Assessment of Narragansett Bay Quahogs Using a Size Structured Model Applied to Landings and Survey Data and Suggestions for a Monitoring and Management Program

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Introduction-

The northern quahog resource in Narragansett Bay supports a valuable commercial fishery that has existed for some time (Olsen and Stevenson 1975, Rice 1992). Long-term landings data show two peaks; in 1955 at 2,277 metric tons meat weight and later in 1983 at 1,933 tons (Figure 1). A commercial dredge fleet operated during the first period (Russell 1972). High landings were not sustainable and dredging was banned in 1969. The second peak in landings occurred after opening of the upper Bay conditional fishing areas in 1982. These landings were also not sustainable. Current landings are low relative to past levels averaging 275 tons worth about 6 million dollars. Over 1,000 individuals have been employed in this fishery in the past (Holmsen and Horsley 1981). Current dealer transaction records indicate that 460-490 individuals sell quahogs each year but only 270-301 are regular diggers selling over 10,000 pieces per year. The last stock assessment of Bay quahogs was done by Gibson (1999). A surplus production model, tuned with auxiliary biomass estimates, was used to produce a bay wide estimate of stock biomass and fishing mortality rates for the period 1947 to 1998. It showed stock biomass at relatively low levels after a sustained period of high fishing mortality. While the stock was considered overfished, fishing effort and mortality rate were declining toward levels associated with maximum sustainable yield (MSY). Size composition data from fishery independent dredge surveys indicated that mortality rates varied spatially within the Bay. Depletion models applied to detailed catch and effort data from Greenwich Bay confirmed high mortality rates and suggested high grading of product. Fishing mortality rate for MSY was estimated at 0.17. A target mortality rate of 75% F_{msy} was recommended which required a 32% reduction from the 1998 baywide fishing mortality. A metapopulation simulation indicated that some larval subsidy from closed areas and periodic closure of conditional areas was necessary for population persistence under the rates of mortality estimated.

During public presentations, commercial fishers disputed some of the assessment results. They argued that the bay wide production model did not reflect known changes in the fishery, particularly changes in the manner in which product was purchased by shellfish buyers. In the mid-1980's, shellfish buyers began to purchase choice count neck clams by the piece rather than by the pound. This had the result of inflating the value of count necks relative to the larger cherrystones and chowder clams. This would have modified the selection pattern in the fishery, a change which the lumped production model could not account for. They also disputed the agencies' interpretation of the Greenwich Bay data. Catch per unit effort was shown to decline through the fishing season forming the basis of a Leslie depletion model. The resulting estimates of initial stock size were corroborated by a pre-fishery dredge survey indicating that the depletion model was reliable. However, the catch data when examined by market class, showed a seasonal decline in the proportion of count necks and increases in the proportion of larger clams over time. Gibson (1999) interpreted these data as evidence of "high grading", and sequential depletion of the most valuable smaller size classes. Commercial fishers countered that the Greenwich Bay data were contaminated with catch from other areas, the bag and tag regulations notwithstanding. They argued that the increase in proportion of the larger clams later in the season resulted from fishers moving to other areas.

Setting aside the merits of specific arguments, one general point emerged. The assessment had failed to fully exploit the information in the size composition of the catch and survey data. To that end, a new assessment model was developed which utilizes landings and survey data by market class. The Division has invested heavily in a fishery independent shellfish survey since 1993 and has improved the quality of landings data collected from dealers since 1999. The Standard Atlantic Fisheries Information System (SAFIS) commercial reporting system now provides trip level landings by market class and area harvested within the Bay. A hydraulic dredge survey in Narragansett Bay provides fishery independent estimates of quahog abundance by size class. Growth increment data from shell sectioning of clams sampled from the Bay in 2006 recently became available (Henry and Nixon 2008). These new data allow for the estimation of contemporary growth transition probabilities and are crucial to the assessment as Henry and Cerrato (2007) have

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shown that quahog growth in the Bay has undergone a decadal reduction probably due to an increase in water temperatures. A size/stage structured model is a logical advance in assessing the states quahog resource.

Methods and Data Sources-

Landings and Effort Data- Gibson (1999) summarized aggregate landings data for quahogs from 1946 to 1998 and provided landings by market class from 1983 to 1998. The industry and RIDFW scientific staff currently recognizes four market classes above the 25.4 mm legal shell width (Ganz et al. 1994). They are currently reported to the RIDFW SAFIS monitoring system as:

Count Necks	25-34 mm
Top Necks	35-39 mm
Cherrystones	40-43 mm
Chowders	44+ mm.

National Marine Fisheries Service (NMFS) data from 1983 to 1998 did not specify a top neck category. Gibson (1999) arbitrarily apportioned NMFS cherrystones into 2/3 top necks and 1/3 cherrystones by weight. For this assessment, that convention was reconsidered because landings of the smallest and largest market classes declined over time while the cherrystone category increased. Accepting the pattern as true requires that either abundance increased in the middle class while other classes declined or a major fishery selectivity change occurred. An abundance increase is not the reason since this would require spontaneous generation. The market classes are ontogenic and abundance cannot increase in the older stages of a cohort. Increased selectivity for top necks and cherries is unlikely as well since the count necks are more valuable. Rather, the pattern is likely due to changes in the fishery with respect to how landings were processed and market grade categorized. It is known for example that the change to per piece compensation in the early 1980's inflated the value of small clams relative to larger clams. It is also known that mechanical sorters with adjustable rollers were introduced into the buying houses in the early 1990's (Mackenzie et al. 2002). This technological advance allowed for faster processing of product and a refined separation of count necks. These changes are reflected in the observed proportions by market class over time. The count neck category increased from about 50% of total landings to about 75% from 1983 to 1990. Cherrystones declined from about 3% to less than trace levels. From 1991 to

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1999, the pattern reversed. Count necks dropped back to 50% and cherrystones increased to about 20% of total. This suggests that the true top necks were transferred from count necks to cherrystones.

To provide a more consistent set of landings by market class which map better into the modern RIDFW system, historic NMFS total landings in weight from 1983 to 1998 were multiplied by the 1983-1998 average proportions (0.50, 0.20, and 0.30) to estimate landings in weight for count necks, cherrystones, and chowder clams. The cherrystone class was the further subdivided into 0.11 top necks and 0.09 true cherrystones based on RIDFW 1999-2001 dealer report data. The four classes in weight were then raised to numbers using mean weights per clam derived from length-weight data. Landings by modern market class from 1999 to 2006 were collected using an interactive voice response (IVR) dealer reporting system. From 2007 to present, quahog landings by market class were collected using the SAFIS system. Classification of landings into market classes remains a source of uncertainty as dealers can adjust the classes depending on customer preferences. Over 95% of the current landings come from the upper bay conditional area, Greenwich Bay, and mid-bay east and west passages (Appendix I). Fishable area for the landings zones was calculated using GIS by subtracting waters deeper than 30 feet and those closed by pollution from the zone total.

Quahog fishery effort data in the form of a time series of shellfish license units was also summarized by Gibson (1999). He noted the problems in using licenses as an effort index because of latent effort from inactive licenses. Lazar et al. (1995) found that the number of shellfish licenses issued was roughly 3 times the level of participants actually observed in boat counts made during 1994-1995 sea sampling. Also, with the recent increases in soft shell clam abundance, some active effort has shifted to that species. Time-area pollution closures further impact effective fishing by rendering inaccessible otherwise productive fishing grounds. Pollution closure records were reviewed from 1982 to present. The original index from Gibson (1999) was updated and considered in tuning fully recruited fishing mortality rates in the assessment.

<u>Survey Data</u>- The RIDFW has conducted a hydraulic dredge survey of the quahog population in Narragansett Bay since 1993. Details of the vessel, survey gear, and methods are given in Ganz et al. (1994). The current survey is of a random stratified design conducted in the summer. A total of 19 sampling strata have been identified

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in Narragansett Bay in waters up to 30 feet deep. Within each stratum, grids of sampling quadrats have been identified and are randomly selected with intensity proportional to stratum area (20% of total with minimum of 2). The hydraulic dredge is deployed for a standard tow that covers 10.8 m^2 of bottom. Sampling of quahogs is a statistically challenging exercise because of their patchy distribution (Murphy and Erkan 2006). Saila et al. (1965) found that quahogs exhibited a super dispersed pattern that could be described by the negative binomial distribution. This means that significant quantities of clams exist in high density but infrequent patches. The length of a dredge tow integrates small scale variations along the path. Captured quahogs are enumerated and measured for shell width. Mean number per m^2, disaggregated by market class, was used to tune the catch at size model. Survey data were available from 1993 to 2008. The survey was limited to Greenwich Bay in 1993 and moved to other areas in 1994. It assumed its current baywide form in 1996. No survey was conducted in 2009 due to a vessel break down. Proxy values for 2009 were estimated by ratio using the SAFIS cpue data by market class for years 2008-2009. The dredge indices were considered a relative abundance measure, the model was not tuned to absolute swept area biomasses. Additional research on dredge efficiency in different substrate types is needed before this can be done.

Growth Data- Estimating fishing mortality rates by size class requires an estimate of the transition probabilities between size classes. It is necessary to distribute survivors into appropriate size classes in each time step. Depending on the width of the size class and growth rates, some individuals will remain in the original class while some may advance one or more classes. Promotion probabilities, or the likelihood that an animal in size class i will advance to size class i+1 given that it survives were estimated from new growth data. Quahog growth in Narragansett Bay varies by area in response to a number of factors (Pratt and Campbell 1956, Rice et al. 1989, Rice and Pechenik 1992). Gibson (1999) summarized historical growth data and fit an average von Bertalanffy curve. For this assessment, von Bertalanffy growth parameters for Narragansett Bay quahogs were updated using findings from the Henry and Nixon (2008) study. von Bertalanffy L_∞ and k parameters were estimated for each area sampled using aging data provided by the author (K. Henry-pers. comm.). The VBG model is a decelerating nonlinear function used to relate size to age in animals that display asymptotic growth (Quinn and Deriso 1999):

$$L(t) = L_\infty[1-\exp-k(t-t_0)] \qquad (1)$$

where: L= length
t= age
L_∞= asymptotic length
k= growth coefficient
t_0= age when length equals zero.

Parameters to eq.2 were estimated using EXCEL SOLVER. Mean growth parameters, weighted by sample size, were used to estimate promotion probabilities. I assumed that length distributions within a commercial market class were uniform across 1 mm increments. Using the Fabens (1965) increment formulation of the von Bertalanffy equation:

$$L_f=[(L_\infty-L_i)(1-\exp(-k)+L_i] \qquad (2)$$

where:

L_f= final shell width
L_i= initial shell width

probabilities of advancement (p) were computed. For each 1 mm interval in a market class, the next year's length was projected using eq.2. If that length met or exceeded the next class lower limit, promotion occurred. The promotion probability was estimated as the proportion of individuals in a size class that would advance in one year. Multiple steps did not occur with this approach so that an animal either advanced one class or remained in the original class. Recruitment from sublegal clams occurred only into the first legal class (count necks).

