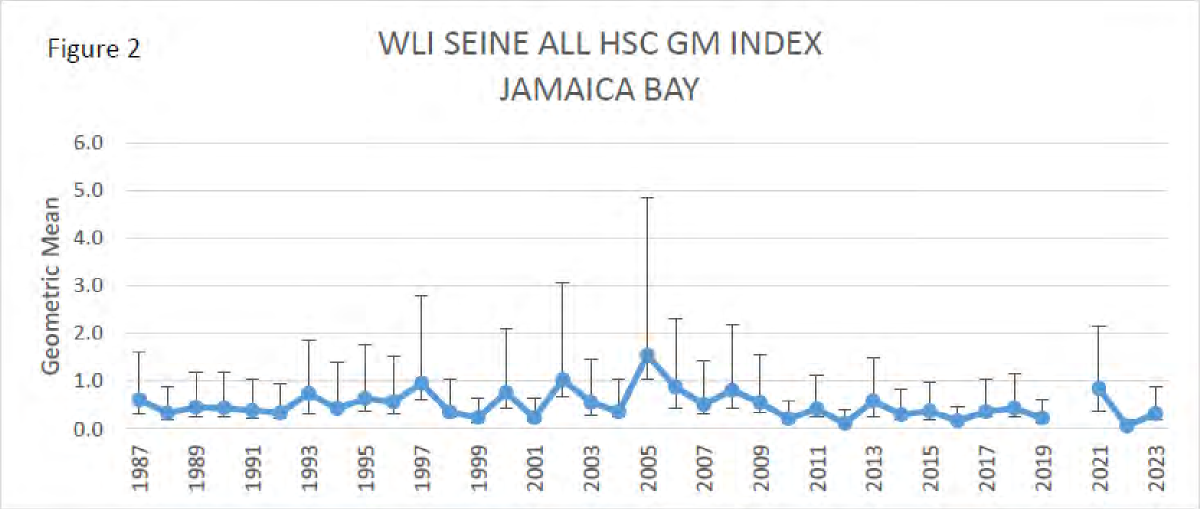

Figure 6. NYSDEC WLI Jamaica Bay Beach Seine Survey All Horseshoe Crab GM Index, 1987-2023. *Due to the COVID-19 pandemic, in 2020 sampling did not begin until July.

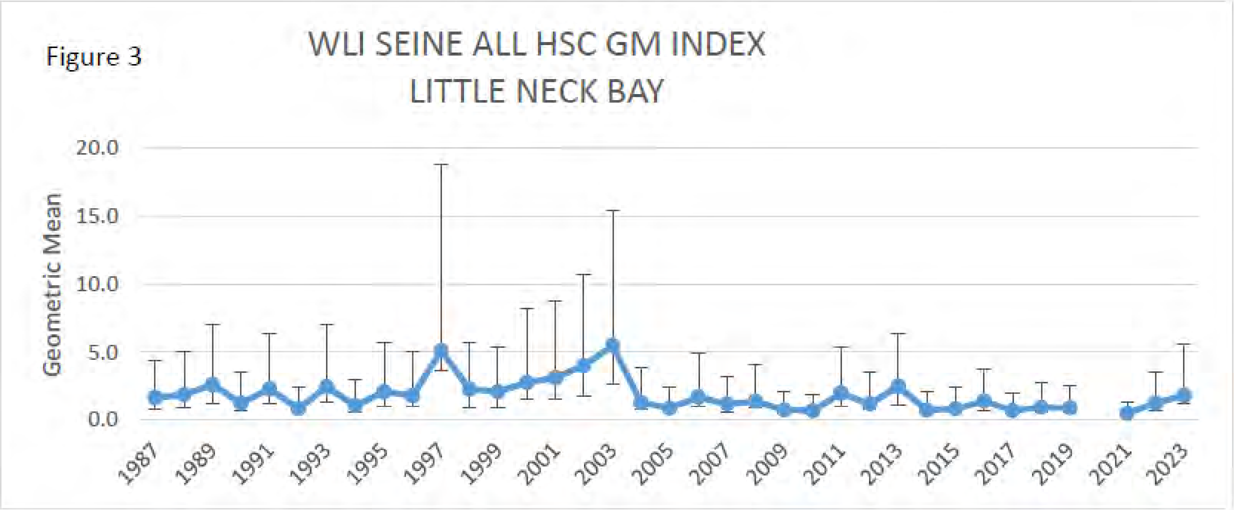

Figure 7. Little Neck Bay Seine Survey All Horseshoe Crab GM Index, 1987-2023. *Due to the COVID-19 pandemic, in 2020 sampling did not begin until July.

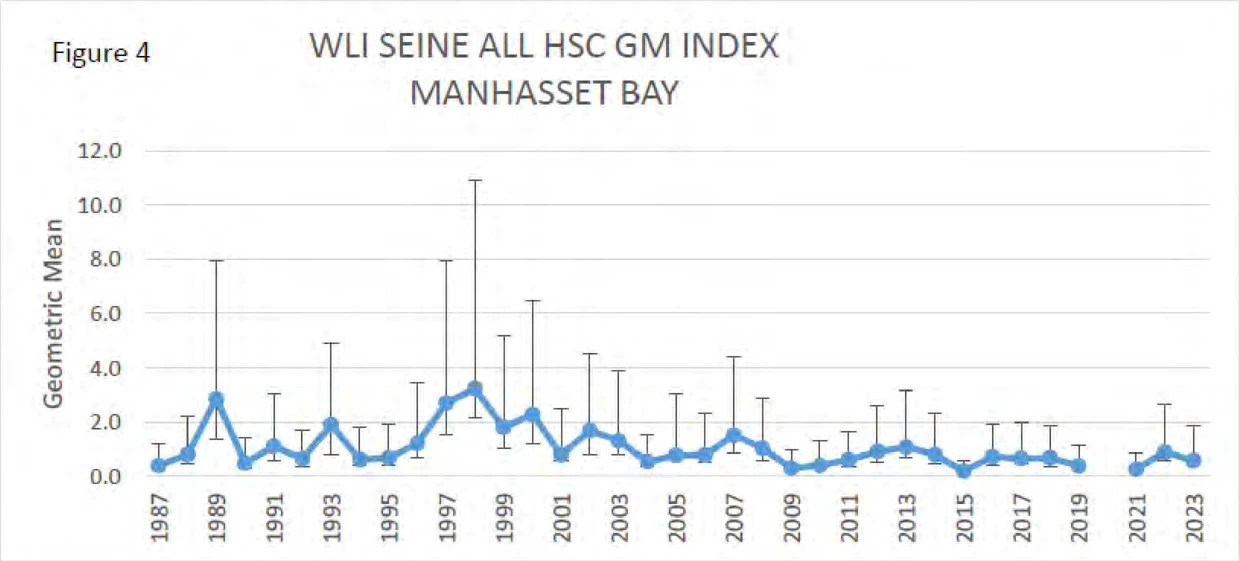

Figure 8. Manhasset Bay Seine Survey All Horseshoe Crab GM Index, 1987-2023. *Due to the COVID-19 pandemic, in 2020 sampling did not begin until July.

V. Status of Management Measures and Issues

ASMFC

Initial state harvest quotas were established through Addendum I. Addendum III outlined the monitoring requirements and recommendations for the states. Addendum IV set harvest closures and quotas, and other restrictions for New Jersey, Delaware, Maryland, and Virginia, which were continued in Addenda V and VI.

In February 2012 the Board approved Addendum VII to implement the ARM Framework; it was implemented in 2013. The ARM Framework was updated in 2021, and the Board adopted use of the revised ARM Framework through Addendum VIII in 2022. Addendum VIII maintains the Addendum VII allocation mechanism to divide the Delaware Bay optimized harvest output from the ARM Framework among the four Delaware Bay states (New Jersey, Delaware, Maryland, and Virginia east of the COLREGS line).

In reviewing state compliance with the FMP, the PRT noted that while New Jersey (through a moratorium) and Delaware do not allow harvest from January 1 to June 7, which was a provision of Addendum VI. Maryland regulations allow horseshoe crab harvest starting May 1. The PRT has some concerns that this creates an inconsistency within the Delaware Bay region. According to Addendum VI, the season closure provisions for New Jersey, Delaware, and Maryland (no harvest from January 1 to June 7) expired in April 2013. Subsequent Addenda VII and VII do not contain any seasonal provisions. Therefore, the PRT recommends the Board clarify whether the season closure provisions were intentionally or unintentionally excluded from these Addenda.

State-specific charts outlining compliance and monitoring measures are included in Section VII. Massachusetts did not report all required data to ASMFC by the required deadline. The PRT finds that all other jurisdictions appear to be in compliance with the FMP and subsequent Addenda in 2023.

Changes to State Regulations

- Massachusetts decreased its state quota to 140,000 crabs.
- The State of Connecticut passed bill no. 6484 that prohibits the hand harvesting of horseshoe crabs or their eggs in state waters, effective October 1st, 2023.
- Delaware changed its daily harvest limit from a volumetric quantity to a numerical quantity (3,000 male horseshoe crabs). Delaware also revised the dredging lottery process to reflect current fishery operation. The lottery date of January 1 was changed to a date and time announced annually by the Division based off fishery performance up to that point.

Alternative Baits

Trials testing effectiveness of alternative baits to horseshoe crab for the American eel and whelk fisheries have previously been conducted. Additionally, a survey of bait usage in the eel and whelk fisheries was conducted in 2017. This survey is available at: http://www.asmfc.org/uploads/file/5a04b785HSC_BaitSurveyTCReport_Oct2017.pdf.

Shorebirds

The USFWS received petitions in 2004 and 2005 to emergency list the red knot under the Endangered Species Act. In fall 2005, it determined that emergency listing was not warranted at the time. As part of a court settlement, the USFWS agreed to initiate proposed listings of over 200 species, including the red knot. In fall 2013, the USFWS released a proposal for listing the red knot as threatened. In January 2015 the USFWS designated the red knot as threatened under the Endangered Species Act.

In 2022 the USFWS conducted an analysis of the changes to horseshoe crab management that would occur under the 2021 ARM Revision to determine the likelihood of impacts to the red knot. The finding from analysis is that there is a < 1% chance of a red knot population decline due to the implementation of potential female harvest under the revised ARM. Therefore, the Service concluded that take, defined under the Endangered Species Act as killing or injuring, of red knots is not likely.

The red knot has been listed as an endangered species in the state of New Jersey since 2012.

VI. PRT Recommendations and Research Needs

De Minimis

States may apply for *de minimis* status if, for the last two years, their combined average horseshoe crab bait landings (by numbers) constitute less than one percent of coastwide horseshoe crab bait landings for the same two-year period. States may petition the Board at any time for *de minimis* status, if their fishery falls below the threshold level. Once *de minimis* status is granted, designated States must submit annual reports to the Board justifying the continuance of *de minimis* status.

States that qualify for *de minimis* status are not required to implement any horseshoe crab harvest restriction measures, but are required to implement components A, B, E and F of the monitoring program (Section 3.5 of the FMP; further modified by Addendum III). Since *de minimis* states are exempt from a harvest cap, there is potential for horseshoe crab landings to shift to *de minimis* states and become substantial, before adequate action can be taken. To control shifts in horseshoe crab landings, *de minimis* states are encouraged to implement one of the following management measures:

1. Close their respective horseshoe crab bait fishery when landings exceed the *de minimis* threshold;
2. Establish a state horseshoe crab landing permit, making it only available to individuals with a history of landing horseshoe crabs in that state; or
3. Establish a maximum daily harvest limit of up to 25 horseshoe crabs per person per day. States which implement this measure can be relieved of mandatory monthly reporting, but must report all horseshoe crabs harvests on an annual basis.

The following states have been removed from the Management Board since its formation: Pennsylvania (2007), Maine (2011), and New Hampshire (2014). South Carolina, Georgia, and Florida are requesting *de minimis* status for the 2024 fishing season based on the 2022-2023 season landings, and meet the FMP requirements for being granted this status (Table 1). The PRT recommends granting these jurisdictions *de minimis* status.

Biomedical Threshold

The 1998 FMP established a biomedical mortality threshold of 57,500 crabs that, if exceeded, requires the Board to consider management action. This threshold has been exceeded in all but one year since 2008. Results of the 2019 Benchmark Stock Assessment indicate that levels of biomedical mortality prior to 2017 (the terminal year of data used in the assessment) did not have a significant effect on horseshoe crab population estimates or fishing mortality in the Delaware Bay region.

In 2020 the Board tasked the PDT to review the threshold for biomedical use to develop biologically-based options for the threshold and to develop options for action when the threshold is exceeded. It also tasked the PDT to review the best management practices (BMPs) for handling biomedical catch and suggest options for updating and implementing BMPs. The PDT concluded that given the lack of coastwide population estimates for horseshoe crabs, it is not possible to develop a biologically-based threshold for biomedical mortality. Thus, the PDT did not recommend a change to the threshold. Based on this information the Board determined no action is warranted. A Board-appointed work group was formed in 2023, which reviewed and updated the best management practices for biomedical handling to further reduce stress, injury, and mortality to horseshoe crabs collected for biomedical purposes.

Funding for Research and Monitoring Activities

The PRT strongly recommends the funding and continuation of the VT benthic trawl survey. 2023 sampling had to be reduced due to increased costs. This effort provides a statistically reliable estimate of horseshoe crab relative abundance that is essential to continued ARM implementation and use of the CMSA stock assessment model.

Discard Mortality Estimation

Results of the 2019 Benchmark Stock Assessment indicate that discard mortality may be significant, of similar or greater magnitude than bait harvest. The Review Panel’s report indicated that these estimates could be further refined to reduce their uncertainty and more precisely characterize this mortality source. The PRT recommends the Board take steps to increase access to and use of data from the NEFOP, allowing for improved monitoring and estimation of discard mortality.

Improvement of the New York Regional Population

Results of the 2019 Benchmark Stock Assessment and 2024 update indicate a “Poor” status for the New York regional population, due to negative trends in regional abundance indices. New York and Connecticut have indicated that they will take actions within their states to improve this population. The PRT and Board have recommended such actions so that this population’s status may improve.

Prior to the 2022 Spring season, Connecticut implemented measures to reduce harvest, including the commercial fishing season moving from May 22 to the calendar date three days after the last full or new moon (whichever is later) in May, and a new 5-day closure centered on the first moon phase in June. The daily possession limit for commercial hand-harvest was also decreased from 500 to 150 crabs. Effective October 1, 2023, hand harvest of horseshoe crabs and their eggs is prohibited in Connecticut. The New York state legislature is currently considering a bill that would prohibit all commercial and biomedical harvest of horseshoe crabs. If approved by the Governor it would take effect January 1, 2025.

The PRT will continue to annually report regional indices of abundance so that progress of management actions may be tracked through the annual FMP Reviews.

VII. State Compliance and Monitoring Measures

MASSACHUSETTS		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota (Voluntary State Quota)	330,377 (140,000)	330,377 (165,000)
Landings	139,746	--
Other Restrictions	Bait: 400 crab daily limit year round; limited entry; Biomedical: 1,000 crab daily limit; Conch pot and eel fishermen: no possession limit Mobile gear: 75 crab trip limit, exempted from "no-fishing days" starting 10/9/2020; All: May and June 5-day lunar closures; 7" PW minimum size; Pleasant Bay Closed Area	Bait: 300 crab daily limit year round; Biomedical: 200,000 crab quota; 1,000 crab daily limit; Conch pot and eel fishermen: no possession limit All: Closure April 15th-June 7th; No mobile gear harvest Fri-Sat during summer flounder season; 7" PW minimum size; Closed Areas
Landings	139,746	-
Monitoring Component A_1		
Mandatory monthly reporting	Yes, plus weekly dealer reporting through SAFIS	Yes, plus weekly dealer reporting through SAFIS
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	Yes – w/NPS and USFWS; Pleasant Bay, Monomy NWR, Waquoit Bay	Yes – w/NPS and USFWS; Pleasant Bay, Monomy NWR, Waquoit Bay

RHODE ISLAND		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota (Voluntary State Quota)	26,053 (8,398)	26,053 (8,398)
Other Restrictions	State Restrictions: - Daily possession limit: 60 crabs per permit - Bait Fishery Closure: May 1-May 31 - Biomedical Fishery Closure: 48 hours prior to and 48 hours following new and full moons during May. - Biomedical quota and best management practices	State Restrictions: - Daily possession limit: 60 crabs per permit - Bait Fishery Closure: May 1-May 31 - Biomedical Fishery Closure: 48 hours prior to and 48 hours following new and full moons during May - Biomedical quota and best management practices
Landings	2,314	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes, weekly call in and monthly on paper	Yes, weekly call in and monthly on paper
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes, since 2000	Yes
Monitoring Component B_4 Tagging program	No	No

CONNECTICUT		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota	48,689	48,689
Other Restrictions	- Limited entry program - Hand-harvest possession limit of 150 crabs - seasonal and lunar closures -Prohibit harvest effective Oct. 1, 2023	Prohibit hand harvest of horseshoe crabs or eggs in state waters, effective Oct. 1, 2023
Landings	3,927	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	No – exempt under Addendum III because landings are < 5% of coastwide total	No – exempt under Addendum III because landings are < 5% of coastwide total
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes, since 1999 (methods differ from DE Bay survey)	Yes
Monitoring Component B_4 Tagging program	Yes, in collaboration with local universities (Sacred Heart University since 2015)	Yes

NEW YORK		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota (Voluntary State Quota)	366,272 (150,000)	366,272 (150,000)
Other Restrictions	Ability to close areas to harvest; seasonal quotas and daily harvest limits Five-day lunar closures around the full moon in May and the new moon in June. Initial trip limit dropped to 150 crabs in period 2.	Ability to close areas to harvest; seasonal quotas and daily harvest limits - Five-day lunar closures around the full moon in May and the new moon in June. -Initial trip limit dropped to 150 crabs in period 2.
Landings	130,658	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	Yes	Yes

NEW JERSEY		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de miminis*	Does not request *de miminis*
Bait Harvest Restrictions and Landings		
ASMFC Quota (Voluntary State Quota)	164,364 (male only) (0)	173,014 (male only) (0)
Other Restrictions	Bait harvest moratorium	Bait harvest moratorium
Landings	0	--
Monitoring Component A_1		
Mandatory monthly reporting	Not Applicable	Not Applicable
Characterize commercial bait fishery	Not Applicable	Not Applicable
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	No	No
Monitoring Component B_5 Egg abundance survey	Yes, no longer mandatory	Yes
Monitoring Component B_6 Shorebird monitoring program	Yes	Yes

DELAWARE		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota	164,364 (male only)	173,014 (male only)
Other Restrictions	Closed season (Jan 1 – June 7)	Closed season (Jan 1 – June 7)
Landings	168,208 (male only)	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes (daily call-in reports & monthly logbooks)	Yes
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	No state program but has assisted in the past with various Delaware Bay horseshoe crab tagging initiatives	No
Monitoring Component B_6 Shorebird monitoring program	Yes	Yes

MARYLAND		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota	255,980 (male only)	255,980 (male only)
Other Restrictions	Season closure until May 1, catch limits, no harvest Saturday and Sunday	Season closure until May 1, catch limits, no harvest Saturday and Sunday
Landings	186,466 (male only)	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes (weekly reports for permit holders; monthly for non-permit holders)	Yes (weekly reports for permit holders; monthly for non-permit holders)
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	Yes	Yes

POTOMAC RIVER FISHERIES COMMISSION		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Ability to close fishery if *de minimis* threshold is reached	No horseshoe crab fishery	No horseshoe crab fishery
Daily possession limit <25 for *de minimis* state		
HSC landing permit		
Bait Harvest Restrictions and Landings		
ASMFC Quota	0	0
Other Restrictions	None	None
Landings	0	0
Monitoring Component A_1		
Mandatory monthly reporting	Yes - weekly	Yes - weekly
Characterize commercial bait fishery	Not Applicable	Not Applicable
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Not Applicable	Not Applicable
Monitoring Component B_3 Implement spawning survey	Not Applicable	Not Applicable
Monitoring Component B_4 Tagging program	Not Applicable	Not Applicable

VIRGINIA		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota (Voluntary State Quota)	172,828 (81,331 male-only east of COLREGS line)	172,828 (81,331 male-only east of COLREGS line)
Other Restrictions	Closed season (January 1 – June 7) for federal waters. Harvest of horseshoe crabs east of the COLREGS line limited to trawl gear and dredge gear.	Closed season (January 1 – June 7) for federal waters. Harvest of horseshoe crabs east of the COLREGS line limited to trawl gear and dredge gear.
Landings	107,166 (85,788 males)	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Not Applicable	Not Applicable
Monitoring Component B_3 Implement spawning survey	No	No
Monitoring Component B_4 Tagging program	No	No

NORTH CAROLINA		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	Did not request *de minimis*	Did not request *de minimis*
Bait Harvest Restrictions and Landings		
ASMFC Quota	24,036	24,036
Other Restrictions	Trip limit of 50 crabs; Proclamation authority to adjust trip limits, seasons, etc.	Trip limit of 50 crabs; Proclamation authority to adjust trip limits, seasons, etc.
Landings	934	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	No	No
Monitoring Component B_4 Tagging program	No	No

SOUTH CAROLINA		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	*De minimis* status granted for 2023.	*De minimis* requested for 2024 and meets criteria.
Ability to close fishery if *de minimis* threshold is reached	No horseshoe crab bait fishery	No horseshoe crab bait fishery
Daily possession limit <25 for *de minimis* state		
HSC landing permit		
Bait Harvest Restrictions and Landings		
ASMFC Quota	0	0
Other Restrictions	None	None
Landings	0	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes (Biomedical)	Yes (Biomedical)
Characterize commercial bait fishery	Not Applicable	Not Applicable
Monitoring Component A_2		
Biomedical reporting	Yes	Yes
Required information for biomedical use of crabs	Yes	Yes
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	Yes	Yes

GEORGIA		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	*De minimis* status granted in 2023.	*De minimis* requested for 2024 and meets criteria.
Ability to close fishery if *de minimis* threshold is reached	Yes	Yes
Daily possession limit <25 for *de minimis* state	25/person; 75/vessel with 3 licensees	25/person; 75/vessel with 3 licensees
HSC landing permit	Must have commercial shrimp, crab, or whelk license; LOA permit required	Must have commercial shrimp, crab, or whelk license; LOA permit required
Bait Harvest Restrictions and Landings		
ASMFC Quota	29,312	29,312
Other Restrictions	None	None
Landings	0	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	Not Applicable	Yes
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	No	No
Monitoring Component B_4 Tagging program	No	No

FLORIDA		
	2023 Compliance	**2024 Management Proposal**
***De minimis* status**	*De minimis* status granted in 2023.	*De minimis* requested for 2024 and meets criteria.
Ability to close fishery if *de minimis* threshold is reached	Yes	Yes
Daily possession limit <25 for *de minimis* state	25/person w/ valid saltwater products license; 100/person with marine life endorsement	25/person w/ valid saltwater products license; 100/person with marine life endorsement
HSC landing permit	See above	See above
Bait Harvest Restrictions and Landings		
ASMFC Quota	9,455	9,455
Other Restrictions	Daily possession limit	Daily possession limit
Landings	Confidential	--
Monitoring Component A_1		
Mandatory monthly reporting	Yes	Yes
Characterize commercial bait fishery	Yes	Yes
Monitoring Component A_2		
Biomedical reporting	Not Applicable	Not Applicable
Required information for biomedical use of crabs	Not Applicable	Not Applicable
Monitoring Component B_2 Continue existing benthic sampling programs	Yes	Yes
Monitoring Component B_3 Implement spawning survey	Yes	Yes
Monitoring Component B_4 Tagging program	No	No

Horseshoe Crab Management Board, Atlantic States Marine Fisheries Commission
Comments Submitted by: Amanda Dey, PhD., September 24, 2024.

Dear Members of the Horseshoe Crab Management Board:

During the period 2001 to 2022, I served on ASMFC technical committees representing the NJ Div. of Fish and Wildlife's Endangered and Nongame Species Program (shorebirds). During this time, I oversaw the horseshoe crab surface egg survey in NJ. The ARM Sub-committee never requested surface egg density data during this period or thereafter. Had the ARM Subcommittee requested egg density data at any time, it would have been willingly shared in its entirety including historic egg density data.

From 2005 to 2012, NJ and DE conducted surface egg density surveys, and provided annual reports to the ASFMC and its technical committees. Raw surface egg density data (DE & NJ 2005 – 2012) were openly shared with technical committees including the HS Crab Technical Committee whose members primarily comprised the ARM Subcommittee. This included Horseshoe crab biologists Jordan Zimmerman (DE) and Jeffrey Brust (NJ), DE fisheries biometrician Rich Wong, ASFMC Fisheries Management Plan Coordinator Danielle Chesky, USFWS Gregory Breese [1].   Data were also provided to David Smith, USGS Leetown Aquatic Center, WV, as evidenced in a February 22, 2012, email from Dr. Smith to Kevin Kalasz, the DE Shorebird biologist (and my counterpart) [2].

In 2005 the States of NJ and DE implemented a "core-sample method" developed by Dr. Dave Smith USGS Leetown Center, WV [3].   This was meant to address variability of surface egg densities within/between beaches and standardize surface egg density data collection in NJ and DE. DE had not conducted surface egg surveys prior to 2005. Drs. Dick Weber (DE) and Daniel Hernandez (NJ) conducted egg surveys on behalf of state fish and wildlife agencies. We provided annual reports to the ASFMC and technical committees including detailed information on surface egg densities and description of differences in egg enumeration methods (volumetric estimation in DE, hand count in NJ) [4]. In 2013, DE disbanded its egg survey because of these differences. Surface egg surveys were conducted in NJ in the late 1980s, early 1990s, and 2000 to present. The results are described in Smith et al. 2022. [5]

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[1] Email 9-17-2012 from A. Dey, NJ Div. of Fish and Wildlife, to R. Wong, DE Marine Fisheries Biometrician with 2005-2012 raw surface egg data attached. The agency people listed above were copied on the email.

[2] Email 2-22-2012 from D. Smith, USGS, to K. Kalasz, DE Div. of Fish and Wildlife, cc: A Dey

[3] Pooler, P.S., D.R. Smith, R.E. Loveland, M.L. Botton, and S.F. Michels. 2003. Assessment of sampling methods to estimate horseshoe crab (Limulus polyphemus L.) egg density in Delaware Bay. Fish. Bull. 101:690-703.

[4] Delaware Bay Horseshoe Crab Egg Survey: 2005-2012. Report to the Atlantic States Marine Fisheries Commission. March 14, 2012. This report was updated on 3-14-13 and resubmitted to ASFMC to include results of 2012 site visits by DE & NJ fisheries biologists (pg. 9 bottom).

[5] Smith, J.A.M., A. Dey, K. Williams, T. Diehl, S. Feigin, and L. J. Niles. Horseshoe crab egg availability for shorebirds in Delaware Bay: Dramatic reduction after unregulated horseshoe crab harvest and limited recovery after 20 years of management. Aquatic Conserv: Mar Freshw Ecosyst. 2022;32:1913–1925.

Dr. Joseph Smith, probably in 2019, presented egg cluster and surface egg data, and their relationship, to a joint meeting of the HS Crab and Delaware Bay Ecosystem Technical Committees at ASFMC offices in Arlington VA. [6] Briefly, spawning beaches reached egg-cluster carrying capacity early in May, surface eggs increase rapidly and remained high through the shorebird stopover period. This condition was documented by Drs. Robert Loveland and Mark Botton in their comparison of early vs. late 1990s egg surveys in NJ. After overharvests of crabs, a reduced crab population, lower crab densities per spawning event, and less frequent spawning events, no longer functioned to generate "windrows" of eggs. There was much head-nodding and recognition by technical committee members, but no action was taken by ASFMC or fisheries biologists to consider the relationship between spawning crab population size, egg clusters, surface eggs and red knots.

State and federal fisheries biologists continue to wave away horseshoe crab egg data by characterizing it as "too variable" to be useful.

While surface egg densities and egg clusters are the most relevant measure of spawning crab population status vis-à-vis shorebirds, it is easier to "maximize" harvest and avoid conservation action by using fisheries trawl data -- including trawl data dismissed in 1998 as inadequate because it was "not geared to sample HS crabs".

Three such trawl surveys: DE 30-foot trawl, the NJ Ocean and NJ Delaware Bay Trawls, were recently used the Catch Multiple Survey Analysis in the ARM Model Revision.

In a 2015 composite estimate of crab population size (2012-2015), these same 3 trawls produced a doubling of the female crab population, and an increase by half of male crabs, over population estimates produced by the Virginia Tech Trawl Survey (which is geared to sample Horseshoe Crabs). This composite estimate was meant to fill in "gap" years where the Virginia Tech trawl was not funded (2012-2015).

This doubling of the female crab population was waved off as "variability" by Dr. John Sweka, USFWS at the October 9, 2015, joint technical committee meeting in Arlington, VA. [7]

The standard of "best available data" is being seriously misused.

Thank you for your time and consideration.

Amanda Dey, PhD

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[6] Smith, J. A. M. 2019 white paper, The Case for Beach-based Metrics 20191007.pdf

[7] ASFMC Horseshoe Crab and Delaware Bay Ecosystem Technical Committees Meeting, October 9, 2015, Doubletree Crystal City, 300 Army-Navy Drive, Arlington, VA 22202. Meeting Summary.

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September 27, 2024

Horseshoe Crab Management Board
Atlantic States Marine Fisheries Commission
1050 N. Highland Street, Suite 200 A-N
Arlington, VA 22201
comments@asmfc.org

VIA ELECTRONIC MAIL

Re: ASMFC's "Technical Response to External Review of the 2022 ARM Framework Revision"

Dear Members of the Horseshoe Crab Management Board:

New Jersey Audubon and Defenders of Wildlife urge the Atlantic States Marine Fisheries Commission ("ASMFC" or the "Commission") to maintain the prohibition on the bait harvest of female Delaware Bay-origin horseshoe crabs. The attached report by Dr. Kevin Shoemaker reaffirms that the Commission's adaptive resource management ("ARM") model fails to represent the relationship between red knots[1] and horseshoe crabs, underestimates the risks to both species, and is not suitable for determining bait harvest quotas. The ARM model therefore cannot legitimately serve as a basis for resuming the female bait harvest, and its recommendation for a female harvest should not be adopted.

Dr. Shoemaker has prepared two prior analyses of the ARM model: first during the public comment period in 2022, which was held before the model's computer code was publicly available, and again in 2023 after the computer code was released and analyzed by Dr. Shoemaker. Both of his analyses identified critical flaws demonstrating the grave risks that utilizing the ARM model would pose for the fragile Delaware Bay ecosystem. ASMFC responded to the merits of those analyses for the first time in April 2024, and Dr. Shoemaker addresses that response in his new report attached to this letter.[2]

In addition to Dr. Shoemaker's analyses, more than 34,000 members of the public opposed adopting the new model and resuming a female horseshoe crab harvest during the 2022 comment period, compared to only seven commenters in support. The public expressed concern about horseshoe crabs and the species that rely upon them, including the red knot, a

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[1] In these comments, "red knot" refers to the *rufa* subspecies unless otherwise noted.

[2] Dr. Shoemaker's new report is attached as Exhibit A. Dr. Shoemaker's 2022 and 2023 analyses (hereinafter "Shoemaker 2022" and "Shoemaker 2023") are available at https://earthjustice.org/wp-content/uploads/2023/09/nj-audubon-defenders-of-wildlife-2023-comments-to-hsc-board.pdf. ASMFC's "Technical Response to External Review of the 2022 ARM Framework Revision" appeared in the Horseshoe Crab Management Board's spring 2024 meeting materials.

shorebird that migrates up to 17,000 miles every year and requires horseshoe crab eggs as a crucial energy source. In 2015, red knots were listed as a threatened species under the federal Endangered Species Act ("ESA"), with the overharvest of horseshoe crabs identified as a key contributor to their decline. If ASMFC authorized a bait harvest of female horseshoe crabs that reduced the food source available to migrating red knots, it would risk violating the ESA by depriving red knots of essential nutrition and thereby committing "take" of this threatened shorebird.

In his attached report, Dr. Shoemaker has carefully assessed ASMFC's response and demonstrated that it does not undermine his core conclusions. Critically, the model fails to accurately represent red knots' reliance on horseshoe crabs. It would not predict a decline in red knots even under a collapse of the horseshoe crab population, and it ignores horseshoe crab egg surveys, which are much more closely linked to red knot survival than the data inputs used by the model. The model also significantly overestimates red knots' survival rate—and ASMFC has misread or misconstrued many of the studies that it relies on to support its erroneously high estimate. In the few instances where ASMFC's claims provided a legitimate basis for Dr. Shoemaker to update his prior analyses, he has done so. Nevertheless, his updated analysis continues to demonstrate significant flaws in the ARM model.

This cover letter describes key points from Dr. Shoemaker's analysis and raises other concerns with the ARM model, including ASMFC's shifting strategies for gap-filling the extremely low estimates of newly mature female horseshoe crabs, which offer additional reasons that the model-generated female harvest recommendation should not be adopted. While elements of Dr. Shoemaker's analysis are summarized below, please refer to his attached report for his complete response.

I. The ARM model would fail to predict a decline in red knots even under a collapse of the horseshoe crab population.

At the outset, a key conclusion that Dr. Shoemaker reached two years ago holds true today and continues to counsel against relying on the ARM model to set harvest quotas: the model fails to accurately reflect the relationship between the red knot and horseshoe crab populations. In his 2022 analysis, Dr. Shoemaker evaluated the weak relationship between red knots and horseshoe crabs in the ARM model and calculated that the model would predict an increase in red knots passing through Delaware Bay even if horseshoe crabs disappeared entirely from the region.[3] This finding raised concerns about the model's ability to predict future declines in red knot abundance in Delaware Bay, including under new proposed horseshoe crab harvest scenarios, as it would not have predicted the historical decline that occurred in the wake of severe horseshoe crab overharvest in the late 20th century. Because ASMFC held its 2022 public comment period on the model at a time when the federal government was denying repeated requests to release the model's computer code to the public for independent review, Dr. Shoemaker by necessity based this finding on a back-of-the-envelope calculation, as he repeatedly noted in his analysis.[4]

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[3] Shoemaker 2022 at 6-12.

[4] *Id.* at 7, 9.

ASMFC's April 2024 response nevertheless criticizes Dr. Shoemaker based on technical information that was not available to the public when he conducted his analysis. Regardless, the points raised in the April 2024 response are misguided. The response contains two principal contentions. First, with the benefit of the computer code, it is evident that an increase in red knots when there are zero horseshoe crabs in Delaware Bay is "mathematically impossible."[5] But this argument misses the point. The importance of Dr. Shoemaker's critique is not merely that the ARM model would be inadequate if horseshoe crab numbers actually reached zero, but that the model fails to represent red knots' response generally across a wide range of horseshoe crab abundance, including abundance figures that have been historically observed. Further, while the model would not predict an increase in red knots if the horseshoe crab population were literally zero, ASMFC has not—and could not—deny that the model *would* predict an increase in red knots at breathtakingly low horseshoe crab abundance levels indicating an ecosystem collapse.

ASMFC neglected to provide the precise horseshoe crab abundance threshold at which the model would begin to predict a decline in red knots at Delaware Bay, so Dr. Shoemaker reran his analysis using the model's computer code to answer that question. He calculated that the model would not predict a decline in red knot abundance unless the number of mature female horseshoe crabs in Delaware Bay fell below approximately 300,000—less than a tenth of the lowest number ever estimated from empirical data. Of course, red knot abundance plummeted when the relevant crab population actually reached that prior low. Yet the ARM model predicts that red knot abundance would remain stable even if the horseshoe crab population plunged dramatically lower still. Thus, for management purposes, whether the model begins to show a decline in red knots at zero or 300,000 female horseshoe crabs is immaterial. The material fact is that the model cannot accurately predict the red knot population response to horseshoe crab harvest scenarios such as the female harvest recommendation that is now being considered.

ASMFC's second argument is to accuse Dr. Shoemaker of conducting a "dangerous exercise"[6] for running a scenario well outside of the ARM model's training data. Furthermore, ASMFC forecasts unanimous support for curtailing the horseshoe crab harvest under such dire conditions in which the horseshoe crab population plummeted. Again, this misses the point, which is that the model would fail to predict a decline in red knots even under conditions that have been historically observed to cause such a decline. If the model is intended to be functional only within limited bounds of female horseshoe crab abundance, ASMFC should specify as much—especially if the model cannot function within the full range of historically observed conditions. Speculation that fisheries managers would intervene under catastrophic circumstances, even if well founded, does not alter the conclusion that the ARM model fails to accurately represent the environmental conditions that it purports to reflect.

II. The ARM model significantly overstates red knot survival rates.

The ARM model is also plagued by critical reliance on an assumed survival rate for red knots that is insupportably high. Dr. Shoemaker explained that the ARM model's finding that red

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[5] ASMFC Response 26.

[6] *Id.*

knots have a 93% survival rate is likely erroneously high.[7] He hypothesized that this error resulted from relatively rare but consequential mistakes in the dataset. Specifically, the survival rate formula is based largely on resighting observations—birds that are spotted over multiple years, as identified by leg flags bearing unique codes that can be read from a distance without requiring physical recapture. However, the difficulty of reading leg flags from afar gives rise to the possibility of error. If the same leg flag is spotted more than once in a season, the subsequent sightings help to verify the initial identification, and there is a high likelihood that the bird was truly present in Delaware Bay. Conversely, flag codes spotted only once in a season (approximately 9% of total resighting observations) lack that verification and carry a higher probability that they were misreads. These misreads are likely to bias the estimated survival rate higher because the birds bearing those flag codes may be dead and are mistakenly recorded as living longer than they did, potentially by many years.

In his 2023 analysis, Dr. Shoemaker recalculated the red knot survival rate with the same dataset used by ASMFC but excluded birds that were resighted only once in a season. He found that the survival rate plunged to around 80%. He also calculated the survival rate exclusively from birds whose leg bands were read upon recapture—when misreads are likely to be negligible—and again calculated around 80%. The difference in survival rates has profound consequences: with ASMFC's likely erroneous survival rate, the average red knot would live nearly 14 years, but using the more realistic survival rate, the average lifespan drops to less than 5 years.

ASMFC's April 2024 analysis makes no attempt to refute or explain the discrepancy between the ARM model's survival rate and the survival rate calculated with more verified data. Instead, it undermines its own position by presenting data that directly support Dr. Shoemaker's findings. ASMFC's response states, "[O]bservations of birds more than 5 years old are common in the mark-recapture data set (approximately 20% of birds), with a maximum of 17 years between physical recaptures."[8] But as Dr. Shoemaker explains in his attached report, those figures are consistent with (if not lower than) what would be expected with an 80% survival rate. In contrast, under a 93% survival rate—as assumed by ASMFC—70% of birds would survive to age 5, and more than 2% would survive past 17 years. Yet ASMFC does not report any such results from the mark-recapture data, because they do not exist. Instead, ASMFC appears to have inadvertently raised the question of why, if the survival rate is 93%, there are so few red knots that are confirmed to be at least 5 years old.

ASMFC's next defense of its high survival rate estimate in the April 2024 response is to point to scientific publications, including Piersma et al. (2016), which studied a different subspecies of red knot (*Calidris canutus piersmai*) in Australia. While studies of a different subspecies across the world cannot substitute for a rigorous interpretation of the data collected at Delaware Bay, they may be informative. But Piersma et al. does not support ASMFC's

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[7] In its April 2024 response, ASMFC implies that the ARM model found a survival rate of 90%, but the actual figure is 93%. ASMFC Response 6; ASMFC, *Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation (Draft for Board Review)* 74 (2021). While the discrepancy may seem trivial, it amounts to a four-year difference in red knots' mean expected lifespan.

[8] ASMFC Response 6.

conclusions, and ASMFC appears to have misinterpreted the study. ASMFC asserts that Piersma et al. found "annual apparent survival for red knots in Western Australia were well above 90% in most years of their study."[9] Yet the study says no such thing: for most years of the study, the annual apparent survival percentage rate hovered in the 80s; it never reached 90%, and in the final two years, it plummeted to 76% and 67%.[10] (ASMFC may have confused *annual* survival rates with *seasonal* survival rates, which were also discussed in the study.) Moreover, Piersma et al. attributed the plunging survival rate observed in its study to habitat loss in a key staging area. Thus, the study found that red knot survival rates were *never* as high as ASMFC stated, and in fact the study supports the conclusion that problems at a staging area—like Delaware Bay for the *rufa*—can harm the species.

ASMFC's April 2024 response then references another scientific study (also of non-*rufa*), Boyd & Piersma (2001), for the proposition that some red knots have long lifespans—which, as explained above, is not in dispute and would be expected even under lower survival rates. Confoundingly, ASMFC's response fails to disclose that the study also estimated mean adult survival of red knots using two different methods, both of which yielded estimates below 80% over the duration of the study.[11] Again, ASMFC's response erroneously claims support from a scientific publication that does not support ASMFC's conclusions, and, to the contrary, supports Dr. Shoemaker's analysis. More fundamentally, the Commission fails to square its defense of a 93% red knot survival rate with the contrary data reported in the very studies cited in ASMFC's own response.

A third article that ASMFC cites, Tucker et al. (2022), was authored predominantly by researchers who collaborated to create the ARM model[12] and used the same method of counting singlet observations that Dr. Shoemaker critiques. The study and the ARM model made the same error and thereby generated similar results. The study therefore does not provide independent validation of the ARM model's methodology or estimated survival rate. All told, of the five studies that ASMFC cites to support a higher survival rate, three of them either directly refute ASMFC's position or replicate the ARM model's contested approach.

In addition, the scientific evidence for a red knot survival rate far lower than 93% continues to grow. A new study of red knots wintering in Texas, Louisiana, and Florida found mean apparent annual survival rates of 76.8%, 81.9%, and 79.0%, respectively.[13] Further, Amie MacDonald of Birds Canada recently presented research estimating that the true annual survival for adult red knots staging in Canada's James Bay is 81%.[14] Concerningly, both of

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[9] *Id.*

[10] Theunis Piersma et al., *Simultaneous declines in summer survival of three shorebird species signals a flyway at risk*, Journal of Applied Ecology vol. 53, 479, at 486 tbl. 5 (Apr. 2016).

[11] Hugh Boyd & Theunis Piersma, *Changing Balance Between Survival and Recruitment Explains Population Trends in Red Knots Calidris Canutus Islandica Wintering in Britain, 1969-1995*, Ardea vol. 89(2) 301, at 307 tbl. 2 (Jan. 2001).

[12] *Compare* ASMFC Response 1 (listing contributors to response) *with id.* at 31 (listing authors of Tucker et al.). Anna Tucker, Conor McGowan and James Lyons appear in both places.

[13] David J. Newstead et al., *Survival of red knots in the northern Gulf of Mexico*, Frontiers in Ecology and Evolution, at 7 tbl. 2 (Apr. 9, 2024) (attached as Exhibit B).

[14] Amie MacDonald et al., *Uniting* rufa *Red Knot resighting data throughout the western Atlantic Flyway offers myriad opportunities for survival analysis* 24, PowerPoint presentation (2024) (attached as Exhibit C).

these studies, like Piersma et al. (2016), found survival rates declining significantly over time. The red knot survival rate utilized in the ARM model is out of step with these research findings.

III. ASMFC provides no compelling reason to exclude horseshoe crab egg density surveys from the ARM model.

ASMFC's April 2024 response does not dispute Dr. Shoemaker's analysis that egg density—the concentration of horseshoe crab eggs on the beach—has a significant positive correlation to red knot survival. And ASMFC expressly (and accurately) "does not deny that eggs are the true link between horseshoe crabs and red knots."[15] Nevertheless, to explain the omission of egg density from the ARM model, ASMFC's response states, "Ultimately, egg density data could not be considered in the ARM Revision because they were not provided to the ARM Subcommittee when requested."[16]

Whatever data availability issues may have arisen previously, ASMFC presents no evidence that they persist. Moreover, ASMFC may have been at least partly responsible for any past availability issues: when excluding egg density data from the prior version of the ARM model, ASMFC made no mention of data availability and wrote, "We do not foresee using the egg survey data in our models or in our decision analysis in the foreseeable future, and we place low priority on continuing this survey and researching/improving survey methodologies."[17] In 2013, at the request of the state of Delaware, ASMFC dropped egg density surveys as a compliance requirement.[18] Thus, any data availability issues that ASMFC previously encountered may have arisen at least partly from ASMFC's own actions. In light of that history, it is especially inappropriate for ASMFC to criticize Dr. Shoemaker's analysis on the basis that it did not include egg density data from Delaware.[19] But regardless, now that the data availability concerns appear resolved, ASMFC's statement that it "is not opposed to using the egg density data" is welcome.[20]

While ASMFC describes challenges associated with incorporating egg density data into the ARM model, there is no justification for continuing to rely exclusively on measures (horseshoe crab trawl surveys) that bear minimal correlation to red knot survival while ignoring measures (egg surveys) that bear a strong correlation. The technical challenges raised by ASMFC center on the lack of a modeled connection between egg density and female horseshoe crab abundance, which the Commission acknowledges "must ultimately be linked."[21] More research into this system would be beneficial, but that should not prevent or

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[15] ASMFC Response 11.
[16] *Id.*
[17] ASMFC, *A Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Constrained by Red Knot Conservation* 40 (Sept. 2009).
[18] *See* ASMFC Horseshoe Crab Delaware Bay Ecosystem Technical Committee, Meeting Summary 3 (Sept. 24, 2013) (recommending to discontinue egg surveys as a requirement); ASMFC, Proceedings of the Atlantic States Marine Fisheries Commission Horseshoe Crab Management Board 16-17 (Oct. 31, 2013) (formally removing egg surveys as a requirement).
[19] ASMFC Response 12.
[20] *Id.*
[21] *Id.*

delay ASMFC from including egg surveys in the ARM model. Indeed, the connection between female horseshoe crab abundance and red knot survival must logically include egg availability as an intermediate step. Thus, by modeling red knot survival as a linear function of horseshoe crab abundance, ASMFC implicitly assumes that horseshoe crab abundance strongly corresponds to egg availability. Although there are mechanistic questions about that link, ASMFC has nonetheless attempted to model the connection between horseshoe crab abundance and red knot survival. Given the availability of long-term egg survey data, the case is at least as strong for explicitly modeling the connection between red knot survival, egg density, and female horseshoe crab abundance.

IV. Dr. Shoemaker has reaffirmed his analysis of uncertainty in the ARM model and updated his assessment of trends in female horseshoe crab abundance.

