U.S. Fish and Wildlife Service Evaluation of the Atlantic States Marine Fisheries Commission Horseshoe Crab/Red Knot Adaptive Resource Management Revision

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Contact: eric_schrading@fws.gov

Background

Since 2012, Atlantic States Marine Fisheries Commission (ASMFC) harvest management of horseshoe crabs in the Delaware Bay region has been guided by the Adaptive Resource Management (ARM) framework. Red knots depend on the eggs of spawning horseshoe crabs as a food resource to sustain migration to breeding grounds in the arctic. The ARM framework uses linked population dynamics models of horseshoe crabs and red knots to make annual harvest recommendations for horseshoe crabs by the bait industry such that harvest does not limit the potential population growth of red knots.

The collection of a decade more of data on both species and advances in adaptive management expertise and techniques spurred the revision of the ARM framework following the 2019 horseshoe crab coast wide benchmark stock assessment. This revision of the ARM framework was peer reviewed and endorsed in November 2021 by an outside panel of scientists representing expertise in horseshoe cab and shorebird biology, fisheries stock assessment modeling, and adaptive management modeling.

The ARM Revision represents several advantages over the previous ARM framework, including:

- Population dynamics models for both species were originally based on theoretical models parameterized with life history information obtained from the literature, many of which were from other species or from areas outside the Delaware Bay. The ARM Revision now uses models based on empirical data specific to the Delaware Bay for both species. There is no longer an artificial construct of horseshoe crab abundance influencing the weight class of red knots with different weight classes having different survival values. Population level survival is now directly predicted by the abundance of horseshoe crabs.
- The revised population models are structured such that routine annual monitoring data can be used to update the models without the need for additional novel research.
- The previous ARM Framework only had five discrete harvest packages to choose from, which would likely lead to an "all or nothing" management system. Recommended harvest tended to include either no female harvest or harvest at the maximum allowable level. Intermediate harvest packages would likely never be selected. The ARM Revision allows for continuous ranges of harvest with a more gradual increase in harvest as populations of both species increase.
- The previous ARM model was coded in software that is now antiquated, not supported, and cannot run on contemporary computer operating systems. The ARM Revision is

coded in the program R which is readily available and runs much faster than the previous version.

Models

The previous population model for horseshoe crabs was based on a theoretical model parameterized with life history parameters obtained from the literature, many of which were not specific to Delaware Bay. The revised horseshoe crab model is based on a Catch Multiple Survey Analysis (CMSA) model specific to Delaware Bay. This model uses data from three fishery-independent surveys of horseshoe crabs combined with estimates of removals of horseshoe crabs (bait landings, biomedically-bled crabs, and dead discards in other fisheries) to estimate the abundance of horseshoe crabs. The model can be projected into the future to make predictions of future horseshoe crab abundance under various harvest scenarios.

The previous red knot population dynamics model was also largely based on literature derived life history parameters and expert opinion. The revised red knot model is based on an integrated population model (IPM) which uses Delaware Bay-specific mark-recapture data and annual red knot count data to estimate red knot survival and recruitment. The model also includes covariates such as the abundance of female horseshoe crabs and arctic snow cover data to determine the influence of these factors on red knot survival and recruitment. The IPM model can also be projected into the future to make predictions of red knot abundance as influenced by the abundance of female horseshoe crabs.

These population models are combined in an optimization routine to determine a harvest policy that maximizes the reward from both species. The optimization routine in the previous ARM framework placed value only on horseshoe crab harvest constrained by red knot abundance and the abundance of female horseshoe crabs. This resulted in “all or nothing” harvest of female crabs depending on female crab abundance. The revised optimization routine places value on both allowable harvest of horseshoe crabs and the abundance of red knots in the reward function. The reward function is formulated in such a way that no single species can contribute solely to the total reward and the reward reaches its greatest value in a situation in which the maximum allowable harvest of horseshoe crab is attained (210,000 females and 500,00 males) and red knots are at high abundance (>81,900). The optimization routine determines a harvest policy that is most likely to move the state of horseshoe crab and red knot abundance to the ideal situation of high harvest and high red knot abundance (i.e., the greatest reward).