<u>Natural Mortality Rate</u>- Assessing quahogs requires an external estimate of natural mortality rate (M) as there is insufficient information in the fishery and survey data to resolve M from selectivity and catchability. This is not a serious problem since M in long-lived, sedentary animals should be relatively low and stable. M rate in mollusks is likely inversely related to size and longevity (Robertson 1979, Hoenig 1983, Appledorn 1988, Caddy 1989). Quahogs as a family are long-lived. The ocean quahog, *Artica islandica*, has very a low natural mortality rate (Kilada et al. 2007) and, with a longevity in excess of 400 years, is recognized as the longest lived invertebrate (Schone et al. 2005). Northern quahogs, *Mercenaria mercenaria*,

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were aged to 46 years in North Carolina (Peterson 1986) and 36 years in Georgia (Walker and Stevens 1991). They reach comparable ages in Rhode Island (Jones et al. 1989, Rice et al. 1989). The recent work of Henry and Nixon (2008) found a maximum age of 26 years in Narragansett Bay samples. This longevity indicates a low natural mortality rate which has been experimentally confirmed at 2-4% per year (Malinowski 1993, Harding 2007, Kraeuter et al. 2009). For this assessment, longevity was assumed to be 40 years. Size specific estimates of M were made using the inverse power relationship of Lorenzen (1996) but with intercept adjusted so that M in the chowder class (ages 13-40) converged on 0.1 per year:

$$M=0.51*W^{-0.29} \qquad (3)$$

where: W= shell weight in grams.

<u>Size Structured Model</u>- A size structured model was developed for quahogs assuming that mortality followed an exponential decay process, that catch was realized in accordance with Baranov's catch equation with fishing mortality separable by year and size, and that growth was of the von Bertalanffy form. A population dynamics process can be written in difference form as:

$$N_{ij}= [(N_{ij-1}*(1-p)*\exp(-(F_{ij-1}+M)))] + [(N_{i-1j-1}*(p)*\exp(-(F_{i-1j-1}+M)))] +\varepsilon_p \quad (4)$$

where:

N= population size
F= fishing mortality rate
p= promotion probability
M= natural mortality rate
i= size class
j= year
ε_p= process error.

Eq.4 constructs size class abundance in a given year as the sum of same class survivors from the prior year that did not advance plus survivors from the next smallest class that did advance. The total population is equal to the sum of the class specific abundances. Fishing mortality rate is separable into a year effect and a size selection effect:

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$$F_{ij}= F_j*s_i \tag{5}$$

where:

F= fully recruited fishing rate
s= selectivity coefficient.

Under eqs. 4 and 5, catch at size and by year is equal to the beginning year population multiplied by the fishery exploitation rate:

$$C_{ij}=N_{ij}* (F_{ij}*(1-\exp(-(F_{ij}+M)))/(F_{ij}+M)) \qquad (6).$$

Fully recruited F rate is further assumed to be proportional to nominal fishing effort (f) through an effort catchability coefficient (q).

$$F_j=q*f_j. +\varepsilon_m \tag{7}$$

Since actual population sizes are unknown, an observation model is needed to relate dredge survey abundance proportionally to population size:

$$N_{ij}= (I_{ij})/q_i +\varepsilon_m \tag{8}$$

where:

I= survey abundance index
q= catchability parameter
ε_m= measurement error.

The system of equations 4-8 provide the means to make a statistical estimation of population abundance by size class, fishing mortality rate by size class, and the scaling parameters that relate survey abundance to population size and fishing effort to fishing mortality for years 1983 to 2009. Parameters estimable include a vector of 4 starting abundances by size class in 1983, recruitment abundances in the first size class from 1984 to 2009, fully recruited F rates from 1983 to 2009, selectivity coefficients for top necks, cherrystones, and chowder clams (count neck selectivity is set equal to 1.0), a catchability parameter relating the effort index to full F, and

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survey catchability parameters for the 4 market classes. Biomass can be computed from the size class estimates and weight at size. Abundance estimates refer to the fished areas since they are reconstructed from landings data. The model can be considered analogous to a forward projecting statistical catch at age model but with size classes replacing age groups and movement through the size classes governed by the growth model. With M fixed and the promotion probabilities set according to growth data, parameter estimates can be obtained by minimizing squared deviations between the observational data and the modeled quantities or:

$$\Sigma \left[(\ln C_{ij} - \ln \hat{C}_{ij})^2 + \alpha (\ln f_{ij} - \ln \hat{f}_{ij})^2 + \alpha (\ln I_{ij} - \ln \hat{I}_{ij})^2\right]$$

The second and third terms in the objective function represents model "tuning" to the auxiliary effort and survey abundance estimates. As with the original statistical catch at age model, catch data alone cannot reliably estimate population size (Doubleday 1976). The α are the penalty weights determining how much influence the auxiliary data has on the estimation. For minimum variance parameter estimates, α should equal the ratio of catch variance to auxiliary data variance (Gallucci et al. 1996, Quinn and Deriso 1999). Bay wide survey estimates of mean quahog density since 1996 have had coefficients of variation of 17% or less. It is unlikely that the catch and effort estimates are more precise so equal weighting of the sum of squares components was used (α=1). The model at this point does not include stock-recruitment elements. Although estimates of recruiting size classes and total abundance of spawners emerge from the solution, they are not forced toward a parametric S-R curve. This constraint could be imposed if additional model structure were added to the objective function. This may prove useful in future model iterations that include spatial strata and source-sink terms to account for transplanting and seeding programs. The abundance of quahog predators in the Bay is monitored in the URIGSO trawl survey (Collie et al. 2008). While the abundance of crabs, lobsters, and whelks has generally increase during the assessment period, additional model structure for predation was not added because Polyakov et al. (2007) did not find increasing predator abundance to be a primary factor in the Great South Bay quahog decline. Should evidence of a predation effect emerge, it may be possible to configure natural mortality rate as a constant plus a time varying function of predator abundance.

A measurement error model was assumed so that all of the error associated with eqs. 4 to 8 is allocated to estimation error in the catch, effort, and index data. Future model refinements might address a combined measurement and process error estimation. The EXCEL SOLVER was used to minimize the objective function. Residuals were computed in the log scale assuming multiplicative error. Uncertainty in estimated quantities was evaluated with bootstrapping (Efron 1982). Residuals from the original model fit were resampled with replacement and used to construct new catch, index and effort inputs for successive model fits. The bootstrapping exercise was expanded to include a Monte Carlo simulation of uncertainty in the growth transition matrix. For each replication, in addition to residual resampling, a value of von Bertalanffy k parameter was drawn from the normal distribution indicated by the Henry and Nixon (2008) study. This k was used to recompute the growth transition probabilities for fitting the model. A total of 1000 bootstrap Monte-Carlo replications were made and 95% confidence bounds on parameters and derived management quantities were calculated directly from the frequency distributions.

<u>Biological Reference Points</u>- The Thompson-Bell yield and spawning biomass per recruit model from Gibson (1999) was updated to estimate reference fishing rates such as $F_{0.1}$, F_{max}, and $F_{40\%}$. YPR and SSB/R analysis was conducted using the NMFS NFT toolbox implementation of the Thompson-Bell model (vers. 2.7.2). A description and application of the model can be found in Gabriel et al. (1989). YPR analysis involves modeling the fate of a cohort during its fishable life span given user specified levels of natural and fishing mortality, selectivity pattern, growth, and maturation. Outputs include yield to the fishery and spawning stock biomass, both on a per recruit basis. Modifications to inputs from Gibson (1999) included an update to the von Bertalanffy growth parameters as noted above and revised estimates of the fishery selection pattern. The selection coefficients for top neck, cherrystone, and chowder clams were estimated as above and the von Bertalanffy growth equation was used to determine which age groups these applied to. Natural mortality rate was an inverse power function of body mass (Lorenzen 1996), declining at a rate of -0.29. M at age 1 was 0.50 and declined 0.17 at the transition to legal count necks (4.5 years). M stabilized at 0.10 for ages 15-40. The Thompson-Bell model was run over a range of F from 0 to 2.0 in 0.1 increments.

<u>Projections</u>- A preliminary deterministic projection exercise was run out 10 years assuming that growth, natural mortality, and selectivity were constant. Recruitment to the count neck class followed the relationship in Figure 13. Terminal year (2009) abundance by size class was propagated forward under an F ranging from 0 to 0.20

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to determine the scope for stock rebuilding. More complex stochastic projections using the bootstrap outcomes and Monte Carlo methods are possible but are not warranted at this time given the development level of the assessment model.

Results-

Landings and Effort- Total quahog landings during the assessment period peaked at 11,465 metric tons shell weight in 1985 (Figure 2). A steady decline to 2,042 metric tons by 2009 is evident. The reformulated landings by market class are shown in Figure 3 and decline over time in parallel with the total. Count necks dominate the landings numerically (Figure 4) although chowders are important from a weight standpoint. The best performing index of effort was total licenses applicable to the quahog fishery as used in Gibson (1999). This long-term index is consistent with recent SAFIS dealer transaction records in showing a slow decline over time of about 3% per year. Further adjustment to the index to reflect latency and time-area rainfall closures did not improve the fit. The selected index is plotted in Figure 5. Like landings, it also declines over time from 2,200 in 1983 to less than 1,000 units currently. These data indicate a drop in clam abundance since implied CPUE (catch divided by effort) declines about 50% from 1983 to 1995 but is stable thereafter. It is an important observation since catch and effort are the only information on abundance trend early in the assessment.

Dredge Survey Abundance Estimates- Estimated quahog abundance by market class from the dredge survey is summarized in Table 1. Overall legal density fluctuated between 1.5 and 3.0 clams per square meter and showed no long-term trend (Figure 6). The proportional standard error (PSE) on mean abundance typically runs between 0.10 and 0.15. It should be remembered that annual surveys conduct between 100 and 120 tows and each is 100 m long. The mean densities are averaged across small-scale spatial variations. Sublegal quahogs are infrequent in the survey (7%) because of the 25.4 mm bar spacing in the dredge that allows small clams to pass through (Figure 7). Because of their low catchability, they were not considered further in the assessment. Chowder clams were the most abundant class sampled accounting for about 34% of the samples followed by count necks at 26%. The ascending left hand side of Figure 7 suggests that count necks are not fully recruited to the survey gear despite the 1" spacing on the dredge. It should be noted that the RIDFW dredge survey began in 1993 and lacks temporal contrast since it does not span the entire 1983-2009 assessment period. Gibson (1999) assembled data from shellfish surveys conducted since the 1950's and concluded that quahog abundance in the 1990's was lower than in past decades. Additional work is warranted to examine historical shellfish surveys for possible inclusion in assessment updates.

Growth Parameters- von Bertalanffy growth parameters estimated for 10 sample sites in Narragansett Bay from the Henry and Nixon (2008) study are summarized in Table 2. Mean asymptotic shell width and growth rate weighted by sample size were L_{∞}= 51.2 mm (SE=2.95) and k=0.16 per year (SE=0.02) respectively. At this rate of growth, quahogs would reach the legal minimum size in 4.5 years. This is in the upper end of the range reported by Bricelj (1993). Estimates of the transition probabilities by market class for the mean growth rate are given in Table 3. In one year, 30% of the count neck market class would promote to top necks. A somewhat larger proportion of top necks would promote to cherrystones (.40). The probability of cherrystone clams recruiting to the final chowder clam stage was 0.25. It is important to note the variability in the growth parameters, particularly k, on the transition probabilities. With a between site coefficient of variation of 30%, the 95% confidence bound on k was 0.12 to 0.20. This corresponds to a count neck transition probability ranging from 0.20 to 0.40. It is handled in the assessment uncertainty calculations by Monte Carlo sampling from a defined distribution but remains a major source of uncertainty for a baywide assessment.