As detailed in his attached report, Dr. Shoemaker has considered ASMFC's response regarding technical flaws in the horseshoe crab catch multiple survey analysis ("CMSA") model. Two aspects of that report bear noting here.

First, ASMFC acknowledged that Dr. Shoemaker's critique of how the CMSA model propagates uncertainty has merit and should be considered in future ARM revisions.[22] That acknowledgment is welcome, although it is inappropriate for ASMFC to continue using the inferior method pending some future revision. The Commission seeks to downplay this issue by noting that Dr. Shoemaker's suggested method of propagating uncertainty produces a similar equilibrium number of mature female horseshoe crabs as the CMSA model's method. But an essential question when propagating uncertainty is whether the model appropriately recognizes the degree of uncertainty (e.g., 95% confidence interval) associated with various harvest scenarios. Dr. Shoemaker has demonstrated that the CMSA model does not.

The critique about propagating uncertainty stems from the CMSA's treatment of the recruitment rate for mature female horseshoe crabs. The recruitment rate is an important parameter in the CMSA model, and this type of uncertainty is called "parameter uncertainty." The model's flawed treatment of parameter uncertainty is separate from—and additional to—the ARM model's flawed treatment of structural uncertainty, which Dr. Shoemaker explains in his first opening statement in the attached report. ASMFC characterizes the model as adaptive resource management, but such management entails testing various hypotheses. The relative weight given to each hypothesis changes as new information is learned about the ability of each hypothesis to represent the system. In contrast, the ARM model incorporates only one hypothesis and excludes consideration of any alternatives. While the model may be updated every few years to reflect new data, iterative updates do not amount to adaptive resource management. Under this flawed approach, the model never has to earn the 100% confidence value it is given, and ASMFC's asserted commitment to adaptive resource management is illusory. It is critical for the model to recognize all types of uncertainty when representing the ecosystem.

Second, Dr. Shoemaker reviewed ASMFC's response regarding trends in mature female horseshoe crab abundance. In his prior analyses, he observed that there had not been a

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[22] *Id.* at 23.

statistically significant increase in such crabs since 2000, the first year when state-based harvest quotas became effective. ASMFC argued that the trend should be measured from 2010 to reflect the roughly ten years needed for female horseshoe crabs to reach maturity.[23] Dr. Shoemaker agreed that 2010 is a non-arbitrary threshold and re-ran his analysis from that year. He confirmed that the data from each of the three trawl surveys that inform the CMSA show apparent increases in adult female horseshoe crab abundance since 2010. Nevertheless, this finding is based only on the data reported from the trawl surveys and does not resolve concerns about the reliability of those surveys or the methodology for incorporating the data into the CMSA and the larger ARM model.

V. Unsupported estimates of newly mature female horseshoe crabs further compromise the ARM model's harvest recommendations.

The ARM model's recommendations are further undermined by the modelers' reliance on speculative estimates of a key data point needed to make the model work at all. Since 2019, the estimated abundance of newly mature female horseshoe crabs in the Delaware Bay population has been alarmingly low—even as low as zero. ASMFC has explained that the CMSA cannot operate with such low recruitment numbers and has devised various methods to "gap-fill" that data input.[24] Last year, the ARM Subcommittee and Delaware Bay Ecosystem Technical Committee ("DBETC") hypothesized that the low newly mature female horseshoe crab numbers did not reflect a true recruitment failure but rather a classification error, and responded by "re-proportion[ing]" 19.9% of the mature female estimate to the newly mature age class.[25] Their management recommendation to the Board, which included a substantial female bait harvest, was based on that recommendation.

However, at its meeting on September 13, 2024, the ARM Subcommittee and DBETC concluded that the previous hypothesis was incorrect. Accordingly, they now hypothesize that surveyors had misclassified newly mature female horseshoe crabs as immature, not fully mature, and they propose to gap-fill the newly mature female estimate by reallocating a quantum of immature female horseshoe crabs equal to a designated percentage of the newly mature *male* abundance estimate.

As of this writing, ASMFC has not released a written explanation of the new method, but it appears to lead to troubling results. Because the method will be applied retroactively, it will significantly increase the gap-filled estimates used since 2019, resulting in much larger population estimates. While the committees may have reason to believe that the newly mature females were misclassified as immature rather than fully mature, that does not mean that the estimate should be gap-filled based on surveys of newly mature males. How newly mature females were possibly misclassified is a separate question from how their abundance should be estimated.

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[23] *Id.* at 14.

[24] Memorandum from Delaware Bay Ecosystem Technical Committee and Adaptive Resource Management Subcommittee to Horseshoe Crab management Board re: "Delaware Bay Horseshoe Crab Harvest Recommendation for 2024" 2 (Oct. 2, 2023).

[25] *Id.*

More troublingly, the whiplash over newly mature female estimates demonstrates the peril of patching up the ARM model with speculative hypotheses even as it is being used to generate management recommendations. For the second consecutive year, ASMFC cannot credibly claim that it is running a peer-reviewed model because a significant function of the model has been assembled on the fly. What ASMFC believed to be the best hypothesis last year was immediately utilized for management recommendations and turned out to be erroneous. Now a new hypothesis is being substituted without peer review or any meaningful public scrutiny. And because it is already known that the newly mature female estimate will be zero again next year, the pattern of utilizing unproven methods to generate harvest recommendations will continue.

This new development compounds a long history of ASMFC using unfounded estimates of newly mature female horseshoe crabs in its modeling analyses. In his 2022 analysis, Dr. Shoemaker observed that the ARM model's estimate of horseshoe crab recruitment was strongly influenced by nonsensical estimates that ASMFC plugged in for the years 2013-2016, when the survey that measures newly mature females was not performed. The average annual estimated recruitment for 2003-2012 was 1.2 million newly mature females, and the average annual estimate for 2017-2019 was 1.9 million. But for 2013-2016, lacking the empirical measurement, ASMFC plugged in extraordinary estimates averaging *4.2 million*—nearly *2 million more than the highest empirical estimate ever recorded*.[26] That average masks even more absurd estimates for individual years, including *9.6 million* in 2013.[27]

Understandably, ASMFC's peer reviewers for the ARM model specifically emphasized that estimates of newly mature females needed to become more reliable over time by utilizing empirical counts.[28] And in its April 2024 response to Dr. Shoemaker, ASMFC acknowledged that the CMSA's volatile recruitment estimates for 2013-2016 were "nonsensical."[29] But the use of nonsensical, unempirical estimates has persisted well beyond anything that the peer reviewers contemplated. Under ASMFC's latest method for gap-filling the missing recruitment data, the estimates return to nonsensical territory, swinging from 8.2 million in 2020 to 1.3 million in 2021 and back up to 6.5 million in 2022.[30] ASMFC offers little reason to believe that these wildly diverging estimates reflect actual biological reality in the Delaware Bay ecosystem.

As a result of all the foregoing gap-filling efforts, the model now significantly deviates from the version that was peer-reviewed, both by the absence of actual newly mature female data and by the increased weight being placed on the newly mature male estimate. While all data inputs are imperfect, ideally the use of multiple inputs will balance out those imperfections.

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[26] ASMFC, *Supplemental Report to the 2021 Revision to the Adaptive Resource Management Framework* 16 tbl. 3 (2022).

[27] *Id.*

[28] *See* ASMFC, *Horseshoe Crab Adaptive Resource Management Revision Peer Review Report*, at 270 of PDF ("[T]he primiparous estimates for [the missing survey] years are not reliable, potentially introducing large uncertainties (and biases) in the projection model and ARM. The Panel agrees that such uncertainty will be reduced when more years of survey catch data become available in future.").

[29] ASMFC Response 23.

[30] Again, these data were presented at the September 13, 2024, ARM Subcommittee and DBETC meeting. No written explanation or additional context has been released to the public.

But if one input (newly mature females) is based entirely on another (newly mature males), any errors in the latter input will be replicated in the former and compromise more of the model. The ARM model's peer reviewers did not approve placing so much weight on—or taking that risk with—the estimate of newly mature males. The appropriate course now is to exercise caution and not recommend a female bait harvest based on an untested, unreviewed model. And regardless of any recommendations that the model may produce, ASMFC certainly should not reauthorize a female harvest.

As noted above, the problem with the newly mature female horseshoe crab estimate has been recognized and acknowledged for many years. When ASMFC accepted comments on the ARM revision in 2022, commenters were already raising concerns about low estimates dating to 2019. Now ASMFC suggests, based on a discussion with surveyors, that newly mature females were simply not being counted. It is striking that ASMFC spent five years devising hypotheses if the explanation was so straightforward, and it seems emblematic of a serious disconnect between ASMFC's complex computer model and conditions on the ground.

VI. Conclusion

The ARM model contains fundamental flaws rendering it unfit for managing the harvest of Delaware Bay-origin horseshoe crabs. Now that ASMFC has responded to Dr. Shoemaker's analysis, it remains evident that the model does not accurately represent the ecosystem, and its outputs are not a defensible basis for imposing additional risk on red knots and horseshoe crabs in Delaware Bay. Most importantly, the model cannot justify—and ASMFC must continue to prohibit—the bait harvest of female horseshoe crabs. Longer term, ASMFC should discontinue using the ARM model or make fundamental improvements through a transparent public process.

Respectfully submitted,

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EXHIBIT A

Report of Dr. Kevin Shoemaker

Review of the Atlantic States Marine Fisheries Commission's (ASMFC) Adaptive Resource Management (ARM) framework for regulating Horseshoe Crab bait harvest in Delaware Bay

Kevin T. Shoemaker, Ph.D.

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September 2024

This document is submitted in reference to the Atlantic States Marine Fisheries Commission's (ASMFC) response to two peer review reports examining the 2021 revised ASMFC Adaptive Resource Management (ARM) framework – which has been approved for use in managing the Horseshoe Crab fishery in Delaware Bay. This document, and the 2022 and 2023 peer review reports referred to in the ASMFC response, were written by Kevin Shoemaker, Ph.D.

Dr. Shoemaker holds an M.S. and Ph.D. in Conservation Biology from SUNY-ESF in Syracuse, NY, and a B.S. degree in Biology from Haverford College. He was a Postdoctoral Fellow in the Department of Ecology and Evolution at Stony Brook University and has served as Senior Scientist at Applied Biomathematics, an ecological research and development company located in Setauket, NY. Dr. Shoemaker is currently an Associate Professor at the University of Nevada, Reno, where he uses quantitative models to inform wildlife conservation and management. He has over 15 years of experience as a wildlife ecologist and conservation modeler and has authored over 50 peer-reviewed scientific articles and book chapters on topics in ecology and conservation. He has expertise in Bayesian inference, population ecology, population viability analysis (PVA) and ecological modeling.

Overview

In 2022 and 2023 I was asked by Earthjustice (a not-for-profit public interest legal organization) to provide an independent peer review of the quantitative models used by the Atlantic States Marine Fisheries Commission (ASMFC) in their '*Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation*' (ASMFC 2021; hereafter, 'revised ARM'). In both peer review reports, I identified several lines of evidence that suggest the revised ARM framework, as approved by ASMFC in 2022, underestimates the risk of commercial harvest of female horseshoe crabs on the Federally Threatened *rufa* Red Knot (*Calidris canutus* rufa) and other shorebirds that rely on the Delaware Bay staging area. Earlier this year (2024) ASMFC's ARM subcommittee released a statement in response to my review of the revised ARM (hereafter, "ASMFC response"). In this document I explain why my analysis generally holds up to the critiques raised in the ASMFC response, and highlight a couple of areas where the ASMFC response led me to reconsider my original conclusions. My overall conclusion remains the same: the revised ARM fails to recognize evidence that commercial harvest of female horseshoe crabs could harm the red knot and other migratory shorebird populations, nor does it acknowledge the extent to which recovery of the red knot population may be tied to the growth of the Delaware Bay horseshoe crab population. Therefore, the revised ARM framework does not live up to its stated mission to "*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*" (ASMFC 2021).

I begin with a short essay (opening statement #1) arguing that the revised ARM framework failed to implement a key component of the Adaptive Resource Management (ARM) paradigm: multiple competing hypotheses. Not only does the revised ARM framework assume the relationship between red knots and horseshoe crabs is extremely weak, there are several compelling lines of evidence (including the re-analyses I presented in my 2023 peer review report) that this ecological relationship may in fact be much stronger than the "weak relationship" hypothesis that is currently formalized in the revised ARM. By assigning 100% of model weight to a "weak relationship" model -- whereby harvest of female horseshoe crabs is expected to have negligible impact on red knots -- the revised ARM misrepresents the risk of horseshoe crab harvest to red knots in contradiction with well-established science. Therefore, I argue that the ARM framework should be revised to incorporate at least one additional model that acknowledges the possibility of a strong and meaningful ecological relationship between red knots and horseshoe crabs.

Following this initial opening statement, I provide a revised analysis (opening statement #2, responding to ASMFC's comments on an analysis presented in my 2022 peer review report) that reinforces an important assertion from my reviews of the revised ARM framework -- specifically, that the fitted relationship between horseshoe crab abundance and red knot vital rates (survival and fecundity) is of insufficient magnitude to induce a decline in projected red knot population growth even under a major collapse of the horseshoe crab population. This point is central to my critique of the current ARM framework, as it clearly demonstrates that (1) the model is incapable of predicting the observed decline of red knots in the early 21st century, which is widely attributed to over-harvest of horseshoe crabs, and (2) the modeled relationship between red knots and horseshoe crabs is too weak to meaningfully constrain harvest recommendations of female horseshoe crabs. Finally, I provide a point-by-point response to ASMFC's comments.

Before I respond to the specific critiques raised by ASMFC, I emphasize that my peer review was motivated by the same stated principles that guide the ARM subcommittee: a commitment to science-based decision making in natural resources conservation and management. I reject the implication that my perspectives were infused with advocacy, or that my peer review reflected a "reluctance to learn within an adaptive management framework and a desire to cling to previous beliefs in spite of scientific advances". To the contrary, in the interest of encouraging productive scientific dialog, I reached out to the ASMFC reviewers soon after they began their review with an offer to share code and information and address any questions or concerns directly -- and although they did not respond, I would be happy to engage with the ARM subcommittee to discuss any of these issues in more depth. While I was compensated for my time by Earthjustice, no one attempted to exert any influence over my scientific conclusions, and my comments should be received in the spirit they were offered: as an independent scientific evaluation of the revised ARM framework. As a quantitative ecologist and conservation biologist, I promote the use of data and simulation models in support of conservation decisions, and I believe in the value of adaptive management for making decisions in the face of uncertainty.

Opening statement #1: *the revised ARM framework fails to account for structural uncertainty by incorporating multiple alternative hypotheses*

Under the adaptive resource management (ARM) paradigm, regular monitoring of the managed system enables decision makers to (1) react to new information (e.g., reducing or eliminating harvest quotas after observing population declines) and (2) update their assumptions and understanding of the managed system, learning from mistakes and reinforcing successes to continually develop improved management recommendations (Nichols et al. 2007; Williams 2011; Runge 2011). Furthermore, the objectives and other key premises of the system (data sources, monitoring protocols, allowable management actions, etc.) are revisited periodically: a process commonly known as the “double loop” (Williams et al. 2011; ASMFC 2021). Adaptive management, when properly applied, is central to science-based management of natural systems. However, I argue that the revised ARM (and ASMFC’s response to my peer review reports) fails to embrace a core feature of the adaptive resource management (ARM) paradigm: the incorporation of multiple alternative hypotheses (Williams 2011). That failure results in a misrepresentation of the risk of horseshoe crab harvest to red knots and a missed opportunity to learn about the system.

In any ARM problem there is an inherent trade-off between maximizing the rate of learning and minimizing the risk of harming or destabilizing the system (Runge 2011). For example, we might be able to learn more about the resilience of the horseshoe crab population and the ecological dependency of red knots on horseshoe crabs by harvesting as many female horseshoe crabs as possible and then closely monitoring the population response of both species to this disturbance. In contrast, placing a moratorium on commercial harvest of female horseshoe crabs may reduce the learning rate but it also minimizes the risk of imperiling or impeding the recovery of a threatened species. It seems clear that the risk calculus must shift to some extent when a threatened or endangered species (TES) is part of the equation (Runge 2011), as is the case for the horseshoe crab harvest in Delaware Bay (involving a federally listed shorebird). A fully precautionary approach might lead to paralysis (possibly precluding beneficial conservation actions), while an opposing strategy that prioritizes action in the face of substantial risk to TES would risk irrevocable consequences. By formally embracing multiple alternative hypotheses, the ARM paradigm offers a compelling middle ground (Runge 2011).

In a multi-hypothesis ARM framework, each alternative model formalizes a plausible alternative hypothesis about how the focal system works (Williams 2011; Runge 2011). This enables ARM frameworks to accommodate structural uncertainty: one of the key sources of uncertainty that must be considered in natural resources management (Williams 2011). Together, the ensemble of models represents the current state of scientific knowledge (including a range of plausible hypotheses and assumptions) and captures the uncertainty and risks inherent to a managed natural system. Each alternative model is assigned a weight, or confidence value, that reflects its current standing relative to the other models included in the ARM framework. The weights assigned to each model at each successive decision point reflect each model's current degree of empirical support (the degree to which it effectively predicts current and historical system states and the observed response to prior management actions) and the degree to which the model captures the prior beliefs and risk tolerances of the stakeholder community (Williams 2011; Runge 2011).

By contrast, in the revised Delaware Bay ARM framework, a single hypothesis is effectively assigned a confidence value of 100%. Under this hypothesis, the relationship between horseshoe crab abundance and red knot demographic rates is so weak that it has little to no practical relevance to the dynamics of this system, as documented in this report (below) and in my 2022 peer review report. I will refer to this as the "weak relationship" hypothesis. My reanalysis, in which I detected a strong link between horseshoe crab egg densities and red knot survival (documented in my 2023 peer review report), along with numerous other published studies and government reports (e.g., Niles et al. 2009; USFWS 2014), provide evidence that the biotic interaction between horseshoe crabs and red knots may be substantially stronger and more ecologically meaningful than the ASMFC's model suggests. I will refer to this as the "strong relationship" hypothesis. The "strong relationship" hypothesis (unlike the "weak relationship" hypothesis) is capable of explaining the observed decline of the *rufa* red knot in the early years of the 21st century, for which the unregulated exploitation of horseshoe crabs in Delaware Bay is widely believed to be a primary cause (Niles et al. 2009; USFWS 2014). To accommodate structural uncertainty under the multi-hypothesis ARM paradigm (Williams 2011), it seems clear that a "strong relationship" model should be incorporated as a plausible hypothesis, and assigned some degree of credibility.

Furthermore, given the overwhelmingly negative public response to the prospect of harvesting female horseshoe crabs, it appears that the risk tolerance of the revised ARM may not be well aligned with that of the broader stakeholder community. By adding a plausible "strong relationship" model to the ARM framework, and by assigning an initial weight to this model that reflects diverse stakeholder perspectives, the ARM subcommittee could retain a robust, science-based management framework while also satisfying the many shorebird advocates within the stakeholder community that their perspectives are being formally considered and appropriately weighted. If the "weak relationship" model offered by ASMFC proves a more robust predictor of the future dynamics of this managed system relative to the "strong relationship" model and any other plausible alternative models, then this "weak relationship" model (the dominant hypothesis under the current ARM framework) will accrue a high credibility value over time and will come to dominate future recommendations for horseshoe crab harvest.

Regardless of the problematic issues with the original ARM framework that motivated the development of the revised ARM framework (documented in ASMFC 2021), the original ARM framework incorporated several alternative plausible hypotheses, including a weak, moderate, and strong biotic linkage between horseshoe crabs and red knots, respectively (McGowan et al. 2015). Furthermore, the original ARM framework used a formal stakeholder elicitation process to assign initial model weights to these models, ultimately leading ASMFC to assign substantial model weights to the moderate and strong interaction models, despite the fact that their empirical analyses suggested a much weaker relationship (McGowan et al. 2015). For reasons I do not fully understand, ASMFC abandoned a multi-hypothesis approach in developing their revised ARM framework. ASMFC supplied several reasons why they believe the revised ARM framework was an improvement over the original; for example, they point out some inadequacies and technology limitations with the previous framework, and highlight the fact that the revised ARM framework makes extensive use of empirical data from Delaware Bay (ASMFC 2021). However, none of these factors precludes the use of a multi-hypothesis ARM framework: for example, formally incorporating one ore more hypotheses that mechanistically link horseshoe crab surface egg densities (for which long-term data are available) with red knot demography.

In the conclusion of their response, ASMFC criticized my peer-review reports for failing to include concrete suggestions for improvement. While offering specific solutions was not a primary objective of my peer review reports, I will offer one suggestion: I encourage the ARM subcommittee to work with other independent researchers and the stakeholder community to develop an ARM framework that formally incorporates alternative plausible hypotheses about the strength of this two-species interaction. There is a well-developed literature that provides concrete recommendations for implementing the multi-hypothesis ARM paradigm. Although there are several data gaps and challenges to address, the explicit mechanism linking horseshoe crabs to red knots must be formally recognized: red knots depend on horseshoe crab eggs available near the ground surface, which requires perturbation of egg masses deposited by sufficient numbers of spawners prior to or concurrent with the arrival of red knot migrants. These mechanistic linkages will greatly benefit from the incorporation of available data on horseshoe crab surface egg densities as well as spawning counts and egg mass counts if available. Although some of the linkages in this system remain uncertain, the spirit of ARM encourages modelers and stakeholders to confront uncertainty by developing a comprehensive program for iterative learning through constructive and well-conceived actions. Following the above discussion, the multi-hypothesis ARM paradigm offers a compelling solution for making well-considered decisions in the face of uncertainty, while continually gaining new insights about how the system works. The ingredients are in place for a well-designed, multi-hypothesis ARM framework for this system and I hope ASMFC rises to this challenge.

Opening statement #2: *the relationship between horseshoe crabs and red knots in the revised ARM framework is exceptionally weak*

In my peer review reports I have paid particularly close attention to the strength of the relationship between red knot demography and horseshoe crabs, as this relationship is in many ways the crux of the matter: if the relationship is weak, then harvesting female horseshoe crabs is not a major issue for red knots, and if the relationship is strong, then red knot populations may suffer or their recovery may be stifled. My decision to focus on the strength of this relationship was not because of some preconceived bias or “clinging to belief” (as ASMFC claims in the conclusion of their response) but because this relationship is so important that it deserves special scrutiny. One of the most important issues I raised in my 2022 peer review report was that the relationship between red knot demographic rates (survival and recruitment) and horseshoe crab abundance (later published in Tucker et al. 2023) was so weak that changes in the horseshoe crab population would (under this model) have a negligible effect on the viability of the red knot population. Consequently, the revised ARM framework appeared unsuitable as a tool for making projections and contributing to policy decisions concerning management of this two-species system.

In their response, ASMFC criticized the back-of-the-envelope calculations in my 2022 report, noting that my calculations (performed before I gained access to the data and code for the red knot IPM) failed to recognize that ASMFC had log-transformed the horseshoe crab abundance values prior to incorporating these values in their integrated population model (IPM) (for my original report I used the raw values instead of the log-transformed values). This argument by ASMFC has more to do with mathematical technicalities than with ecology, and their objection is ultimately immaterial. When I run the same calculation with the log-transformed relationship, the conclusion remains the same: under the revised ARM framework, it would take a massive collapse of the horseshoe crab population (well under 0.5 million female horseshoe crabs across Delaware Bay) to cause a decline of the red knot population using mean parameter values from the red knot IPM (see below). Therefore, I do not concede that I was “wrong” (or “prejudicial”) on this issue in any of my analyses, as ASMFC claimed in their response under the “Criticism 8” header (below).

Prompted by the ASMFC review, I revised my original calculations to reflect the log-transformation used in the red knot demographic model – specifically, modeling red knot demographic rates as a function of log-transformed horseshoe crab abundance (Tucker et al. 2023). I generated figures illustrating these demographic effects to validate that they matched the relationships displayed in ASMFC 2021 and Tucker et al. (2023). After verifying a match (Fig. 1, left panels), I used this model to extrapolate the expected red knot survival and recruitment rates at very low horseshoe crab abundances (approaching zero) (Fig. 1, right panels). I then computed the expected population growth rate (lambda) for horseshoe crab abundances ranging from near-complete collapse (e.g., 1000 female horseshoe crabs) to recovery (around 20 million females), where values of lambda greater than or equal to one indicate a sustainable or growing red knot population.

These tests demonstrate that, under the revised ARM framework, red knot populations are expected to exhibit strong and sustained growth (lambda > 1) across all but the most extreme scenarios of horseshoe crab collapse (Fig. 2): red knot population growth would only be expected to exhibit mean net declines (lambda < 1) if the number of female horseshoe crabs in the Delaware Bay region fell below around 300,000 (the lowest recorded estimate from the last two decades places the number of females at around 4 million). Accordingly, the substance of my critique remains valid: the relationship between red knots and horseshoe crabs that was formalized within the revised ARM framework is exceptionally weak. Furthermore, this exercise demonstrates that the ARM model would not have predicted the decline of red knots due to horseshoe crab overharvest in the 1990s (which remains the dominant hypothesis for this observed population decline), which calls into question its usefulness in making projections and contributing to policy decisions that could help both species recover.

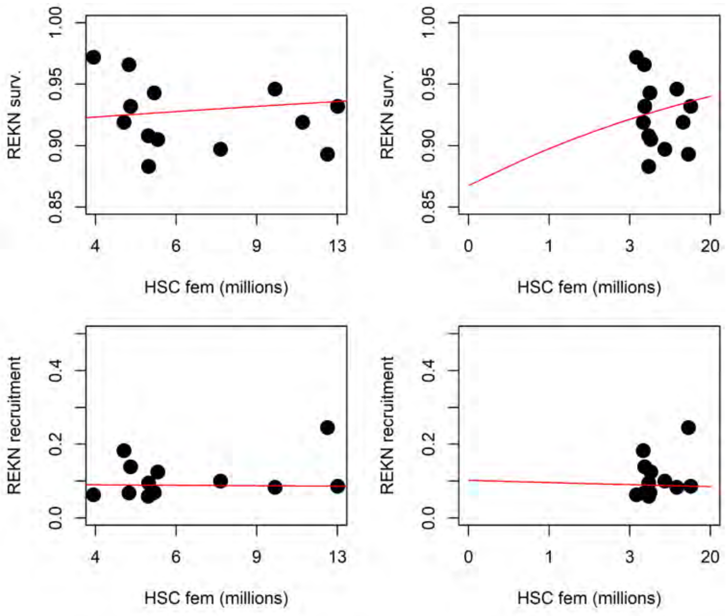

***Figure 1**. Visualizations of Red Knot (REKN) survival (y axis, top panels) and recruitment (y axis, lower panels) as a function of horseshoe crab abundance (x axis, all panels), derived from ASMFC's ARM model, later published as Tucker et al. (2023). Left-hand panels replicate Figure 4 from Tucker et al. (2023), whereas right-hand panels extend the x-axis to visualize these relationships at levels of horseshoe crab abundance ranging from well under 1 million (near-complete collapse of the stock) up to 20 million (an approximation of full recovery).*

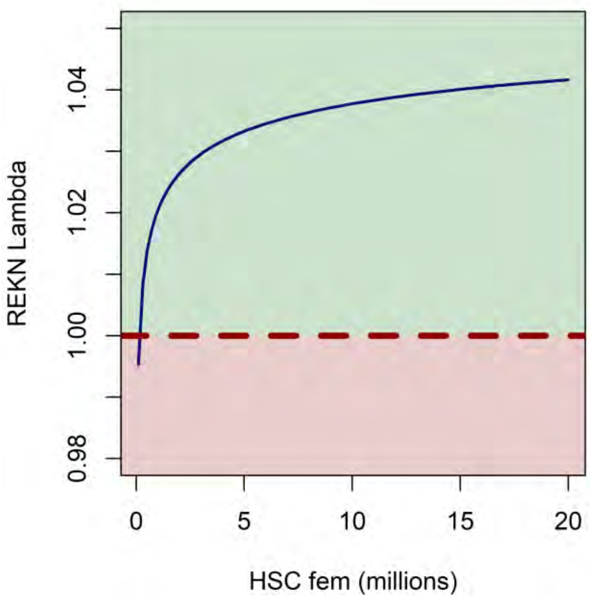

***Figure 2**. "Back of the envelope" illustration of the relationship between Red Knot (REKN) population growth, Lambda (y axis) and female horseshoe crab abundance (x axis, in millions), derived from ASMFC's ARM model, and published in Tucker et al. (2023). The*

> *range of the x-axis is intended to visualize the expected growth of the REKN population for horseshoe crab abundances ranging from well under 1 million (near-complete collapse of the stock) up to 20 million (an approximation of full recovery). Lamba ≥ 1 (green shaded region) represents a growing population whereas Lambda < 1 (red shaded region) represents a declining population. Under the revised ASMFC model, declines of the REKN population would only be expected under a near-complete collapse of the horseshoe crab population (total population less than 300,000 individuals across Delaware Bay).*

Point-by-point response

NOTE: for the remainder of this document, all original text from the ASMFC response is in gray font, while my responses are indented and in dark green font. For clarity, I have removed some text from the original ASMFC response (for instance, historical summaries or overview statements) that I did not feel required a response. Also, I removed all figures from the ASMFC response- to view these figures, please refer to the original ASMFC response.

EXECUTIVE SUMMARY

While the ARM Revision represents significant advances in modeling and data use, the conversation around the revised ARM Framework quickly focused on the allowance of female horseshoe crab harvest when horseshoe crab population estimates are sufficiently high as to not limit red knot populations. The original ARM Framework had a technical flaw where it recommended 0 female horseshoe crab harvest when the adult female population was estimated to be less than 11.2 million, as it did from 2013-2022, or maximum female harvest (210,000 female horseshoe crabs) when the population was estimated to be greater than 11.2 million females, as it did in 2023. Rarely were the intermediate harvest levels selected by the model, as was shown through a simulation study. To correct this, the ARM Revision allowed a *gradual* increase of female harvest from 0-210,000 females as population estimates of female horseshoe crabs increased. The nuance of this change was lost in the discourse as stakeholders greatly opposed female harvest at any level, despite the original ARM Framework also recommending female harvest in recent years.

> Based on my revised tests, which are discussed in opening statement #2, “sufficiently high as to not limit red knot populations” in the context of the revised ARM framework means all levels of female horseshoe crab abundance except for extreme collapse of the horseshoe crab fishery (<=300,000 females; Fig. 2). I acknowledge that the revised ARM framework incorporated some improvements over the original ARM, but I was not tasked with reviewing the original ARM framework: since the revised ARM was formally approved in 2022, the revised ARM is now the legitimate subject of scrutiny.

Briefly, the ARM Subcommittee maintains that the red knot and horseshoe crab population models used in the ARM Framework currently represent the best use of the available data. Red knot survival rates and horseshoe crab population trends from the ARM Revision are consistent with other published values or data sources in the Delaware Bay region. This includes horseshoe crab egg density data, which were not provided to the ARM Subcommittee, but were subsequently published in the literature and show a similar trend to the horseshoe crab relative abundance indices.

> While the red knot demographic rates used in the revised ARM are consistent with some prior estimates, there are also many examples of lower survival rates in the published literature. While the previous literature is not conclusive on this point, in my re-analysis the Delaware Bay banding and resighting data support a survival rate of approximately 80%, much lower than the estimate of 93% that was used in the revised ARM framework. These two estimates have vastly different implications for the population ecology of this species, including the expected resilience of this population to horseshoe crab harvest and other threats (for example, a population with lower survival rates would likely be less resilient to a series of years with low resource availability) and the levels of recruitment that would be required to ensure population viability.
>
> I remain convinced that ASMFC's estimates of red knot survival are biased high due to the presence of misread errors in the resighting database. Perhaps the most convincing evidence for this is that survival estimates become substantially lower when "singlet" observations (resighting observations by a single observer at a single occasion, which are likely contaminated with flag misread errors) are dropped from the analysis. This method of subsetting the data has been suggested as a simple and effective technique for correcting potential biases in estimates of survival and survival trends due to misread errors (Tucker et al. 2019). If misread errors were not an issue, mean survival estimates should be similar whether or not these "singlet" observations are removed from the data set.

The ARM Subcommittee reiterates that an important benefit of the adaptive management process is the ability to make decisions even with imperfect knowledge of an ecological system. The overall goal of the ARM was to produce a decision-making framework informed by science and stakeholder values, given the available knowledge about the Delaware Bay ecosystem and horseshoe and red knot populations. At the time of the original ARM Framework, this knowledge was limited. However, the re-evaluation of the data, values, and knowledge on a regular basis is essential to the adaptive management process and is built into the ARM Framework. The 2022 ARM Revision represented a learning event where population models were re-designed to accommodate the advancement of data and knowledge since 2009. The peer reviews from Earthjustice fail to provide any real recommendations for improvement to the ARM Framework or provide other means for helping managers make an informed harvest decision beyond a mandate for zero female harvest at any population level. If the values of all stakeholders have changed (i.e., no female harvest under any circumstances), that change could be considered in a new approach in the future by the ARM Subcommittee. As it stands, the current ARM Framework represents the objectives previously established through stakeholder engagement: to 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.

First, I agree with the ARM subcommittee on the value of adaptive management for enabling informed decision making in the face of uncertainty and learning about the system via ongoing management and monitoring. However, navigating potential risks to a threatened or endangered species (TES) adds some complexity to the problem (as I discuss in opening statement #1 of this response). As I documented in my peer review reports, there are multiple lines of evidence suggesting that the revised ARM does not effectively account for the very real ecological risks of re-opening a commercial harvest on female horseshoe crabs. In failing to acknowledge the risks to red knots and the potential to jeopardize the recovery of this and other migratory shorebirds, the revised ARM appears to be mis-aligned with its own core objectives (from ASMFC 2021: "*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*".

As for the critique that my peer review failed to "provide any real recommendations for improvement to the ARM Framework or provide other means for helping managers make an informed harvest decision", my task as a peer reviewer was to evaluate the revised ARM on its merits rather than to develop an improved alternative. Nevertheless, in opening statement #1 above, I outline how a multi-hypothesis adaptive management framework could effectively incorporate alternative quantitative descriptions of the relationship between red knots and horseshoe crabs in Delaware Bay and reflect stakeholder perspectives, thereby representing a more legitimate approach to adaptive resource management than is reflected in the current version of the ARM framework.

Finally, I have read this review carefully and I thank ASMFC for their feedback. I continue to stand by the main conclusions from my 2022 and 2023 peer reviews -- with one notable exception: upon further consideration, ASMFC raised legitimate points regarding my use of linear regression to analyze the long-term trawl capture records for female horseshoe crabs. Nevertheless, the thrust of my critique of the revised ARM model remains valid. My re-analysis was offered as an independent evaluation of the data and was intended to contribute to a scientific dialog. In this spirit, I hope my peer-review reports and re-analyses contribute to ASMFC's ongoing efforts to understand and manage this system.

Criticism 1: Estimates of red knot survival used in the ARM appear to be artificially inflated, resulting in falsely optimistic estimates of population resilience.

- High survival and long lifespans are common for red knots and other shorebirds of similar size and life histories.
- Survival rates used in the ARM are calculated from the tagging data for red knots in the Delaware Bay region and are comparable with other published survival values.
- The tagging data were critically analyzed by the ARM Subcommittee to represent the

best available data and caveats to the survival estimates were provided in the ARM Revision. The analysis of the tagging data and its use in the modeling was commended by the peer review panel.

Technical Response: Dr. Shoemaker asserts that red knot annual survival probability is more likely closer to 0.8 than the 0.9 used in the revised ARM Framework, corresponding to an expected lifespan of about 5 years. There is not strong evidence for this lower annual survival probability for *rufa* red knot. In fact, previous studies of *rufa* red knot in Delaware Bay (McGowan et al. 2011) and Florida (Schwarzer et al. 2012) also estimated annual survival probability at approximately 0.9. In a separate published analysis, only using data collected by the state of Delaware, Tucker et al. (2022) estimated red knot annual survival probability at 0.89, and at 0.91 for ruddy turnstones, a species with similar body size and a similar annual life cycle.

> The evidence I provided in my 2023 peer review report strongly suggests that the ASMFC's estimates of red knot survival are biased high, and average survival is closer to 80% in this system (versus 93% per the revised ARM framework). The primary evidence for this is that red knot survival estimates become much lower after "singlet" observations of flag codes (unconfirmed sightings that are likely to be contaminated with misread errors) are removed from the analysis, suggesting that flag misread errors are likely biasing the ASMFC's survival estimates high. A strong secondary line of evidence is that when the banding data are used as the sole source of information (these observations involve direct capture and are therefore much less likely to include misread errors), the mean survival estimate is again around 80%.
>
> Finally, I think it is important to note that the adult red knot survival estimate used by ASMFC averages 93%, not 90% as stated in the comment above. While this may seem like a trivial point, the difference between 93% survival (corresponding to median expected lifespan of around 9.5 years and mean lifespan of nearly 15 years) and 90% survival (corresponding to median lifespan of around 6.5 years and mean lifespan of nearly 10 years) can make the difference between growth and decline for many real-world populations.

Additionally, observations of birds more than 5 years old are common in the mark- recapture data set (approximately 20% of birds), with a maximum of 17 years between physical recaptures. These observations are a conservative minimum estimate of lifespan.

> This comment appears to confuse the concept of maximum lifespan with average lifespan. Even if median or expected lifespan is low, some fraction of individuals would be expected to reach more advanced ages; an expected lifespan of 5 years old does not preclude some fraction of individuals from reaching age 20 or beyond. At a constant survival rate of 80% (median lifespan of 3.1 years, mean lifespan approaching 5 years), we would expect more than 30% of individuals to live to age 5 and beyond (close to the "20% of birds" referred to in the above comment) and about 25% of individuals to live to age 6 and beyond (ignoring for simplicity that survival is likely to be lower in the first year of life). At a constant 80% survival rate, a little over 2% of birds would be expected to live past 17 years of age and

around 1% would live as long as 20 years. With thousands of unique individuals in the database, we would expect to observe many cases of high longevity in the database even if the mean annual survival rate was approximately 80%.

In contrast, the expected distribution of ages under a constant annual survival rate of 93% appears inconsistent with the Delaware Bay capture-recapture database: under this scenario, nearly 70% of individuals would be expected to survive to 5 years of age and beyond (far greater than the 20% cited in the above response by ASMFC), around 30% would reach 17 years of age and beyond, and around 3% would live to 50 years of age and beyond. Therefore, the information ASMFC cited above (i.e., that approximately 20% of birds in the database are more than 5 years old, with a maximum of 17 years verified age) is much more consistent with an average survival rate of 80% per year (as my reanalysis suggests) than with an average survival rate of 93% (as in the revised ARM).

Further, it is worth noting that almost all vertebrate species with delayed maturation life cycles, like red knots, that do not recruit to the breeding population until their third year, exhibit high adult survival rates. This is especially true when annual reproductive output is low, as it is with red knots, which lay only four eggs in a single nest per year.

This comment is hard to interpret, given that “high” and “low” are not defined. The red knot recruitment estimates used in the revised ARM are indeed very low (around 0.1 adult females recruited per female per year) and would require a very high survival (greater than approximately 90%) to result in a stable or growing population. However, red knot recruitment rates (in the revised ARM framework, a compound of reproductive output and survival to the first breeding migration) are poorly understood, and further research is needed to better understand this critical demographic process.

Outside of the Delaware Bay system, high survival and long lifespans are also reported for red knots and other shorebirds of similar size and annual cycle. For example, Piersma et al. (2016) report that annual apparent survival for red knots in Western Australia were well above 90% in most years of their study. In another example, Boyd and Piersma (2001) reported that they recaptured 155 birds in their sample >14 years after initial capture and 2 over 24 years after initial capture. There are published studies that report survival rates at 80% or lower, but to assert that the estimated survival rates used in the ARM based on the mark-recapture data are outliers or excessively high is erroneous.

While the previous literature is not definitive on this topic, I was primarily basing my conclusions on a reanalysis of the raw banding and resighting data from Delaware Bay rather than on prior studies. Regardless, the question of mean survival rates (and the role of staging areas in regulating survival and trends in survival) for red knots and other similar shorebirds is important for conservation and management and I hope this discussion continues in the form of peer-reviewed publications and other constructive scientific dialog.

In his report, Dr. Shoemaker claims that the survival estimates in the ARM are biased by individual misidentification, or flag misreads. Before analyzing the data, the ARM Subcommittee conducted a thorough QA/QC, including filtering records to only lime and dark green flags that were first deployed by New Jersey or Delaware, removing records of 5 duplicate flags (n = 36), flags apparently resighted before they were deployed (n = 711), and flags that were never deployed (n = 1). Removal of these records represents only 0.35% of the total resightings.

Members of the ARM Subcommittee have worked extensively on the issue of flag misreads, including conducting a thorough simulation study investigating the situations in which misreads might bias survival estimates and the implications of that bias (Tucker et al. 2019). The key points from that work are: 1) misreads disproportionately affect survival estimates from the first years of the study, causing apparent negative trends in survival over time, and 2) there is an important tradeoff to consider between potential bias due to misreads and loss of precision if data filtering is applied. In that paper, the authors suggest a data filtering step of removing all observations of flags that were only seen once in a year as a way to potentially mitigate misidentification errors. However, there are nuances to consider when determining whether this is necessary, because this data filtering will inevitably remove some number of valid observations, and the authors identify thresholds that depend on study length and error rate. For a 10-year study, removing single observations becomes beneficial if the error rate is >5%; below that rate the bias is minimal relative to the detrimental effects of removing valid observations. In the Delaware Bay mark-recapture dataset, the misread error rate is between 0.38% (712 impossible observations/187,587 total) and 4.5% (8,448 single observations).

Additionally, the characteristic apparent negative trend in survival over time that would indicate bias due to misreads is not observed. To examine this further, the distribution of the number of resightings in a year for every flag (Figure 1) was plotted, with and without removing single observations. The shape of the resulting histogram indicates that removing these records results in fewer flags being seen once in a year than would be expected, i.e., that the data filtering removes a large number of valid records (> 3,000).

> First, I acknowledge the important work done by members of the ARM subcommittee related to the issue of flag misread errors in shorebird resighting surveys. Notably, I relied heavily on Tucker et al. (2019) in my reanalysis of the resighting data, and used the method they suggested (removing 'singlet' observations from the analysis) to correct the potential bias in survival rates due to misread errors. Given the prior work on this issue by members of the ARM subcommittee, I was surprised that they did not attempt to correct for this possible source of bias when estimating red knot vital rates for the revised ARM. While they claim that the characteristic negative trend in survival across time (an artifact of this type of flag misread errors) is not observed, I am not convinced on this point. Upon visual inspection, there does appear to be a negative trend in survival across time in Fig. 3a from Tucker et al. (2023; also Fig. 44 from the revised ARM; ASMFC 2021), and this pattern also appeared in my analyses of the same data using data that included the "singlet" observations (which were potentially contaminated by misreads).
>
> While I understand that ASMFC performed quality checks and removed obvious misread errors (e.g., flag codes observed before they were deployed) there is simply no way to detect an errant flag code if that code had been previously deployed in Delaware Bay

> (although one recent paper suggested a model-based approach for estimating the misread process; Rakhimberdiev et al. 2023). The longer the period of flag deployment and the more birds that are tagged, the more likely an errantly recorded flag code may match with a previously deployed code. Importantly, if the errant match is to a bird that died many years prior, the capture-recapture analysis will adjust the estimated survival rate upward to reflect the "survival" of the long-dead bird (therefore, the longer the time series, the stronger the potential bias due to this class of flag misread errors). Finally, I note here (as I did in my 2023 peer review report) that all or nearly all of the available flag codes have been deployed at Delaware Bay (at least for the lime green flags). If so, any misread errors are likely to match with previously deployed flag codes and thereby inflate survival estimates.
>
> To be safe, it makes sense to remove "singlet" observations, retaining only those flag codes that were confirmed via multiple observations to be present in Delaware Bay each year. This ensures that survival estimates are not biased from the potential misreads. Clearly, many of those "singlet" observations are true observations, and discarding these records necessarily involves omitting a substantial amount of valid data from downstream analyses. As an ecologist I understand the drive to use all available data. But in this case, even a small number of misread errors can induce an unacceptable bias in survival estimates. Furthermore, the dataset is so information-rich that we can afford to filter out a relatively small fraction of the data ("singlets" comprised approximately 9% of total resighting observations and around 35% of unique individual-year occurrences) to address an important source of potential bias in survival estimates.
>
> Finally, I reiterate that the primary evidence that ASMFC's estimates of red knot survival are biased high is that there was a marked decline in the mean survival estimate after the singlet observations were removed (per Tucker et al. 2019). I do not know of a reasonable alternative interpretation of this result except as strong evidence for the influence of misread errors in the resightings database. Moreover, analyzing the capture/banding data (where misread errors are likely negligible) as the sole source of information also yielded a mean survival rate of around 80% after accounting for potential transients. Overall, I remain convinced that the red knot survival estimates used by ASMFC were biased high due to the presence of misread errors. I recommend that the ARM subcommittee correct for this source of bias, either by eliminating "singlet" observations or by explicitly modeling the flag misread process (e.g., Rakhimberdiev et al. 2023).

The integrated population model uses the mark-recapture data to estimate survival as well as parameters related to stopover site use within each year. There were concerns that removing single observations would bias estimation of within-year parameters, and because the error was below the thresholds identified by Tucker et al. (2019) and the characteristic negative trend in survival was not observed, single observations were kept in the data set for the analysis.

> In this statement, the ARM subcommittee indicates that their decision not to account for potential misread errors was due largely to the perception that the "singlet" observations were necessary for fitting additional parameters in their open robust design (ORD) model

(the component of the red knot integrated population model that is primarily responsible for survival estimation). The ORD model uses the mark-resight data to fit multiple parameters related to within-year stopover use and availability for capture (e.g., timing of entry and exit to the staging area), in addition to among-year processes -- most notably, survival. The ORD model is impressively complex, and appears to perform well at parameter estimation when the data do not violate key assumptions (see Tucker et al. 2023 and my 2023 peer review report). However, like all statistical models, biases can arise due to violation of model assumptions. One of the key assumptions of the ORD model (like most capture-recapture analyses) is that the unique identification marks assigned to each individual (in this case, flag IDs) are neither lost nor mis-identified. Violation of this assumption can result in biased parameter estimates (especially survival).

