The Stock Status of Horseshoe Crabs in Rhode Island 2012

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Introduction-

Horseshoe Crab Biology- The horseshoe crab (*Limulus polyphemus)*, has existed in current form for millions of years (Walls et al. 2002). It is a marine arthropod that utilizes both estuarine and continental shelf habitats. The species is not a true crab but is more closely related to spiders and scorpions, comprising a single taxonomic class (Merostomata). They are ancient descendents of the trilobites (Shuster 1982). The family Limulidae consists of four species of which *polyphemus* is the American species (Walls et al. 2002). The horseshoe crab is considered an opportunistic feeder, consuming a variety of mollusks, polychaetes and vascular plant material. Horseshoe crabs range from Central America through the Gulf of Mexico and along the Atlantic coast to the Gulf of Maine (ASMFC 2009). Delaware Bay is considered the epicenter of crab spawning along the US coast (Botton and Ropes 1987). US populations have undergone a long-term decline from both anthropogenic and climatic influences (Faurby et al. 2010). With warming spring waters, horseshoe crabs move from the deep water of bays and sounds into shallows in preparation for spawning on beaches. High energy areas and beaches prone to strong wave action are avoided. Low energy environments reduce tidal stranding and secure egg deposition. The spawning period generally lasts from March through July in Rhode Island. Peak activity occurs during evening new and full moon high tides in May and June (Smith et al. 2002). The crabs spawn on a variety of bottom types ranging from mud/sandy sediments to rocky/sandy sediments. Spawning adults prefer sandy beach areas within bays and coves that are protected from wave action. The eggs are deposited deeper than 10 centimeters into the sediment to evade predation from long billed shore birds. The crabs become sexually mature in 9 to 11 years and spawn multiple times during the spawning season depositing 3,000 to 4,000 eggs each spawn. Horseshoe crabs have been known to deposit up to 80,000 eggs annually. The species is characterized by high fecundity, high egg and larval mortality and low adult mortality. Eggs hatch within 14 to 30 days. In the northern part of their range, crabs have longevity of about 20 years. (ASMFC 1998, 2009).

The State of Rhode Island began fishery independent data collection and monitoring of the horseshoe crab fishery in 1998. Active cooperation between industry, environmental groups and the Rhode Island Division of Fish and Wildlife (RIDFW) are vital to conserve the horseshoe crab resource for the future and to insure that all user groups participate in management. The horseshoe crab fishery has existed in Rhode Island for many years. Anecdotal harvest reports from participants date back to the 1970's when extensive eel and whelk fisheries existed that used crabs for bait (Olsen and Stevenson 1975). As these fisheries became more profitable and bio-medical uses emerged, landings of horseshoe crabs increased through the 1980's and 1990's. Prior to the late 1990's, little or no data existed on the horseshoe crab fishery in Rhode Island. Until addressed by the Atlantic States Marine Fisheries Commission (ASMFC), abundance records came from private individuals who had an interest is these animals and observed and counted crabs on area beaches (Prentiss Stout- pers. comm.).

The Rhode Island horseshoe crab fishery is prosecuted with a number of harvest methods. Crabs are harvested manually on beaches during their spring spawning period around the new and full moons of May, June and July. Horseshoe crabs are also landed to a lesser extent by otter trawls and floating fish traps. The expansion of effort in the commercial horseshoe crab fishery was driven by bait demand in the American Eel *(Anguilla rostrata)* and whelk *(Busycoptypus canaliculatus)* pot fisheries and more recently, for horseshoe crab blood used by the biomedical industry in the production of Limulus Amoebocyte Lysate (LAL). Under FDA regulation, crabs used in the biomedical industry must be returned to the waters from which they were taken within 72 hours. Soon after adoption of the ASMFC Fishery Management Plan (FMP), pressure mounted from environmental groups and other stakeholders to manage more conservatively (Berkson and Shuster 1999). The red knot (*Calidrus canutus rufa*), a migratory shorebird, depends on horseshoe crab eggs for food energy to power long distance migrations (McGowan et al. 2011a, 2011b). Horseshoe crabs also play an important role for other migrating shorebirds, finfish and sea turtles. Horseshoe crab eggs and larvae are a seasonal food source for a variety of marine animals.

<u>Rhode Island Horseshoe Crab Management 2012</u> **-** In response to the 1998 ASMFC FMP for Horseshoe Crab, the Rhode Island began management of the species in 1999. To comply with the FMP, a number of management measures were implemented. The FMP required a 25% reduction in the harvest of horseshoe crabs for the bait fishery as well as fishery monitoring and reporting requirements. Biological data collection was a priority of the plan which also required regular stock assessments and identification of essential habitats. Prior to this, the fishery was relatively unregulated, with only a commercial shellfish license required for harvest and no means of reporting crab landings. To comply with ASMFC, Rhode Island issued horseshoe crab permits to all harvesters and dealers of horseshoe crabs. The permit required holders to submit monthly landings reports of all crab harvest. Information supplied by harvesters includes reporting period, number of crabs harvested, location of harvest, disposition (i.e. biomedical and or bait) and location of release. The catch reports are processed by the RIDFW.

At the inception of management, the status of horseshoe crab populations along the Atlantic Coast was poorly understood due to the scarcity of information on the stock. With this in mind, the ASMFC horseshoe crab management Board adopted Addendum I to the FMP in 2000. This action addressed the amount of crabs harvested by the bait fishery and the need for better collection of biological and landings data in all sectors of the fishery. In response, Rhode Island began collecting biological data from commercial horseshoe crab fishermen. Data collected included size and sex composition of the harvest. An extensive spawning beach survey was initiated in 2000 during the new and full moons in the months of May, June and July in Narragansett Bay and the south shore coastal salt ponds. With the help of volunteer organizations, RIDFW was able to monitor close to fifty potential horseshoe crab spawning beaches and collected data on beach area coverage, bottom type, numbers of crabs present, spawning activity, presence of shorebird activity and fishing activity. The spawning beach survey has been continued through 2013 with an improved sampling design. A tagging study may be added to estimate fishery exploitation rates. The RIDFW continues to sample horseshoe crabs in the agency trawl survey in Narragansett Bay and coastal waters. Additional ASMFC management actions (Addenda II-VI) have fine tuned management particularly in the critical Delaware Bay area.

The first Rhode Island stock assessment was done in 2001 using surplus production modeling (Gibson and Olszewski 2001). The Rhode Island population was found to be at low abundance and overfished. Uncertainty was high owing to poor landings data but a constant harvest policy of 26 metric tons was recommended to allow for stock rebuilding. On a coast wide basis, improvements in data collection have allowed stock assessments to evolve to a higher level of sophistication (Davis et al. 2006, Sweka 2007, ASMFC 2009a). The ASMFC (2009a) assessment found regional differences with resource declines in New York and New England but increasing abundance in the southeast and Delaware Bay regions. A sophisticated, adaptive resource management (ARM) strategy has been developed and adopted by the ASMFC (ASMFC 2009b). This approach allows for sustainable management of horseshoe crabs subject to ecological constraints imposed by other species needs.

Stock Assessment Methods and Data Sources-

Fishery Data- Landings data for horseshoe crabs are notoriously poor due to the obscure nature of the fishery. Crabs are used as bait in conch and eel fisheries and may be procured directly by fishermen prosecuting those fisheries. Historically, these landings may not have been accounted for by the National Marine Fisheries Service (NMFS) weighout and general canvas landings acquisition system. The NMFS did report significant landings of horseshoe crabs in Rhode Island for years 1987-1989 although it is not known if this was a complete census. Crabs caught and sold to the biomedical industry may not be included in NMFS statistics either. The Rhode Island Division of Fish and Wildlife (RIDFW) permitted all horseshoe crab harvesters in 1999 and have required them to report landings since then. The major biomedical user of crabs from Rhode Island, Associates of Cape Cod (ACC) voluntarily provided records of Rhode Island origin crabs processed since 1985. Total state landings for 1985 to 1998 were estimated by raising the ACC number by the mean ratio of bait to biomedical landings for 1999-2012 from the RIDFW reporting data. This assumes that all crabs used for biomedical purposes were effective mortalities. Although it is required that bled crabs be returned to the water, there is a potential for them to be re-sold as bait or disposed of in waters other than from which they originated. It is also possible that the harvesting process, which interrupts spawning, reduces reproductive success. Assuming 100% mortality in biomedical crabs is a risk-averse approach for assessment. Biological sampling of the commercial catch was begun by RIDFW in 2000. Landings prior to 1985 back to 1959 were estimated as a function of the NMFS reported Atlantic coast total with a fundamental assumption that RI landings followed the same time pattern as coast wide. A ratio estimator using multiplicative deviations from the mean was used:

$$RI_t = RI_x * AC_t/AC_x \qquad (1)$$

where: *RI= Rhode Island landings*
AC= Atlantic coast landings
x= mean 1985 to 2010 landings
t= year.

Several authors report that the coast wide fishery in the 1950's and 1960's was minimal (Botton and Ropes 1987, Walls et al. 2002) but escalated later with development of whelk fisheries and discovery of biomedical uses. This seems to be the case for Rhode Island as well (Olsen and Stevenson 1975).

Abundance Indices- Several abundance indices for horseshoe crabs in Rhode Island waters were available. The RIDFW began counting the species in the agency trawl survey in 1998 in compliance with the developing ASMFC plan. Sixteen years (1998-2013) of bottom trawl indices are available. The survey is a random-stratified design covering Narragansett Bay and the adjacent Rhode Island and Block Island Sounds. Seasonal survey cruises are conducted in April-May and September-October, comprising 42 tows each. A monthly cruise in Narragansett Bay is conducted at 13 fixed stations as well. The University of Rhode Island Graduate School of Oceanography (URIGSO) trawl survey began in 1959 and a weekly record of horseshoe crab abundance is available for the Fox Island and Whale rock stations in the lower west passage of Narragansett Bay though 2012. Normandeau Associates Inc. (NA), a consultant to the owners of Brayton Point Power Station, conducts a fixed station trawl survey each month in Mt. Hope Bay. NA also maintains counts of the number of crabs impinged on the traveling screens at Manchester Street Power Station (MSPS) on the Providence River. NA trawl abundance indices were available for 1972-2012 and impingement records from 1992-2012. Horseshoe crab density (no. per m2) is available from the RIDFW and volunteer beach counts 2000-2013. Catch per unit effort (landings per permit) is available from the RIDFW commercial monitoring program since 2000. Lastly, a Rhode Island citizen counted horseshoe crabs along standard transects in Pt. Judith Pond from 1975 to 2002 and made the long-term data available to RIDFW (Prentiss Stout- pers. comm.).

Collectively, these surveys provide good spatial and temporal coverage of the states marine waters. We also examined abundance indices to the east for the Massachusetts Vineyard Sound area (MADMF 2012) and to the west at Millstone Power Station (DRS 2012) and Long Island Sound (CTDEP 2012). A methodological overview of all surveys is given in ASMFC (2009a).

<u>Surplus Production Estimation of Stock Size and Mortality Rates</u>- A biomass dynamic model (BDM) for the Rhode Island stock was fit to landings and biomass indices for years 1959 to 2013. This approach has been applied to horseshoe crabs before (Gibson and Olszewski 2001, Davis et al. 2006). Sweka et al. (2007) questioned the use of BDM for horseshoe crab on the grounds that the time lag from spawner to recruit is long and that age-structured dynamics are ignored. However, BDM have been successfully applied to long-lived animals with recruitment delays (Punt 1991, Prager et al. 1994, Abaunza et al. 2003, Hammond and Ellis 2005). Problems seem more related to poor or uninformative data and obsolete equilibrium estimation (Hilborn and Walters 1992) than weaknesses inherent in the method (Ludwig et al. 1988). BDMs are a mass balance approach in which stock biomass in a given year is formulated as biomass the year before plus new production minus the catch removed (Hilborn and Walters 1992). New production is the net difference between additions from growth and recruitment and mortality losses. If stock growth is assumed to follow the familiar logistic curve, a Schaeffer biomass model in finite difference form from Walters and Hilborn (1976) is:

$$B_t = (B_{t-1} + r_m B_{t-1}(1-(B_{t-1}/k)) - C_{t-1})\ exp(e_p) \qquad (2)$$

where: B= *population biomass*
C= *catch biomass*
r_m= *intrinsic rate of increase*
k= *unfished population biomass.*
t= *year*
e_p= *lognormal process error term.*

The r_m parameter is a measure of population growth rate at very low abundance when density dependent factors are inoperative. The term in parenthesis in eq. 2 is the density dependent feedback mechanism that reduces stock growth when abundance is high. The discrete time step form of the production model is a simplification over the differential equation that forms the basis of continuous production models. Hilborn and Walters (1992) note that the discrete and differential forms of the model are essentially equivalent except for extreme values of r_m and fishing mortality (F). Useful management quantities for sustainable fisheries can be derived from the logistic model parameters as follows:

$MSY = r_m k/4$
$F_{msy} = r_m/2$
$B_{msy} = k/2.$
$F_{coll} = r_m.$

Maximum sustainable yield (MSY) is the maximum yield that a stock can deliver year after year over the long term. It is a function of both carrying capacity and stock productivity. In order to produce MSY, a stock needs to be at a biomass level equal to one-half carrying capacity (B_{msy}) and be subject to a fishery removal rate no greater than F_{msy}. The latter is equal to one-half the intrinsic rate of stock growth. A fishing mortality rate that approaches the intrinsic rate will lead to stock collapse (F_{coll}).

Since the actual biomass levels in eq.2 are not known, an observation model is needed in the form of research survey catch per unit effort:

$$U_t = q(B_t)\ exp(e_m) \qquad (3)$$

where: *B= biomass*
U= survey relative abundance
q= catchability coefficient
t= year
e_m= lognormal measurement error.

The q parameter is a scaler that relates survey relative abundance to absolute stock abundance. Substitution of eq.3 into eq.2 and combining error terms gives the final biomass dynamic model for the Rhode Island stock:

$$U_t = (U_{t-1} + r_m U_{t-1}(1 - U_{t-1}/kq) - q(C_{t-1}))\ exp(e) \qquad (4)$$

Parameters in eq. 4 (r,k,q) can be estimated by minimizing the sum of squared deviations between observed and predicted log catches per unit effort or:

$$minimize\ SSQ = \sum_{j=1}^{n} \sum_{t=1}^{n} (lnU_t - ln\hat{U}_t)^2 \qquad (5)$$

where j and t denote survey and year respectively. The double summation indicates that multiple abundance indices are used. A separate q parameter is estimated for each index. A mixed error model was assumed so that the residual sum of squares (RSSQ) is composed of process error in the population dynamics model and measurement error in the CPUE indices (Polachek et al. 1993). This procedure involves estimation of additional parameters in the form of process errors and a starting biomass level (U_0). It is accomplished in EXCEL by comparing, in a least squares sense, the observed indices to their parameter estimated values as well as to the step-ahead forecasts from the population dynamics model. The procedure cannot resolve measurement from process error without external information. Therefore, weighting in the minimization was adjusted until process error accounted for 10-20% of the RSSQ (Conser and Idoine 1992). This allows for some deviation from the logistic population model but allocates most of the error to the input indices. Solutions were found using the EXCEL problem solver configured with quadratic approximation, forward differentiation, and quasi-Newton search method. The model was adapted from an EXCEL catch-survey application provided by J. Collie from the University of Rhode Island Graduate School of Oceanography (Collie and Sissenwine 1983). Input data can be given various weights (α) depending on the level of confidence in the data. In this study, all α weights were set equal to 1.0 as there was no objective basis to emphasize one data set over another. Eq. 4 was fit to the landings and RI abundance index data for years 1959 to 2013. Model F was calculated from exploitation rate assuming a type I fishery (F= -ln(1-u)). Initial model runs with U_0 free produced estimates in excess of k. This was deemed implausible given the history of the fishery so all succeeding runs constrained starting biomass to less than or equal to k.