Estimates of Stock Size and Mortality Rates- The catch-size model generally fit well with most bootstrap CV's on stock sizes, exploitation rates, and selection-catchability parameters ranging from 0.15 to 0.27 (Table 4). Parameters relating to the chowder class were less precise (CV=0.32-0.39). This relates to the high year to year variability in the dredge survey catch of chowder clams and the compounding of error in the forward calculations of chowder class dynamics. Estimates of population sizes and exploitation rates by market class are given in Table 5. Count neck clam abundance declined from 260.2 million in 1983 to 80.1 million by 2009 (Figure 8). The 2009 abundance had a bootstrap 95% confidence bound of 35.9-123.3 million. Top necks declined from 68.5 million in 1983 to 39.5 million by 2009 (Figure 9). The 2009 abundance had a 95% confidence bound of 19.5 to 56.1 million. Both cherrystone and chowder clam abundance declined as well (Figures 10 and 11). Cherrystones fell from 105.2 to 30.3 million while chowder clams fell from 40.6 to 19.6 million during the assessment period. Confidence bounds on the 2009 abundances were 13.7-40.7 and 7.5-35.3 for cherries and chowders respectively. Total abundance of legal quahogs declined from 474.5 million to 169.5 million

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(Figure 12). The 2009 total abundance had a 95% confidence bound of 95.9-236.2. Total biomass in the fished areas declined from 53,385 tons in 1983 to 19,896 tons by 2009. The terminal year estimate had a 95% confidence bound of 11,650 to 27,506).

Model estimated nominal effort well tracked the observed series with a catchability coefficient estimated at $2.79*10^{-4}$ (95% CI: $1.73\text{-}4.33*10^{-4}$). Full recruited fishing mortality rate rose from 0.47 in 1983 to a peak in 1991 of 0.69 and then declined through 2009 (Figure 13). F in 2009 was estimated at 0.20 with a 95% confidence bound of 0.11-0.31. Model based F in 1994 and 1997 was quite close to the independent estimates made by depletion fishing and reported in Gibson (1999). These are believed to be particularly reliable since they are backed up by a pre-fishery dredge survey. Fishery selectivity pattern was u-shaped. Count necks have a default selectivity of 1.0, consistent with their high market value. The selectivity coefficient for top necks was estimated at 0.46 with a 95% CI of 0.33 to 0.62. Estimated selectivity for cherrystones declined further to 0.19 (95% CI: 0.13-0.30). Chowder clams were intermediate to counts and tops with selectivity of 0.78 but the precision was poor (95% CI: 0.18-1.36). Dredge survey catchability increased with clam size (Table 4). The catchability coefficient for count necks was estimated at 0.62 with a 95% confidence bound of 0.39 to 0.94. Top necks had catchability estimated at 1.64 (95% CI: 0.92-2.74). Cherrystones had catchability estimated at 1.72 (95% CI: 0.71-3.52). Chowder clams had the highest catchability at 4.43 but the precision on the estimate was poor (95% CI: 1.42-7.60). Correlation analysis of the bootstrap outcomes indicated several strong correlations between fishery selectivity and survey catchability within market classes. This suggests an over parameterized model and "loose ends" in the estimation. Future model refinements should consider specifying functional forms for fishery selectivity and survey catchability to reduce the number of parameters and "tighten" the solution.

<u>Model Diagnostics</u>- Notable model residual patterns were found for survey count necks showing a block of positives switching to negatives in later years and for top necks and cherrystones catch that were opposite one another (Figure 14). In the former, negative residuals indicate an underestimation of abundance by the model relative to observed survey data. Model deficits of smaller clams in later years could be due to changes in growth transition probabilities or natural mortality rates that were modeled as time invariant. Gibson (1999) noted an increase in benthic predators of quahogs and suggested that this could be related to reduce stock

productivity. Time varying M seems likely but cannot be distinguished from changes in selectivity and errors in input catch data. The catch residual patterns between top neck and cherrystone clams probably result from the conventions used to break out early NMFS data by market classes. Sensitivity to the 1983 to 1998 data will diminish as additional years of SAFIS and dredge survey data are added. Future assessments should consider time blocks of selectivity so that the "old" and "new" data periods can be decoupled and modeled separately.

Stock and Recruitment- The emergent relationship between recruiting count neck abundance and spawning stock assuming a four-year lag earlier is plotted in Figure 15. A power curve best fit the data and explained 79% of the variation in count neck abundance. The exponent to the curve was estimated at 0.56 with a 95% confidence bound of 0.43-0.69. A positive slope less than 1.0 indicates a compensatory relationship between recruits and spawners since plausible curves should pass through the origin. This finding is consistent with that of Kraeuter et al. (2005) for Great South Bay, New York quahogs. They found a parabolic relationship between recruits and spawners drawing upon many years of survey data in a fished area. Their data indicate that at spawner densities below 1.5 per square meter, recruitment is impaired and below 0.75, there may be no reproduction at all. Peterson (2002), working in North Carolina, also found that quahog recruitment declined under heavy fishing pressure that reduced spawning stock. The relationship in Figure 15 may be criticized on grounds that not all recruiting count necks are 4 years old. The growth variability noted above insures that is the case. However, varying lags from 3 to 5 years gave virtually the same relationship.

Estimated density of Narragansett Bay quahogs is plotted in Figure 16 compared to the Great South Bay limit. Assessment model density is computed as the population estimate of legal clams divided by an estimate of fishable area. The survey density is directly from the dredge survey. The former has fallen below the limit while the later is still above. There are several possible reasons for the discrepancy between model and survey results. First, the assessment model only considers commercial landings. There is a recreational fishery for quahogs in the Bay that is popular with shoreline residents and visiting summer non-residents but landings are unknown. Missing landings would cause a negative bias in estimated populations and densities (Kraeuter et al. 2008). It is also possible that the fishing area was overestimated inducing the negative bias in density. Future assessments should consider constraining model abundance estimates to absolute rather than relative survey

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densities if they are sufficiently precise and conform spatially to fished areas.

Biological Reference Points- Yield per recruit (YPR) and spawning stock biomass per recruit (SSB/R) for a range of F values are plotted in Figure 17. $F_{0.1}$ was estimated at 0.17 while F_{max} was estimated at 0.44. Fishing mortality rate providing for 40% of unfished SSB/R was 0.15. These estimates are lower than those reported in Gibson (1999) because of changes to growth parameters and fishery selectivity. The most recent growth estimates indicate that clams recruit to the fishery at a younger age. Also, the estimates of selection for top neck and older clams are higher. Gibson (1999) suggested using F_{msy} as an overfishing definition and 75% F_{msy} as a target. The F_{msy} estimate from the surplus production model in that assessment (F_{msy} =0.17) was corroborated by indirect life history methods. The surplus production model ignores fishery selectivity so that the F_{msy} was biomass weighted. Gibson (1999) indicated that F_{msy} =0.17 was associated with 19% of maximum spawning potential. This updated SSB/R analysis indicates that 19% of MSP is achieved with a fully recruited F=0.34.

The phase plot of population abundance vs. fishing mortality rate is shown in Figure 18. Stock abundance declined substantially under fishing mortality rates of 0.50 to 0.70. Abundance was stable but low at F ranging from 0.30 to 0.50. A small increase in abundance has occurred after F was reduced to about 0.20. Given the findings of this assessment and others, $F_{20\%}$=0.32 and $F_{30\%}$=0.21 are suggested as overfishing definitions and target mortality rates respectively. Mean fully recruited F in 2009 was estimated at 0.20 with a 95% confidence bound of 0.11-0.31. It is unlikely based on the bootstrap results that fishing mortality in 2009 exceeded the overfishing $F_{20\%}$ rate but was close to the target. Rebuilding stock abundance to higher levels will be slow and require F rates lower than the target. The projections indicate that the stock would increase about 45% in 10 years if F were reduced to 0.10 (Figure 19). Reducing F even to 0 however could not return the stock to 1983-1985 levels in 10 years (Figure 20). These observations are consistent with the simulations of Kraeuter et al. (2008) who found that heavy fishing mortality would reduce population abundance substantially and that recovery times were decadal in magnitude under low fishing rates.

Discussion-

As a result of upgrades to sewage treatment facilities and improving water quality,

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the upper Narragansett Bay conditional shell fishing area was established in 1981. Upon opening, quahog landings jumped by 40% between 1981 to 1982 and remained at high levels for several years (Figure 1). Elevated landings likely resulted from fishing down the accumulated stock in areas formerly closed to fishing. They were not maintained and by 1986 landings were in steady decline that did not bottom out until 1999. This assessment indicates that quahog numerical abundance declined from 1983 to 1997 by 67% under excessive fishing mortality rate and then stabilized at lower levels when F rate moderated (Figure 18). Similar stock declines were reported for Great South Bay (Bricelj 2009), Chesapeake Bay (Harding 2007), and in North Carolina (Peterson 2002). The Rhode Island stock and recruitment data indicate that quahog density in the main fishing areas has been reduced substantially and may be approaching the limiting density where recruitment was impaired in Great South Bay (Kraeuter et al. 2005). Low recruitment in the face of continued fishing can prolong periods of low quahog abundance by slowing rebuilding or when coupled with increased natural mortality can prevent it altogether (Kraeuter et al. 2008, 2009). Projections indicate that a return to former abundance levels in the short-term is unlikely. New research on the growth rate of Narragansett Bay quahogs indicates that growth seasonality has changed so that the scope for rapid growth has been reduced (Henry and Cerrato 2007, Henry and Nixon 2008). In all, these findings suggest that the productivity of the quahog resource in Narragansett Bay has been reduced. Managers should review the current management program and consider strategies to offset the loss in productivity.

It is clear from this work and the scientific literature that quahog density and associated body condition are critical quantities for successful management. That density can shape quahog populations by influencing growth, survival, and reproductive success is not new (Rice et al. 1989, Malinowski 1993, Peterson 2002). However, a series of new studies since the Gibson (1999) assessment sharpens that view. The study of Kraeuter et al. (2005) established the first quantitative relationship between spawner density and resulting recruitment. Their data indicate both a limiting density below which recruitment is impaired (~1.5 per m^2) and a critical density below which there may be no recruitment (~0.7 per m^2). The lower limit is likely due to Allee effects where fertilization of free-spawned gametes does not occur at low densities (Levitan 1991). Kraeuter et al. (2008) established conclusively that recruitment overfishing occurs and leads to stock declines. A the other end of the spectrum, it was found that dense populations in areas closed to fishing do not achieve the same reproductive output of clams in less dense, fished areas (Marroquin-Mora and Rice 2008). This called into question the long-held belief that dense aggregations of quahogs in closed areas serve as broodstock for down-stream fished areas. Further, Doall et al. (2008) showed that the condition of quahogs in the fall was a key factor in determining reproductive output the following spring and fall condition was influenced by density especially in larger clams that carry many eggs but require disproportionate food resources (Kraeuter et al. 2008). Adding to the density dependent dynamics, there is evidence that environmental factors such as increased water temperature, hypoxia, brown tides, and reduced food supply have lowered the growth rates of quahogs (Henry and Cerrato 2007, Bricelj 2009). Taken together, the new information compels state scientists and managers to review their best management practices (BMP) and modify them as appropriate. To that end, there is a need for a monitoring and assessment program that can track performance and evaluate management alternatives.

