Atlantic States Marine Fisheries Commission

Horseshoe Crab Adaptive Resource Management Subcommittee & Delaware Bay Ecosystem Technical Committee Conference Call

Call Summary

Thursday, September 23, 2021
9:00 AM - 11:00 AM

Call Attendees Representing Each Committee:
Horseshoe Crab Adaptive Resource Management Subcommittee: John Sweka (Chair), Jim Lyons (Vice Chair), Conor McGowan, Dave Smith, Henrietta Bellman, Jason Boucher, Linda Barry, Steve Doctor, Wendy Walsh, Margaret Conroy
Delaware Bay Ecosystem Technical Committee: Wendy Walsh (Chair), Henrietta Bellman (Vice Chair), Eric Hallerman, Yan Jiao, Jordy Zimmerman, Steve Doctor
Horseshoe Crab Technical Committee Members*: Jeff Brunson (Chair), Derek Perry, Jeffrey Dobbs, Jordy Zimmerman, Samantha MacQuesten, Steve Doctor, Chris Wright
ASMFC Staff: Caitlin Starks, Kristen Anstead
*HSC TC was not required to attend

The Adaptive Resource Management (ARM) Subcommittee and the Delaware Bay Ecosystem Technical Committee (DBETC) met via conference call to review the most recent population estimates for horseshoe crabs and red knots, the results of the ARM for 2022, and supporting horseshoe crab and red knot data sets. Below are the agenda items and summary of the committee's discussion and decisions.

1. **Survey Results for 2020 Horseshoe Crab (Eric Hallerman)**

Eric presented the Virginia Tech Trawl Survey results for 2020. Yan Jiao provided analytical support for the report given to the ARM and DBETC. The survey began in early August, earlier than most years to accommodate the increased frequency of fall storms, and continued through early September. The average bottom temperature was the highest seen in the time series. The mean catch-per-tow of newly mature female and male horseshoe crabs show no trend but remain below peak values and mean catch-per-tow of mature horseshoe crabs show increasing trends since 2002. Additionally, mean prosomal widths of newly mature and mature horseshoe crabs in the coastal Delaware Bay area show decreasing trends.

In 2019, the ARM and DBETC agreed that for running the ARM model each year, primiparous crabs should be included in the adult abundance estimates (from the swept area delta distribution values) and that half a year of the annual mortality from the assessment (0.274) should be applied to account for the ~6 month time lag between the survey and the spawning season when they interact with red knots. Therefore, the adult horseshoe crab abundance inputs for this year's ARM run is 9.5 million females and 29.7 million males.

The 2021 sampling season is currently underway, although they had to start in early August again to accommodate expected poor weather. Eric noted that, anecdotally, the abundance of horseshoe crabs appears to be high again in 2021. In fact, the survey experienced some gear saturation which is very rare. Whether horseshoe crab abundance is increasing or the crabs are staying inshore longer due to warming temperatures cannot be determined at this time. Funding for this survey for next year is unknown, although Eric usually does not hear about funding until the summer before the survey.

2. **Survey Results for 2020 Red Knots (Jim Lyons)**

Jim Lyons presented the red knot stopover population estimate. The population estimate for red knots is 42,271 birds for 2021. This estimation is an increase from 2020 but remains lower than the 2018-2019 estimates. May 21st saw an arrival of a lot of birds this year, which was unusual since it is later than most years. The persistence pattern was also unusual this year since it decreased mid-sampling season and then rose back up. The resight probability was high at the beginning of sampling but declined to low at the end of the season.

It was noted by the ARM subcommittee that there was a decline in the accompanying aerial counts for 2021. Jim said he could not really speak to that because that survey is run by Mandy Dey, who was not present on the call. Jim said he knew that COVID restrictions led to limited sampling in 2020, which was reported as a ground count. Henrietta Bellman chimed in that while she was also not responsible for those results, it has been discussed among the red knot representatives that the aerial flights in 2021 were done on May 23rd and 27th, while Jim's analysis indicated that peak arrival occurred on May 21st. So therefore, it might be a survey timing issue.

3. **Review Results of ARM Model Run (Conor McGowan)**

Conor reviewed the ARM model structure and annual process for the committees. He used the horseshoe crab and red knot abundance indices in the optimization matrix of the ARM model and determined that the harvest recommendation is harvest package 3, or 500,00 male-only harvest. He noted that both red knots and female horseshoe crabs are still below their population thresholds.

4. **Review of Supplementary Surveys for Horseshoe Crabs and Red Knots**
    a. **NJ Ocean Trawl Survey (Lindy Barry)**

Lindy reminded the groups that the NJ Ocean Trawl has not run since January, 2020, due to COVID restrictions. NJ is hoping to restart sampling in October of this year, but the pandemic and vessel issues have continued to delay the survey. John asked if the NJ Ocean Trawl samplers were still planning on staging horseshoe crabs. Lindy indicated that they began staging the crabs in 2019 and still plan on doing that to support future modeling efforts. John also asked how missing years of data might affect the results of the catch multiple survey analysis (CMSA). Kristen said that the CMSA can handle missing years of data, as it does for the missing years of the Virginia Tech Trawl Survey. While it isn't ideal to have missing years of data that is one reason the model includes three surveys of relative abundance now. Additionally, the upcoming Revision to the ARM Framework did a sensitivity run that excluded the NJ Ocean Trawl altogether which indicated fairly consistent results to the run with its inclusion.

Last year, Lindy showed the indices of relative abundance for horseshoe crabs from the New Jersey Ocean Trawl Survey. Since 2010, there has been an increasing trend through the terminal year of 2019.

   b. **DE Bay 30 ft. Trawl Survey and Spawning Survey (Jordy Zimmerman)**

Jordy reviewed the DE Bay 30ft and 15ft Trawl Survey methods and sampling routine for horseshoe crabs. He noted that April and May sampling was missed in 2020 due to COVID restrictions on fieldwork. The calculated abundance indices from these surveys indicated a decline in adult and an increase in juvenile horseshoe crabs, but both were near their time series average.

The spawning survey is used by the ARM for providing a sex ratio of males to females on the spawning beaches. Jordy noted that sampling was reduced in 2020 due to COVID restrictions. The sex ratio in 2020 was 5.65 male horseshoe crabs to every 1 female, which indicated that there should be enough males to females for spawning. In 2021, high spawning densities were observed in the first half of May but two minor storms caused the sampling to be cancelled and reduced counts on most beaches.

c. Shorebird survey (Mandy Dey)

Mandy was not on the call, so Henrietta Bellman offered to give a summary of red knot sampling that she has been involved in, some of which was with Mandy and Larry Niles. Henrietta said that there was a lower sampling effort this year due to COVID restrictions. The NJ estimates were similar to prior years according to Larry on a separate call she had with him and other red knot representatives. Henrietta said the DE estimates were lower than previous years and she spoke to Mandy about possible explanations which ranged from fewer birds to the effects of decreased sampling. Overall, DE recorded approximately 700 unique red knot flags which is about half of what they report when they have a larger team.