Uncertainty in model estimated and derived quantities were evaluated with bootstrapping (Efron 1982). Residuals from the original model fit were re-sampled and added to the estimated survey abundance indices. The model was then successively refit to the alternate input data series and output quantities accumulated over 1,000 replications. Confidence intervals for parameters and calculated quantities were estimated directly from the bootstrap results. Ten-year projections of stock size relative to carrying capacity were made by propagating each terminal year bootstrap realization of stock biomass forward in time under several assumed rates of fishing mortality and stock productivity using eq. 2. Five and ten year periods are typical planning horizons for assessing rebuilding opportunities in depleted fish stocks under the national standards imposed by the Magnuson and Sustainable Fisheries Acts.

Prior Likelihood of r Parameter- As noted above, the intrinsic rate of increase (r) specifies the amount of accrual to a stock in the absence of compensatory stock dynamics. It is a critical quantity determining the fishing rate that will collapse a population i.e. the vulnerability to exploitation (Shepherd 1982). In the finite difference form of the BDM it is equivalent to the ratio of stock production to standing biomass (Chapman 1978). It is rare for abundance indices and catch data alone to support reliable estimation of stock productivity (Hilborn and Walters 1992). Multiple explanations for the observed data often cannot be resolved (small stock-high productivity vs. large stock-low productivity). Rhode Island horseshoe crabs were no exception. Trial runs indicated high correlation between r and k (r=0.83) and low bootstrap precision on the estimates (CV=0.3 to 1.2). A substantial proportion of the bootstraps estimated r at or near zero implying no productivity so the 1959 to present fishery was a depletion or mining process. Auxiliary information for k or r can reduce uncertainty and resolve the conundrum (Hilborn and Walters 1992, Hammond and Ellis 2005). The P/B ratio has been correlated with life history traits such as longevity (Robertson 1979), body size (Boudreau and Dickie 1989, Anderson et al. 2009), and environmental conditions (Myers et. al 1997). Intrinsic rates have been found inversely correlated to body mass (Fenchel 1974), inverse to body mass and temperature (Savage et al.

2004), inverse to body length and fecundity (Denney et al. 2002), and inverse to body size and age at maturity (Reynolds et al. 2005). This suggests that the estimation of r and vulnerability to fishing can be informed by life history information (Cheung et al. 2005). Robertson's (1979) longevity equation for invertebrates is:

$$ln(P/B) = -0.628*ln(A_{max})+1.356 \qquad (6)$$

where: A_{max}= *lifespan in years.*

A maximum age of 20 years was assumed for horseshoe crabs (ASMFC 1998, 2009). Eq. 6 predicts a P/B of 0.59 for 20 year longevity. Fenchel's equation for mid-range heterotherms is:

$$log(r) = -1.64-0.27* log(w) \qquad (7)$$

where: *w= body mass in grams*

and r is in units of per day. Using a mean weight of 2 kg, eq. 7 predicts an r value of 1.04 per year. The Savage et al. (2004) regression model added more observations to extend the range of body size and included an Arrhenius temperature modifier:

$$ln(r)= 22.72-0.21*ln(M)-k^{-1}0.60*(1/T) \qquad (8)$$

where: *w= body mass in micrograms*
T= temperature in Kelvin
k= Bolzmann constant in eVK^{-1}

and r is per day. Eq.8 predicts r=0.68 per year for horseshoe crabs living at an average temperature of 11.5 C. Boudreau and Dickie's (1989) regression model predicts P/B as a function of body mass at maturity:

$$log_{10}(P/B)= -0.12-0.38\ log(w) \qquad (9)$$

where: *P/B= production to biomass ratio*
w= weight at first reproduction expressed as kilocalories
a= regression slope
b= regression intercept.

Horseshoe crabs mature late in life (9-11 years) so the mean RIDFW survey weight of 1.9 kilograms was used in eq.9 with a conversion coefficient of 1.3 calories per gram. This yielded an estimate of P/B=0.54 which is very close to the estimate from eq. 6. Anderson et al. (2009) recommended using asymptotic size to predict P/B. They didn't report a regression equation but their Figure 2 suggests a P/B of 0.35 for a 2 kg animal. The Denney et al. (2002) regressions were not directly usable since an independent variable is body length and the response variable is the stock recruit slope (α). Horseshoe crabs would fall in the middle of the range of body sizes (mass converted) and fecundities examined by the authors. Also, horseshoe crabs have a long stock-recruit lag approaching 10 years (Sweka et al. 2007). Based on these generalizations, an intrinsic rate of about 0.5 per year is likely.

Davis et al. (2006) did not report the estimate of r in their production model but their no harvest projection for Delaware Bay increased at a rate of 0.4 yr^{-1} from 2004 to 2008. The ASMFC (2009a) update yielded a no-harvest projection that grew at 0.1 yr^{-1} from 2009 to 2013. Loveland et al. (1996) reported a 13 fold increase for a New Jersey beach in the 1950’s and 1960’s after harvest reduction. This would correspond to an r of 0.13 to 0.26 depending on time elapsed (10-20 yrs). Smith et al. (2009) reported that Delaware Bay trawl surveys displayed a rate of increase equal to 0.35 yr^{-1} following harvest restrictions and establishment of a sanctuary. Catch-survey estimates of abundance in Delaware Bay have increased at a rate of 0.23 yr^{-1} from 2003 to 2008 under very restrictive management (ASMFC 2010). Southern New England trawl surveys showed bursts of abundance with rates ranging from r=0.11 to 0.30 yr^{-1}. In contrast to life history and abundance series estimators, stage based modeling has produced much lower rates. The Sweka et al. (2007) no harvest-low egg mortality simulation of the Delaware Bay area grew at only 0.03 yr^{-1}. Grady (2006) reported similar low productivity for a lightly harvested Massachusetts population that grew at 0.07 yr^{-1}. Smith et al. (2009) discussed this discrepancy and conjectured that low rates in modeling studies could be due to misspecification of early life survival rates. Buckland et al. (2007) stressed the importance of estimating vital rates within models in conformance to observed population data. Considering all the estimates, the geometric mean r of 0.22 with 95% asymmetric confidence interval of 0.13 to 0.36 was considered the most likely point estimate and prior distribution. The final bootstrap run was configured using a Monte Carlo draw from the r distribution followed by estimation of the other parameters with SOLVER. This procedure prevented r from drifting to extreme values while providing more realistic parameter variation. Sensitivity runs were also configured for a range of fixed values (0.03 to 1.0).

<u>Catch-Survey Model Estimation of Stock Size and Mortality Rates-</u> A prototype catch-survey model (CSM) of the Collie and Sissenwine (1983) type was configured for the period 1998-2012. Earlier years cannot yet be considered as the only size structured indices are the RIDFW that begin in 1998. A CSM model was considered in the last horseshoe crab assessment (ASMFC 2009a) and has been used to assess lobster (Conser and Idoine 1992, ASMFC 2009c) and blue crab (Miller et al. 2005). The CSM approach is intermediate to surplus production modeling and full age-structured assessment and recognizes two groups, new recruits and fully recruited adults. It has been shown with simulated data to capture relative stock trends adequately but estimation of absolute population size and fishing mortality rate depends on reliable specification of the selectivity ratio (Mesnil 2003). This was an issue in the ASMFC (2009a) assessment effort where a ratio less than 1.0 (recruits less susceptible to adults) was needed to produce realistic results. The RIDFW spring trawl survey was assumed to index new recruit crabs and the fall survey the

adult crab population following recruitment and harvest. Rational was that the spring survey catches about 1/3 the number as the fall and they are 12% smaller animals on average. Abundance indices are not yet available on a primiparous (1st time spawner) and multiparous (2nd or more spawns) basis. Other abundance indices were considered representative of the total population.

The assessment year begins in the fall coincident to the fall trawl survey. Recruitment occurs the following year during the spring trawl survey. Fishery catch is assumed to be pulsed following recruitment. In numbers, a simple difference equation is the basis of the model:

$$N_{t+1} = [(N_t \exp(-M/2) + R_{t+1} - C_{t+1}) \exp(-M/2)] \qquad (10)$$

where: *N= fall population size adults*
R=spring population size new recruits
M= natural mortality rate
C= fishery landings in numbers.
t= year.

In addition to the population dynamics model, an observation model is needed so that trawl survey indices can be used as an index of population size:

$$N_t = n_t / q_1 \qquad (11)$$

and

$$R_t = r_t / q_2 \qquad (12)$$

where: *n= the fall trawl index of adults*
r= the spring trawl index of recruits
q_1= the adult catchability scaler
q_2= the recruit catchability scaler.

Substituting eqs. 11 and 12 into eq. 10 and adding a process error term yields the estimation equation:

$$n_{t+1} = [(n_t \exp-(M/2) + r_{t+1}/s_r - q_1 C_{t+1}) \exp(-M/2)] \exp(\varepsilon_p). \qquad (13)$$

where: *s_r= ratio of selectivity of recruits to selectivity of legals.*
E_p= process error term.

In mass balance terms, new year abundance of adult horseshoe crabs in the fall is equal to last falls abundance of adult crabs decremented by one-half year of M, plus new year recruits, minus new year catch, the remainder decremented by another one-half year of M. S_r cannot be estimated and must be specified based on external information Catch data are assumed measured without error. Trawl indices are measured with error and are related to true abundance indices as:

$$n'_t = n_t \, e^{\eta}{}_t \qquad (14)$$

and

$$r'_t = r_t \, e^{\delta}{}_t \qquad (15)$$

The terms η_t and δ_t represent the survey measurement errors. The complete, single index model has 3Y data points where Y is the number of years. Parameters to be estimated include 1 catchability scaler ($\hat{q}$), Y stock indices ($\hat{n}_t$) and Y-1 recruitment indices ($\hat{r}_t$) for a total of 2Y. If there are multiple abundance indices assumed to be replicate samples of the same process differing only in scale, the observation to parameter ratio grows (Y or Y-1 observations for 1 catchability parameter). Conser and Idoine allow for differential weighting on the error terms in the objective function to be minimized:

$$\lambda_{\varepsilon} \sum_{y=1}^{Y-1} \varepsilon_p^{2} \;+\; \sum_{y=1}^{Y} \eta^{2} \;+\; \lambda_{\delta} \sum_{y=1}^{Y-1} \delta^{2} \qquad (16)$$

where: λ_{ε} and λ_{δ} are relative weights for the process error and recruit measurement error relative to measurement error of adults which is fixed at 1.0. Differential weighting allows for optimization of the amount of smoothing applied to the abundance indices. Realistic treatment of measurement error in abundance indices has been emphasized by Polachek et al. (1993). Estimates of absolute stock sizes (N_t) and recruit populations (R_t) are made by dividing the estimated trawl indices ($\hat{n}_t$, $\hat{r}_t$) by the estimated catchability coefficient ($\hat{q}_1$). Fishing mortality rate was calculated as pulsed type 1, a direct transformation of exploitation rate:

$$F_t = -ln(u_t - 1) \qquad (17)$$

and

$$u_t = C_t / (N_t / exp(-M/2) + C_t) \qquad (18)$$

where: *F= fishing mortality rate*
M= natural mortality rate

u=exploitation rate.

Natural mortality rate for legal and recruit crabs were fixed at 0.15 per year, the current assessment convention (ASMFC 2009a). Survey and catch data were treated with sexes combined. The recruit measurement error weight was set to 1.0, the same as for legal. As recommended by Conser and Idoine (1992), the process error weight was iterated until the fraction of residual sums of squares due to process error was between 0.10 and 0.20. This allowed most of the error to reside in the abundance indices which are smoothed by the population dynamics process. Parameter estimation was accomplished with the EXCEL problem solver using a quasi- Newton search method and quadratic approximation near the solution. Residuals were accumulated in logarithmic scale assuming multiplicative error. The EXCEL application was modified from an early version of catch-survey analysis provided by J. Collie at the University of Rhode Island Graduate School of Oceanography. Bootstrapping was not conducted as sensitivity testing indicated that the prescription for s_r swamped estimation error. The final configuration fixed s_r at 0.36, the same value used in ASMFC (2009a).

Results-

Fishery Landings- A summary of the landings data used in this report is found in Tables 1a and 1b. Landings were generally low from 1959 to 1975 (Figure 1). From 1976 to 1991, they ranged from 19 to 171 tons. A steep increase followed and landings reached 366 tons by 1993 before declining back to 12 tons in 2004. Under ASMFC quota management, landings increased to 72 tons by 2012. Mean weight of crabs has ranged from 1.7 to 2.2 kilograms in the DFW trawl survey. Landings in number since 1998 are plotted in Figure 1b. They approached 200,000 crabs in 1993 but have dropped to 32,000 in recent years. Since 1999, bait crabs have constituted from between 45% and 100% of the state landings. Commercial landings have been sampled since 2000. Pooled prosomal width frequency is plotted in Figure 3. Male crabs rarely exceed 24 cm in width and females are rarely smaller than 22 cm.

Abundance Indices- Rhode Island survey indices for horseshoe crabs are summarized in Table 2. All of the long term indices indicate that current abundance is low (Figure 4). A steady decline from high crab abundance in the mid 1970's to present is apparent. The abundance peak in the 1970's was preceded by low abundance in the 1960's suggesting that horseshoe crab populations can undergo fluctuations in abundance. The RIDFW trawl survey shows an upward trend from 1998 to 2010, with abundance approximately doubling. However, the increase is small in the context of the long-term indices and appears to have ceased in 2011-2013. Abundance of horseshoe crabs in the MADMF Vineyard Sound trawl survey also declined from 1978 to present (Figure 5). At Millstone Power Station on the eastern end of Long Island Sound, abundance peaked in 1994 and then declined to low levels (Figure 6). On a sound-wide basis however, abundance has not declined in the CTDEP trawl survey.

Estimates of Stock Size and Mortality Rates- Estimated crab population biomass and harvest from the BDM are plotted in Figure 7. Abundance peaked at over 3,300 metric tons in 1975 but fell to only 528 mt by 2002. A modest increase occurred with biomass rising to 735 tons by 2010. However that increase ceased and biomass in 2013 was estimated at 471 mt (CV=0.22) and well below the estimated B_{msy} level of 1,291 mt (CV=0.19). Based on the bootstrap results, there is only a 1.5% chance that biomass in 2013 was at or above the B_{msy} level (Figure 8). There is a high probability (0.78) that biomass in 2013 was at the ½ B_{msy} level that defines overfished status. Fishing mortality rates are compared to the F_{msy} overfishing definition in Figure 9. F was below the F_{msy} level from 1959 to 1988 when stock abundance was low. Fishing mortality rates first exceeded F_{msy} in 1989 and then greatly so from 1992 to 2000. Under quota management, F remained below F_{msy} from 2001 to 2010 but was increasing. F in 2012 was estimated at 0.14 (CV=0.21), above the F_{msy} level of F=0.12 (CV=0.25). Based on the bootstrap results, there is a 64% chance that F in 2012 was at or above F_{msy} (Figure 10) Based on point estimates (ignoring probability distributions), the resource is overfished in terms of biomass and subject to over fishing in terms of F rate.