It appears the red knot modelers were concerned that removing "singlet" observations could bias the estimates for some of the within-year parameters estimated in the ORD model, such as the dates of entry and exit each year. I can understand why the authors of the revised ARM wanted to fit a complex model that incorporated within-year processes. But there are always trade-offs when building ecological models. In this case, there is an apparent tradeoff between potential biases in survival estimates and potential biases in estimating within-year parameters like entry/exit dates. The modelers could have chosen to use a simpler capture-recapture model that did not explicitly incorporate detailed within-year processes (such as the Cormack Jolly Seber models I used in my 2023 peer review report) -- in this case, there would have been little downside to removing the "singlet" observations. However, the ARM subcommittee ultimately chose to use the more complex ORD framework.

Although I am sympathetic to the modelers in this case, I ultimately disagree that the benefits of adopting the more complex model should outweigh the potential biases in survival estimation due to misread errors. From a conservation and management perspective, survival represents one of the key processes of population ecology (survival and reproduction rates are typically referred to as "vital" rates in wildlife demography). Biased survival estimates can easily tip the balance between a growing and declining population. Biases in the estimated date of entry into the staging area (for example) would tend to be much less consequential for the revised ARM than biases in adult survival rates. Nonetheless, simulation trials would be necessary to quantify the degree to which removing "singlet" observations could bias the within-year parameter estimates and whether biases in within-year parameters could have an effect on survival estimates in the ORD model.

The ARM Revision (ASMFC 2022) contains a thorough discussion of this topic on pages 63-64, in which several hypotheses for the disagreement in annual survival probability estimates from the older studies was described. Dr. Shoemaker points to lower estimates of survival from studies from the early 2000s, when red knot annual survival probability was estimated to be close to 0.8. It is likely that older estimates were negatively biased to some extent due to short study periods, low detection probably, and unmodeled temporary emigration from the system. It is also possible that during that time, when horseshoe crab populations were lower, red knot survival probability was truly lower. Alternatively, because permanent emigration from the system cannot be distinguished from mortality in older mark-recapture studies, a higher rate of permanent emigration (i.e., birds abandoning Delaware Bay for other spring stopover sites) would appear as lower survival probability. It is possible that there is a threshold of horseshoe crab abundance below which red knot survival probability might be expected to drop dramatically. If such a threshold exists, it was not observed over the time series included in the model (2005-2018). It has also been proposed that southern-wintering birds (with longer migrations) have lower annual survival probabilities than northern-wintering birds. Declines in the number of red knots overwintering in Argentina (Niles et al. 2009) suggest a decline in the southern-wintering subpopulation and therefore it is possible that in more recent years a greater proportion of the Delaware Bay stopover population are northern-wintering birds. As discussed in the report, this is a key area for future research.

> I appreciate this discussion and I understand there are many nuances that must be considered when comparing survival estimates across multiple populations or time periods. However, none of this information contradicts my reanalyses.
>
> In the above statement ("It is possible that there is a threshold of horseshoe crab abundance below which red knot survival probability might be expected to drop dramatically"), ASMFC acknowledges that the relationship between horseshoe crabs and red knots may in fact be stronger than the weak relationship they detected using the 2005-2018 time series. If a stronger relationship is plausible and consistent with the observed red knot decline (which has been attributed to unregulated commercial harvest of horseshoe crabs), it seems prudent to include this hypothesis within an ARM framework for this system. ASMFC maintains that the revised ARM represents a major advance because it uses data from the Delaware Bay system. However, in this case I think the ARM subcommittee may have prioritized mathematical elegance (ability to fit a single integrated model using only data collected from the target population) over comprehensiveness (e.g., including knowledge about the system prior to the deployment of leg flags). The more comprehensive approach (incorporating data from additional populations and time periods, including multiple alternative models) may be messier, but will better reflect relevant knowledge and more effectively guide critical decisions about this system. Furthermore, by fitting and comparing multiple models and data sources we can learn more rapidly about this two-species system and better understand where potential biases lie.

Criticism 2: Trawl-based indices of horseshoe crab abundance are inadequate for modeling the biotic interaction between red knots and horseshoe crabs.

- The inclusion of trawl surveys as indices of horseshoe crab abundance may be imperfect but it is the best available science and its use has been approved by several independent peer reviews.
- Most of the criticisms and caveats relevant to trawl surveys would also apply to egg

density and red knot abundance estimates.

- There is consensus among the trawl surveys for an increasing trend in horseshoe crab abundance since 2010.
- Trawl surveys are the standard for bottom dwelling organisms and for evaluating the abundance of many species.

Technical Response: Dr. Shoemaker argues that the trawl surveys used to monitor horseshoe crab abundance and serve as the basis of the catch multiple survey analysis (CMSA) are "…imperfect snapshots of the abundance of horseshoe crabs occupying Delaware Bay, obscured by differing survey methodologies and poorly understood aspects of horseshoe crab ecology, including seasonal and daily activities, habitat preferences, and degree of clustering on the seafloor." The ARM Subcommittee agrees that the trawl surveys are imperfect; catchability differs in each survey and possibly differs both within and between years. Such is the nature of fishery-independent surveys, and these same arguments also apply to indices of abundance for red knots and horseshoe crab egg density estimates. However, the use of the trawl surveys to index horseshoe crab abundance has gone through multiple peer reviews (e.g., ASMFC 2009b, ASMFC 2019, ASMFC 2022, Anstead et al. 2023) and found to be a scientifically sound measure of horseshoe crab abundance.

> I agree that there is substantial uncertainty in all of the data sets related to horseshoe crab abundance in Delaware Bay, including the trawl surveys, spawning surveys and surface egg density estimates. Since ASMFC primarily used trawl-based indices of abundance (in addition to harvest, bycatch estimates, etc.), I focused my peer review reports on the uncertainty inherent to the trawl-based surveys. The presence of substantial uncertainty in this system underscores the critical importance of treating uncertainty appropriately--from acknowledging measurement uncertainty (uncertainty in the raw measurements), parameter uncertainty (uncertainty about the true value of a particular parameter) to formally incorporating structural uncertainty (multiple alternative hypotheses for how the system works). Furthermore, given that a Federally Threatened species is involved, I argue that plausible "worst-case" scenarios or hypotheses should be assigned substantial weight until they can be effectively ruled out. In this case, given the extreme uncertainty about horseshoe crab demography, behavior and abundance, I think it is prudent to acknowledge a non-negligible possibility that this population is not currently experiencing a strong recovery. While the ARM subcommittee claims that the revised ARM accounts for uncertainty, their accounting is incomplete. Most importantly, the revised ARM fails to acknowledge structural uncertainty; in effect, they are assigning a 100% credibility score to their chosen model structures (e.g., the CMSA model) and data sources (e.g., assigning substantial weight to the trawl-based surveys while ignoring the horseshoe crab egg density data). The horseshoe crab population may indeed be recovering (and as discussed below, there is some evidence for a recent population increase) but multi-model inference (using model weights to express the uncertainty among alternative models) is needed if we want to more realistically express our overall belief in this hypothesis.

Dr. Shoemaker faults the trawl-based indices of abundance used by the ARM Subcommittee for not considering environmental covariates that could influence the catch of horseshoe crabs, and he obtained the raw data to recalculate the indices using generalized linear models (GLM) and generalized additive models (GAM). The ARM Subcommittee does not disagree with this approach to standardizing abundance indices based on environmental covariates, and this sort of analysis was conducted as part of the 2019 stock assessment (ASMFC 2019) but it did not improve the indices of abundance (e.g., decrease errors, reduce large annual fluctuations). The peer review panel for the ARM Revision (2022 ASMFC) recommended using a model-based index for the Delaware Trawl Survey because it is a fixed station survey; consequently, the ARM Subcommittee applied this approach prior to using this survey in the CMSA. The Virginia Tech Trawl Survey has a well-designed sampling scheme that stratifies sampling based on habitat; thus, habitat features that could influence catchability are already incorporated into the abundance estimates from this survey. Finally, and as stated earlier, a GLM did not improve the precision of the New Jersey Ocean Trawl Survey (ASMFC 2019) and the ARM Subcommittee continued using a simpler calculation of the abundance estimate (the delta-mean catch-per-unit-effort).

> I agree that both model-based and design-based approaches can be useful in this context. In this case, ASMFC chose to use a fully design-based approach for generating abundance indices from the three trawl surveys. While the approach used by the ARM subcommittee was a fairly standard approach for analyzing trawl survey data, I was surprised that they did not use model-based standardization to further control for environmental and seasonal factors known to influence horseshoe crab capture rates. The rationale for performing model-based standardization is particularly strong considering that (1) horseshoe crab captures are known to be strongly influenced by factors like temperature, depth and season, and (2) these key environmental drivers are measured as part of all three trawl surveys used in the revised ARM. The decision to ignore the available covariate data places a degree of trust in the design-based controls that does not seem warranted in this case. Importantly, ignoring the covariate data implicitly assumes that these data have zero effect on the trawl survey results -- a strong assumption that is likely to be false in this case. I maintain that ASMFC should use all available covariates to help standardize observations across surveys and across years, although I would welcome continued dialogue about the nuances of this analysis.

Like trawl surveys for any aquatic species, there is considerable variation in the catches of horseshoe crabs among individual trawl samples resulting in high inter-annual variation in abundance indices. Dr. Shoemaker concludes there is a lack of statistically significant correlation coefficients among the trawl surveys, and there is a fatal flaw in using those data to infer abundance. The ARM Subcommittee disagrees with this analysis and can demonstrate that there is in fact a significant correlation between trawl surveys and with the CMSA estimates of abundance (see response to Criticism 3). There is observation error associated with each survey (e.g., being in the right place at the right time) and it is not uncommon for a relatively high catch in one survey to correspond with a relatively low catch in another for the same survey year, so it is not surprising that there could be some “non-significant” correlations or correlation coefficients that one may consider low. However, each trawl survey could very well show a statistically significant trend. It is the consensus among surveys about the trend that is important, not how closely individual observations from the respective surveys track one another. The ARM Subcommittee acknowledges that each survey does not perfectly track the population, which is why the CMSA uses multiple surveys. In addition, it is very possible, from a statistical sense, that two time series of abundance data could not show a statistically significant correlation, but could still both show a statistically significant trend (Figure 2).

> Here I agree that more data is better than less data, and more independent datasets are better than fewer. Correlation tests and scatterplots remain a valuable exploratory analysis for detecting the degree to which different datasets share information. However, as ASMFC points out above, uncorrelated datasets can yield emergent patterns when their information is combined. In fact, after reviewing the ASMFC response to my peer review reports, and after running some confirmatory analysis, I see evidence for a recent increase in the Delaware Bay horseshoe crab population. Taken together, I agree that the three trawl-based surveys provide some evidence for a recent increase in the horseshoe crab population since around 2010.
>
> However, the evidence for a recent increase in the Delaware Bay horseshoe crab population based on the trawl-based surveys is predicated on several important assumptions, including: (1) all three trawl-based surveys are equally valid (and therefore should be assigned equal weight in the analysis), (2) each survey is equally informative with respect to the key state variable of interest (e.g., the abundance of female horseshoe crabs), and (3) that each survey is an independent sample from the population of interest. Potential violations of each of these assumptions should be carefully considered; it would be prudent to perform additional sensitivity tests to evaluate the effects of plausible violations -- and possibly to formally incorporate alternative models in which one or more of these assumptions is relaxed.

Dr. Shoemaker also conducted his own capture-recapture analysis to determine the relationship between trawl-based indices of horseshoe crab abundance, horseshoe crab egg density, and red knot survival. Contrary to the results of the ARM Subcommittee, Dr. Shoemaker did not find any positive relationships between horseshoe crab abundance and red knot survival. Although additional analysis of these data is welcome, the ARM Subcommittee questions the value of such a comparison due to the many differences in how the data were analyzed. Dr. Shoemaker's analysis only used information about whether a bird was seen at least once in a year in a standalone Cormack-Jolly-Seber model, whereas the ARM Revision uses both within-year and among-year observations in an open robust design model that is embedded within an integrated population model. These differences in modeling approaches make it difficult to draw meaningful conclusions regarding differences in results. The analysis done by the ARM Subcommittee did find a positive relationship between horseshoe crab abundance and red knot survival, providing the demographic link between population models used in the ARM Framework.

> Here I do not find ASMFC's response convincing. In my reanalysis of the banding and

resighting data, I used a Cormack-Jolly-Seber (CJS) framework to estimate annual survival rates. The CJS method has for many decades been the gold standard for estimating survival on the basis of capture-recapture data. In fact, the open robust design (ORD) model used in ASMFC's integrated population model for red knots uses a modified CJS framework to estimate survival and other inter-annual population processes (Tucker et al. 2023). Regardless, estimates of apparent survival from different analytical methods are comparable, as they represent the same fundamental ecological process. Of course, this statement requires that both approaches are statistically valid-- but ASMFC does not appear to be questioning the validity of my methods.

Given that it is meaningful to compare my results with ASMFC's capture-recapture results, the fact that the CJS approach failed to detect a statistical signal linking red knot survival to trawl-based horseshoe crab population estimates is notable. This was true whether I used the CMSA estimates of horseshoe crab abundance (following ASMFC's approach) or any of the trawl-based surveys (NJ, DE, VT) separately (whether or not these indices were adjusted to control for seasonality and environmental conditions). Although I do not have a ready explanation for why my results differed from ASMFC's integrated population model, I think it would be prudent and instructive to run additional tests to try to understand the underlying reasons for these differing results - especially given the fundamental importance of this relationship to this two-species ARM framework.

Finally, I reiterate that, although ASMFC detected a positive relationship between red knot demographic rates (specifically, adult survival) and horseshoe crab abundance, this relationship was not ecologically meaningful (see my response under section titled "Criticism 8", below). Therefore, in one sense the results of our two independent analyses yield the same conclusion: that red knot demographic rates are not directly or meaningfully correlated with trawl-based indices of horseshoe crab abundance during the time period for which data are available. In contrast, using the same CJS modeling framework, I found that red knot survival was meaningfully and positively related to an alternative horseshoe crab population index -- surface egg densities.

Criticism 3: Red knot survival is strongly sensitive to horseshoe crab egg density, indicating that persistent degradation of the horseshoe crab egg resource could have dire consequences for the red knot population.

- During the development of the ARM Revision, horseshoe crab egg density data were requested, but were not provided to the modeling team. Therefore, these data could not be considered as an input to the models.
- Trends in horseshoe crab egg density (extracted from Smith et al. 2022 following the publication of the ARM Revision) are correlated with other data inputs for the years included in the ARM models and thus the inclusion of egg density data in the models is unlikely to result in any meaningful difference from the current ARM Framework in terms of harvest recommendations.

- Smith et al. (2022) showed a general increasing trend in horseshoe crab egg density in recent years similar to that of horseshoe crab abundance, consistent with findings from the ARM Revision.

Technical Response: The debate over the inclusion or exclusion of egg density data has been ongoing since the ARM Framework was initiated in 2007. The ARM Subcommittee does not deny that eggs are the true link between horseshoe crabs and red knots. However, the reasons for excluding egg density data from the ARM model, which range from sampling design to data availability, have been extensively discussed since the inception of the original ARM Framework, in both published versions of the ARM Framework (ASMFC 2009a, 2022) and in response to a minority report on the ARM Revision (ASMFC 2022). Ultimately, egg density data could not be considered in the ARM Revision because they were not provided to the ARM Subcommittee when requested. When egg density data were published (Smith et al. 2022), the trends appeared to be increasing during the years modeled, consistent with trends of the trawl- based indices used in the model.

> I am not able to comment on data availability issues. Nevertheless, reading the minority reports on the revised ARM prompted the idea of running capture-recapture analyses using surface egg density data as an alternative metric to represent year-to-year variation in the horseshoe crab resource at the Delaware Bay staging area. As discussed above, this analysis demonstrated that red knot survival was meaningfully and positively related to surface egg densities.

Egg density data are highly variable, both spatially and temporally within a spawning season, and discrepancies in egg density results have been noted depending on who processed samples and how they were processed.

> I agree that the surface egg density data is variable from sample to sample, but the sample size is large each year (hundreds to thousands of samples), and covers a large area within 16 beach segments that span most of the New Jersey side of Delaware Bay. Therefore, the average egg density observed each year still seems likely to contain useful information about annual mean densities via the law of large numbers. Furthermore, I did my best to use model-based controls to account for differences in effort and differing sampling methods.

To incorporate egg density data into the ARM would require development of two linked models, in which the relationship between horseshoe crab abundance and observed egg density is quantified in one, and the relationship between egg density and red knot survival/recruitment is quantified in the other. Such analysis and data exploration were not conducted during the ARM Revision primarily because the egg density data were not provided. The ARM Subcommittee is not opposed to using the egg density data as another index of horseshoe crab abundance once a reliably quantifiable relationship can be established. However, the first time the ARM Subcommittee saw the recent egg density results was in 2021 in the form of a draft manuscript (later published as Smith et al. 2022) as part of a minority report by Dr. Larry Niles. If the owners of the egg density data had been willing to provide the raw data, those data would have been considered in the revision of the ARM Framework. Instead, the ARM Subcommittee accounted for egg availability to shorebirds by including the timing of horseshoe crab spawning in the red knot integrated population model and made a research recommendation to examine the relationship between egg density estimates and horseshoe crab abundance estimates.

> I am pleased to hear that the ARM subcommittee is amenable to using the surface egg density data in the ARM. However, it does not seem appropriate to treat the egg density data as just "another index of horseshoe crab abundance" for use in the CMSA model. The CMSA model (which I have some additional concerns about; see below) is meant to provide an index of horseshoe crab abundance in and around Delaware Bay. The egg density data, on the other hand, is a measure of the usable food resource available to red knots. My re-analysis of the Delaware Bay red knot data strongly suggests that the egg density data provide a crucial empirical link between the red knot population and the horseshoe crab population. I suggest that a more useful and ecologically informed approach would be to use the surface egg density data to specify a mechanistic link between female horseshoe crab abundance (as described in the next paragraph) and the red knot population (possibly even mediated by a spawning process model). Simply incorporating the egg density data into the CMSA model would inappropriately combine fundamentally different data and ecological processes (and would raise difficult questions about how to weight these data relative to the trawl surveys), and would dilute key information about the functional link between these two species.
>
> I think ASMFC should consider incorporating the egg density data even if a precise functional relationship between horseshoe crab abundance estimates and surface egg densities cannot be immediately established. Logic dictates that a relationship must exist, although there are several intermediary mechanisms linking these system states (female abundance linking to egg masses deposited prior to red knot arrival, linking to surface egg availability via beach disturbance processes; perhaps as part of a structural equation model; Grace et al. 2010) that will add ecological realism to the overall process model. While there is uncertainty about the exact functional form of the relationship between surface egg density and horseshoe crab abundance (as is the case for many ecological relationships), it is a known causal linkage and so even a linear model could provide a simple and logically defensible quantitative description of this relationship. Furthermore, the adaptive resource management paradigm enables researchers to incorporate uncertainty into policy decisions. In this spirit, the ARM could incorporate several alternative plausible functional forms to describe the relationship between horseshoe crab abundance and surface egg densities just as the original version of this ARM framework incorporated several alternative functions relating red knot mass (itself a function of horseshoe crab population) to red knot survival (McGowan et al. 2015).

In Dr. Shoemaker's report, he finds that surface egg densities are uncorrelated or negatively correlated with the CMSA results and other indices of abundance used in the ARM Framework. In this analysis, he uses data from 1990-2022 although the CMSA and ARM Framework use data beginning in 2003. The CMSA model starts in the early 2000s to coincide with the start of many of required data sets used in the analysis (e.g., Virginia Tech Trawl, biomedical harvest, estimated dead discards from other fisheries). If the correlation analysis is abbreviated to include only the years used in CMSA modeling, all time series are positively correlated (Figure 3) for female horseshoe crabs (Dr. Shoemaker's analysis does not specify if his correlation analysis is for males, females, or both). In fact, the egg density time series from Smith et al. (2022) is positively and significantly correlated with the CMSA estimates of female horseshoe crabs. Therefore, it is likely that if the egg density time series were included in the ARM Framework as another index of horseshoe crab abundance, the CMSA results would not be much different from the current results.

> I reached out to the ARM subcommittee on Oct 21 2023, soon after ASMFC announced that they would issue a formal response to my peer review report, to inform them that I would be happy to address any questions that came up during their review of my work. If they had a question about how I analyzed or subsetted the trawl data (all of my analyses of the trawl data were for females only), then they could have asked me directly. They did not do so.
>
> In response to the above comments, I re-ran the correlation tests with a subset of the data that only included years from 2003 onward. The results were no different from my original analysis- there were weak (statistically inconclusive) negative correlations between the trawl-based abundance indices and the surface egg density index. However, the sign of the correlation flipped when I used the raw (without model-based standardization) trawl-based indices and the unadjusted egg density index. Nonetheless, correlation coefficients for the raw indices remained very weak (0.2 to 0.3) and were statistically inconclusive at alpha = 0.05.
>
> However, this discussion is of limited importance in comparison with the key point -- surface egg densities (whether raw or adjusted) strongly influenced red knot survival in my reanalysis of the capture-recapture data. In contrast, abundance indices from the trawl-based surveys showed no conclusive relationship with red knot survival. These facts provide strong support for incorporating the surface egg density data in the revised ARM (and not simply as another index of horseshoe crab abundance for use in the CMSA model- see above). I conclude that the trawl-based abundance estimates are not an adequate substitute for the information contained in the surface egg density data.

Additionally, Dr. Shoemaker analyzed the egg density data from Smith et al. (2022) and accounted for differences in survey methodology through time. The results of his reanalysis showed no trend in egg density although Smith et al. (2022) showed a general increasing trend in recent years similar to that of horseshoe crab abundance from the CMSA (Figure 4).

> In my re-analysis of the long-term egg density data, I added an offset term to account for differences in survey methodologies through time and thereby enable more robust comparisons among these different time periods. I have discussed this issue with the lead author of Smith et al. (2022), who agrees that the methods I used to re-analyze the trend in the long-term surface egg density data improved upon the methods used for trend estimation in Smith et al. (2022); which did not account for differences in survey effort in

> different segments of the time series (J.A.M. Smith, *pers. comm.*).

Dr. Shoemaker also conducted an analysis that shows the effect of egg density on red knot survival. However, this survival analysis is not documented in great detail and only includes data from the New Jersey side of the Delaware Bay. Thus, it is questionable whether this analysis is representative of the red knot population as a whole.

> It is unfortunate that similar egg density data were not available for the Delaware side, but that fact does not invalidate my analysis; in ecological modeling we do the best we can with the available data in spite of known limitations. Furthermore, I fail to see why this relationship would not hold on one side of the bay if it holds for the other. Nonetheless, my results strongly suggest that it will be important to continue collecting surface egg density data. Fortunately, it appears that standardized horseshoe crab egg density surveys will be available on both sides of the bay going forward.
>
> While my peer review report admittedly did not contain the level of analytical detail that would be expected of a scientific paper, I offered to share the code for running these analyses with ASMFC and to address any questions or concerns about my reanalyses. This offer still stands.

If these analyses by Dr. Shoemaker are correct, it still begs the question of how to incorporate this into the ARM Framework. In Dr. Shoemaker's report, red knot survival is positively correlated with egg density but egg density has not changed over time; however, female horseshoe crab abundance has increased. Therefore, while egg density and female horseshoe crab abundance must ultimately be linked, this relationship is not evident in the data. The lack of an empirical relationship ultimately complicates any effort to quantify a model linking horseshoe crab abundance to red knot survival through egg density. Dr. Shoemaker falls short of proposing a way to do this.

> If my analysis is correct, there is reason to believe the relationship between red knots and horseshoe crabs is much stronger than the current ARM framework suggests, and that surface egg densities provide a critical link for understanding and describing this relationship. Regardless of the nuances and complications that might be involved in incorporating these data in the revised ARM, the rationale for incorporating surface egg density data into this ARM framework is very clear.
>
> In my peer review of the revised ARM, I was only tasked with evaluating its scientific merits; offering suggestions for improvement was not a primary objective of my previous reports. However, I would be happy to work with ASMFC to discuss incorporating horseshoe crab surface egg density data in the next iteration of this ARM framework.

Regardless, for the time series of the CMSA model, egg density is positively correlated with the other time series of horseshoe crab abundance used. Because egg density data are not readily available to the ARM Subcommittee (either for the model development in 2021 or possibly on an annual basis that would be required for their inclusion), the data only cover New Jersey beaches, and their use and sampling design have been questioned over the years, the trawl surveys remain the best available data for horseshoe crab abundance in the ARM Framework.

The surface egg density data are now available. Further, it seems likely that the results of future surface egg density data would be furnished to ASMFC on a regular basis. If these data are important for linking red knot demographic rates to horseshoe crab abundance, and if they are indeed available, then ignoring these data seems to contradict the spirit of the term “best available data”.

Criticism 4: The ARM exaggerates the evidence for an increasing trend in the number of female horseshoe crabs in the Delaware Bay.

- The analysis provided in Dr. Shoemaker’s report contains errors, including the use of incorrect data subsetting for the indices and application of an analysis that was inappropriate for the data.
- The trawl-based indices were thoroughly considered by the ARM modelers and represent the best available data for tracking horseshoe crab abundance.
- The goal of the ARM modelers was not to find an increasing trend, but to develop the data in the most statistically sound way possible regardless of the answer.

Technical Response: Dr. Shoemaker suggests the ARM Subcommittee exaggerates the evidence for an increasing trend in horseshoe crab abundance through time. A long time to maturity for horseshoe crabs (9-10 years) suggests that recovery from overfishing would take some time to become evident in fishery-independent surveys. With reductions in harvest in the Delaware Bay region in the early 2000s, it makes sense that any increase in abundance would not be seen until approximately 10 years later (~2010). This is what was observed in the three trawl surveys used to index abundance. When a simple linear regression model is fit to each one of the trawl surveys beginning in 2010, all of them show statistically significant increasing trends (Figure 5). Dr. Shoemaker argues that “…trawl-based indices of horseshoe crab abundance are a noisy and unreliable indicator of annual fluctuations in the horseshoe crab population, and are likely an inadequate metric for quantifying the biotic interactions between red knots and horseshoe crabs in the Delaware Bay.” The ARM Subcommittee emphatically disagrees with this statement given the life history of horseshoe crabs, the amount of time since bait harvest has been curtailed, and the agreement of the three trawl surveys for an increasing trend in abundance. Harvest management appears to have worked to increase abundance. A rebuttal to this point is also given in Criticism 2.

First, I agree that we would expect to observe a delay between the initiation of regulation and the initiation of an observable population recovery due to the delayed maturation of female horseshoe crabs. I also agree that a segmented regression (or even a spline or polynomial fit), rather than an ordinary linear regression, is an appropriate approach for analyzing trends in the long-term trawl data (see below). Therefore, I agree that linear regression was too simplistic to be used for this purpose (Fig. 12 from my 2023 peer review report).

I ran additional tests to confirm the ARM subcommittee’s statement that “when a simple linear regression model is fit to each one of the trawl surveys beginning in 2010, all of them show statistically significant increasing trends”. Using my adjusted catch per unit effort (CPUE) indices that controlled for several potentially confounding factors, my analyses confirmed the apparent increases in horseshoe crab CPUE since 2010 (note that, as of this writing, I do not have access to the trawl survey results after 2022; Fig. 3). It is interesting to note that none of these relationships were statistically significant at alpha = 0.05 when trawl data from 2000 and onward were included in these regression analyses. However, since the 2010 threshold was not arbitrary, but was based on the expected delay in an observed population rebound (see above), there is nevertheless evidence for a recent increase in the Delaware Bay horseshoe crab population.

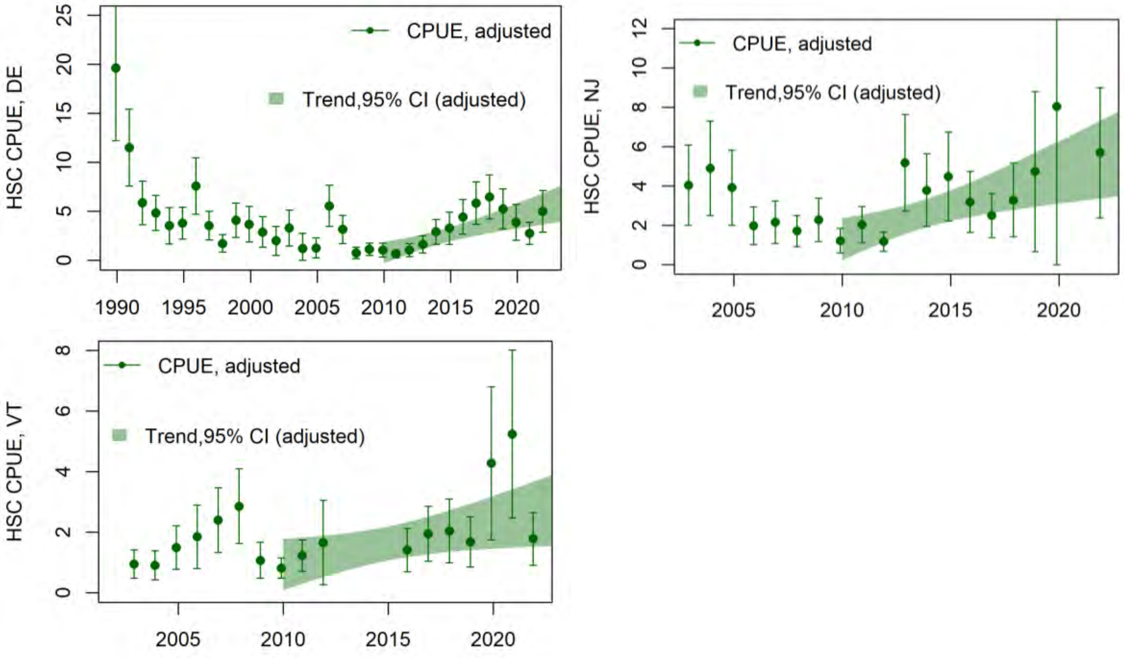

Figure 3. *Analyses indicating that there is an apparent positive linear relationship between three trawl-based horseshoe crab abundance indices (from NJ, DE, and Virgina Tech data) since the year 2010. Each figure displays catch per unit effort (CPUE) estimates adjusted for the effects of seasonality, water temperature, depth, and dissolved oxygen. Error bars represent 95% credible intervals for a linear regression of CPUE over time since. The green polygons represent 95% confidence intervals for the linear regression of the adjusted CPUE against time in years since 2010.*

Dr. Shoemaker again faults the indices of abundance used by the ARM Subcommittee for not being standardized according to environmental covariates in a GLM approach, and he specifically demonstrates his standardization on the New Jersey Ocean Trawl data. However, during an initial review of his report by New Jersey and Delaware staff, it was recognized that he subset the data incorrectly, using the wrong time periods including sample periods when the crabs are not fully available to the survey, resulting in data and an index of abundance that are not used the by ARM Subcommittee. Dr. Shoemaker included the January samples, when the overwintering crabs may remain farther offshore than the survey’s sample area, accounting for the significantly decreased catches during this period. He also included the June samples, when most of the adult crabs have migrated into bays and estuaries to spawn, again making them unavailable to the survey. The inclusion of these two sampling periods has an inappropriately dampening effect on the resulting indices which cannot be corrected through a GLM standardization and will not provide an accurate index of relative abundance. Again, a GLM standardization was attempted with the New Jersey Ocean Trawl data during the 2019 benchmark stock assessment (ASMFC 2019), but it was found to not provide any improvement over a simple delta-mean index. Standardization of the trawl survey catches by a GLM or GAM is still something worth exploring in future assessments as additional years of data may provide the necessary information to better evaluate the true effects of covariates on catches.

> I stand by my reanalysis of the New Jersey Ocean Trawl survey data. For these trawl data, as with the red knot data, I made an effort to analyze the data independently, using my training and experience rather than relying on ASMFC's analytical methods. In their response, ASMFC claims that my analysis of the New Jersey trawl data (which included survey data collected from all months of the year) was incorrect, stating that "the inclusion of these two sampling periods has an inappropriately dampening effect on the resulting indices which cannot be corrected through a GLM standardization and will not provide an accurate index of relative abundance". However, ASMFC did not provide further evidence or rationale for this statement, and I maintain that my methods were appropriate.
>
> In my re-analysis of the NJ trawl data (and the other two trawl surveys; more detail can be found in my 2023 peer review report), I relied on a model-based approach to control for potentially confounding factors such as water temperature, trawl depth and seasonal effects (ordinal date). Specifically, I modeled horseshoe crab captures as a complex, non-linear function of survey effort, environmental factors, and season. By using spline fits within a Generalized Additive Model (GAM) framework I was able to account for complex relationships between catch-per-tow and factors such as ordinal date (controlling for seasonality and allowing for strong fluctuations across different times of year; see Fig. 10 from my 2023 peer review report). Therefore, I was able to use the full NJ trawl dataset while accounting for times of year during which crabs were not fully available for capture. These models passed tests of model adequacy (using quantile residuals, implemented in the 'DHARMa' package in R) and appeared to perform admirably in accounting for these complex, potentially confounding factors.
>
> In contrast, the ASMFC experts relied on sampling design and data sub-setting to control for any potentially confounding factors. I argue that there are very good reasons to use model-based controls to enable standardized comparisons across surveys and years. Sampling design and data sub-setting cannot control for all the factors known to affect horseshoe crab detection rates. Furthermore, data sub-setting effectively discards data that could potentially help to shed light on key questions of interest; in contrast, model-based controls enable us to use all available data. Horseshoe crab capture rates are known to be strongly influenced by multiple factors, including temperature and seasonality. Since information on environmental factors is collected as part of each trawl survey used in the

> revised ARM, failure to use these data is a notable oversight of ASMFC's approach. By failing to use model-based standardization, ASMFC is implicitly assuming that these factors have zero effect on horseshoe crab captures -- which is a strong and likely false assumption.
>
> After a research scientist from the New Jersey DEP contacted me with their concerns, I re-ran my analyses with only the April and August samples. Finding no substantive difference in my results (and after running additional tests to confirm that the GAM standardization analysis was adequately accounting for the effects of seasonality), I proceeded with my original analyses in my 2023 peer review report. Of course, it is possible that there are legitimate reasons for a different analytical choice, and I would be happy to have a further discussion on the merits of sub-setting this dataset.
>
> Overall, I maintain that there are strong reasons to use model-based standardization methods (e.g., GLM, GAM, or machine learning approaches like random forest) to control for factors that could confound the inter-annual variation in catch-per-tow, and I am glad to hear the ARM subcommittee is open to using model-based standardization methods in future assessments.

Beyond the issue of the erroneous data standardization of the New Jersey Ocean Trawl Survey data by Dr. Shoemaker, he made a questionable analytical choice leading to the conclusion that female horseshoe crab abundance has not increased. Dr. Shoemaker used both the "raw" and "adjusted" catch-per-tow data from the entire time series of the three trawl surveys in a linear regression analysis to determine if there was a trend in abundance through time (Figure 6). The Delaware Bay crab population is known to have declined to a minimum level by the early 2000s (prompting harvest restrictions), thus, a linear model fit through the entire time series (1990 to present) of all surveys is nonsensical. The near zero slope of the linear model is driven by the high CPUE from the Delaware Trawl Survey at the very beginning of the time series (1990 – 1992). That horseshoe crabs declined in the 1990s and early 2000s is undisputed. All surveys show a low point around 2010, with an increase afterwards. The pattern of the combined surveys looks like a "U" – decreasing and then increasing. A linear model fit to such a pattern will show a non-significant slope (i.e., trend) over the entire time period. It is unclear whether Dr. Shoemaker investigated the resulting residual pattern, as that would have confirmed the inappropriateness of using a simple linear trend model. Perhaps this analysis is indicative of Dr. Shoemaker's unfamiliarity with the changes in horseshoe crab harvest management through time, but it nevertheless perpetuates the unfounded belief that the horseshoe crab population has not responded positively to harvest restrictions. As previously stated in the rebuttal to Criticism 2, all surveys have shown an increasing trend since 2010 (Figure 5). Alternatively, a segmented regression model could be fit to the time series of data to demonstrate how abundance trends have changed through time. When this is done, both the Delaware and New Jersey Ocean Trawl Surveys show declining abundance followed by an increase after 2010 (Figure 7). Given the lengthy time to maturity of horseshoe crab, it has long been understood that it would take about a decade to begin seeing an increase in abundance following the initiation of harvest restrictions.

After further consideration, I agree that there is a detectable statistical signal of a recent population increase in the trawl data. I also agree that horseshoe crabs are a long-lived species, and one would expect to observe a substantial delay between the implementation of harvest regulation (in 2000) and the recovery of the population (a large cohort born in 2005 would only mature and contribute to population growth in 2015 or later). Therefore, (1) time periods prior to the initiation of harvest regulations should not be included in this analysis (Fig. 12 from my 2023 peer review report), as few would claim that the horseshoe crab population was increasing in the 1990s (in fact, excessive commercial harvest of horseshoe crabs in Delaware Bay during this decade is widely believed to have caused a major decline in both horseshoe crab and shorebird populations; Niles et al. 2009) and (2) a segmented or nonlinear regression model makes sense for this analysis, as it can accommodate an initial period of decline or depletion followed by a more recent period of increase (e.g., decline in capture rates during the early 2000s followed by a recent recovery since around 2015).

For the sake of completeness, I am including a revised version of Figure 12 from my 2023 report that has been updated to use a GAM and GLM (with a quadratic relationship with time) to allow for a non-linear relationship with catch per unit effort over time (Fig. 4). Both methods yield the same result: an increase in the abundance of female horseshoe crabs since around 2010, indicating that the trawl surveys (considered together) contain evidence for a recent increase in female horseshoe crab abundance.

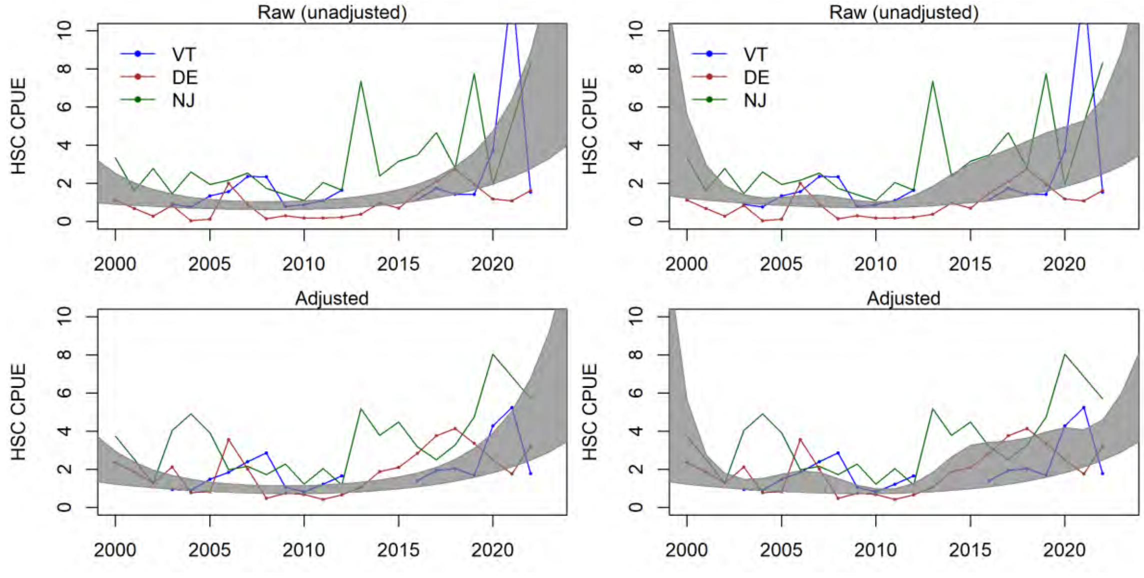

Fig. 2. *Updated version of Fig. 12 from my 2023 report, modified to add a (left) quadratic and (right) spline (GAM) trend of horseshoe crab catch-per-unit-effort (CPUE) over time. Both methods suggest a positive trend in female horseshoe crab abundance beginning around 2010, regardless of whether the raw or adjusted CPUE estimates are used.*

Dr. Shoemaker also reanalyzed egg density data from New Jersey to further argue that horseshoe crab abundance has not increased. These data were published by Smith et al. (2022) and showed a variable but increasing trend in egg densities over the last two decades (Figure 4). However, upon reanalysis, Dr. Shoemaker contradicts Smith et al.'s (2022) conclusion for an increasing trend, suggesting that it was an artifact of differing sampling methodologies through time. There is not much the ARM Subcommittee can say concerning trends in egg density data beyond what is published by Smith et al. (2022) because those data were not supplied to the ARM Subcommittee when requested during the ARM Revision. The acknowledgement by Dr. Shoemaker of the changing methodology in egg density data does corroborate one of the reasons the ARM Subcommittee has been reluctant to make use of egg density data since the development of the original ARM Framework in 2007. If the owners of the egg density data would follow the established ASMFC data acquisition processes by sharing the data when requested at the beginning of a stock assessment, the ARM Subcommittee would certainly evaluate the utility and inclusion of such data in the ARM modeling process just like any other data source.

> Notably, the strong positive relationship between horseshoe crab egg density and red knot survival did not depend on whether or not I used the results from Smith et al. (2022) or my adjusted numbers. I am glad that the ARM subcommittee is open to using these data in the ARM framework.

Criticism 5: The integrated population model used for estimating red knot population parameters is overparameterized and likely to yield spurious results.

- Dr. Shoemaker's criticism of the red knot model is unsubstantiated and misrepresents the models used in the ARM Framework.
- Much like the trawl surveys, the red knot data are imperfect but represent the best available data.
- Dr. Shoemaker assumes that too many parameters will produce incorrect results, when the relationship between overparameterization and biased models is more nuanced.

Technical Response: The critique of the state-space model ignores the fact that this model is not analyzed independently, but as a sub-model within an integrated analysis. This viewpoint is apparent in several places in Dr. Shoemaker's critique, as he writes about using the two data sources (i.e., red knot count data and mark-recapture data) to "train" the two sub-model components as if they were separate endeavors where information from one has no influence on the model parameters in the other. Integrated population models combine the likelihoods of two or more sub-models, allowing researchers to estimate demographic parameters from multiple models and data sources simultaneously (Schaub and Abadi 2011). In the ARM Framework, the admittedly limited count data are integrated with 100,000s of mark-resight observations from Delaware Bay. A third component, a Markov population model, provides a strong structural prior that links estimates from multiple sub-models based on an understanding of the life history of the species. One key benefit of this approach is the ability to estimate parameters that would not be estimable with any one model or data source alone. In the case of the ARM Framework, the estimation of the red knot recruitment rate is informed by both the analysis of the count data (state-space sub-model) and the mark-recapture data (open robust design sub-model).

First, I point out that integrated population models (IPMs) such as the red knot model used in the revised ARM framework are complex, and their statistical properties are not fully understood by practitioners or statisticians (Schaub and Kery 2021). Second, I do not dispute the value of integrated models for conservation and management, and I agree that the red knot IPM is an integrated model whose components borrow information and inherit constraints from one another. However, it is also true that (1) the red knot IPM consists of two primary submodels (state-space submodel and open robust design [ORD] submodel), (2) the available data sources do not contribute equally to informing each submodel, and (3) one of the available data sources is very information-rich (the banding and resighting data, with tens of thousands of observations each year) and the other is very information-poor (the peak count data, with a single observation per year). Therefore it is instructive to deconstruct this IPM into a set of separate component models for heuristic reasons even as we acknowledge this is not strictly the case.

Ultimately, the red knot population simulation model (used for optimizing the harvest functions and fit within the red knot IPM) is a Markov population process described by (1) initial adult abundance, (2) adult survival (including an effect of horseshoe crab abundance in addition to arctic snow cover and spawn timing), and (3) recruitment (a compound parameter incorporating reproduction and first-year survival, also including an effect of horseshoe crab abundance). The information-rich data source (the mark-resight data) primarily informs the open robust design (ORD) submodel, resulting in well-informed estimates of annual survival (although likely biased high due to misread errors; see earlier discussion). Importantly, the information-rich mark-resight data are virtually non-informative with respect to two of the three demographic processes: initial abundance and recruitment. The reason for this is that the ORD likelihood (like all Cormack-Jolly-Seber variants) is conditioned on the initial capture event and is therefore only informed by the history of subsequent recaptures (i.e., it isolates the survival and state-transition processes from other demographic processes such as abundance and recruitment). Aside from survival, the ORD submodel (informed by the mark-resight data) is also used to estimate the fraction of the flyway population using the Delaware Bay staging area each year -- a process that appears to be mis-specified in ASMFC's red knot IPM (see discussion of 'pi' parameter below).

With the information-rich mark-resight data contributing little to the critical initial abundance and recruitment processes, the information-poor source of data (the peak count data) necessarily does the heavy lifting when it comes to estimating these parameters (but contributes very little to the survival estimates). Some components of the state-space submodel are informed by the information-rich dataset- notably, the fraction of the stopover population available to be observed during each 3-day interval is derived largely from the ORD submodel but forms an important part of the state-space likelihood.

> However, this “cross-over” between the two likelihoods does little to mitigate the central issue that the information-poor peak count data is the primary source of information for estimating red knot recruitment and initial abundance.
>
> The ARM subcommittee seems to be making the claim that the recruitment parameters are estimated jointly from the mark-resight data and the peak-count data. While true in a strict mathematical sense (in any integrated model there will likely be at least some information leakage among the joint model components), this is not the case in any important practical sense. As I mentioned above, the way these data enter the likelihood function, as specified in the L1 component of the open robust design (ORD) model, ensures that this data can only directly inform the survival process (along with temporary emigration and some within-year processes like the timing of stopover entry and exit). Effectively, the information-poor peak-count data are used to estimate initial abundance as well as the changes in abundance from year to year (annual lambda, or population growth). The model then solves for the unknown recruitment rates, conditional on the estimated survival rates (from the mark-resight data) and the annual population growth rates (from the peak-count data). The ORD model by itself is largely uninformative with respect to recruitment- it is the addition of the peak-count data that makes it possible to estimate recruitment. Therefore, it is disingenuous to claim that the mark-resight data contribute to the estimation of recruitment in any real sense.
>
> Finally, a claim like “the admittedly limited count data are integrated with 100,000s of mark-resight observations from Delaware Bay” ignores the fact that the 100,000s of mark-resight observations contribute virtually no information for fitting two of the three key demographic processes estimated by the IPM: abundance and recruitment. The implication that the red knot IPM is rescued from standard statistical concerns (such as over-fitting to the data) because it borrows information from the information-rich band-resight observations to supplement deficiencies in the information-poor peak-count data is misleading and dangerous. It can become all too easy to claim “empirical” support for poorly specified or unsupported model components by making facile but rhetorically appealing claims about integrated likelihoods. For this reason, it is very important to break down these complex models (for heuristic reasons) into their subcomponents and discuss which data sources are doing the heavy lifting for fitting all key parameters-- at least until the statistical properties of integrated population models are more fully understood and documented.