Henrietta said the field team reported that there was increased horseshoe crab spawning activity in early May when compared to last year and that may be due to the increased temperatures. The field team also noted increased peregrine falcon activity this season which causes disturbances to the red knot feeding behavior. She showed a figure of red knot capture weights through the sampling season, which showed an increasing trend although not all birds appeared to reach the 180 grams. The ARM had a good discussion about the importance of the 180 g threshold, a value the ARM uses to indicate sufficient weight gain during stopover, and its effect on survival. Conor said he cannot say if the threshold has held up with increased data collection, but he noted that Anna Tucker's dissertation did find that most years the birds were hitting 180 g on average, which means about half are not getting to 180 g. Perhaps the severity of not hitting the 180 g is not as serious as previously thought and it is a research question worth pursuing. Wendy recalled that Conor's previous work (McGowan 2011) found that there was a small difference in survival for birds that did not reach 180 g, but on the scale of a 2-5% decrease which was less severe than what was proposed by Baker et al. (2004). While not reaching the 180 g weight might not be as severe as once thought, a small decrease in survivorship could matter over time.

5. Board Recommendation

The ARM Subcommittee and DBETC recommend harvest package 3, or 500,000 male-only harvest, for the Delaware Bay states for 2022.

6. Other Business

The Revision to the ARM Framework is complete and the ARM subcommittee and DBETC will be reviewing that work in the coming weeks to approve it for peer review. Upcoming meetings and webinar details are posted on the Commission website calendar: http://www.asmfc.org/calendar/10/2021.

Steve Doctor asked about the Virginia Tech Trawl Survey estimates for primiparous and multiparous, noting that one cannot track the stages with these values. He wondered if a stage based model was appropriate. In his experience with tanner crab and Maine shrimp, one can see the intermediate stage going to the adult stage but that does not seem to be the case for horseshoe crab. Many agreed that this was a good question and something that has been considered through previous ARM model efforts and the benchmark assessment. Conor said that from the ARM modeling perspective, both juvenile crabs and birds are treated as unobservable variables but that there is a strong assumption that the surveys are not capturing all of them. Kristen also noted that the CMSA was tested with simulated data as part of the 2019 assessment, as was a surplus production model. The CMSA performed well whereas the surplus production model did not. John reiterated that primiparous represents one age-class and multiparous represents several age-classes so it sometimes appears a little mismatched at times.

Red Knot Stopover Population Size and Migration Ecology at Delaware Bay, USA, 2021 [1]

A report submitted to the Adaptive Resource Management Subcommittee and Delaware Bay Ecosystem Technical Committee of the Atlantic States Marine Fisheries Commission

22 September 2021

J. E. Lyons
U.S. Geological Survey
Eastern Ecological Science Center at the Patuxent Research Refuge, Laurel, MD
jelyons@usgs.gov

Abstract

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 Division of Fish and Wildlife), Amanda Dey (New Jersey Division of Fish and Wildlife), Lena Usyk (bandedbirds.org), and numerous volunteers in Delaware and New Jersey for data entry and data management. We are grateful to David Kazyak and William Link for helpful peer-review as part of U.S. Geological Survey Fundamental Science Practices. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1] Suggested citation: Lyons, J.E. 2021. Red Knot stopover population size and migration ecology at Delaware Bay, USA, 2021. Atlantic States Marine Fisheries Commission, Arlington, VA. Available at: http://www.asmfc.org/species/horseshoe-crab. bioRxiv doi:

2 Background

Red Knots (*Calidris canutus rufa*) stop at Delaware Bay during northward migration to feed on eggs of horseshoe crabs (*Limulus polyphemus*). The northward migration of *C. c. rufa* coincides with the spawning of horseshoe crabs whose eggs are the perfect food for a migrating Red Knot (Karpanty et al. 2006, Haramis et al. 2007). Horseshoe crabs are therefore an important food resource for Red Knots as well as other shorebirds at Delaware Bay.

Horseshoe crabs have been harvested since at least 1990 for use as bait in American eel (*Anguilla rostrata*) and whelk (*Busycon*) fisheries (Kreamer and Michels 2009). In the late 1990s and early 2000s the number of Red Knots found at Delaware Bay declined dramatically from ~50,000 to ~13,000 (Niles et al. 2008). At the same time the number of horseshoe crabs harvested also declined and avian conservation biologists hypothesized that unregulated harvest of horseshoe crabs from Delaware Bay in the 1990s prevented sufficient refueling during stopover for successful migration to the breeding grounds, nesting, and survival for the remainder of the annual cycle (McGowan et al. 2011).

The harvest of horseshoe crabs in the Delaware Bay region has been managed by the Atlantic States Marine Fisheries Commission (ASMFC) since 2012 using an Adaptive Resource Management (ARM) framework (McGowan et al. 2015b). The ARM framework was designed to constrain the harvest so that number of spawning crabs would not limit the number of Red Knots stopping at Delaware Bay during migration. This management framework to achieve multiple objectives requires an estimate each year of both the crab population and the Red Knot stopover population size to inform harvest recommendations (McGowan et al. 2015a). We have estimated the stopover population size using mark-resight data on individually-marked birds and a Jolly-Seber model for open populations since 2011.

3 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 in 2021 according to the methods for mark-resight investigations of Red Knots at Delaware Bay (Lyons 2016). This protocol has been used at Delaware Bay since 2011.

Surveys to locate leg-flagged birds were conducted on each beach in 2021, every three days in May and June 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 are not available for validation purposes in bandedbirds.org; therefore, all resightings of orange engraved flags were included in the analysis without validation using banding data. We also omitted resightings of 12 flagged individuals in 2021 whose flag codes were previously accidentally deployed in both New Jersey and South Carolina (Amanda Dey, New Jersey Division of Fish and Wildlife, pers. comm., 31 May 2017) because it is not possible to confirm individual identity in this case. Section 4 "Summary of Mark-resight and Count Data Collected in 2021" describes additional quality control procedures and the potential for other types of errors in the mark-resight dataset.

While searching for birds marked with engraved leg flags, observers also periodically used a scan sampling technique to count marked and unmarked birds in randomly selected portions of Red Knot flocks (Lyons 2016).

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

In our analyses for Delaware Bay, the days of the migration season were aggregated into 3-day sampling periods (a total of 10 sample periods possible each season, Table 1). Data were aggregated to 3-day periods because this is the amount of time necessary to complete mark-resight surveys on all beaches in the study (a summary of the mark-resight data from 2021 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.