Model Outputs

The ARM Revision produces a harvest policy that is optimized to reflect the values that are incorporated into the reward function (Figure 1). This policy specifies a harvest level of male and female horseshoe crabs given the current abundance of male and female crabs and red knots. As abundance of crabs or birds increases, recommended harvest can increase. If crabs or birds decrease in abundance, recommended harvest decreases. Thus, year-to-year harvest is not static, but is adaptive to changes in the population size of both species.

The ARM Revision also produces long-term projections of abundance for both species with associated uncertainty (Figures 2 & 3).

Risk to Red Knot Recovery

The underlying IPM model for red knot population dynamics demonstrated the linkage between horseshoe crabs and red knots with a small but significant positive relationship between female horseshoe crab abundance and red knot survival. However, the IPM also showed the abundance of female horseshoe crabs did not influence recruitment of red knots over the time period in which data were available.

Although red knot survival is influenced by the abundance of female horseshoe crabs, the harvest of female horseshoe crabs within the optimal harvest policy poses negligible risk to red knot recovery and negligible risk of take under the Endangered Species Act.

- There is much uncertainty in population projections, but red knot abundance is expected to increase under ARM management.
- Population projections of both species under ARM management are very similar to those assuming no directed harvest of male or female crabs by the bait industry (*i.e.*, a complete bait harvest moratorium; Figure 4).
- The probability of having fewer red knots under ARM management relative to a no harvest scenario can be quantified from the uncertainty around the model's current population projections. Consider the 5th percentile of the distribution of a population projection under a no harvest scenario as a baseline for comparison. If ARM management had no effect on red knots, we would expect 5% of the distribution of the population projection under ARM management to be below the baseline. Quantities greater than 5% represent the impact of ARM management. The probability that the population projection under ARM management fell below the 5th percentile baseline from a no harvest scenario was:
    - 5.1% in 10 years
    - 5.3% in 25 years
    - 5.4% in 50 years
    - 5.5% in 100 years
    - Thus, there is a very small probability (<1%) ARM management will result in a lower abundance of red knots.

Because there is much uncertainty in population projections, our confidence in these model outputs relies on frequent updates of model inputs and model functions to reflect both the learning generated by the adaptive management itself as well as other efforts that continue to refine our understanding of these two species and the linkage between them. The ARM Revision is easily updated with routine monitoring data to decrease model uncertainty and adaptable to changing conditions in the future.

Models used to annually assess the abundance of horseshoe crabs and red knot survival are of the same structure used to project the populations in the optimization simulations. These abundance estimates are not only used to make annual harvest decisions, but also provide input for model updating, including updating the probability of having fewer knots under ARM management relative to a no harvest scenario.

Re-running the models and formulating a revised optimal harvest policy can be done regularly (even annually if desired). Frequent model updating was recommended by the peer review panel over the next several years given recent changes in red knot count data.

Although, there was no significant relationship between female horseshoe crab abundance and red knot recruitment, this relationship is retained in the model if additional data begin to show a significant effect. Also, the arctic snow cover covariate did not show a significant effect on red knot survival, but this covariate also remains in the model if such a relationship would emerge with more data. If other environmental covariates that significantly influence red knot survival or recruitment become evident, these can also be easily added. The reward function can be adjusted in future model updates if needed to ensure continued avoidance of take and alternative forms that may better represent red knot recovery criteria can be considered.