Precision on estimated model parameters and management quantities was moderate to good although uncertainty is understated due to the need to constrain r to a prior distribution. Logistic model parameters and catchability coefficients had CV's less than 23% (Table 3). Terminal year F rates and biomass had CV's of 0.21-0.22. MSY reference points had CV's ranging from 0.10 to 0.25. Process errors showed tendency for a sine wave pattern (Figure 11). This suggests that there are factors such as year-class effects or bursts of stock productivity that cannot be accommodated by constant surplus production parameters. Changes in survey catchability are possible as well. Test models suggest that variable r or q configurations might help to resolve this pattern and would be more mechanistically satisfying than the "black box" process error parameters. Nye et al. (2009) examined changes in species distribution and abundance on the northeast continental shelf and found that the Atlantic Multidecadal Oscillation (AMO) was most correlated with the widespread changes observed. Horseshoe crab abundance in the base BDM model was significantly ($P<0.01$) and inversely correlated with the AMO. The best fitting model was an inverse exponential ($r^2=0.46$, Figure 12). The statistical relationship occurs because the large drop in horseshoe crab abundance is simultaneous to an AMO shift from negative to positive (Figure 13). No causality of course can be invoked from the relationship. However, the AMO is a dominant mode of climatic variation primarily expressed in sea surface temperature distributions and thermohaline circulation (Dijkstra et al. 2006). Periods of high phase AMO are associated with higher sea temperatures and reduced rainfall in the NW Atlantic. Nye et al. (2009) proposed a number of ways that AMO could produce the results they observed; direct movement by resident animals to preferred water temperatures, impacts to migration timing and pattern for seasonal migrants, elevated mortality rate in the stressed portion of the range, and impacts to food web productivity. Horseshoe crab correlations were highest for lags 0 and 1 year rather than generational (10-12 years) suggesting that any mechanism operated on adults since the BDM estimates adult fishable biomass. The phase change in the AMO has been associated with a significant increase in water temperature in the RI area. A plausible mechanism for the observed

AMO-crab correlation is changes in the distribution and timing of horseshoe crab migrations that are expressed as changing catchability in the surveys. Examination of the trawl surveys on finer temporal scales than annual might be revealing.

Projections of Population Size- The trajectory of the Rhode Island horseshoe crab stock under status quo fishing beginning in year 2012 is plotted in Figure 14. The stock cannot recover to the estimated B_{msy} level if fishing mortality is maintained at 0.14 or a quota of 35,000 crabs in 2013. Stock trajectory under a fishery closure (F=0) in 2012 is graphed in Figure 15. Recovery to B_{msy} occurs in about 8 years.

Sensitivity to Intrinsic Rate and Starting Biomass- Biomass in 2013 relative to ½ B_{msy} was robust to the likely range of r (Figure 16). The stock is over fished (B_{2013} < ½ B_{msy}) for r less than about 0.75. Relative fishing mortality rate in 2012 was above F_{msy} for values of r less than 0.30. For productivity greater than 0.30, relative F was below F_{msy}, that is overfishing not occurring. The most plausible range for r (0.13 to 0.36) falls on the areas for overfished and overfishing. While high productivity is possible, it seems unlikely given the fishery history of declines and recoveries and the current rate of increase in Delaware Bay under restrictive management. The condition of the stock with respect to overfishing was not very sensitive to the starting biomass convention (Figure 17). Overfishing in 2012 is likely for all starting biomass levels examined. Similarly, biomass is below the threshold over a wide range of starting biomass conventions.

Preliminary CSM Results- Population sizes and fishing mortality rates from the catch-survey model are shown in Figures 18 and 19. Fall population abundance of adults (after fishing and recruitment) increases from about 200 to 350 thousand crabs from 1998 to 2011. These compares to 275 to 400 thousand from the BDM for the same period and mean weight equal to 1.9 kg. The consistency is comforting suggesting at least that fundamental assumptions for catch-survey (M=0.15, s=.36), are consistent with those made independently for the BDM (r=0.22, B_0=k). Spring recruitment varies between 88 and 385 thousand individuals. Estimates of fishing mortality rate are around 0.5 early in the time series but plummet to less than 0.1 since 2001 coincident to reduced landings. The pattern is very similar to the BDM but with higher absolute value since the CSM estimates are fully recruited while the BDM are biomass weighted. Process errors show a distinct pattern changing from positive to negative (Figure 20). This pattern can be rectified by an increasing trend in natural mortality rate or increasing under-reporting of landings. Further development of this model is not warranted until the abundance indices can be better disaggregated into primiparous and multiparous animals.

Discussion and Management Recommendations-

The available data and assessment results indicate that the Rhode Island horseshoe crab population is at low abundance, overfished, and subject to over fishing. Stock biomass is well below the estimated B_{msy} level and fishing mortality rate above the estimated F_{msy} level based on point estimates. Life history models indicate that stock productivity is relatively low and the species is vulnerable to overfishing. Uncertainty in the assessment remains high as only a portion of the landings are reliably known and a continuum of assessment solutions in r-k space are possible (Figure 21). Projection results indicate that the species cannot rebuild under status quo F. Reducing F to allows for recovery to B_{msy} in about 8 years Consistency of three long term abundance indices measured in different areas of the states marine waters indicates that the population decline since the 1970's is substantial and consistent with coast wide trends. Given the overfishing, low abundance, and the slow population growth observed since management began in 1999, consideration should be given to further restrictions on the fishery. Efforts should be made to improve the accuracy of landings data, particularly the bait component. The inverse correlation between horseshoe crab abundance and the AMO is intriguing and warrants more review given the world wide evidence for changes in distribution and abundance patterns in marine resources.

Research Recommendations-

1. Initiate a tagging study to estimate mortality rates in the RI horseshoe crab population.

2. Improve the spawning survey with formal statistical methods which allow for absolute abundance estimation with GIS mapping of distributions.

3. Expand the sampling of commercial landings to include additional dealers.

4. Review alternative production model formulations including variable intrinsic rate as a function of environmental or ecological covariates.

5. Propagate assessment uncertainty through stock projections.

6. Continue development of the catch-survey assessment especially desegregation of abundance indices into primiparous and multiparous individuals.

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Table 1- Horseshoe Crab Landings Data for Rhode Island, 1985-2012

Year	NOAA/NMFS RI Metric Tons	Ass. of Cape Cod Cod No.RI Crabs	RIDFW Bait No. Crabs	Total RI No. Crabs	MT	Prop Bait	1000's crabs
1985	0.0	17966		62428	115.5		62.43
1986	0.0	23418		81372	150.6		81.37
1987	26.1	19635	14106	33741	62.4	0.42	33.74
1988	109.9	10000	59397	69397	128.4	0.86	69.40
1989	128.3	22137	69342	91479	169.3	0.76	91.48
1990	0.0	18517		64342	119.1		64.34
1991	0.9	22378		77759	143.9		77.76
1992	4.5	43628		151598	280.5		151.60
1993	0.0	56842		197513	365.5		197.51
1994	0.1	45606		158471	293.2		158.47
1995	0.1	38776		134738	249.3		134.74
1996	1.6	31946		111005	205.4		111.01
1997	0.1	39274		136468	252.5		136.47
1998	1.6	47716	61269	108985	185.1	0.56	108.99
1999	9.1	29423	77843	107266	227.4	0.73	107.27
2000	0.0	28853	46751	75604	141.3	0.62	75.60
2001	0.0	7238	11198	18436	32.2	0.61	18.44
2002	0.0	0	10549	10549	19.2	1.00	10.55
2003	0.0	0	13957	13957	23.0	1.00	13.96
2004	0.0	0	6030	6030	11.6	1.00	6.03
2005	0.0	0	8260	8260	14.5	1.00	8.26
2006	9.1	0	15274	15274	28.7	1.00	15.27
2007	28.1	2850	15564	18414	36.8	0.85	18.41
2008	41.5	9318	15549	24867	50.8	0.63	24.87
2009	36.7	7600	18682	26282	52.7	0.71	26.28
2010	13.3	11533	12502	24035	49.9	0.52	24.04
2011	39.7	15517	12632	28149	57.5	0.45	28.15
2012		12345	19306	31651	72.2	0.61	31.65

Table 1b- Horseshoe Crab Landings Data for Rhode Island and the Atlantic Coast, 1959-1984

Year	RI Metric Tons /1	NMFS Atlantic
1959	6.45	34.9
1960	49.09	265.6
1961	93.06	503.5
1962	28.50	154.2
1963	16.88	91.3
1964	29.68	160.6
1965	17.74	96
1966	11.16	60.4
1967	4.66	25.2
1968	6.88	37.2
1969	0.89	4.8
1970	1.33	7.2
1971	1.00	5.4
1972	3.53	19.1
1973	7.43	40.2
1974	1.40	7.6
1975	5.27	28.5
1976	171.28	926.7
1977	39.66	214.6
1978	61.07	330.4
1979	101.92	551.4
1980	47.48	256.9
1981	27.39	148.2
1982	44.16	238.9
1983	39.30	212.6
1984	18.87	102.1

/1 RI Landings estimated as 19.3% of Atlantic Coast, see text for details

Table 2- Horshoe Crab Abundance Index Data Used in the BDM and Catch Survey Assessments, 1959-2011

Year	Comm CPUE	Spring RIDFW #/tow	Fall RIDFW #/tow	Monthly RIDFW #/tow	Weekly URIGSO #/tow	Monthly MRI #/tow	Stout Count	MSS Impinge	Beach Count per M2
1959					3.34				
1960					3.63				
1961					3.74				
1962					1.74				
1963					0.39				
1964					1.25				
1965					0.15				
1966					1.32				
1967					0.01				
1968					0.01				
1969					0.33				
1970					0.65				
1971					0.70				
1972					0.85				
1973					2.17	6.86			
1974					3.73	3.35			
1975					7.00		103		
1976					3.61		93		
1977					6.24		106		
1978					2.85		91		
1979					2.94		86		
1980					1.58		73		
1981					2.96		53		
1982					2.27		51		
1983					0.45		42		
1984					0.52		38		
1985					0.44		35		
1986					0.38		23		
1987					0.31		36		
1988					0.25	1.83	30		
1989					0.95	1.14	29		
1990					0.44	2.81	48		
1991					0.34	2.66	12		
1992					0.67	4.63	8	0	
1993					0.20	2.75	14	37	
1994					0.06	2.89	6	0	
1995					0.93	1.38	3	6	
1996					0.40	2.02	5	78	
1997					0.10	0.19	3	13	
1998			0.27	0.19	0.10	0.39	3	5	
1999		0.07	0.24	0.15	0.08	0.15	4	14	
2000		0.12	0.70	0.37	0.19	0.30	4	7	0.02
2001	255	0.22	1.02	0.17	0.09	0.31	13	0	0.04
2002	182	0.02	0.65	0.42	0.09	0.77	6	0	0.03
2003	199	0.27	0.90	0.66	0.11	0.20		7	0.14
2004	262	0.57	1.00	0.55	0.06	0.65		0	0.20
2005	223	0.35	0.95	0.29	0.02	0.62		0	0.04
2006	477	0.10	0.62	0.30	0.05	0.15		0	0.05
2007	362	0.29	0.76	0.31	0.07	0.16		7	0.06
2008	457	0.31	0.64	0.29	0.08	0.10		25	0.13
2009	694	0.17	0.48	0.28	0.08	0.10		14	0.36
2010	284	0.56	1.17	0.66	0.08	0.18		14	0.17
2011	238	0.33	0.42	0.40	0.21	0.18		61	0.12
2012	371	0.18	0.36	0.18	0.11	0.19		0	0.08
2013	563	0.11		0.03					0.04
Mean	334	0.24	0.68	0.33	1.16	1.37	36.36	14	0.11
STD	149	0.16	0.29	0.18	1.60	1.67	33.85	21	0.10

Table 3- Parameters and Derived Quantities for the RI Horseshoe Crab BDM Assessment

Parameter	SOLVER	Boot Mean	SE	CV	Low 95%	Up 95%
Intrinsic Rate (r)	0.220	0.218	0.051	0.232	0.119	0.321
Carrying Capacity (k)	2581.3	2792.8	537.7	0.193	1506.0	3656.6
URIGSO q	0.00051	0.00049	0.00008	0.169	0.00034	0.00067
DFW Trawl q	0.00060	0.00057	0.00011	0.193	0.00038	0.00082
MRI Trawl q	0.00092	0.00088	0.00016	0.179	0.00060	0.00123
Beach Count	0.00015	0.00014	0.00003	0.200	0.00009	0.00020
Stout Count	0.00326	0.00312	0.00055	0.175	0.00217	0.00435
Comm CPUE	0.54958	0.52743	0.10410	0.197	0.34137	0.75778
MSS Impinge	0.00084	0.00080	0.00014	0.172	0.00056	0.00111
MADMF Trawl q	0.00019	0.00018	0.00003	0.178	0.00012	0.00025
B 2013	471.4	517.2	113.6	0.220	244.1	698.7
F 2012	0.141	0.135	0.028	0.211	0.084	0.198
N 2012	198.9	218.2	48.0	0.220	103.0	294.8
Bmsy	1290.7	1396.4	268.8	0.193	753.0	1828.3
Fmsy	0.117	0.116	0.029	0.248	0.059	0.174
MSY	142.0	146.7	14.1	0.096	113.7	170.2
B ratio	0.365	0.374	0.067	0.178	0.232	0.499
F ratio	1.211	1.192	0.222	0.186	0.768	1.655

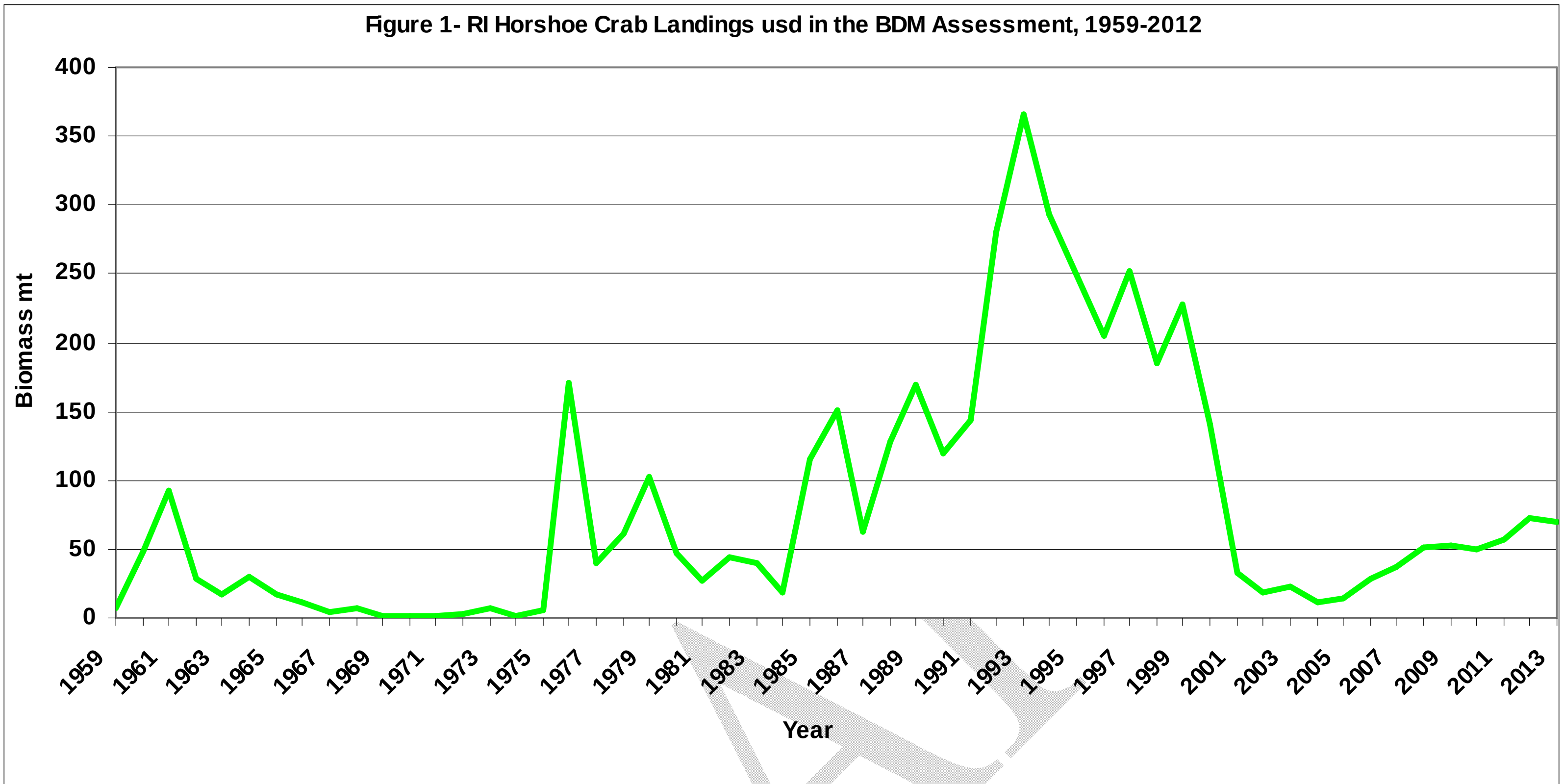
Figure 1- RI Horshoe Crab Landings usd in the BDM Assessment, 1959-2012
Biomass mt
400
350
300
250
200
150
100
50
0
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
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2007
2009
2011
2013
Year