By ignoring the structural linkage that shares information between model sub-components, Dr. Shoemaker set up a misleading basis to make unsubstantiated claims about model overparameterization and to falsely demonstrate spurious results produced by the ARM model. Regarding overparameterization, he referred to the familiar rule-of-thumb of 30 data points per model parameter as sample size guidance for robust estimation. While this guidance is useful in traditional applications where data are used to inform the parameters of a single model, its relevance for integrated modeling – where information is shared across multiple model components – is unclear. His assessment that 18-28 parameters were estimated from 14 data points is a serious mischaracterization of the model and requires overlooking the fact that information from mark-resight data also informs the state-space model. In the ARM Framework, the number of parameters estimated from the count data alone is three: one initial population size and two counting errors. The recruitment parameters (three parameters: mean, variance, and effect of horseshoe crab abundance) are estimated jointly using information from all three components of the integrated population model. The availability parameters are specified with highly informative priors, which were developed externally to the model. In the ARM Subcommittee's view, the availability parameters should be more appropriately thought of as data informing the model, not estimates on which inference was based.

> I do not think it is misleading, unsubstantiated or false to claim that the peak count data are the primary source of data for estimating recruitment and initial abundance. In counting up the number of parameters estimated primarily using the 14 peak-count data points I acknowledged that some of these parameters (such as the 'availability' parameters) were assigned strong priors, and that some represented individual random effects (for which the calculus for estimating degrees of freedom is unclear). I dispute that any of the parameters in Table 2 (including the recruitment parameters) are estimable on the basis of the information-rich mark-resight data. Therefore, there are at least 8 to 10 free parameters (and probably more) estimated primarily from the information-poor peak count data- which approaches or even exceeds the available sample size ($n = 14$). As IPMs have poorly understood statistical properties, I referenced a common rule of thumb in statistics that is generally relevant to non-informative statistical models (those without good prior information).

Dr. Shoemaker used a simulation exercise to purportedly demonstrate production of spurious results by the model. By replacing the peak counts with white noise in the simulation runs, he anticipated that the simulated abundance at the end of the time series should match the initial abundance on average. Instead, he was surprised to discover negative trends in simulated abundance and that final abundances produced by the model were most often lower than initial abundance. He did not know the cause of this outcome, and he speculated on a variety of reasons having to do with simulation methods, starting values, etc. The cause is simple to explain, but it requires acknowledgement that the information sources are linked to each other through the Markov population model. By providing a stream of pattern-less peak count data to the model, Dr. Shoemaker effectively contaminated information about recruitment, leaving survival rate as the only reliably informed parameter. Therefore, a population simulated with no recruitment and survival probability <1 will most often decline. Though he failed to understand the cause of the observed simulation behavior, and he cautioned against using his results to infer a systemic bias in the model, he nevertheless concluded that the model is unstable and has a strong tendency to produce spurious results.

> IPMs are a relatively new - and particularly complex - class of ecological models, and the statistical properties and biases inherent to these models are poorly understood by statisticians. It is possible that the simple tests I ran using "white noise" (random numbers from a normal distribution with mean, variance and sample size that matched the peak

count data and with no temporal trend) to substitute for the peak count data (which was meant to assess the tendency for spurious estimates of growth or decline) may not have been sufficiently informative. It is also possible that the constraints introduced by the Markov population model had the effect of inducing a negative bias in these tests. Nevertheless, the rationale provided by the ARM subcommittee seems overly simplistic. While it is true that a population will necessarily decline with zero recruitment (and survival <1) the explanation for this issue is certainly more nuanced; in my tests, the IPM estimated recruitment as a free parameter- and recruitment was constrained to be greater than zero. Nonetheless I had limited time to run tests, and given the results of my simulations (well over half of the tests resulted in an estimated population decline) an unintended source of bias may have affected my test results.

A better (but more time consuming) validation test would be to develop a complete simulation of the *rufa* red knot population, including a demographic process model (including survival, fecundity, abundance) and an observation model capable of generating data similar to the real-world system (including mark-resight and peak-count data) under a wide range of demographic scenarios (e.g. differing levels of survival and recruitment), and a wide range of observation error scenarios. With simulated data from such a model, researchers could test how often the IPM was able to successfully recover the true parameter values, including recruitment, variation in recruitment, and covariate effects on recruitment (including HSC abundance). The open robust design submodel has been extensively tested using similar tests with simulated data (Tucker et al. 2022), but I did not find any evidence that the full IPM was subjected to similar validation tests. If they did run simulation-based trials using data generated under known assumptions and parameter values, they did not report the results in the ARM report or in Tucker et al. (2023)(or in the code release for the IPM). Such tests require a good deal of time and thought to develop and run. However, investing such time and thought in such testing is necessary and important given the central role of the IPM in informing important ASMFC policy decisions affecting a threatened species.

Integrated population models are complex and largely untested, and there are unintended biases that can occur (Riecke et al. 2019), so it is important to test these models extensively, especially when used in the context of decisions that can detrimentally affect threatened and endangered species. Therefore, the ARM subcommittee should run a battery of validation tests before concluding the model is stable and that it reliably is able to recover key demographic information about the system -- including temporal variability and covariate effects. We cannot assume that complex models like the red knot IPM are free from serious biases and other statistical issues. Because they are relatively new and untested, IPMs should be presumed flawed until they have been adequately validated (such as running the simulation tests described above) -- this is especially true for an IPM that is used for making important decisions that could impact a threatened or endangered species. In this case, the burden is on ASMFC to demonstrate that the red knot IPM is capable of serving its intended role in the revised ARM.

The critique of the state-space sub-model also contains an assertion that overparameterized models are necessarily biased. While overparameterization can result in poor generalization to new datasets, it does not guarantee biased results. In fact, bias could also arise if models are under-parameterized and fail to capture system complexity. The relationship between bias and overparameterization is not as straightforward as is portrayed in Dr. Shoemaker's report.

> Indeed, over-parameterized models are not guaranteed to be biased. Instead, over-parameterized models tend to overpredict the training data (predicting the data used for training the model with high precision) but perform very poorly when confronted with independent data not used to train the model (out-of-sample data). The fact that the red knot IPM is being used to predict the population response to harvest management in the future means that over-parameterization could be a serious issue for the revised ARM.
>
> The above point about under-parameterization is important and relevant to this discussion. The trade-off between under-parameterization and over-parameterization is often known (somewhat confusingly) as the "bias-variance" trade-off. In this case, the term bias refers to under-parameterized models, which can provide biased estimates even for the data used for training. The term "variance" refers to the property of an over-parameterized model making inaccurate and often wildly off-base predictions when challenged with new data (the model treats the noise in the training data as if it were a useful signal, and therefore models fitted to different samples from the same statistical populations will make very different [variable] predictions despite the fact that the data samples reflect identical underlying processes). In general, over-parameterization can be assessed by withholding some data from the training set and testing to see how well the model is able to predict the left-out data. This is an important part of the model validation process -- and one that could add substantial credibility to the red knot IPM if applied to the Delaware Bay system.

The ARM Subcommittee readily acknowledges that the red knot count data are a much weaker data set than the mark-recapture data, but they were the only count data collected consistently over the all of the years of the monitoring program, so the ARM Subcommittee made the best use of them to better understand the system. As described in ASMFC 2022 (page 80), this model could be greatly improved by including auxiliary information such as survey-specific covariates (e.g., observer ID, tide state, weather conditions), integration of simultaneous ground count data, or future implementation of digital photography or double-observer methods. One of the challenges of working with historical monitoring data is the inability to influence study design or data collection processes. There were no auxiliary data that were consistently collected (or, at least, made available to the ARM Subcommittee) for aerial surveys that would allow counting error to be better estimated. Similarly, the ARM Subcommittee knows that concurrent ground counts were conducted in at least some years, but those data were not provided. The ARM Subcommittee made the best use of the available data, and conducted these analyses within the management decision context. Sometimes in decision support roles, scientists have to develop the best analysis to support decisions even when data are imperfect (McGowan et al. 2020). All modeling exercises require assumptions and constraints, and those included in this model represent the best understanding of the system at this time; the ARM Subcommittee hopes and intends for this model to be updated as more information and more data become available. It should be noted that all previous attempts to model red knot populations in this system and assess the linkages between knots and horseshoe crabs in this management context required significant assumptions, and the ARM Subcommittee believes that their approach in the ARM Revision alleviates or improves many of those assumptions. Previously, all attempts to model productivity and recruitment in this population relied upon estimates from Europe and basic assumptions about life history (i.e., setting juvenile survival as a percentage of adult survival, see McGowan et al. 2011) and this approach uses data from this flyway in a complex but much improved model to estimate those parameters.

I appreciate the thoughtful discussion on the low information content of the count data and ways in which this critical information source for the IPM model could be improved in the future. Overall, I maintain that the peak count data are asked to do some heavy lifting in the red knot IPM for which they are ill-suited.

Stating that this is a 'much improved model' does not make it so. Complex models like the red knot IPM must be subjected to rigorous testing, and it appears the IPM (unlike the open robust design subcomponent) has not been adequately tested (see above). Also, I do not really understand why the use of data from other populations (e.g., European red knots, which have a similar life history) and time periods (e.g., the period of recent population declines in the early 21st century) is so heavily devalued by the ARM subcommittee. If there is useful information on the recruitment process that can be gleaned from other populations, why not use this information? I am not sure it is an improvement to use only data from the western Atlantic flyway if the best available information for this population comes in the form of 14 low-precision data points.

Criticism 6: The integrated population model exhibits poor fit to the available data.

- Dr. Shoemaker provides conflicting arguments for the use of the goodness of fit test for the red knot model.
- Goodness of fit tests applied to the red knot model indicated poor fit in one model component, but the portion of the model including the survival probability of red knots did not fail the test.

Technical Response: There are no unified goodness of fit tests for integrated population models, so the commonly-accepted approach is to assess model fit independently for each sub-model. Posterior predictive checks (PPCs) are the standard type of goodness of fit tests for Bayesian models. The PPC for the state space model indicated adequate fit (P = 0.44 where P = 0.5 indicates no evidence of either over- or under-dispersion, and P near 0 or 1 suggests poor model fit), but the PPC for some components of the open robust design model indicated lack of fit to the data.

I also made this point in my 2023 report, but I agree there are no unified goodness of fit tests for IPMs, and that PPCs (in spite of some known flaws) are currently the preferred method for checking model adequacy. Nevertheless, I was not able to confirm adequate fit for any of the three subcomponents of the open robust design submodel, including the likelihood component responsible for estimating adult survival. I was able to confirm that the PPC for the state-space model indicated adequate fit, but the most authoritative available manual for IPMs (Schaub and Kery 2021) notes that this test has been shown to indicate model validity even in cases in which the model is demonstrably not valid. Therefore, following Schaub and Kery (2021), I do not consider the PPC results for the state-space model to constitute convincing evidence for adequate model fit (as I stated in my 2023 peer review report).

This critique contains shaky logic. First, Dr. Shoemaker asserts that PPCs are a good method for checking model fit and criticizes the lack of fit of the open robust design model. Indeed, Dr. Shoemaker used a PPC in his analysis of banding data to conclude that his model had "reasonable fit." Next, he states that PPCs are not a reliable indicator of goodness of fit to cast doubt on the ARM Subcommittee's statement that the state space model "passed" the test. By Dr. Shoemaker's logic, PPCs are only to be trusted when they indicate lack of fit. Dr. Shoemaker's inconsistent logic with respect to checking goodness of fit casts doubt on the integrity of the analysis. Putting that aside, the apparent lack of fit for the open robust design model will be discussed. The open robust design model consists of three likelihoods, and PPCs indicated lack of fit for likelihood L3 (P = 0.9), which describes the process of reencountering individuals within years. This lack of fit could arise due to unmodeled heterogeneity in true arrival and persistence probabilities as a result of pooling encounters into three-day sampling periods. If aggregations occur over a time period that is short relative to the expected length of stay, the expected bias is minimal (Lindberg and Rexstad 2002; O'Brien et al. 2005). Average stopover duration for red knot at this site has been estimated to be 12 days (Gillings et al. 2009); 3 days should be a short enough window to avoid biased estimates of arrival and persistence but could introduce heterogeneity and overdispersion. The likelihood that contains the apparent annual survival probability is likelihood L1, which describes the process of encountering marked birds across years. PPCs for this likelihood did not indicate lack of fit (P = 0.31).

The ARM subcommittee misunderstood my argument in my 2023 report (see above). I did not state or imply broadly that PPCs are not useful in the context of IPMs. The only PPC test I raised questions about was the PPC test specifically for the state-space model; the PPC test (Bayesian *p*-value) in this particular case has been shown to indicate adequate fit even in cases where the model is known to be incorrectly specified (Schaub and Kery 2021). I did not broadly question the value of PPCs, nor did I unfairly imply that I only trust PPCs when they indicate lack of fit. Indeed, I used PPCs to assess goodness-of-fit for my survival models, and I used any indications of lack of fit as motivation to improve these models. In my tests with the red knot IPM, the open robust design subcomponents all exhibited poor fit to the data, whereas the state-space component exhibited adequate fit (as stated above).

> In addition to the points raised by Schaub and Kery (2021), questioning the value of the PPC results in the context of the state-space component, it is important to note that “passing” posterior predictive checks is much more challenging for rich data sets like the mark-resight data and much less challenging for smaller datasets like the peak-count data (the primary data source for fitting the state space model). Therefore, “passing” PPC-based tests for very small datasets like the peak-count data can be a pretty low bar that does not generally validate model adequacy.

CONCLUSIONS

Continuous scientific review and critique is welcome as that is how science advances. There will always be room for improvement in any modeling effort in the management of natural resources. This is part of the double-loop learning in an adaptive management effort whereby model design and management are periodically reevaluated (Fabricius and Cundill 2014; Williams and Brown 2018). In this specific case, however, advocacy is infused into the scientific debate. The 2022 ARM Revision represented some great advancements in the understanding of the population dynamics of horseshoe crabs and red knots, and their interactions during the double-loop of the adaptive management process.

> I agree about the value of scientific critique and debate, and I hope this exchange is useful for advancing scientific understanding of this system. I have taken my role as an independent scientific reviewer seriously, and my critiques are meant to ensure rigorous use of the best available science in this important decision-making context. I think it is unfair to claim that I infused advocacy into the debate or undermined the scientific process in any way.

It is curious that these advancements have stirred so much controversy because the technical criticisms of the ARM Revision could have equally applied to the original ARM Framework. In fact, the original framework merited specific criticism because it relied on life history parameters informed by literature values taken from outside the Delaware Bay or based on expert opinion. The ARM Subcommittee questions if the true problem is not with the process or technical modeling, but rather with the final result and harvest recommendation.

> It seems clear that if a model recommends action that could potentially harm a threatened or endangered species (or impede their recovery), it is only prudent that the model is subjected to increased scrutiny.

An important benefit of the adaptive management process is the ability to make decisions even under imperfect knowledge of an ecological system (Williams et al. 2002). The overall goal of the ARM Framework was to produce a decision tool informed by science and stakeholder values, given the available knowledge about the Delaware Bay ecosystem and horseshoe and red knot population dynamics. In the original ARM Framework, knowledge about some system components, for instance red knot population dynamics, was quite limited. The ARM Revision represented a double-loop learning event, in adaptive management terms, and population models were re-designed to accommodate 1) the large volumes of high-quality data collected on both species since the original ARM's inception, and 2) changes to both populations over that period. In the view of the ARM Subcommittee, the effect of a change to an ecological model must be judged according to its effect on both the properties of the overall decision framework, and the ability of the ARM Framework to incorporate new monitoring data to improve understanding of the system. One important goal in the development of the ARM Revision was to design population models for horseshoe and red knot that would allow for rapid and efficient learning given the monitoring efforts in place for each species (Williams 2011). This critical feature of the ARM Framework—the ability to learn from monitoring—is not addressed by Dr. Shoemaker or Earthjustice; and yet it was a major consideration by the ARM Subcommittee. The design of ecological models for use with adaptive management should also be guided by the decision objectives (Fuller et. al. 2020), a point not addressed by Earthjustice.

> I generally agree that adaptive management has great value for managing systems in the face of uncertainty. However, I think a multi-hypothesis approach to adaptive management is essential for capturing the spirit of adaptive management (see opening statement #1). By accommodating a range of plausible models of the system, including at least one model that formalizes a strong and ecologically meaningful link between red knots and horseshoe crabs, a multi-hypothesis approach to adaptive management will better encapsulate the scientific literature on this system (in which a strong relationship between these two species is indeed plausible). In addition, from a purely scientific perspective, a multiple hypothesis approach can yield more effective inference than a single model approach (Platt 1964). Finally, this approach is better able to accommodate the full spectrum of values within the stakeholder community.

Much of the 2022 and 2023 criticism by Dr. Shoemaker (as well as the comments by Earthjustice) stem from the belief that there must be a strong relationship between horseshoe crab abundance, horseshoe crab egg density on the beaches, and red knot survival. They claim that because the ARM Subcommittee did not find this “strong” relationship when examining the empirical data from the Delaware Bay region, the ARM Revision must therefore be fraught with error. It is apparent that Dr. Shoemaker reviewed the ARM Subcommittee’s work with an unwillingness to entertain the idea of anything but a “strong” relationship. A specific example of this is his statement in his 2022 report where he postulated that the collection of additional data may show that the relationship between horseshoe crab abundance and red knots survival could disappear or become negative. He states, “This outcome would pose an existential problem for the ARM Framework, decoupling the two-species Framework and rendering the red knot model unusable in the context of management.” Of course, the “no relationship” outcome would be expected if horseshoe crabs become sufficiently abundant to not limit red knot survival, but that knowledge does not challenge the scientific validity and usefulness of an adaptive management framework for decision making. Such comments demonstrate a reluctance to learn within an adaptive management framework and a desire to cling to previous beliefs in spite of scientific advances.

> I think I was clear: the only point of including a red knot population simulation model within this ARM framework is because of the potential risk to this population posed by

> horseshoe crab harvest. If the model showed no response of the red knot population to horseshoe crab harvest (even under scenarios involving an extreme collapse of the horseshoe crab stock) then there would be no point in including a red knot simulation model as part of the ARM framework in the first place. Please refer to opening statement #2 for more discussion about the rationale for focusing on the strength of the relationship between red knots and horseshoe crabs.

There is no doubt that Dr. Shoemaker is a very knowledgeable quantitative ecologist. However, his critiques are unhelpful in advancing a two-species adaptive management effort. His criticisms focus on specific components of the overall ARM Framework, and why each may be wrong, but nowhere does he provide any recommendations for how to assemble the pieces into a unifying framework to make management decisions. For example, he makes strong arguments for using egg density to predict red knot survival but provides no recommendations for how to link egg density to female horseshoe crab abundance, which is directly affected by harvest management. He also makes a large issue about uncertainty in the horseshoe crab population projections but fails to recognize how uncertainty is handled in the optimization (approximate dynamic programming) or make any recommendations on alternative methods to conduct an optimization given the uncertainty.

> As an independent peer reviewer, my primary goal was to review the existing ARM framework on its merits and not to provide a vision for how this system could be improved. Nevertheless, I suggest that a multi-hypothesis approach could offer important benefits in this case, and I would be very happy to engage in further discussions with the ARM subcommittee.

The ARM Framework is designed to continuously improve the underlying models through double-loop learning, and the ARM Subcommittee welcomes constructive input on how to do so. Unfortunately, the critiques by Dr. Shoemaker (and Earthjustice) fail to make any real recommendations for improvement or provide any other means for helping managers make an informed harvest decision beyond consideration of the values of a single stakeholder group. If the values of all stakeholders have changed (i.e., no female harvest under any circumstances), that change could be considered in a new approach in the future by the ARM Subcommittee. As it stands, the current ARM Framework represents the values previously established through stakeholder engagement: to 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.

> While it was not my role to suggest recommendations for improvement, I hope ASMFC considers adopting a multi-hypothesis ARM framework. I certainly do not advocate for a framework that only considers the values of a single stakeholder group, and I hope ASMFC can find a way forward that uses science to bring stakeholders together rather than driving them further apart.

Criticism 7: The estimate of mean horseshoe crab recruitment and propagation of error

within the horseshoe crab population dynamics model is inappropriate.

- The estimate of mean horseshoe crab recruitment used by the ARM Subcommittee is the most biologically realistic. If mean recruitment were lower, as Dr. Shoemaker suggests, the current population estimate of horseshoe crabs would be well above a predicted “carrying capacity” of the Delaware Bay region.
- Dr. Shoemaker’s proposed method of error propagation is worth considering in a future revision of the ARM model, but comparison of his population projections to those by the ARM Subcommittee are nearly identical.

Technical Response: The revised ARM Framework uses the same mathematical model to estimate the abundance of horseshoe crabs (the CMSA) and to project the horseshoe crab population into the future while accounting for annual removals of individuals due to bait harvest, dead discards from other fisheries, and mortality associated with biomedical facilities. In his 2022 critique, Dr. Shoemaker expresses his opinion that uncertainty in model parameters was not propagated through time in an appropriate manner. This criticism does have some merit and his proposed methodology is worth the ARM Subcommittee considering in future revisions of the ARM Framework. Dr. Shoemaker contends the current horseshoe crab projection model greatly underestimates uncertainty and its effects on predicted future abundance. Although Dr. Shoemaker’s proposed methodology may be more appropriate, the ARM Subcommittee believes these concerns are overstated as there is still much uncertainty in the projected population – female horseshoe crab abundance can range between 5 – 15 million under a no harvest scenario.

> I agree that the proper treatment of uncertainty is critical for decision making and I am glad to hear that ASMFC is considering incorporating some of the changes I suggested within future iterations of this ARM framework.

Another parameter Dr. Shoemaker criticized was the estimate of mean horseshoe crab recruitment because of the gap in the Virginia Tech data from 2013 - 2016. The ARM Subcommittee agrees that CMSA estimates of recruitment during these years are poor; therefore, the average of them was used when calculating the overall mean recruitment level. One could argue that recruitment estimates during the Virginia Tech gap years should simply be thrown out. However, doing so ignores the obvious above-average recruitment during those years that must have occurred to increase the multiparous population to the degree that was observed in the following years. The treatment of the missing years of recruitment data balanced the nonsensical estimates of the CMSA with the biological reality that recruitment during these years had to have been relatively high. All other things being equal, changing the mean female horseshoe crab recruitment from 1.67 to 1.26 million, as suggested by Dr. Shoemaker, would result in an unexploited population size at equilibrium of 6.4 million (95% CI: 3.4 – 14.5 million) compared to 8.5 million (95% CI: 4.5 – 19.2 million) in the current parameterization of mean recruitment. If Dr. Shoemaker were correct in his estimate of mean recruitment, the latest population estimates from the Virginia Tech Trawl Survey swept area estimate and CMSA are well above this equilibrium level and the population will likely decline even in the absence of any harvest. It is also interesting to note that Smith et al. (2006) estimated the female population size via a mark-recapture study at 6.25 million in 2003, shortly after the period of high horseshoe crab harvest. This is another line of evidence that the mean recruitment parameter used in the ARM Framework (1.67 million) is more appropriate than the one proposed by Dr. Shoemaker (1.26 million) given the observed increases in female abundance since the population was estimated by Smith et al. (2006).

> First, it is important to point out (as I did in my 2022 report) that the mean recruitment rate parameter is as critical to this ARM framework as any other parameter, since the recruitment process determines the degree to which the horseshoe crab population is resilient to harvest. Therefore, the methods used by ASMFC to estimate horseshoe crab recruitment deserve special scrutiny.
>
> While I understand the rationale of the ARM subcommittee for using the average recruitment estimate from the CMSA model from the Virginia Tech (VT) gap years when computing the mean recruitment rate parameter, I do not find this rationale convincing. If the CMSA results for these years were nonsensical (which we all agree upon), it does not necessarily follow that the arithmetic mean of those nonsensical results will be meaningful. In general, when a model produces nonsensical results, it should provide a signal to the modelers that there is something fundamentally wrong with the model. Furthermore, although the mean recruitment rate during the VT gap years is more sensible than the wildly non-credible estimates for the individual years, the mean value across these years (for which no data was available) was still greater than any single year for which data were available. In this sense, the mean value for the VT gap years also seems inconsistent with the data; such a discrepancy should prompt a re-evaluation of the underlying assumptions, and (ideally) modifications to the model that bring the model more in line with real-world observations of the system.
>
> The ARM subcommittee argues that recent estimates of multiparous abundance from the Virginia Tech trawl are most consistent with the CMSA model results. Specifically, they argue that mean recruitment (under the CMSA model) would need to be higher than the estimate I suggested in my 2022 peer review report (which was based only on the years for which data are available) in order to produce an equilibrium abundance consistent with recent abundance estimates. This argument requires two assumptions: (1) the current horseshoe crab population is at an equilibrium state, and (2) most importantly, that their simulation model is an adequate representation of the horseshoe crab population. However, the nonsensical results from the VT gap years casts serious doubt on the adequacy of the model in the first place (see above).
>
> I do not follow the argument regarding the Smith et al. (2006) study so I will not comment further on that point. Overall, the use of a “worst-case” scenario is commonly used in cases where a risk-averse approach is warranted (for example, when, as here, an action has a risk of harming a threatened or endangered species). In this case, the worst-case scenario (recruitment of 1.26 million) is also supported by the only available data source directly relevant for estimating recruitment rates for this population: the VT trawl surveys.

> Therefore, I maintain that there is a strong case for including this as a plausible value to represent mean recruitment in this poorly understood population.

Dr. Shoemaker shows his female horseshoe crab population projection from his reformulated Bayesian CMSA model that includes his parameterization for recruitment and method for propagating uncertainty. It is interesting that given all his criticism of the ARM model, his model produces nearly identical results with respect to an equilibrium number of primiparous and multiparous females (Figure 8) and associated uncertainty. If anything, his equilibrium population size may be slightly higher than what the revised ARM Framework predicts and the uncertainty on each seems equivalent.

> Simulation results from my Bayesian CMSA model were similar to the results from the ASMFC simulations under baseline conditions. However, a more important test would be to see if these two models produce similar results under a more extreme harvest scenario: that is, whether the ASMFC framework properly represents the stability or instability of the system under plausible future harvest regimes. The simple tests I included in my 2022 peer review report indicated that the way the ASMFC model propagated uncertainty may have overstated the stability of this system and its resilience to harvest (Fig. 3 of my 2022 report, middle and lower panels). Additional tests would be required to confirm this hypothesis. Regardless, I think there is a strong case for ASMFC to revise the horseshoe crab simulation model to ensure proper treatment of uncertainty.

Dr. Shoemaker did not comment on the harvest policy functions, which are the mathematical equations that actually tell the ARM Subcommittee how many horseshoe crabs to harvest given the abundance of horseshoe crabs and red knots. He also did not comment on the Approximate Dynamic Programming (ADP) process by which the harvest policy functions were derived. When solving for the optimal harvest policy functions, ADP incorporated the full range of uncertainty in population projections for both horseshoe crabs and red knots, and within the ADP process, the optimal harvest policy functions would be more conservative with greater uncertainty. Thus, any recommendation of harvest coming from the revised ARM Framework explicitly incorporates uncertainty in population projections.

> During my peer review of the revised ARM framework, I focused my attention on reviewing the demographic models, which was appropriate because this is my primary area of expertise.

Criticism 8: That the ARM model would not predict a decline in red knots under a total collapse of the horseshoe crab population is evidence that the model is fatally flawed.

- Dr. Shoemaker is incorrect that the ARM model would not predict a decline in red knots if the horseshoe crab population collapsed. The assertion that red knots would continue to increase in the absence of horseshoe crabs is mathematically impossible in the model.

<u>Technical Response:</u> In his 2022 critique, Dr. Shoemaker states, "…the apparent inability of the ARM model to predict a decline in red knot abundance under a total horseshoe crab population collapse…undermines the apparent purpose of the model." This judgment can be seen echoed

throughout the materials submitted by Earthjustice in 2022 and 2023, where the narrative is peppered with claims of predicted red knot population increases even at complete depletion of horseshoe crabs from Delaware Bay. The critics' implication is this: if the model is unreliable at the population level of zero horseshoe crabs, how can it be trusted for harvest management at any population level of crab? This is an unfortunate and prejudicial coloring of the model because Dr. Shoemaker was wrong in his 2022 judgment. He not only failed to correct the false assertion in his analysis, but he also amplified it (p. 22) in his later critique.

In Dr. Shoemaker's 2022 critique, he acknowledged that he relied on a "back of the envelope" calculation to arrive at his conclusion because he lacked access to the model data and code at the time. Were he to obtain access to the materials, he fairly asked, "[w]hat would happen to the red knot population projections if female horseshoe crab abundance were set to zero?" For his 2023 evaluation, Dr. Shoemaker was provided access to the data and code, yet he failed to address his own question. He would have observed that the data used to establish the relationship between female horseshoe crab abundance and red knot survival was the logarithm of female horseshoe crab abundance (ASMFC 2022) and not female abundance as it comes straight from the CMSA estimates. Consequently, the model predicts that red knot survival declines to 0 as female horseshoe crab abundance decreases, and a population increase in red knots under this condition is mathematically impossible.

> This argument by the ARM subcommittee has more to do with mathematical technicalities than with ecology. Please see opening statement #2 for a detailed response to this comment.

Misunderstanding and mischaracterization of the model aside, prediction by any model for a scenario well outside of the data bounds of model development is a dangerous exercise. A complete loss of horseshoe crabs through harvest is an extreme and unlikely hypothetical scenario that was not considered by the ARM Subcommittee. Such a collapse would require a harvest level greatly exceeding any previously observed harvest level, let alone any harvest level that is within the range of possible values given the current fishery management plan stipulations. The critics should give the ARM Subcommittee and Board some benefit of the doubt: if the horseshoe crab population should fall below any historically observed levels, and outside the bounds of model development, the ARM Subcommittee is sure all would agree that horseshoe crab harvest should be drastically reduced or ceased. This demonstrates an attempt to sensationalize an extremely rare possibility and paint scientific management of the species as reckless.

> First of all, there is great heuristic value in understanding how the red knot population model, as implemented in the revised ARM, would fare under a collapse of the horseshoe crab stock. Importantly, this exercise illustrates that the ASMFC model, as currently specified, could not predict the observed decline of red knots in the late 1990s and early 2000s, which has been attributed largely to the decline of horseshoe crabs due to unregulated harvest in the 1990s (Niles et al. 2009). Notably, the original ARM used by ASMFC included candidate models with a stronger relationship between red knot demography and horseshoe crabs, and the modelers took care to demonstrate that these

models were capable of explaining the observed declines in the red knot (McGowan et al. 2011), thereby recognizing the value of performing this scenario test and of including a "strong interaction" model within the candidate model set.

Further, ASMFC argues that statistical extrapolation (making predictions outside the bounds of the data) can be dangerous and misleading. While there is some merit to this argument in a general sense, it ignores the fact that the model's primary utility was to make predictions across a broad range of future scenarios. In the context of the ARM optimization routine, simulation results from scenarios spanning a wide range of horseshoe crab abundance and harvest rates are used to generate optimal harvest functions for use in setting harvest quotas. This exercise requires extrapolation- the red knot simulation model must be able to predict what would happen under scenarios of reduced horseshoe crabs (and/or increased and recovering red knot populations, which in aggregate may require a higher total abundance of eggs) to be useful for making informed decisions across a wide range of plausible future system states. Finally, if ASMFC argues that the model is valid only within a particular range of horseshoe crab abundance, they should identify that range and explain why such limitation doesn't raise broader concerns about the revised ARM framework.

I don't think anyone seriously believes (or has claimed) that ASMFC would continue recommending commercial harvest of horseshoe crabs in the face of an observed and ongoing collapse of the horseshoe crab population. But that is not the point of my analysis. The point is that the decision-making value of this framework requires that the underlying models are able to make reasonable predictions across a wide range of scenarios- including a major decline (or increase) in one or both species. The revised ARM proved unable to do so.

Finally, in reviewing the methods used by the ARM subcommittee to prepare the horseshoe crab abundance estimates for use in the red knot IPM, I noticed that they log-transformed the CMSA estimate (in units of millions) and used this log-transformed covariate directly in their analyses. In Bayesian modeling (and GLMs more generally) it is common practice to center and scale all covariates, which typically involves subtracting raw measurement by the sample mean (zero-centering), often followed by dividing the resulting quantity by the sample standard deviation. This practice is useful for enabling regression coefficients to be directly comparable, but even more importantly, zero-centering aids in model convergence by reducing collinearity among the free parameters being estimated (for example, it reduces collinearity between intercept terms and regression coefficients). In the red knot IPM, all covariates were centered and scaled prior to analysis, with the exception of horseshoe crab abundance (which was log-transformed but not centered and scaled). I point this out because it is a surprising choice by the modelers, and it may have added to the instability of model convergence and potentially influenced the model results. For this reason, and as an appropriately cautionary approach, I would recommend running some tests to ensure that this decision did not unintentionally influence key model outputs.

Criticism 10: There is an incorrect specification of "pi" parameter in the red knot integrated population model.

- This is a criticism that does warrant further consideration by the ARM Subcommittee.

Technical Response: Dr. Shoemaker asserts that there is a missing parameter that should be included in the derivation of π_{jj} (the probability of being present in Delaware Bay in occasion *t* of year *j*) to represent the fraction of the population using Delaware Bay in the previous year. This seems to be a valid criticism, but requires further scrutiny to understand whether this parameter is derived incorrectly and, if so, what the implications might be. The ARM Subcommittee is exploring solutions.

> I am glad to hear the ARM subcommittee is looking into this issue. I agree that the implications of this issue for the results of this analysis are unclear- and not necessarily minor.

Criticism 11: There is an over-representation of Mispillion Harbor in red knot resighting data.

- Use of data from Mispillion Harbor does not result in biased inferences.

Technical Response: More resighting data is collected in Mispillion Harbor than any other site in Delaware Bay. However, red knots move around the Bay during the stopover period and are often resighted in more than one location within a year. The open robust design sub-model makes use of those repeated observations instead of collapsing all information about each bird into a single 0 or 1, as Dr. Shoemaker did to fit his Cormack-Jolly-Seber model. Given this, it is unclear how Dr. Shoemaker decided that a given bird belonged to the "Mispillion" or "Not Mispillion" group, given that many birds are seen both within and outside of Mispillion Harbor in a given year. The proportion of birds seen only in Mispillion ranges from 0.12 to 0.54 (0). The proportion of birds never seen in Mispillion ranges from 0.17 to 0.69. Given this variation and lack of systematic bias towards birds only being resighted in Mispillion Harbor, we do not believe there is reason to think that the large number of observations from this site result in biased inference.

> I do not think this is a major area of concern (which is why I included it as a supplement). My tests did not indicate a strong bias that was induced by the over-representation of this site in the resighting dataset. I do think it is worth noting, though, that the resighting data are so heavily dominated by this one site.
>
> The method I used to separate "Mispillion" birds from "non-Mispillion" birds was simply to filter the red knot resightings data frame to include or exclude all observations from this site. I performed this sub-setting operation before I collapsed within-year observations into zeros and ones- therefore, some birds were included in both analyses. I made it clear from the outset that I was happy to address any questions the ARM subcommittee had, but on this issue, as on others, no one from the ARM subcommittee reached out to ask such questions directly.

Literature cited

Atlantic States Marine Fisheries Commission (ASMFC). 2021. Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation and Peer Review Report. Arlington, VA. 302 pp. http://www.asmfc.org/species/horseshoe-crab

Grace, J.B., Anderson, T.M., Olff, H. and Scheiner, S.M., 2010. On the specification of structural equation models for ecological systems. Ecological monographs, 80(1), pp.67-87.

McGowan, C.P., Smith, D.R., Sweka, J.A., Martin, J., Nichols, J.D., Wong, R., Lyons, J.E., Niles, L.J., Kalasz, K., Brust, J. and Klopfer, M., 2011. Multispecies modeling for adaptive management of horseshoe crabs and red knots in the Delaware Bay. Natural Resource Modeling, 24(1), pp.117-156.

McGowan, C.P., Smith, D.R., Nichols, J.D., Lyons, J.E., Sweka, J., Kalasz, K., Niles, L.J., Wong, R., Brust, J., Davis, M. and Spear, B., 2015. Implementation of a framework for multi-species, multi-objective adaptive management in Delaware Bay. Biological Conservation, 191, pp.759-769.

Nichols, J.D., Runge, M.C., Johnson, F.A. and Williams, B.K., 2007. Adaptive harvest management of North American waterfowl populations: a brief history and future prospects. Journal of Ornithology, 148, pp.343-349.

Niles, L.J., J. Bart, H.P. Sitters, A.D. Dey, K.E. Clark, P.W. Atkinson, A.J. Baker, K.A. Bennet, K. Kalasz, N.A. Clark, J. Clark, S. Gillings, A.S. Gates, P.M. González, D.E. Hernandez, C.D.T. Minton, R.I.G. Morrison, R.R. Porter, R.K. Ross, and C.R. Veitch. 2009. Effect of horseshoe crab harvest in Delaware Bay on red knots: are harvest restrictions working? BioScience 59:153-164.

O’Brien, S., B. Robert, and H. Tiandry. 2005. Consequences of violating the recapture duration assumption of mark-recapture models: A test using simulated and empirical data from an endangered tortoise population. Journal of Applied Ecology 42:1096–1104.

Platt, J.R., 1964. Strong Inference: Certain systematic methods of scientific thinking may produce much more rapid progress than others. science, 146(3642), pp.347-353.

Rakhimberdiev, E., Karagicheva, J., Saveliev, A., Loonstra, A. J., Verhoeven, M. A., Hooijmeijer, J. C., ... & Piersma, T. (2022). Misidentification errors in reencounters result in biased estimates of survival probability from CJS models: Evidence and a solution using the robust design. Methods in Ecology and Evolution, 13(5), 1106-1118.

Riecke, T.V., Williams, P.J., Behnke, T.L., Gibson, D., Leach, A.G., Sedinger, B.S., Street, P.A. and Sedinger, J.S., 2019. Integrated population models: model assumptions and inference. Methods in Ecology and Evolution, 10(7), pp.1072-1082.

Runge, M.C., 2011. An introduction to adaptive management for threatened and endangered species. Journal of Fish and Wildlife Management, 2(2), pp.220-233.

Schaub, M. and Kéry, M., 2021. Integrated population models: Theory and ecological applications with R and JAGS. Academic Press.

Smith, J.A.M., A. Dey, K. Williams, T. Diehl, S. Feigin, and L.J. Niles. 2022. Horseshoe crab egg availability for shorebirds in the Delaware Bay: dramatic reduction after unregulated horseshoe crab harvest and limited recovery after 20 years of management. Aquatic Conservation: Marine and Freshwater Ecosystems. 2022:1-13. DOI: 10.1002/aqc.3887.

Tucker, A.M., C.P. McGowan, R.A. Robinson, J.A. Clark, J.E. Lyons, A. Derose-Wilson, R. Feu, G.E. Austin, P.W. Atkinson, and N.A. Clark. 2019. Effects of individual misidentification on estimates of survival in long-term mark-resight studies. The Condor: Ornithological Applications 121:1–13.

Tucker, A.M., McGowan, C.P., Lyons, J.E., DeRose-Wilson, A. and Clark, N.A., 2022. Species-specific demographic and behavioral responses to food availability during migratory stopover. Population Ecology, 64(1), pp.19-34.

Tucker, A.M., McGowan, C.P., Nuse, B.L., Lyons, J.E., Moore, C.T., Smith, D.R., Sweka, J.A., Anstead, K.A., DeRose-Wilson, A. and Clark, N.A., 2023. Estimating recruitment rate and population dynamics at a migratory stopover site using an integrated population model. Ecosphere, 14(2), p.e4439.

U.S. Fish and Wildlife Service (USFWS), 2014. *Rufa* red knots: Background Information and Threat Assessment. Supplement to Endangered and Threatened Wildlife and Plants; Final Threatened Status for the Rufa red knots (*Calidris canutus* Rufa). U.S. Fish and Wildlife Service, Pleasantville, New Jersey, USA (2014) [Docket No. FWS-R5-ES-2013-0097; RIN AY17]

Williams, B.K., 2011. Adaptive management of natural resources—framework and issues. Journal of environmental management, 92(5), pp.1346-1353.

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Survival of red knots in the northern Gulf of Mexico

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Highly migratory shorebirds are among the fastest declining avian guilds, so determining causes of mortality is critically important for their conservation. Most of these species depend on a specific geographic arrangement of suitable sites that reliably provide resources needed to fuel physiologically demanding life histories. Long-term mark-resight projects allow researchers to investigate specific potential sources of variation in demographic rates between populations. Red Knots (*Calidris canutus*) occur in three relatively distinct regions across the northern Gulf of Mexico, and two of these areas have been experiencing episodic harmful algal blooms (red tide) with increased frequency in recent decades. Since knots are mostly molluscivorous during the nonbreeding season in the Gulf, they are potentially exposed to red tide toxins at high concentrations via their filter-feeding prey. We used long-term mark-resight data from Texas, Louisiana, and Florida (USA) to estimate apparent survival, and to assess the effects of red tides on survival of Red Knots. We also assessed effects of tracking devices deployed in conjunction with the projects over the years. While overall apparent annual survival rates were similar across the three locations (0.768 – 0.819), several red tide events were associated with catastrophically low seasonal (fall) survival in Florida (as low as 0.492) and Texas (as low as 0.510). Leg-mounted geolocators, but not temporary glued-on VHF tags, were associated with a reduction in apparent survival (~8%/year). Movement of knots between the three areas was rare and site fidelity is known to be high. Harmful algal blooms are predicted to increase in frequency and severity with climate change and increased anthropogenic degradation of coastal habitats, which may further endanger these as well as other shorebird populations around the world.

KEYWORDS

survival, shorebird, harmful algal bloom, red tide, molluscivore, red knot, Gulf of Mexico, mark-resight

1 Introduction

Understanding demographic parameters is fundamental to monitoring and managing wildlife populations, but the highly migratory nature of many shorebird species makes estimation of these parameters distinctly challenging (Faaborg et al., 2010). Species may have broad or disjunct breeding ranges, geographically distinct nonbreeding populations, and rely differentially on migratory stopovers between the two. Being able to isolate parameters (and factors that may affect them) to specific populations requires knowledge of connectivity (Webster et al., 2002; Rushing et al., 2017), since consequences of factors affecting one part of the annual cycle can have carry-over effects on subsequent ones (Goss-Custard et al., 1995; Norris, 2005; Duijns et al., 2017). Survival rates of adults and post-fledged juveniles have been demonstrated to be the most consequential to population growth rates of several migratory shorebirds (Hitchcock and Gratto-Trevor, 1997; Calvert et al., 2006). For migratory shorebirds that use different geographic areas for discrete parts of their annual cycle, changes in habitat quality in any part of the cycle can have a strong effect on survival (Johnson et al., 2006; Duriez et al., 2012).

Coastal habitats worldwide have been degraded by human activities such as shoreline development, pollution, and freshwater diversions (Kennish, 2002), decreasing their capacity to support populations of migratory shorebirds (Fernández and Lank, 2006). Beyond direct losses, anthropogenic disturbance can be functionally equivalent to habitat loss or degradation by rendering sites unusable (Gill and Sutherland, 2000). Norris and Marra (2007) demonstrated that differences in habitat quality in one part of the annual cycle can have interseasonal effects on population dynamics depending on the strength of migratory connectivity. When connectivity is strong, further habitat loss from projected sea level rise is likely to result in bottlenecks with potential consequences to populations proportionately larger than the habitat loss itself (Iwamura et al., 2013).

Harmful algal blooms (HABs) occur in aquatic environments and can be considered extreme biological events resulting in major disruption to coastal ecosystems through complex food web dynamics (Landsberg et al., 2009). HABs have occurred in the Gulf of Mexico far back into recorded history (Magaña et al., 2003). They have increased in frequency and now occur commonly on the coasts of Texas/Mexico and western Florida (Hallegraeff, 1993, van Dolah 2000, Walsh et al., 2006; Brand and Compton, 2007; Tominack et al., 2020). Blooms in the Gulf of Mexico resulting in fish kills associated with the dinoflagellate *Karenia brevis* are typically known as "red tides." The organism produces brevetoxin, a very potent neurotoxin that kills fish through absorption across gill membranes (Abbott et al., 1975) or consumption of toxic biota (Tester et al., 2000). These toxins can accumulate and result in mortalities of higher vertebrates directly and indirectly through food web dynamics (Landsberg et al., 2009). Filter-feeding molluscs – especially bivalves – readily accumulate brevetoxins in high concentrations (Bricelj et al., 2012; Van Hemert et al., 2022) and occasionally experience direct lethal effects, as well as sublethal effects that result in subsequent recruitment failure (Summerson and Peterson, 1990). However, most mollusk species survive exposure to brevetoxins, accumulating high concentrations of toxins that can then be ingested by consumers (Landsberg, 2002). In addition to effects from direct consumption, brevetoxin from lysed cells can reach extremely high concentrations that can persist in waters and sediments for several weeks after the bloom organism has dissipated (Pierce and Henry, 2008; Castle et al., 2013), exposing probe-feeding shorebirds to additional dosages through passive uptake. Despite strong evidence correlating bird mortalities with HABs (Van Hemert et al., 2021, 2022), data from experimental studies or laboratory examination of tissue samples are relatively scarce (Shumway et al., 2003). Impacts are likely underestimated due to depredation and decomposition of carcasses, and removal of carcasses through tidal action (Sutherland et al., 2012). Further, a lack of long-term demographic monitoring of affected avian species has confounded determination of population level effects, though a recent study found a relationship between HAB occurrence and survival in Gulf-wintering Piping Plovers (Ellis et al., 2021).

The Red Knot (*Calidris canutus*) is a Holarctic breeding shorebird comprising six currently recognized subspecies. In the Western Hemisphere, the *C. c. rufa* subspecies spends nonbreeding seasons in the southern US and neighboring Mexico, especially the states bordering the Gulf of Mexico (henceforth, the "Gulf"), the Caribbean, and several regions in South America from northern Brazil to Tierra del Fuego (Niles et al., 2008). Additionally, some knots wintering on the Pacific coast of southern Mexico (Oaxaca) south to Chiloé Island, Chile occur in Texas and Louisiana during migration – primarily during spring – and consist of both *C. c. rufa* and *C. c. roselaari* (Newstead, unpubl. data). Though the total population of knots that do this is not known, it is suspected to be considerably less than those wintering in the Gulf. Knots in the Gulf are concentrated primarily in three general areas: southwestern Florida, the barrier islands of Louisiana, and the coast of south Texas and Tamaulipas. These Gulf states are among the highest latitude wintering sites (~24° – 29° N) of the *C.c. rufa* subspecies, used not only during the extensive nonbreeding season but also for pre-migratory and post-breeding stages. Observations of marked individuals (Tuma and Powell, 2021, Newstead, unpubl. data) confirm high site fidelity to each of these locations, consistent with studies on other subspecies (Harrington et al., 1998; Leyrer et al., 2006; Buchanan et al., 2012; Musmeci et al., 2022).