The USFWS will continue participation in ASMFC management at multiple levels to ensure the ARM framework is functioning as intended and horseshoe crab harvest is not posing risk of impeding red knot recovery. This includes:

- Representation on the ARM Subcommittee, DE Bay Ecosystem Technical Committee, and Horseshoe Crab Management Board
- Annual review of ARM inputs (horseshoe crab and red knot abundance estimates)
- Review of any model updating with new data as it occurs

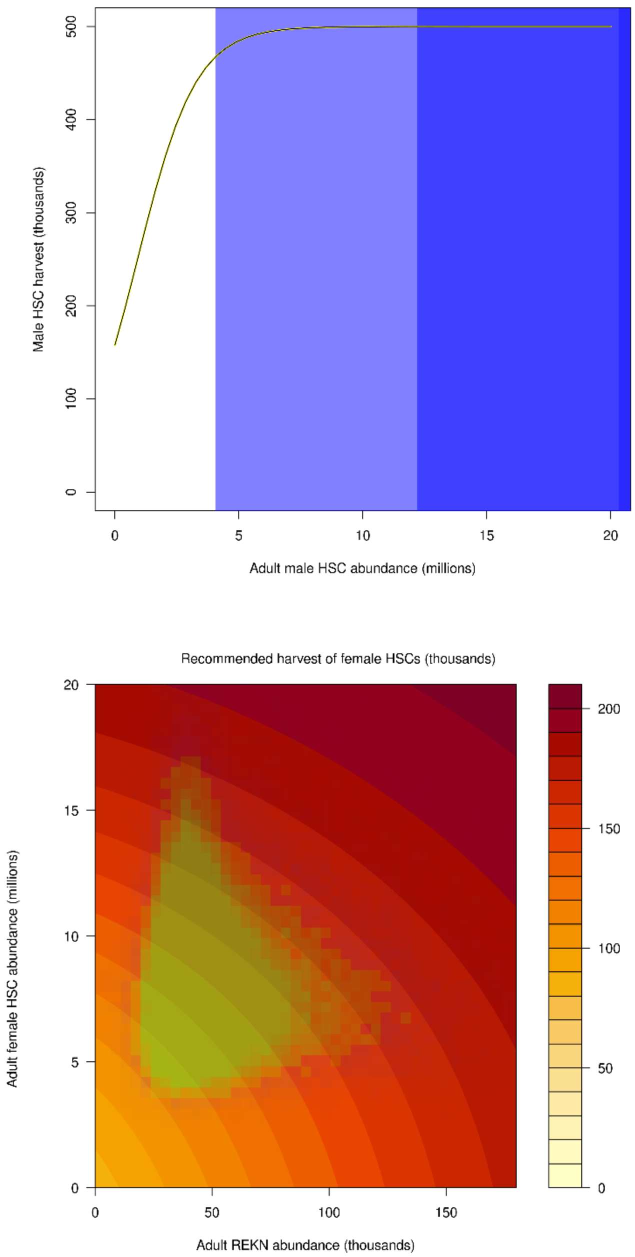

Figure 1. Optimal harvest policy by the ARM Revision. The top figure shows the optimal harvest of male horseshoe crabs as a function of male horseshoe crab abundance. The blue vertical area represents predictions of male horseshoe crab abundance over the next 10 years. The bottom figure shows the optimal harvest of female horseshoe crabs as a function of female horseshoe crab abundance (y-axis) and red knot abundance (x-axis). The green blob of points represents predictions of female horseshoe crab and red knot abundance over the next 10 years.