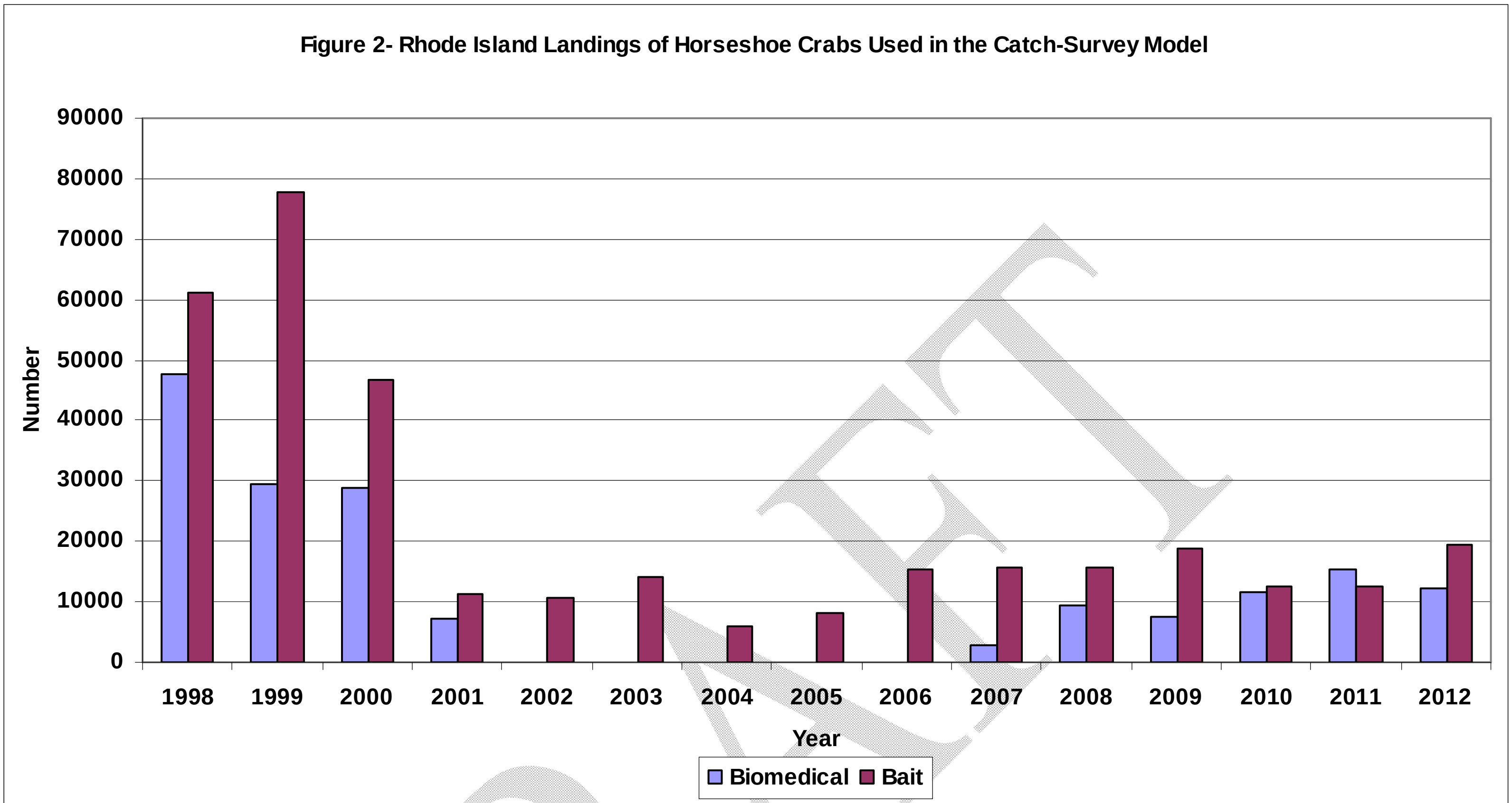


Figure 2- Rhode Island Landings of Horseshoe Crabs Used in the Catch-Survey Model
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Number
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Year
Biomedical
Bait

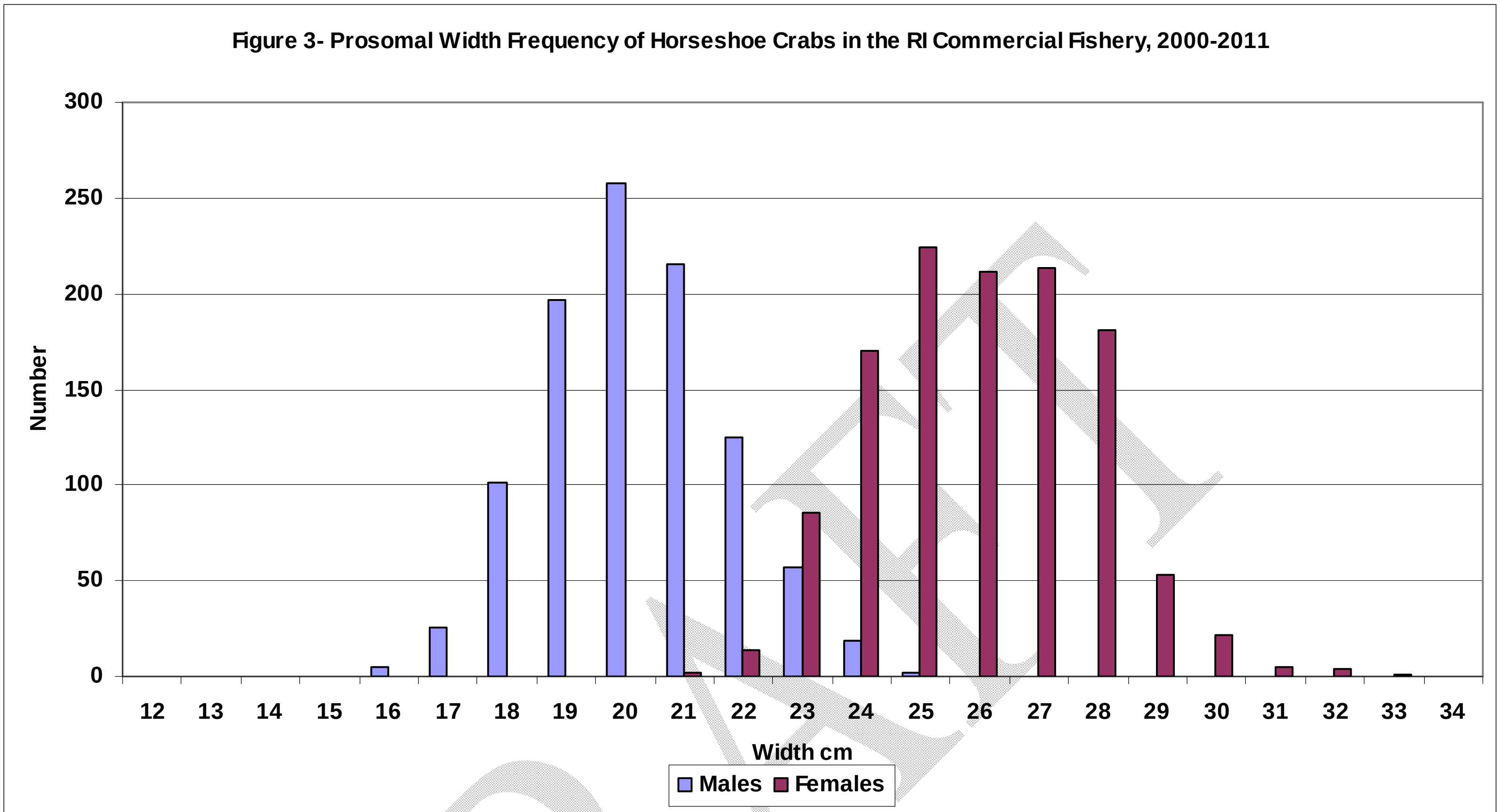


Figure 3- Prosomal Width Frequency of Horseshoe Crabs in the RI Commercial Fishery, 2000-2011
Number
300
250
200
150
100
50
0
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
Width cm
Males
Females

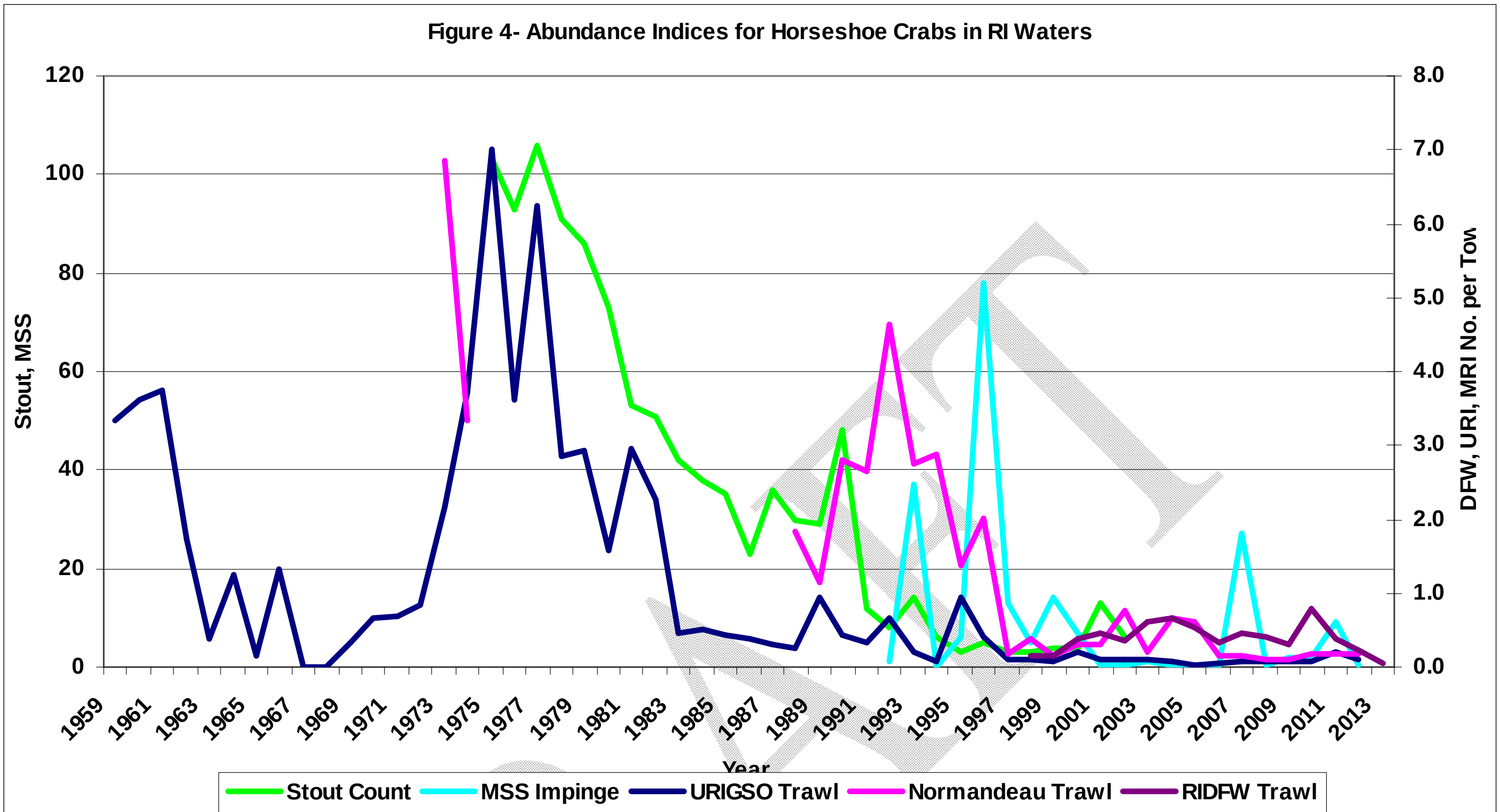


Figure 4- Abundance Indices for Horseshoe Crabs in RI Waters
Stout, MSS
DFW, URI, MRI No. per Tow
Year
Stout Count
MSS Impinge
URIGSO Trawl
Normandeau Trawl
RIDFW Trawl