An Assessment and Management Framework-

Management of Rhode Island's shellfish resources and fisheries has become increasingly complex with many moving parts and diverse stakeholders interests. Wild harvest fisheries, aquaculture operations, and restoration programs utilizing transplant/seeding need to be coordinated and brought to bear on a common set of management objectives. These objectives may be as narrow as profitable and sustainable commercial operations or as wide as restoration of ecological services from filtering bivalves. A strong scientific basis for management that is responsive to new understandings is needed. This will require a supporting triad of fishery dependent monitoring, fishery independent monitoring, and targeted biological research (Appendix 2). An adaptive feedback loop is essential so that new findings can influence BMP. Adaptation should be active in the sense of Walters (1986) and this concept is developed further below.

Fishery dependent monitoring involves collection of data from fishermen through logbooks (spatial dimension), dealer data through SAFIS (landings volumes), and bio-sampling of the landings (catch attributes). In Rhode Island, there are currently no shellfish logbook or catch sampling programs. All fishery landings, spatial details, and catch composition come through the SAFIS program. After lobbying by industry, a decision was made to exclude shellfishers from the state logbook program. This decision should be reconsidered as SAFIS is inadequate to capture individual harvester details. Transplant activities could be configured as fishery dependent surveys and could provide information on densities and size composition in closed areas if properly conducted and sampled. Transplant and seeding programs are important collaborative efforts with industry and environmental stakeholders committed to Bay restoration. They can also play a direct role in assessment and management. Transplanted and seeded stock, if uniquely identifiable, can be used in mark-recapture experiments to estimate biomass, fishing mortality rates, and recruitment. Fishery independent data is collected through the RIDFW hydraulic dredge survey. As noted above, it provides relative abundance estimates by size and area. With appropriate modification and evaluation of efficiency, it could provide swept area estimates of biomass by stratum. Targeted biological research consists of studies on key life history attributes or aspects of the fishery. A good example is the Henry and Nixon (2008) study on age and growth of quahogs that filled a vital assessment need for this work.

With appropriate data collection and research programs in place, a spatially stratified assessment model including closed areas can be developed from the Bay wide version above. It is a straightforward task to apply eqs. 4-8 to stratum specific data including appropriate stratum linkages for stock-recruitment relationships. Model mark-recapture elements corresponding to transplanting/seeding activities can be included. For example, the population dynamics in the closed areas are driven by growth and losses due to natural mortality and transplanting while recruitment is from local spawners. Open areas likely have different growth rates and lose clams from fishing and natural mortality but may receive recruitment from local spawners and subsidies from transplanted or seeded stock. Landings and survey samples may contain marked animals from releases of known magnitude. As long as stratum specific data are collected and mass-balance principles are obeyed, a comprehensive stratified assessment is possible. A rotational harvesting program could be supported. Estimation efficiencies may be possible by sharing key parameters across strata. The most challenging element will likely be the S-R connections between strata related to larval dispersion. With a retrospective assessment in hand that includes S-R elements, it should be possible to develop a projection capability to be used for management policy evaluation and in guiding research. In principle, the status of any stratum could be projected given chosen policies for fishing, transplanting, seeding, and habitat manipulations.

Research and Monitoring Needs-

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Fishery Dependent Monitoring-

1) Logbooks- Commercial shellfishers should be required to fill out state logbooks providing catch and effort data on appropriate temporal and spatial scales. A subset should be recruited to conduct “test digging” in areas of interest to the Division.
2) SAFIS- Continue coverage and conduct periodic review of the market classes being used by dealers. Consider refining catch accounting areas to be consistent with survey strata.
3) Bio-sampling- Quahogs should be sampled at the dealers to provide adequate characterization of the catch.
4) At Sea Observation- RIDFW staff should conduct periodic boat counts during high participation openings. A combination of on-water and aerial assets should be considered.
5) An estimate of recreational harvests should be made periodically.
6) Transplants- Configure transplants to collect density data from closed areas and sample transplanted stock for size composition.

Fishery Independent Monitoring-

1) Dredge Survey- The annual bayside survey should be reconfigured to concentrate on specific areas of concern on a rotational basis. Sampling intensity should be sufficient to produce precise estimates of biomass by size class. Surveys should include pollution closed areas and spawner sanctuaries.
2) Survey Catchability- Depletion experiments in several substrate types should be conducted to estimate the one-pass efficiency of the hydraulic dredge for biomass estimation purposes.
3) Habitat mapping- Develop side-scan sonar habitat relationships with survey densities for purposes of improving survey precision, biomass estimation, and mapping.

Targeted Research-

1) Continue an age-growth study of quahogs in assessment strata.
2) Support genetic and hydrodynamic studies on the source-sink linkages of quahogs in assessment strata.
3) Support research on the fate and performance of transplanted and seeded stock.
4) Conduct experiment to calibrate industry “test diggers” to hydraulic dredge.

5) Develop marking methods and protocols for use in transplant/seeding programs so that mark-recapture estimation can be included in the stock assessment.

Adaptive Management and Rhode Island Quahogs-

Most fishery managers today use the phrase adaptive management and have an intuitive understanding of it at least the passive type. However, what is done in practice is mostly reactionary not adaptive. Management of quahogs is based on an old paradigm and managerial reactions are made to industry problems or stakeholder interests on a regular basis. The paradigm is constructed as limits on fishing time and harvest in certain areas, spawner sanctuaries and transplant/seeding to subsidize fished areas, and reliance on permanent pollution closures to failsafe the entire production system. The extent of time-area pollution closures is reduced as improvements to water quality occur. Economic pressures on industry are growing with recessionary impacts coupled with market competition from aquacultured products. Very little science supports the paradigm as it is mostly based on a belief system from past practices. Random environmental perturbations such as heavy rainfalls and hypoxic events add unpredictability to the system. The result is an annual bargaining session between industry and managers to respond to past and current problems. For example, a new pollution closures leads to reduced income and crisis that must be offset by increasing harvesting opportunities elsewhere. Then, excess harvest causes a price reduction that must be addressed by limiting harvests but only those harvests made by interlopers that "caused" the crisis. Or, a massive Bay fish kill from hypoxia triggers public demand for bay restoration programs including increasing abundance of filtering bivalve agents. Many partners gather to plan public-private ventures. Initiatives are approved and executed in a vacuum of objectives. The intent here is not to be condescending and belittle what are mostly noble efforts but to point out the failure to truly design and utilize adaptive management strategies.

In his 1986 text that brought adaptive management concepts to the desk of many managers, Walters (1986) lays out four fundamental elements that are summarized as follows:

1) setting bounds on the objectives of management including practical constraints that may exist;
2) developing a dynamic model of the system that embodies current

understanding and allows for identification of areas where improved understanding is needed;

3) incorporating statistical uncertainty and it's propagation through time in the model so that alternative hypotheses on the system can be considered;
4) Development of policies that balance continued system productivity with active experimentation on the system for learning.

Obviously element one, bounding the problem, is critical and requires extensive input from industry, the public, elected officials, other professionals and so forth. Internal development of straw men is a logical starting point but eventually forums such as Director Roundtables, facilitated workshops, and legislative hearings will be needed for vetting and adoption. The size based model above is offered as a starting point for the instrument called for in element two. Once further developed, the projection exercise envisioned above including resampling of model residuals and incorporation of Monte Carlo elements for unknown inputs should satisfy item three. Maintaining system productivity while conducting active probing of the system (element 4) is the hallmark of active adaptive management. More specifically, probing to learn in areas specific to the objectives not learning in general is the goal. For example, experimental manipulation of quahog density to see if the Kraeuter et al. (2005) asymptotic recruitment limit exists is warranted but deliberate overfishing to see if depensation exists at low densities would not be appropriate. Since quahogs are a sedentary species of considerable fishery and ecological value, they are a logical candidate for the state to embark on a review and modernization of a fishery management program.

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Publishing Company, New York. 374 pp.

Table 1- Quahog Abundance Indices from the RIDFW Hydraulic Dredge Survey in Narragansett Bay						
	Mean Legal No.		Count Neck No.	Top Neck Number	Cherrystone No.	Chowder No.
Year	Per Square Meter	SE	Per Square Meter	Per Square Meter	Per Square Meter	Per Square Meter
1994	2.15	0.42	0.79	0.36	0.29	0.70
1995	1.80	0.23	0.50	0.65	0.45	0.20
1996	2.20	0.38	0.60	0.70	0.50	0.40
1997	2.63	0.31	0.61	0.72	0.53	0.77
1998	2.43	0.28	0.49	0.45	0.34	1.15
1999	2.01	0.23	0.56	0.47	0.33	0.65
2000	1.78	0.23	0.51	0.41	0.34	0.52
2001	1.76	0.21	0.62	0.45	0.30	0.39
2002	2.86	0.37	0.64	0.58	0.54	1.10
2003	1.53	0.20	0.41	0.37	0.27	0.48
2004	1.72	0.18	0.47	0.33	0.30	0.62
2005	2.29	0.31	0.57	0.52	0.48	0.72
2006	2.10	0.27	0.67	0.39	0.38	0.66
2007	2.16	0.29	0.57	0.46	0.44	0.69
2008	2.65	0.27	0.72	0.60	0.50	0.83
2009	2.52		0.61	0.59	0.46	0.86
Sum	34.59		9.34	8.05	6.45	10.74
Proportion	1.00		0.27	0.23	0.19	0.31

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Table 2- Summary of RI Quahog Growth Parameters Estimated by Fitting the von Bertalanffy Model to Data in Henry and Nixon (2008).

Location	Date	N	Linf	k	t0	Max Age
Brenton Cove	9/1/2005	10	45.278	0.115	-0.427	21
Bristol Harbor	8/16/2006	3	49.177	0.123	0.209	20
Conimicut Point	6/29/2005	14	49.440	0.143	-0.054	16
Dyer Island	9/1/2005	11	47.680	0.166	0.083	18
Greenwich Bay	6/24/2005	21	51.840	0.181	0.465	22
Graduate School Oceano	9/2/2005	5	46.908	0.180	0.418	26
Ohio Ledge	8/16/2005	16	71.000	0.075	0.251	17
Providence River	8/11/2005	6	42.803	0.219	0.092	23
Upper West Passage	9/19/2005	17	42.186	0.214	0.128	20
Wickford Harbor	7/13/2005	1	66.770	0.083	0.318	17
/1						
Mean			51.124	0.157	0.149	
STD			9.328	0.047	0.254	
CV			0.182	0.303	1.709	
SE			2.950	0.015	0.080	

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Mean is weighted by sample size (N)

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Table 3- Growth Transition Matrix for RI Quahogs Used in the Size Based Assessment Model.						
Probabilities are Calculated with the Mean Growth Parameters from Table 2.						
				Initial Stage		
		Sublegals	Count Necks	Top Necks	Cherrystones	Chowders
	Sublegals	0.545	0.000	0.000	0.000	0.000
	Count Necks	0.455	0.700	0.000	0.000	0.000
Ending	Top Necks	0.000	0.300	0.600	0.000	0.000
Stage						
	Cherrystones	0.000	0.000	0.400	0.750	0.000
	Chowders	0.000	0.000	0.000	0.250	1.000
	Total	1.000	1.000	1.000	1.000	1.000