4 Summary of Mark-resight and Count Data Collected in 2021

Mark-resight encounter data.—The 2021 Red Knot mark-resight dataset included a total of 1,591 individual birds that were recorded at least one during mark-resight surveys at Delaware Bay in 2021; these birds were originally captured and banded with leg flags in five different countries (Table 2). This total is remarkably close to the 2020 total detected at Delaware Bay: 1,587 individual birds were recorded in 2020 (Table 2).

Approximately the same number of flagged Red Knots were detected at Delaware Bay 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 individuals resighted within a season 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 2021 but were not in fact present at Delaware Bay in 2021. It is not possible to identify this second type of false positive with banding data validation or other quality assurance/quality control methods.

Marked-ratio data.—In 2021, 564 marked ratio scan samples were collected: 297 and 267 samples 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).

5 Summary of 2021 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 at Delaware Bay during sampling period i is present at sampling period $i+1$. In 2021, 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%]).

6 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 (33,627 – 49,966), and slightly lower than the 2018-2019 estimates (Table 4).

Like 2020, the 2021 population 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).

7 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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table 1. Dates for mark-resight survey periods (3-day sampling occasions) at Delaware Bay. Survey period 10 was not used in 2021 because the mark-resight data were sparse in this period.

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

Table 2. Number of Red Knot (*C. c. rufa*) 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, Endangered and Nongame 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 birds) 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. Red Knot stopover (passage) population estimate using mark-resight methods compared to peak-count index using aerial- or ground-survey methods at Delaware Bay. 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

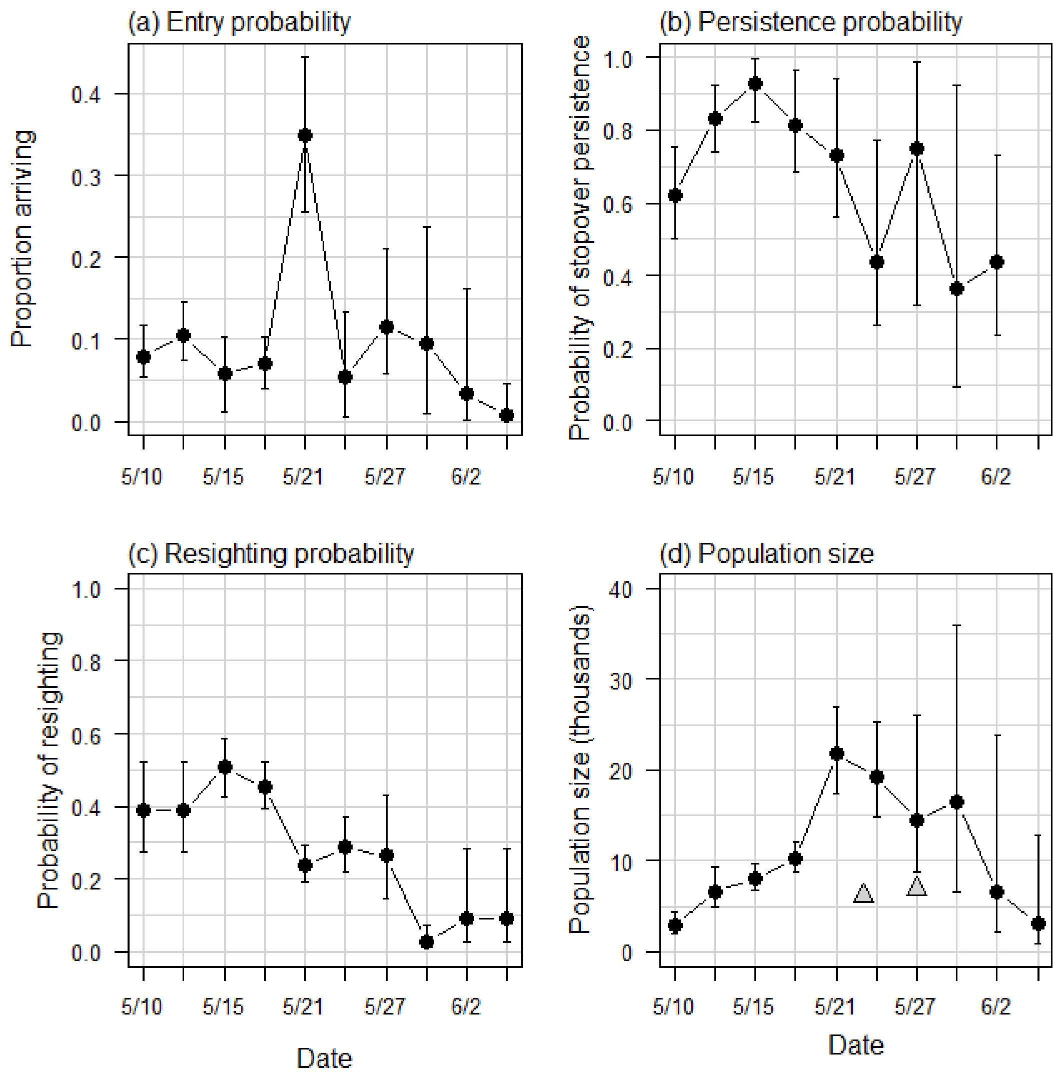

Figure 1. Estimated Jolly-Seber (JS) model parameters from a mark-resight study of Red Knots at Delaware Bay in 2021: (a) proportion of stopover population arriving at Delaware Bay, (b) stopover persistence, (c) probability of resighting, and (d) time-specific stopover population size. Dates on the x-axis 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.