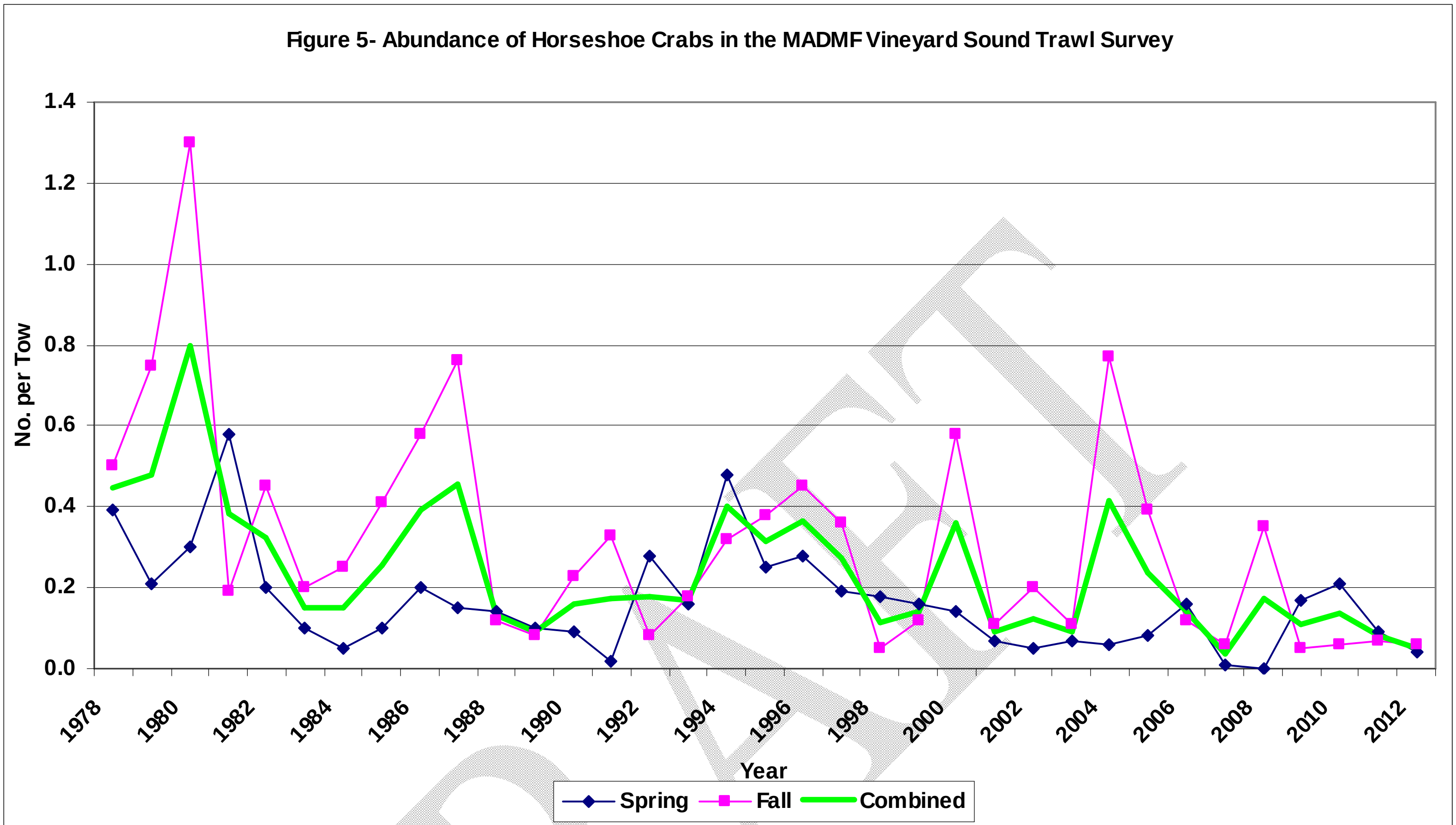


Figure 5- Abundance of Horseshoe Crabs in the MADMF Vineyard Sound Trawl Survey
No. per Tow
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Spring
Fall
Combined

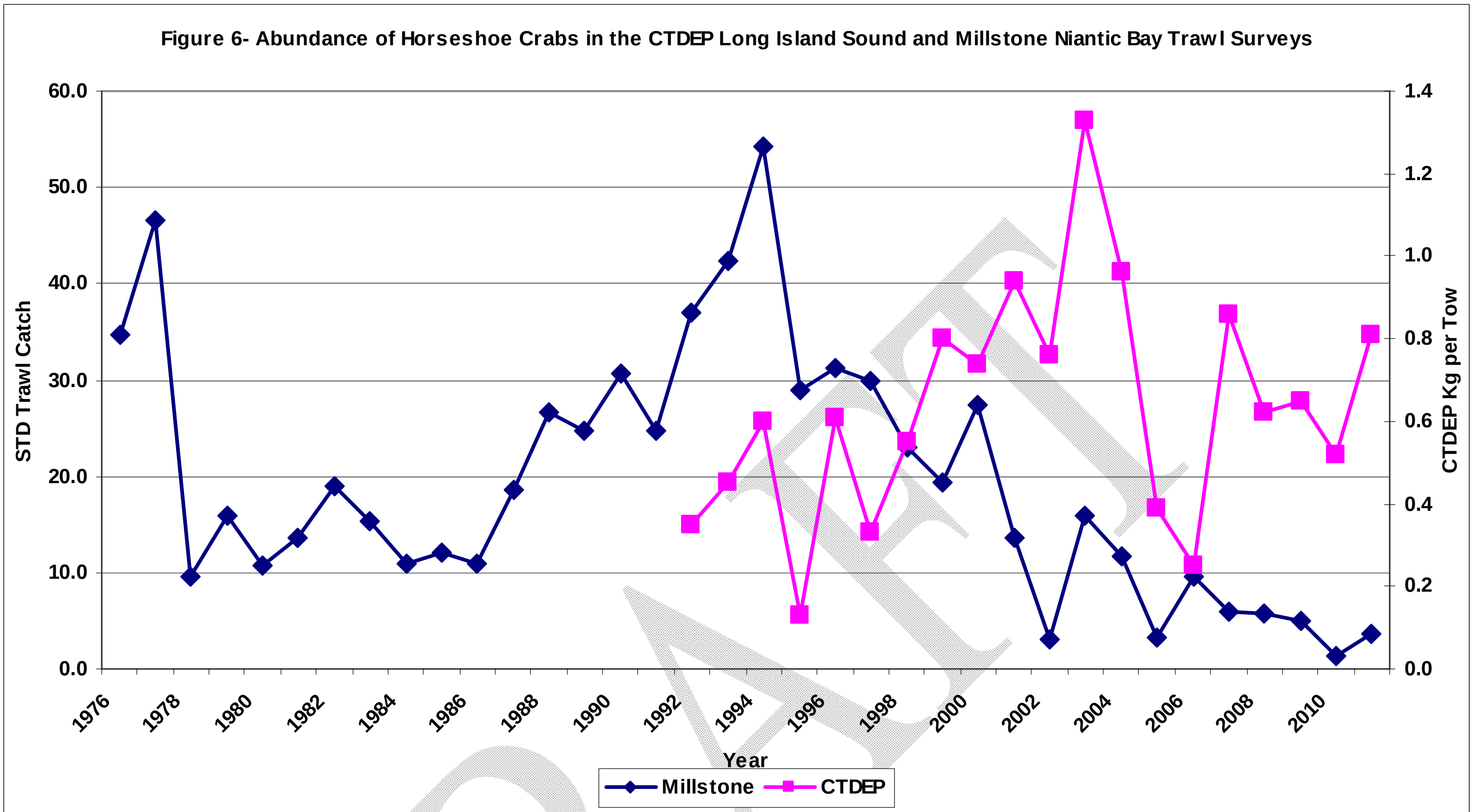


Figure 6- Abundance of Horseshoe Crabs in the CTDEP Long Island Sound and Millstone Niantic Bay Trawl Surveys
STD Trawl Catch
CTDEP Kg per Tow
Year
Millstone
CTDEP
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

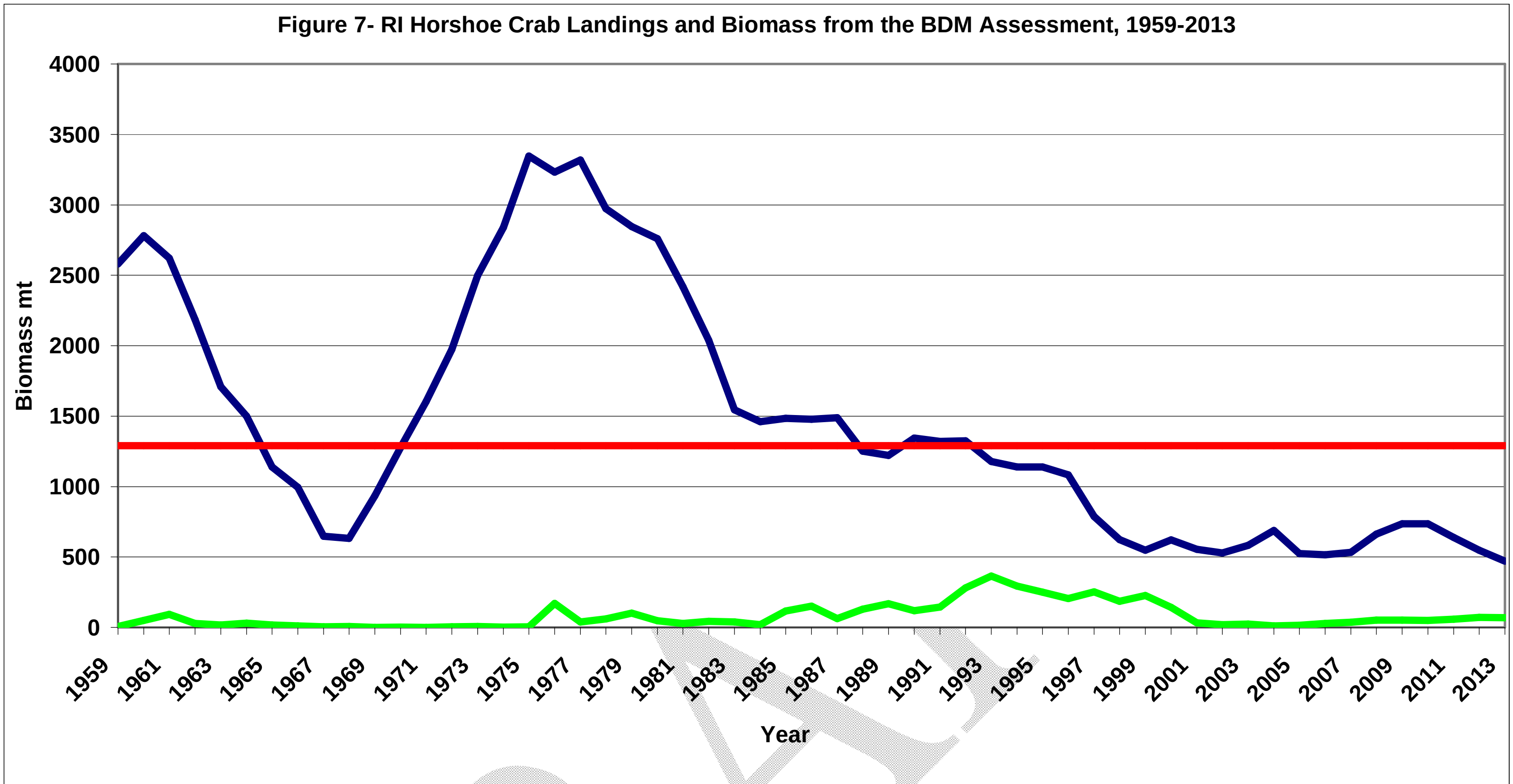


Figure 7- RI Horshoe Crab Landings and Biomass from the BDM Assessment, 1959-2013
Biomass mt
0
500
1000
1500
2000
2500
3000
3500
4000
1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year

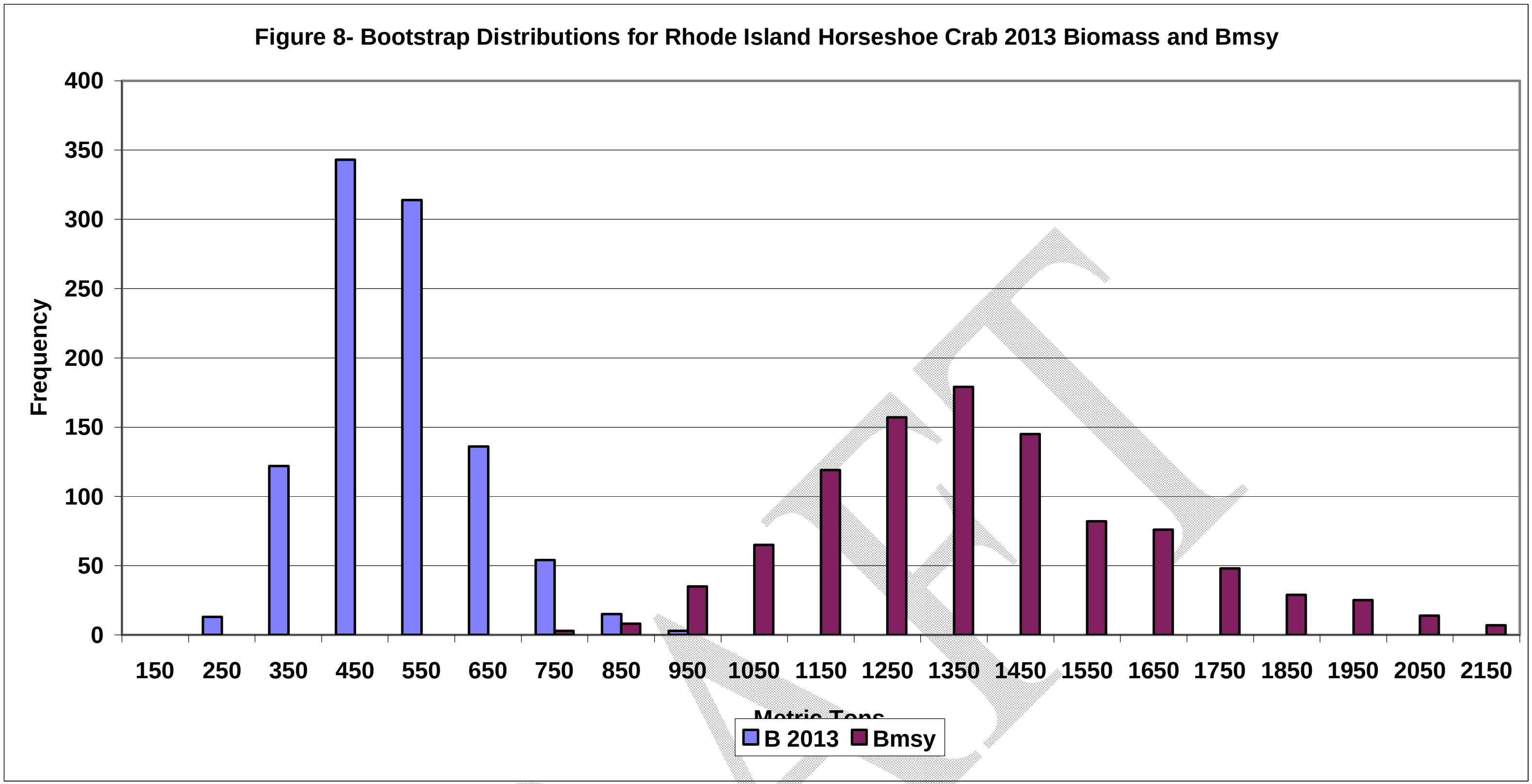


Figure 8- Bootstrap Distributions for Rhode Island Horseshoe Crab 2013 Biomass and Bmsy
Frequency
400
350
300
250
200
150
100
50
0
150 250 350 450 550 650 750 850 950 1050 1150 1250 1350 1450 1550 1650 1750 1850 1950 2050 2150
Metric Tons
B 2013
Bmsy