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Table 4- Parameter Estimates, Derived Quantities, and Bootstrap Measures of Uncertainty						
From the Rhode Island Size Based Quahog Assessment Model.						
Parameter/Quantity	SOLVER Est.	Bootstrap Mean	Bootstrap SD	CV	Lower 95%	Upper 95%
Count Neck Selectivity	1.000	Set Equal to 1.0				
Top Neck Selectivity	0.45504	0.47179	0.07164	0.15184	0.31177	0.59831
Cherrystone Selectivity	0.18621	0.21390	0.04293	0.20071	0.10035	0.27207
Chowder Clam Selectivity	0.77794	0.76682	0.29589	0.38586	0.18617	1.36971
Effort Index qhat	0.00028	0.00030	0.00007	0.21468	0.00015	0.00041
Count Neck Survey qhat	0.61924	0.66385	0.13818	0.20814	0.34289	0.89560
Top Neck Survey qhat	1.63686	1.83119	0.45593	0.24898	0.72501	2.54871
Cherrystone Survey qhat	1.72419	2.11245	0.70315	0.33286	0.31789	3.13049
Chowder Clam Survey qhat	4.42576	4.51252	1.54458	0.34229	1.33660	7.51492
Full F in 2009	0.19574	0.20980	0.04870	0.23211	0.09835	0.29313
Count Neck Abundance 2009	80.13605	79.61886	21.85428	0.27449	36.42749	123.84460
Top Neck Abundance 2009	39.49118	37.82764	9.14810	0.24184	21.19498	57.78738
Cherrystone Abundance 2009	30.28082	27.18323	6.74582	0.24816	16.78918	43.77245
Chowder Clam Abundance 2009	19.56251	21.43987	6.94751	0.32405	5.66749	33.45753
Total Legal Abundance 2009	169.47056	166.06960	35.06554	0.21115	99.33947	239.60164
Growth Parameter (k)	0.160	Drawn from normal distribution with mean =0.16 and variance =0.00023				

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Table 5- Estimates of Population Size and Fishing Mortality Rate by Market Class for Quahogs in Rhode Island from the Size Based Assessment Model.

			Millions Clams				Fishing Mortality Rate			
Year	Count Necks	Top Necks	Cherrystones	Chowders	Total Legal	Count Necks	Top Necks	Cherrystones	Chowders	N Weighted
1983	260.21	68.49	105.16	40.60	474.46	0.47	0.21	0.09	0.36	0.34
1984	265.30	71.35	83.60	46.95	467.20	0.51	0.23	0.09	0.40	0.38
1985	258.40	71.06	70.48	45.48	445.42	0.56	0.25	0.10	0.43	0.42
1986	226.17	67.30	61.64	40.78	395.88	0.53	0.24	0.10	0.41	0.40
1987	204.84	62.09	55.68	36.75	359.36	0.55	0.25	0.10	0.43	0.42
1988	180.40	56.00	50.41	32.82	319.64	0.51	0.23	0.09	0.40	0.38
1989	162.36	51.41	46.10	30.16	290.03	0.51	0.23	0.10	0.40	0.38
1990	153.80	46.63	42.20	27.64	270.27	0.55	0.25	0.10	0.43	0.42
1991	153.32	42.02	38.08	24.74	258.17	0.70	0.32	0.13	0.55	0.54
1992	132.89	35.72	32.96	20.38	221.95	0.70	0.32	0.13	0.55	0.54
1993	119.67	30.70	28.36	17.10	195.83	0.55	0.25	0.10	0.43	0.43
1994	136.69	30.46	25.43	15.78	208.36	0.51	0.23	0.09	0.40	0.41
1995	99.81	33.95	23.88	14.74	172.38	0.51	0.23	0.10	0.40	0.39
1996	89.86	29.62	23.89	13.77	157.13	0.35	0.16	0.06	0.27	0.26
1997	86.70	29.72	23.78	14.47	154.67	0.47	0.21	0.09	0.36	0.35
1998	77.10	26.68	22.93	13.93	140.65	0.41	0.18	0.08	0.32	0.30
1999	84.77	24.96	21.94	13.91	145.58	0.50	0.23	0.09	0.39	0.38
2000	88.67	23.73	20.27	12.95	145.62	0.48	0.22	0.09	0.38	0.38
2001	99.03	24.15	19.01	12.16	154.35	0.44	0.20	0.08	0.34	0.35
2002	98.11	26.93	18.61	11.71	155.35	0.43	0.19	0.08	0.33	0.34
2003	84.15	28.19	19.21	11.40	142.95	0.34	0.15	0.06	0.26	0.26
2004	82.78	28.21	20.48	11.93	143.40	0.31	0.14	0.06	0.24	0.24
2005	89.44	28.53	21.45	12.75	152.17	0.18	0.08	0.03	0.14	0.14
2006	109.00	33.13	23.03	14.62	179.78	0.21	0.10	0.04	0.16	0.16
2007	95.47	38.67	25.30	16.14	175.59	0.23	0.10	0.04	0.18	0.17
2008	102.18	38.06	28.40	17.64	186.28	0.21	0.10	0.04	0.17	0.16
2009	80.14	39.49	30.28	19.56	169.47	0.20	0.09	0.04	0.15	0.14

Draft

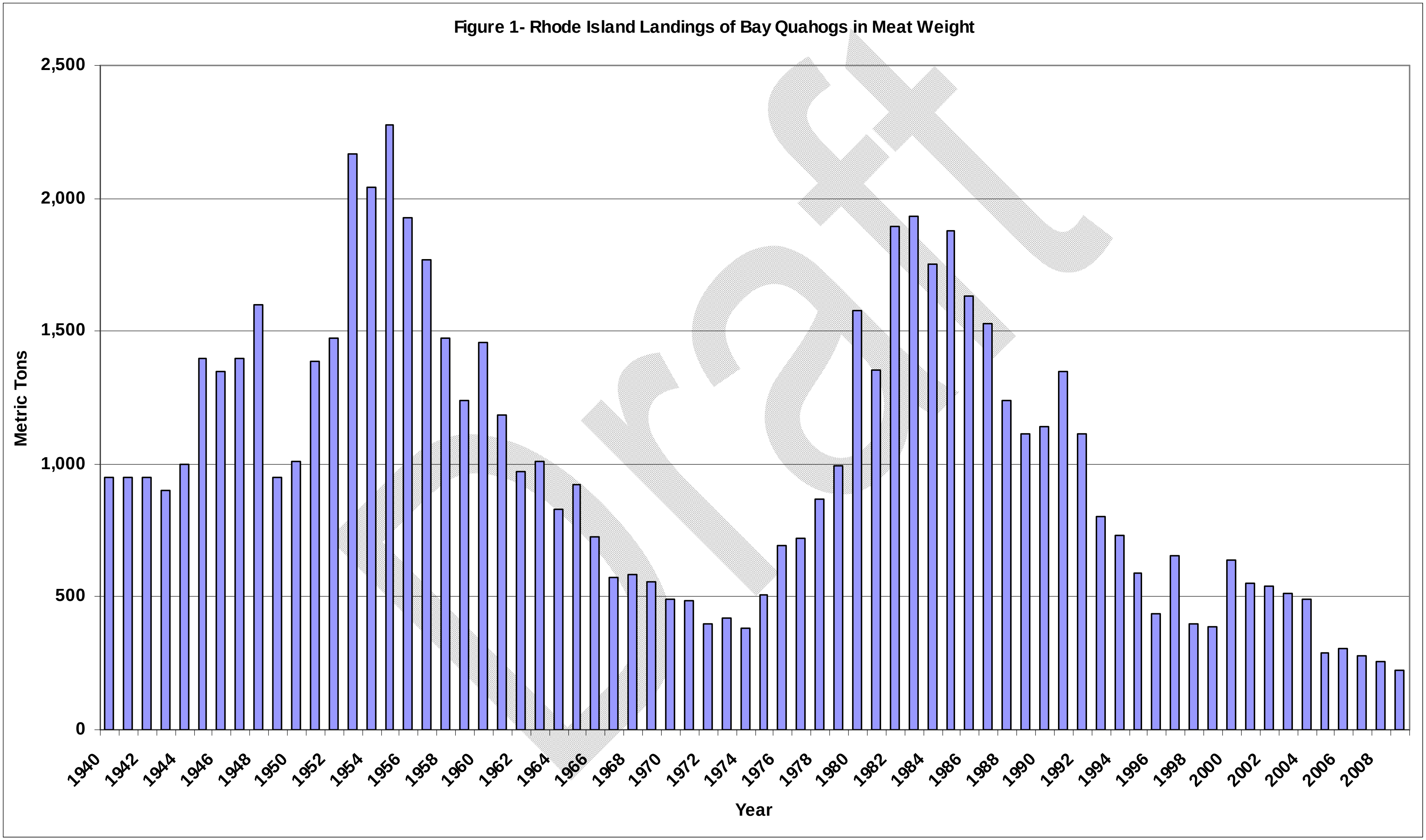


Figure 1- Rhode Island Landings of Bay Quahogs in Meat Weight
Metric Tons
2,500
2,000
1,500
1,000
500
0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year

Draft

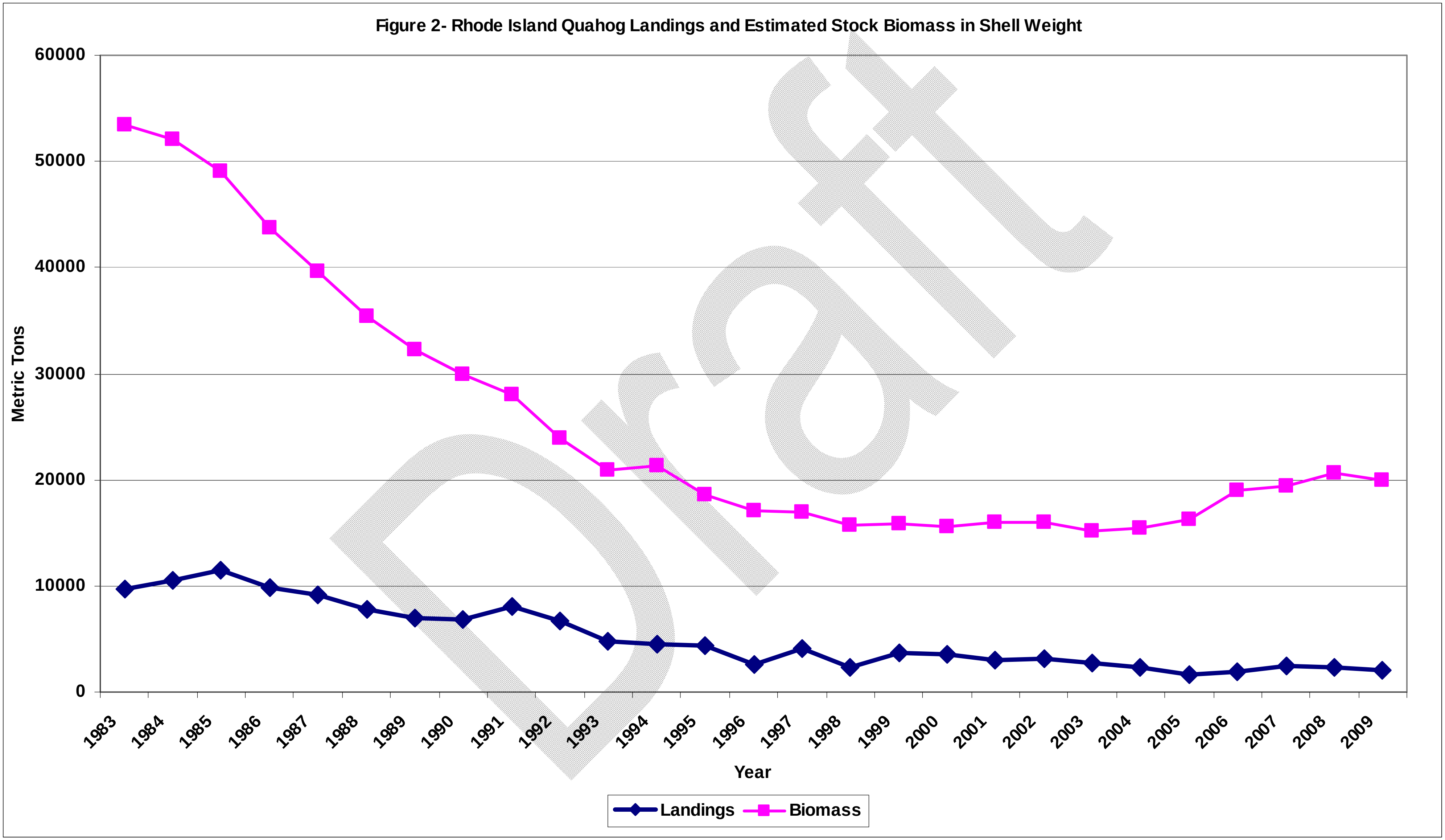


Figure 2- Rhode Island Quahog Landings and Estimated Stock Biomass in Shell Weight
60000
50000
40000
30000
20000
10000
0
Metric Tons
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Landings
Biomass
Draft

