Atlantic States Marine Fisheries Commission

Horseshoe Crab Management Board

October 21, 2021
8:30 – 10:00 a.m.
Webinar

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. Cimino)*	8:30 a.m.
2.	Board Consent • Approval of Agenda • Approval of Proceedings from October 2020	8:30 a.m.
3.	Public Comment	8:35 a.m.
4.	Set 2022 Harvest Specifications **Final Action** • Review Horseshoe Crab and Red Knot Abundance Estimates and 2021 Adaptive Resource Management Model Results *(J. Sweka)* • Set 2022 Specifications *(C. Starks)*	8:45 a.m.
5.	Progress Update on Revision to the ARM Framework *(J. Sweka)*	9:15 a.m.
6.	Consider Fishery Management Plan Review and State Compliance for the 2020 Fishing Year *(C. Starks)* **Action**	9:45 a.m.
7.	Election of Vice Chair *(J. Cimino)* **Action**	9:55 a.m.
8.	Other Business/Adjourn	10:00 a.m.

MEETING OVERVIEW

Horseshoe Crab Management Board Meeting
Wednesday, October 21, 2020
8:30 – 10:00 a.m.
Webinar

Chair: Joe Cimino (NJ) Assumed Chairmanship: 10/19	Horseshoe Crab Technical Committee Chair: Jeff Brunson (SC)	
Vice Chair: VACANT	Horseshoe Crab Advisory Panel Chair: Allen Burgenson (MD)	Law Enforcement Committee Representative: Doug Messeck (DE)
Delaware Bay Ecosystem Technical Committee Chair: Wendy Walsh (FWS)	Adaptive Resource Management Subcommittee Chair: Dr. John Sweka (FWS)	Previous Board Meeting: October 21, 2020
Voting Members: MA, RI, CT, NY, NJ, DE, MD, DC, PRFC, VA, NC, SC, GA, FL, NMFS, USFWS (16 votes)		

2. Board Consent
- Approval of Agenda
- Approval of Proceedings from October 21, 2020

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. Set 2022 Harvest Specifications (8:45-9:15 a.m.) Final Action
Background • In September 2021, the DBE TC and Adaptive Resource Management (ARM) Subcommittee met to review results of 2020-2021 horseshoe crab and red knot population abundance surveys in the Delaware Bay region (**Supplemental Materials**). • The Virginia Tech Trawl Survey was conducted in 2020, so the ARM Subcommittee used population estimates from this survey to estimate horseshoe crab abundance in the Delaware Bay region. A report was also provided on the red knot stopover population estimate for 2021 (**Briefing Materials**). • The ARM model was run using estimated abundances of horseshoe crabs in fall of 2020 and red knots in spring of 2021 to provide a recommendation for harvest specifications for Delaware Bay states in 2022 (**Briefing Materials**).

Presentations

- Horseshoe Crab and Red Knot Abundance Estimates and 2021 ARM Model Results by J. Sweka

Board actions for consideration at this meeting

- Consider ARM harvest recommendations and set specifications for states in the Delaware Bay region in 2022.

5. Progress Update on Revision to the ARM Framework (9:15-9:45 a.m.)

Background

- In October 2019, the Board directed the ARM Subcommittee to begin working on updates to the Adaptive Resource Management (ARM) Framework to revisit several aspects of the ARM model to incorporate horseshoe crab population estimates from the Catch Multiple Survey Analysis (CMSA) model used in the 2019 Benchmark Stock Assessment and the most current scientific information available for horseshoe crabs and red knots.
- In the last year, the ARM Subcommittee has been working on incorporating the CMSA model into the ARM, moving the model to a new software platform, improving model structure, and updating the red knot population model.
- The ARM model revision is tentatively scheduled to go to peer review in late 2021 and be brought to the Board at the Winter 2022 meeting.

Presentations

- Progress Update on ARM Revisions by J. Sweka

6. Consider Fishery Management Plan Review and State Compliance for the 2020 Fishing Year (9:45-9:55 a.m.) Action

Background

- State Compliance Reports were due July 1, 2020.
- The Plan Review Team reviewed each state report and compiled the annual FMP Review (**Supplemental Materials**).
- South Carolina, Georgia, and Florida have requested and meet the requirements of *de minimis* status.

Presentations

- FMP Review of the 2020 Fishing Year by C. Starks

Board actions for consideration at this meeting

- Accept FMP Review and State Compliance Reports for the 2020 Fishing Year.
- Approve *de minimis* requests.

8. Other Business/Adjourn

Horseshoe Crab

Activity level: Medium

Committee Overlap Score: Low (SAS overlaps with BERP)

Committee Task List
• ARM & DBETC – Incorporate Catch Multiple Survey Analysis horseshoe crab population estimates into the ARM model • TC – Communicate with Kepley Biosystems' to determine whether trials should be conducted for OrganoBait • 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: Jeff Brunson (SC, TC Chair), Derek Perry (MA), Natalie Ameral (RI, Vice Chair), Deb Pacileo (CT), Catherine Ziegler (NY), Samantha Macquesten (NJ), Jordan Zimmerman (DE), Steve Doctor (MD), Ellen Cosby (PRFC), Adam Kenyon (VA), Jeffrey Dobbs (NC), Eddie Leonard (GA), Claire Crowley (FL), Chris Wright (NMFS), Joanna Burger (Rutgers), Mike Millard (USFWS), Kristen Anstead (ASMFC), Caitlin Starks (ASMFC)

Delaware Bay Ecosystem TC Members: Wendy Walsh (USFWS, Chair), Amanda Dey (NJ), Samantha Macquesten (NJ), Henrietta Bellman (DE, Vice Chair), Jordan Zimmerman (DE), Steve Doctor (MD), Adam Kenyon (VA), Jim Fraser (VA Tech), Eric Hallerman (VA Tech), Mike Millard (USFWS), Kristen Anstead (ASMFC), Caitlin Starks (ASMFC)

ARM Subcommittee Members: John Sweka (USFWS, Chair), Larry Niles (NJ), Linda Barry (NJ), Henrietta Bellman (DE), Jason Boucher (DE), Steve Doctor (MD), 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

Webinar
October 21, 2020

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

TABLE OF CONTENTS

INDEX OF MOTIONS

1. **Move to approve agenda** by Consent (Page 1).

2. **Move to approve proceedings of October 29 , 2020** by Consent (Page 1).

3. **Move to select Harvest Package 3, 500,000 male only crabs for the 2020 horseshoe crab bait harvest in Delaware Bay** (Page 7). Motion by Adam Nowalsky, second by Roy Miller. Motion carried (Page 7).

4. **Move to approve the FMP Review for the 2019 fishing year, state compliance reports and de minimis status for Potomac River Fisheries Commission, South Carolina, Georgia, and Florida** (Page 11). Motion by Mike Luisi; second by Malcolm Rhodes. Motion carried (Page 12).

5. **Move to appoint Christina Lecker to the Horseshoe Crab Advisory Panel** (Page 12). Motion by Pat Geer; second by Mel Bell. Motion carried (Page 12).

6. **Motion to adjourn** by Consent (Page 12).

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)
David Borden, RI (GA)
Eric Reid, RI, proxy for Sen. Sosnowski (LA)
Bill Hyatt, CT, proxy for J. Davis (AA)
John McMurray, NY, proxy for Sen. Kaminsky (LA)
Maureen Davidson, NY, proxy for J. Gilmore (AA)
Joe Cimino, NJ (AA)
Tom Fote, NJ (GA)
Adam Nowalsky, NJ, proxy for Sen. Houghtaling (LA)
John Clark, DE, proxy for D. Saveikis (AA)
Roy Miller, DE (GA)
Craig Pugh, DE, proxy for Rep. Carson (LA)
Mike Luisi, MD, proxy for Bill Anderson (AA)
Russell Dize, MD (GA)
Phil Langley, MD, proxy for Del. Stein (LA)
Pat Geer, VA, proxy for S. Bowman (LA)
Chris Batsavage, NC, proxy for S. Murphey (AA)
Jerry Mannen, NC (GA)
Mel Bell, SC, proxy for R. Boyles (AA)
Malcolm Rhodes, SC (GA)
Sen. Ronnie Cromer, SC (LA)
Carolyn Belcher, GA, proxy for D. Haymans (AA)
Spud Woodward, GA (GA)
Jim Estes, FL, proxy for J. McCawley (AA)
Chris Wright, NMFS
Mike Millard, USFWS

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

Ex-Officio Members

Allen Burgenson, Advisory Panel Chair
John Sweka, ARM Subcommittee Chair

Staff

Robert Beal
Toni Kerns
Maya Drzewicki
Max Appelman
Kristen Anstead
Pat Campfield
Chris Jacobs
Jeff Kipp
Laura Leach
Savannah Lewis
Sarah Murray
Caitlin Starks
Deke Tompkins

Guests

Bill Anderson, MD (AA)
Mike Armstrong, MA DMF
Pat Augustine, Coram, NY
Linda Barry, NJ DEP
Henrietta Bellman, DE DFW
Sharon Benjamin, NOAA
Alan Bianchi, NC DENR
Nora Blair, Charleston, SC
Jason Boucher, DE DFW
Jeff Brust, NJ DEP
Kristin Butler, US Senate Fellow
Mike Celestino, NJ DEP
Heather Corbett, NJ DEP
Jessica Daher, NJ DEP
Jason Didden, MAFMC
Lynn Fegley, MD DNR
Cynthia Ferrio, NOAA
Lewis Gillingham, VMRC
Angela Giuliano, MD DNR
Walker Golder, Audubon Society
Pam Lyons Gromen, Wild Oceans
Doug Haymans, GA (AA)
Brett Hoffmeister, Assoc. of Cape Cod
Adam Kenyon, VMRC
Kris Kuhn, PA FBC
Rob LaFrance, Quinnipiac Univ.

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

Guests (continued)

Christina Lecker, FujiFilm
Shanna Madsen, VMRC
John Maniscalco, NYS DEC
Kim McKown, NYS DEC
Jason McNamee, RI (AA)
Nichola Meserve, MA DMF
Steve Minkkinen, FL FWS
Brandon Muffley, MAFMC
Allison Murphy, NOAA
Eileen Murphy, NJ Audubon Soc.
Brian Neilan, NJ DEP
Ken Neil
Derek Orner, NOAA
Cheri Patterson, NH (AA)
Derek Perry, MA DMF
Michael Pierdinock
Tim Prudente, *Baltimore Sun*
Samantha Robinson, DE DFW
Tim Sartwell, NOAA
Bill Semrau, NOAA
McLean Seward, NC DENR
Alexei Sharov, MD DNR
Benjie Swan, Limuli Labs
Stephanie Sykes, Cape Cod Fishermen
Helen Takade-Heumacher, FL FWS
Beth Versak, MD DNR
Megan Ware, ME DMR
Anna Weinstein, Audubon Society
John Whiteside
Angel Willey, MD DNR
Jordan Zimmerman, DE DNR

The Horseshoe Crab Management Board of the Atlantic States Marine Fisheries Commission convened via webinar; Wednesday, October 21, 2020, and was called to order at 10:30 a.m. by Chair Joe Cimino.

CALL TO ORDER

CHAIR JOE CIMINO: Good morning everybody. Caitlin, do we have my slide?

MS. CAITLIN STARKS: Oh, you want to put that up now, okay. Maya, could you please pull up the last slide I sent you?

CHAIR CIMINO: Everybody, my name is Joe Cimino. I'm the New Jersey Administrative Commissioner. I'm Chair of the Horseshoe Crab Management Board. I was working on designing a 2020 logo with the ASMFC staff, because New Jersey was going to be hosting. The good news there is that we think we will be able to be hosting in person in 2021, which is the 80th year of the ASMFC Annual Meeting. A little bit of disappointment, but also going to be pretty exciting.

One other thing that bums me about this in particular, is that I'm not going to get a chance to spend some time with Dr. John Sweka, at the Fish and Wildlife Service, who hopefully is joining us virtually. John will walk us through some agenda items. I don't know if we can advance some of the slides here. But I did design a new 79th Annual Meeting logo for us all, for our socially distanced and new virtual reality that we're all living with here.

I just wanted to start out, hopefully get a few smiles from folks again. The best out of this for us in New Jersey, is that hopefully we'll get another crack at this next year.

APPROVAL OF AGENDA

CHAIR CIMINO: We'll move on to the agenda. Now we'll attempt to look at our most up to date version of this. First is Approval of the Agenda. Does anyone have any additions or corrections they feel need to be made to the agenda? Anyone on the Board?

MS. TONI KERNS: I see no hands, Joe.

CHAIR CIMINO: Thanks Toni, we'll consider that approved by consent.

APPROVAL OF PROCEEDINGS

CHAIR CIMINO: Next is the approval of proceedings from the last time this Board met, which was last October. Does anyone have any corrections to the minutes or modifications they would like to see made?

MS. KERNS: I see no hands.

PUBLIC COMMENT

CHAIR CIMINO: Very good, thank you. Next up we'll take public comment. Folks, this is public comment for any items not on the agenda. We have a couple items that are action items. We will be setting the 2021 harvest specifications, and as I mentioned, Dr. Sweka will walk us through the ARM model results. I know in the past there have been some public comments there, so I will, before we vote on a final motion for those items, also take public comment on those agenda items. Is there anything not on the agenda that the public would like to comment on?

MS. KERNS: I don't see any hands, Joe.

CHAIR CIMINO: Okay, Toni.

MS. KERNS: Anna Weinstein has now raised her hand.

CHAIR CIMINO: We'll open the floor, thank you.

MS. ANNA WEINSTEIN: Good morning Chair Cimino, members of the Horseshoe Crab Management Board, can you hear me?

CHAIR CIMINO: Yes, we can.

MS. WEINSTEIN: I'm Anna Weinstein. I am the Director of Marine Conservation for Audubon. I'm representing Audubon today. We're also part of the

Horseshoe Crab Recovery Coalition, which is a collaboration of scientists, NGOs and others dedicated to recovering horseshoe crabs on the Atlantic coast by 2030.

We submitted a brief letter this morning, and the letter describes that we are dismayed to see a continued lack of recovery of horseshoe crabs in the Delaware Bay survey region since the 1990s, as the supplemental materials show, and the decreased relative abundance of horseshoe crabs in 2019, relative to the last five years.

Plus reduced red knot numbers show the adaptive resource management framework is not working to recover horseshoe crab in the Delaware Bay area. The supplemental materials also described a nearly 50 percent increase relative to 2018 of estimated coastwide biomedical harvest. As you know, the rufa red knot was listed as threatened under the ESA recently.

We in our short letter, we list some concrete steps this Board must take in order to not just support, but actually allow recovery of the red knot, toward delisting criteria that are being established by the Fish and Wildlife Service, and also support the entire marine ecosystem that depends on horseshoe crabs. I won't run through all those, but we hope that you take a look at the letter, and we look forward to engaging with the Board toward recovery of horseshoe crabs by 2030. Thank you so much.

CHAIR CIMINO: Thank you, Anna. Yes, the Board will take a look at those materials. We will be getting an update on the ARM model. I would open it up if Dr. Sweka has any comments on the public comment here. From what I've read, I did see that some of the survey trends look better than the idea that it's all declining. Caitlin, we will turn it over to you now.

CONSIDER SETTING THE 2021 HARVEST SPECIFICATIONS

MS. STARKS: The first item on the agenda is actually going to be presented by John Sweka, and that is to consider setting the 2021 harvest specifications. I will go ahead and let him present on that.

DR. JOHN A. SWEKA: Okay, thank you Mr. Chair, thank you, Caitlin. I'll be speaking about the Adaptive Resource Management recommendations for harvest of Delaware Bay horseshoe crabs for 2021. Under our Adaptive Resource Management Framework, our objective statement is to manage the harvest of horseshoe crabs in the Delaware Bay to maximize harvest, but also maintain ecosystem integrity, and provide adequate stopover habitat for migrating shore birds.

REVIEW HORSESHOE CRAB AND RED KNOT ABUNDANCE ESTIMATES AND 2020 ADAPTIVE RESOURCE MANAGEMENT MODEL RESULTS

DR. SWEKA: In particular, red knots is our surrogate species for all shore birds, and the one that we're most concerned with. The red knot, so the Adaptive Resource Management model takes into account red knots and horseshoe crab population threshold, and the inputs of those annual harvest recommendations are the abundance of both red knots and horseshoe crabs.