Geolocator studies (Newstead et al., 2013, Newstead, unpubl. data) show that the Texas and Louisiana populations migrate almost exclusively through the interior of the North American continent rather than using sites along the Atlantic coast. The decline of more than 75% of the Atlantic Flyway *rufa* population over the course of two decades (Niles et al., 2008) prompted its listing as Endangered in Canada in 2007 (COSEWIC, 2007) and as Threatened under the US Endangered Species Act in 2014 (USFWS, 2014a). Recognition and understanding of the Gulf populations – particularly the Texas and Louisiana populations – have been relatively recent discoveries, and there has been no previous estimation of survival parameters that can be compared across the three locations. The Red Knot is considered primarily a molluscivore during the non-breeding season (van Gils et al., 2006; Baker et al., 2013). The species' reliance on coquina clams

(*Donax* spp.) when using Gulf beaches makes it particularly vulnerable to HABs and they have been observed exhibiting symptoms of neurotoxic shellfish poisoning during red tide events (DN, personal observation). Carcasses of knots encountered freshly dead or dying were found to have exceptionally high levels of brevetoxin in all tissues tested, with the highest levels in the liver and gastrointestinal tract (Rafalski, 2012).

New tracking technologies continue to contribute major breakthroughs in our understanding of avian life histories (Bridge et al., 2010; Robinson et al., 2010; Wilmers et al., 2015). The use of archival light-level data loggers (geolocators), radiotransmitters, GPS and cellular technologies has drastically expanded our understanding of migratory strategies and revealed previously-unknown sites of essential importance (Stutchbury et al., 2009; Newstead et al., 2013; McKellar et al., 2015; Chan et al., 2019). While these discoveries have been critical in directing further research and conservation actions to places that can best benefit the species, the effects of tracking devices on the movements, activities, and, ultimately, survival of tracked animals remains a source of concern (Barron et al., 2010; Elliott et al., 2012; Scarpignato et al., 2016). Meta-analyses on device effects on birds (survival, behavior, reproductive success and others) have revealed some significant negative consequences varying by species, device type, attachment method, migration distance, and many other factors (Barron et al., 2010; Costantini and Møller, 2013). Specific to shorebirds, most studies have reported no significant impact of leg-mounted geolocators based on metrics from the year following deployment (Conklin and Battley, 2010; Pakanen et al., 2015; Mondain-Monval et al., 2020). Reductions in one-year return rates were detected for only two of 23 Arctic-breeding shorebird populations carrying geolocators relative to individuals carrying only a unique leg marker, with no detectable effect on the Great and Red knots included in the analysis (Weiser et al., 2016). However, Pakanen et al. (2020) found that when they extended their analysis of Dunlin (*C. alpina*) tracked over multiple years, apparent survival was lower for birds carrying geolocators compared to those without. These findings suggest that negative effects may accumulate over time or result in incremental increases in mortality risk. When possible, longer-term datasets should be analyzed to determine consequences that may not be evident based on one-year return rates alone. Small VHF transmitters attached to birds tracked using direct or automated radiotelemetry have also yielded important findings for many shorebirds, especially for local movements (Green et al., 2002; Warnock and Takekawa, 2003; Rogers et al., 2006; Duijns et al., 2019). Most VHF tag deployments on shorebirds have utilized an adhesive to affix the transmitter to the back, which subsequently falls off the bird with the next molt cycle or sooner, and these studies have generally reported no short-term survival consequences (Drake et al., 2001; Barron et al., 2010; Buchanan et al., 2019; Stantial et al., 2019).

Annual survival is a key underlying demographic parameter that can vary with environmental conditions, and strongly influences population trends. When data are sufficient, annual survival can be apportioned into partial (e.g. seasonal or semi-annual) components, providing greater insight into what particular locations or processes are contributing to demographic change (Gauthier et al., 2001; Leyrer et al., 2013; Piersma et al., 2016; van Irsel et al., 2022). We used mark-resight data from three projects involving captures of Red Knots in the three main Gulf of Mexico wintering areas to compare annual (and seasonal when possible) survival rates between populations, and to assess effects of an increasingly prevalent coastal ecosystem stressor (HABs) and the use of tracking devices on survival.

2 Methods

2.1 Study area

The northern Gulf of Mexico is bordered by a fairly contiguous extent of sandy beaches punctuated by passes connecting to bays and other receiving waters. Sediment grain size composition and origin (biogenic and terrigenous) vary widely across the Gulf, which affects the character of benthic infaunal communities and consequently the distribution of shorebirds that use them. Red Knots occur regularly in three primary areas across the Gulf – Florida, where they are most concentrated in the southwestern region between Clearwater and Marco Island; Louisiana, where they occur on the beaches of Grand Isle and the adjacent Caminada Headlands as well as the offshore barrier islands of the Breton Island National Wildlife Refuge; and Texas, where they are most common on the southern half of the coast from the Corpus Christi area to the border with Mexico, and likely well into contiguous parts of Tamaulipas where habitat is very similar. These three main areas are at least 600 km from one another and are considered as separate population units for the purpose of recovery planning (USFWS, 2021). These three geopolitical states are henceforth referred to as "locations" to avoid potential confusion with conditional states related to the analysis.

2.2 Field methods

For this project, captures of Red Knots occurred in Texas on Mustang and North Padre Islands between October 2009 – October 2019, in Louisiana on Grand Isle and the Caminada Headlands from the eastern end of Elmer's Island west to Port Fourchon between April 2014 – April 2019; and in Florida from Longboat Key to Sanibel Island between October 2005 – March 2010.

All Red Knots were captured using a cannon-net (~ 9 m X 9 m, or ~10 m X 25 m) on beaches where birds were foraging or resting. Standard processing included a federal metal band on tarsus or tibia, a uniquely inscribed alphanumeric green flag on the opposite tibia, measures of bill and total head length (nearest 0.1mm), flattened wing chord length (mm), and mass (grams). A clip of the distal portion of the 6th primary covert was retained from most captured birds for isotopic analysis (carbon, nitrogen, hydrogen isotopes; for a project to assign migrants to wintering sites), and a blood sample was taken by brachial venipuncture on a smaller sample of birds for future genetic analysis.

In Florida, capture effort was concentrated between November – March (>95% of all captures) between years 2005-2010. Capture effort in Texas was mostly focused on fall and spring periods (>90% of all captures between September-November, or April-May) with smaller catches in other months, between 2009-2019. Louisiana captures were all in April, from 2014-2019. The distribution of resights by month was similar to that of the captures, except for Florida when many resights were recorded in months before and after the main winter months which constituted the bulk of the capture efforts.

Multiple tracking projects were conducted during the course of the projects. Archival light-level dataloggers (henceforth, "geolocators"; British Antarctic Survey [BAS] Model MK10 and MK12 or Migrate Technologies Intigeo W65) were mounted on leg flags and attached to the tibiotarsus as described in Niles et al. (2010). All assemblies weighed < 1.4 g. Radiotelemetry studies in Louisiana and Texas included deployment of small VHF transmitters (Lotek NTQB-4-2, 0.9 g) glued to the intrascapular region, as described in Newstead (2014).

2.3 Encounter histories and covariates

Encounter data were compiled from multiple resight projects and public domain records in bandedbirds.org; additional records were made available directly to the author. Encounter occasions began with the first capture effort in Florida in winter 2005/6 and ended in winter 2019/20 season.

Only records from Florida, Louisiana and Texas were used to build encounter histories. Birds were assigned to one of the three locations based on their original capture location. If an individual was encountered outside the location of initial capture (i.e., in one of the other two locations) and there were no subsequent records within the capture location it was removed from the dataset. This eliminated only a small number of birds from the dataset that may have switched wintering location or underwent atypical migrations.

Resightings were divided into three encounter occasions per year: the fall encounter (July 20 – October 31; 104 d; midpoint September 9), winter encounter (December 15 – January 31; 48 d; midpoint January 7), and spring encounter (April 1 – May 30; 60 d; midpoint May 1; Figure 1). Based on the midpoints of the encounter occasions, the year was thus divided into three intervals: (fall to winter – 120 d; winter to spring – 114 d; spring to fall – 131 d). These are referred to as the fall, winter, and summer intervals, respectively. The time range from the earliest captures to the most recent encounters spans 43 occasions (42 intervals).

As defined, the intervals generally reflect distinct and important phases in the annual cycle: during "fall" birds are returning from the Arctic and undergoing a body molt including flight feathers; during "winter" birds are managing a balance of predation risk, prey resource availability and maintaining sufficient fat reserves; during "summer" adult birds undertake a major migratory journey to Arctic breeding grounds, spend two to three months attempting to breed, and then return to nonbreeding areas. While juvenile birds nearly all remain on nonbreeding areas in their first full summer, they are exposed to factors such as extreme heat and increased human disturbance that adults mostly escape.

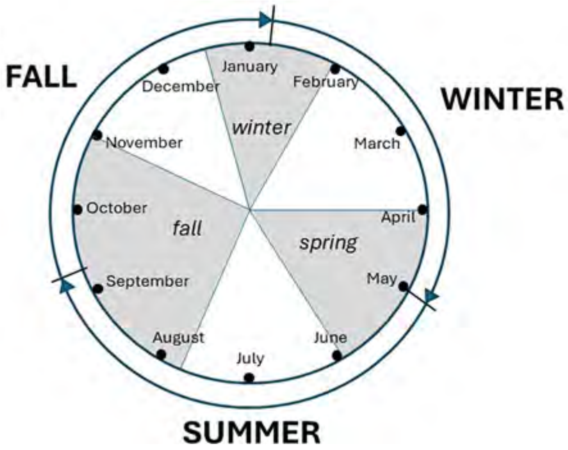

FIGURE 1
Encounter periods (grey), occasion midpoints (lines extending from outer circle), and season interval names for apparent survival analysis on Red Knots in the northern Gulf of Mexico.

Individuals were grouped into one of three age classes based on age at capture. Birds that were not aged upon capture were classified as "unknown" age. Birds classified as hatch-year prior to, or second-year during, a spring occasion were classified as juvenile. Birds aged as second-year or after-hatch-year following a spring occasion (i.e., they had survived the first full oversummer interval so were > 1 year old), and all birds aged as after-second-year were classified as adult. Juveniles and birds of unknown/unspecified age were assumed to recruit into the adult age class following the first summer interval.

Since occasions are assumed to be instantaneous, the initial occasion for birds captured during intervals was assigned to be the subsequent occasion, so that estimates would not be biased by partial interval effects.

We included covariates in the dataset to test whether negative effects of tracking devices resulted in lower apparent survival. Effects of leg-mounted geolocators and glue-on VHF transmitters were assessed using a set of time-varying binary covariates for each. Once deployed, an individual with a geolocator was assumed to retain the geolocator permanently unless it was removed. VHF transmitters glued to the intrascapular region typically fall off within a few months of deployment, so the covariate was applied for only the subsequent interval.

Since HABs (especially "red tides") have been observed to result in direct mortality to Red Knots, we hypothesized that exposure to toxins could result in lower apparent survival either through additional (undetected) direct mortality or sublethal effects. Effects of red tide were assessed using several approaches. Red tide sampling occurs in Florida (inshore and offshore) with good spatial and temporal coverage through the HABSOS system (NOAA National Centers for Environmental Information, 2014). The monthly bloom severity index (BSI) developed by Stumpf et al. (2022) was used to identify intervals when red tide blooms were affecting the southwest Florida coast. Red tide effects can occur at relatively low concentrations, but generally begin having pronounced effects resulting in fish kills at concentrations

>1,000,000 cells/L. The summed BSIs for months corresponding to intervals in this study were used to classify red tide as absent/minimal (summed BSI = 0, covariate = -1), moderate (summed BSI > 0 but < 5, covariate = 0), or severe (summed BSI > 5, covariate = 1). In Texas, red tide monitoring is conducted mostly in response to known or suspected occurrences. Since events vary greatly in their range and extent of impact to marine life, fish kill reports were used as a secondary source to confirm an event to a degree that would have resulted in high likelihood of the shoreline being exposed to the effects of the bloom. For Texas, red tide events were ascribed to seasons based on Tominack et al. (2020), and severity was assigned as appropriate to the geography utilized by knots. A covariate set was thus created for each location based on red tide being absent/minimal, moderate, or severe (-1, 0, and 1, respectively) during each interval. A covariate set including all red tide events was made for each location separately, and another that included all locations together (but the red tide covariates applicable to each location separately).

Because knots are highly mobile and likely vary in their degree of exposure to harmful algal blooms depending on various environmental factors, we also tested the effect of each individual red tide season against all others. Separate covariate sets were created for each red tide season occurrence in Florida and Texas to assess the effect of red tide events independently. The covariate value of 1 was assigned to intervals when red tide was present (either moderate or severe), and 0 for all others. Based on our criteria, there were a total of 17 and 6 red tide season events for Florida and Texas, respectively, applicable to the 42 intervals of the study, so a covariate set was created for each of these.

2.4 Statistical analyses

Models were evaluated using a Cormack-Jolly-Seber (CJS) framework in Program MARK (v. 9.0, White and Burnham, 1999) to estimate apparent survival (φ) and encounter (*p*) probabilities. Apparent survival is the probability that a knot alive at occasion *i* was alive and in the study area at occasion *i + 1*. Its inverse includes mortality and permanent emigration from the study area. Goodness-of-fit testing was run on the fully time-varying model and contingency tables were examined individually to assess whether patterns indicated lack of independence in the data. The median $\hat{c}$ approach was applied to account for overdispersion in all subsequent models. Model evaluation was based on quasi-Akaike's Information Criterion adjusted for sample size ($QAIC_c$) and model weights (ω_i). We built models in an ordered 3-step process described below.

2.4.1 Step 1: determining best underlying model structures

Preliminary evaluation of the dataset indicated major differences in the distribution of encounters between locations and seasons, so model fitting began with a series of models holding φ constant by location and allowing for variation in *p* by location, season, and age. Using the best parameter structure for *p*, models incorporating variability in φ by location, season and age (and combinations thereof) were then tested to determine the best fit for a base model. Models in which covariate parameters were poorly estimated (standard errors of effect coefficient very close to zero or greater than 2.0) were removed from the resulting model set. Models within 2 ΔQAICc of the top model were considered well-supported, and the top model was carried forward for testing of the time-varying covariate datasets.

2.4.2 Step 2: building a candidate model set with red tide index and tracking device effects

We then built a candidate set of models that included covariates added to the most competitive base model. We considered the effect of tracking devices (geolocators, VHF transmitters) independently as well as combined. Given differences in habitat distribution and the character and duration of red tide events between Texas and Florida, we considered the effect of red tide on each location modeled independently, as well as together. We then considered models that included both tracking device and red tide effects. Covariates were considered predictive if the 95% confidence intervals (C.I.) of effect coefficients did not include zero. Apparent survival and encounter probabilities were reported based on the top model that did not include a red tide effect. If all parameters were well estimated in a model including seasonal variation within a location, the model including those terms and the tracking device effects was used to estimate those season-specific parameters (i.e. to provide estimates unaffected by tracking devices). To facilitate comparison with other studies, apparent seasonal survival (φ_a) estimates and 95% C.I.s were converted to apparent annual estimates using the delta method (Powell, 2007), either as a product of the three separate seasonal estimates or exponentiation of the non-season specific estimates.

2.4.3 Step 3: evaluating survival in specific red tide seasons

To evaluate the effect of specific red tide events, we used the most competitive base model and independently added each red tide season to the model as applicable to each location. We considered a red tide event to be poorly estimated if its inclusion resulted in other parameters being poorly estimated. Red tide events (seasons) were considered significant if the 95% C.I.s of the effect coefficient did not overlap zero. For significant seasons, the magnitude of the effect on φ was calculated as the percentage difference between the mean estimate of the survival probability in that season relative to the survival probability of all other seasons for that location.

To estimate survival for each significant red tide season, we ran a *post-hoc* model treating each of those seasons individually and accounted for any significant tracking device effects. If any coefficient became non-significant in this model, that covariate was removed and the reduced model run until all terms were significant.

The strength of differences between locations was assessed by whether 95% C.I.s overlapped, and covariate effects were assessed by whether the 95% C.I. included zero. C.I.s are presented in brackets following the mean, unless otherwise noted.

3 Results

Encounter histories were constructed from 2,412 knots (Florida: 1,373 captured between 2005-2010; Louisiana: 255 captured between 2014-2019; Texas: 784 captured between 2009-2019), and 4,078 resights (Florida: 3,013; Louisiana: 188, Texas, 877; Supplementary Table 1). Geolocators were deployed on 68, 49, and 114 knots in Florida, Louisiana and Texas, respectively. VHF transmitters were deployed on 18 and 115 knots in Louisiana and Texas, respectively.

There were 17 red tide seasons in Florida (8 severe, 9 moderate) during the 42 intervals since marking began. Two were in summer (one moderate, one severe). Both summer events preceded severe fall events. Of nine fall events (three moderate, six severe), six persisted into the subsequent winter interval. There were no winter events that were not preceded by a fall red tide event. In Texas, there were 6 red tide seasons (3 severe, 3 moderate) during the 31 intervals since marking began. All Texas red tide seasons were in fall.

3.1 Best underlying model structures

The goodness-of-fit test indicated some overdispersion in the data but examination of contingency tables did not suggest any systematic source of bias. Differences in resighting effort (p) between years and locations were likely responsible for high model deviance. Subsequently, all models were adjusted using median $\hat{c}$ = 1.155. The best models for the encounter parameters included location and season. All models including age resulted in multiple parameters being poorly estimated, so these were removed from further consideration. All subsequent model runs utilized the $p_{(\text{location, season})}$ parameterization.

The top base model for explaining variation in Red Knot apparent survival included a constant seasonal survival term (φ_c) for each location. A competing model allowed for season-specific (φ_f, φ_w, φ_s) parameters for Florida, but not for Texas and Louisiana. A model with constant seasonal survival across locations received the lowest model weight of the three. The two most competitive models were carried forward for model development incorporating HAB and tracking device covariates.

3.2 Assessment of candidate models including red tide index and tracking device effects

All models testing tracking device and red tide effects on the base model that included seasonal variation in survival in Florida had uniformly higher QAICc than the corresponding models based on the constant seasonal survival base model. Since the inclusion of variation in seasonal survival in Florida did not improve model fit in any case, these models were removed from the candidate model set.

The best fitting model included effects of geolocators and red tide in Florida (Table 1). The four top models each had a likelihood >0.125 (indicating support; Burnham and Anderson, 2002), and all included the geolocator covariate. The geolocator effect was negative and significant in all models that included it. VHF transmitter and red tide covariates were also all negative but non-significant when included in the models. Multiple parameters were poorly estimated in all models that included red tide in Texas only. The effect of geolocator in the top-ranked model without a red tide effect ($\hat{\beta}$ = -0.445 [-0.655, -0.236]) equates to an estimated reduction in seasonal apparent survival of 4.1%, 3.2%, and 3.8% for Texas, Louisiana, and Florida, respectively.

The top-ranked model that did not include a red tide effect was used to estimate apparent survival for each location. With tracking devices accounted for separately in the model, mean apparent seasonal survival was highest for Louisiana, intermediate in Florida, and lowest in Texas, though C.I.s overlapped (Table 2). Resighting probabilities varied between seasons within each location.

TABLE 1 Model ranking including combinations of red tide and tracking device covariates applied to the best-fitting base model (Φ_{location}, $p_{\text{location, season}}$) for Red Knots from Texas, Louisiana, and Florida populations from 2005-2019.

Model	Red tide	Tracking device	Δ QAIC$_c$	ω_i	Likelihood	K	QDeviance
1	Florida	geo	0.00	0.37	1.00	14	21295.7
2[a]	–	geo	0.33	0.32	0.85	13	21298.1
3	–	geo, VHF	1.92	0.14	0.38	14	21297.6
4	All	geo	2.33	0.12	0.31	14	21298.1
5	All	geo, VHF	3.92	0.05	0.14	15	21297.6
6	Florida	–	13.47	0.00	0.00	13	21311.2
7[b]	–	–	14.28	0.00	0.00	12	21314.0
8	–	VHF	16.14	0.00	0.00	13	21313.9
9	All	–	16.19	0.00	0.00	13	21313.9
10	All	VHF	18.03	0.00	0.00	14	21313.8

[a] Top-ranked model not including a red tide effect, on which reported seasonal survival estimates and geolocator effects are based.

[b] Base model (no covariates) from Step 1 on which subsequent model development was based.

Estimation of distinct seasonal apparent survival probabilities was only possible for Florida. When seasonal variation for Florida was added to the top-ranked model, mean apparent survival was highest during winter (0.944 [0.915, 0.963], intermediate in fall (0.914 [0.834, 0.957] and lowest in summer (0.907 [0.821, 0.954]), though C.I.s were wide and overlapping.

3.3 Individual red tide season effects

Parameters were estimable for models including individual red tide seasons on the base model for one (of six) Texas seasons, and nine (of seventeen) Florida seasons (Table 3). The 2009 fall red tide season in Texas was significant ($\hat{\beta}$ = -2.515 [-3.291, -1.739]), as were four total seasons in Florida comprising two extended events in 2012 (fall: ($\hat{\beta}$ = -1.553 [-1.742, -0.764]; winter: ($\hat{\beta}$ = -1.470 [-1.930, -1.010]) and 2018 (fall: ($\hat{\beta}$ = -2.504 [-3.169, -1.840]; winter: ($\hat{\beta}$ = -1.831 [-2.817, -0.845]). Red tide seasons with non-significant terms had higher standard errors, indicating data was insufficient to estimate an effect.

The *post-hoc* model retaining all significant covariates included the geolocator effect and four of the five significant red tide seasons (Table 4). Point estimates of seasonal survival during red tide events in Florida ranged from 0.492 (fall 2018) to 0.884 (fall 2012). Seasonal survival during the Texas fall 2009 red tide was 0.510.

4 Discussion

Our results confirm episodes of sharply reduced survival of Red Knots during red tide events, and suggest this could be a significant driver of survival in Texas and Florida. While only a red tide effect in Florida was included in the top model of the candidate set, tests on individual seasons – when all parameters were estimable – were all either strong and significant, or were weak with relatively high standard errors. This is indicative of sparseness of data in some seasons (especially low winter resight probability in Texas) which likely resulted in a failure to find an effect when one may have occurred. Instead of chronically lower annual survival, knots in these locations may be experiencing relatively high survival punctuated by acute episodes of high mortality from red tide.

Several studies on knots have demonstrated often sharply contrasting survival estimates comparing different time series (Baker et al., 2004; González et al., 2006; Leyrer et al., 2013), population segments (Harrington et al., 1998) and body condition (McGowan et al., 2011), and age (Schwarzer et al., 2012). A robust model accounting for transience, temporary emigration, persistence and food availability at a stopover site illustrated that many different processes can affect estimates of apparent survival over short timeframes (Tucker et al., 2021). Further, the focal populations of these studies often preclude simple comparison of survival estimates across studies. For example, knots captured in Delaware Bay during spring migration are primarily breeding age individuals who have already survived nearly two full years during which mortality is expected to be highest (and thus unaccounted for in estimates), whereas estimates based on populations that included those younger cohorts (including ours) would be expected to be lower. Nevertheless, our estimates of apparent annual survival rates of Red Knots from the three Gulf of Mexico locations were within the ranges of those reported by most other studies on *rufa* Red Knots. Of the three Gulf locations, mean apparent annual survival was lowest in Texas and highest in Louisiana, though differences were not significant.

An effect of age on survival was not detectable in our models, but we note that the first occasion a knot becomes "available" to our study sites follows a critical and typically very high-mortality time interval following hatching in the Arctic, including surviving to fledging and the first southbound migration (~first 3 months of life). However, we are aware of no published survival estimates for this species which include that highly sensitive period. Accurate estimation of age-specific survival in the first- and second-year periods (prior to the first return to the Arctic as a breeder for most knots) was likely related to limitations in data for these age groups.

Our study estimated apparent survival, which is the complement of both mortality *and* permanent emigration. These are the first published survival estimates for knots in Texas and Louisiana, but a relatively recent study examined true survival in

TABLE 2 Mean estimates and standard errors (SE) for apparent seasonal and annual survival and encounter probabilities of Red Knots for each location from the $\varphi_{(location,\ geolocator)}\ p_{\ (location,\ season)}$ base model.

Location	Φ seasonal	Φ annual	Encounter (*p*)	
Texas	0.916 (0.005)	0.768 (0.012)	spring	0.180 (0.011)
			fall	0.264 (0.012)
			winter	0.009 (0.002)
Louisiana	0.936 (0.013)	0.819 (0.033)	spring	0.331 (0.036)
			fall	0.021 (0.006)
			winter	0.071 (0.013)
Florida	0.925 (0.002)	0.790 (0.006)	spring	0.118 (0.005)
			fall	0.271 (0.007)
			winter	0.194 (0.006)

TABLE 3 Effect coefficients ($\hat{\beta}$) and 95% confidence intervals for covariates tested individually on the $\Phi_{\text{(location)}}\ p_{\text{(location, season)}}$ base model for Red Knot apparent survival in the northern Gulf of Mexico.

Covariates		$\hat{\beta}$ [95% C.I.]
Tracking devices		
Geolocator		**-0.445 [-0.655, -0.236]**
VHF		-0.312 [-1.727, 1.103]
Red tide		
Red tide - all		-0.040 [-0.279, 0.199]
Red tide - Florida		-0.203 [-0.422, 0.015]
Individual red tide seasons		
Texas		
2009	**fall**	**-2.515 [-3.291, -1.739]**
2012	fall	0.113 [-1.678, 1.903]
Florida		
2006	fall	0.196 [-1.540, 1.933]
	winter	-0.361 [-0.774, 1.495]
2009	fall	-0.079 [-0.882, 0.723]
2012	**fall**	**-1.253 [-1.742, -0.764]**
	winter	**-1.470 [-1.930, -1.010]**
2015	fall	-0.246 [-1.659, 2.151]
	winter	-1.472 [-4.847, 7.792]
2016	fall	0.386 [-2.094, 2.866]
2018	**fall**	**-2.504 [-3.169, -1.840]**
	winter	**-1.831 [-2.817, -0.845]**

Significant covariates and terms are in bold. Effects could not be estimated for the covariate set "Red tide – Texas" and several individual red tide seasons (Florida – summer 2006, fall and winter 2011, fall and winter 2017, summer 2018; and Texas – fall 2011, fall 2015, fall 2016, fall 2018).

Florida. Between 2005-2010, true annual survival of Florida-wintering knots was estimated at 0.89 for adults and 0.95 for juveniles, using a Barker model (Schwarzer et al., 2012). The Barker model accounts for emigration and re-immigration based on encounters in a secondary encounter area (in this case, James Bay, Ontario, and the US Atlantic coast), resulting in annual survival estimates that separate the two processes by which an individual can leave the population (mortality or permanent emigration). Our dataset encompasses the same individuals and years of the Schwarzer et al. (2012) study, but because of the use of different modeling approaches and longer timespan of our study, we would not expect our estimates to be consistent. However, comparison may provide some insight into the potential population dynamics of the Florida winterers. We explore two potential explanations, which are not mutually exclusive: 1) during the course of the past decade the survival rate has in fact declined since the Schwarzer et al. (2012) study; and, 2) more knots formerly associated with Florida wintering areas are spending extended periods of time or the full nonbreeding period at sites along the southeast US coast, or into the Caribbean.

The significant reduction in survival associated with several red tide events in Florida provides some support for the hypothesis that mean survival rates truly have declined particularly in the past decade. It must be noted that because there were no new birds marked in Florida beyond 2010 in this analysis, it is possible that an age-related effect (i.e. senescence) could have depressed our apparent survival rates. However, the five-year timespan of the Schwarzer et al. (2012) study encompassed only four seasons (two events) that met our criteria as moderate or severe in terms of BSI. Three of these were the contiguous summer-fall-winter seasons during the bloom of 2006-7 (two of those were moderate severity), and the other was the brief and moderate bloom of fall 2009. By contrast, red tide occurred in thirteen seasons over the subsequent decade. Each bloom affected multiple consecutive seasons (including the one beginning in fall 2017 that lasted well over a year and a half), potentially compounding the effects. The years assessed in the Schwarzer et al. (2012) study (the same as the first five years of ours) represent a relative lull in red tide frequency and severity in Florida compared to the latter decade included in our study.

There is also evidence that our apparent survival estimates for Florida could be lower because of permanent shifts in wintering range outside of Florida. Lyons et al. (2018) estimated the wintering population of the southeast US (including Florida) at 10,400 individuals using data from the fall migration in 2011, while surveyors conducting the International Piping Plover Census (Elliott-Smith et al., 2015) counted 5,069 Red Knots during the 2006 count and approximately 3,900 in 2011. These numbers are not directly comparable, as they are based on different methodologies, but they reflect uncertainties as to *where* specifically Red Knots are wintering in the southeastern U.S. While there are not consistent repeated estimates from each location within this region over that time, resight data indicates

TABLE 4 Seasonal apparent survival estimates of Red Knots in each location based on the highest-supported *post-hoc* model incorporating five significant covariates – geolocators, and the four red tide events as applicable to the affected location.

Location	Intercept	Geolocator[a]	Red tide event			
			Fall 2009	Fall 2012	Winter 2012	Fall 2018
Texas	0.918	0.884	0.510	–	–	–
Louisiana	0.935	0.908	–	–	–	–
Florida	0.932	0.902	–	0.884	0.786	0.492

[a] The geolocator effect is assumed the same across locations. A model with a geolocator effect varying by location had less support.

that some birds have indeed shifted from the Florida wintering group to the Atlantic coasts of Georgia and South Carolina (USFWS 2014b, Pelton et al., 2022). The parameter estimates for fidelity and re-immigration based on the Barker model used by Schwarzer et al. (2012) indicate some support for this hypothesis. The apparent survival estimates for Florida in this study confound permanent emigration (such as a shift in wintering area from Florida to Georgia/South Carolina) with mortality, so it is possible that some portion of the decrease in apparent survival was attributable to emigration.

Apparent survival estimates for the Texas and Louisiana populations from this study could also be biased low (relative to true survival), if some proportion of those birds had also shifted to other wintering sites. However, there is currently no solid evidence to support this, and relatively minimal exchange of individuals even between the locations suggests it is unlikely.

The four significant red tide seasons in Florida were actually two prolonged events that lasted through the fall and winter intervals of the 2012 and 2018 nonbreeding season, compounding the effect on annual survival. In those years, estimated annual survival (assuming mean of non-red-tide survival for the unaffected season) would have been ~0.56 (in 2012) and ~0.33 (in 2018). While the 2009 red tide in Texas primarily affected one season (fall), it was severe enough that annual survival would have been ~0.43. These estimates indicate the loss of large proportions (~44 – 67%) of the entire population in a single year. Though there is no fixed quantitative threshold of a "catastrophe" in population dynamics, certainly the scale of these losses for a *K*-selected species are alarming. Simulation studies have demonstrated that population trends tend to be depressed when *variability* in survival is high, relative to a population where it is low, given the same arithmetic mean of survival (Boyce, 1977; Hitchcock and Gratto-Trevor, 1997). Indeed, catastrophic events, especially when combined with other environmental stressors, can drastically accelerate negative population growth rates towards extinction in closed populations (Simberloff, 1988). In this case, the effect of catastrophes on one wintering population may be tempered somewhat depending on the degree of migratory connectivity between breeding and wintering areas. As the processes by which young Red Knots recruit into a particular wintering population remain poorly understood, it is not clear that high recruitment could offset low survival years to stabilize a wintering population over the long term. Population declines documented in other wintering areas for *C. c. rufa* suggest a negative long-run population growth rate, and our results indicate red tides could be contributing to very high variability in Red Knot survival, at least in the Texas and Florida populations. Under these conditions, populations become more vulnerable to extinction especially when the frequency and magnitude of random catastrophes are increasing (Lande, 1993).

Sparse data (low encounter probability) for certain seasons in some locations likely resulted in the inability to fully estimate parameters for multiple red tide events, but is it possible that birds are able to avoid red tide effects in some years, but not in others? Knots could potentially reduce their exposure to toxins either through a shift in prey selection, or a shift in range.

There is evidence that some shorebirds avoid prey with high concentrations of algal toxins. Black oystercatchers (*Haematopus bachmani*) shifted diet to prey items that did not harbor algal toxins when those toxins were present in sea mussels – their preferred prey – and discarded mussel tissue with high toxin concentrations when they did capture it (Kvitek and Bretz, 2005), while other shorebird species tended to avoid areas where toxins were present. Red knots, however, consume bivalve prey whole and crush it in their gizzard rather than removing the flesh first (which would provide an opportunity to taste and reject), potentially making them more susceptible to accumulate high amounts of toxin. A prey selection mechanism to reduce exposure would only be viable if a suitable non-toxic alternate prey source were available. On the Gulf-facing beaches, *Donax* spp. is by far the dominant bivalve mollusk that is most likely to occur in ample densities to support knots, and it is known to concentrate HAB toxins at extremely high levels (Cummins et al., 1971). It is also possible that red tides could affect birds by negatively affecting recruitment of their bivalve prey (Summerson and Peterson, 1990; Rolton et al., 2016), which might have both immediate and long-term effects. A study comparing two red tide outbreaks (2006 and 2011) on beaches of south Texas found that one event resulted in a near complete die-off of the benthic macrofauna while that same faunal community was virtually unaffected in the other event, despite extensive fish-kills occurring in both (Lerma, 2013).

As discussed previously, permanent emigration of birds from the Florida wintering population to another site in the southeast US would be one way to avoid red tide effects. However, avoidance may not require permanent emigration. Since red tides most commonly occur during fall months, simply prolonging a southeast US stopover before moving on to Florida could reduce the degree of exposure. The abundance and duration of knots stopping at the Altamaha River delta (Georgia) varies between years and is likely influenced by availability of the dwarf surf clam (*Mulinia lateralis*; Lyons et al., 2018), so "good years" at this site might reduce the proportion of birds arriving in southwest Florida to toxic conditions, at a time when they are already under high physiological stress due to the demands of molt which is coupled with decreased immunological function (Buehler et al., 2008). If knots stay in the southeast US long enough to complete their molt, they would also likely arrive in better condition. There is isotopic evidence that some knots in the Florida wintering population do in fact complete their molt prior to arrival in Florida (Newstead, unpubl. data). Staying longer further north would also reduce the risk of exposure to tropical storms during the peak of hurricane season (Niles et al., 2012).

In Texas, knots are known to utilize the extensive tidal flats of the Laguna Madre when water levels allow (Newstead, 2014), and when red tides do occur, they tend to be most severe and extensive on the Gulf beach, only occasionally affecting the Laguna Madre. Also, the Laguna Madre complex and the interspersed flats of the Rio Grande Delta extend over 400 km from Corpus Christi, Texas southward to La Pesca, Tamaulipas, Mexico. Aerial radiotelemetry documented that knots move extensively throughout this system during the nonbreeding season (Newstead, 2014), so they could potentially avoid red tide effects by moving to unaffected parts of the same extensive system.

Red tides typically occur beginning in late summer and often persist until early to mid-winter, though in the past decade some events have been initiated or prolonged into the spring and summer seasons (Brand and Compton, 2007; Stumpf et al., 2022). Comparing models allowing seasonal variation in survival for Florida, estimates were lower in all seasons when red tide was not included as a covariate, but within all models season-specific estimates were lower in summer relative to fall and winter. This suggests that, absent red tide, survival in Florida during the extensive nonbreeding period is higher relative to the breeding period, which includes lengthy round-trip migrations for breeding adults. This finding is in contrast to Leyrer et al. (2013) for *C.c. canutus* wintering at Banc d'Arguin in Mauritania, where survival during the migratory and breeding seasons was close to 1.0, with most mortality occurring on the wintering area. Banc d'Arguin, at roughly 20.5 N latitude, is extremely arid and hot even during the boreal winter. Leyrer et al. (2013) suggested that during the period following arrival from breeding grounds, environmental and interspecific competitive constraints may depress survival at a time when birds are already under high physiological stress due to flight feather molt (Leyrer et al., 2013). Additionally, during this phase knots tend to suppress costly immune functions which may make them more vulnerable to novel stressors (Buehler et al., 2008). Climate conditions on wintering sites are more moderate in the subtropical latitudes of this study, though birds may occasionally experience stress from short bouts of cold winter temperatures in addition to a wider array of other stressors such as disturbance from heavy recreational use of beaches. Such conditions could simultaneously increase maintenance metabolism costs and place constraints on foraging opportunity. Prey depletion, or prey toxicity, from red tide events during this time period would introduce another lethal or sublethal stressor on top of those already normally experienced by knots during the nonbreeding period.

Boyd and Piersma (2001) found that relative population stability of Red Knots (*C.c. islandica*) wintering in Great Britain was maintained by alternating trends of survival and recruitment, implicating a potential role of density-dependent processes in population regulation. Knots using Delaware Bay during spring migration experienced consistently high apparent survival which was offset by consistently low recruitment between 2005-2018, resulting in a slightly positive population growth rate (Tucker et al., 2023). Using data from two large shorebird monitoring datasets, Bart et al. (2007) suggested the most likely mechanisms of North American shorebird population declines are reduction in breeding population size and poor reproduction, rather than an artifact potentially explicable by shifting distributions. This is almost certainly the case with Red Knots, as nearly all regular monitoring at key sites across the range indicate a declining trend, while no "new" sites of importance have been discovered in the meantime that balance for losses seen elsewhere. The relatively acute mortality episodes associated with red tides in this study would clearly result in reduced breeding population, but it is not known whether reproductive capacity can offset such population reductions when they occur relatively frequently.

While red tide toxins have been directly tied to the mortality of Red Knots in Texas (Rafalski, 2012) and closely related shorebirds in Florida (van Deventer et al., 2012) through necropsy and tissue sampling, only one other study has quantitatively estimated the effect of HABs on shorebird survival at the population level. Ellis et al. (2021) detected a negative effect of HABs on Piping Plover (*Charadrius melodus*) survival during the nonbreeding season along the Gulf of Mexico coast. This species is not only faithful to wintering areas generally (similar to knots) but even more highly faithful to specific individual territories with small home ranges (Drake et al., 2001; Cohen et al., 2008; Newstead, 2014) and may have a greater disinclination to move away from an area affected by red tide or other factors that may negatively affect survival. Our study provides additional evidence that HABs can negatively impact shorebird populations even when sudden mass mortality events are not observed or perhaps do not occur.

Another HAB dinoflagellate, *Aureoumbra lagunensis*, creates "brown tides" in the Laguna Madre of Texas which could be affecting knots in other ways. Though this organism does not produce potent toxins, it is considered disruptive to ecosystems because of its ability to bloom at low light and nutrient levels, and create a positive feedback mechanism that results in losses to seagrasses and benthic organisms (Gobler and Sunda, 2012). One brown tide event in the 1990s persisted in the Laguna Madre for nearly eight years, the longest HAB ever recorded (Buskey et al., 2001), and blooms have recurred intermittently and at varying spatial extents since then (DeYoe et al., 2007). Major die-offs of *Mulinia lateralis*, formerly the dominant bivalve mollusk in the Laguna Madre, have been coincident with these blooms (Montagna et al., 1993). The diet of Red Knots during the winter months in the Laguna Madre has not been described, but given that *M. lateralis* is a dominant prey item in other parts of the species' range, it is likely that these crashes in local populations would also impact prey availability, and potentially survival, for knots.

While this study focused on populations affected by HABs in the Gulf of Mexico, blooms have been suggested as a potential cause of several significant mortality events on the Atlantic coast of South America, affecting the long-distance migrant *rufa* population wintering in Tierra del Fuego. In Uruguay in April 2007, approximately 1300 knots were found dead in a single event that may have been associated with a HAB, though samples were not collected to confirm the cause of mortality (Aldabe et al., 2015). The loss of ~6% of the total *rufa* population in a single documented event, and the possibility that this may not have been a one-off event but could even occur with some regularity in remote parts of its range provides a potential partial explanation for the dramatic collapse of the Red Knot population that winters on the Atlantic coast of South America. During mortality events in 1997 and 2000 in southern Brazil, Buehler et al. (2010) described similar condition of Red Knots immediately prior to mortality – disorientation, lethargy, unresponsiveness – as witnessed in red tide events in Texas (Newstead, pers. obs.) and Florida, but pathology reports were inconclusive as to the primary cause of death.

Further, Red Knots that winter along the Pacific coasts of Central and South America (the majority of which are suspected to use the focal locations of this study as stopovers; Newstead, unpublished data) may also be encountering increased frequency and intensity of HABs (Band-Schmidt et al., 2019), including several recent events in Ecuador (Torres, 2015; Borbor-Cordova et al., 2019) and Chile (Mardones et al., 2010; Paredes et al., 2019). Several dinoflagellate species that produce paralytic or diarrhetic shellfish poisons can reach bloom concentrations resulting in fish kills and other toxic effects in areas of Central and South America known to be important stopovers. Among these, *Gymnodinium catenatum*, the *Alexandrium tamarense* complex, and *Dinophysis* spp. produce toxins that become highly concentrated in bivalve species such as wedge clams, *Donax hanleyanus*, and blue mussels, *Mytilus edulis* (Carreto et al., 1986; Mee et al., 1986; Méndez and Carreto, 2018), both known to be favored prey items of red knots. The distribution and frequency of HABs appear to be increasing in Central and South America (Band-Schmidt et al., 2019), as well as in the Gulf of Mexico (Tominack et al., 2020).

The magnitude of the geolocator effect was a ~3% reduction in seasonal survival (or ~8% over a year). While many studies reporting tracking device effects on survival have focused on the short-term (often one-year return rates) with projects having highly variable numbers of birds with and without devices, the results of this study are consistent with others (Rodriguez-Ruiz et al., 2019; Pakanen et al., 2020) finding that negative effects of some tracking devices may be statistically undetectable in the short term but accrue to the level of significance over the course of longer-term studies. The use of tracking devices on wildlife has yielded transformative new insights into our understanding of life histories and factors affecting distribution and movements of animals, especially Red Knots (Niles et al., 2010; Burger et al., 2012; Niles et al., 2012; Newstead et al., 2013; Tomkovich et al., 2013; Piersma et al., 2021). However, consideration must be given to the potential costs of such deployments on survival, reproduction, movement, and other concerns. As new findings are added to the literature and technological advances lead to ever smaller and more efficient tracking devices, researchers should continue to assess the potential benefits to be gained for species conservation relative to the potential impacts to birds when planning new studies.

This study provides the first long-term apparent survival estimates for Red Knot populations in the Gulf, and strong evidence that HABs are negatively affecting populations in Texas and Florida. Preventing such large-scale events presents many challenges, although where their apparent causes are linked to excessive nutrients these factors can be mitigated by better managing anthropogenic landscape changes along the coast and through the watershed. Since HABs are considered a “co-stressor” associated with climate change (Griffith and Gobler, 2020), these findings indicate the impacts to knots could become even more severe in the future.

Accurate estimation of population size of these three Gulf wintering groups has not been possible, and is hindered by several factors including the potential shift of some portion of the Florida wintering population to the southeast US (Pelton et al., 2022), logistical difficulties in accessing habitats used by the Louisiana and Texas populations during winter, and the fact that some knots that pass through the northern Gulf in spring likely wintered somewhere further south. These are all surmountable obstacles provided adequate support for dedicated and coordinated monitoring programs. While we have presented estimates of one key demographic parameter (survival) for these populations, a better understanding of processes and rates of recruitment is needed to evaluate population trajectories.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements because Researchers conducting field work were not affiliated with institutions with their own ethics review process. USFWS Recovery Permits (which were obtained for this work) require extensive explanation of capture/handling procedures and contingencies.

Author contributions

DN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. SD: Formal analysis, Methodology, Writing – review & editing. BB: Methodology, Supervision, Writing – review & editing. LN: Conceptualization, Writing – review & editing. JB: Writing – review & editing.

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Conflict of interest

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2024.1375412/full#supplementary-material

References

Abbott, B. C., Siger, A., and Spigelstein, M. (1975). "Toxins from the blooms of *Gymnodinium breve*," in *Proceedings of the First International Conference on Toxic Dinoflagellate Blooms*. Ed. V. R. LoCicero (Massachusetts Science and Technology Foundation, Wakefield, Massachusetts), 355–366.

Aldabe, J., Rocca, P. I., González, P. M., Caballero-Sadi, D., and Baker, A. J. (2015). Migration of endangered Red Knots *Calidris canutus rufa* in Uruguay: important sites, phenology, migratory connectivity and a mass mortality event. *Wader Study* 122, 221–235. doi: 10.18194/ws.00024

Baker, A. J., González, P. M., Morrison, R. I. G., and Harrington, B. (2013). "Red Knot (*Calidris canutus*), *v.2.0*," in *The Birds of North America*. Ed. A. F. Poole (Cornell Lab of Ornithology, Ithaca, NY, USA). doi: 10.2173/bna

Baker, A. J., González, P. M., Piersma, T., Niles, L. J., de Lima Serrano do Nascimento, I., Atkinson, P. W., et al. (2004). Rapid population decline in red knots: fitness consequences of decreased refuelling rates and late arrival in Delaware Bay. *Proc. R. Soc London* 271, 875–882. doi: 10.1098/rspb.2003.2663

Band-Schmidt, C. J., Durán-Riveroll, L. M., Bustillos-Guzmán, J. J., Leyva-Valencia, I., López-Cortés, D. J., Núñez-Vázquez,, et al. (2019). Paralytic toxin producing dinoflagellates in Latin America: ecology and physiology. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00042

Barron, D. G., Brawn, J. D., and Weatherhead, P. J. (2010). Meta-analysis of transmitter effects on avian behavior and ecology. *Methods Ecol. Evol.* 1, 180–187. doi: 10.1111/j.2041-210X.2010.00013.x

Bart, J., Brown, S., Harrington, B., and Morrison., R. I. G. (2007). Survey trends of North American shorebirds: population declines or shifting distirbutions? *J. Avian Biol.* 38, 73–82. doi: 10.1111/j.2007.0908-8857.03698.x

Borbor-Cordova, M. J., Torres, G., Mantilla-Saltos, G., Casierra-Tomala, A., Bermúdez, J. R., Renteria, W., et al. (2019). Oceanography of harmful algal blooms on the Ecuadorian Coast, (1997–2017): Integrating remote sensing and biological data. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00013

Boyce, M. S. (1977). Population growth with stochastic fluctuations in the life table. *Theor. Popul. Biol.* 12, 366–373. doi: 10.1016/0040-5809(77)90050-8

Boyd, H., and Piersma, T. (2001). Changing balance between survival and recruitment explains population trends in Red Knots *Calidris canutus islandica* wintering in Britain 1969-1995. *Ardea* 89, 301–317.