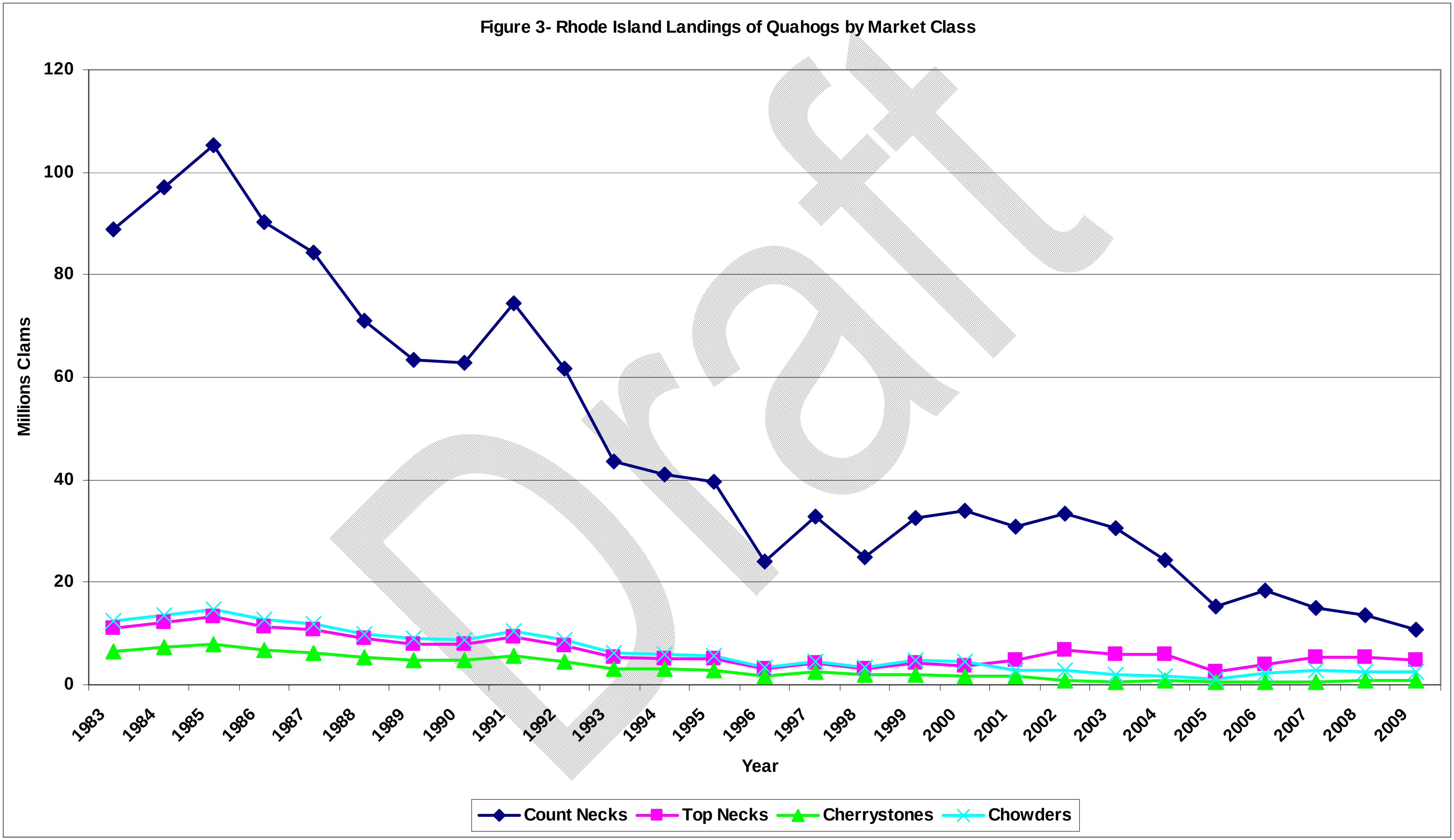


Figure 3- Rhode Island Landings of Quahogs by Market Class
Millions Clams
120
100
80
60
40
20
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Count Necks
Top Necks
Cherrystones
Chowders
Draft

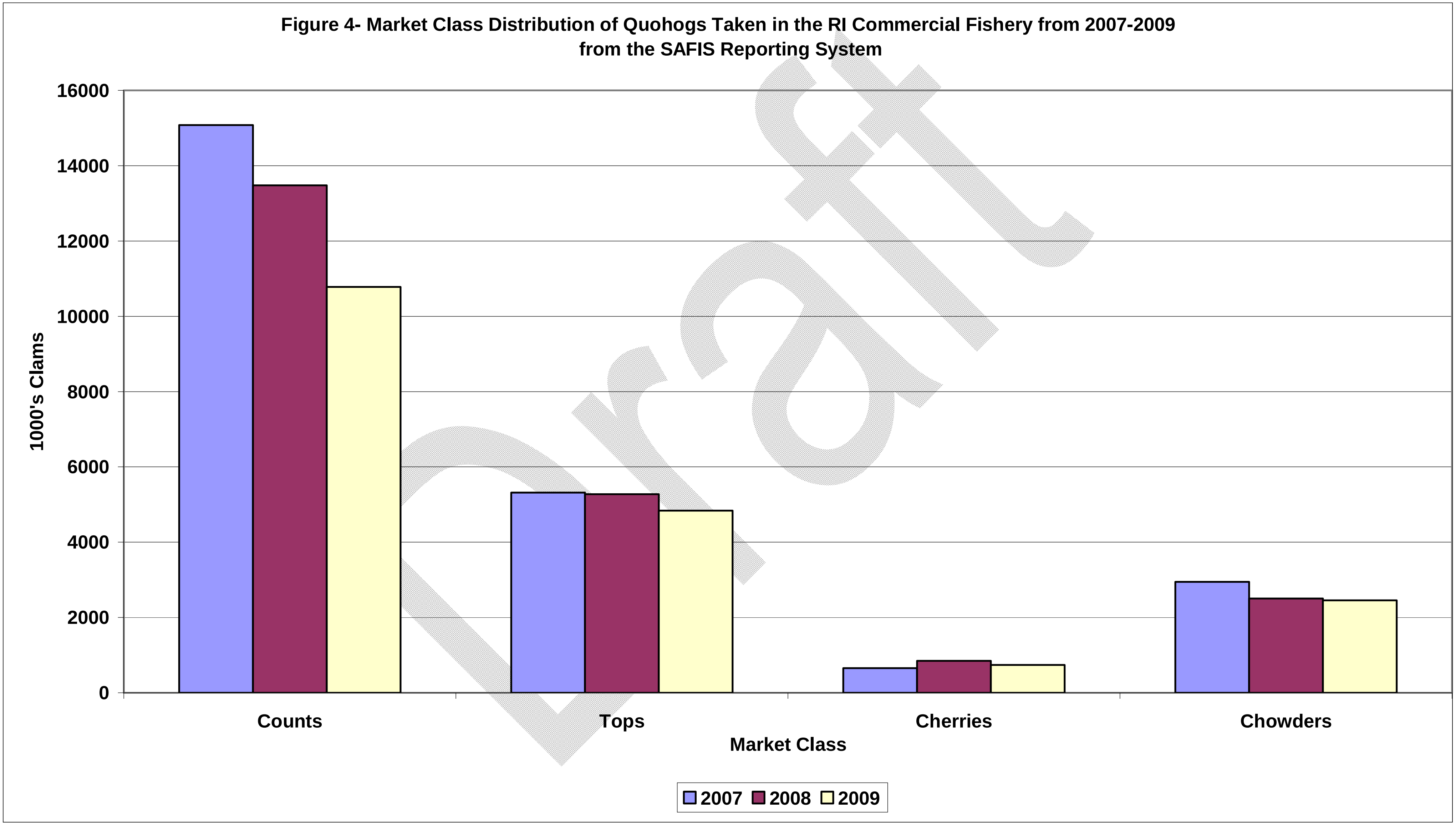


Figure 4- Market Class Distribution of Quohogs Taken in the RI Commercial Fishery from 2007-2009
from the SAFIS Reporting System
16000
14000
12000
10000
8000
6000
4000
2000
0
1000's Clams
Counts
Tops
Cherries
Chowders
Market Class
2007
2008
2009
Draft