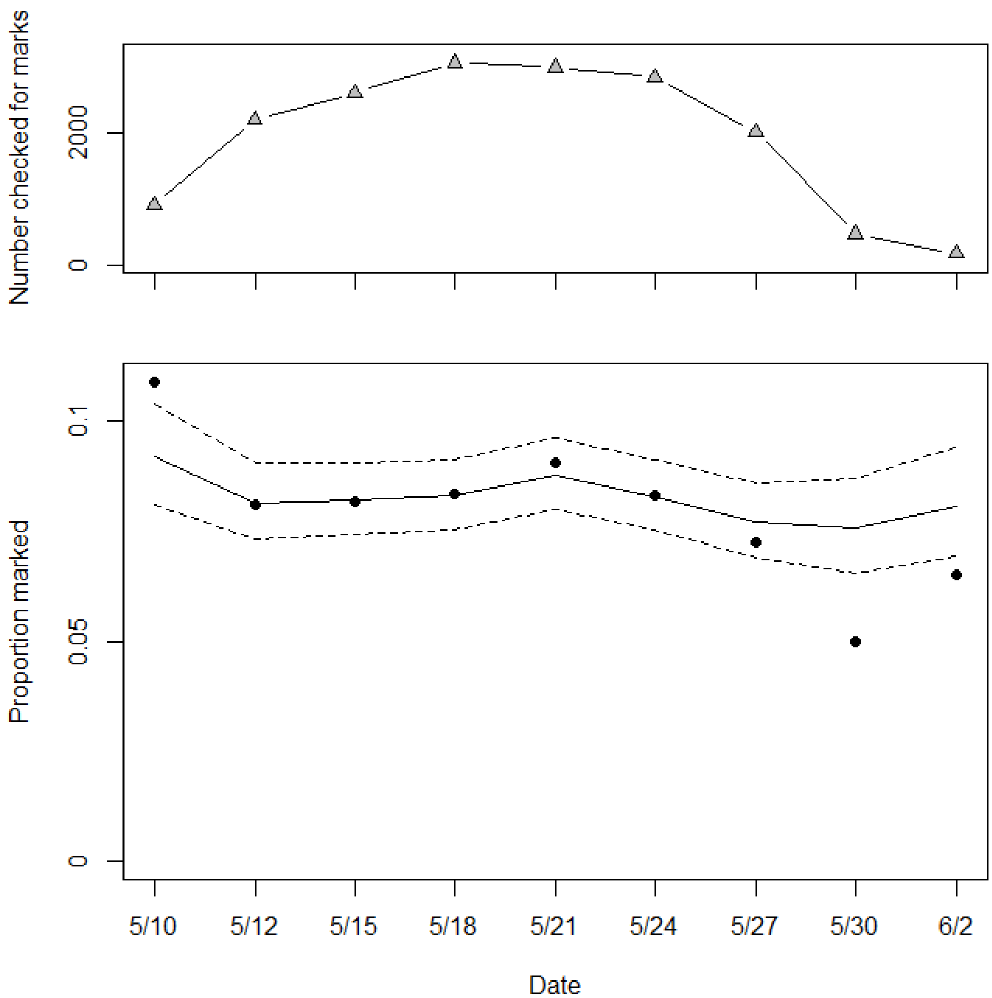

Figure 2. Estimated proportion of the Delaware Bay stopover population carrying leg flags in 2021. The marked proportion was estimated from marked-ratio scan samples for each 3-day sampling period. The dates for the sampling periods are shown in Table 1. The upper panel shows the sample size (number 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 Appendix 1.

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

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

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

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

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

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

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

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

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.

Appendix 3. Number of marked-ratio scan samples.

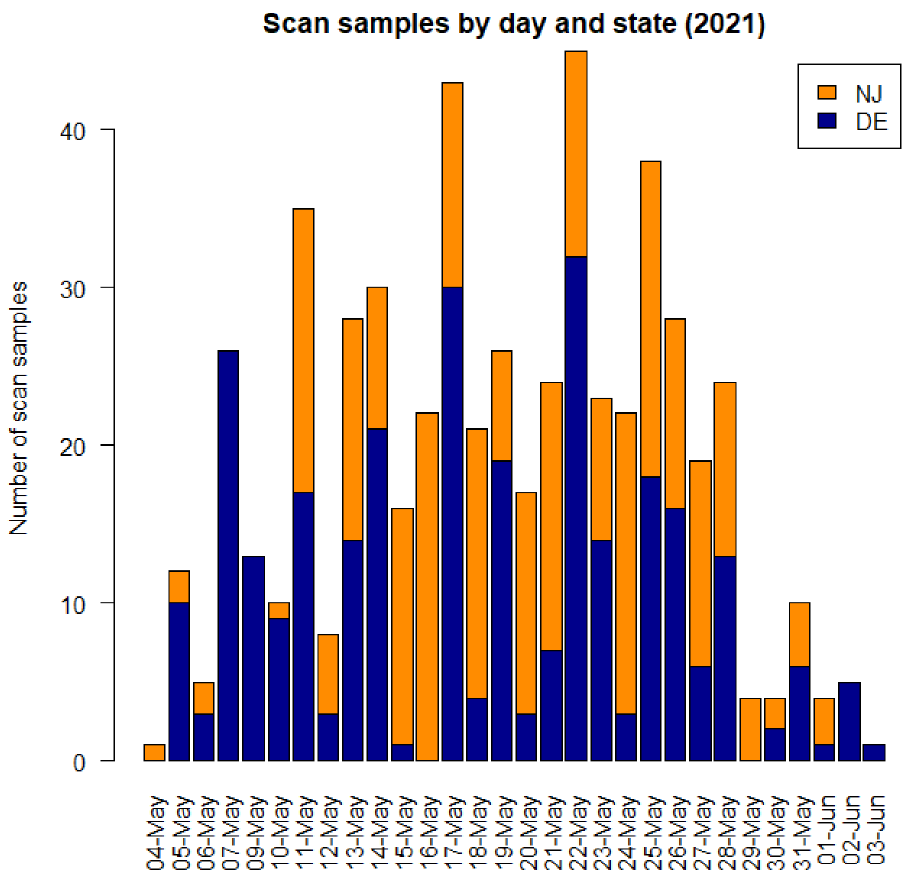

Figure A3.1. Number of marked-ratio scan samples (n = 564) collected in Delaware Bay in 2021 by field crews in Delaware (blue) and New Jersey (orange) and date. In 2021, observers in Delaware and New Jersey collected 297 and 267 scan samples, respectively.

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

31 August 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. 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

Delaware Bay area

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 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 mature crabs occurred 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.
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.