Within the framework there are five possible harvest packages that we can select from, and annually we make harvest recommendations at this meeting, which will be implemented the following year. This table shows the five possible harvest packages to be implemented, and these were adopted back in 2012, when the ARM was accepted for management.

The harvest policies or packages range from a complete moratorium of no male and no female harvest up to a maximum of 420,000 males and 210,000 females within a year. Since the ARM Framework has been adopted for management, we have been consistently recommending Harvest Package 3, which is a 500,000 male harvest and 0 female horseshoe crab harvest.

The way the optimization program works is that the program looks through all the possible states of populations of those species, and different life stages of both species. Then it builds a giant matrix of the combinations of population sizes of red knots and horseshoe crabs, and applies a harvest package to that, and calculates the reward of that harvest under each possible state of population for both species.

Ultimately, this is how we select the optimal harvest package, given our current state of red knots and current state of horseshoe crabs. The population threshold should dictate when the harvest of horseshoe crab has value are based on abundance of both species. The threshold for horseshoe crabs is a female horseshoe crab abundance that is equal to at least 80 percent of the theoretical carrying capacity of horseshoe crab, or essentially 11.2 million female horseshoe crabs in the Delaware Bay population.

For red knots the threshold is 81,900 birds. These thresholds dictate that when the harvest of horseshoe crabs has value, and there is value in female horseshoe crab harvest if either one of these thresholds is met. If the red knots are meeting their threshold, we can safely say that horseshoe crabs aren't limiting red knot population growth and sustainability. If the female horseshoe crab meets their threshold, we can say that there are plenty of horseshoe crabs, and again not limiting red knots. This graph illustrates the population estimate of red knots stopping over in the Delaware Bay since 2011. You can see as it has fluctuated annually, and these annual fluctuations could be due to changes in stopover duration, or changes in the proportion of the total red knot population that visits Delaware Bay in a given year.

The 2020 estimates were slightly lower than 2016 to 2019 estimates, but there is greater uncertainty on our 2020 estimates, compared to the previous four years. Twenty-twenty was kind of a unique year, in that the abundance of red knots in the Bay at a particular point in time during the stopover season was greatest in the first time period.

Usually the population that stopped over at the Bay tends to increase through time, and then decrease as the birds eventually continue on in their migration. But 2020 was kind of a unique year, because the greatest number of birds encountered was at the first time period in the stopover. Also, in 2020, obviously with the pandemic going on, you know that impacted some of the resighting ability, which can also contribute to the wider confidence intervals on the estimate for 2020.

In 2020 the estimated stopover duration was 10.7 days, which was less than the 12.1 days in 2019. There is a typo on that slide, that should say 2020 estimated stopover population or stopover duration, and also, it's the 2020 population was estimated at 40,444 birds, which of course is below the threshold of 81,900 birds, but still within the range that we've seen since 2011.

The green line here on the graph just demonstrates the peak aerial counts that are observed each year since 2011, and you can see those have fluctuated somewhat through time as well. The abundance of horseshoe crab is assessed from the Virginia Tech Trawl Survey, which is generally conducted in the fall of the year, typically around October.

The Virginia Tech Trawl Survey did lose funding for a few years, so between 2012 and 2015, we used a composite index that was correlated to and based on the Delaware 30 foot trawl, and New Jersey's Delaware Bay trawl, and the New Jersey Ocean Trawl Survey, and we came up with a correlation to the overlapping years with Virginia Tech Trawl to fill in those missing years.

The 2019 estimates in the fall ended up being 4.7 million females, and of course this is also under the 11.2 million threshold for horseshoe crab abundance. 2019 did show a decrease in abundance from previous years. This is a little bit perplexing, we're not exactly sure why the abundance of horseshoe crab declined, you know from 2018 to 2019, but part of the reason may be due to the timing of the Virginia Tech Trawl Survey.

In 2019 it was conducted approximately a month earlier than it is typically conducted. A lot of this has to do with, and since it was conducted earlier than normal, water temperatures were higher than normal. That earlier timing of the trawl survey, and also the warmer water temperatures, may have affected the catchability of the trawl survey.

Perhaps horseshoe crabs hadn't migrated to the coastal waters like they typically do another year, and just weren't available for the trawl survey intercepting and capture them. This is something that we are examining, moving forward, is to include the timing of the survey, and also water temperature, to try to standardize these catches, and take into account the possible effect on catchability. In the end, 2019 we had 4.7 million females, and 8.9 million males for our population estimate, which is then carried over to the spring of 2020, when the birds are stopping over in Delaware Bay.

Just a summary table here of horseshoe crab and red knot abundance estimates, for horseshoe crab 8.9 million males, 4.7 million females. For red knots, 40,444 red knots, both males and females combined. When we put these inputs into the decision maker that is generated by the ARM optimization routine, the recommended harvest package is consistent with previous years, and that is Harvest Package Number 3, that calls for a harvest of 500,000 males and 0 females.

At this time, you can think of it this way, since both of these population estimates for crabs and birds are still below their threshold, there is no value in harvesting females, and no female harvest is recommended at this time. When we apply our allocation schemes to the recommended total harvest of Delaware Bay origin crabs, it comes out to an allocation of 162,000 male only for Delaware and New Jersey.

For Virginia and Maryland, they are allowed to harvest more males, because not all crabs in their state waters are of Delaware Bay origin. For Maryland it's approximately 256,000 males, and for Virginia 81,000 males, and those states again are harvesting males. I guess with that I will take any questions that we have on the recommendations for 2021 harvest year.

SET 2021 HARVEST SPECIFICATIONS

CHAIR CIMINO: Excellent, thank you, John. We're looking for questions from the Board right now. Toni, do we have any hands?

MS. KERNS: So far Joe, I don't see any hands. I'll give folks a second. John Clark.

MR. JOHN CLARK: Thank you for the presentation, John. I was just curious, you mentioned that the Virginia Tech Trawl had to trawl a month earlier in 2019. Did you have a chance to look at the other surveys to get horseshoe crabs? The Delaware 30' trawl, the New Jersey Delaware Bay Trawl. Did they also show similar results, or were they more what you were expecting?

DR. SWEKA: Yes, John, I guess I should have looked at that prior to the meeting here. Off the top of my head I can't remember exactly how their numbers trended. I don't recall any significant decline like we saw in the Virginia Tech Survey, so again perhaps, you know it is a timing issue, and the hot water temperature issue affected catchability of Virginia Tech.

MS. KERNS: Joe, you also have Mike Millard.

CHAIR CIMINO: Okay great, Mike.

MR. MIKE MILLARD: Thanks, John, for the presentation. I think I ask this every year. Imbedded in that ARM process in the modeling, are three competing models that attempt to further explain the relationship between the horseshoe crabs and red knots survival. I'm not going to attempt to characterize those three. You might do it to remind folks. But I'm wondering, after another year of data, are we getting any closer to one of those competing models showing strength, or showing that relationship stronger than the others? Are we learning anything from this process, after another year of data?

DR. SWEKA: Yes, thanks for that question, Mike. I'll just reiterate the three possible models governing the population dynamics for red knots are Model Number 1 is a no effect model, so red knot abundance and population dynamics are clearly independent of horseshoe crab population dynamics.

Model Number 2 is what we kind of term the fecundity only model, where horseshoe crabs have an influence on the probability of red knots gaining weight while they are stopped over in the Delaware Bay, and then there is differential fecundity for light versus heavy birds. Then Model 3 is essentially a full effect model, where horseshoe crab abundance affects both fecundity and survival of birds that stopover in Delaware Bay.

Yes, are we getting any closer to adding weight in one of the models? That is going to be part of our ongoing update and revisions to the ARM Framework, which I'll discuss also during this Board meeting. Really, right now the population of red knots has been fairly stable through time. Horseshoe crabs have trended upward, but now have trended downward.

Right now, Mike, I would say the decision on that, have we put more faith in one versus the other two of the red knot models? I would say stand by, and that will be something that we'll be examining and discussing as our third ARM revision for dates.

MS. KERNS: Joe, you have David Borden as well.

CHAIR CIMINO: Okay good, go ahead, David.

MR. DAVID V. BORDEN: I've got a question on red knots. Have the governmental agencies that manage it, I think primarily U.S. Fish and Wildlife Service, apportioned mortality on red knots, and looked at it from a perspective of, within the United States versus outside of the United States? Then the related question is, what are the major sources of mortality on the red knot population?

DR. SWEKA: Well, I must admit that I am not a red knot expert. But under the listing document, you know the listing decision by the Fish and Wildlife Service, the Fish and Wildlife Service has expressed climate change and conditions in the Arctic as possibly one of the major factors, you know influencing red knot populations. But specifically, you know dictating the relative merits of various mortality sources on red knots, I'm probably not the best person to ask that question to.

MS. KERNS: We have Mike Luisi and Roy Miller.

CHAIR CIMINO: Okay, go ahead, Mike.

MR. MIKE LUISI: Thanks for the presentation, John. When you were talking about the years when the trawl survey was not in operation, you discussed a composite index that was used to produce an estimate for the horseshoe crab population. Was that just a compilation of other work being done by the states in that surrounding area? Is that how that estimate was determined?

DR. SWEKA: Yes. We came up with a composite index through a linear mixed random effects model that included those surveys. That composite index was then compared to the years when we had overlap with the Virginia Tech Trawl Survey, and used it to fill in the blanks.

MR. LUISI: Okay, yes. Just a quick follow up, Mr. Chairman. I think it would be interesting, given the fact that the Trawl Survey in 2019 was conducted a month early. Personally, I think it would be interesting to see what the results of that, if you were to run that modeling like you did the years when the trawl survey didn't operate, and kind of compare those results with what occurred as a result of working a month early.

Personally, I think it would be an interesting comparison of the model output, based on other surrounding work, versus the actual work, although it was early. Just wanted to throw that out there as an idea.

DR. SWEKA: That is certainly something we can look at.

CHAIR CIMINO: Thanks, Mike, that was a good thought. I appreciate that. Toni, it slipped my memory. Who's in the queue?

MS. KERNS: Roy Miller.

CHAIR CIMINO: Roy, go ahead, thank you.

MR. ROY W. MILLER: Thank you, Joe. Two questions for Dr. Sweka. That 2019 Virginia Tech Trawl Survey. I didn't catch the reason why it was conducted a month early. Was it strictly because water temperatures were warmer, or was it some issue with the vessel? The second question is, do you think there will be a trawl survey done this year in 2020? Thanks.

DR. SWEKA: Like any trawl survey, you know when they can get out on the water is weather dependent. They anticipate getting out on the water, and of course being that the survey is conducted in the fall of the year, looking at potential forecasts for hurricane season. It just so happened when they started the weather was apparently pretty decent.

They happened to be able to get all the trawls, all the tows in, in a quicker time period than normal. Other years, you know the survey can linger on in through November, given poor weather conditions. It was just an early start, given a potential forecast for hurricane season, to try to get all the sampling in. Your second question, to answer that, yes, Virginia Tech has funding to conduct the trawl survey this year.

MR. MILLER: Just a follow up, if I may. I assume that the 2020 survey will go forward as planned, barring any COVID issues. Is that a correct assumption?

DR. SWEKA: That is correct, yes.

MS. KERNS: Joe, you have Rob LaFrance.

CHAIR CIMINO: Broken up.

MR. ROBERT LAFRANCE: Thanks, Mr. Chair, and just a quick question. Thank you for the presentation. I'm new to this Board, and learning a lot, so I really appreciate it. Just a quick question, maybe this is speculative, but I'll ask it anyway. Are there any other reasons, we've talked about water temperature as being a potential impact for the downward trend? I'm just wondering whether there are other things we should be keeping our eye open for, for potential reasons for the downward trend.

DR. SWEKA: That is a good question. Like I said, we're examining the timing in the survey and water temperature as a possible reason why there was a decrease in the Virginia Tech catch. Other, I mean possible reasons could be just overall changes in migration timing of crabs into and out of the Bay, for whatever reason. But yes, it is very difficult to say why we saw that decrease. You know perhaps it is a change, a decrease in abundance.

MR. LAFRANCE: Thank you, I appreciate you giving me the time.

MS. KERNS: There are no other hands raised at this time, Joe. I lied. Hold on, we have two new hands, Chris Wright and Adam Nowalsky.

CHAIR CIMINO: Sure, okay. Go ahead, Chris.

MR. CHRIS WRIGHT: I just wanted to give a little bit more insight into the timing for 2019. When I was issuing the permit, they had requested to start a little earlier for that year, because of the New Jersey welk fishery, so that could be a reason also why they moved up and started a little bit earlier. At least I just checked my e-mail, that is what the rationale was that they were trying to avoid some of those gear conflicts in that area, in certain parts of the area where they were doing the survey.

CHAIR CIMINO: Okay, well thank you for that addition. We have Adam Nowalsky.

MR. ADAM NOWALSKY: Great, thank you very much. If you're ready for a motion, I'm prepared to make it.

CHAIR CIMINO: I think so, Adam. Unless Toni says we have any other hands.

MS. KERNS: No other hands.

MR. NOWALSKY: Great, I would like to go ahead and move to select Harvest Package 3, 500,000 male only crabs for the 2020 horseshoe crab bait harvest in Delaware Bay.

CHAIR CIMINO: Thank you, Adam, and do we have a second to that motion?

MS. KERNS: You have Roy Miller.

CHAIR CIMINO: Thank you, Roy. We had some great questions. Is there any discussion on the motion from the Board?

MS. KERNS: I see no hands, Joe.

CHAIR CIMINO: Very good, thank you, Toni. As I mentioned, I do want to give the public the chance to comment here. We do have a pretty tight schedule, as far as the time to get through this agenda. If there are any public comments, I would ask that you keep it to three minutes. Thank you. Toni, any hands?

MS. KERNS: I'm just going to give folks a second to see if they would like to raise their hand. I see no hands raised on the public.

CHAIR CIMINO: Very good, thank you. I'm going to ask, are there any objections to this motion?

MS. KERNS: Joe, no objection, but should it be 2021, or is 2020 correct?

MS. STARKS: It should be 2021, Maya, can you correct that typo? Thank you.

CHAIR CIMINO: Well, with that excellent correction, if there is no objection then I think we can just approve this by consent.

PROGRESS UPDATE ON ARM REVISIONS

CHAIR CIMINO: With that, we'll move back to John to hear more about the ARM Model itself, and the Updates and Revisions.

DR. SWEKA: This will go pretty quick. Last year at the October 2019 Board meeting, the Board approved moving forward with a revision of the ARM Model. The 2019 stock assessment was approved for management use, and the big advancement in that was the Catch Multiple Survey Analysis for horseshoe crab was peer reviewed and deemed acceptable the estimated abundance of horseshoe crab.

We also have more than twice the amount of red knot data since the ARM was initiated and we first started working on this back in 2008. The bottom line is that we know more now about those species. Very briefly, this is a synopsis of our terms of reference in the ARM revision. That is to incorporate the stock assessment model, the Catch Multiple Survey Analysis, into the ARM Framework, and account for all sources of mortality, which includes bait, dead discards, biomedical, and natural mortality.

We want to reevaluate the definition of Delaware Bay crabs, update on red knot models, given the new information on red knots and their relationship to horseshoe crabs. We also need to move the model into a new step software platform, because the previous platform is obsolete, and isn't maintained anymore. We're moving it to a new software that can be updated, and continued to be run. We also are going to be conducting sensitivity runs to compare platforms of the previous model platform and the new model, to make sure that we can get the same relative answers and possible harvest decisions.

Our progress to date, we have been in collaboration with Bryan Nuse, who is a University of Georgia Admin post doc student, and Paul Fackler from NC State to convert the optimization model from ASDP to MDPSolve. Paul Fackler, he's the one who originated MDPSolve, so he is the expert on that.

In April 2020 we had our data workshop, bringing all the information together on horseshoe crab and red knot. In July of 2020 we had our first Assessment Workshop, where we discussed replacement of a horseshoe crab age structured model, with the Catch Multiple Survey Analysis model to describe the population dynamics of horseshoe crab, and how this would be done.

We also refined our dead discard estimation method with additional input from literature and TC members. We refined our natural mortality estimates of horseshoe crabs, based on more recent tagging information. Since that time, we've had biweekly meetings of a subgroup of the entire ARM Workgroup. The subgroup is specific to modeling and coding of the models in the new platform.