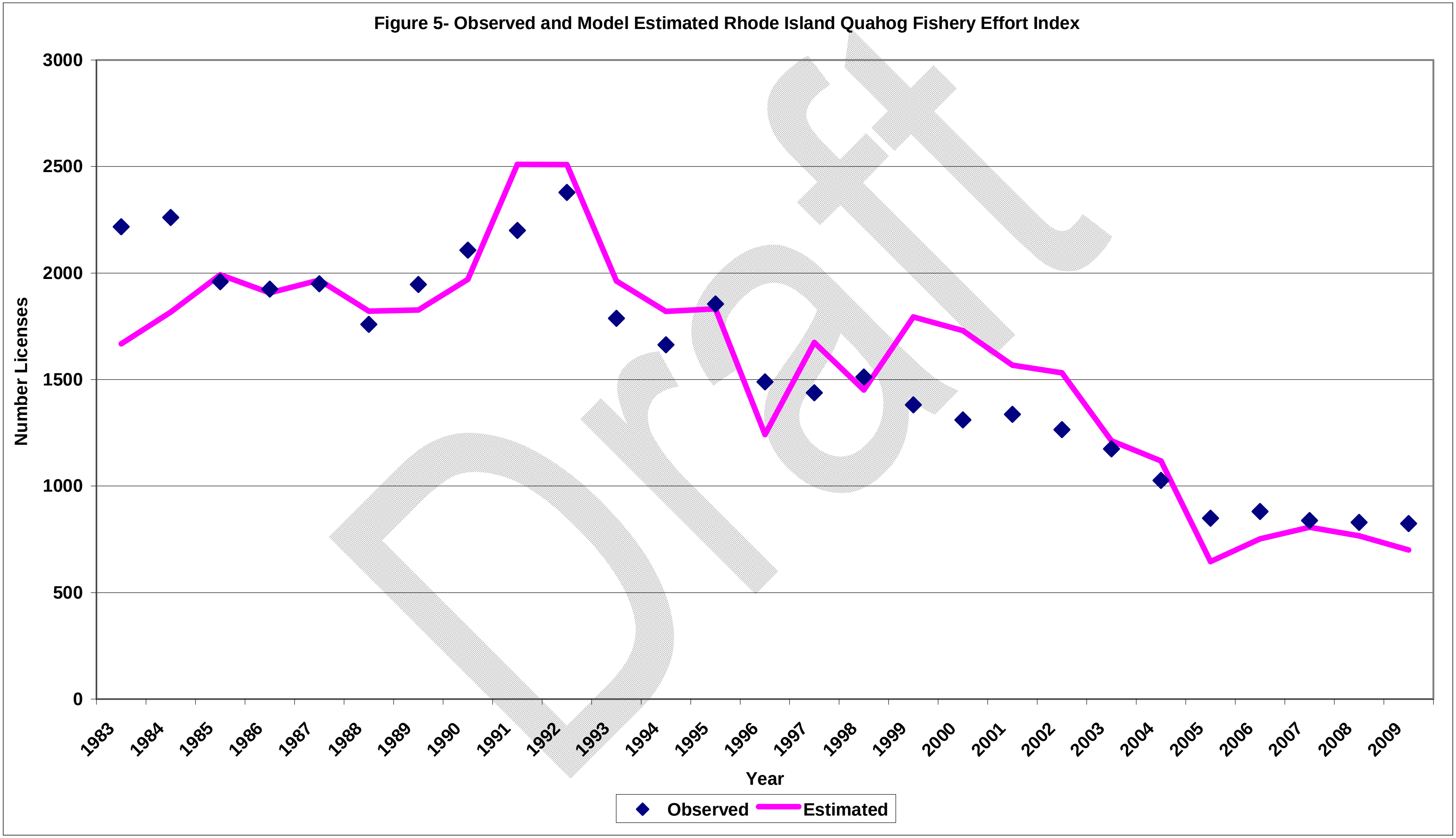


Figure 5- Observed and Model Estimated Rhode Island Quahog Fishery Effort Index
Number Licenses
3000
2500
2000
1500
1000
500
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Observed
Estimated
Draft

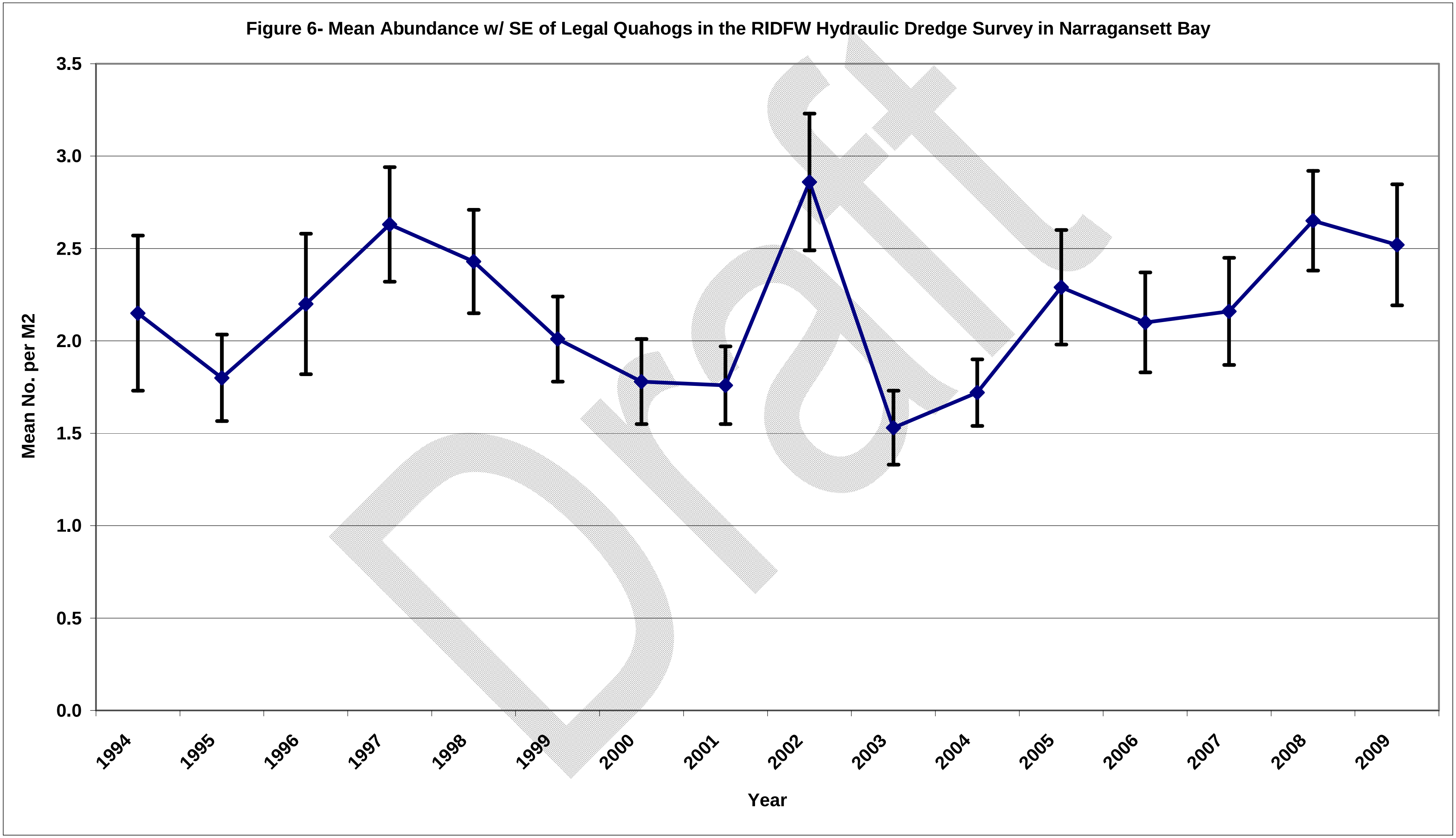


Figure 6- Mean Abundance w/ SE of Legal Quahogs in the RIDFW Hydraulic Dredge Survey in Narragansett Bay
Mean No. per M2
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year

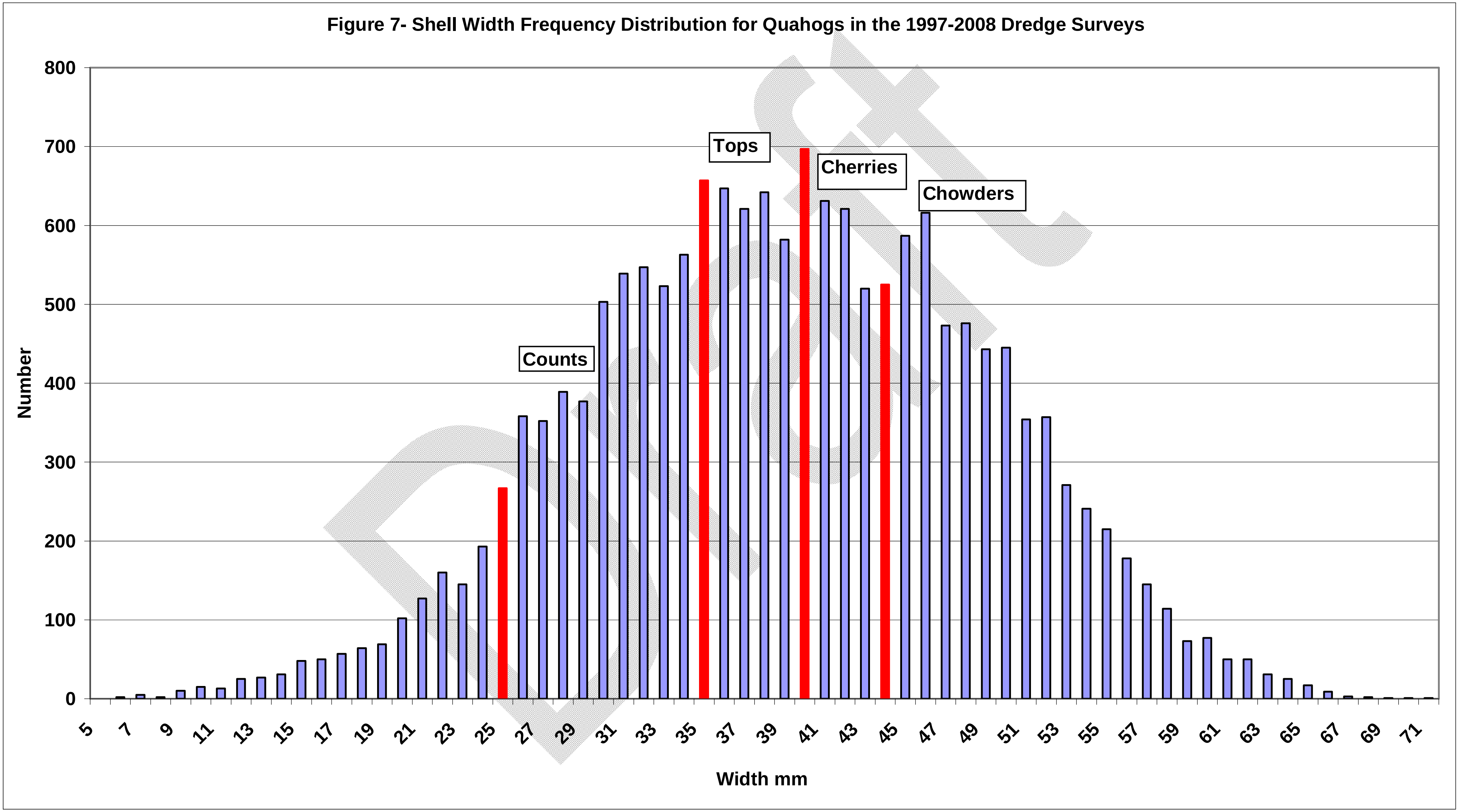


Figure 7- Shell Width Frequency Distribution for Quahogs in the 1997-2008 Dredge Surveys
Number
Width mm
Counts
Tops
Cherries
Chowders
0
100
200
300
400
500
600
700
800
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
57
59
61
63
65
67
69
71