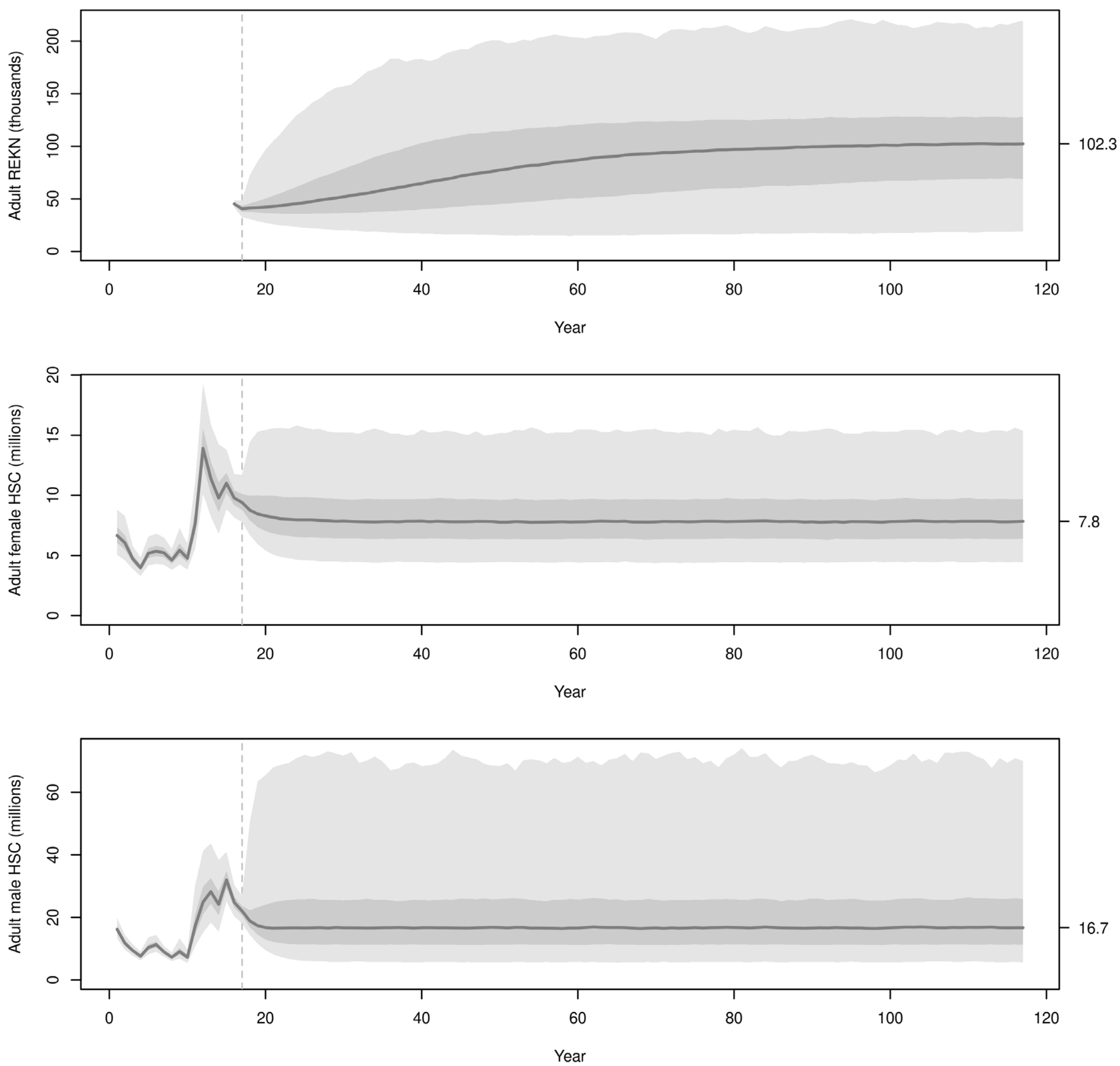

Figure 2. Projections of red knot, female, and male horseshoe crabs from the ARM Revision assuming no directed bait harvest of horseshoe crabs of either sex. These projections do include average levels of removals of horseshoe crabs by the biomedical industry, as well as dead discards from bycatch in other commercial fisheries that are currently not controlled by ASMFC horseshoe crab management. The solid black line represents median projected populations, dark gray area represents 25th and 75th percentiles, and the gray area represents 2.5th and 97.5th percentiles.