Our future activities, the reanalysis of red knot tagging data is ongoing by Jim Lyons of USGS. We anticipate by January or February of 2021 having our second assessment workshop, where all the models will now be in their updated forms. By April 2021, a preliminary report completed, May 2021, it will be presented to the Delaware Bay Ecosystem TC, and the Horseshoe Crab TC for review.

In July, we plan to have our peer review workshop, and then by either the August or October 2021 Board meeting, we will present the results of that peer review workshop to the Management Board. Hopefully it is accepted for management use by that time. I think yes that's all, and so I am happy to take any questions on our current progress, and where we're headed.

CHAIR CIMINO: Thank you, John, I appreciate all the work that you guys are doing, especially digging into any available information on the discards. I know that was a concern with our last assessment, and rightly so. Toni, do we have any hands for questions?

MS. KERNS: We have John Clark and Bill Hyatt.

CHAIR CIMINO: Go ahead, John.

MR. CLARK: I'm just curious, what did you mean by reevaluate the definition of Delaware Bay crabs?

DR. SWEKA: That was a term of reference. I mean there has always been some discussion, you know the farther away from the mouth of Delaware Bay you get, what proportion of those crabs are truly Delaware Bay origin crabs? We defaulted to the definition of Delaware Bay origin crabs are crabs that could potentially spawn within Delaware Bay during some portion of their life. We know that there is mixing of populations, both to the north and in the south. We've looked at tagging information on how crabs migrate. We've looked at genetic information on how populations in various areas along the coast are related.

Kind of a spoiler alert, not much is going to change. Essentially, the Delaware Bay population is the area that is sampled by the Virginia Tech Trawl Survey. Given the most recent genetic information and tagging information, it is reaffirming that when that Virginia Tech Trawl Survey was originally set up, they had a good idea of what were really Delaware Bay crabs. That is essentially going to be our population of interest.

CHAIR CIMINO: I'm sorry, was it Bill Hyatt next?

MR. WILLIAM HYATT: Yes, thank you, this is a question for John. It doesn't have to do specifically with the information that he just presented, but it is a follow up to some discussion that took place at previous meetings. I think a year ago the question was raised regarding the crab egg densities on (broke up) and some concern that those densities are going down over time, and may have decoupled from our index estimates of a number of female crabs.

At that time, you responded that there were some problems with that egg density data relative to the methodology being used to collect it, and the time series information that was available, and the fact that actually different methods were being used to collect it in different areas.

My question this time around is, is there any research that you're aware of underway to improve the methodology being used to monitor egg densities, or to identify a better methodology to be applied, or is there any research underway to better explore and understand the relationship between female crab numbers, and ultimate egg densities that are produced? The assumption here is that while there may be a relationship between the number of female crabs and red knots, the direct link is in effect eggs that are deposited on the beach, and the energy source that they represent to the birds, thank you.

DR. SWEKA: Yes, there still are egg surveys being conducted in New Jersey, you know Universities and other NGOs are refining the methods that are being used in collecting the egg density data. Those methods in the past, as you mentioned, in the past there were differences in methodology between New Jersey and Delaware.

Delaware is no longer doing any egg surveys, but they are still being conducted on the New Jersey side of the Bay. Methods are continually being refined by the stakeholders that are still interested in the egg density data. Hopefully, you know with more refinement in those methods, if additional information, we can still examine and look at to see how it correlates with abundance estimates of horseshoe crab.

But one of the problems with egg density data and will always be a problem, you know the number of eggs that you select and count on a beach is not only a function of horseshoe crab, but it's also a function of the weather conditions, you know prior to when those eggs were sampled. You know wind and wave action will obviously influence the density of eggs, especially the density of eggs in the surface sediment that are actually available to shore birds. It's something that we will still continue to keep an eye on and monitor. Whether or not that was the plan, a direct linkage to abundance of horseshoe crabs remains to be seen.

In our modeling and estimation within the ARM Framework, the new analysis of bird tagging data. If we can have a direct link or make that link between abundance of horseshoe crabs, the timing of their spawning, and possible weight gain and survival of red knots. That is actually an easier avenue to go down, because we have more confidence in our estimates of horseshoe crab abundance than what we would in egg density, given all those environmental factors that could influence egg density on a beach at a given point in time in a particular year.

MR. HYATT: Very good, thank you.

CHAIR CIMINO: Thanks for the question, Bill. Toni, any other hands?

MS. KERNS: Chris Wright has his hand up.

CHAIR CIMINO: Go ahead, Chris.

MR. CHRIS WRIGHT: Some of the materials that we had; I think it was noted that 118,000 roughly crabs were caught in the biomedical mortality. I was wondering, what percentage of those 118,000 were female crabs?

DR. SWEKA: That would be a question for Caitlin. If we can give that data out publicly, I'm not sure.

MS. STARKS: Sorry, could you repeat the question? I was having a sidebar.

MR. WRIGHT: There was 118,000 plus crabs that were caught, or the mortality rate was slated at 118,000 or estimated at 118,000. I was wondering how many of those were female crabs because it wasn't really specified, and I couldn't recall.

MS. STARKS: It's not specified, and I would have to go back to the data given to us by the biomedical facilities to sort that out. I don't have an answer in front of me right now.

MR. WRIGHT: Okay, thank you, because it was up a little bit higher this year compared to previous years. I was just wondering if there was a little bit more female mortality. Anyway, we can follow up later.

CHAIR CIMINO: Very good, thank you, Chris. Toni, any other hands?

MS. KERNS: No additional hands, Joe.

CONSIDER APPROVAL OF THE FISHERY MANAGEMENT PLAN REVIEW AND STATE COMPLIANCE FOR THE 2019 FISHING YEAR

CHAIR CIMINO: Okay great, thank you again, John. With that our next agenda item is Consider Approval for the Fishery Management Plan Review and State Compliance for the 2019 Fishing Year, and that is over to you, Caitlin.

MS. STARKS: We are running a little bit behind, so I am going to try and condense this. This is the management history. We've had seven addenda since the FMP was approved in 1998, and those are listed here, and for time I will skip to the next slide. This figure shows the coastwide bait harvest, biomedical collections, and estimated biomedical mortality over time.

Coastwide bait harvest declined following the establishment of the FMP, and it's remained fairly stable since about 2004. Then similarly, coastwide biomedical-only collections and estimated mortality have been fairly consistent since 2010, with some increases in the last few years. Then in 2019, the bait landings totaled 660,091 crabs, and that number does exclude unreported landings from Massachusetts, and confidential landings from Rhode Island.

Of the states that reported those 2019 landings, New York, Delaware, and Virginia contributed the most, and they account for 73 percent of the total when combined. The total landings equate to about 42 percent of the coastwide ASMFC quota, which is 1.59 million crabs. But again, that number is likely higher when you account for Massachusetts.

Then Delaware did exceed their adjusted state quota for 2019 by 5,014 crabs, and therefore they reduced their quota for 2020 to account for that overage. The biomedical only crabs that were collected in 2019 totaled 748,376 crabs, which is a 46 percent increase from 2018 collections, and the biomedical-only mortality estimate for 2019 is 102,758 crabs.

This number includes the reported number of crabs observed dead before bleeding, plus 15 percent of the reported number of biomedical-only crabs bled. That total biomedical mortality estimate represents 15 percent of the total directed removals in 2019 with that total, including biomedical mortality and bait harvest.

The biomedical mortality in 2019 does exceed the biomedical mortality threshold of 57,000 crabs that was established in the FMP. For horseshoe crab the states that qualify and requested de minimis were—and jurisdictions—were PRFC, South Carolina, Georgia, and Florida, and they all meet that criteria set in the FMP. New Jersey also meets the criteria, but it does not request de minimis status.

In this year's review, the Plan Review Team has continued to recommend that long term funding be established for the Virginia Tech Trawl Survey, which is currently funded through 2021. The PRT found that all states appear in compliance with the requirements of the FMP, and they recommend approval of the FMP review, state compliance reports and de minimis requests.

However, they did note some concern regarding New York's bait harvest, which increased by 25 percent in 2019, despite the poor stock status in that region. The PRT recommends that the Board make an effort to encourage and monitor actions for the New York region that would improve the population trend. The

PRT also notes that the biomedical mortality threshold has been exceeded in 2019, which requires the Board to consider management action.

Then lastly, the PRT recommends the Board consider efforts to annually characterize dead discard removals in other fisheries, and specifically they're calling for increasing access to and use of data from the Northeast Fishery Observer Program, and that would allow for improved monitoring and estimation of discard mortality. Next slide, that's a brief summary of the FMP review, and I can take any questions.

CHAIR CIMINO: We are looking for a motion here, and we are running late, but that was a lot of information. Are there any questions from the Board?

MS. KERNS: You have two hands up, Tom Fote and then Mike Luisi.

CHAIR CIMINO: Go ahead, Tom.

MR. THOMAS P. FOTE: Yes, can you refresh my memory. Is this the first time or is this a trend with the biomedical industry by going over?

MS. STARKS: This is the 12th year in the last 13 years that the biomedical mortality estimate exceeded that threshold. Previously, in the stock assessment, it was found that the levels that were occurring prior to 2019 did not appear to be having a significant negative impact on the stock. Just noting that the level this year, or last year, did increase from that level before. But yes, it is a trend in the past years.

CHAIR CIMINO: Follow up, Tom?

MR. FOTE: I'm looking at this trend over the years. You know we pride the states to stay in compliance, but the biomedical are supposed to be good partners. But they need to stay in compliance, and we let them slide for twelve years in a row, maybe we need to take some action.

CHAIR CIMINO: Okay, we'll look at it, Board members, if there is interest. You know I have had some conversations with staff, and we have some ideas on discussions that need to be run through our Technical Committee first. We have Mike Luisi.

MR. LUISI: Based on your request to have a motion if you're ready for that.

CHAIR CIMINO: Yes, go ahead, Mike.

MR. LUISI: All right, I would move to approve the FMP Review for the 2019 fishing year, state compliance reports and de minimis status for Potomac River Fisheries Commission, South Carolina, Georgia, and Florida.

CHAIR CIMINO: Thank you, do we have a second?

MS. KERNS: Malcolm Rhodes.

CHAIR CIMINO: Thanks, Dr. Rhodes. Any discussion on this?

MS. KERNS: You had two additional hands come up, Maureen Davidson and Bill Hyatt. It was before Mike made the motion.

CHAIR CIMINO: If there are further questions then we'll go to Maureen. We can, I think wrap them into this discussion. Go ahead, Maureen.

MS. MAUREEN DAVIDSON: I just wanted to respond to some of the comments made concerning the assessment findings for New York, where we had the decrease in abundance. For 2020, New York State did take further management efforts in response to the decrease in abundance of horseshoe crab. We did harvest closures around the last moon in May, and the first moon in June, and we also decreased the daily trip limit during that peak spawning period. Now obviously this went into effect in 2020, and the effects of that have not been seen.

Unfortunately, because of the COVID-19 pandemic, we're concerned that our harvest for horseshoe crabs for this year are not really going to be normal, as they would have been in a normal year. But I just wanted to say that New York state has taken steps in response to the noted declined of horseshoe crabs in our local waters. Thank you.

CHAIR CIMINO: Thank you very much for speaking. That is important information for the Board. Bill.

MR. HYATT: Yes, I just wanted to speak briefly in support of the comment that Tom Fote made. I understand that the stock assessment determined that the previous overages were not affecting the population significantly, but the increase to 2020, the last increase was very significant, and I think regardless of whether or not there is a decision made to take action, we at least need to have some assessment done, as to whether or not that increase is significant.

CHAIR CIMINO: I don't disagree at all. In the interest of time, as I said. I've begun those discussions with staff. I think for our next Board meeting we will have some report out from the Technical Committee, or the Plan Review Team. To the motion, are there any other hands, Toni?

MS. KERNS: No other hands.

CHAIR CIMINO: Okay, we're good. Is there any opposition to this motion?

MS. KERNS: I see no hands in opposition.

CHAIR CIMINO: That sounds good to me. We'll consider the approval of the FMP review for 2019 unanimous**.**

REVIEW AND POPULATE ADVISORY PANEL MEMBERSHIP

CHAIR CIMINO: That brings us to, we have the AP nomination, so the Advisory Panel and Tina, if you could run us through that quickly. Thank you.

MS. TINA L. BERGER: Yes, I would offer for the Board's consideration the following, Christina Lecker as an addition to the Horseshoe Crab Advisory Panel. She is a biomedical representative from the Commonwealth of Virginia.

CHAIR CIMINO: Okay thank you, and that information is in the Board materials. Do we have a motion?

MS. KERNS: Pat Geer, seconder, Mel Bell.

CHAIR CIMINO: Go ahead, Pat. Pat, I think we're good, unless there was anything you wanted to add.

MR. PAT GEER: Yes, I was muted. I talked to Ms. Lecker a couple times. She's the Plant Manager of FUJI Wako Chemical U.S. Corporation. She's been there for a number of years, and they've been bleeding horseshoe crabs since about 2002. You know from my discussions with here, I think she would be an excellent representative to the Panel, you know representing the eastern shore of Virginia, Maryland and DelMarVa area as well for biomedical.

CHAIR CIMINO: Okay thanks.

MS. STARKS: Sorry, I just wasn't sure that the motion got read out loud, so I wanted to make sure that we did that.

CHAIR CIMINO: Much appreciated, I can do that. This is a motion to appoint Christina Lecker to the Horseshoe Crab Advisory Panel, motion was made by Pat Geer and seconded by Mel Bell. Is there any opposition to this motion?

MS. KERNS: I see no hands raised.

CHAIR CIMINO: Very good, we'll consider that approved by consent.

ADJOURNMENT

CHAIR CIMINO: I believe that wraps us up. I apologize for running this a little late. We had some great questions for Dr. Sweka, I think that was important for us all to hear. With that do we have a motion to adjourn?

MS. KERNS: Yes, Pat Geer.

CHAIR CIMINO: Pat again, thank you, we are adjourned, and Toni, sorry to run us late.

(Whereupon the meeting adjourned at 11:30 a.m. on October 21, 2020.)

Horseshoe Crab Harvest Recommendations Based on Adaptive Resource Management (ARM) Framework and Most Recent Monitoring Data

Report to the Delaware Bay Ecosystem Technical Committee by the ARM Subcommittee

September 2021

This report summarizes annual harvest recommendations. Detailed background on the ARM framework and data sources can be found in previous technical reports[1].

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

Alternative harvest packages
These harvest packages were compared to determine which will best meet the above objective given the most recent monitoring data. Harvest is of adult horseshoe crabs of Delaware Bay origin.

Harvest package	Male harvest (×1,000)	Female harvest (×1,000)
1	0	0
2	250	0
3	500	0
4	280	140
5	420	210

Population models
Population dynamics models that link horseshoe crabs and red knots were used to predict the effect of harvest packages. Three variations in the models represent the amount and type of dependence between horseshoe crabs and red knots. Stochastic dynamic programming was used to create a decision matrix to identify the optimal harvest package given the most recent monitoring data.

Monitoring data
Sources of data for horseshoe crab abundance were a set of trawl surveys conducted by Virginia Tech university.[2] Red Knot abundance estimates are taken from a mark-resight estimate for red knot abundance[3]. These data and methods can be evaluated in the respective reports from those studies.

Horseshoe crab abundance (millions)			Red knot abundance	
Year	Male	Female	Year	Male and female
2020 (Fall)	29.7	9.5	2021 (Spring)	42,271

Harvest recommendations

Decision matrix was optimized incorporating recommendations on red knot stopover population estimates and associated calibration of red knot threshold[4]. I followed the accepted procedure used in all past years where the empirical abundance estimates did not exactly fit the discretized population size "bins." For each empirical estimate I use the closest discretized abundance "bin" that was not larger than the estimate, in other words I rounded down to the nearest bin.

Recommended harvest package	Male harvest (×1,000)	Female harvest (×1,000)
3	500	0

Quota of horseshoe crab harvest for Delaware Bay region states. Allocation of allowable harvest under ARM package 3 (500K males, 0 females) was conducted in accordance with management board approved methodology in *Addendum VII to the Interstate Fishery Management Plan for Horseshoe Crabs*. Note: Maryland and Virginia total quota refer to that east of the COLREGS line.