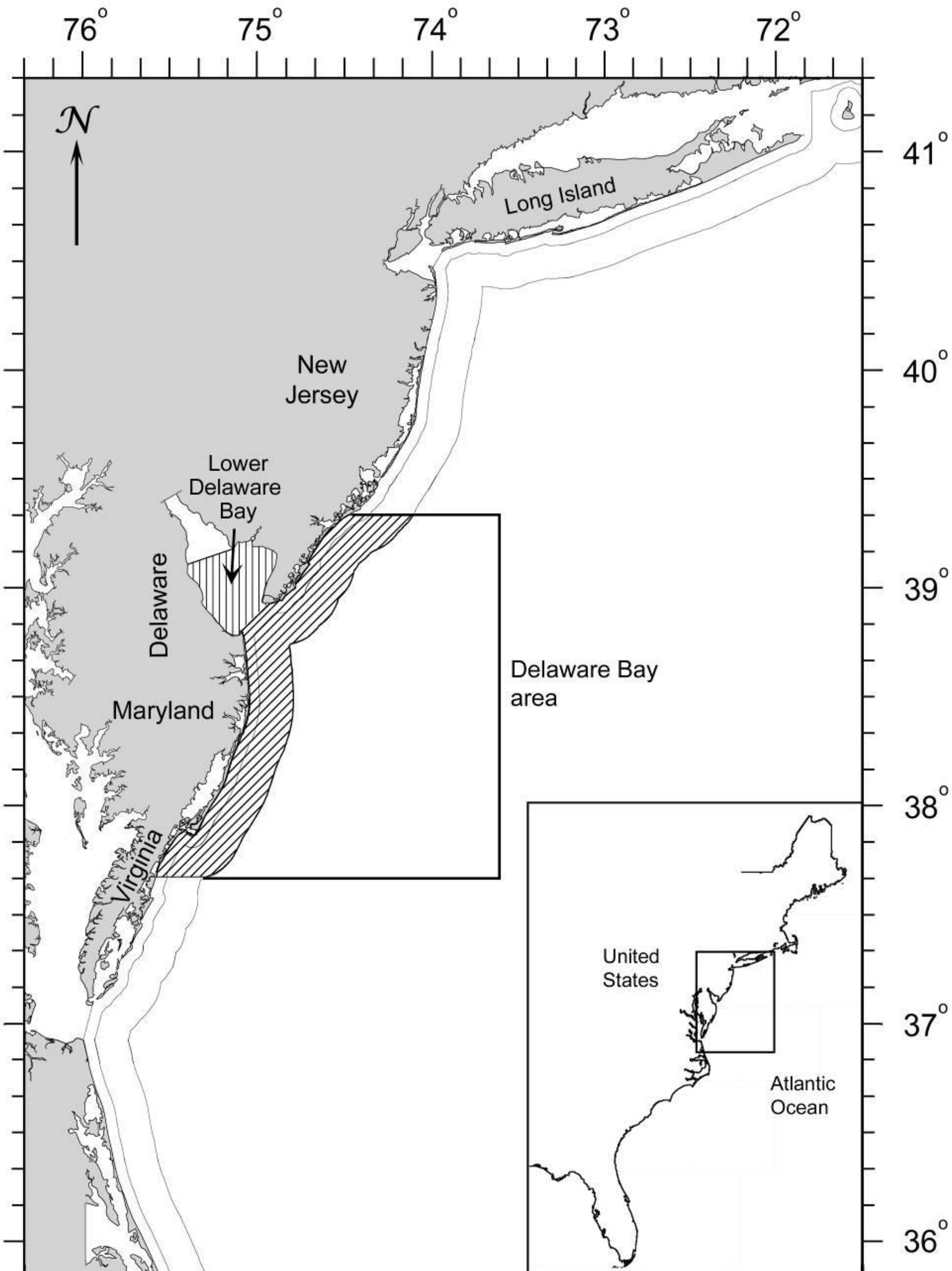

Figure 1. Fall 2020 horseshoe crab trawl survey sampling area. The coastal Delaware Bay area (DBA) and Lower Delaware Bay (LDB) survey areas are indicated. Mean catches among years were compared using stations within the shaded portions of the survey areas.

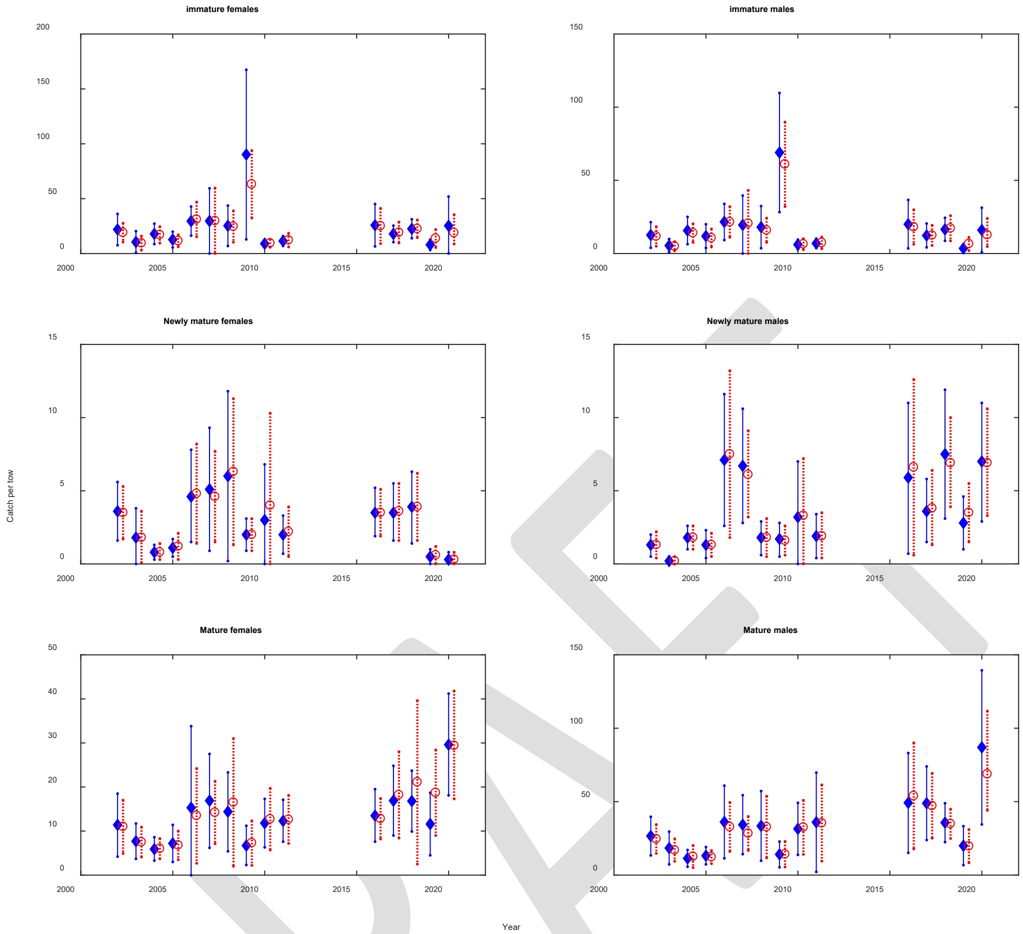

Figure 2. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the coastal **Delaware Bay area** survey by demographic group. Vertical lines indicate 95% confidence limits. Solid symbols and lines indicate the **delta distribution** model. Open symbols and dashed lines indicate the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