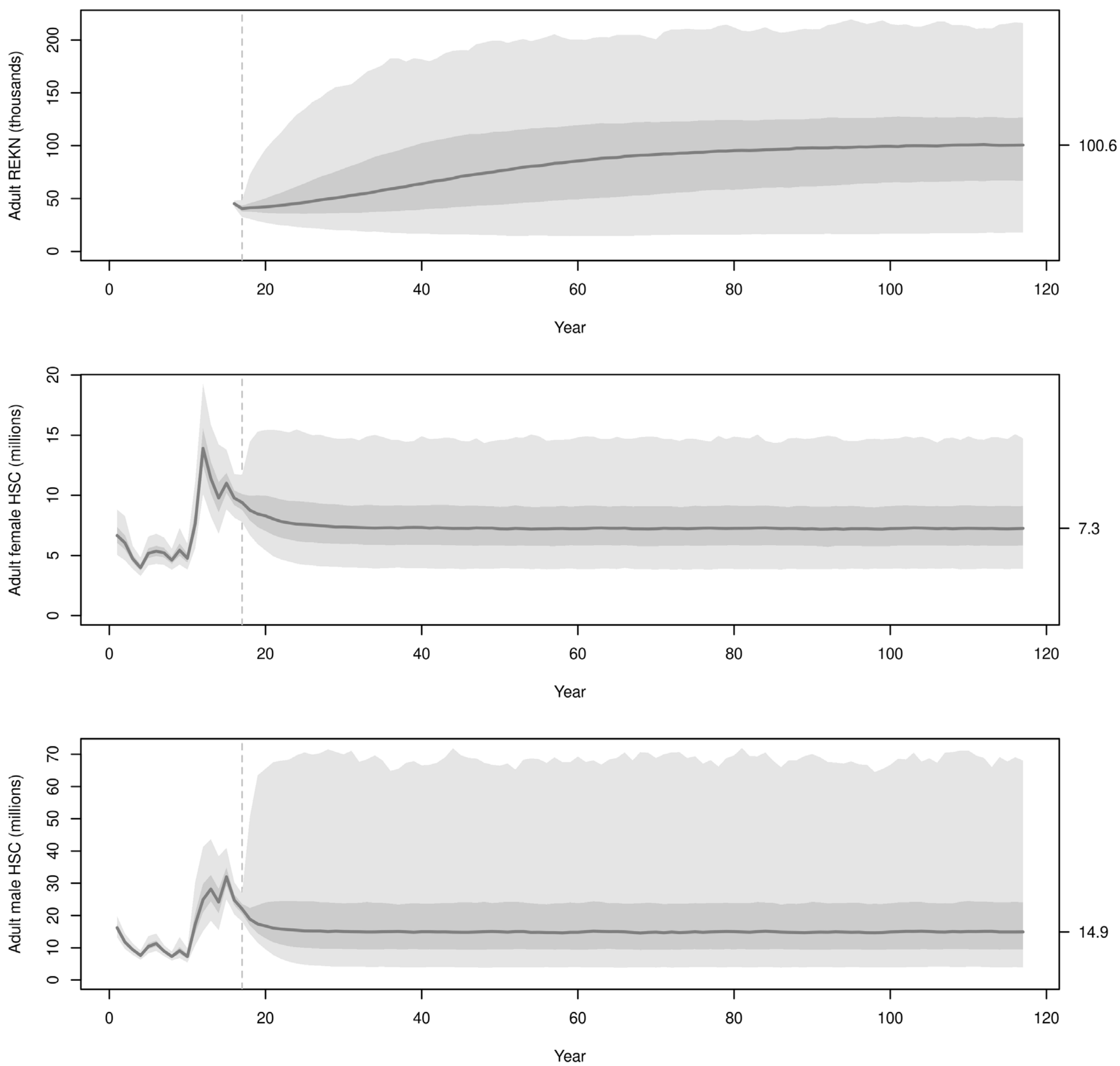

Figure 3. Projections of red knot, female, and male horseshoe crabs from the ARM Revision assuming management using the optimal harvest policy shown in Figure 1. These projections also include average levels of removals of horseshoe crabs by the biomedical industry, as well as dead discards from bycatch in other commercial fisheries that are currently not controlled by ASMFC horseshoe crab management. The solid black line represents median projected populations, dark gray area represents 25^{th} and 75^{th} percentiles, and the gray area represents 2.5^{th} and 97.5^{th} percentiles.