	Delaware Bay Origin HSC Quota		**Total Quota**	
State	**Male**	**Female**	**Male**	**Female**
Delaware	162,136	0	162,136	0
New Jersey	162,136	0	162,136	0
Maryland	141,112	0	255,980	0
Virginia	34,615	0	81,331	0

References

[1] McGowan, C. P., D. R. Smith, J. D. Nichols, J. Martin, J. A. Sweka, J. E. Lyons, L. J. Niles, K. Kalasz, R. Wong, J. Brust, M. Davis. 2009. A framework for the adaptive management of horseshoe crab harvests in the Delaware Bay constrained by Red Knot conservation. Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab Technical Committee.

ASMFC Horseshoe Crab Stock Assessment Subcommittee. 2009. Horseshoe crab 2009 stock assessment report. Report to the Atlantic States Marine Fisheries Commission Horseshoe Crab Technical Committee.

ASMFC 2009. Terms of Reference and Advisory Report to the Horseshoe Crab Stock Assessment Peer Review. Stock Assessment Report No. 09-02.

[2] Virginia Tech Trawl Survey report, August 31, 2021

[3] Jim Lyons' 2019 estimate in the 22 September, 2021 Memo

[4] ARM's recommendations for improved estimates of red knot stopover population size and associated calibration of red knot threshold

Results of the 2020 Horseshoe Crab Trawl Survey:

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

Eric Hallerman and Yan Jiao

Department of Fish and Wildlife Conservation
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061-0321

23 September 2021

Abstract

To properly manage the mid-Atlantic horseshoe crab *Limulus polyphemus* fishery, a time-series of data on relative abundance of all demographic groups is needed. We conducted a trawl survey in the coastal Delaware Bay area and the lower Delaware Bay, quantified mean catch per 15-minute tow, and compared relative abundance of demographic groups with results from previous years. Mean catch-per-tow of immature and newly mature horseshoe crabs in the coastal Delaware Bay area have been variable since 2002 with no trend. Catches of mature females and males were both relatively high in 2020, although not statistically higher. Mean catch-per-tow of mature females and males are correlated, and both appear to display an increasing trend over time. Mean catches of immature and mature crabs in lower Delaware Bay are generally larger than catches in the coastal area, although usually not statistically significantly so. Mean catch-per-tow and population estimates of newly mature males are correlated with values for newly mature females of the same year-class the following year. Our findings will be used to parameterize the Adaptive Resource Management model used to set annual harvest levels for horseshoe crabs.

Introduction

To properly manage the mid-Atlantic horseshoe crab *Limulus polyphemus* fishery, accurate information on relative abundance levels and trends is needed. The Adaptive Resource Management 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 2020 trawl survey.

We have provided the Adaptive Resource Management (ARM) Subcommittee relative abundance estimates of horseshoe crabs in the DBA and LDB surveys to inform the ARM model runs. Herein, we present the population estimates through the 2020 survey. Gear catchability has not been evaluated for these estimates, so they should be considered conservative.

Methods

The 2020 horseshoe crab trawl survey was conducted in two areas (Figure 1). The coastal Delaware Bay area (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 2020. The lower Delaware Bay (LDB) survey area extended from the Bay mouth to a line between Egg Island Point, New Jersey and Kitts Hummock, Delaware. The LDB was previously sampled from 2010 to 2012 and in 2016- 2020. The surveys were conducted over a protracted period from 6 August to 8 September 2020.

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. Start and end positions of each tow were recorded when the winches were stopped and when retrieval began, respectively. Bottom water temperature was recorded for each tow. We sampled 44 stations in the DBA survey and 4 stations in the LDB. Three planned LDB sites were not completed due to netting of excessive vegetation.

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 are 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. All examined females that were not obviously mature (i.e., bearing rub marks) or immature (too small or soft-shelled) were probed with an awl to determine 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. The remainder were counted separately by classification and released. Characteristics of the examined subsamples were then extrapolated to the counted portions of the catch.

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 calculate the relative proportions for each size interval. Those proportions then were 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 then would represent the stratified mean catch per tow at each size interval.

The average 15-minute tow in the DBA was 1.17 kilometers at 4.7 KPH. The average 15-minute tow in the LDB was 1.20 km at 4.8 KPH. Valid net-spread measurements were obtained from 44 tows and averaged 10.1 meters. We used the net- spread (S, in meters)/tow speed (C, in KPH) relationship developed from previous trawl surveys to estimate net-spread for collections in which net-spread was invalid or not measured ($S = 13.84 - 0.858 \times C$).

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):

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

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 ($\overline{X}_{st}$) 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 ($\overline{X}_{st}$) by survey area (DBA = 5127.1 km^2; LDB = 528.4 km^2):

$$\text{Population total} = \overline{X}_{st} \times (5127.1 \text{ or } 528.4 \text{ km}^2).$$

Results

<u>Delaware Bay area</u>

Stratified mean catches-per-tow for all demographic categories were relatively consistent from 2016 to 2018, but showed variations in the two most-recent years (Tables 1 and 2; Figure 2). Stratified mean catches of mature females and males have been variable over the time-series, but are significantly correlated ($r = 0.779$; $T = 4.48$; $p < 0.001$; $n = 15$). Both mature females and males were relatively less abundant in 2019 and more abundant in 2020 than in the previous five years. Yearly trends from the delta- and normal-distribution models followed similar patterns for all demographic groups.

Mean catches of newly mature males generally are correlated with mean catches of newly mature females the following year from 2002-2018 ($r = 0.746$; $T = 3.36$; $p = 0.008$, $n = 11$). In the two recent years, the trend of newly mature females and males are quite different. By adding results in 2019 and 2020, the correlations are no longer statistically significant ($r = 0.25$; $T = 0.91$; $p = 0.378$, $n = 15$), potentially due to low mean catches of newly mature females in 2019 and 2020.

Lower Delaware Bay

This was the eighth year of sampling within the Delaware Bay. Stratified mean catches of immature female and male crabs and newly mature female crabs in 2019 and 2020 were the least for the time-series (Tables 3 and 4; Figure 3). Mean catches of mature females were lower than in 2019 and further decreased in 2020, Both the male and females in all the three maturity groups were low in 2020. Mean catches of mature males are significantly correlated with mean catches of mature females ($r = 0.919$; $T = 5.71$; $p = 0.001$; $n = 8$).

Size distributions

Size-frequency distributions of immature horseshoe crabs in the DBA survey display considerable variability (Figure 4). Modal groups are generally indistinct, except for one large group of both females and males in 2009. However, that modal group, which would presumably be larger in size the following year, becomes indistinct again in 2010. Size-frequency distributions from the lower Delaware Bay do not show that modal group in 2010 either (Figure 5).

We had previously reported that mean prosomal widths of mature and newly mature male and female crabs in the DBA survey displayed slight but detectable decreases over time (Hata and Hallerman 2017, 2019). Those trends appear to continue through the 2020 survey (Table 5; Figure 6). In addition, decreasing trends in mean PW were observed for mature females and males in the lower Delaware Bay survey, but an increasing trend was detected for newly mature males.

Sex ratios

Mature males were typically more than twice as numerous as mature females throughout the survey time-series. Sex ratios (M:F) from mean catch-per-tow in the DBA surveys ranged from 1.72 in 2019 to 3.64 in 2016, averaging 2.41 over all years. The ratio of newly mature males to females was highly variable, ranging from 0.11 in 2003 to 5.60 in 2019, and averaged 1.44. This may reflect sampling effects, temporal variability in recruitment to the newly mature class relative to survey period, or differences in year-class abundance because females are believed to mature a year later than males.

Sex ratios of mature horseshoe crabs were higher within the lower Delaware Bay than on the coast. Sex ratios (M:F) ranged from 2.60 in 2018 to 6.15 in 2016, averaging 3.98. As on the coast, sex ratios of newly mature crabs within the Bay were variable, and ranged from 0.45 in 2010 to 6.10 in 2012, averaging 3.09, with an exception of 2019 and 2020 in which mean catches of newly mature females were both very low and sex ratios were higher than historical observations (5.60 and 23.33). 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). Similarly, population estimates of newly mature crabs increased from 2002 to 2008, but have remained consistently low since 2009. Estimated numbers of mature males and females have been greater since 2006. Population estimates of mature females are significantly correlated with estimates of mature males ($r = 0.779$; $T = 4.48$; $p < 0.001$; $n = 15$), as observed for mean catches per tow above. Population estimates of newly mature females are significantly correlated with estimates of newly mature males, as observed for mean catches per tow above. Assuming males entering the newly mature category are of the same year-class as females entering that category the following year, annual trends for males may forecast similar trends for females. However, population estimates of newly mature females are not significantly correlated with estimates of newly mature males as in the previous year when incorporating estimates in 2019 and 2020, as observed for mean catches per tow above.

Population estimates of immature crabs in lower Delaware Bay 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 composed 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 Delaware Bay, and 9% of newly mature males. In 2020, 0 and 0.2% of newly mature females and males, respectively, occurred within Delaware Bay with the percentage of immature males the lowest in the history. 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 2010-2020, and averaged 3.02, with a ratio of 2.93 in 2020.

Effects of sampling period

The 2020 DBA survey was conducted from early August to early September. The average bottom water temperature in 2020 was close to those for the past four survey years and was among those for the highest values in the time series (Table 10; Figure 7). The 2020 lower Delaware Bay survey was conducted in early September, much earlier than in the past years, and later than the DBA survey. As a result, the average LDB water temperature was for the first time higher than the average DBA temperature. Horseshoe crabs that were within the Bay during most of the DBA survey because of the warm temperature and not enumerated, may have moved out of the Bay by the time the LDB survey was conducted and again not enumerated. This may have resulted in underestimates of horseshoe crabs in both survey areas and contributed to the apparent decrease in mature M:F ratios in both survey areas since 2016.

When comparing survey time-frames and water temperatures, it appears that the DBA mean catches of immature crabs are correlated with mean sampling dates, but not with water temperature ($p = 0.062$ and 0.051 respectively for immature females and males); in contrast, mean catches of mature crabs were correlated with both mean water temperatures and ordinal dates (Table 11). Within the lower Delaware Bay, mean catches were not correlated with mean water temperatures or sampling dates.

Key findings

1. Mean catch-per-tow of immature male and female horseshoe crabs in the coastal Delaware Bay area have been variable since 2002 with no trend, and remain below the peak of 2009.
2. Mean catch-per-tow of newly mature crabs in the coastal Delaware Bay area have remained below peaks in 2006 (males) or 2008 (females) and show no long-term trend.
3. Mean catch-per-tow of mature males and females in the coastal Delaware Bay area have been variable throughout the time-series, but show increasing trends since 2002, and were relatively high in 2020.
4. Mean catch-per-tow of immature horseshoe crabs in the coastal Delaware Bay area may be related to sampling date. Mean catch-per-tow of mature horseshoe crabs may be related to water temperature.
5. Annual mean prosomal widths of newly mature and mature horseshoe crabs in the coastal Delaware Bay area show decreasing trends.

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.

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.

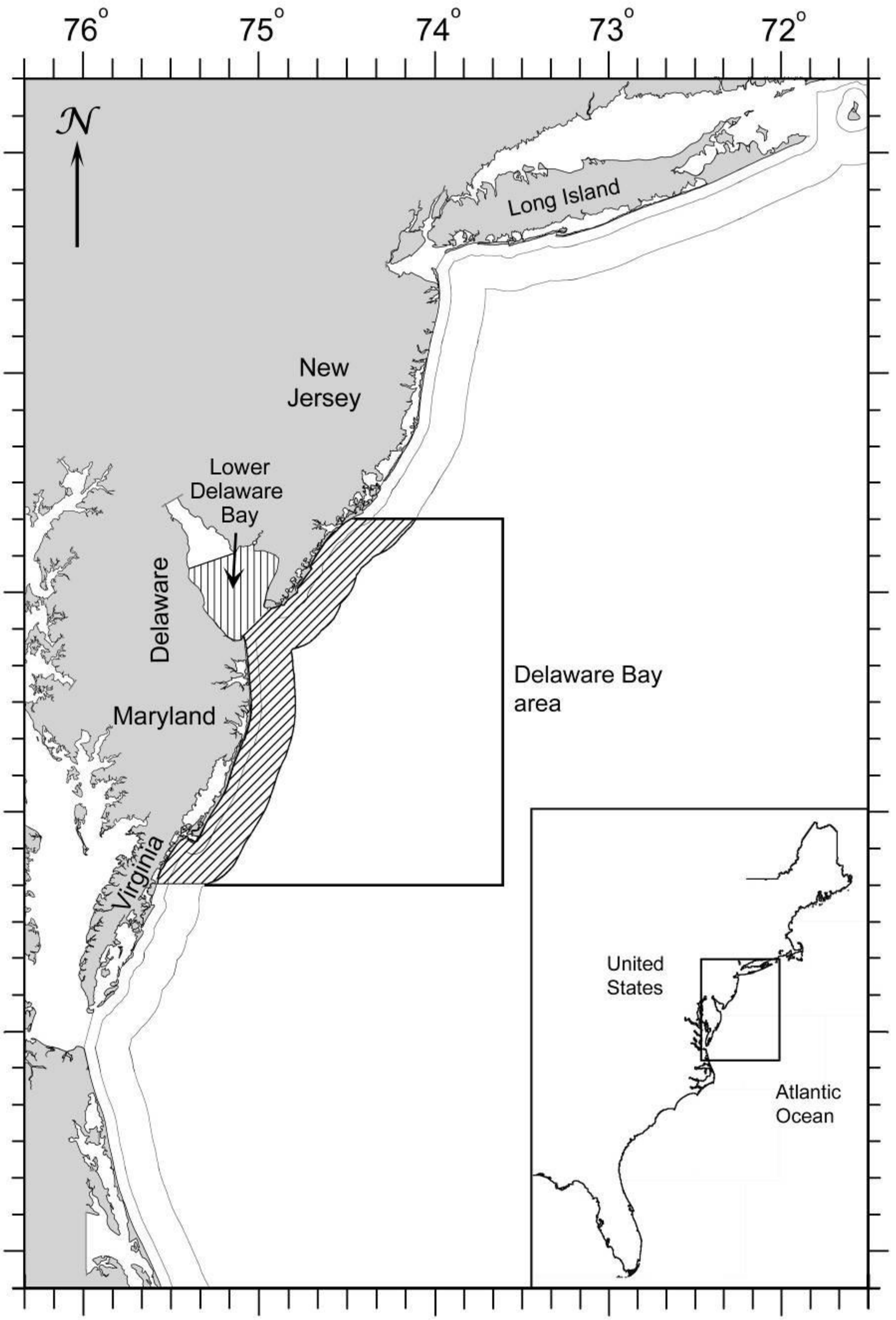

Figure 1. Fall 2020 horseshoe crab trawl survey sampling area. The coastal Delaware Bay area (DBA) and Lower Delaware Bay (LDB) survey areas are indicated. Mean catches among years were compared using stations within the shaded portions of the survey areas.