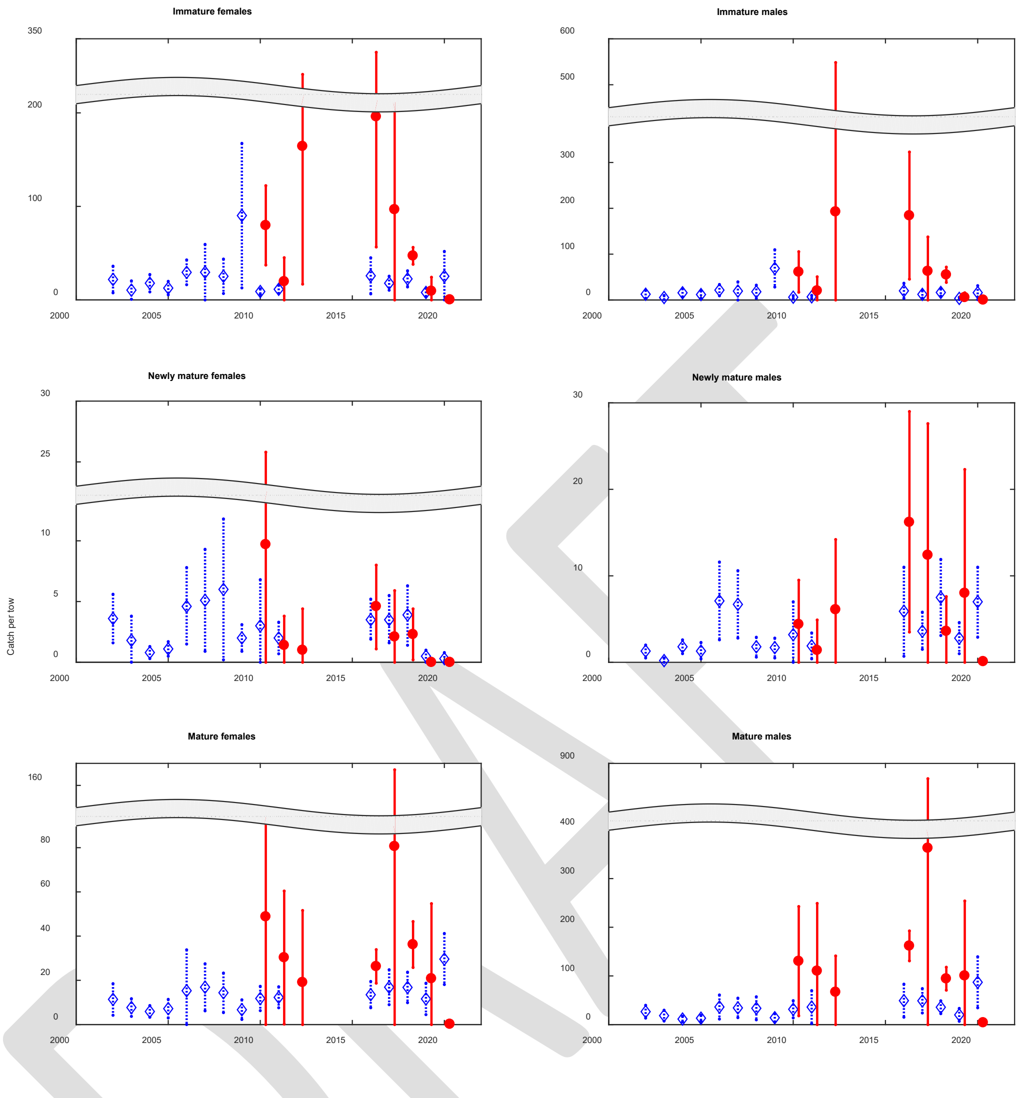

Figure 3. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the **lower Delaware Bay** survey by demographic group, with coastal **Delaware Bay area** survey means for comparison. Vertical lines indicate 95% confidence limits. Only the **delta distribution** model means are presented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

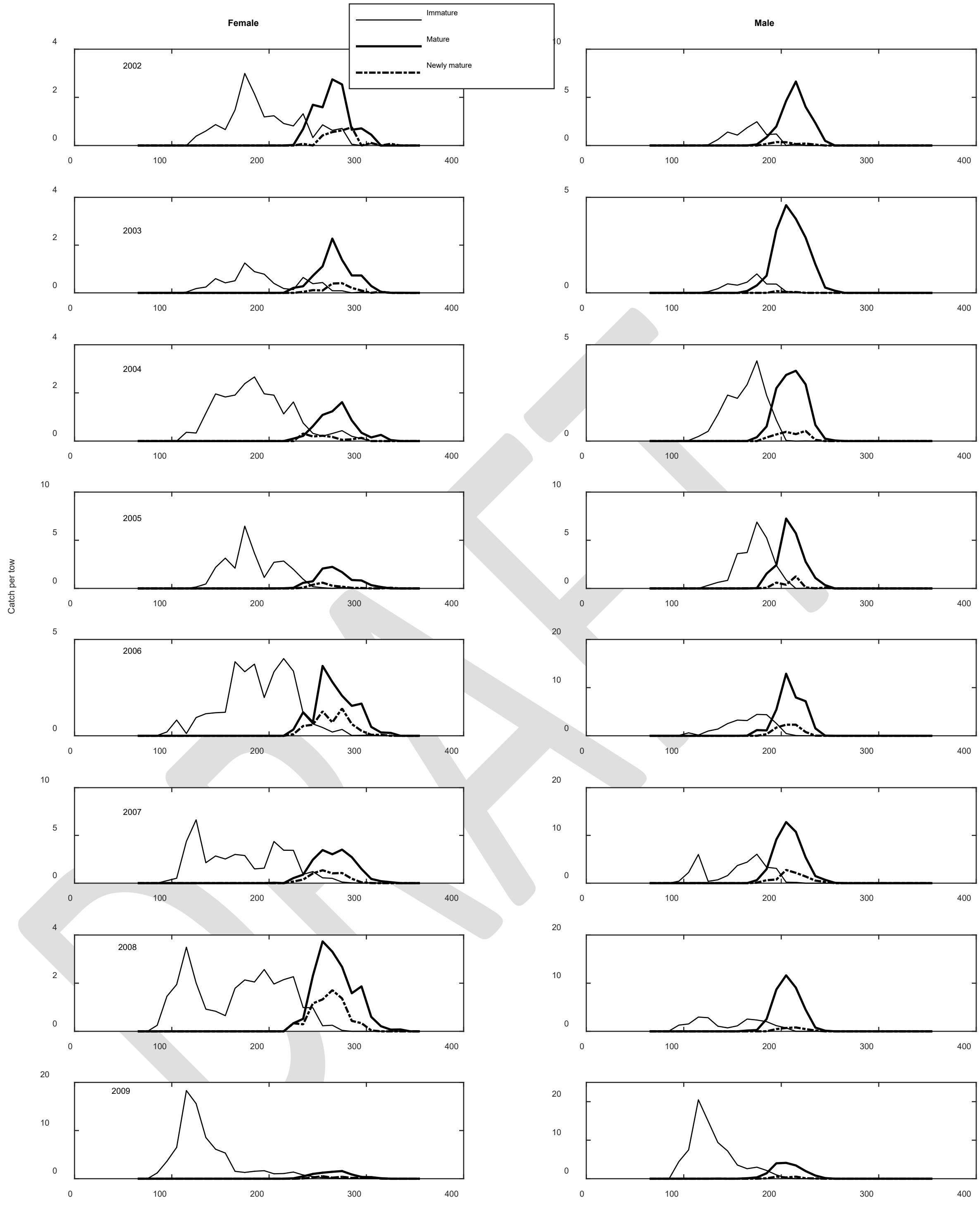

Figure 4. Relative size-frequency distributions of horseshoe crabs, by demographic group and year, in the coastal **Delaware Bay area** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 1.