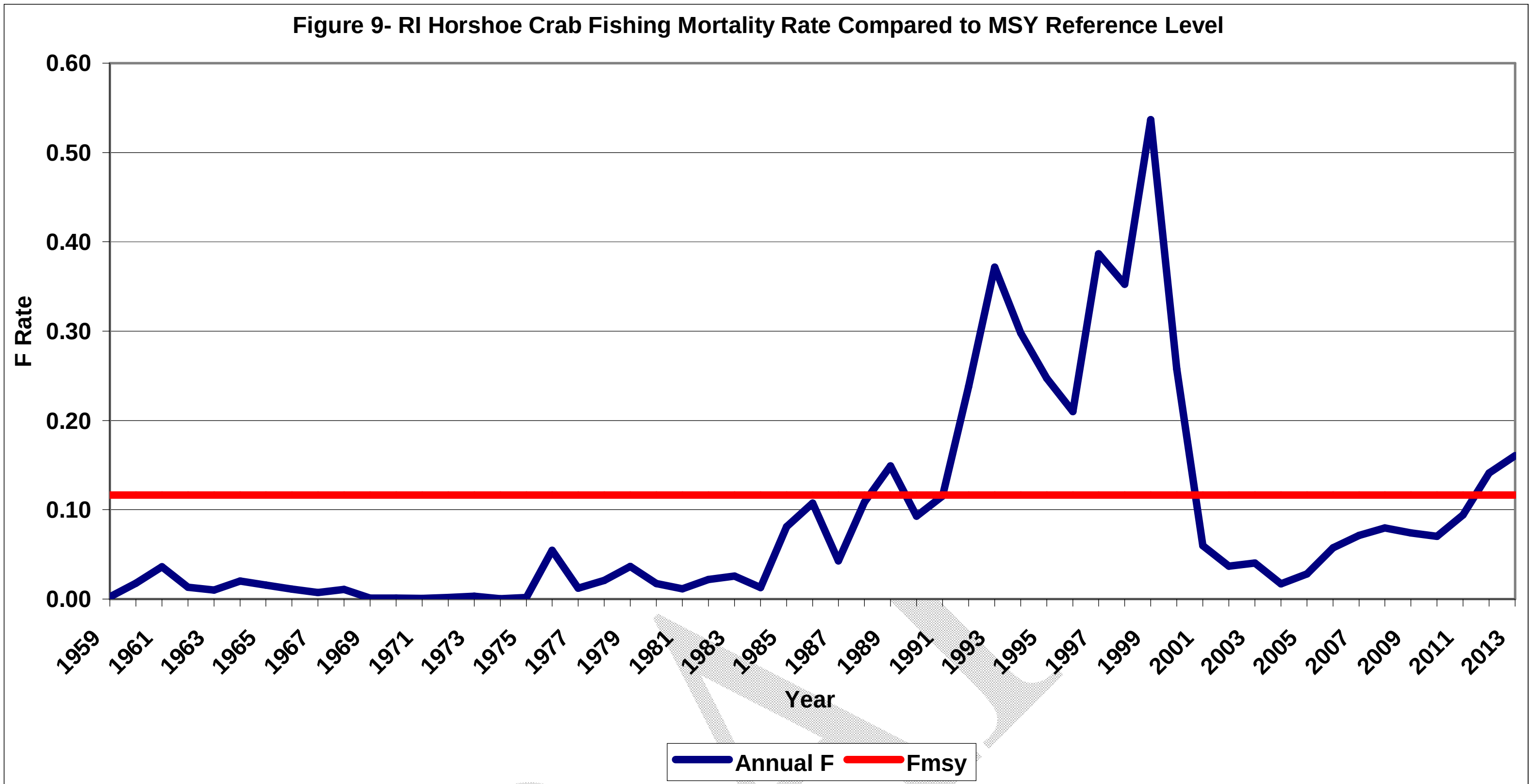


Figure 9- RI Horshoe Crab Fishing Mortality Rate Compared to MSY Reference Level
F Rate
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007 2009 2011 2013
Year
Annual F
Fmsy

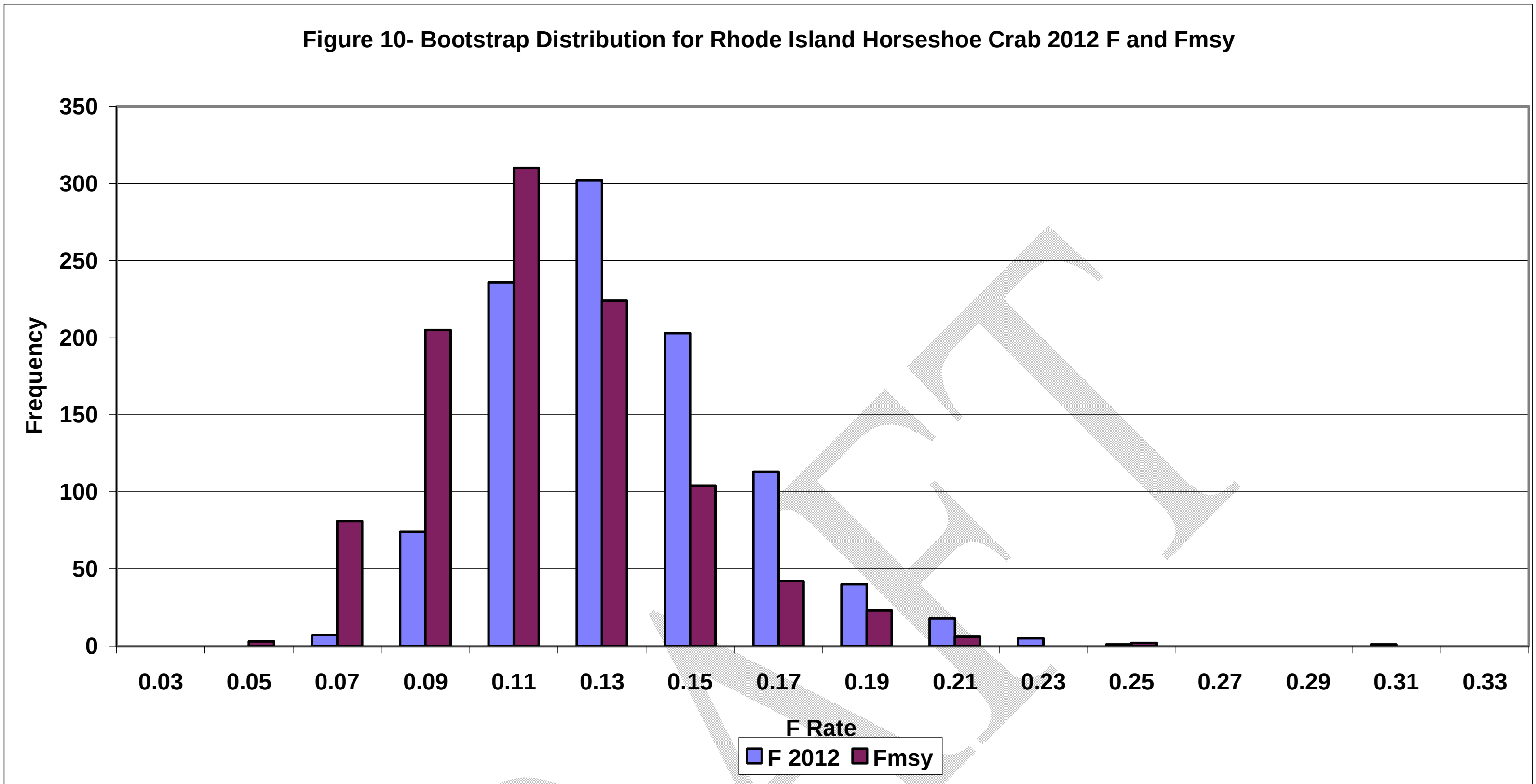


Figure 10- Bootstrap Distribution for Rhode Island Horseshoe Crab 2012 F and Fmsy
Frequency
350
300
250
200
150
100
50
0
0.03
0.05
0.07
0.09
0.11
0.13
0.15
0.17
0.19
0.21
0.23
0.25
0.27
0.29
0.31
0.33
F Rate
F 2012
Fmsy

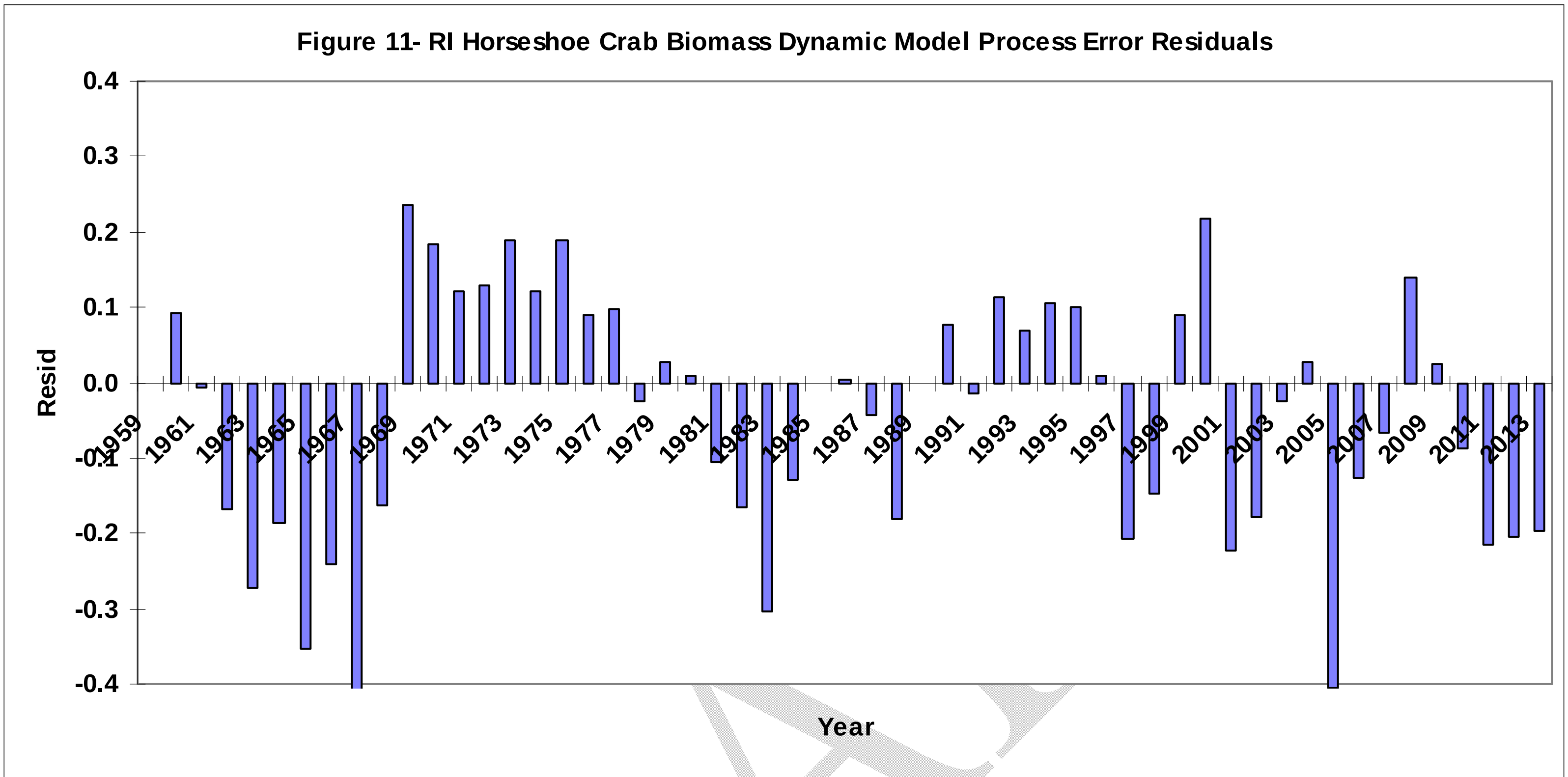


Figure 11- RI Horseshoe Crab Biomass Dynamic Model Process Error Residuals
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
Resid
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year

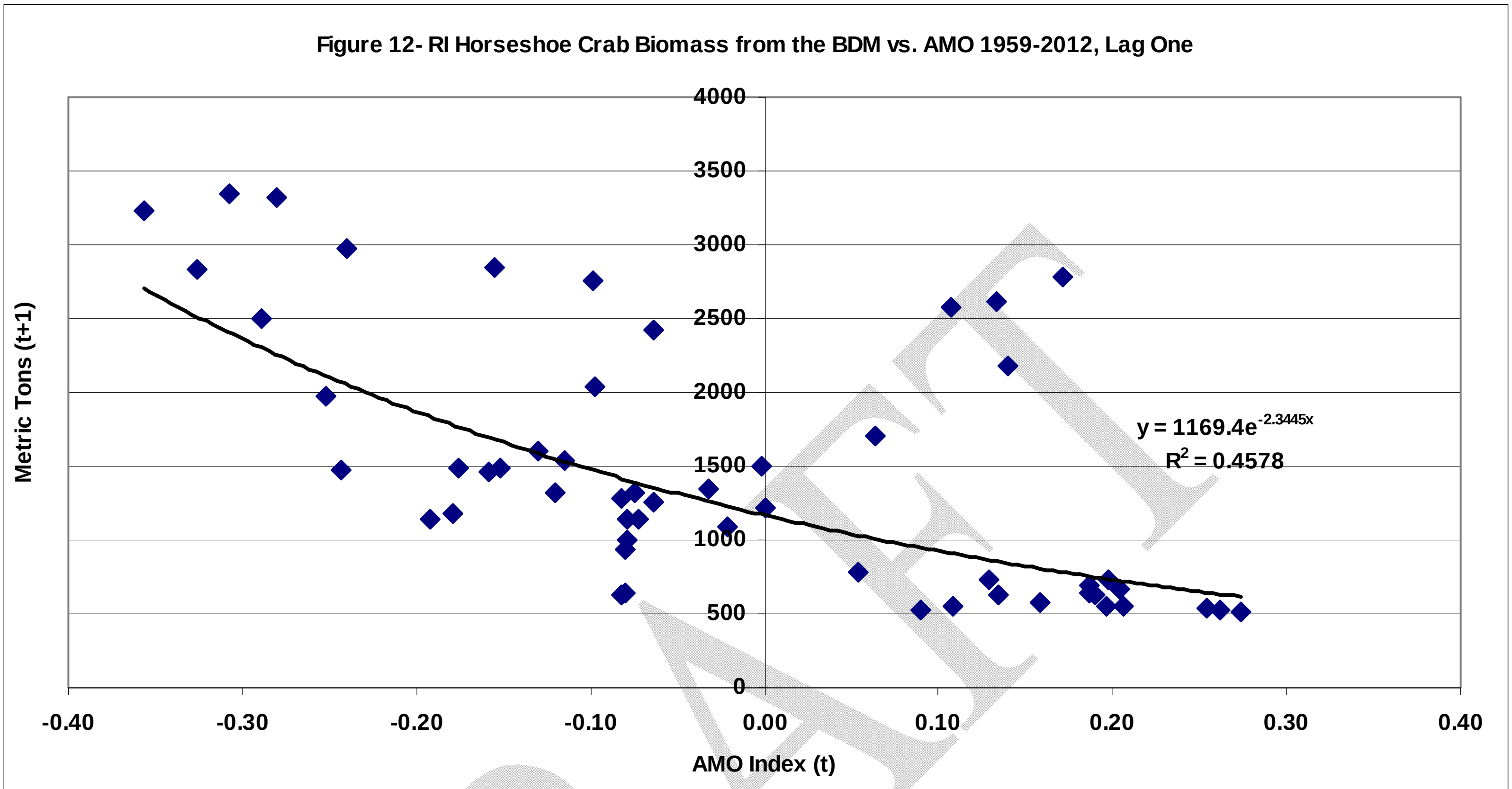


Figure 12- RI Horseshoe Crab Biomass from the BDM vs. AMO 1959-2012, Lag One
Metric Tons (t+1)
4000
3500
3000
2500
2000
1500
1000
500
0
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
AMO Index (t)
y = 1169.4e-2.3445x
R2 = 0.4578