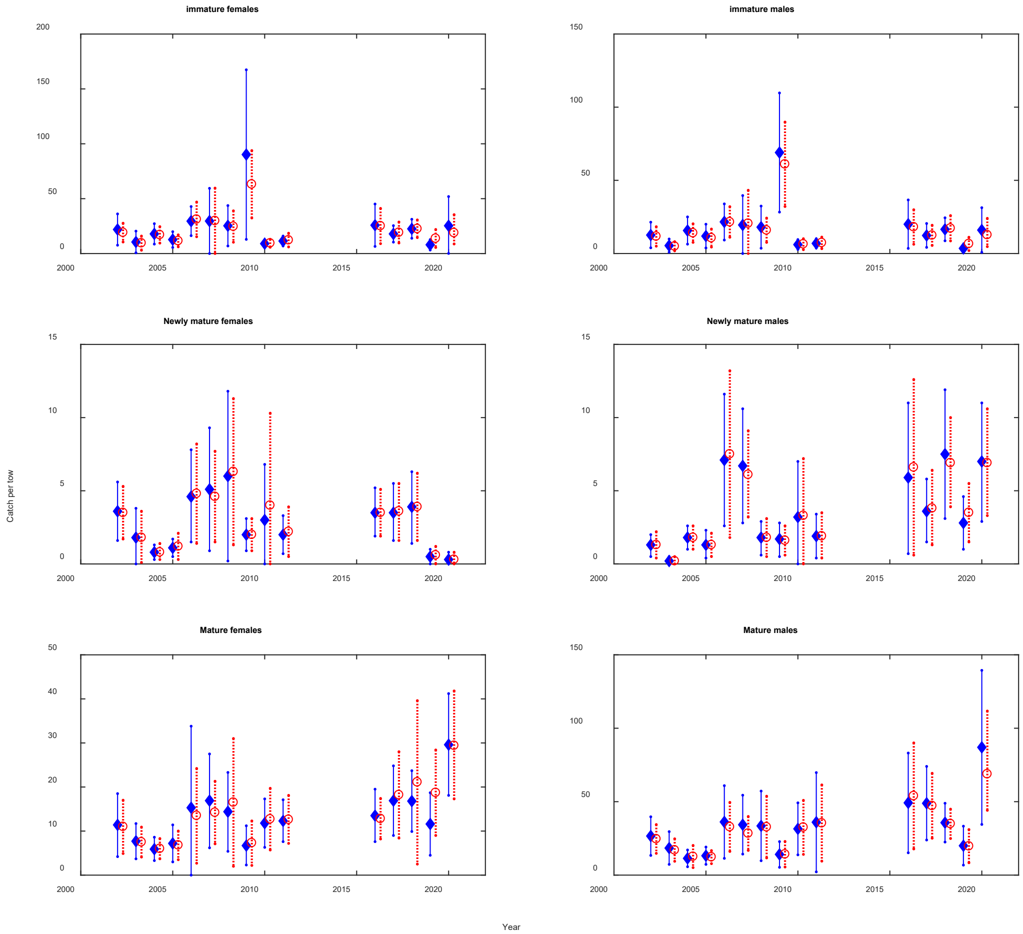

Figure 2. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the coastal **Delaware Bay area** survey by demographic group. Vertical lines indicate 95% confidence limits. Solid symbols and lines indicate the **delta distribution** model. Open symbols and dashed lines indicate the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

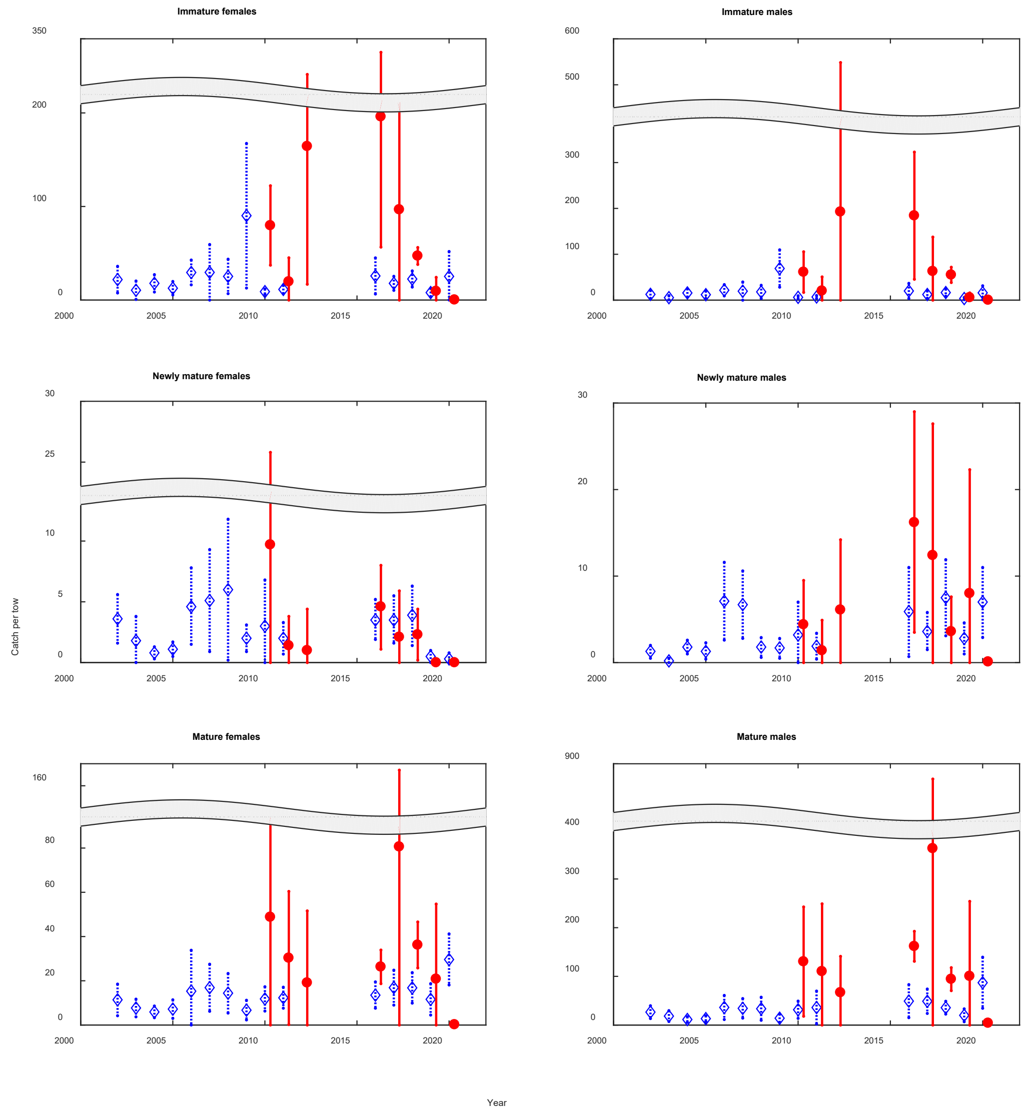

Figure 3. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the **lower Delaware Bay** survey by demographic group, with coastal **Delaware Bay area** survey means for comparison. Vertical lines indicate 95% confidence limits. Only the **delta distribution** model means are presented 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.

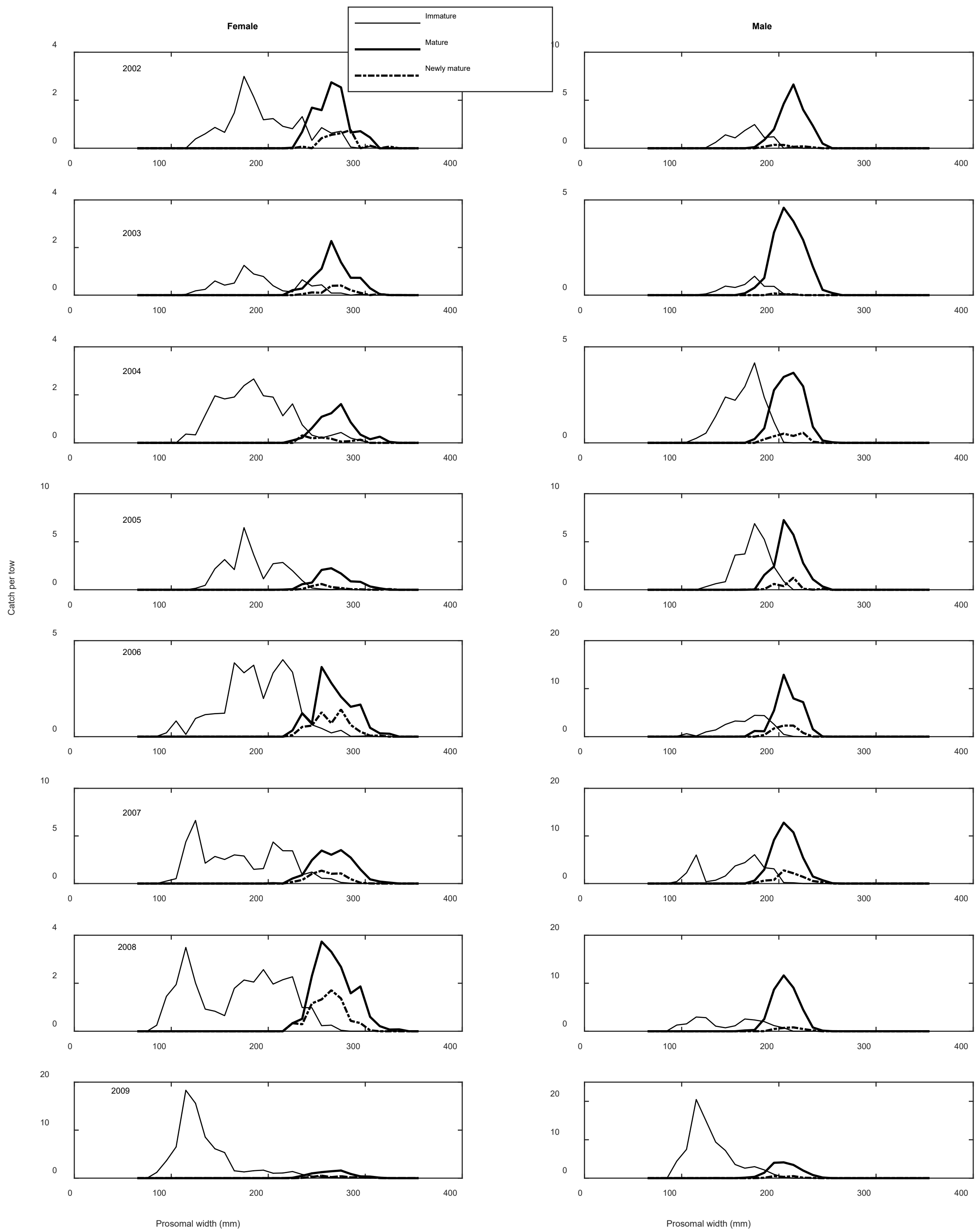

Figure 4. Relative size-frequency distributions of horseshoe crabs, by demographic group and year, in the coastal **Delaware Bay area** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 1.

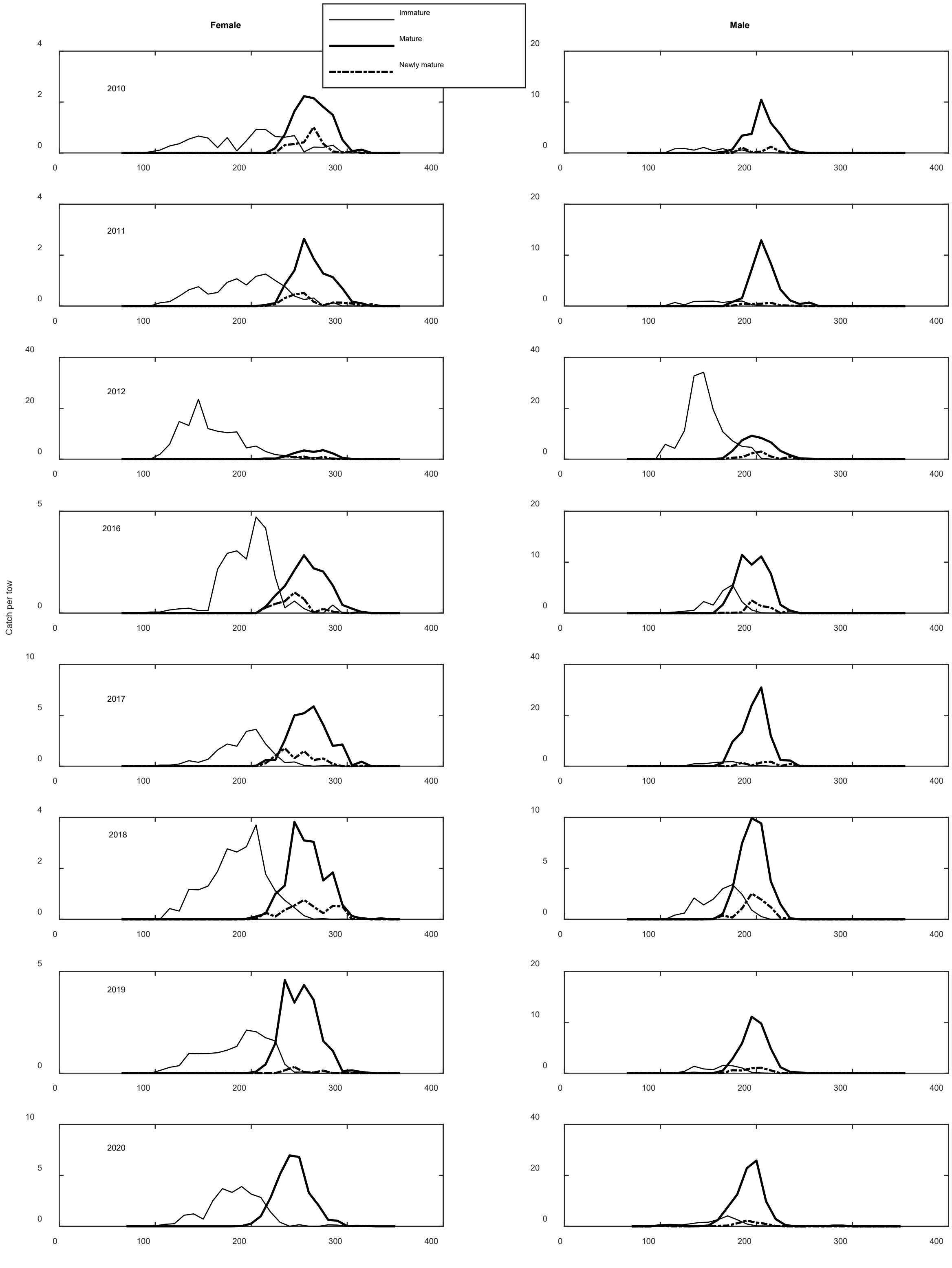

Figure 4. (continued).

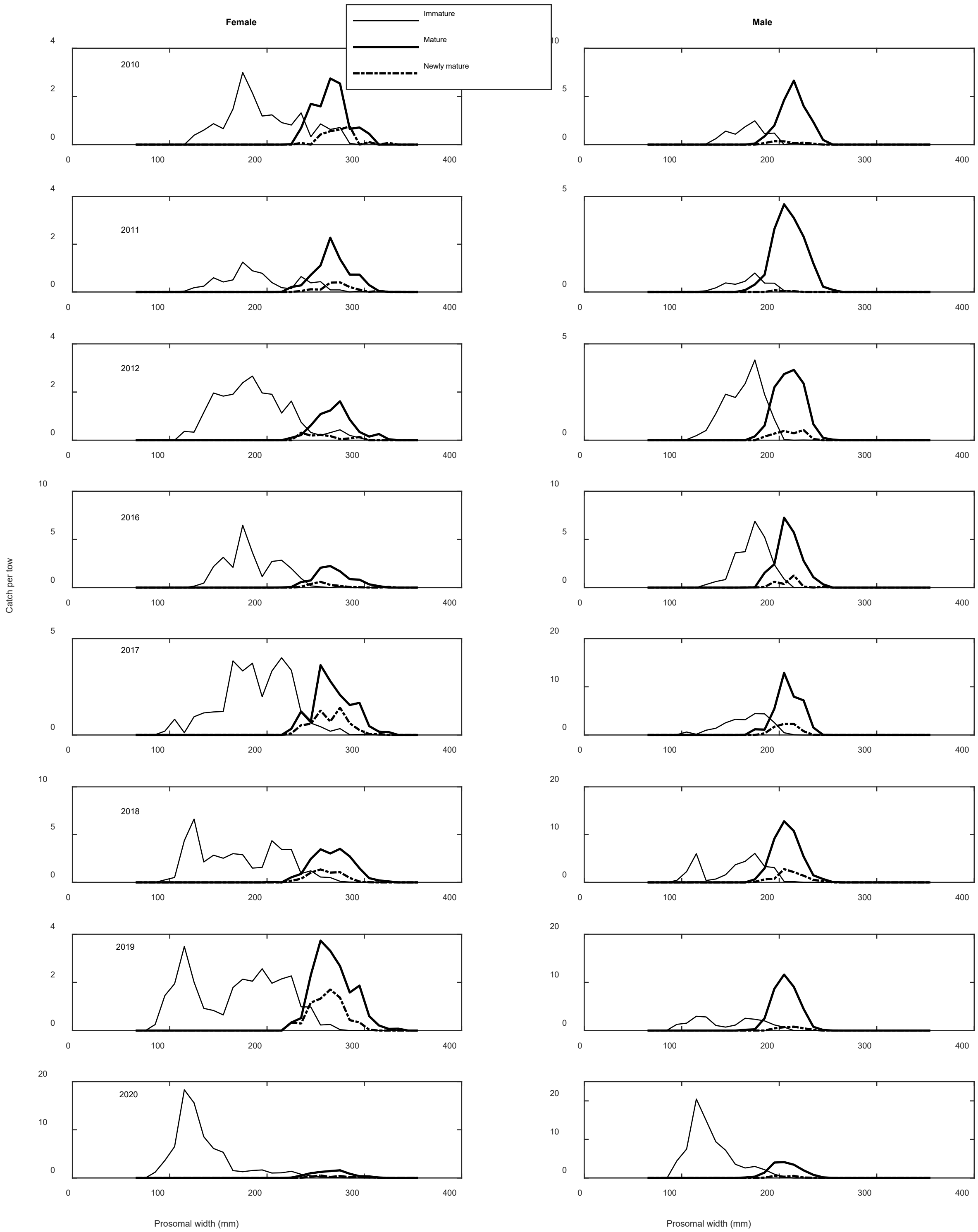

Figure 5. Relative size-frequency distributions of horseshoe crabs, by demographic group and year, in the **lower Delaware Bay** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 3.