Brand, L. E., and Compton, A. (2007). Long-term increase in Karenia brevis abundance along the Southwest Florida Coast. *Harmf. Algae* 6, 232–252. doi: 10.1016/j.hal.2006.08.005

Bricelj, V. M., Haubois, A.-G., Sengco, M. R., Pierce, R. H., Culter, J. K., and Anderson, D. M. (2012). Trophic transfer of brevetoxins to the benthic macrofaunal community during a bloom of the harmful dinoflagellate *Karenia brevis* in Sarasota Bay, Florida. *Harmf. Algae* 16, 27–34. doi: 10.1016/j.hal.2012.01.001

Bridge, E. S., Thorup, K., Bowlin, M. S., Chilson, P. B., Diehl, R. H., and Fléron, R. W. (2010). Technology on the move: recent and forthcoming innovations for tracking migratory birds. *BioScience* 61, 689–698. doi: 10.1525/bio.2011.61.9.7

Buchanan, J. B., Johnson, J. A., Bishop, M. A., DeCicco, L. H., Hajdukovich, N., Salzer, L. J., et al. (2019). Does radio transmitter attachment influence resighting rates of Red Knots in the Pacific Flyway, USA? *Wader Study* 126, 151–154. doi: 10.18194/ws

Buchanan, J. B., Lyons, J. E., Salzer, L. J., Carmona, R., Arce, N., Wiles, G. J., et al. (2012). Among-year site fidelity of Red Knots during migration in Washington. *J. Field Ornithol.* 83, 282–289. doi: 10.1111/jofo.2012.83.issue-3

Buehler, D. M., Bugoni, L., Dorrestein, G. M., González, P. M., Pereira-Jr, J., Proença, L., et al. (2010). Local mortality events in migrating sandpipers (*Calidris*) at a staging site in southern Brazil. *Wader Study Group Bull.* 117, 150–156.

Buehler, D. M., Piersma, T., Matson, K., and Tieleman, I. (2008). Seasonal redistribution of immune function in a migrant shorebird: annual-cycle effects override adjustments to thermal regime. *Am. Nat.* 172, 783–796. doi: 10.1086/592865

Burger, J., Niles, L. J., Porter, R. R., Dey, A. D., Koch, S., and Gordon, C. (2012). Migration and over-wintering of red knots (Calidris canutus rufa) along the atlantic coast of the united states. *Condor* 114 (2), 302–313. doi: 10.1525/cond.2012.110077

Burnham, K. P., and Anderson, D. R. (2002). *Model Selection and Multimodel Inference: a Practical Information-theoretic Approach. 2nd ed* (New York: Springer-Verlag).

Buskey, E. J., Liu, H., Collumb, C., and Bersano, J. G. F. (2001). The decline and recovery of a persistent Texas brown tide algal bloom in the Laguna Madre (Texas, USA). *Estuaries* 24, 337–346. doi: 10.2307/1353236

Calvert, A. M., Amirault, D. L., Shaffer, F., Elliot, R., Hanson, A., McKnight, J., et al. (2006). Population assessment of an endangered shorebird: the Piping Plover (*Charadrius melodus melodus*) in eastern Canada. *Avian Conserv. Ecol. - Écol. Conserv. Des. oiseaux* 1, 4. doi: 10.5751/ACE-00091-010304

Carreto, J. I., Benavides, H. R., Negri, R. M., and Glorioso, P. D. (1986). Toxic red-tide in the Argentine Sea. Phyoplankton distribution and survival of the toxic dinoflagellate Gonyaulax excavata in a frontal area. *J. Plankton Res.* 8, 15–28. doi: 10.1093/plankt/8.1.15

Castle, K. T., Flewelling, L. J., Bryan, J. II, Kramer, A., Lindsay, J., Nevada, C., et al. (2013). Coyote (*Canis latrans*) and domestic dog (*Canis familiaris*) mortality and morbidity due to a *Karenia brevis* red tide in the Gulf of Mexico. *J. Wildl. Dis.* 49, 955–964. doi: 10.7589/2012-11-299

Chan, Y.-C., Tibbitts, T. L., Lok, T., Hassell, C. J., Peng, H.-B., Ma, Z., et al. (2019). Filling knowledge gaps in a threatened shorebird flyway through satellite tracking. *J. Appl. Ecol.* 56, 2305–2315. doi: 10.1111/1365-2664.13474

Cohen, J. B., Karpanty, S. M., Catlin, D. H., Fraser, J. D., and Fischer, R. A. (2008). Winter ecology of Piping Plovers at Oregon Inlet, North Carolina. *Waterbirds* 31, 472–479. doi: 10.1675/1524-4695-31.3.472

Conklin, J. R., and Battley, P. F. (2010). Attachment of geolocators to Bar-tailed Godwits: a tibia-mounted method with no survival effects or loss of units. *Wader Study Group Bull.* 117, 56–58.

COSEWIC. (2007). *COSEWIC assessment and status report on the Red Knot Calidris canutus in Canada* (Ottawa: Committee on the Status of Endangered Wildlife in Canada). Available at: www.sararegistry.gc.ca/status/status_e.cfm. Vii + 58 pp.

Costantini, D., and Møller, A. P. (2013). A meta-analysis of the effects of geolocator application on birds. *Curr. Zool.* 59, 697–706. doi: 10.1093/czoolo/59.6.697

Cummins, J. M., Jones, A. C., and Stevens, A. A. (1971). Occurrence of toxic bivalve molluscs during a *Gymnodinium breve* "red tide". *Trans. Am. Fish. Soc* 100, 112–116. doi: 10.1577/1548-8659(1971)100

DeYoe, H. R., Buskey, E. J., and Jochem, F. J. (2007). Physiological responses of *Aureoumbra lagunensis* and *Synechococcus* sp. to nitrogen addition in a mesocosm experiment. *Harmf. Algae* 6, 48–55. doi: 10.1016/j.hal.2006.06.001

Drake, K. R., Thompson, J. E., Drake, K. L., and Zonick, C. (2001). Movements, habitat use, and survival of nonbreeding Piping Plovers. *Condor* 103, 259–267. doi: 10.1093/condor/103.2.259

Duijns, S., Anderson, A. M., Aubry, Y., Dey, A., Flemming, S. A., Francis, C. M., et al. (2019). Long-distance migratory shorebirds travel faster towards their breeding grounds, but fly faster post-breeding. *Sci. Rep.* 9, 9420. doi: 10.1038/s41598-019-45862-0

Duijns, S., Niles, L. J., Dey, A., Aubry, Y., Friis, C., Koch, S., et al. (2017). Body condition explains migratory performance of a long-distance migrant. *Proc. R. Soc B* 284, 20171374. doi: 10.1098/rspb.2017.1374

Duriez, O., Ens, B. J., Choquet, R., Pradel, R., and Klaassen, M. (2012). Comparing the seasonal survival of resident and migratory oystercatchers: carry-over effects of habitat quality and weather conditions. *Oikos* 121, 862–873. doi: 10.1111/j.1600-0706.2012.20326.x

Elliott, K. H., McFarlane-Tranquilla, L., Burke, C. M., Hedd, A., Montevecchi, W. A., and Anderson, W. G. (2012). Year-long deployments of small geolocators increase corticosterone levels in murres. *Mar. Ecol. Prog. Ser.* 466, 1–7. doi: 10.3354/meps09975

Elliott-Smith, E., Bidwell, M., Holland, A. E., and Haig, S. M. (2015). *Data from the 2011 International Piping Plover Census* (Reston, Virginia, USA: U.S. Geological Survey).

Ellis, K. S., Anteau, M. J., Cuthbert, F. J., Gratto-Trevor, C. L., Jorgensen, J. G., Newstead, D. J., et al. (2021). Impacts of extreme environmental disturbances on piping plover survival are partially moderated by migratory connectivity. *Biol. Conserv.* 264, 109371. doi: 10.1016/j.biocon.2021.109371

Faaborg, J., Holmes, R. T., Anders, A. D., Bildstein, K. L., Dugger, K. M., Gauthreaux, J. S.A., et al. (2010). Recent advances in understanding migration systems of New World land birds. *Ecol. Monogr.* 80, 3–48. doi: 10.1890/09-0395.1

Fernández, G., and Lank, D. B. (2006). Effects of habitat loss on shorebirds during the non-breeding season: current knowledge and suggestions for action. *Ornitol. Neotro.* 19, 633–640.

Gauthier, G., Pradel, R., Menu, S., and Lebreton, J.-D. (2001). Seasonal survival of Greater Snow Geese and effect of hunting under dependence in sighting probability. *Ecology* 82, 3105–3119. doi: 10.1890/0012-9658(2001)082[3105:SSOGSG]2.0.CO;2

Gill, J. A., and Sutherland, W. J. (2000). "Predicting the consequences of human disturbance from behavioural decisions," in *Behaviour and Conservation*. Eds. L. M. Morris and W. J. Sutherland (Cambridge Univ. Press, Cambridge, UK), 51–64.

Gobler, C. J., and Sunda, W. G. (2012). Ecosystem disruptive algal blooms of the brown tide species, *Aureococcus anophagefferens* and *Aureoumbra lagunensis*. *Harmf. Algae* 14, 360–345. doi: 10.1016/j.hal.2011.10.013

González, P. M., Baker, A. J., and Echave, M. E. (2006). Annual survival of red knots (Calidris canutus rufa) using the san antonio oeste stopover site is reduced by domino effects involving late arrival and food depletion in delaware bay. *El hornero* 21 (2), 109–117.

Goss-Custard, J. D., Clarke, R. T., Durell, S. E. A., dit., L., Caldow, R. W. G., and Ens, B. J. (1995). Population consequences of winter habitat loss in a migratory shorebird. II. model predictions. *J. Appl. Ecol.* 32, 337–351.

Green, M., Piersma, T., Jukema, J., De Goeij, P., Spaans, B., and van Gils, J. A. (2002). Radio-telemetry observations of the first 650 km of the migration of Bar-tailed Godwits *Limosa lapponica* from the Wadden Sea to the Russian Arctic. *Ardea* 90, 71–80.

Griffith, A. W., and Gobler, C. J. (2020). Harmful algal blooms: A climate change co-stressor in marine and freshwater ecosystems. *Harmf. Algae* 91, 1–12. doi: 10.1016/j.hal.2019.03.008

Hallegraeff, G. M. (1993). A review of harmful algal blooms and their apparent global increase. *Phycology* 322, 79–99. doi: 10.2216/i0031-8884-32-2-79.1

Harrington, B. A., Hagan, J. M., and Leddy, L. E. (1998). Site fidelity and survival differences between two groups of new world Red Knots (*Calidris canutus*). *Auk* 105, 439–445. doi: 10.1093/auk/105.3.439

Hitchcock, C. L., and Gratto-Trevor, C. (1997). Diagnosing a shorebird local population decline with a stage-structured population model. *Ecology* 78, 522.534. doi: 10.1890/0012-9658(1997)078[0522:DASLPD]2.0.CO;2

Iwamura, T., Possingham, H. P., Chadès, I., Minton, C., Murray, N. J., Rogers, D. I., et al. (2013). Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations. *Proc. R Soc. B* 280, 20130325. doi: 10.1098/rspb.2013.0325

Johnson, M. D., Sherry, T. W., Holmes, R. T., and Marra, P. P. (2006). Assessing habitat quality for a migratory songbird wintering in natural and agricultural habitats. *Conserv. Biol.* 20, 1433–1444. doi: 10.1111/j.1523-1739.2006.00490.x

Kennish, M. J. (2002). Environmental threats and environmental future of estuaries. *Environ. Conserv.* 29, 78–107. doi: 10.1017/S0376892902000061

Kvitek, R., and Bretz, C. (2005). Shorebird foraging behavior, diet, and abundance vary with harmful algal bloom toxin concentrations in invertebrate prey. *Mar. Ecol. Prog. Ser.* 293, 303–309. doi: 10.3354/meps293303

Lande, R. (1993). Risks of population extinction from demographic and environmental stochasticity and random catastrophes. *Am. Nat.* 142, 911–927. doi: 10.1086/285580

Landsberg, J. H. (2002). The effects of harmful algal blooms on aquatic organisms. *Rev. Fish. Sci.* 10, 113–390. doi: 10.1080/20026491051695

Landsberg, J. H., Flewelling, L. J., and Naar, J. (2009). *Karenia brevis* red tides, brevetoxins in the food web, and impacts on natural resources: decadal advancements. *Harmf. Algae* 8, 598–607. doi: 10.1016/j.hal.2008.11.010

Lerma, L. (2013). The effects of a red tide, *Karenia brevis* episode on the benthic macroinvertebrate communities of South Padre Island, TX. University of Texas at Brownsville, Brownsville, Texas.

Leyrer, J., Lok, T., Brugge, M., Spaans, B., Sandercock, B. K., and Piersma, T. (2013). Mortality within the annual cycle: seasonal survival patterns in Afro-Siberian Red Knots *Calidris canutus canutus*. *J. Ornithol.* 154, 933–943. doi: 10.1007/s10336-013-0959-y

Leyrer, J., Spaans, B., Camara, M., and Piersma, T. (2006). Small home ranges and high site fidelity in red knots (*Calidris c. canutus*) wintering on the Banc d'Arguin, Mauritania. *J. Ornithol.* 147, 376–384. doi: 10.1007/s10336-005-0030-8

Lyons, J. E., Winn, B., Keyes, T., and Kalasz, K. S. (2018). Post-breeding migration and connectivity of Red Knots in the western Atlantic. *J. Wildl. Manage.* 82, 383–396. doi: 10.1002/jwmg.21389

Magaña, H. A., Contreras, C., and Villareal, T. A. (2003). A historical assessment of *Karenia brevis* in the western Gulf of Mexico. *Harmf. Algae* 2, 163–171. doi: 10.1016/S1568-9883(03)00026-X

Mardones, J., Clement, A., Rojas, X., and Aparicio, C. (2010). Alexandrium catenella during 2009 in Chilean waters, and recent expansion to coastal ocean. *Harmf. Algae News* 41, 8-9.

McGowan, C. P., Hines, J. E., Nichols, J. D., Lyons, J. E., Smith, D. R., Kalasz, K. S., et al. (2011). Demographic consequences of migratory stopover: linking red knot survival to horseshoe crab spawning abundance. *Ecosphere* 2, 1–22. doi: 10.1890/ES11-00106.1

McKellar, A. E., Ross, R. K., Morrison, R. I. G., Niles, L. J., Porter, R. R., Burger, J., et al. (2015). Shorebird use of western Hudson Bay near the Nelson River during migration, with a focus on the Red Knot. *Wader Study* 122, 1–11. doi: 10.18194/ws.00020

Mee, L. D., Espinosa, M., and Diaz, G. (1986). Paralytic shellfish poisoning with a *Gymnodinium catenatum* red tide on the Pacific coast of Mexico. *Mar. Environ. Res.* 19, 77–92. doi: 10.1016/0141-1136(86)90040-1

Méndez, S. M., and Carreto, J. I. (2018). "Harmful Algal Blooms in the Río de la Plata Region," in *Plankton Ecology of the Southwestern Atlantic: From the Subtropical to the Subantarctic Realm*. Eds. M. Hoffmeyer, M. E. Sabatini, F. Brandini, D. L. Calliari and N. H. Santinelli (Springer International Publishing, Switzerland). doi: 10.1007/978-3-319-77869-3

Mondain-Monval, T. O., du Feu, R., and Sharp, S. P. (2020). The effects of geolocators on return rates, condition, and breeding success in Common Sandpipers *Actitis hypoleucos*. *Bird Study* 67, 217–223. doi: 10.1080/00063657.2020.1808592

Montagna, P. A., Stockwell, D. A., and Kalke, R. D. (1993). Dwarf surfclam *Mulinia lateralis* (Say 1822) populations and feeding during the Texas brown tide event. *J. Shellfish Res.* 12, 433–442.

Musmeci, L. R., Bala, L. O., Tschopp, A., Hernandez, M. A., and Coscarella, M. A. (2022). Red knot (*Calidris canutus rufa*) site fidelity at Península Valdés, Argentina. *Wilson J. Ornithol.* 134, 302-309. doi: 10.1676/19-00108

Newstead, D. J. (2014). *Habitat use of North Padre Island and Laguna Madre habitats by Piping Plovers (*Charadrius melodus*) and Red Knots (*Calidris canutus*) in the vicinity of current and proposed wind energy development* (Austin, Texas: Report to Texas Parks & Wildlife Department, project E-137-R). 47 pp.

Newstead, D. J., Niles, L. J., Porter, R. R., Dey, A., Burger, J., and Fitzsimmons, O. N. (2013). Geolocation reveals mid-continent migratory routes and Texas wintering areas of Red Knots *Calidris canutus rufa*. *Wader Study Group Bull.* 120, 53–59.

Niles, L. J., Burger, J., Porter, R. R., Dey, A. D., Koch, S., Harrington, B., et al. (2012). Migration pathways, migration speeds and non-breeding areas used by northern hemisphere wintering Red Knots *Calidris canutus* of the subspecies *rufa*. *Wader Study Group Bull.* 119, 195–203.

Niles, L. J., Burger, J., Porter, R. R., Dey, A. D., Minton, C. D. T., Gonzalez, P. M., et al. (2010). First results using light level geolocators to track Red Knots in the Western Hemisphere show rapid and long intercontinental flights and new details of migration pathways. *Wader Study Group Bull.* 117, 123–130.

Niles, L. J., Sitters, H. P., Dey, A. D., Atkinson, P. W., Baker, A. J., Bennett, K. A., et al. (2008). Status of the Red Knot, *Calidris canutus rufa*, in the Western Hemisphere. *Stud. Avian Biol.* 36, 1–185.

NOAA National Centers for Environmental Information. (2014). *Physical and biological data collected along the texas, mississippi, alabama, and florida gulf coasts in the gulf of mexico as part of the harmful algal BloomS observing system from 1953-08-19 to 2023-07-06 (NCEI accession 0120767)* (NOAA National Centers for Environmental Information). Dataset. Available at: https://www.ncei.noaa.gov/archive/accession/0120767.

Norris, D. R. (2005). Carry-over effects and habitat quality in migratory populations. *Oikos* 109, 178–186. doi: 10.1111/j.0030-1299.2005.13671.x

Norris, D. R., and Marra, P. P. (2007). Seasonal interactions, habitat quality, and population dynamics in migratory birds. *Condor* 109 (3), 535–547. doi: 10.1093/condor/109.3.535

Pakanen, V.-M., Rönkä, N., Thomson, R. L., Blomqvist, D., and Koivula, K. (2020). Survival probability in a small shorebird decreases with the time an individual carries a tracking device. *J. Avian Biol.* 51, e02555. doi: 10.1111/jav.02555

Pakanen, V.-M., Rönkä, N., Thomson, R. L., and Koivula, K. (2015). No strong effects of leg-flagged geolocators on return rates or reproduction of a small long-distance migratory shorebird. *Ornis Fennica* 92, 101–111. doi: 10.51812/of.133872

Paredes, J., Varela, D., Martínez, C., Zúñiga, A., Correa, K., Villarroel, A., et al. (2019). Population Genetic Structure at the Northern Edge of the Distribution of Alexandrium catenella in the Patagonian Fjords and Its Expansion Along the Open Pacific Ocean Coast. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00532

Pelton, M. M., Padula, S. R., Garcia-Walther, J., Andrews, M., Mercer, R., Porter, R., et al. (2022). Kiawah and Seabrook islands are a critical site for the *rufa* Red Knot. *Wader Study* 129, 105–118. doi: 10.18194/ws

Pierce, R. H., and Henry, M. S. (2008). Harmful algal toxins of the Florida red tide (*Karenia brevis*): natural chemical stressors in South Florida coastal ecosystems. *Ecotoxicology* 17, 623–631. doi: 10.1007/s10646-008-0241-x

Piersma, T., Kok, E. M. A., Hassell, C. J., Peng, H.-B., Verkuil, Y. I., Lei, G., et al. (2021). When a typical jumper skips: itineraries and staging habitats used by Red Knots (*Calidris canutus piersmai*) migrating between northwest Australia and the New Siberian Islands. *Ibis* 163, 1235–1251. doi: 10.1111/ibi.12964

Piersma, T., Lok, T., Chen, Y., Hassell, C. J., Yang, H.-Y., Boyle, A., et al. (2016). Simultaneous declines in summer survival of three shorebird species signals a flyway at risk. *J. Appl. Ecol.* 53, 479–490. doi: 10.1111/1365-2664.12582

Powell, L. A. (2007). Approximating variance of demographic parameters using the delta method: a reference for avian biologists. *Condor* 109, 949–954. doi: 10.1093/condor/109.4.949

Rafalski, A. V. (2012). Evaluation of brevetoxin accumulation and degradation in coastal mammals, birds, and fish found moribund on Texas beaches during red tide blooms. Texas A&M University – Corpus Christi, Corpus Christi, Texas.

Robinson, W. D., Bowlin, M. S., Bisson, I., Shamoun-Baranes, J., Thorup, K., Diehl, R. H., et al. (2010). Integrating concepts and technologies to advance the study of bird migration. *Front. Ecol. Environ.* 8, 354–361. doi: 10.1890/080179

Rodriguez-Ruiz, J., Mougeot, F., Parejo, D., de la Puente, J., Bermejo, A., and Aviles, J. M. (2019). Important areas for the conservation of the european roller coracias garrulus during the non-breeding season in southern africa. *Bird Conserv. Int.* 29 (1), 159–175. doi: 10.1111/ibi.12317

Rogers, D. I., Piersma, T., and Hassell, C. J. (2006). Roost availability may constrain shorebird distribution: Exploring the energetic costs of roosting and disturbance around a tropical bay. *Biol. Conserv.* 133, 225–235. doi: 10.1016/j.biocon.2006.06.007

Rolton, A., Vignier, J., Volety, A. K., Pierce, R. H., Henry, M., Shumway, S. E., et al. (2016). Effects of field and laboratory exposure to the toxic dinoflagellate *Karenia brevis* on the reproduction of the eastern oyster, *Crassostrea virginica*, and subsequent development of offspring. *Harmf. Algae* 57, 13–26. doi: 10.1016/j.hal.2016.04.011

Rushing, C. S., Hostetler, J. A., Sillett, T. S., Marra, P. P., Rotenberg, J. A., and Ryder, T. B. (2017). Spatial and temporal drivers of avian population dynamics across the annual cycle. *Ecology* 98, 2837–2850. doi: 10.1002/ecy.1967

Scarpignato, A. L., Harrison, A.-L., Newstead, D. J., Niles, L. J., Porter, R. R., van den Tillaart, M., et al. (2016). Field-testing a new miniaturized GPS-Argos satellite transmitter (3.5 g) on migratory shorebirds. *Wader Study* 123, 240–246. doi: 10.18194/ws.00046

Schwarzer, A. C., Collazo, J. A., Niles, L. J., Brush, J. M., Douglass, N. J., and Percival, H. F. (2012). Annual survival of Red Knots (*Calidris canutus rufa*) wintering in Florida. *Auk* 129, 725–733. doi: 10.1525/auk.2012.11269

Shumway, S. E., Allen, S. M., and Boersma, P. D. (2003). Marine birds and harmful algal blooms: sporadic victims or under-reported events? *Harmf. Algae* 2, 1–17.

Simberloff, D. (1988). The contribution of population and community biology to conservation science. *Annu. Rev. Ecol. Systematics* 19 (1), 473–511.

Stantial, M. L., Cohen, J. B., Loring, P. H., and Paton, P. W. C. (2019). Radio transmitters did not affect apparent survival rates of adult Piping Plovers (*Charadrius melodus*). *Waterbirds* 42, 205–209. doi: 10.1675/063.042.0207

Stumpf, R. P., Li, Y., Kirkpatrick, B., Litaker, R. W., Hubbard, K. A., Currier, R. D., et al. (2022). Quantifying *Karenia brevis* bloom severity and respiratory irritation impact along the shoreline of Southwest Florida. *PloS One* 17, e0260755. doi: 10.1371/journal.pone.0260755

Stutchbury, B. J. M., Tarof, S. A., Done, T., Gow, E. A., Kramer, P. M., Tautin, J., et al. (2009). Tracking long-distance songbird migration by using geolocators. *Science* 323, 896. doi: 10.1126/science.1166664

Summerson, H. C., and Peterson, C. H. (1990). Recruitment failure of the bay scallop, *Argopecten irradians concentricus*, during the first red tide, *Ptychodiscus brevis*, outbreak recorded in North Carolina. *Estuaries* 13, 3, 322–331. doi: 10.2307/1351923

Sutherland, W. J., Alves, J. A., Amano, T., Chang, C. H., Davidson, N. C., Finlayson, C. M., et al. (2012). A horizon scanning assessment of current and potential future threats facing migratory shorebirds. *Ibis* 154, 663–679. doi: 10.1111/j.1474-919X.2012.01261.x

Tester, P. A., Turner, J. T., and Shea, D. (2000). Vectorial transport of toxins from the dinoflagellate *Gymnodinium breve* through copepods to fish. *J. Plankton Res.* 22, 47–62. doi: 10.1093/plankt/22.1.47

Tominack, S. A., Coffey, K. Z., Yoskowitz, D., Sutton, G., and Wetz, M. S. (2020). An assessment of trends in the frequency and duration of *Karenia brevis* red tide blooms on the South Texas coast (western Gulf of Mexico). *PloS One* 15, e0239309. doi: 10.1371/journal.pone.0239309

Tomkovich, P. S., Porter, R. R., Loktionov, E. Y., and Niles, L. J. (2013). Pathways and staging areas of Red Knots Calidris canutus rogersi breeding in southern Chukotka, Far Eastern Russia. *Wader Study Group Bull.* 120, 181–193.

Torres, G. (2015). Evaluación de mareas rojas durante 1968-2009 en Ecuador. *Acta Oceanográfica del Pacífico* 20, 89–98.

Tucker, A. M., McGowan, C. P., Lyons, J. E., DeRose-Wilson, A., and Clark, N. A. (2021). Species-specific demographic and behavioral responses to food availability during migratory stopover. *Popul. Ecol.* 2021, 1–16.

Tucker, A. M., McGowan, C. P., Nuse, B. L., Lyons, J. E., Moore, C. T., Smith, D. R., et al. (2023). Estimating recruitment rate and population dynamics at a migratory stopover site using an integrated population model. *Ecosphere* 14, 1–16. doi: 10.1002/ecs2.4439

Tuma, M. E., and Powell, A. N. (2021). The southeastern U.S. as a complex of use sites for nonbreeding *rufa* Red Knots: fifteen years of band encounter data. *Wader Study* 128, 265–273. doi: 10.18194/ws

U.S. Fish and Wildlife Service [USFWS]. (2014a). *Threatened species status for the Rufa red knot*. 73706–73748, 79 Federal Register 238 (2014 December 11).

U.S. Fish and Wildlife Service [USFWS]. (2014b). Rufa *red knot background information and threats assessment. Supplement to Endangered and Threatened Wildlife and Plants; Final Threatened Status for the* Rufa *red knot (*Calidris canutus rufa*) [Document No. FWS-R5-ES-2013-0097; RIN AY17]* (Pleasantville, New Jersey, USA: U.S. Fish and Wildlife Service).

U.S. Fish and Wildlife Service [USFWS]. (2021). Rufa *Red Knot Critical Habitat Methods [Document No. FWS-R5-ES-2021-0032-0009]* (Pleasantville, New Jersey, USA: U.S. Fish and Wildlife Service). 12 pp.

van Deventer, M., Atwood, K., Vargo, G. A., Flewelling, L. J., Landsberg, J. H., Naar, J. P., et al. (2012). *Karenia brevis* red tides and brevetoxin-contaminated fish: a high risk factor for Florida's scavenging shorebirds? *Botanica Marina* 55, 31–37. doi: 10.1515/bot.2011.122

van Dolah, F. M. (2000). Marine algal toxins: origins, health effects, and their increased occurrence. *Environ. Health Perspect.* 108, 133–141. doi: 10.1289/ehp.00108s1133

van Gils, J. A., Piersma, T., Dekinga, A., and Battley, P. F. (2006). Modelling phenotypic flexibility: an optimality analysis of gizzard size in Red Knots (*Calidris canutus*). *Ardea* 9), 409–420.

Van Hemert, C., Dusek, R. J., Smith, M. M., Kaler, R., Sheffield, G., Divine, L. M., et al. (2021). Investigation of algal toxins in a multispecies seabird die-off in the Bering and Chukchi Seas. *J. Wildl. Dis.* 57, 399–407. doi: 10.7589/JWD-D-20-00057

Van Hemert, C., Harley, J. R., Baluss, G., Smith, M. M., Dusek, R. J., Lankton, J. S., et al. (2022). Paralytic shellfish toxins associated with Arctic Tern mortalities in Alaska. *Harmf. Algae* 117, 102270. doi: 10.1016/j.hal.2022.102270

van Irsel, J., Frauendorf, M., Ens, B. J., van de Pol, M., Troost, K., Oosterbeek, K., et al. (2022). State-dependent environmental sensitivity of reproductive success and survival in a shorebird. *Ibis* 164, 692–710. doi: 10.1111/ibi.13038

Walsh, J. J., Jolliff, J. K., Darrow, B. P., Lenes, J. M., Milroy, S. P., Remsen, A., et al. (2006). Red tides in the Gulf of Mexico: Where, when, and why? *J. Geophys. Res.* 111, 1–46. doi: 10.1029/2004JC002813

Warnock, N., and Takekawa, J. Y. (2003). Use of radio telemetry in studies of shorebirds: past contributions and future directions. *Wader Study Group Bull.* 100, 1–14.

Webster, M. S., Marra, P. P., Haig, S. M., Bensch, S., and Holmes, R. T. (2002). Links between worlds: unraveling migratory connectivity. *Trends Ecol. Evol.* 17, 76–83. doi: 10.1016/S0169-5347(01)02380-1

Weiser, E. L., Lanctot, R. B., Brown, S. C., Alves, J. A., Battley, P. F., Bentzen, R., et al. (2016). Effects of geolocators on hatching success, return rates, breeding movements, and change in body mass in 16 species of Arctic-breeding shorebirds. *Move. Ecol.* 4, 1–19. doi: 10.1186/s40462-016-0077-6

White, G. C., and Burnham, K. P. (1999). Program MARK: Survival estimation for populations of marked animals. *Bird Study* 46, 120–139.

Wilmers, C. C., Nickel, B., Bryce, C. M., Smith, J. A., Wheat, R. E., and Yovovich, V. (2015). The golden age of bio-logging: how animal-borne sensors are advancing the frontiers of ecology. *Ecology* 96, 1741–1753. doi: 10.1890/14-1401.1

EXHIBIT C

MacDonald, A. et al. 2024
Uniting rufa Red Knot resighting data throughout the western Atlantic Flyway offers myriad opportunities for survival analysis
10th Western Hemisphere Shorebird Group Meeting. Sackville, NB, Canada
August 11-16, 2024

Uniting *rufa* Red Knot resighting data throughout the western Atlantic Flyway offers myriad opportunities for survival analysis

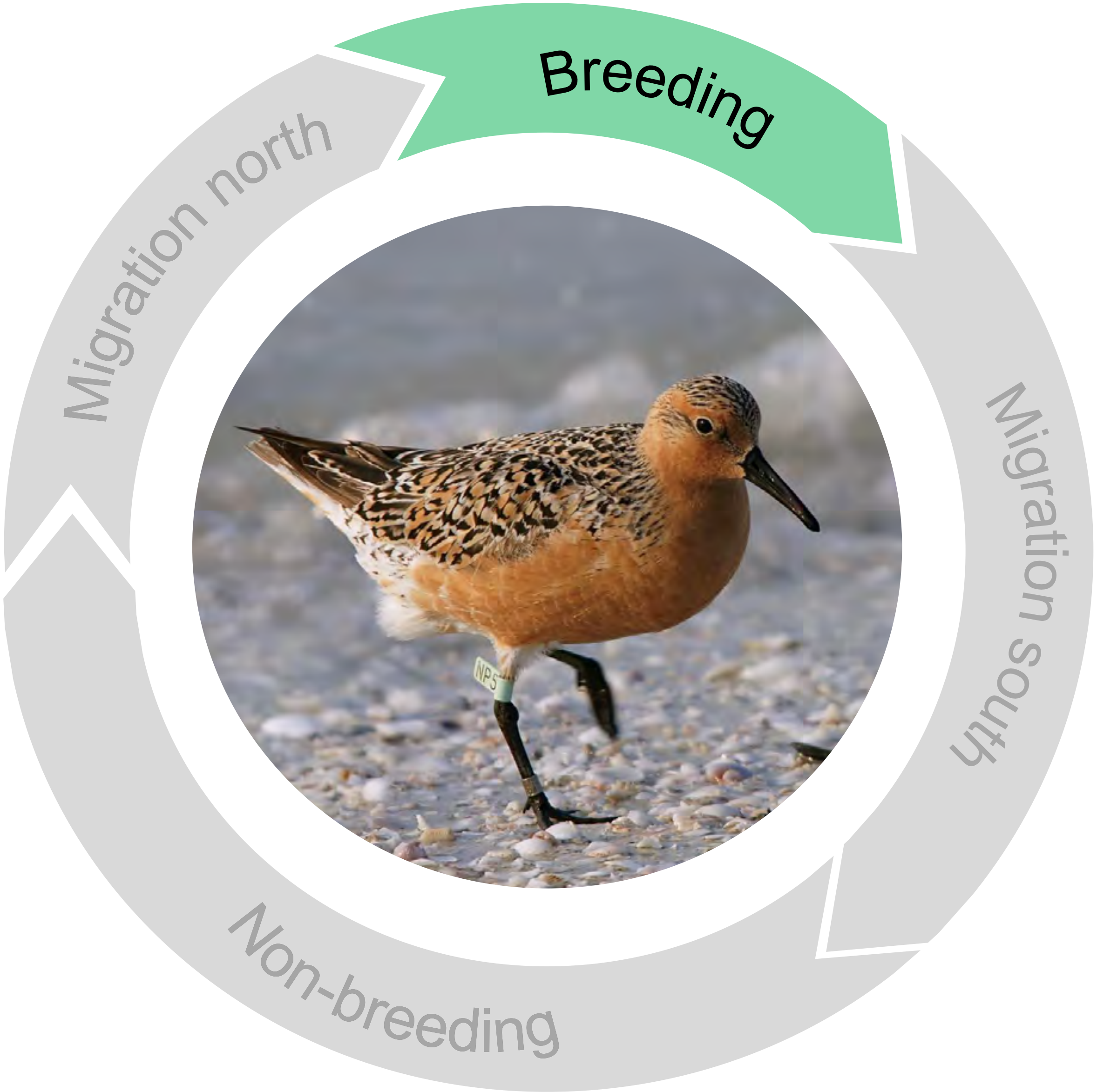
La unión de los datos de reencuentro de Calidris canutus rufa *en todo el hemisferio occidental ofrece múltiples oportunidades para el análisis de la supervivencia*

Amie MacDonald, Yves Aubry, Henrietta Bellman, Janell Brush, Christophe Buidin, Jacquie Clark, Nigel Clark, Audrey DeRose-Wilson, Amanda Dey, Theo Diehl, Stephanie Feigin, Christian Friis, Patricia González, Brian Harrington, Kevin Kalasz, Timothy Keyes, Stephanie Koch, Patrick Leary, James Lyons, Natalia Martínez Curci, David Mizrahi, Jason Mobley, David Newstead, Lawrence Niles, Erica Nol, Julie Paquet, Mark Peck, Yann Rochepault, Roberta Rodrigues, Felicia Sanders, Fletcher Smith, Bryan Watts, and Paul Smith