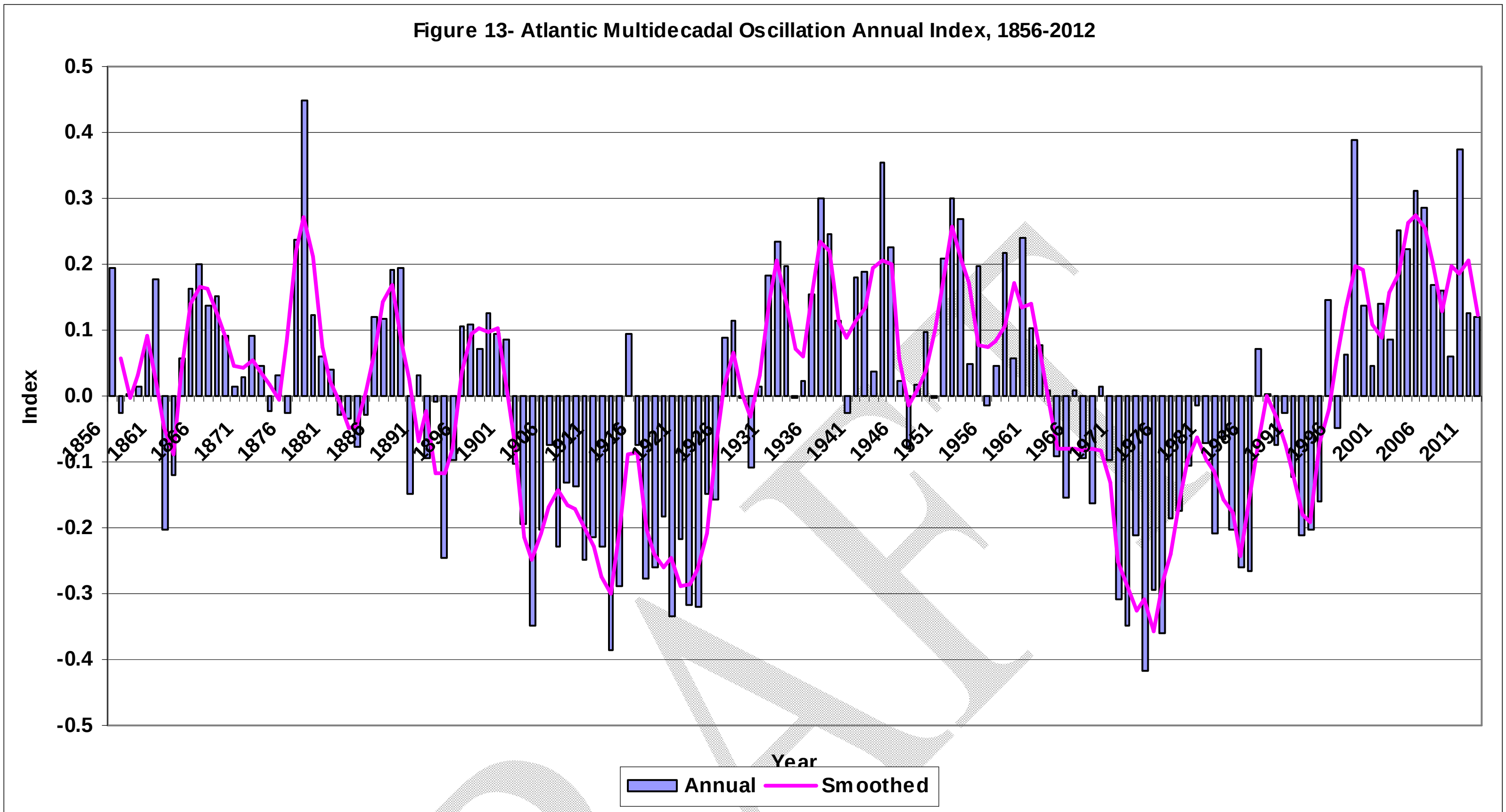
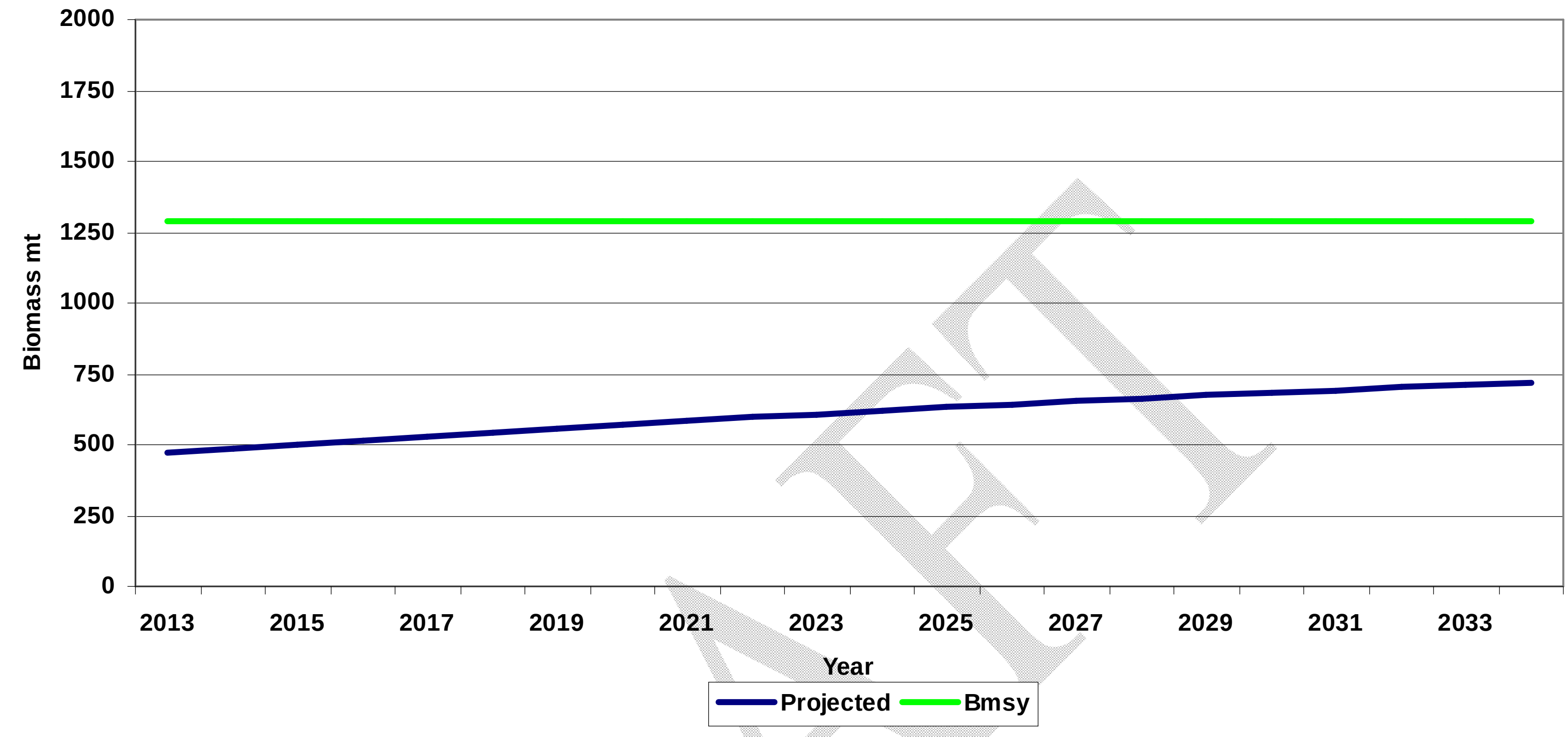


Figure 13- Atlantic Multidecadal Oscillation Annual Index, 1856-2012
Index
Year
Annual
Smoothed
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
1856
1861
1866
1871
1876
1881
1886
1891
1896
1901
1906
1911
1916
1921
1926
1931
1936
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011

Figure 14- Projected Trajectory of RI Horseshoe Crab Population Under Status Quo in 2013 (F=0.14)



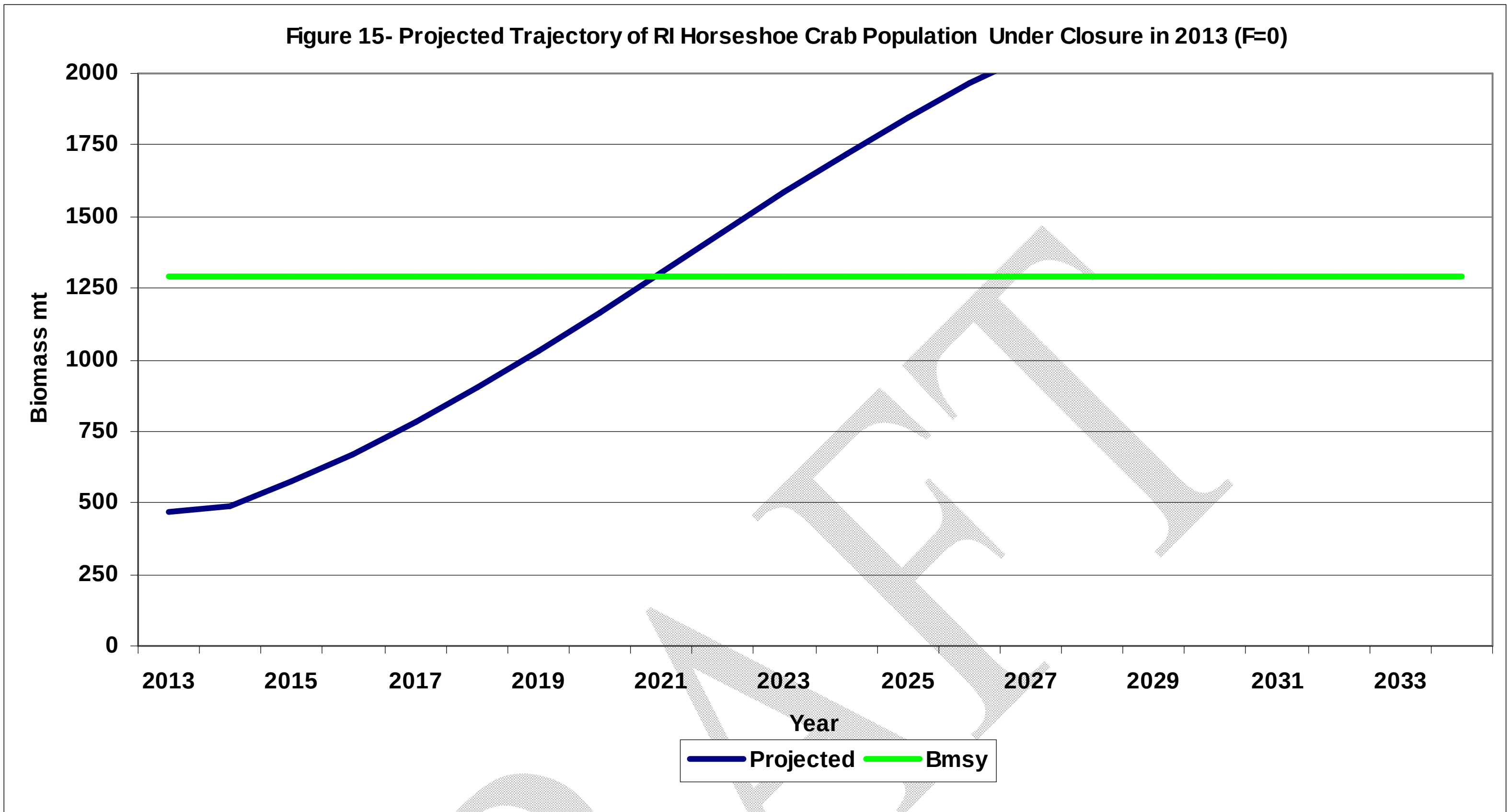


Figure 15- Projected Trajectory of RI Horseshoe Crab Population Under Closure in 2013 (F=0)
Biomass mt
2000
1750
1500
1250
1000
750
500
250
0
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
Year
Projected
Bmsy

Figure 16- Sensitivity of RI Horseshoe Crab Relative Stock Status to Intrinsic Rate

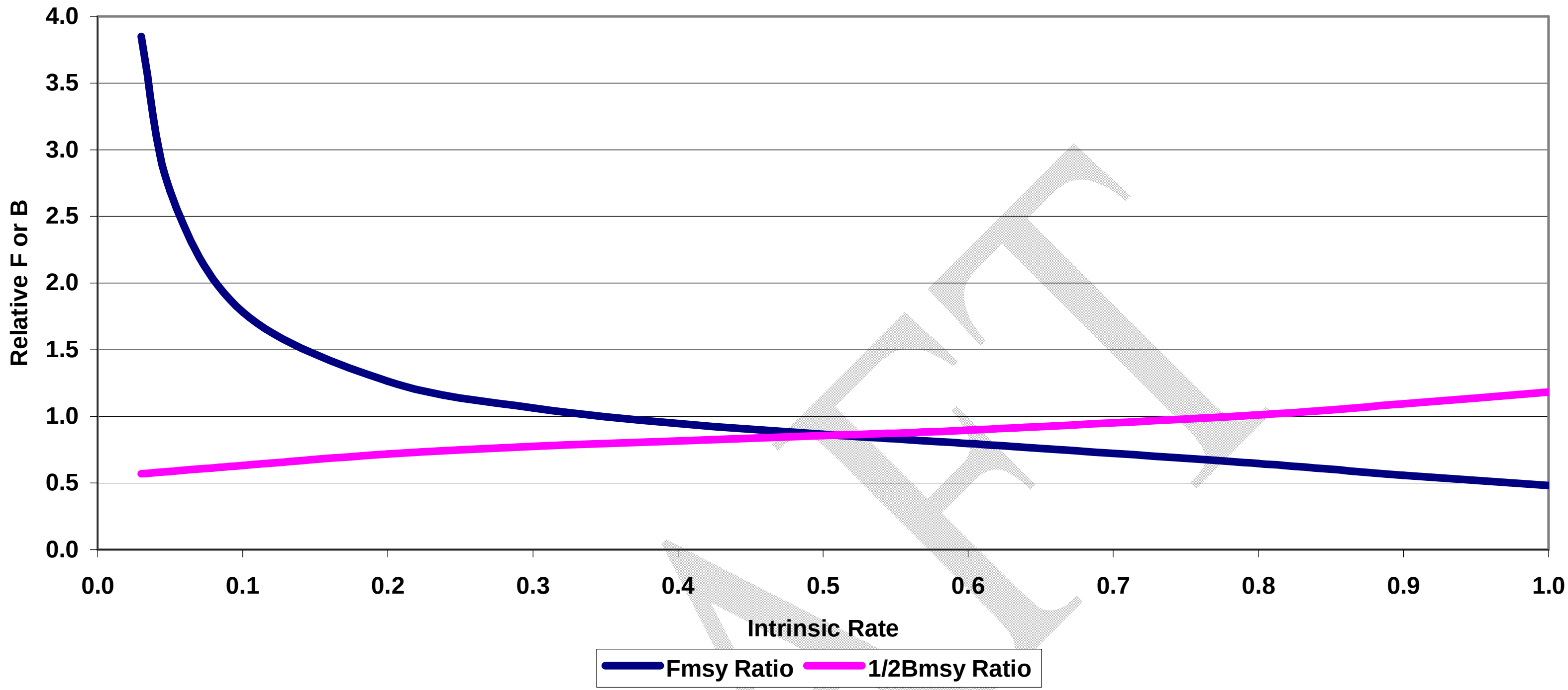
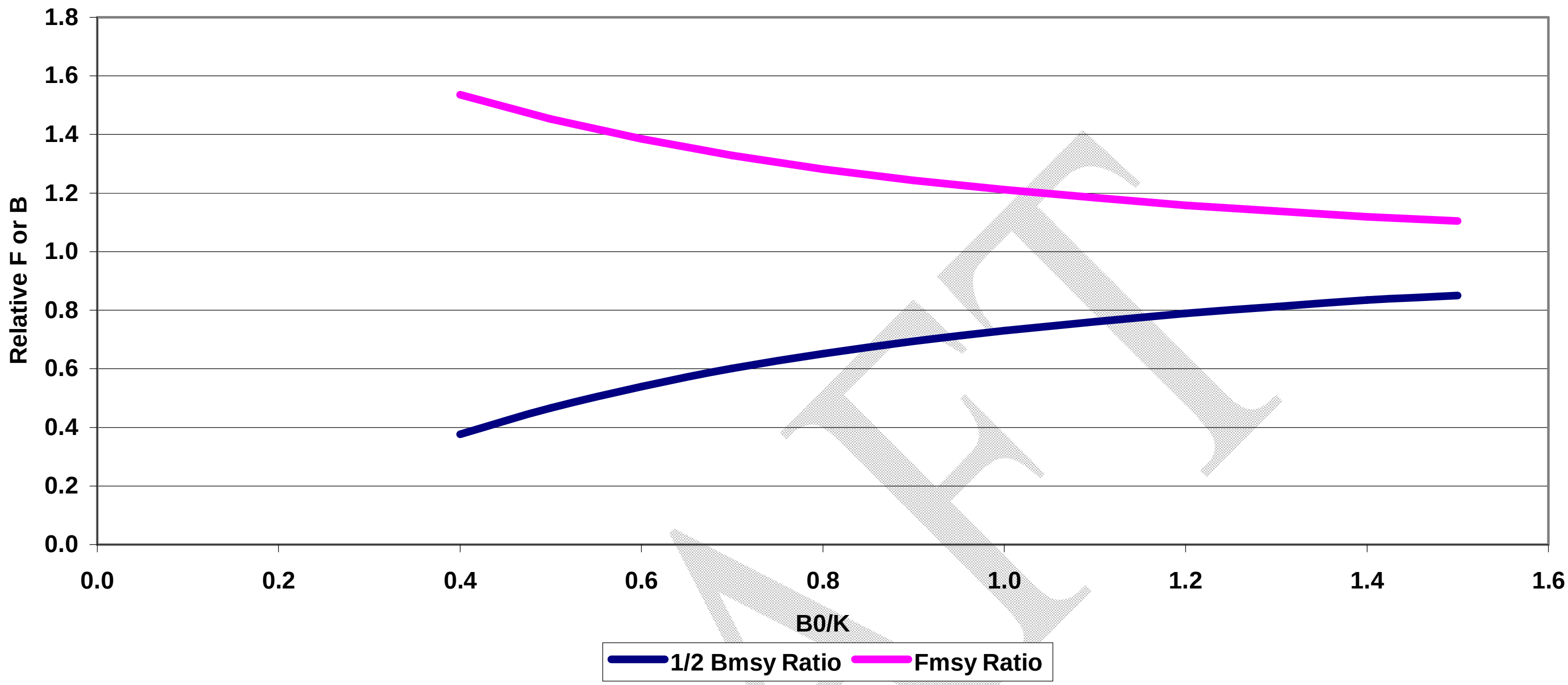