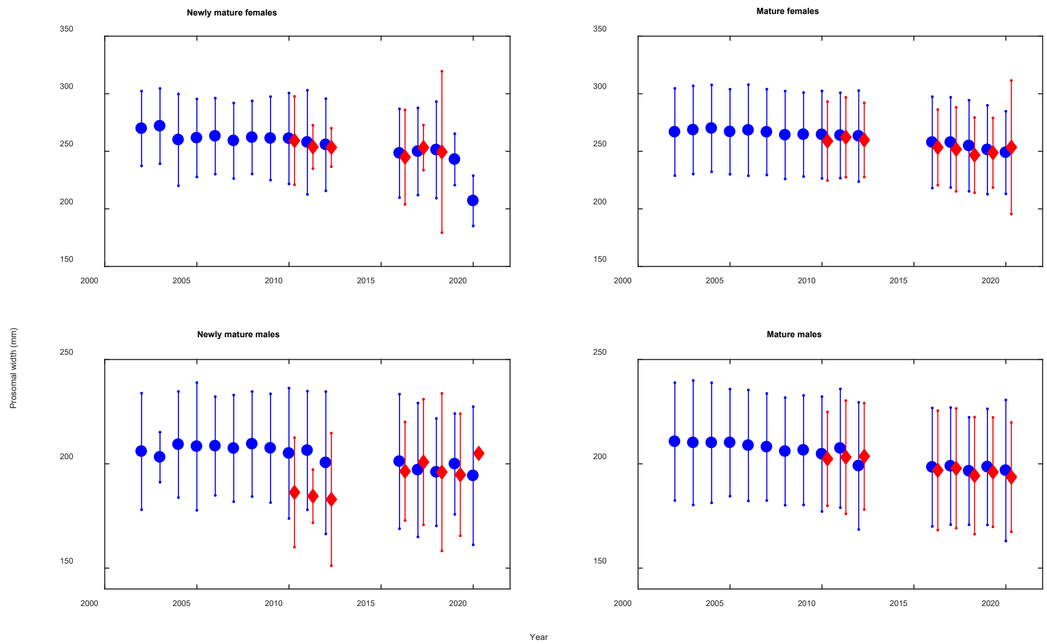

Figure 6. Mean prosomal widths (mm) (± 2 standard deviations) of mature and newly mature female and male horseshoe crabs in the Delaware Bay area (blue symbols and lines) and lower Delaware Bay (red symbols and lines) surveys.

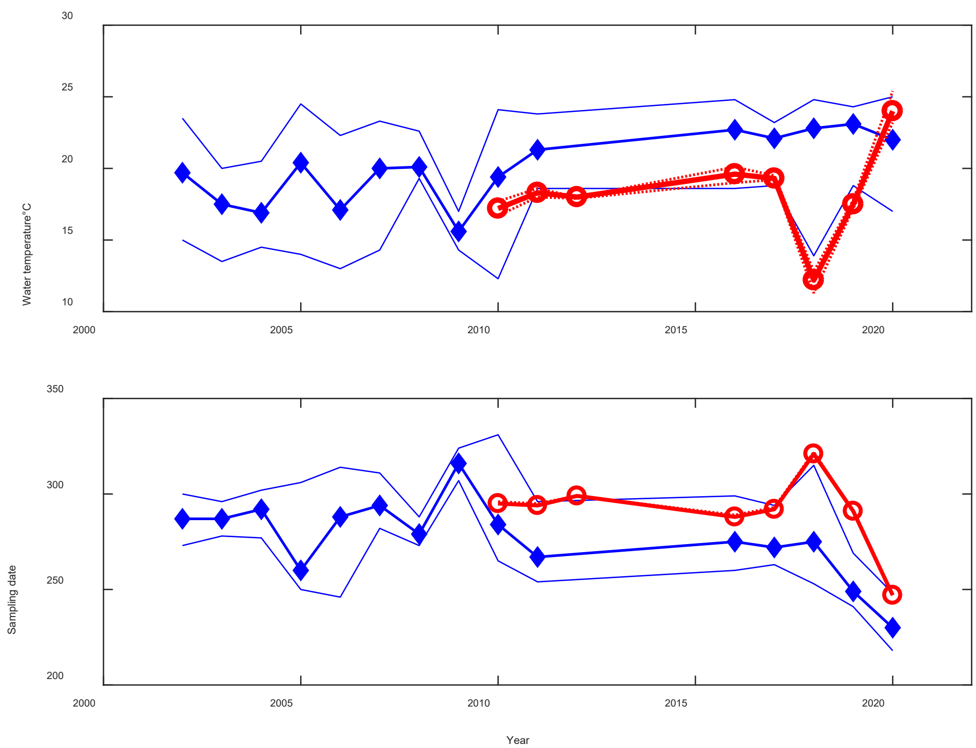

Figure 7. Plots of bottom water temperatures and ordinal sampling dates (days since 1 January) in the coastal Delaware Bay area and lower Delaware Bay trawl surveys. Solid symbols and blue lines indicate coastal Delaware Bay area. Open symbols and red lines indicate lower Delaware Bay. Points indicate mean values. Thinner lines indicate maximum and minimum values. Approximate calendar dates are indicated by gray horizontal lines for reference (ordinal dates are shifted by one day for leap years).

Table 1. Stratified mean catch-per-tow of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2020, 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).

	mean	UCL	LCL	CV	sd		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	-0.2	0.41	12.2	2007	19.5	39.6	-0.6	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	0.30	2.4	2019	3.5	6.0	1.0	0.35	1.2
2020	25.3	51.9	0.1	0.60	15.2	2020	16.0	31.3	0.8	0.56	9.1
Mature females						Mature males					
2002	11.4	18.5	4.2	0.30	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	-3.2	0.44	6.7	2006	36.2	60.9	11.4	0.28	10.1
2007	16.9	27.5	6.2	0.30	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	0.20	3.3	2018	35.7	48.9	22.5	0.17	6.2
2019	11.6	18.7	4.5	0.30	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
Newly mature females						Newly mature males					
2002	3.6	5.6	1.6	0.26	0.9	2002	1.3	2.0	0.5	0.28	0.4
2003	1.8	3.8	-0.1	0.49	0.9	2003	0.2	0.5	-0.1	0.84	0.2
2004	0.8	1.3	0.3	0.30	0.2	2004	1.8	2.6	1.0	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	0.30	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	-0.7	0.59	1.8	2010	3.2	7.0	-0.5	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	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	0.30	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

Table 2. Stratified mean catch-per-tow of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2020, 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).

	mean	UCL	LCL	CV	sd		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	-2.3	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	0.30	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	4.75
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	0.20	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
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	-0.2	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	-2.3	0.74	3.0	2010	3.3	7.2	-0.6	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	0.28	2020	6.9	10. 6	3.3	0.31	2.1

Table 3. Stratified mean catch–per-tow of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2020, 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).

	mean	UCL	LCL	CV	sd		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	-5.9	0.47	9.2	2011	20.2	50.7	-10.4	0.55	11.0
2012	164.3	311.8	16.9	0.32	53.1	2012	192.6	548.4	-163.3	0.43	82.7
2016	196.0	335.5	56.6	0.29	57.0	2016	184.2	322.9	45.5	0.32	58.7
2017	96.7	210.0	-16.7	0.46	44.1	2017	62.9	137.6	-11.7	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	-5.3	0.60	5.7	2019	5.7	15.8	-4.5	0.70	4.0
2020	0.3	0.8	0.0	0.97	0.3	2020	0.2	0.6	0.0	0.97	0.2
Mature females						Mature males					
2010	48.8	98.9	-1.2	0.40	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	-28.6	0.45	50.0
2012	19.1	51.6	-13.4	0.40	7.6	2012	66.8	141.1	-7.4	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	-5.8	0.39	31.1	2017	362.7	868.5	-143.2	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	-13.0	0.63	13.2	2019	100.4	254.0	-53.2	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
Newly mature females						Newly mature males					
2010	9.7	25.8	-6.3	0.64	6.2	2010	4.4	9.5	-0.8	0.46	2.0
2011	1.4	3.8	-0.9	0.58	0.8	2011	1.4	4.9	-2.2	0.94	1.3
2012	1.0	4.4	-2.3	0.76	0.8	2012	6.1	14.2	-2.0	0.48	2.9
2016	4.6	8.0	1.1	0.31	1.4	2016	16.2	29.0	3.5	0.30	5.0
2017	2.1	5.9	-1.7	0.65	1.4	2017	12.4	27.6	-2.7	0.44	5.4
2018	2.3	4.4	0.2	0.35	0.8	2018	3.6	7.6	-0.5	0.44	1.6
2019	0.0	0.0	0.0	NA	0.0	2019	8.0	22.3	-6.4	0.70	5.6
2020	0.0	0.0	0.0	NA	0.0	2020	0.1	0.3	0.0	0.97	0.1

Table 4. Stratified mean catch-per-tow of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2020, 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).

	mean	UCL	LCL	CV	sd		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	-11.5	0.55	11.8	2011	21.5	57.2	-14.3	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	109.0	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	-0.4	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
Mature females						Mature males					
2010	49.1	99.8	-1.7	0.40	19.7	2010	128.0	227.9	28.2	0.30	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	-8.9	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	-4.0	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	90.0	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
Newly mature females						Newly mature males					
2010	9.6	24.9	-5.7	0.62	5.9	2010	4.3	9.1	-0.5	0.43	1.9
2011	1.4	3.8	-0.9	0.58	0.8	2011	1.4	4.9	-2.2	0.94	1.3
2012	1.0	4.4	-2.3	0.76	0.8	2012	6.1	14.1	-1.9	0.47	2.9
2016	4.5	8.0	1.1	0.30	1.3	2016	16.0	27.2	4.9	0.27	4.3
2017	2.1	5.9	-1.7	0.65	1.4	2017	12.4	25.7	-1.0	0.42	5.2
2018	2.3	4.3	0.3	0.34	0.8	2018	3.6	7.6	-0.5	0.44	1.6
2019	0.0	0.0	0.0	NA	0.0	2019	8.5	22.9	-5.9	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

Table 5. Results of correlation analyses of mean prosomal width (mm) and survey year for newly mature and 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 2002-2019				
Mature females	16	-11.09	<0.001	-0.948
Newly mature females	16	-4.84	<0.001	-0.791
Mature males	16	-11.85	<0.001	-0.954
Newly mature males	16	-5.58	<0.001	-0.831
Lower Delaware Bay 2010-2019				
Mature females	8	-4.04	0.007	-0.855
Newly mature females	8	-2.00	0.116	-0.707
Mature males	8	-7.47	<0.001	-0.950
Newly mature males	8	4.78	0.003	0.890

Table 6. Estimated population (in thousands) of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2020, 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).

	mean	UCL	LCL	CV	sd		mean	UCL	LCL	CV	sd
Immature females						Immature males					
2002	9,470	15,665	3,275	0.31	2,936	2002	5,483	9,284	1,683	0.33	1,809
2003	4,585	8,848	321	0.43	1,972	2003	2,303	4,217	390	0.39	898
2004	7,774	11,770	3,778	0.25	1,944	2004	6,810	10,895	2,725	0.29	1,975
2005	5,630	8,856	2,404	0.28	1,576	2005	5,260	8,839	1,681	0.33	1,736
2006	12,928	18,691	7,164	0.21	2,715	2006	9,327	14,554	4,100	0.24	2,238
2007	13,684	27,486	-118	0.41	5,610	2007	8,966	18,246	-314	0.42	3,766
2008	10,933	18,650	3,216	0.32	3,499	2008	7,841	13,917	1,766	0.35	2,744
2009	39,032	72,868	5,197	0.39	15,222	2009	29,864	47,269	12,460	0.28	8,362
2010	3,954	5,220	2,688	0.16	633	2010	2,686	4,144	1,229	0.26	698
2011	4,965	6,945	2,985	0.20	993	2011	3,092	4,547	1,637	0.23	711
2016	11,699	20,462	2,935	0.36	4,212	2016	9,102	16,649	1,555	0.39	3,550
2017	7,505	10,708	4,302	0.19	1,426	2017	5,091	8,465	1,717	0.27	1,375
2018	10,173	14,285	6,061	0.19	1,933	2018	7,507	11,173	3,842	0.23	1,727
2019	3,397	5,516	1,279	0.31	1,053	2019	1,487	2,614	360	0.38	565
2020	9,475	19,779	0	0.65	6,159	2020	5,925	11,967	0	0.61	3,614
Mature females						Mature males					
2002	4,959	8,084	1,834	0.30	1,488	2002	11,584	17,335	5,834	0.24	2,780
2003	3,379	5,160	1,599	0.25	845	2003	8,069	13,029	3,110	0.29	2,340
2004	2,735	4,043	1,426	0.23	629	2004	5,150	7,788	2,511	0.25	1,288
2005	3,138	4,942	1,333	0.27	847	2005	5,844	8,461	3,228	0.22	1,286
2006	6,611	14,330	-1,108	0.42	2,777	2006	15,825	26,060	5,589	0.27	4,273
2007	7,746	12,704	2,789	0.31	2,401	2007	15,795	25,104	6,487	0.28	4,423
2008	6,311	10,202	2,419	0.29	1,830	2008	14,647	24,995	4,299	0.33	4,834
2009	2,975	4,971	979	0.32	952	2009	6,240	10,197	2,283	0.30	1,872
2010	5,178	7,616	2,740	0.23	1,191	2010	13,963	21,910	6,015	0.28	3,910
2011	5,290	7,282	3,297	0.18	952	2011	15,060	29,000	1,120	0.40	6,024
2016	6,024	8,635	3,413	0.21	1,265	2016	21,941	37,216	6,665	0.29	6,363
2017	7,185	10,525	3,844	0.23	1,653	2017	20,664	31,208	10,119	0.25	5,166
2018	7,326	10,520	4,131	0.21	1,538	2018	15,749	21,880	9,619	0.18	2,835
2019	5,110	8,454	1,767	0.32	1,635	2019	8,924	15,202	2,646	0.35	3,108
2020	10,803	15,359	6,247	0.25	2,706	2020	31,546	51,050	12,042	0.36	11,583
Newly mature females						Newly mature males					
2002	1,537	2,400	675	0.26	400	2002	548	869	227	0.28	153
2003	794	1,633	-45	0.49	389	2003	78	221	-65	0.84	66
2004	358	575	141	0.29	104	2004	789	1,127	451	0.21	166
2005	479	753	206	0.27	129	2005	597	1,002	191	0.33	197
2006	2,051	3,509	594	0.31	636	2006	3,113	5,113	1,113	0.31	965
2007	2,373	4,339	408	0.40	949	2007	3,129	4,972	1,287	0.28	876
2008	2,571	4,984	158	0.43	1,106	2008	757	1,254	261	0.31	235
2009	885	1,361	410	0.26	230	2009	725	1,240	210	0.34	247
2010	1,338	2,990	-314	0.59	789	2010	1,422	3,070	-226	0.55	782
2011	845	1,360	331	0.30	254	2011	749	1,335	164	0.36	270
2016	1,608	2,357	860	0.23	370	2016	2,608	4,884	331	0.42	1,095
2017	1,480	2,274	687	0.26	385	2017	1,523	2,392	654	0.28	426
2018	1,773	2,923	622	0.31	550	2018	3,341	5,367	1,316	0.29	969
2019	242	472	12	0.47	114	2019	1,271	2,154	389	0.34	437
2020	133	330	0	0.87	117	2020	2,492	4,030	953	0.37	914