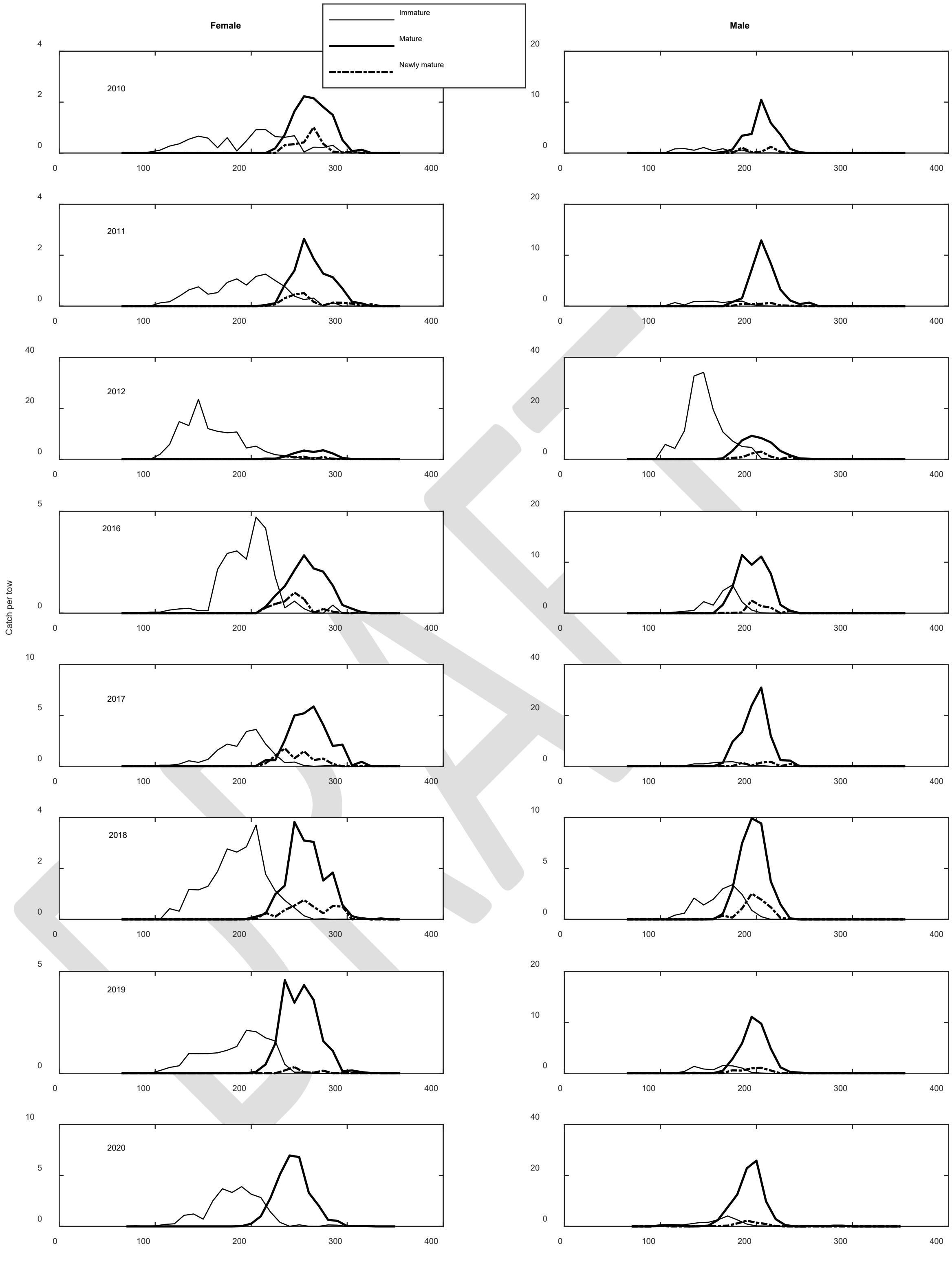

Figure 4. (continued).