Figure 17- Sensitivity of RI Horseshoe Crab Stock Status to Ratio of Starting Biomass to Carrying Capacity



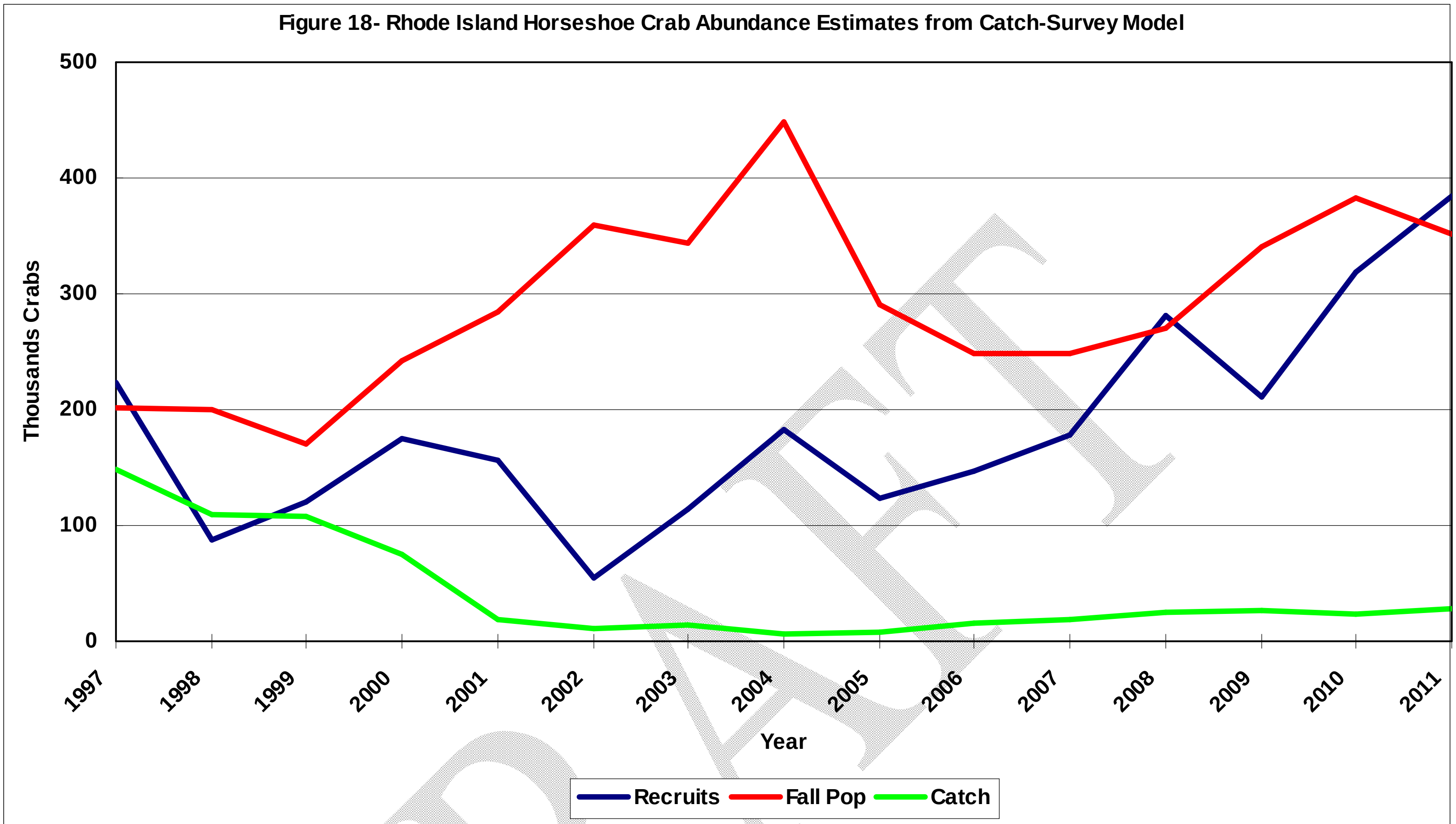


Figure 18- Rhode Island Horseshoe Crab Abundance Estimates from Catch-Survey Model
Thousands Crabs
500
400
300
200
100
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year
Recruits
Fall Pop
Catch

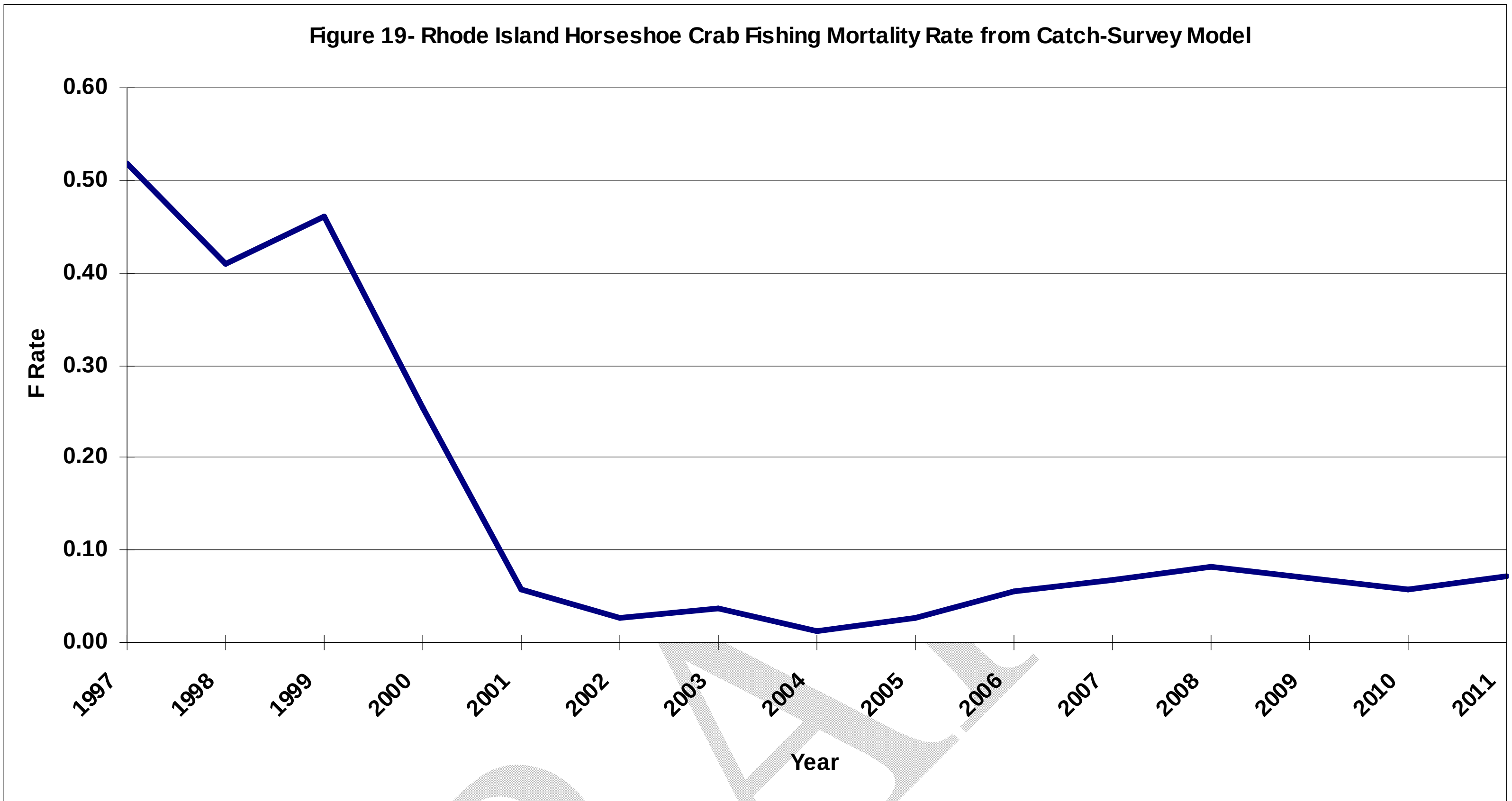


Figure 19- Rhode Island Horseshoe Crab Fishing Mortality Rate from Catch-Survey Model
F Rate
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year

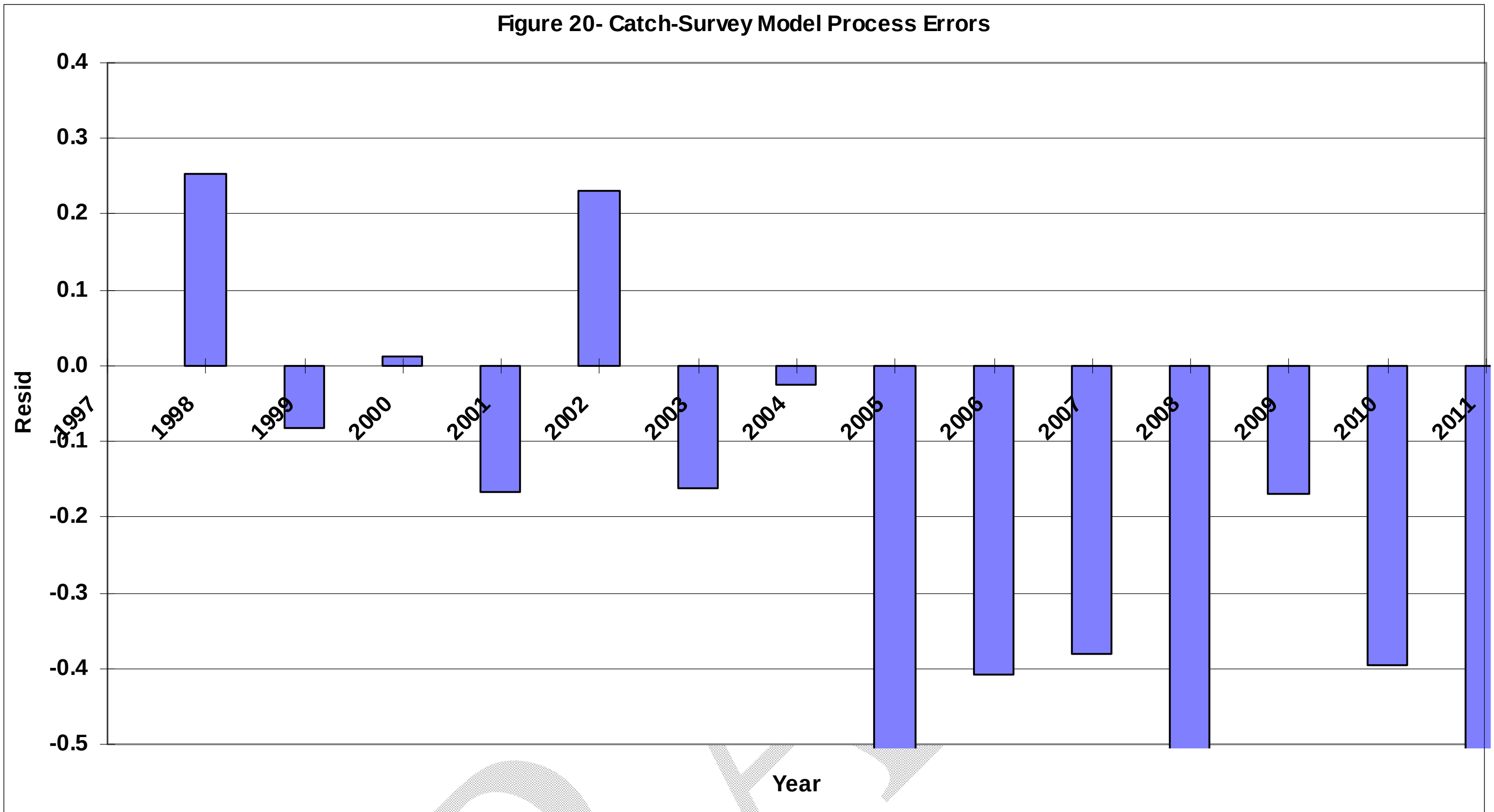


Figure 20- Catch-Survey Model Process Errors
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Resid
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year

Figure 21- Bootstrap Estimates of Intrinsic Rate vs. Carrying Capacity for RI Horseshoe Crabs