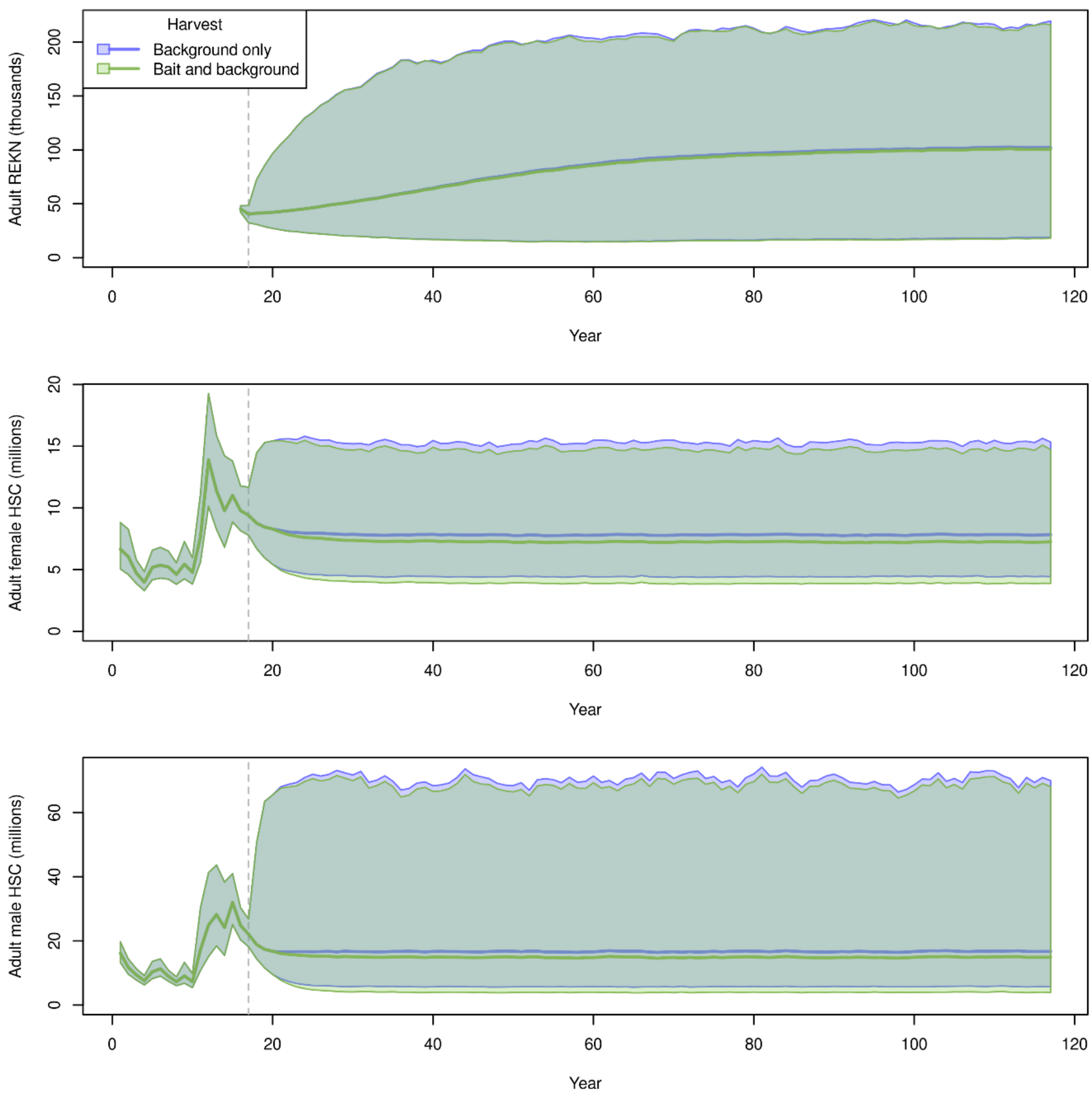

Figure 4. Comparison of the projected populations of red knots, and female and male horseshoe crabs under background harvest only (blue shading) and the optimal ARM harvest policy (green shading) shown in Figure 1. Simulated distributions of red knots are nearly identical indicating negligible effect of ARM harvest on red knot population growth.