BIRDS CANADA
OISEAUX CANADA

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Joe Smith

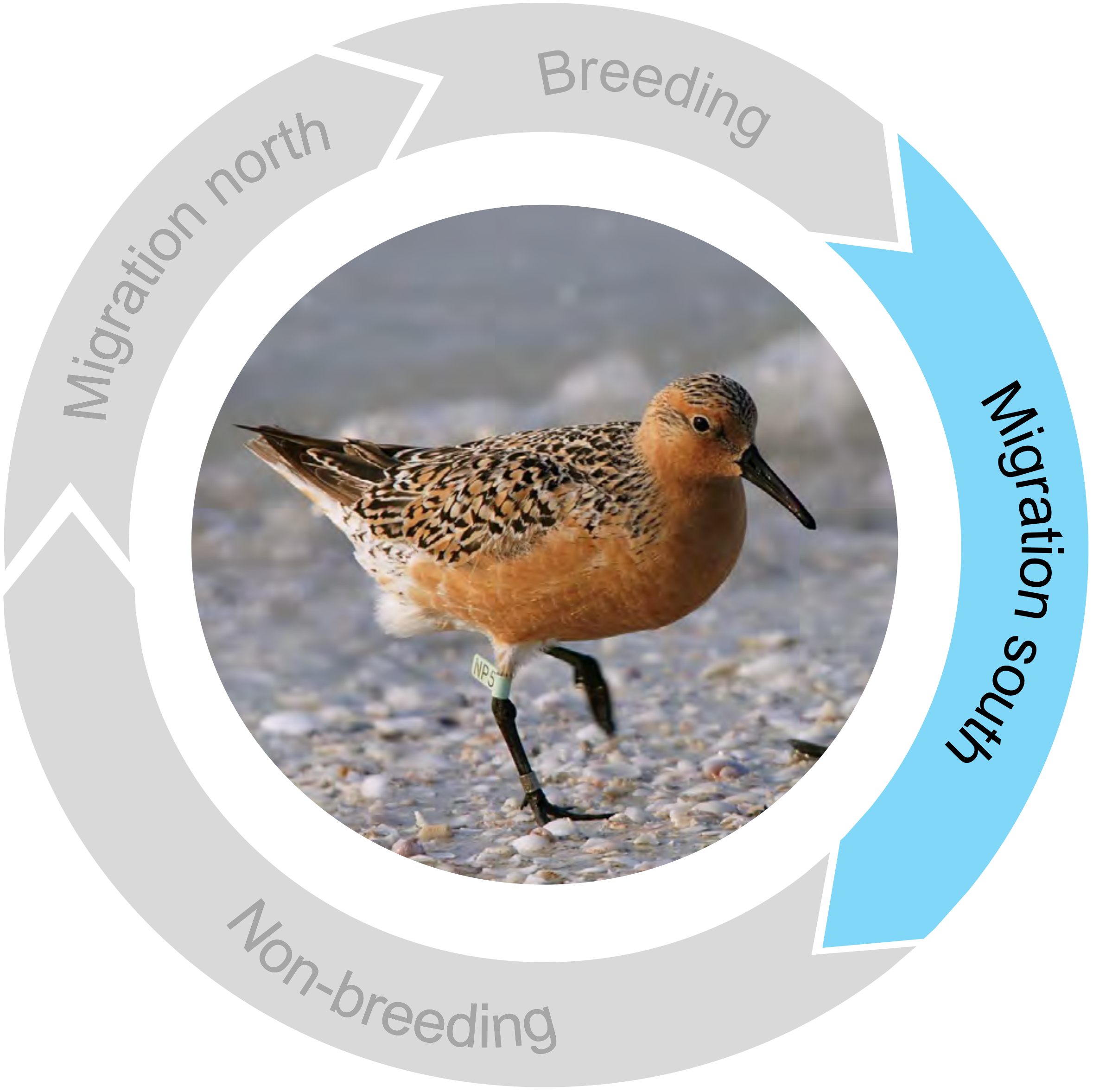

Breeding

Migration south

Non-breeding

Migration north

Joe Smith



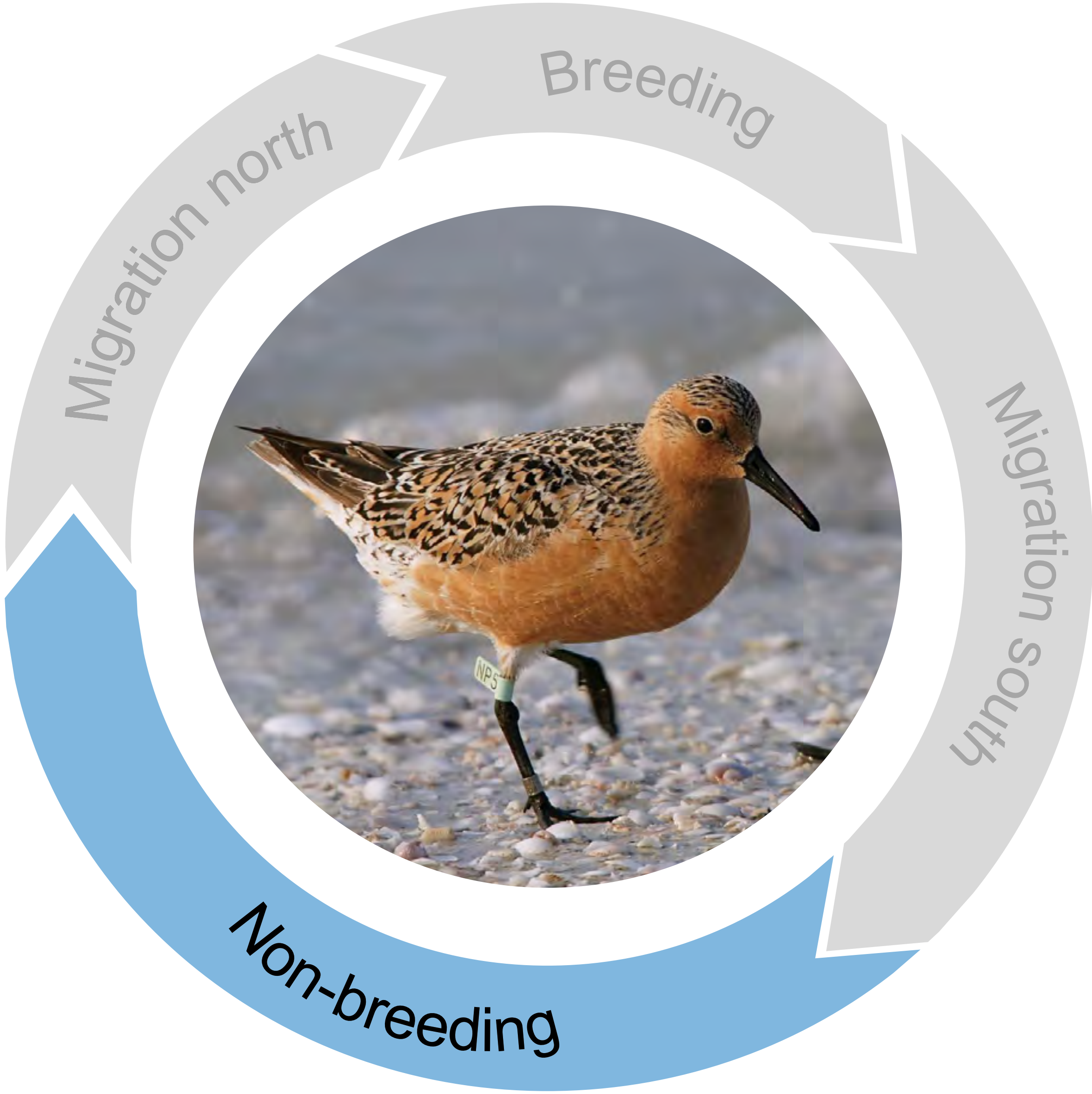
Breeding

Migration south

Non-breeding

Migration north

Joe Smith

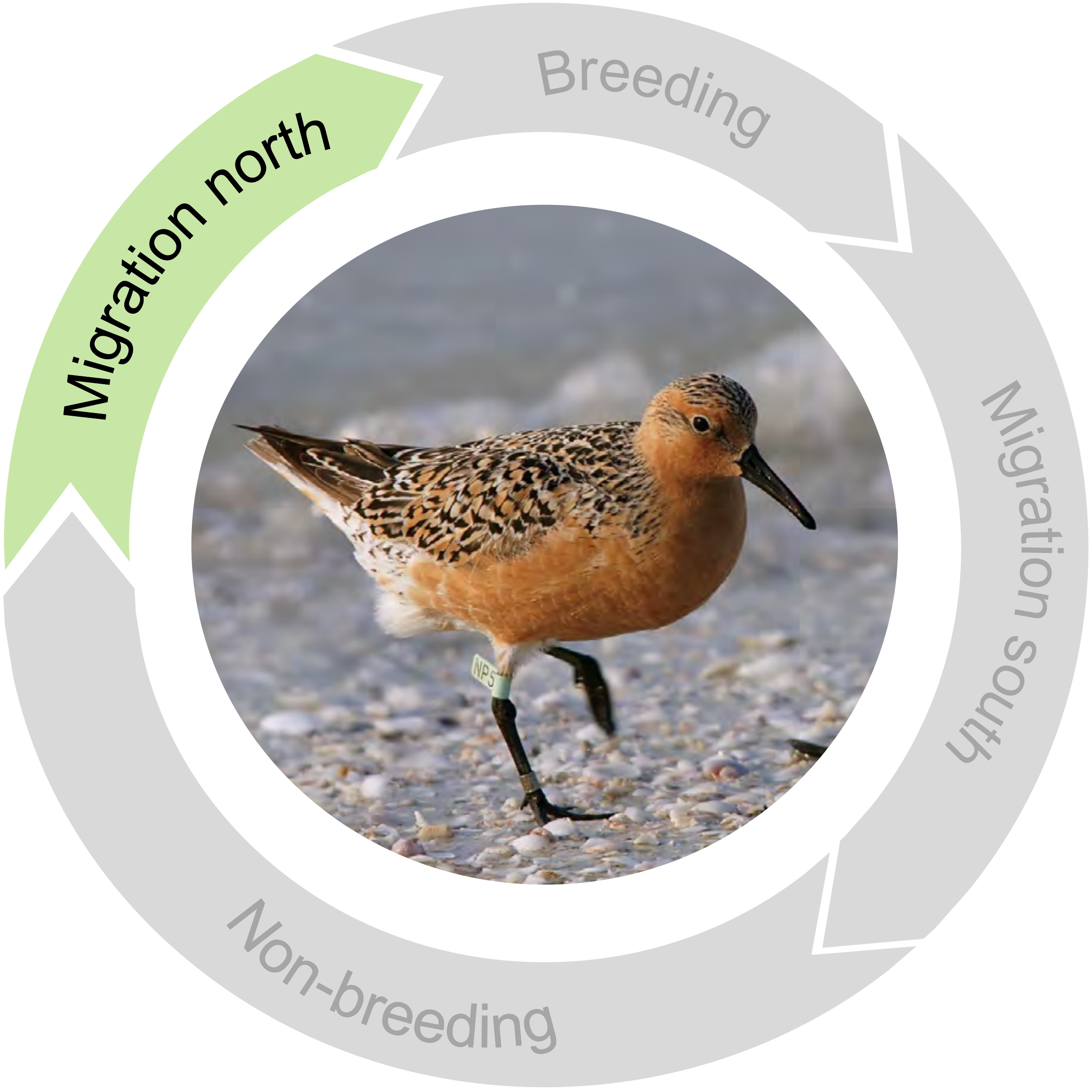

Breeding

Migration south

Non-breeding

Migration north

Joe Smith



Migration north

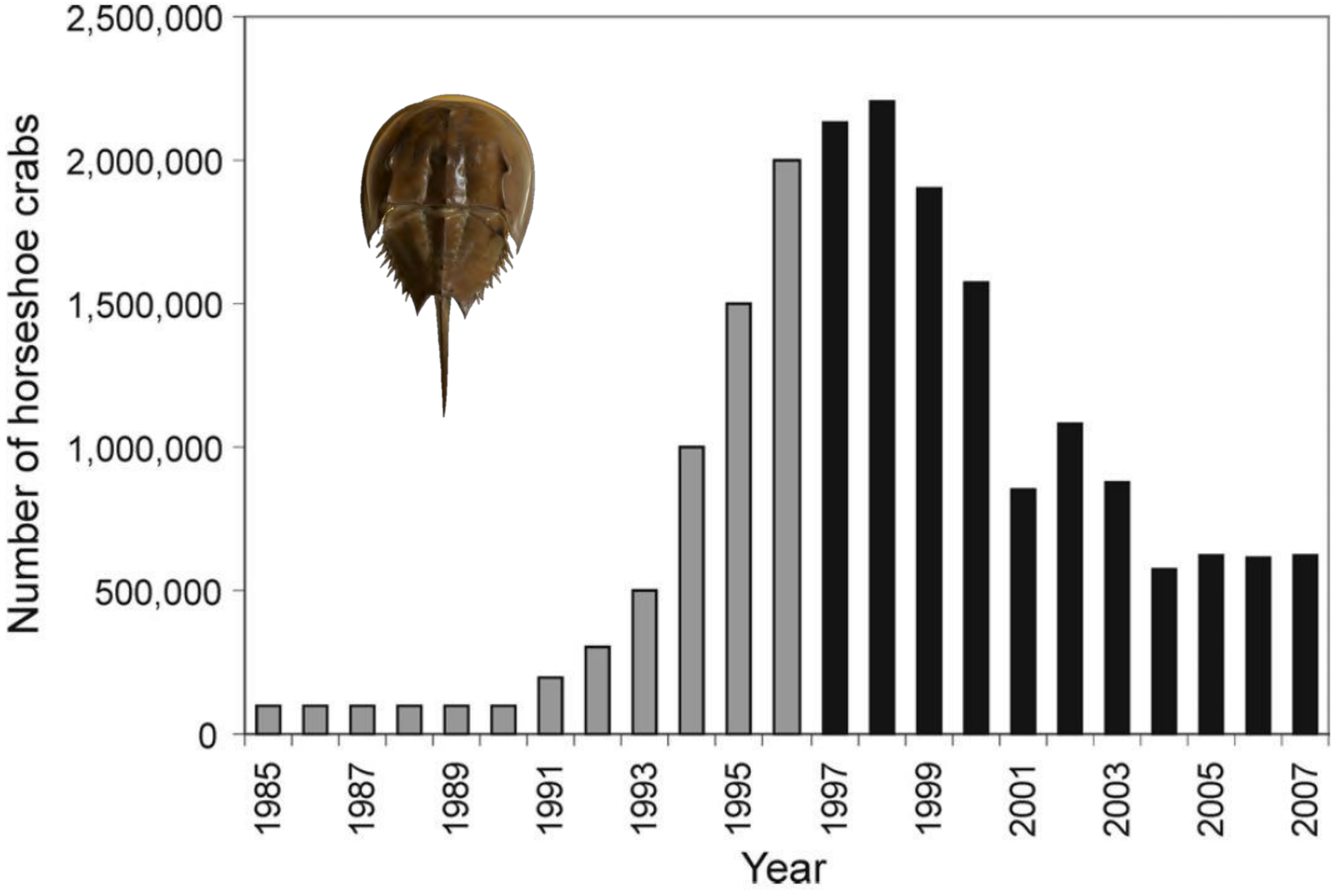
Breeding

Migration south

Non-breeding

Joe Smith

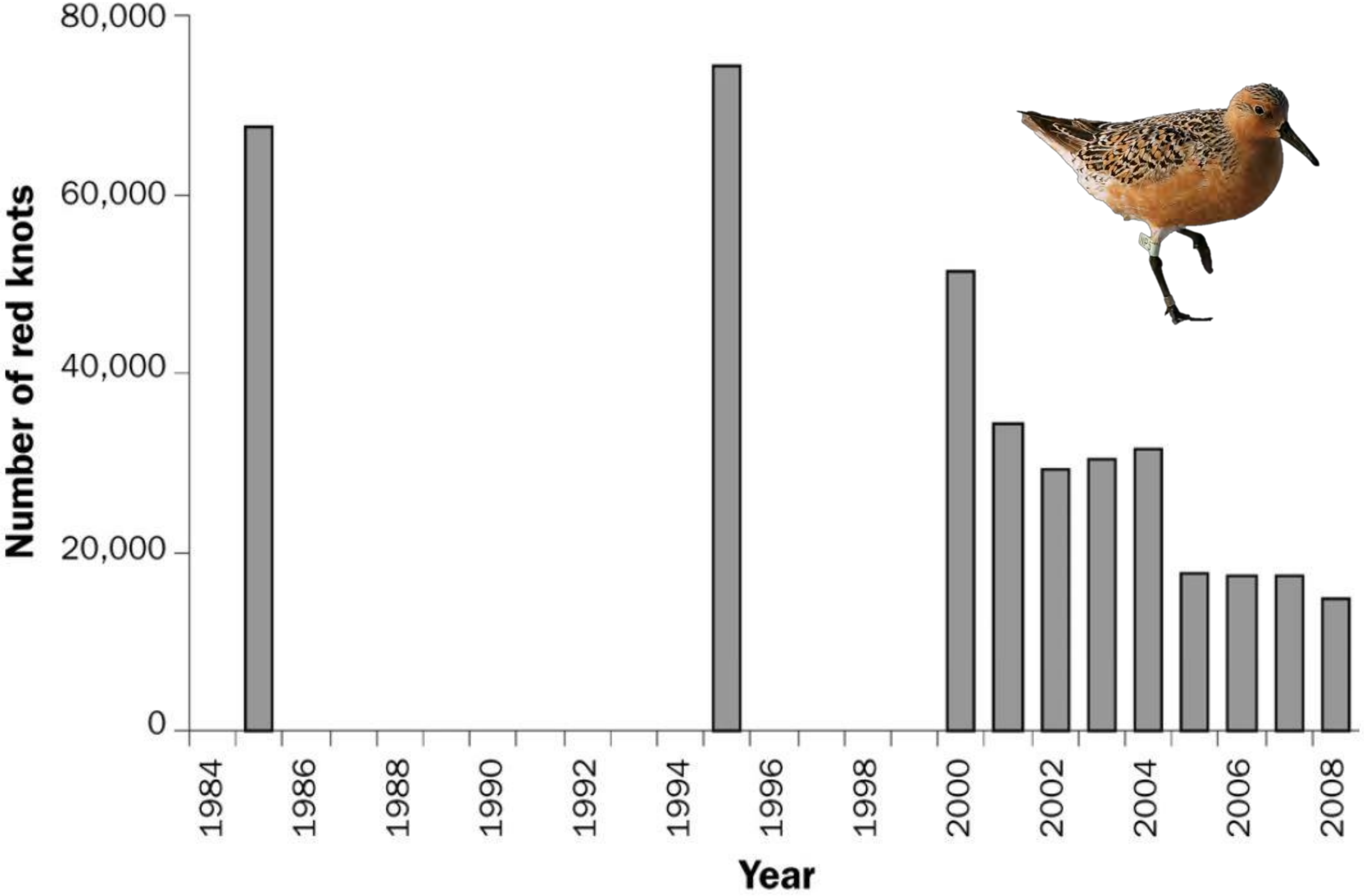
Horseshoe crabs overharvested in late 1990s



Niles et al. (2009)

Joe Smith

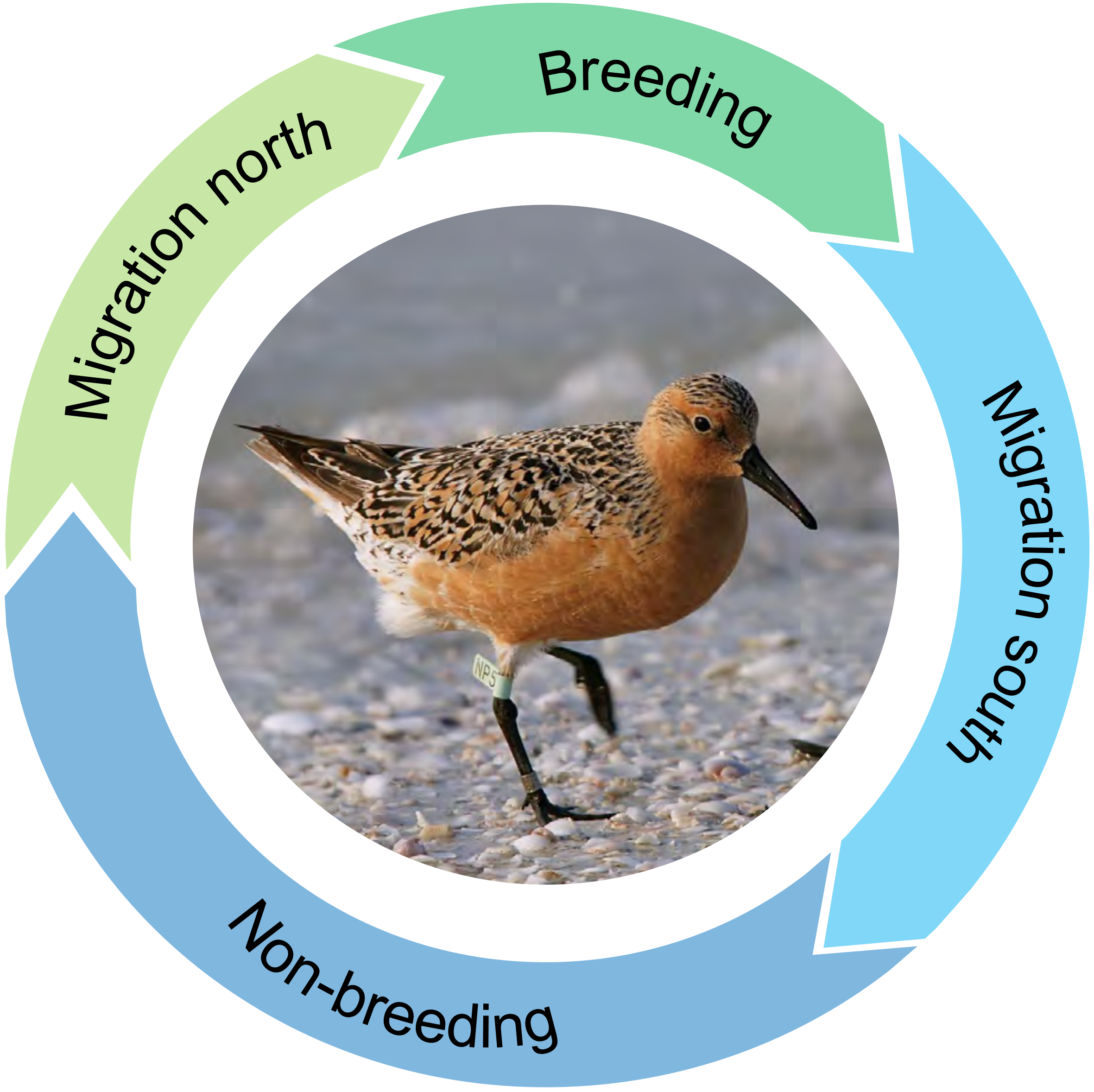
Red Knots declined in 2000s



Niles et al. (2009)


NESTING RANGE
James Bay
Mingan
Delaware Bay
KEY WINTERING AREAS
STOPOVER SITES

Joe Smith

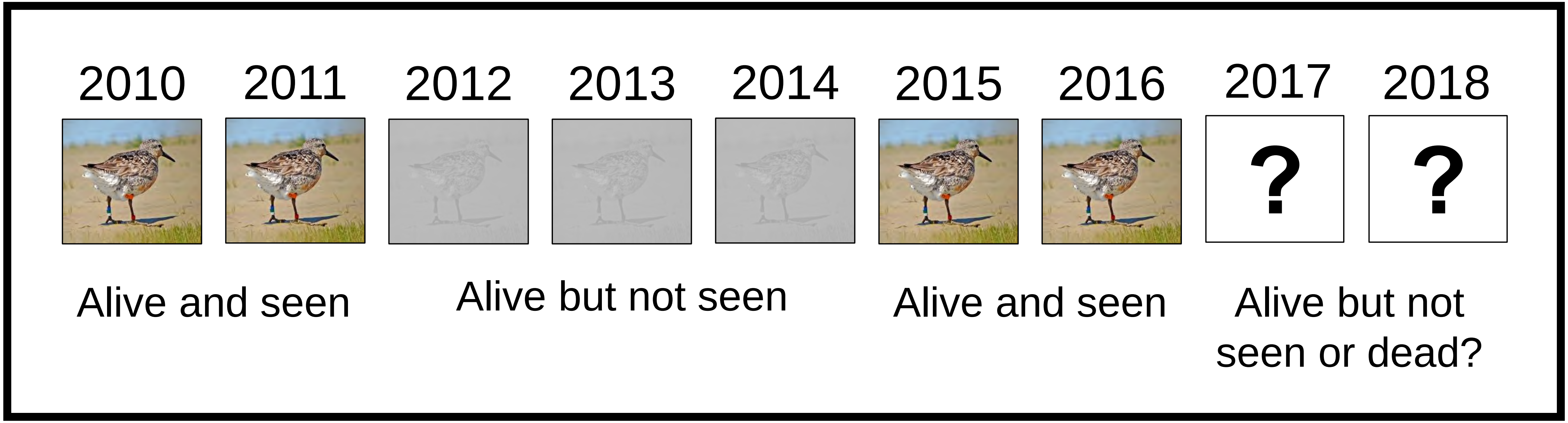

Breeding
Migration south
Non-breeding
Migration north

Many *rufa* red knots are marked with coded leg flags


Yves Aubry

Jean Iron

Analyzing flag resighting data in mark-recapture models permits estimation of demographic parameters



2010 2011 2012 2013 2014 2015 2016 2017 2018

Alive and seen

Alive but not seen

Alive and seen

Alive but not seen or dead?

Bayesian analysis offers flexibility to build models to address various questions about red knot survival

Three case studies

1. Estimate true annual survival for adult red knots staging in James Bay
2. Estimate true annual survival for juvenile red knots at the Mingan archipelago
3. Estimate seasonal survival and transition probabilities among key sites throughout the red knot annual cycle

Three case studies

1. Estimate true annual survival for adult red knots staging in James Bay
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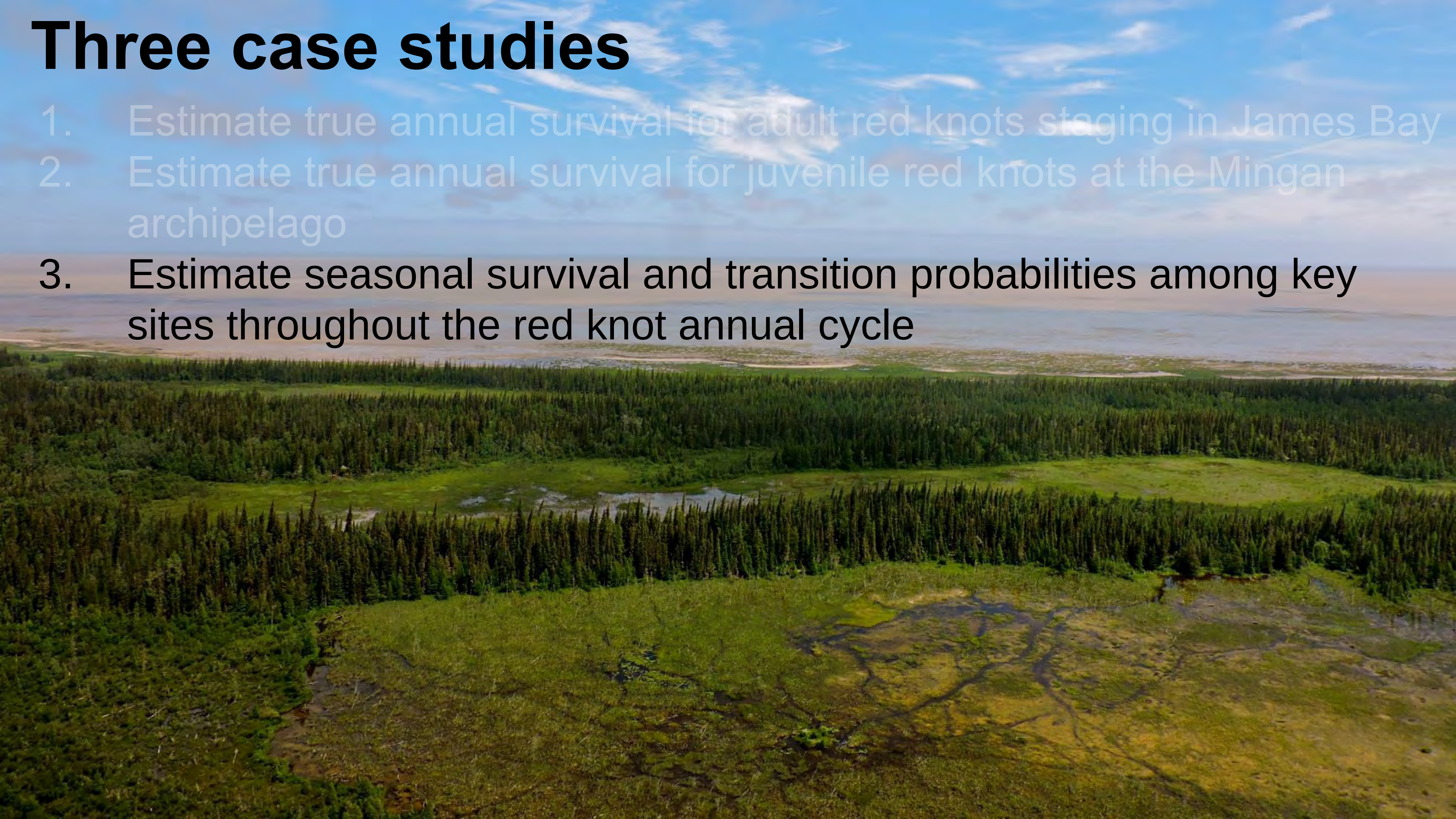
Three case studies



1. Estimate true annual survival for adult red knots staging in James Bay
2. Estimate true annual survival for juvenile red knots at the Mingan archipelago
3. Estimate seasonal survival and transition probabilities among key sites throughout the red knot annual cycle

Survival rates of Red Knots staging in James Bay

Resights from James Bay + Resights from outside James Bay

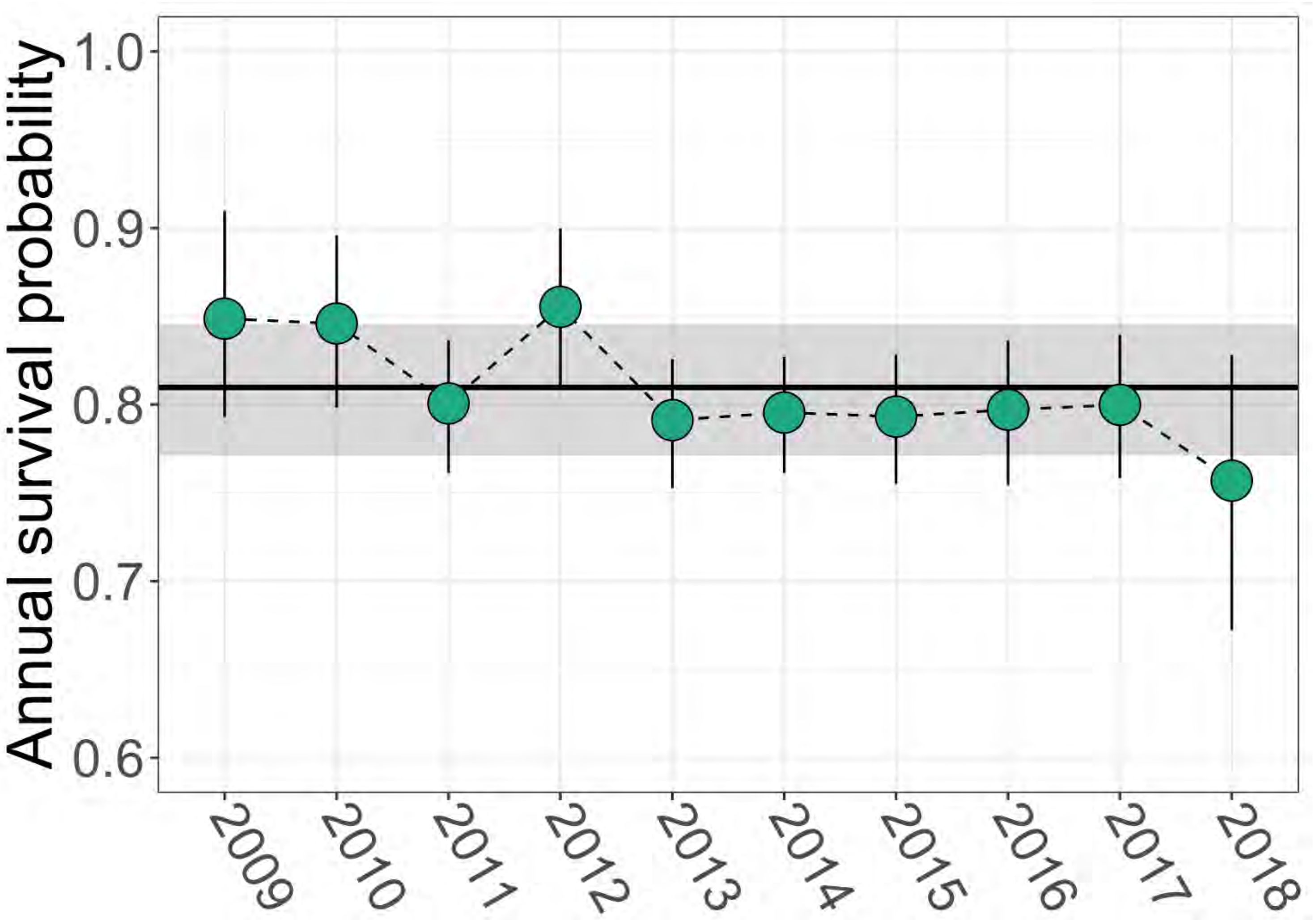
↓

Barker model

↓

True adult survival

Survival rates of Red Knots staging in James Bay



Resights from James Bay

+

Resights from outside James Bay

↓

Barker model

↓

True adult survival = **0.810 (0.771 – 0.846)**

Survival rates of juvenile Red Knots at the Mingan Archipelago

Juvenile banding records + Resights from Mingan

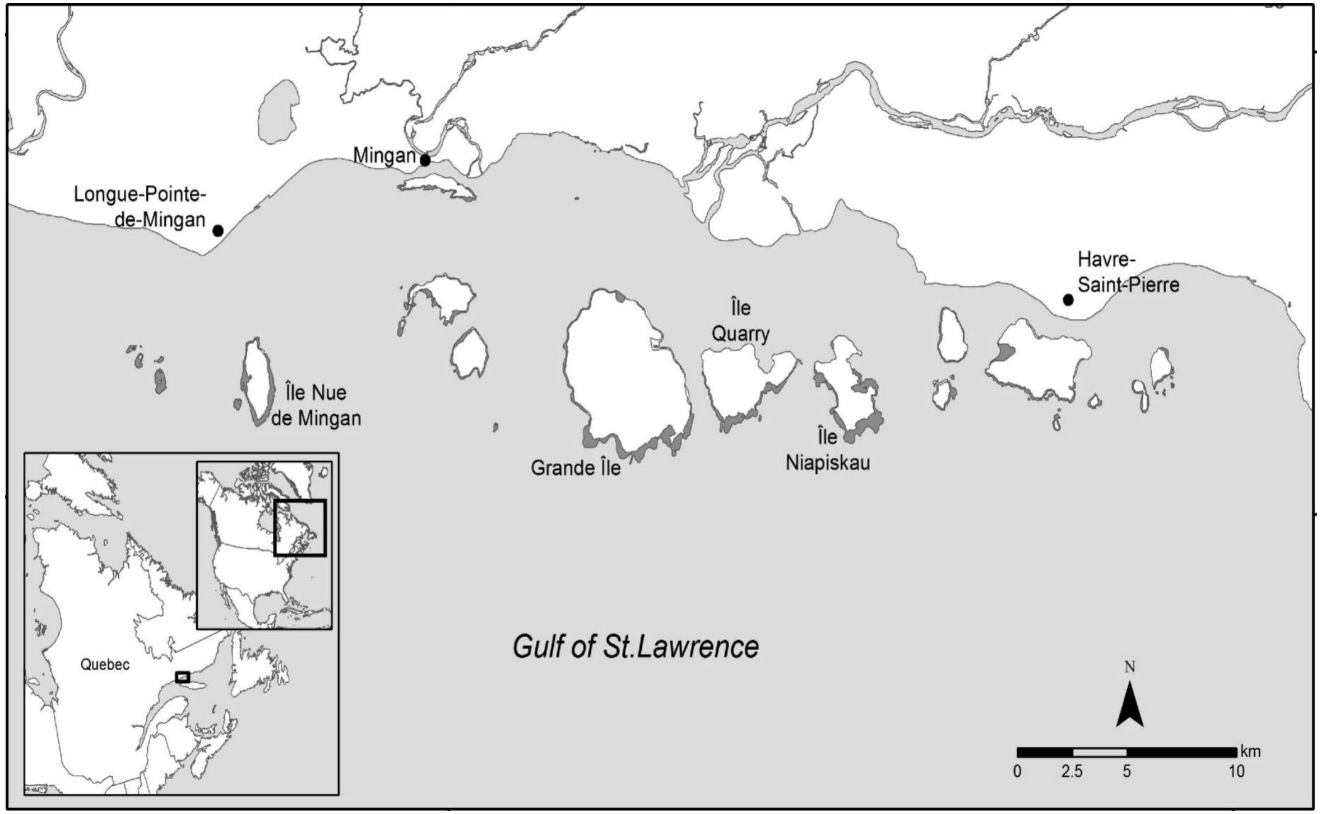
\+

Resights from outside Mingan → Barker model

↓

Juvenile survival

Ian Davies



Lyons et al. (2017)

Survival rates of juvenile Red Knots at the Mingan Archipelago

Juvenile banding records

\+

Resights from Mingan

\+

Resights from outside Mingan

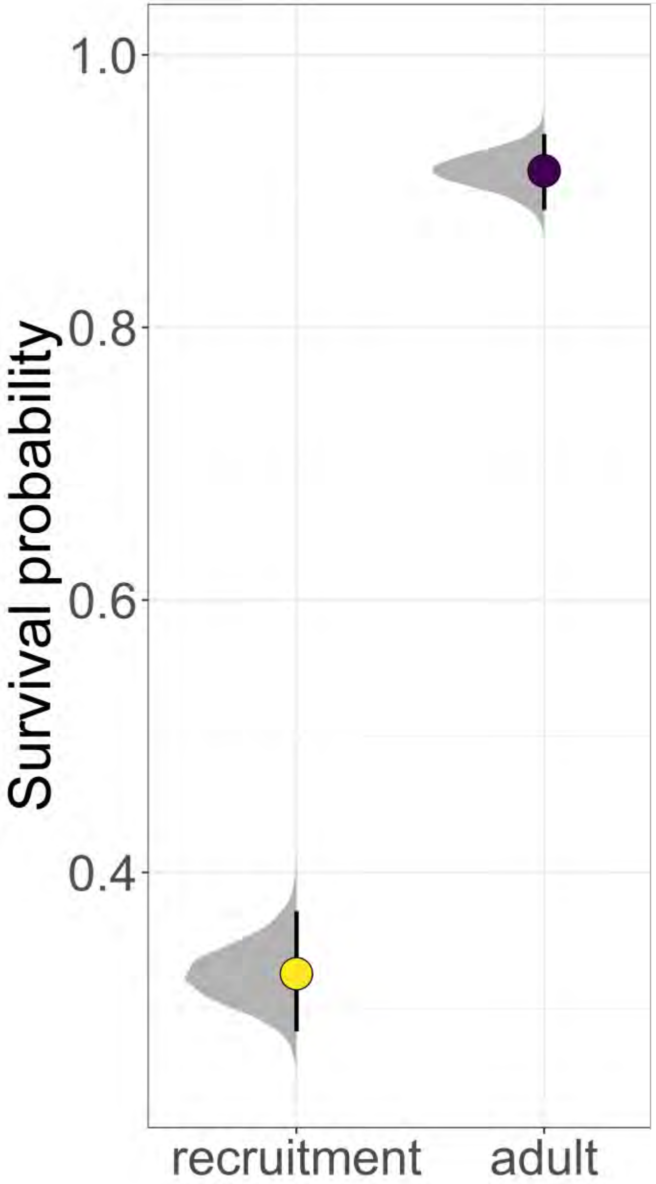
→

Barker model

↓

Juvenile survival

Ian Davies



Survival rates of juvenile Red Knots at the Mingan Archipelago

Juvenile banding records

+

Resights from Mingan

+

Resights from outside Mingan

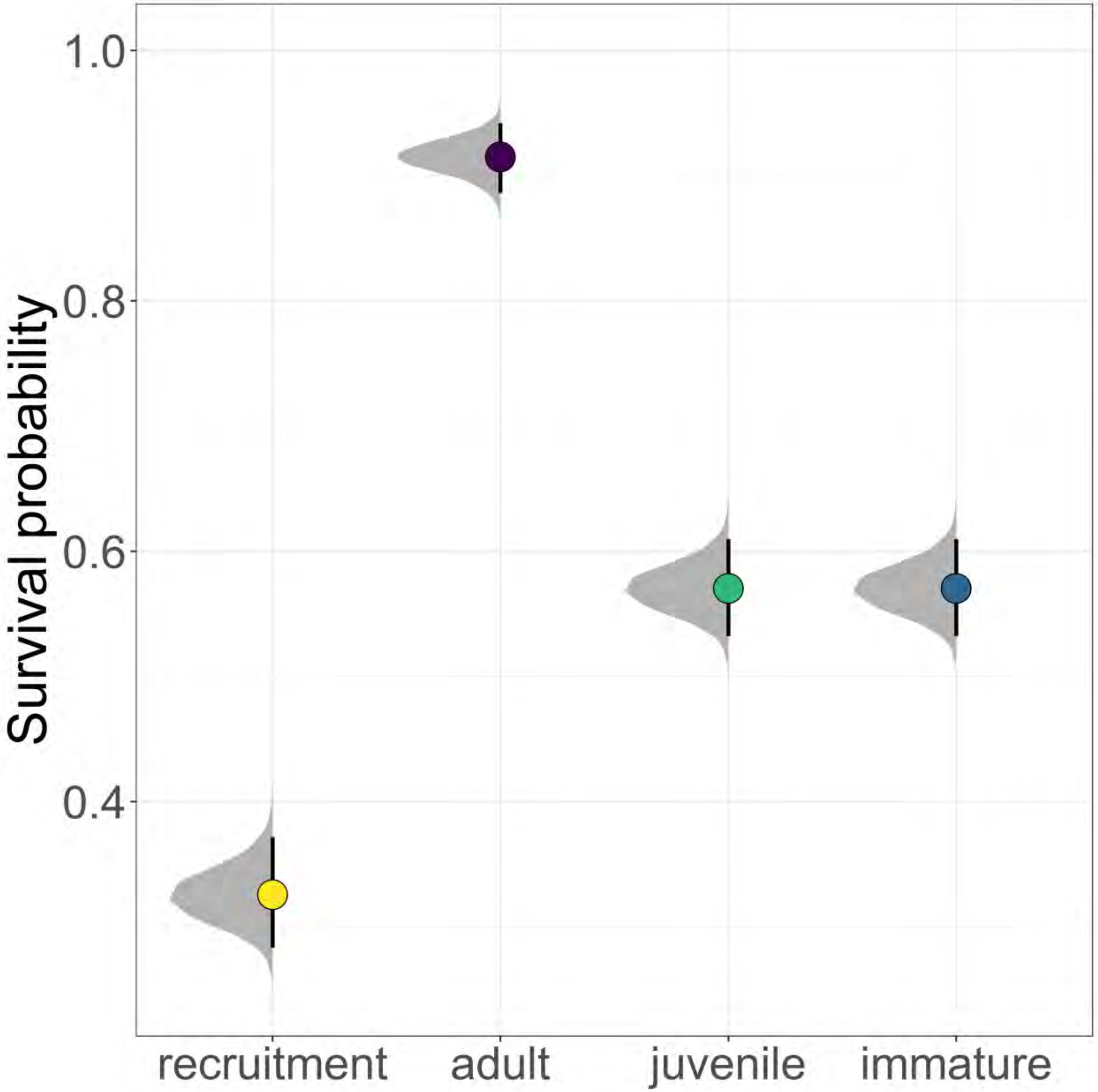
→

Barker model

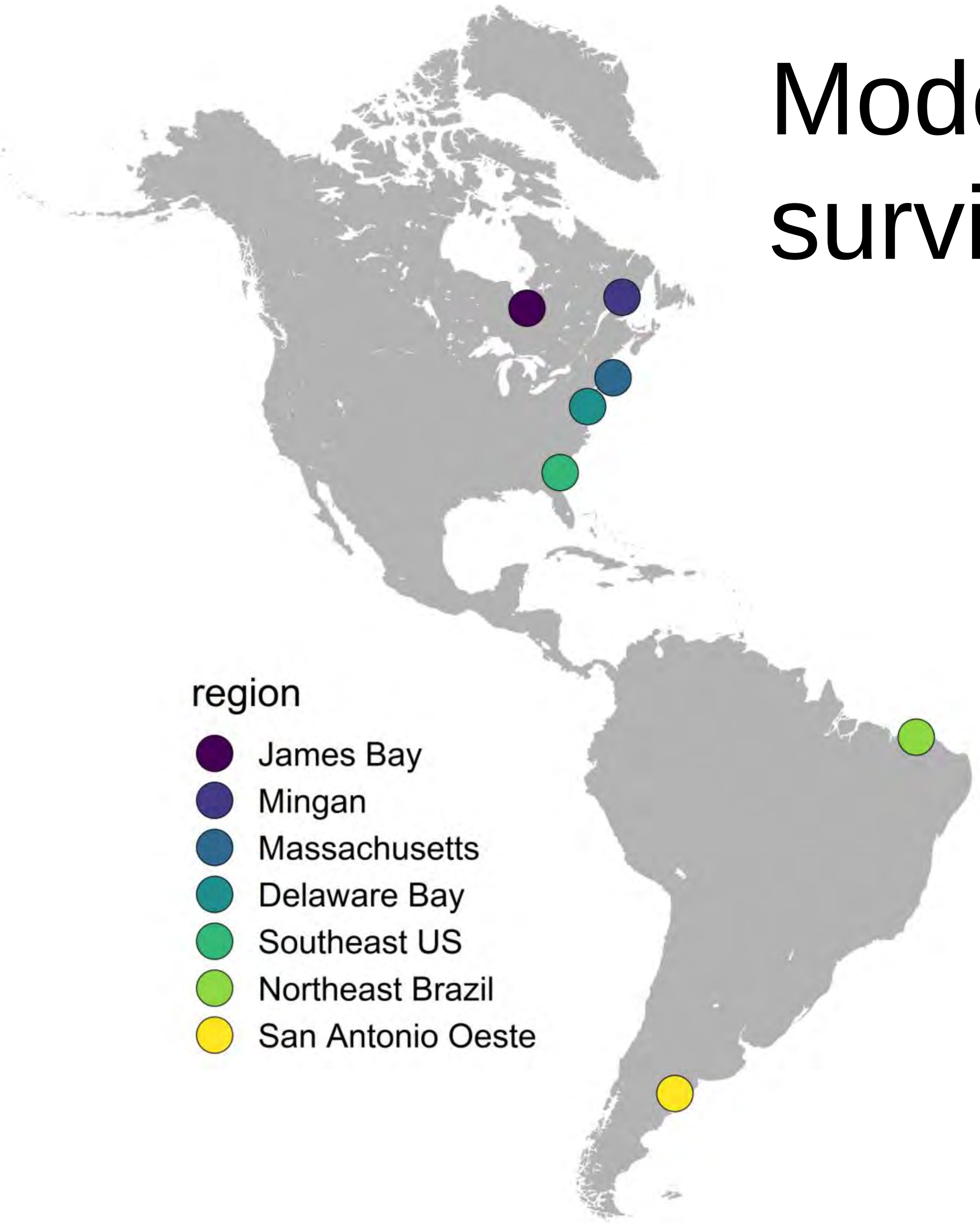
↓

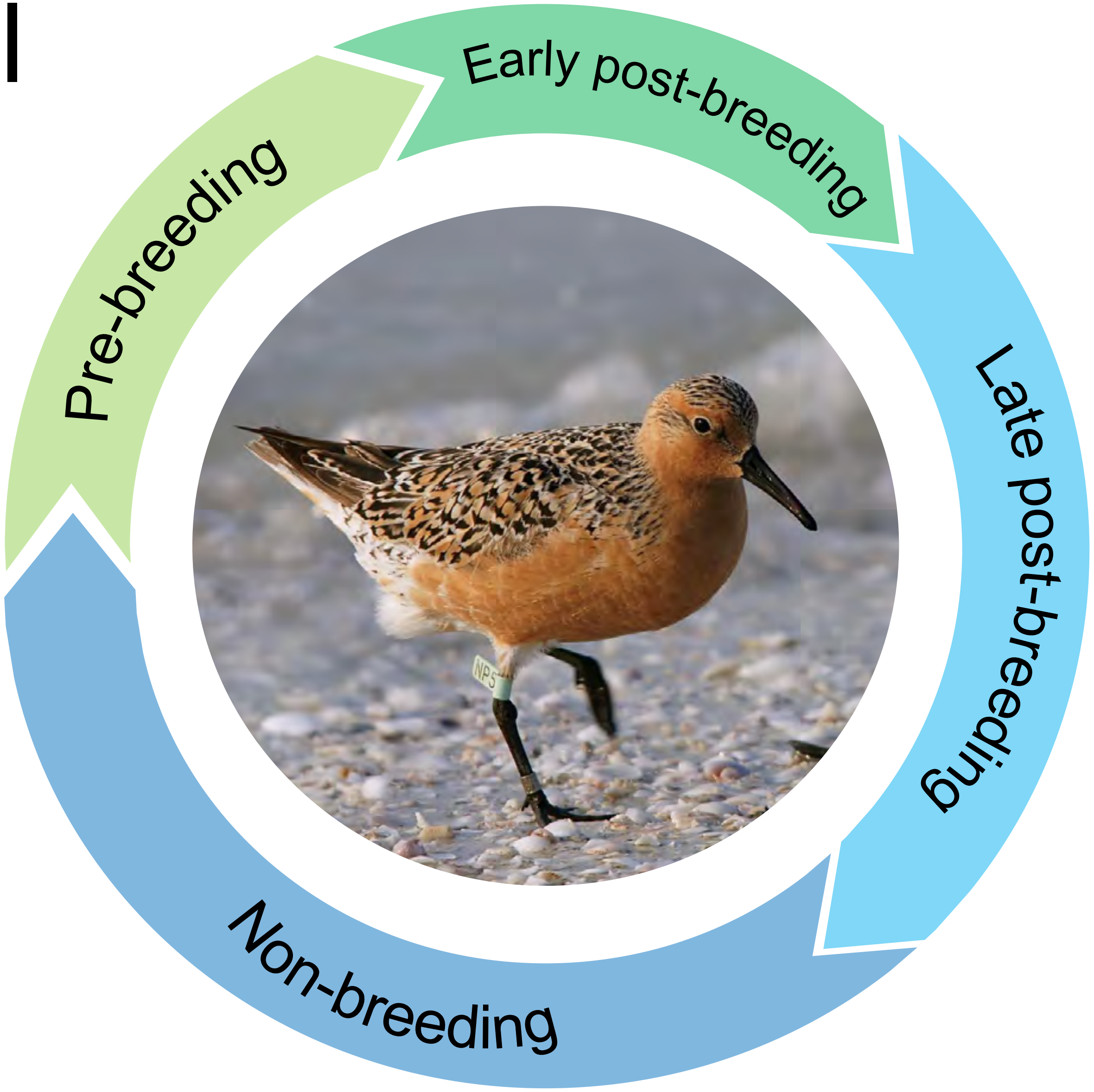
Juvenile survival

Ian Davies

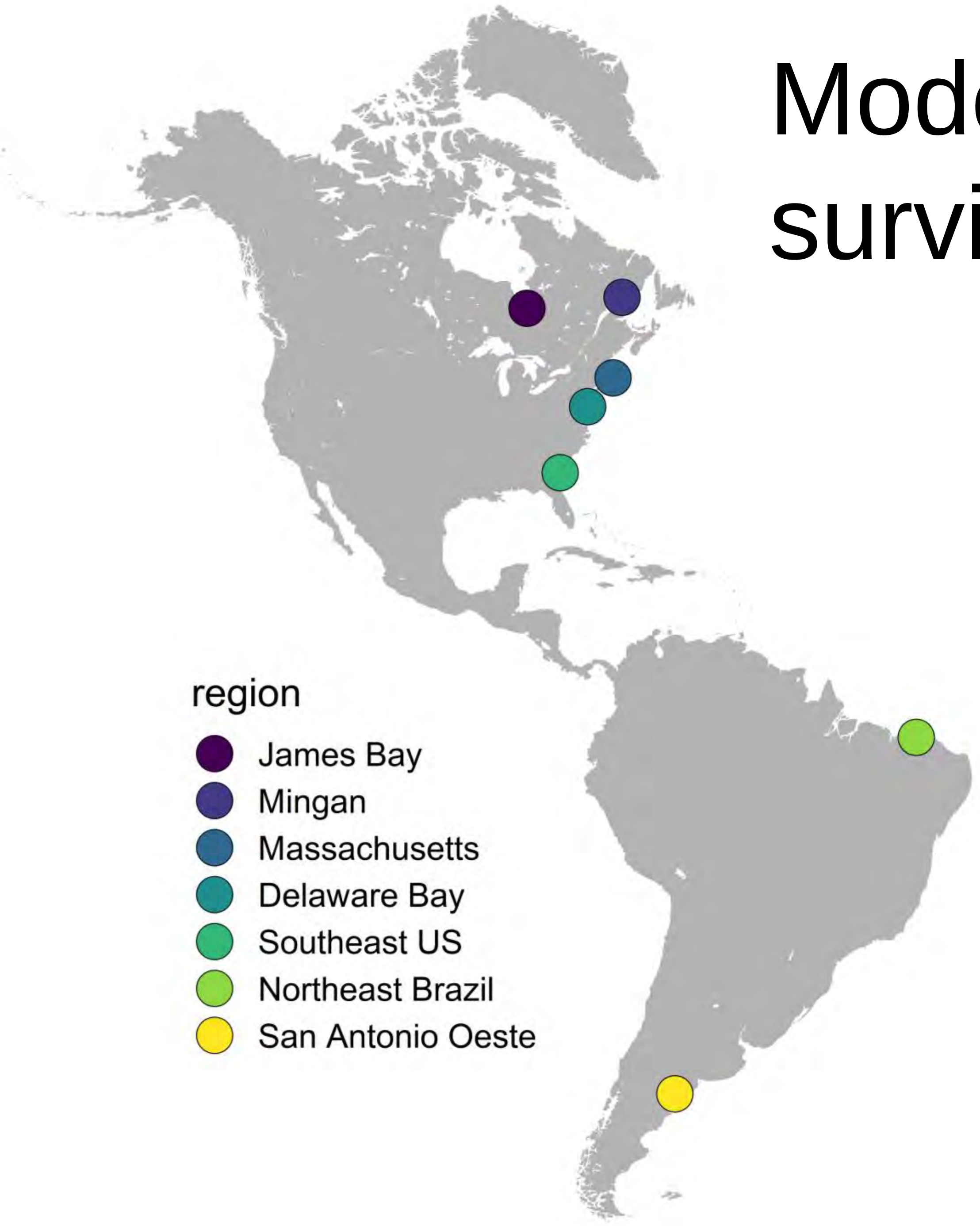


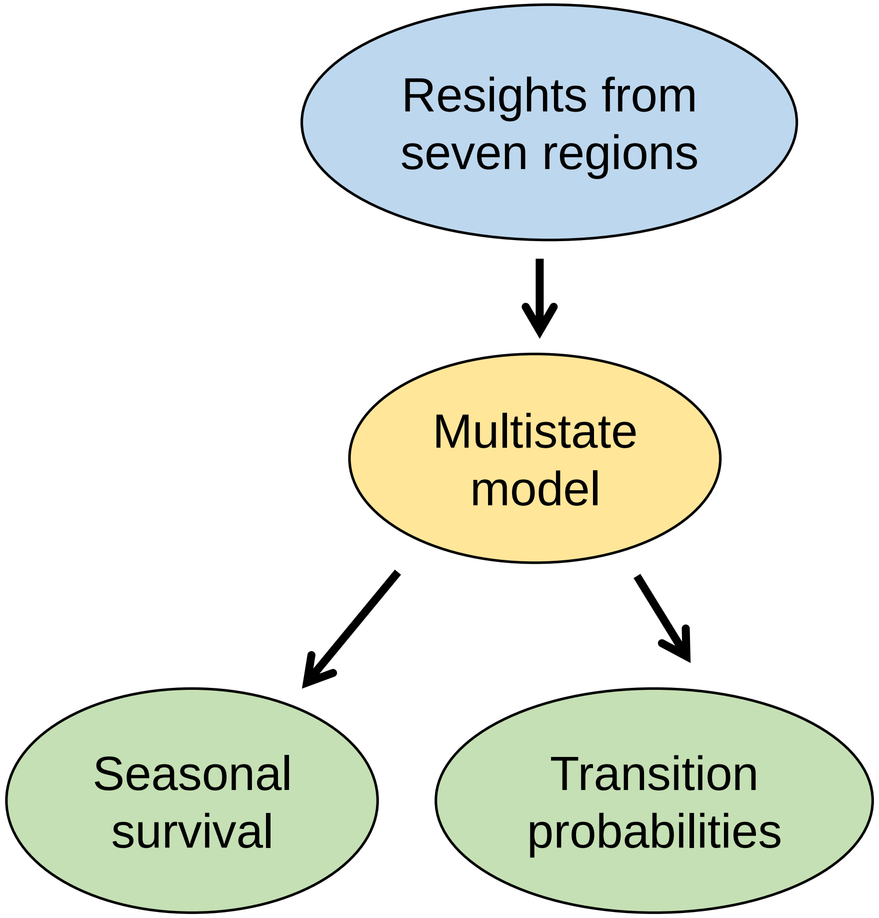
Modelling Red Knot seasonal survival





Modelling Red Knot seasonal survival





Resights from seven regions

Multistate model

Seasonal survival

Transition probabilities

In summary:

7 locations

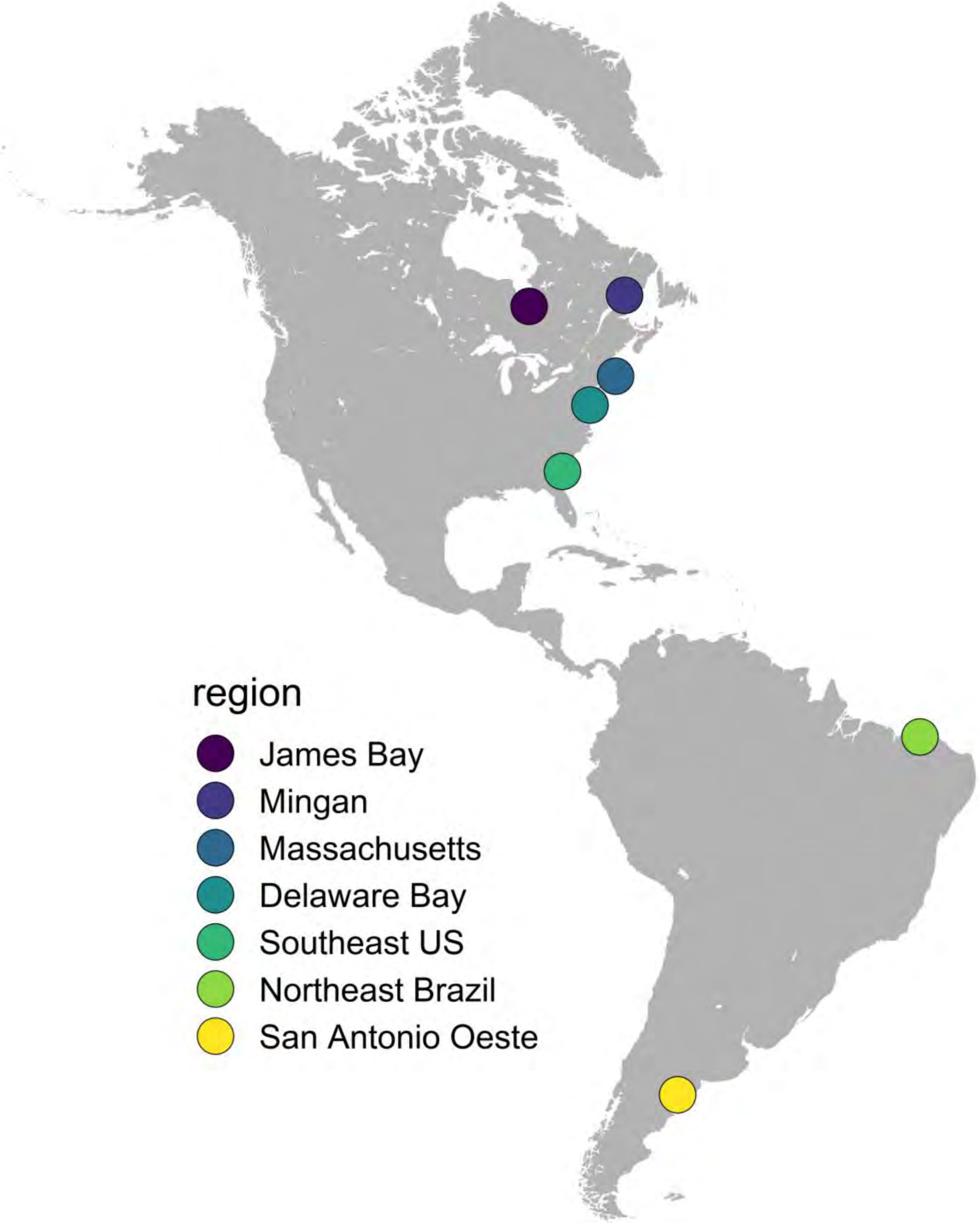
4 seasons

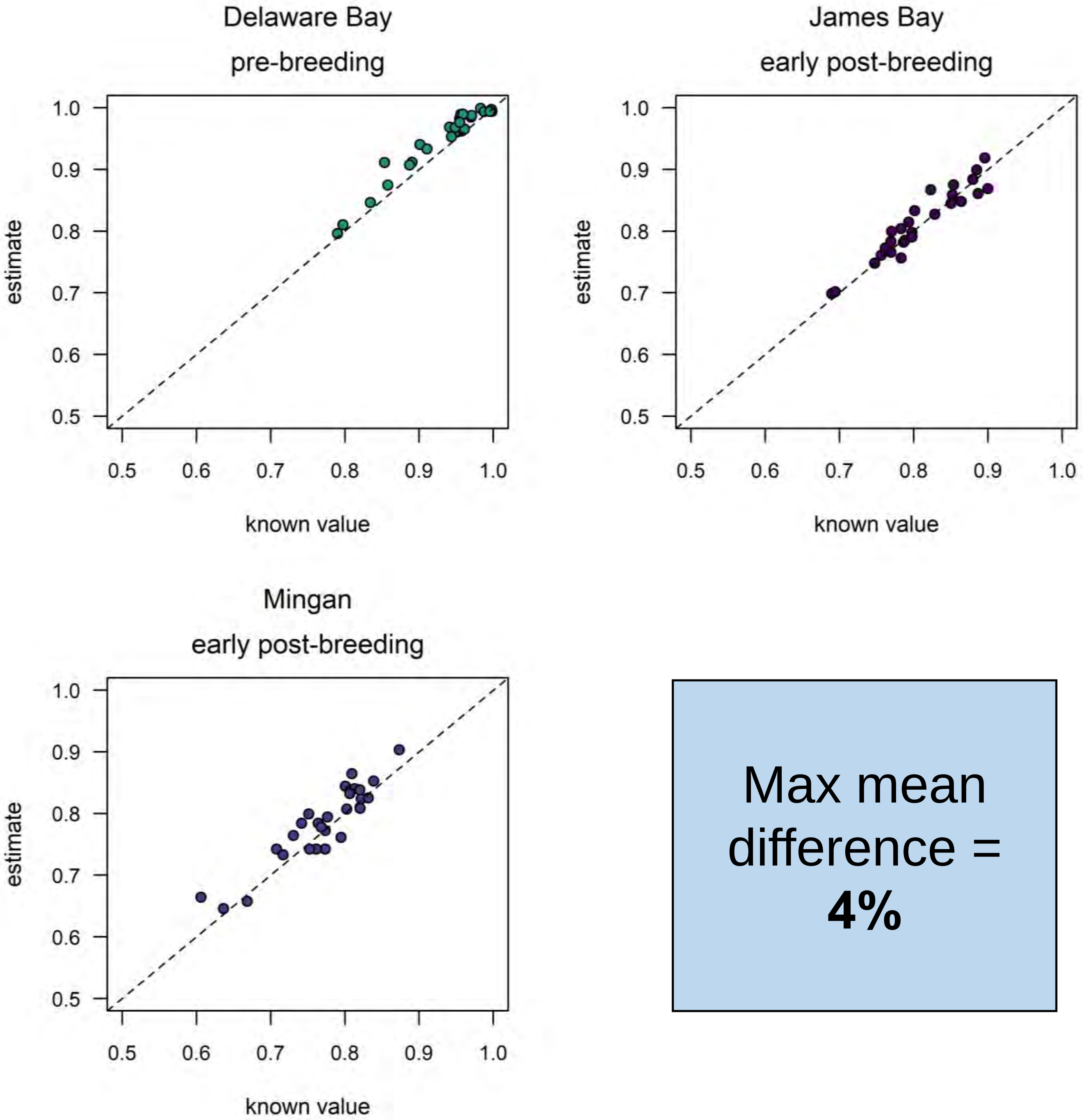
15 survival probabilities

47 transition probabilities

15 resighting probabilities

Karl Bardon

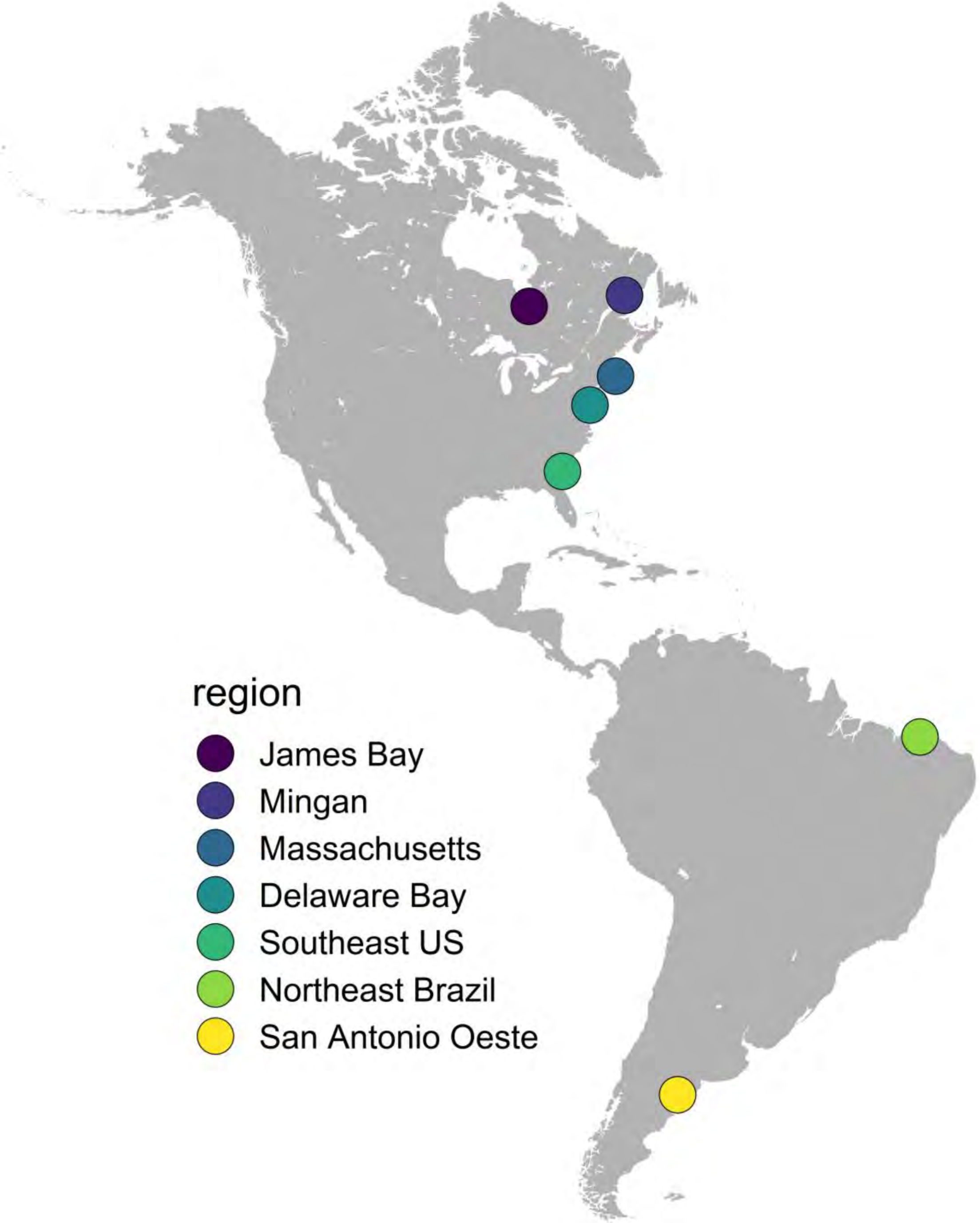


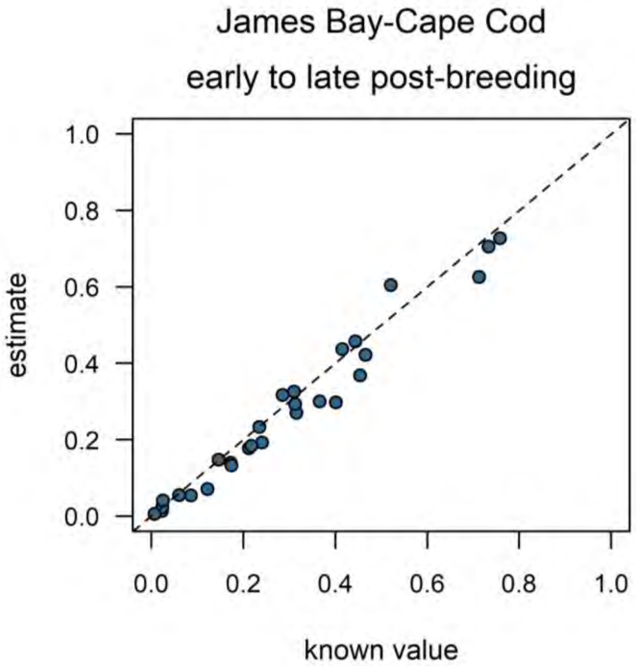

Delaware Bay pre-breeding

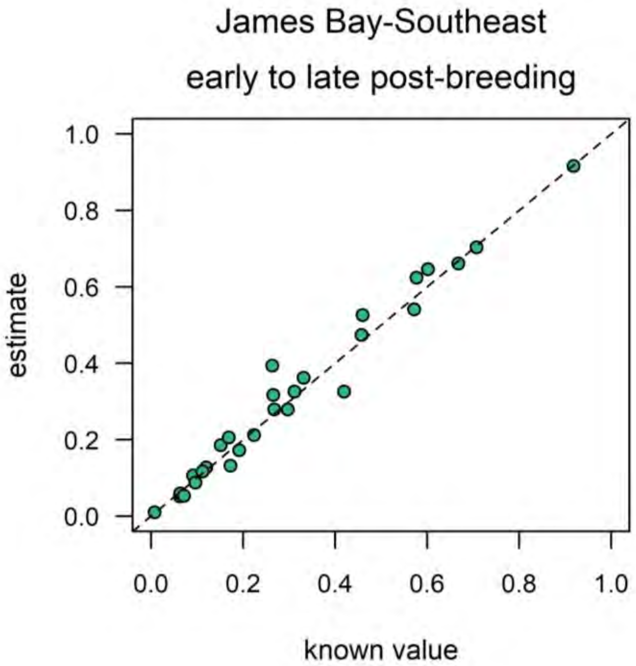
James Bay early post-breeding

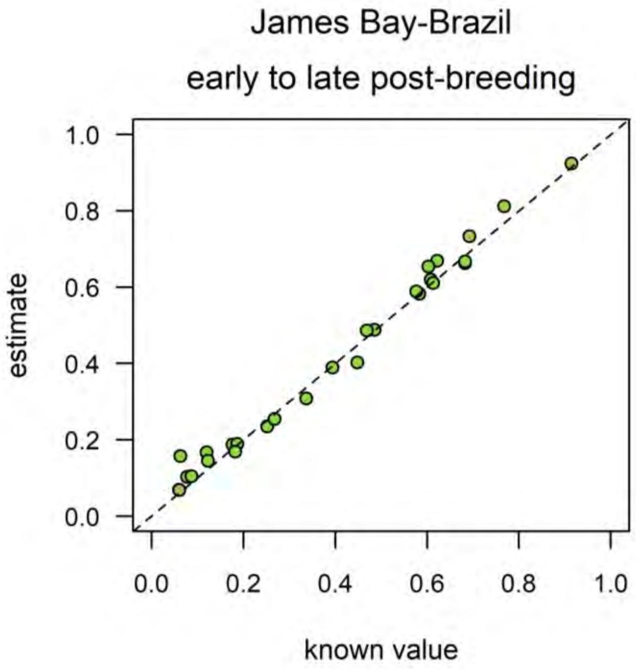
Mingan early post-breeding

Max mean difference = **4%**









Max mean difference = **6%**

Three case studies

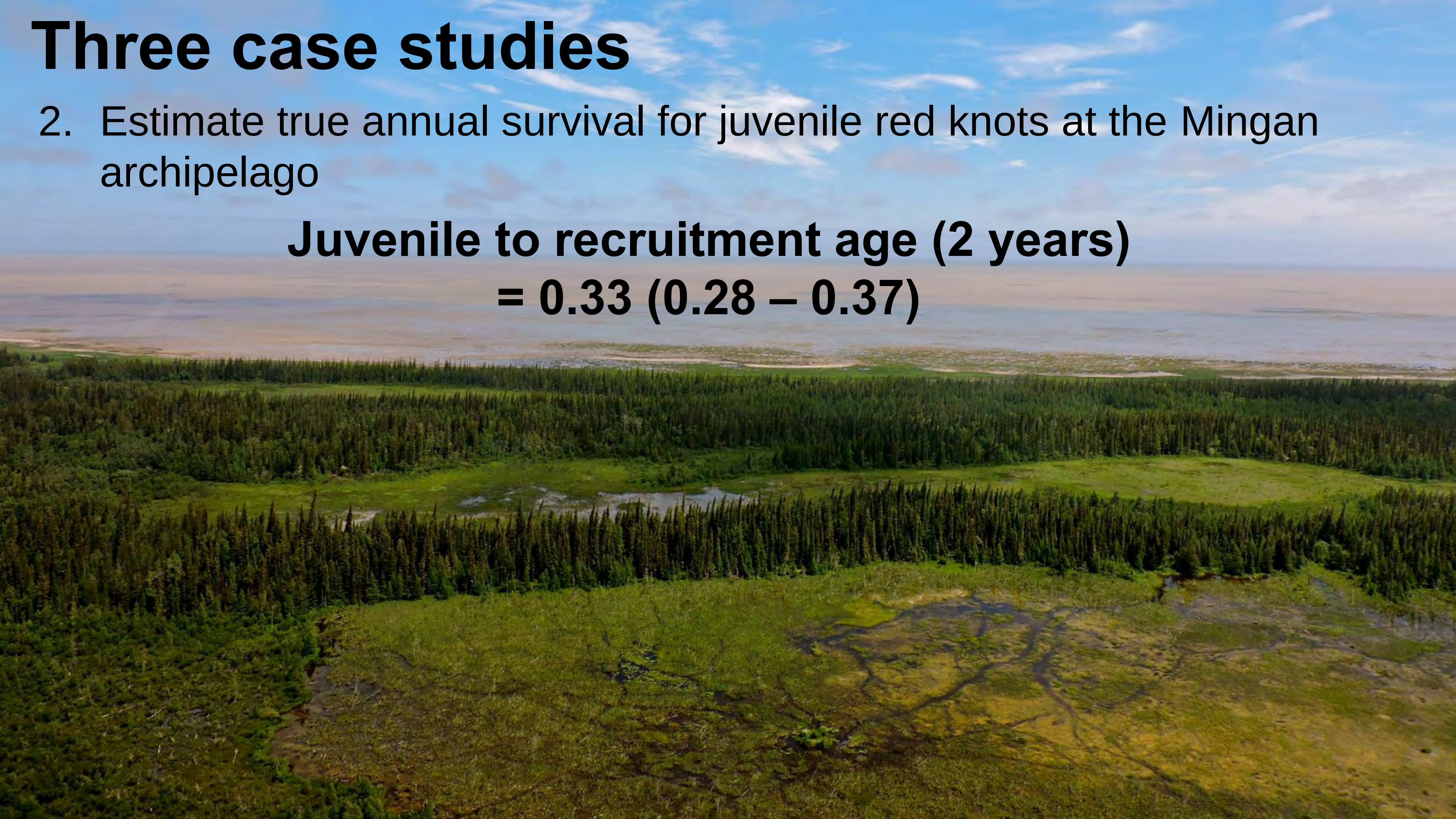
1. Estimate true annual survival for adult red knots staging in James Bay

0.810 (0.771 – 0.846)

Three case studies

2. Estimate true annual survival for juvenile red knots at the Mingan archipelago

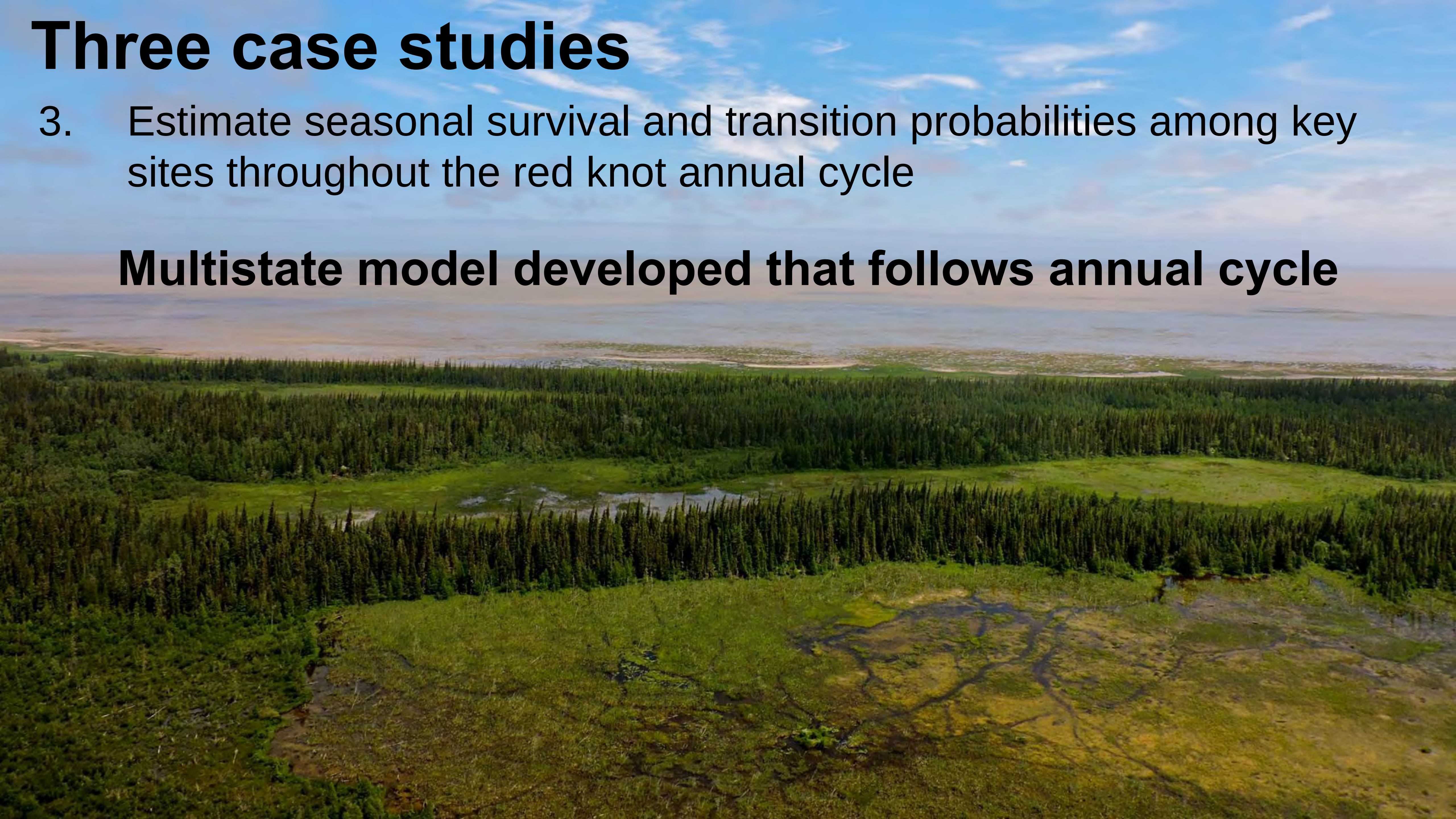
Juvenile to recruitment age (2 years)
= 0.33 (0.28 – 0.37)



Three case studies

3. Estimate seasonal survival and transition probabilities among key sites throughout the red knot annual cycle

Multistate model developed that follows annual cycle



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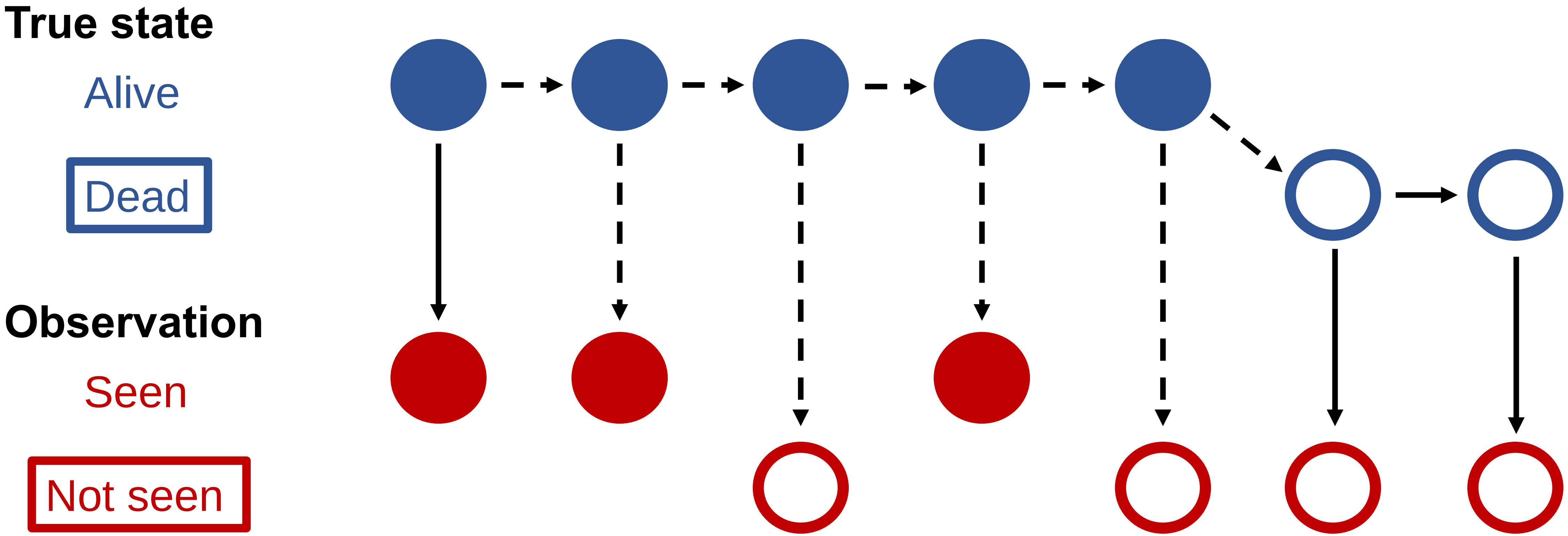
Lena Usyk (bandedbirds.org)
Jim Hines
Many, many red knot banders and surveyors
All collaborators supporting various red knot banding and resighting programs
Joseph Smith

Thank you!

¡Gracias!

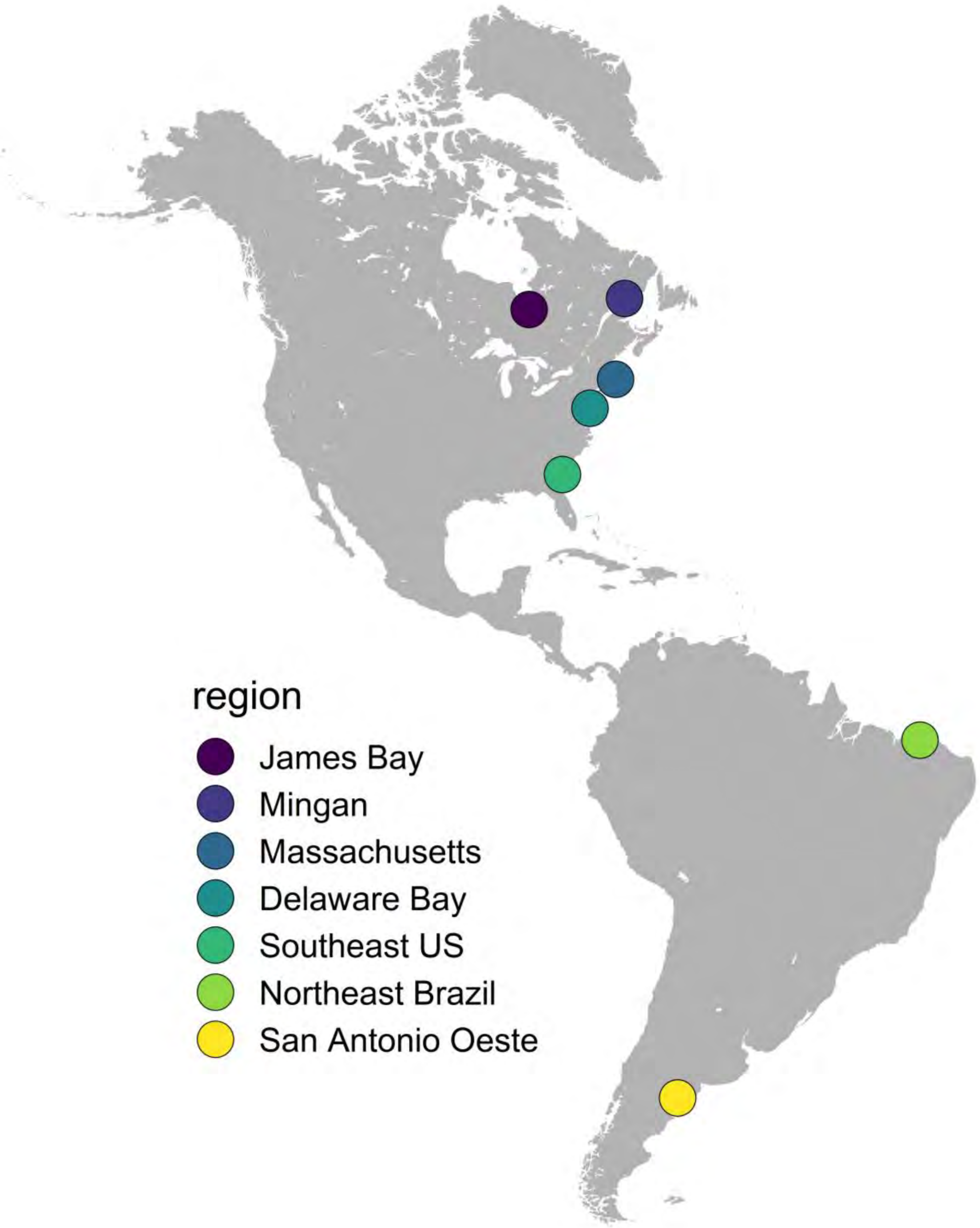
amacdonald@birdscanada.org

Analyzing flag resighting data in mark-recapture models permits estimation of demographic parameters



Kéry and Schaub (2012)

Bayesian analysis offers flexibility to build models to address various questions about red knot survival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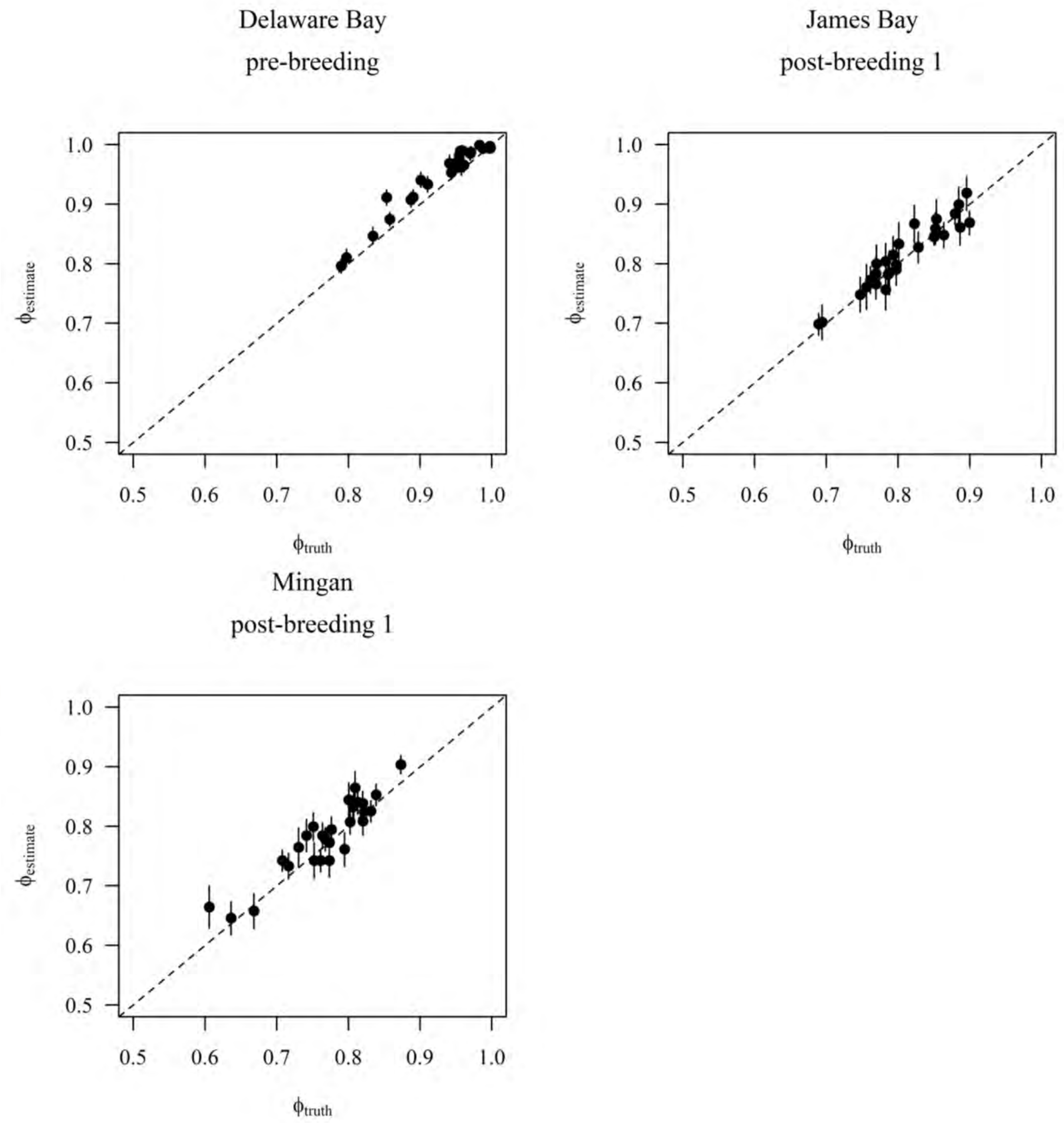
Massachusetts
Delaware Bay
Southeast US
Northeast Brazil
San Antonio Oeste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pre-breeding
James Bay
post-breeding 1
Mingan
post-breeding 1
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ϕ_{truth}
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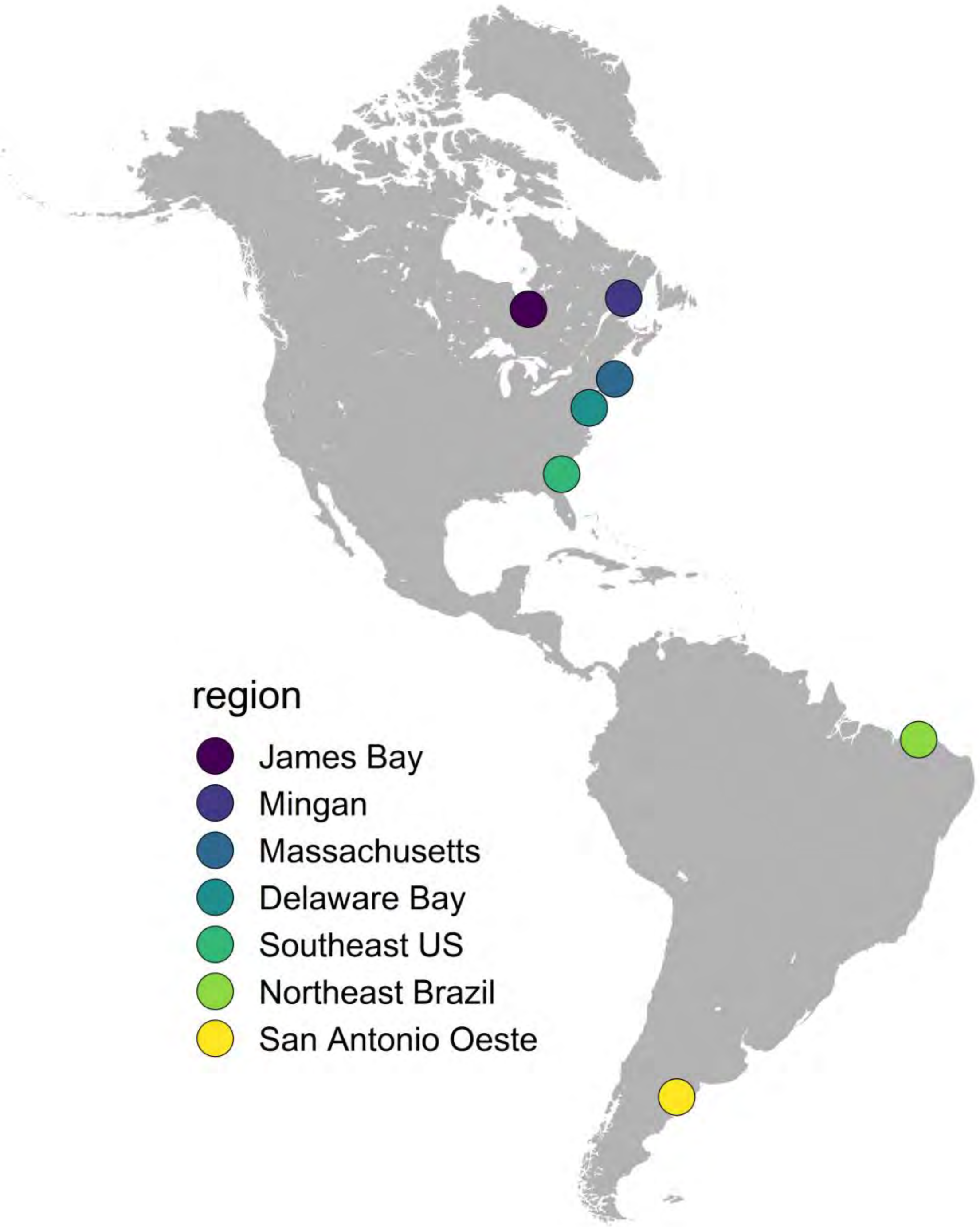
0.6
0.7
0.8
0.9
1.0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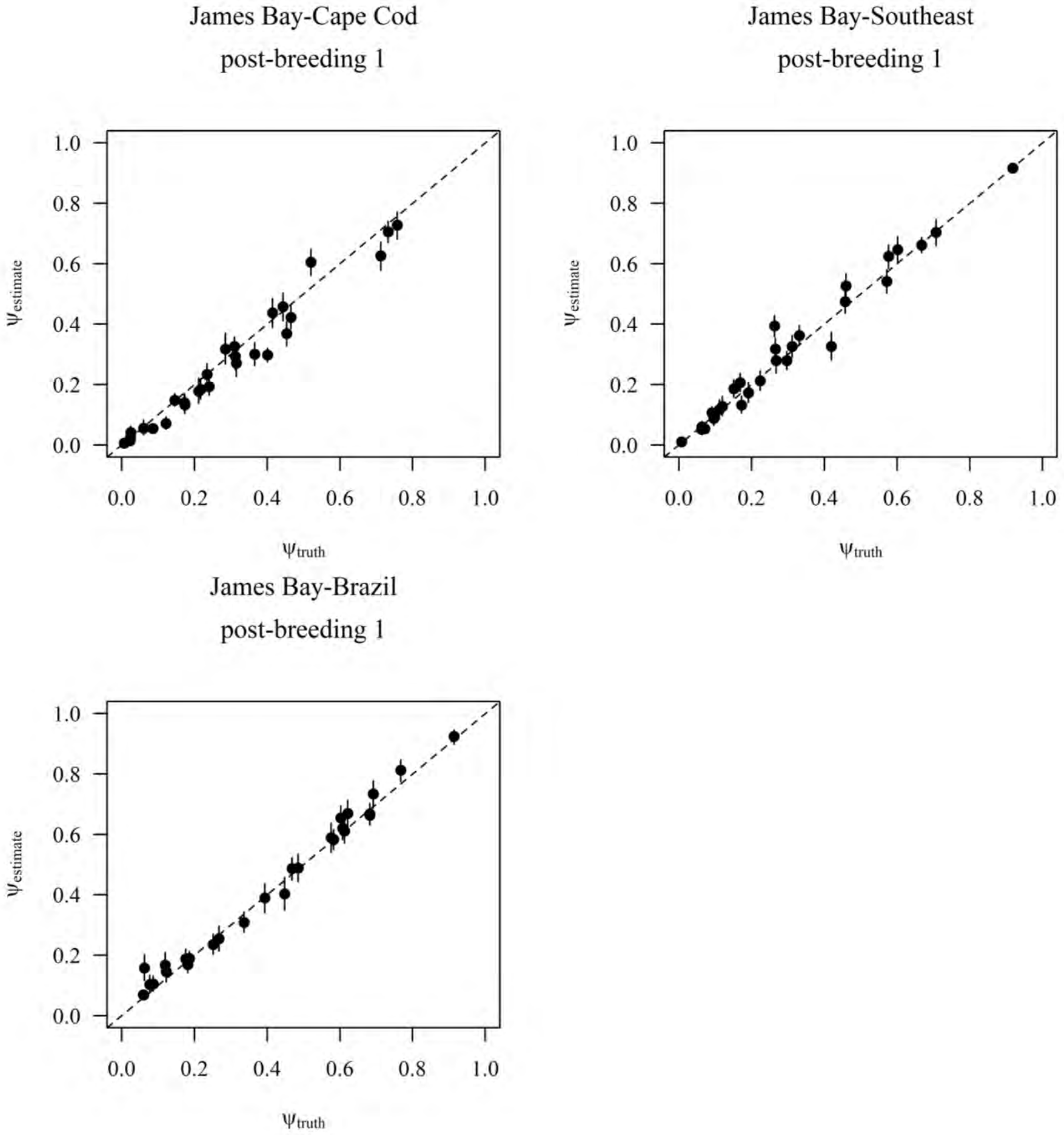
San Antonio Oeste


James Bay-Cape Cod
post-breeding 1
James Bay-Southeast
post-breeding 1
James Bay-Brazil
post-breeding 1
$\psi_{estimate}$
ψ_{truth}
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0.2
0.4
0.6
0.8
1.0

8/2/2024

To: ASMFC Horseshoe Crab Management Board

Let me call to your attention a report titled:

> *Spring migration patterns of red knots in the Southeast United States disentangled using automated telemetry*

The report found at *https://www.nature.com/articles/s41598-023-37517-y* include these excerpt from its abstract:

- *"Most Red Knots migrating north from the Southeast United States **skipped or likely skipped Delaware Bay** (73%) while 27% of the knots stopped in Delaware Bay for at least 1 day.*
- *A few knots used an Atlantic Coast strategy that **did not include Delaware Bay**, relying instead on the areas around Chesapeake Bay or New York Bay for stopovers.*
- *Most knots tracked in our study traveled north through the eastern Great Lake Basin, without stopping, thus making the Southeast United States the last terminal stopover for some knots before reaching boreal or Arctic stopover sites."*

This points out a problem when using only the Delaware Bay (DB) area counts[1] to determine the size of the red knot population in a model that determines the allowable harvest of horseshoe crabs. This study from the southeast Atlantic coast of the United States shows that at least 73% of the knots passing through the SE. U.S.A. area "*likely skipped*" traveling to the DB area and therefore are not included in the estimate of the size of the red knot population used in the model.

The fact is: Red knot flocks that once flew to the DB area may now be using the Southeast United States coastline as a stopover on their migration to the Arctic, completely bypassing the DB area. Since a major proportion (73%)of the knots that stop in the SE. U.S.A. are "*most likely*" by-passing the DB area, a reduced count of knots in the DB area may not indicate a reduction in the actual population of red knots. Therefore: Using only the DB count in the model leads to a total distortion of reality.

My point is made clear on Page 9 of the report where it states:

> "*Population estimates and trends for red knots using the Western Atlantic Flyway are determined by spring surveys of Delaware Bay and Virginia. This study shows a portion of knots do not use either of these regions, highlighting the need to expand the geographic regions included in these estimates. The diversity of spring stopover sites used by red knots must be incorporated in survival and recruitment estimates as well as ongoing population monitoring.*"

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[1] *Jim Lyons* report referred to by Dr. Sweka on page 2 of the Oct 2024 (?) Proceedings of the Horseshoe Crab Management Board. This report can ONLY be found at:
https://documents.dnrec.delaware.gov/fw/Shorebirds/Lyons-2023-REKN-Stopover-Pop-Size-at-Del-Bay.pdf

To base the management (modeling) of horseshoe crab harvest on the estimated HC population and **only** the count of red knots that pass through a small area (DB) compared to the total area in which red knots are found is clearly *myopic*.

I am not an expert of constructing population models, however, it is should be obvious that one at least needs to use correct data.

The Old Fisherman
Walter Chew .... *>(((">*
wdchew@comcast.net

P.S. Why weren't the *graphs* that Dr. Sweka used in his presentation available thru ASMFC??