Table 7. Estimated population (in thousands) of horseshoe crabs in the coastal **Delaware Bay area** survey, 2002-2020, 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).

	mean	UCL	LCL	CV	sd		mean	UCL	LCL	CV	sd
Immature females						Immature males					
2002	8,222	11,875	4,568	0.21	1,727	2002	5,076	7,998	2,155	0.28	1,421
2003	4,089	6,860	1,317	0.32	1,308	2003	2,114	3,462	766	0.30	634
2004	7,376	10,616	4,135	0.21	1,549	2004	6,033	8,786	3,281	0.22	1,327
2005	5,104	7,521	2,687	0.23	1,174	2005	4,673	7,414	1,932	0.28	1,308
2006	13,714	20,988	6,439	0.25	3,429	2006	9,378	13,971	4,786	0.23	2,157
2007	13,692	27,335	48	0.41	5,614	2007	9,350	19,735	-1,035	0.45	4,208
2008	10,595	16,578	4,612	0.26	2,755	2008	6,897	10,443	3,350	0.23	1,586
2009	27,375	40,519	14,232	0.23	6,296	2009	26,435	38,730	14,140	0.23	6,080
2010	4,102	5,706	2,497	0.19	779	2010	2,781	4,423	1,139	0.29	806
2011	5,426	8,433	2,420	0.27	1,465	2011	3,301	5,219	1,382	0.28	924
2016	11,292	18,441	4,144	0.30	3,388	2016	8,185	13,512	2,858	0.31	2,537
2017	7,948	11,818	4,077	0.23	1,828	2017	5,082	7,829	2,335	0.26	1,321
2018	10,115	13,839	6,391	0.18	1,821	2018	7,768	11,653	3,882	0.24	1,864
2019	14,855	15,027	14,682	0.33	4,902	2019	66	236	-104	1.27	84
2020	6,832	10,559	3,106	0.32	2,213	2020	4,610	7,540	1,679	0.38	1,740
Mature females						Mature males					
2002	4,779	7,431	2,128	0.26	1,243	2002	10,711	14,972	6,450	0.19	2,035
2003	3,308	4,851	1,764	0.22	728	2003	7,454	10,827	4,082	0.21	1,565
2004	2,767	3,919	1,615	0.20	553	2004	5,586	8,875	2,297	0.28	1,564
2005	2,957	4,323	1,592	0.22	651	2005	5,408	7,322	3,494	0.17	919
2006	5,867	10,517	1,218	0.31	1,819	2006	14,461	21,734	7,188	0.23	3,326
2007	6,553	9,864	3,243	0.25	1,638	2007	13,100	18,506	7,694	0.20	2,620
2008	7,172	13,336	1,008	0.40	2,869	2008	14,244	23,240	5,247	0.30	4,273
2009	3,230	5,523	936	0.33	1,066	2009	6,319	10,255	2,383	0.29	1,833
2010	5,588	8,698	2,478	0.26	1,453	2010	14,396	22,600	6,192	0.27	3,887
2011	5,388	7,629	3,147	0.20	1,078	2011	14,858	25,890	3,825	0.33	4,903
2016	5,735	7,770	3,700	0.17	975	2016	24,017	40,197	7,837	0.30	7,205
2017	7,785	12,033	3,537	0.27	2,102	2017	19,985	29,245	10,724	0.23	4,597
2018	9,463	18,463	464	0.44	4,164	2018	15,264	19,849	10,680	0.15	2,290
2019	6,420	6,506	6,334	0.32	2,054	2019	11,660	11,824	11,497	0.37	4,314
2020	10.927	16,014	5,840	0.28	3,021	2020	25,200	34,983	15,416	0.23	5,810
Newly mature females						Newly mature males					
2002	1,509	2,278	741	0.24	362	2002	561	925	196	0.31	174
2003	787	1,547	26	0.45	354	2003	78	222	-66	0.84	66
2004	367	613	120	0.32	117	2004	786	1,120	452	0.20	157
2005	531	908	154	0.34	181	2005	580	927	233	0.29	168
2006	2,122	3,705	540	0.33	700	2006	3,377	6,076	678	0.38	1,283
2007	2,129	3,584	674	0.33	703	2007	2,841	4,214	1,468	0.23	653
2008	2,697	4,780	613	0.36	971	2008	776	1,315	237	0.33	256
2009	883	1,366	399	0.26	230	2009	708	1,157	259	0.31	219
2010	1,770	4,532	-992	0.74	1,310	2010	1,464	3,180	-252	0.56	820
2011	882	1,495	269	0.34	300	2011	766	1,343	190	0.36	276
2016	1,583	2,304	863	0.22	348	2016	2,939	5,588	290	0.43	1,264
2017	1,502	2,323	680	0.27	406	2017	1,590	2,623	557	0.32	509
2018	1,780	2,866	695	0.29	516	2018	3,064	4,466	1,663	0.22	674
2019	77	225	-70	0.94	73	2019	112	267	-43	0.68	77
2020	134	330	0	0.87	117	2020	2,430	3,676	1,184	0.30	740

Table 8. Estimated population (in thousands) of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2020, 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).

	mean	UCL	LCL	CV	sd		mean	UCL	LCL	CV	sd
Immature females						Immature males					
2010	3,510	5,199	1,822	0.20	702	2010	2,632	4,476	788	0.29	763
2011	870	1,931	-191	0.44	383	2011	881	2,160	-397	0.52	458
2012	8,021	15,084	958	0.32	2,567	2012	9,381	21,965	-3,204	0.42	3,940
2016	9,046	15,558	2,534	0.29	2,623	2016	8,429	14,813	2,044	0.32	2,697
2017	4,536	10,029	-956	0.47	2,132	2017	2,920	6,458	-618	0.47	1,372
2018	2,211	2,803	1,619	0.10	221	2018	2,597	3,516	1,678	0.15	390
2019	525	1,278	-229	0.56	294	2019	308	816	-201	0.64	197
2020	12	33	0	0.97	12	2020	8	22	0	0.97	8
Mature females						Mature males					
2010	2,117	4,260	-25	0.39	826	2010	5,657	10,247	1,067	0.32	1,810
2011	1,348	2,599	96	0.33	445	2011	4,829	10,570	-912	0.43	2,076
2012	938	2,522	-646	0.39	366	2012	3,263	6,864	-338	0.35	1,142
2016	1,274	1,710	837	0.15	191	2016	7,735	9,709	5,761	0.10	774
2017	3,674	7,501	-153	0.38	1,396	2017	16,794	40,517	-6,929	0.51	8,565
2018	1,771	2,588	953	0.18	319	2018	4,616	6,600	2,631	0.18	831
2019	1,148	3,011	-715	0.63	723	2019	5,746	14,583	-3,092	0.60	3,448
2020	7	19	0	0.97	7	2020	152	332	0	0.68	103
Newly mature females						Newly mature males					
2010	414	1,087	-260	0.63	261	2010	187	409	-35	0.46	86
2011	65	170	-40	0.58	38	2011	58	208	-93	0.94	55
2012	50	214	-114	0.76	38	2012	301	710	-109	0.49	147
2016	206	357	55	0.30	62	2016	727	1,268	186	0.29	211
2017	88	249	-73	0.66	58	2017	542	1,100	-16	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	1,022	-299	0.71	257
2020	0	0	0	NA	0	2020	4	11	0	0.97	4

Table 9. Estimated population (in thousands) of horseshoe crabs in the **lower Delaware Bay** survey area in 2010-2019, 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).

	mean	UCL	LCL	CV	sd		mean	UCL	LCL	CV	sd
Immature females						Immature males					
2010	3,503	5,155	1,851	0.18	631	2010	2,588	4,056	1,120	0.24	621
2011	938	2,311	-435	0.53	497	2011	935	2,437	-567	0.58	542
2012	8,125	14,222	2,027	0.31	2,519	2012	9,023	17,690	356	0.35	3,158
2016	8,618	13,190	4,046	0.22	1,896	2016	7,725	11,638	3,812	0.21	1,622
2017	4,325	8,829	-178	0.41	1,773	2017	2,731	5,408	53	0.38	1,038
2018	2,209	2,780	1,638	0.10	221	2018	2,595	3,529	1,661	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
Mature females						Mature males					
2010	2,124	4,340	-91	0.41	871	2010	5,600	9,916	1,285	0.30	1,680
2011	1,290	2,239	340	0.27	348	2011	4,479	8,332	625	0.31	1,388
2012	915	2,242	-412	0.34	311	2012	3,188	5,456	921	0.28	893
2016	1,264	1,647	880	0.13	164	2016	7,727	9,570	5,883	0.10	773
2017	3,654	7,307	2	0.36	1,315	2017	13,805	23,702	3,908	0.26	3,589
2018	1,782	2,666	898	0.19	339	2018	4,647	6,901	2,393	0.19	883
2019	1,932	1,948	1,916	0.00	0	2019	8,356	8,356	8,356	0.00	0
2020	7	19	0	0.97	7	2020	152	332	0	0.68	103
Newly mature females						Newly mature males					
2010	418	1,097	-260	0.63	263	2010	185	391	-22	0.43	80
2011	65	170	-40	0.58	38	2011	58	208	-93	0.94	55
2012	50	214	-114	0.76	38	2012	302	719	-114	0.50	151
2016	205	355	55	0.28	57	2016	716	1,176	256	0.25	179
2017	88	249	-73	0.66	58	2017	541	1,090	-9	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

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	19.7	23.5	15.0	287	300	273
2003	17.5	20.0	13.5	287	296	278
2004	16.9	20.5	14.5	292	302	277
2005	20.4	24.5	14.0	260	306	250
2006	17.1	22.3	13.0	288	314	246
2007	20.0	23.3	14.3	294	311	282
2008	20.1	22.6	19.3	279	288	273
2009	15.6	17.0	14.3	316	324	307
2010	19.4	24.1	12.3	284	331	265
2011	21.3	23.8	18.6	267	296	254
2016	22.7	24.8	18.6	275	299	260
2017	22.1	23.2	18.8	272	294	263
2018	22.8	24.8	13.9	275	315	253
2019	23.1	24.3	18.8	249	269	241
2020	22.0	25.0	17.0	230	248	218
Lower Delaware Bay						
2010	17.2	17.7	16.7	295	296	295
2011	18.3	18.6	18.0	294	295	294
2012	18.0	18.0	17.9	299	299	299
2016	19.6	20.1	19.0	288	289	288
2017	19.3	19.5	19.2	292	293	292
2018	12.2	12.8	11.3	321	322	321
2019	17.5	17.8	17.2	291	291	291
2020	24.0	25.4	23.2	247	247	247

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		
	r	*T*	*p*	*r*	*T*	*p*
Delaware Bay area						
Immature females	-0.493	-2.04	0.062	0.553	2.39	0.033
Immature males	-0.512	-2.15	0.051	0.566	2.47	0.028
Mature females	0.527	2.24	0.043	-0.594	-2.66	0.020
Mature males	0.517	2.18	0.048	-0.589	-2.63	0.021
Newly mature females	-0.008	-0.02	0.978	0.433	1.73	0.107
Newly mature males	0.372	1.45	0.172	-0.231	-0.86	0.408
Lower Delaware Bay						
Immature females	-0.034	-0.083	0.936	0.258	0.65	0.537
Immature males	-0.081	-0.201	0.848	0.284	0.73	0.495
Mature females	-0.314	-0.811	0.449	0.453	1.24	0.260
Mature males	-0.077	-0.188	0.859	0.270	0.68	0.521
Newly mature females	-0.220	-0.553	0.601	0.241	0.61	0.566
Newly mature males	0.008	0.019	0.986	-0.184	0.46	0.663

MEMO

To: Delaware Bay ARM Working Group
From: Jim Lyons, USGS Eastern Ecological Science Center at the Patuxent Research Refuge, Laurel, MD
Re: Red Knot Stopover Population Estimate for 2021
Date: 22 September 2021

1 Acknowledgments

We thank the many volunteers in Delaware and New Jersey who collected mark-resight data in 2021. We are grateful to Henrietta Bellman (Delaware DFW) and Amanda Dey (New Jersey ENSP), and numerous volunteers in Delaware and New Jersey for data entry and data management, and Lena Usyk (bandedbirds.org) for data management.

2 Methods

Red knots have been individually marked at Delaware Bay and other locations in the Western Hemisphere with engraved leg flags since 2003; each leg flag is engraved with a unique 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 according to the methods for mark-resight investigations of Red Knots in Delaware Bay (Lyons 2016).

Surveys to locate leg-flagged birds were conducted on each beach every three days according to the sampling plan (Table 1). During these resighting surveys, agency staff and volunteers surveyed the entire beach and recorded as many alphanumeric combinations as possible.

As in previous years, 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 not included in the analysis. However, banding data from Argentina for validation purposes are not available 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 2021 whose flag codes were previously accidentally deployed in both New Jersey and South Carolina (A. Dey, pers. comm.) because it is not possible to confirm individual identity in this case.

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).

Table 1. Dates for mark-resight survey periods (3-day sampling occasion) in Delaware Bay.

Survey period	Dates	Survey period	Dates
1	≤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

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-ratio. In this "superpopulation" approach, passage population size is estimated 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 mark-resight data summary is provided in Appendix 1).

With the mark-resight superpopulation approach, we first estimated the number of birds that were carrying leg flags, and then adjusted this number to account for unmarked birds using the estimated proportion of the population with flags. 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 in the bay 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 2.

3 Summary of Mark-resight and Count Data Collected in 2020

Mark-resight encounter data.—The 2021 Red Knot mark-resight database included a total of 1,591 individual birds from six countries recorded at least once by observers in Delaware Bay (Table 2). This total is remarkably close to the 2020 total detected in the bay: 1,587 individual birds were recorded in 2020 (Table 2). **Approximately the same number of flagged Red Knots were detected in 2020 and 2021.**

There was sufficient data for analysis in all 10 sampling periods in 2021 (≤10 May to 6 June; Table 1). In some years, including 2020, the analysis was restricted to periods 1-9 (≤10 May to 3 June) because data beyond 3 June were sparse.

While the number of birds detected in 2021 was similar to the number detected in 2020, this number of resighted individuals is lower than recent (pre-COVID-19) years given the limited use of volunteers for safety reasons. The number of marked birds detected and available for analysis in 2021 was approximately 48% lower than the number in the 2019 analysis (n = 3,072 birds) and 58% lower than the number detected and used for analysis in 2018 (n = 3,820).

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 records available from bandedbirds.org. Again, any engraved flag reported by observers that does not have a corresponding record of physical capture is omitted. Field observers submitted 3,792 resightings in 2021; 50 were not valid (i.e., no corresponding banding data), for an overall misread read of 1.3%. (In 2020, 3,364 resightings were submitted and 100 [2.9%] were not valid.) 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 2020 but were not in fact present in Delaware Bay in 2020. It is not possible to identify this second type of false positive with banding data validation or other QA/QC methods.

Marked-ratio data.—In 2021, 564 marked ratio scan samples were collected: 297 and 267 in Delaware and New Jersey, respectively (Appendix 3). Last year in 2020, 734 marked-ratio scan samples were collected: 376 samples in Delaware and 358 in New Jersey.

Aerial and ground count data.—Aerial surveys were conducted on 23 and 27 May 2021 (Table 3; data provided by A. Dey, New Jersey Division of Fish and Wildlife, Endangered and Nongame Species Program). Ground and boat surveys were conducted twice in New Jersey (on 23 and 27 May) but only once in Delaware (on 23 May; Table 3).

4 Summary of 2020 Migration

The pattern of arrivals at Delaware Bay in 2021 suggests a slow start to the migration season, with few birds arriving before 18 May. A large wave of arrivals occurred on or about 21 May: approximately 35% of the total 2021 stopover population arrived close to 21 May (Fig. 1a). The number of birds arriving in the following period, about 24 May, was low, but there was a small number of late arrivals around 27-31 May (approximately 21% of the stopover population). Thus in 2021, it appears there was one large wave of arrivals near the middle of the season and relatively small fractions arriving in the other the sampling periods before and after the peak of arrivals around 21 May.