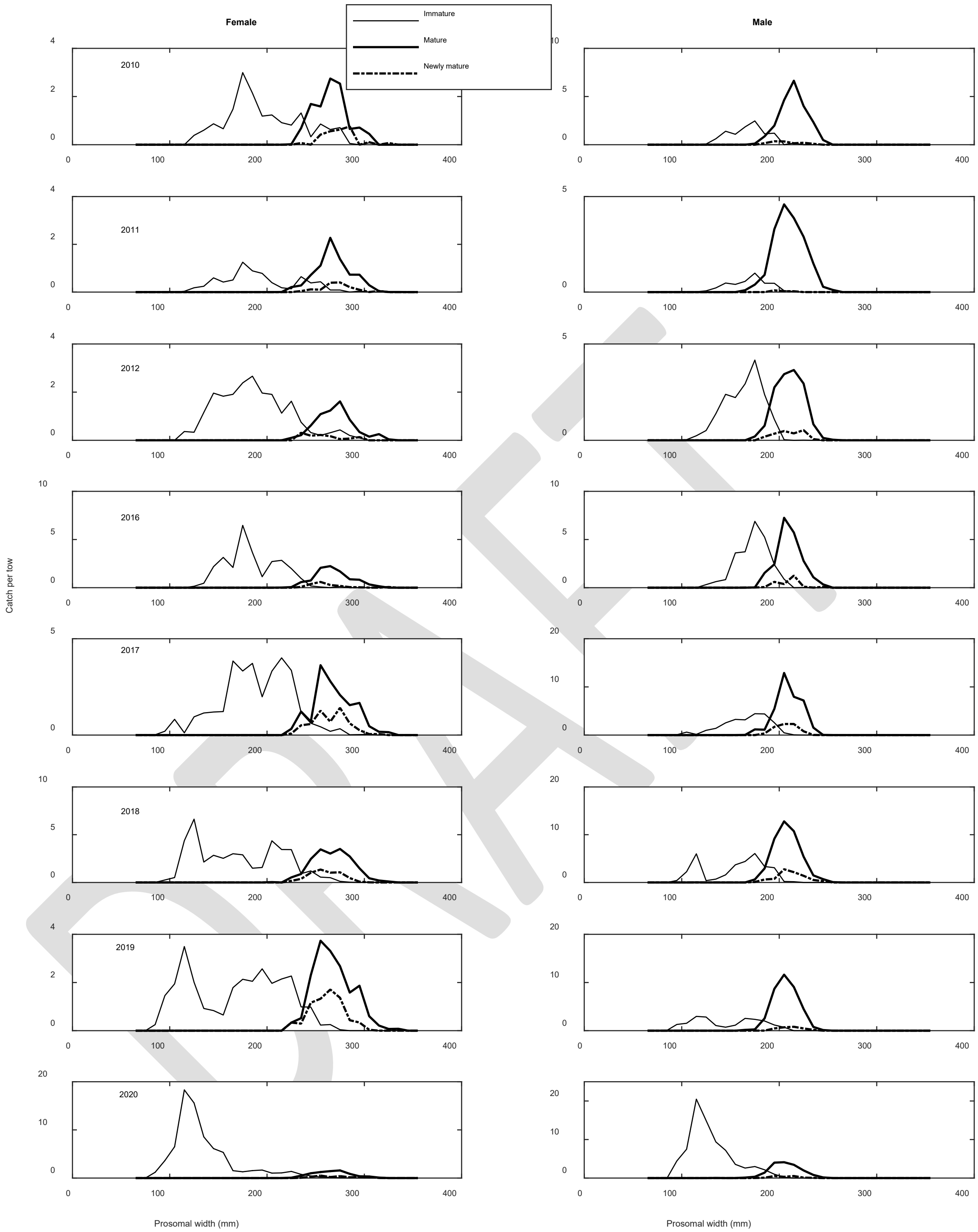

Figure 5. Relative size-frequency distributions of horseshoe crabs, by demographic group and year, in the **lower Delaware Bay** trawl survey. Relative frequencies are scaled to represent stratified mean catches in Table 3.

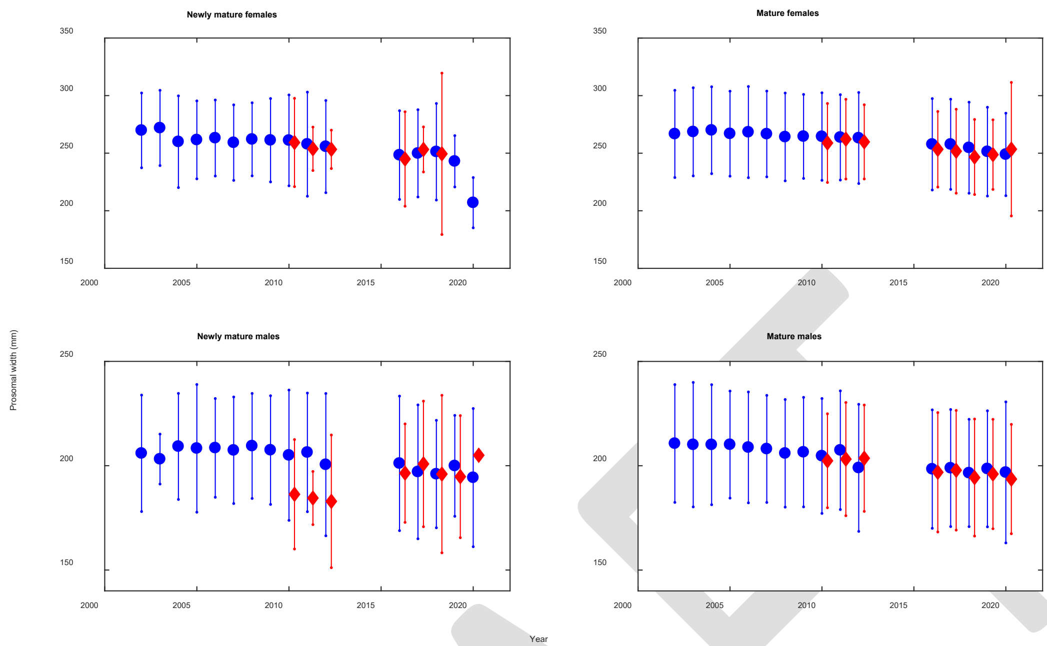

Figure 6. Mean prosomal widths (mm) (± 2 standard deviations) of mature and newly mature female and male horseshoe crabs in the Delaware Bay area (blue symbols and lines) and lower Delaware Bay (red symbols and lines) surveys.

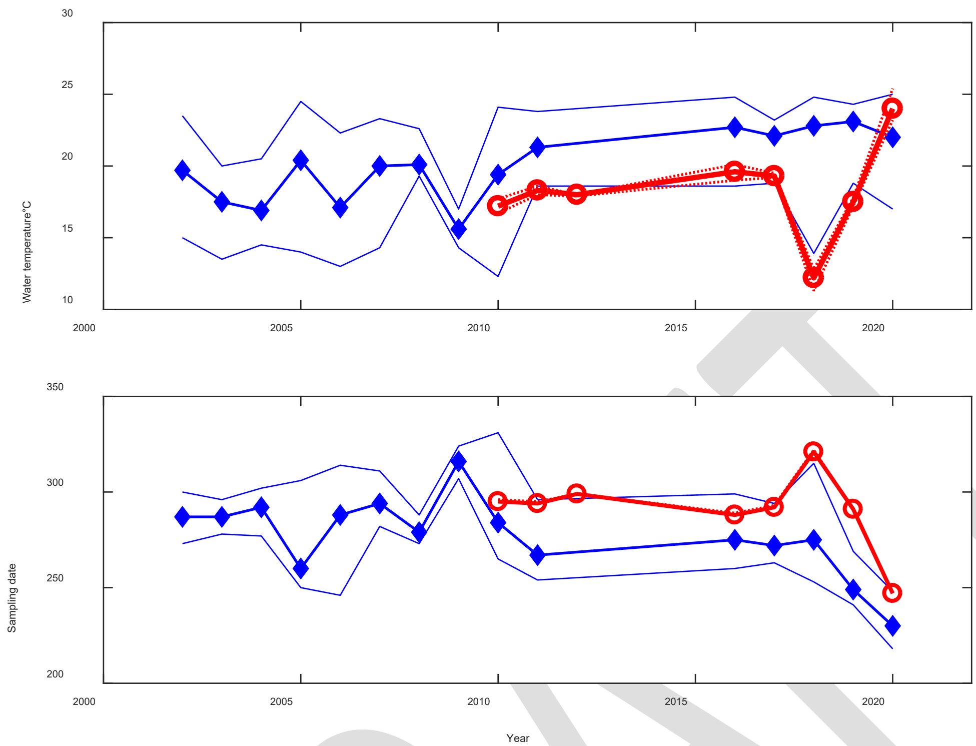

Figure 7. Plots of bottom water temperatures and ordinal sampling dates (days since 1 January) in the coastal Delaware Bay area and lower Delaware Bay trawl surveys. Solid symbols and blue lines indicate coastal Delaware Bay area. Open symbols and red lines indicate lower Delaware Bay. Points indicate 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