Stopover persistence is the probability that a bird present in the bay during sampling period i is present in the bay at sampling period $i+1$. In 2020, stopover persistence started off relatively low (0.6), which is unusual for this time of year (Fig 1b). Often the early-arriving birds remain in the study area with little turnover in the population (but see 2020), but in 2021 there was substantial turnover early in the season. Stopover persistence peaked around 15 May and declined steadily after that until 27 May (Fig 1b). The steady decrease in stopover persistence during 15-24 May suggested a high degree of turnover and shorter stopovers than most years. There was a spike in stopover persistence around 27 May (Fig. 1b), during which turnover slowed briefly, but otherwise, stopover persistence declined steadily from 15 May until the end of the season. That is, turnover was high and increasing from 15 May on, suggesting shorter stays in 2021 than in most other years.

Following Lyons et al. (2016), we used the Jolly-Seber model to estimate stopover duration. In 2021, estimated average stopover duration was 10.3 days (95% credible interval 9.0 – 12.1 days). This stopover duration estimate is slightly shorter than 2020 (10.7 days [9.9 – 11.7]) and shorter than 2019 (12.1 days). This method of estimating stopover duration provides a coarse measure in our Delaware Bay study, however, because it is based on the number of sampling periods that a bird remained in the study area. For our Delaware Bay analysis, sampling periods are 3 days in which the data are aggregated (Table 1). To estimate stopover duration 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) to estimate stopover duration in days. The resolution of the estimate is thus limited by the resolution of the time step in the mark-recapture model.

Probability of resighting in 2021 was relatively high early in the season, approximately 40-50% until around 18 May (Fig 1c). Between 21-27 May, probability of resighting was lower, around 25%. At the end of the season, after 27 May, probability of resighting was lower still, especially the 3-day period around 31 May. Around 31 May, the probability of resighting was close to zero, which is unusual for the mark-resight work at Delaware Bay (Fig 1c). Resighting probability increased slightly during 1-6 June to levels more typical for this time of year.

In 2021, 8.2% of the stopover population carried engraved leg flags (95% CI, 7.0% – 9.1%). This is slightly lower than the 2020 estimate (9.6% with leg flags [95% CI 8.8 – 10.3%]).

5 Stopover Population Estimation

The passage population size in 2021 was estimated at 42,271 (95% credible interval: 35,948 – 55,210). This superpopulation estimate accounts for turnover in the population and probability of detection. The 2021 stopover population estimate is similar to the 2020 stopover population size estimate (given wide confidence intervals in both years), 40,444, and slightly lower than the 2018-2019 estimates (Table 4).

Like 2020, the 2021population estimate is slightly lower than the 2018 and 2019 estimates (Table 4) and the confidence interval is wider. The uncertainty in the population estimate and wide confidence intervals are due in part to the low probability of resighting for many of the sampling periods during 2020-2021 compared to other years (early 2021 notwithstanding).

The time-specific stopover population estimates in 2021 increased steadily from the beginning of the season and peaked around 21 May (21,846 birds; Fig. 1d), corresponding to the large influx of arrivals at this time (Fig. 1a). Time-specific estimates declined steadily from 21 May until 6 June (Fig. 1d). The relatively high degree of uncertainty (wide confidence interval) in the estimate for the 30 May period reflects the low probability of resighting at this time (Fig. 1c).

6 References

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.

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. 2016. Study design guidelines for mark-resight investigations of Red Knots in Delaware Bay. Unpublished report. 13 pp.

This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

Table 2. Number of flags detected in 2021 by banding location (flag color).

	No. flagged individuals detected		
Banding location (flag color)	***2019***	***2020***	***2021***
U.S. (lime green)	2,368	1,255	1,292
U.S. (dark green)	351	161	118
Argentina (orange)	216	89	81
Canada (white)	156	52	78
Brazil (dark blue)	35	21	17
Chile (red)	10	9	5
Total	3,136	1,587	1,591

Table 3. Number of Red Knots detected during aerial and ground surveys of Delaware Bay in 2021. Data provided by A. Dey, New Jersey Division of Fish and Wildlife, Nongame and Endangered Species Program.

	Delaware	New Jersey	Total
Aerial/Ground Surveys			
23 May 2021	1,123*	5,012	6,131
27 May 2021	895	5,985	6,880
Ground/Boat Surveys			
23 May 2021	1,123	3,651	4,774
27 May 2021	—	5,618	5,618

* Delaware ground survey total from 23 May (1,123) used here rather than the aerial count of Delaware on the same day because the aerial count was lower than the corresponding ground count.
"—" = no data; ground survey was not conducted in Delaware on 27 May.

Table 4. Stopover (passage) population estimate using mark-resight methods compared to peak-count index using aerial- or ground-survey methods. The mark-resight estimate of stopover (passage) population accounts for population turnover during migration; peak-count index, a single count on a single day, does not account for turnover.

Year	Stopover population[a] (mark-resight *N**)	95% CI Stopover population *N**	Peak-count index [aerial (A) or 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 (A)[h]

[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

This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

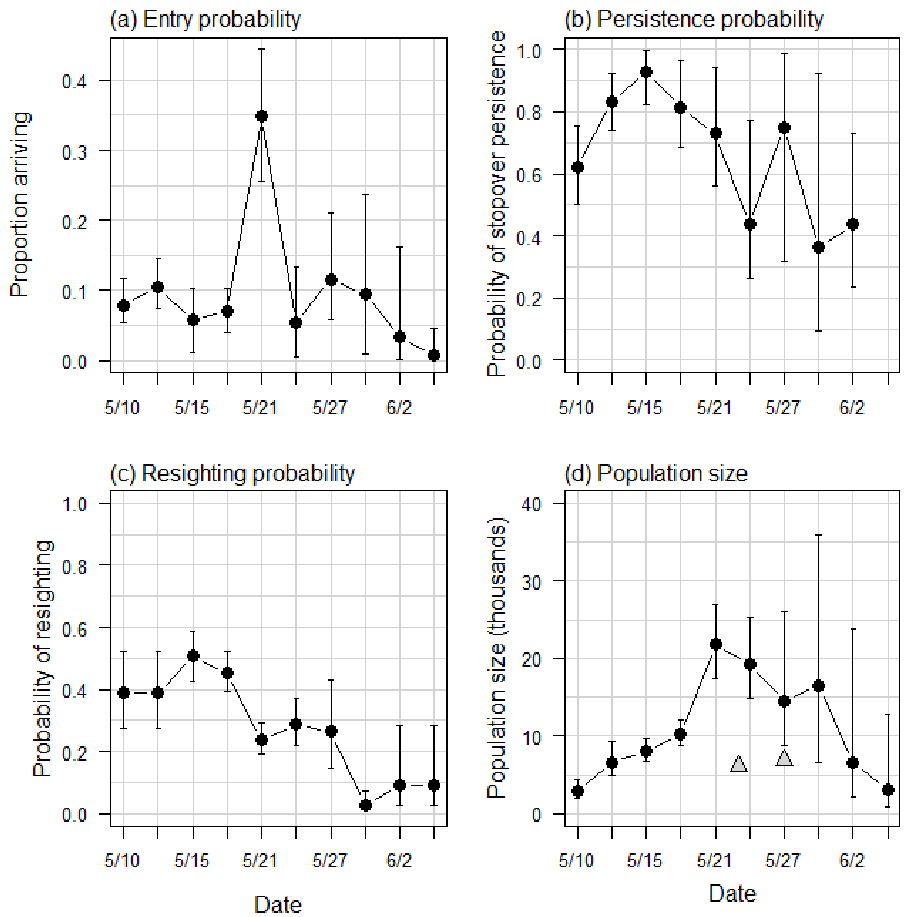

Figure 1. Estimated Jolly-Seber (JS) model parameters from a mark-resight study of Red Knots at Delaware Bay in 2021: (a) proportion of stopover population arriving at Delaware Bay, (b) stopover persistence, (c) probability of resighting, and (d) time-specific stopover population size. Dates on the x-axis represent sampling occasions (3-day survey periods). Triangles in (d) are total counts conducted on 23 (aerial count of NJ; ground count of DE) and 27 May (aerial count for both NJ and DE) 2021.

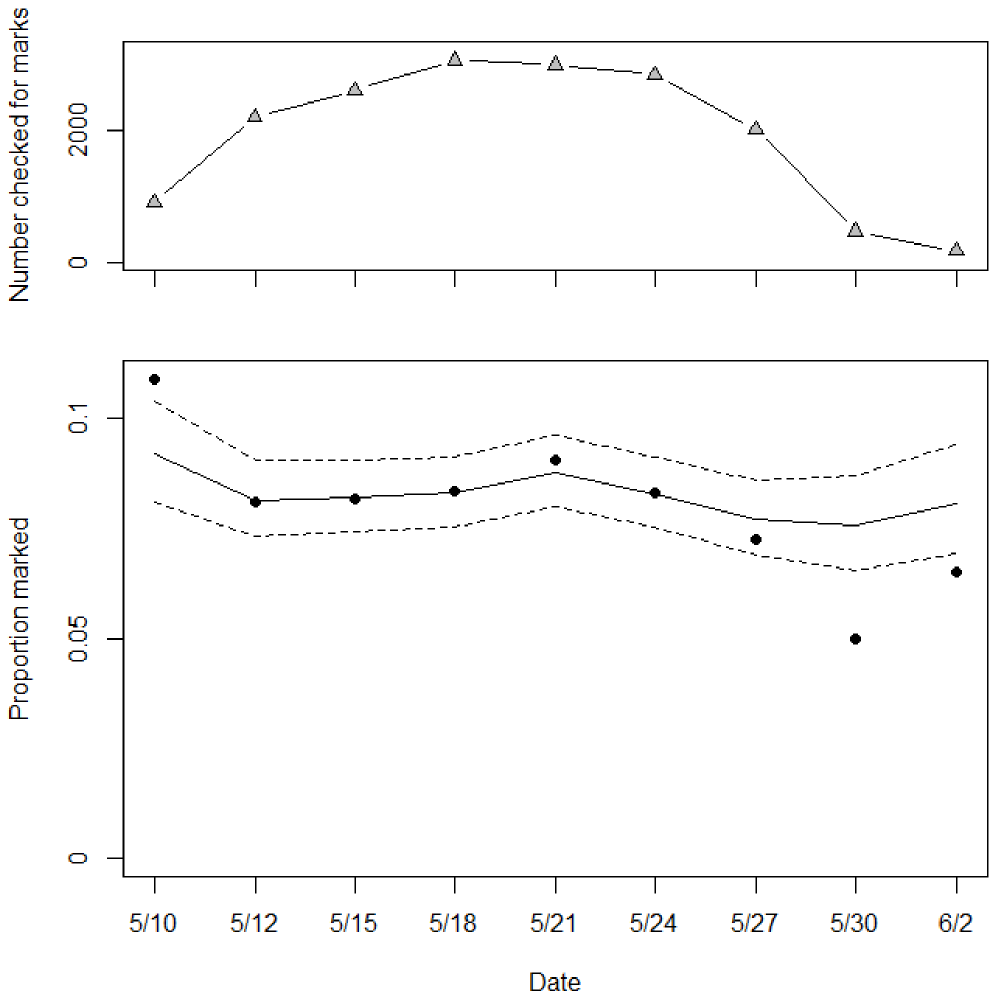

Figure 2. Estimated proportion of the Delaware Bay stopover population carrying leg flags in 2021. The marked proportion was estimated from marked-ratio scan samples for each 3-day sampling period. The dates for the sampling periods are shown in Table 1. The upper panel shows the sample size (number scanned, i.e., checked for marks) for each sample period. The bottom panel shows the estimated proportion marked at 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; filled circles show (number with marks/number scanned).

Appendix 1. Summary of 2021 mark-resight data ("m-array"). NR = never resighted.

			Next resighted at sample								
Sample	Dates	Resighted	2	3	4	5	6	7	8	9	NR
1	≤10 May	48	23	9	3	0	1	0	0	0	12
2	11-13 May	210		95	30	6	9	1	0	0	69
3	14-16 May	331			146	21	24	9	1	1	129
4	17-19 May	385				85	43	11	1	0	245
5	20-22 May	452					96	25	2	1	328
6	23-25 May	458						56	1	4	397
7	26-28 May	290							7	7	276
8	29-31 May	33								0	33
9	1-3 June	48								4	44
10	4-6 June	22									

Appendix 2. Statistical Methods to Estimate Stopover Population Size Using Mark-Resight Data and Counts of Marked Birds

We converted the observations of marked birds 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 an appendix.

We made inference from a fully-time dependent model; arrival, persistence, and resight probabilities were allowed to vary with sampling period [$\beta_t\ \varphi_t\ p_t$]. 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:

$$m_s \sim Bin(C_s, \pi), \quad (1)$$

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

$$\widehat{N^*} = \widehat{M^*}/\hat{\pi} \quad (2)$$

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:

$$m_{s,t} \sim Binomial\left(C_{s,t}, \pi_t\right) \quad (3)$$
$$for\ s\ in\ 1, \ldots, n_{samples}\ and\ t\ in\ 1, \ldots, n_{occasions}$$
$$logit(\pi_t) = \alpha + \delta_t$$
$$\delta_t \sim Normal(0, \sigma^2_{occasions})$$

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.

This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

Appendix 3. Number of marked-ratio scan samples.

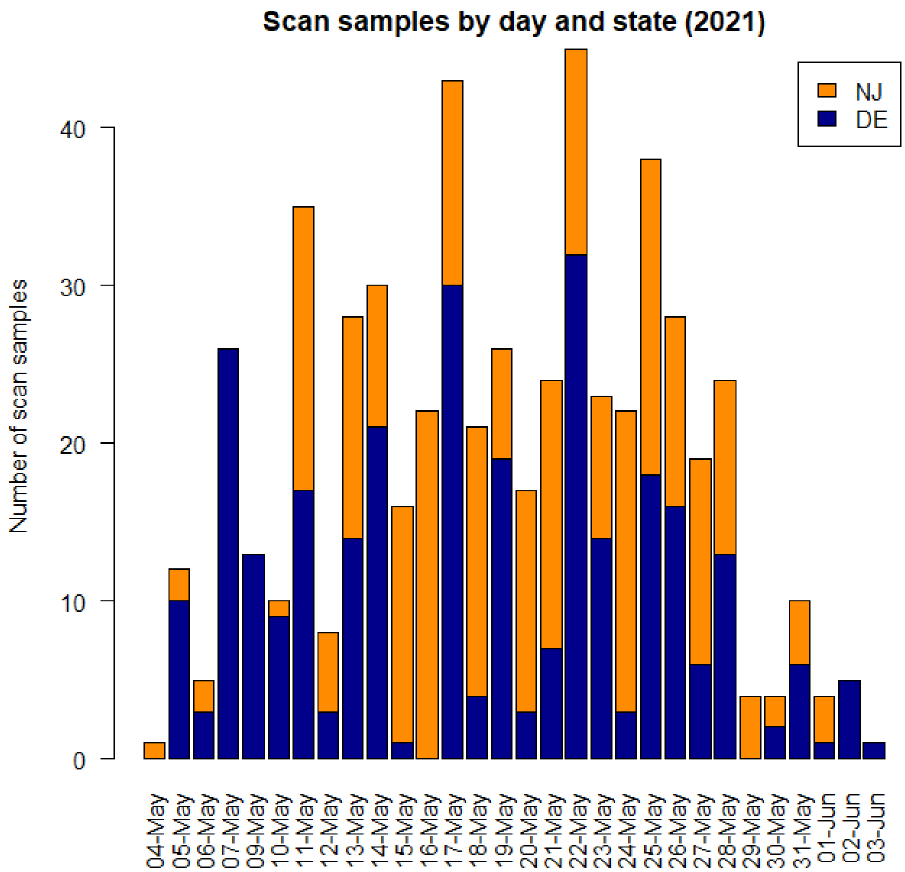

Figure A3.1. Number of marked-ratio scan samples (n = 564) collected in Delaware Bay in 2021 by field crews in Delaware (blue) and New Jersey (orange) and date. In 2021, observers in Delaware and New Jersey collected 297 and 267 scan samples, respectively.