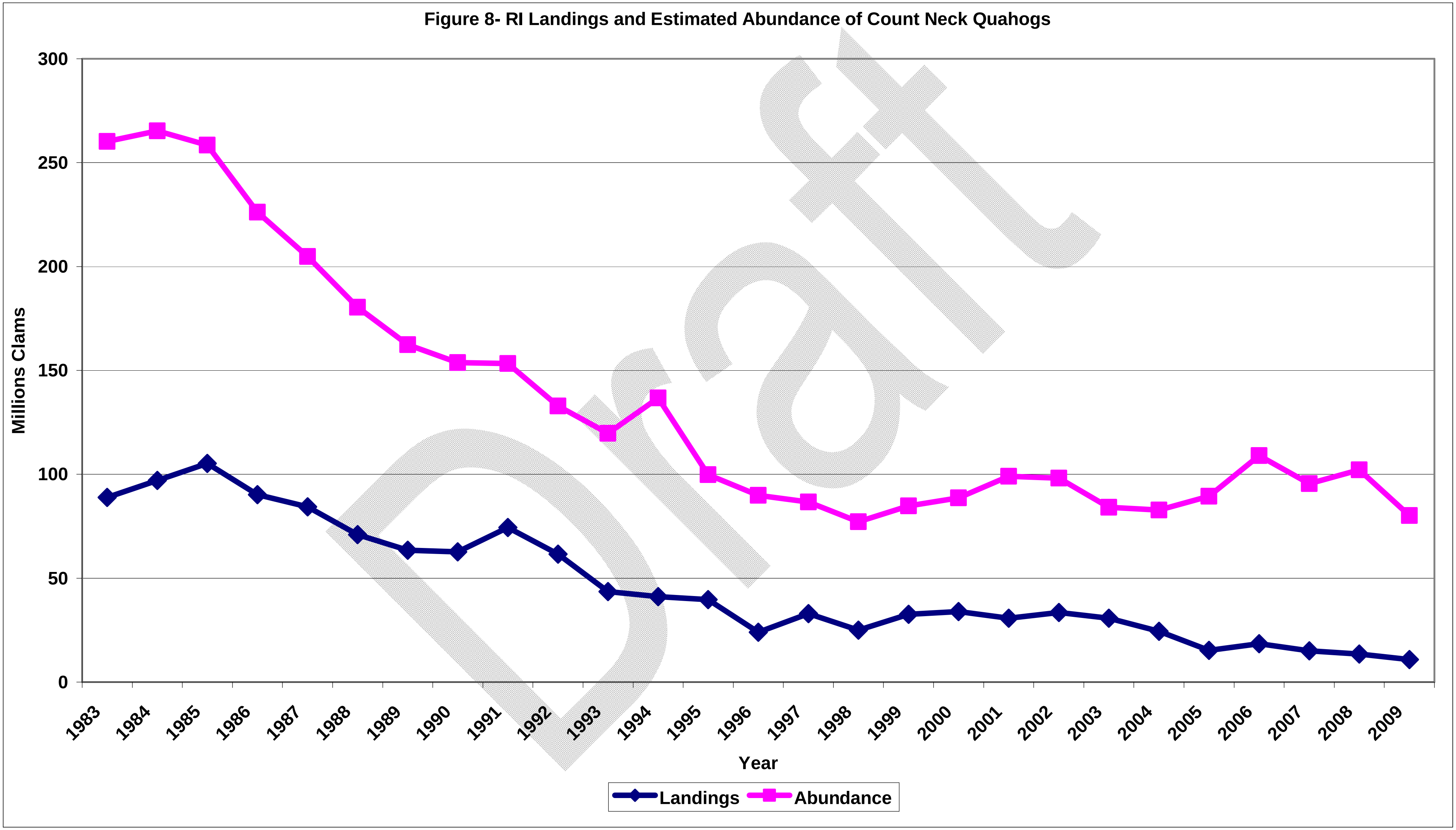


Figure 8- RI Landings and Estimated Abundance of Count Neck Quahogs
300
250
200
150
100
50
0
Millions Clams
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Landings
Abundance
Draft

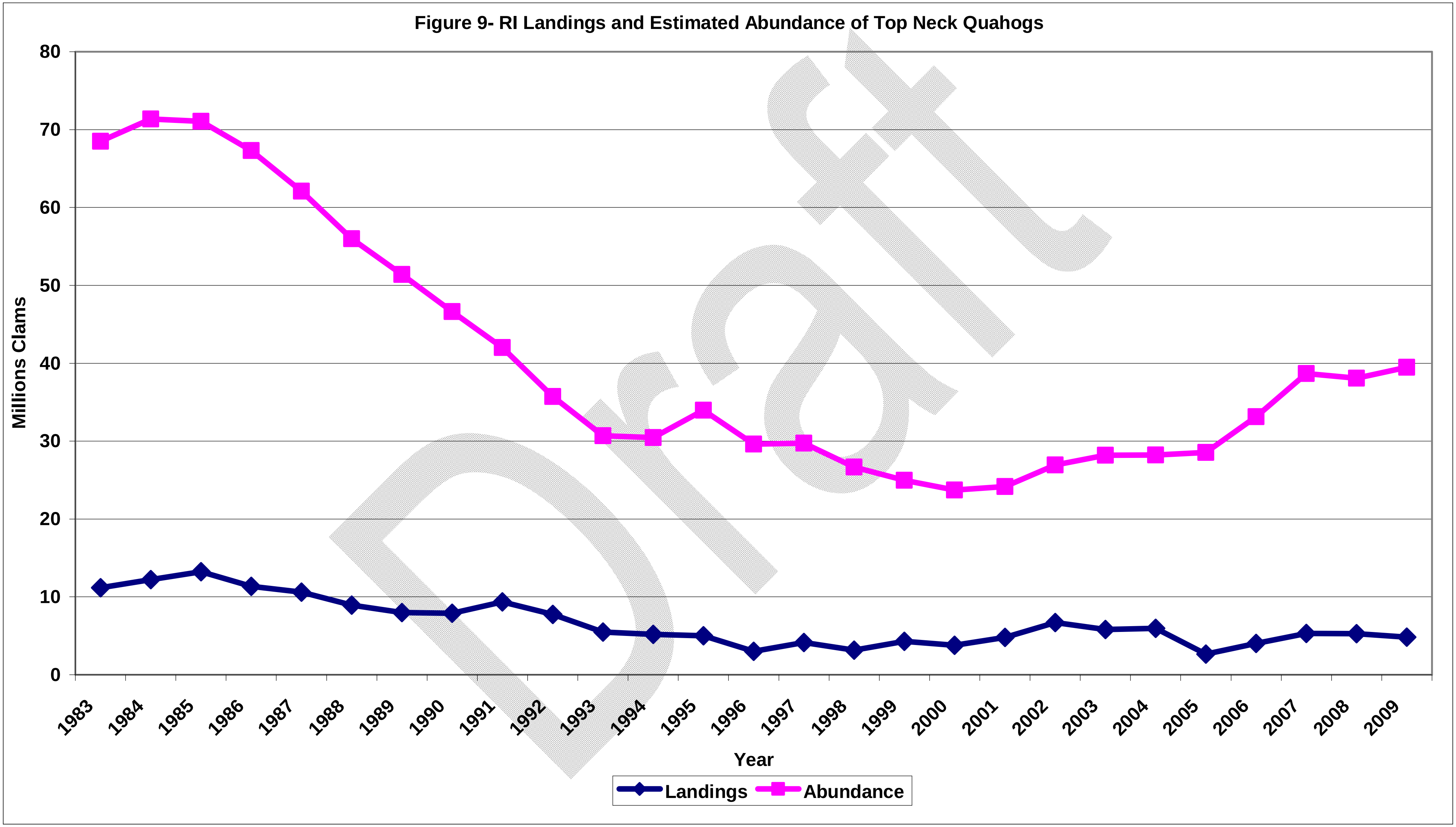


Figure 9- RI Landings and Estimated Abundance of Top Neck Quahogs
Millions Clams
0
10
20
30
40
50
60
70
80
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Landings
Abundance

Draft

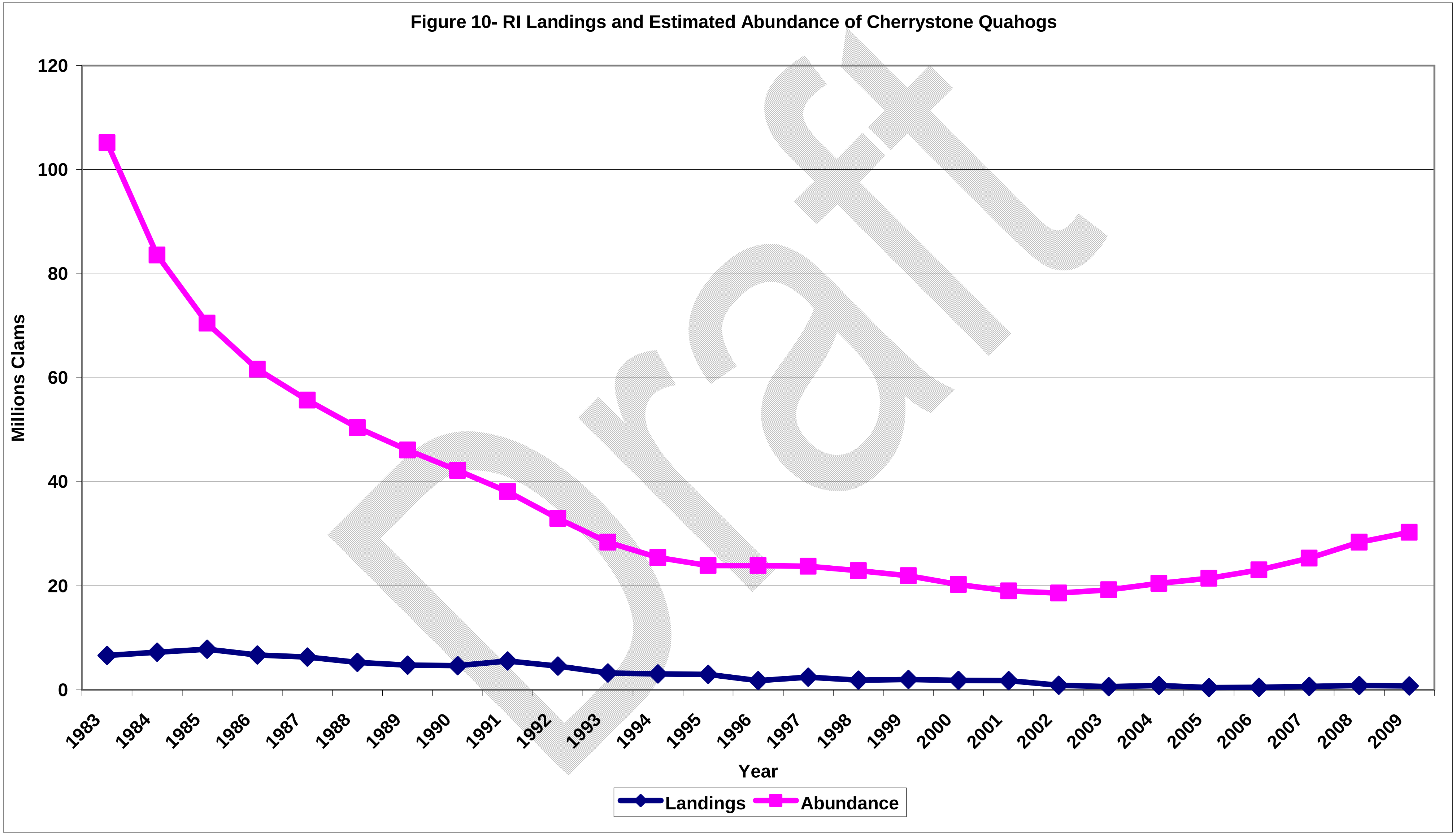


Figure 10- RI Landings and Estimated Abundance of Cherrystone Quahogs
120
100
80
60
40
20
0
Millions Clams
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Landings
Abundance
Draft

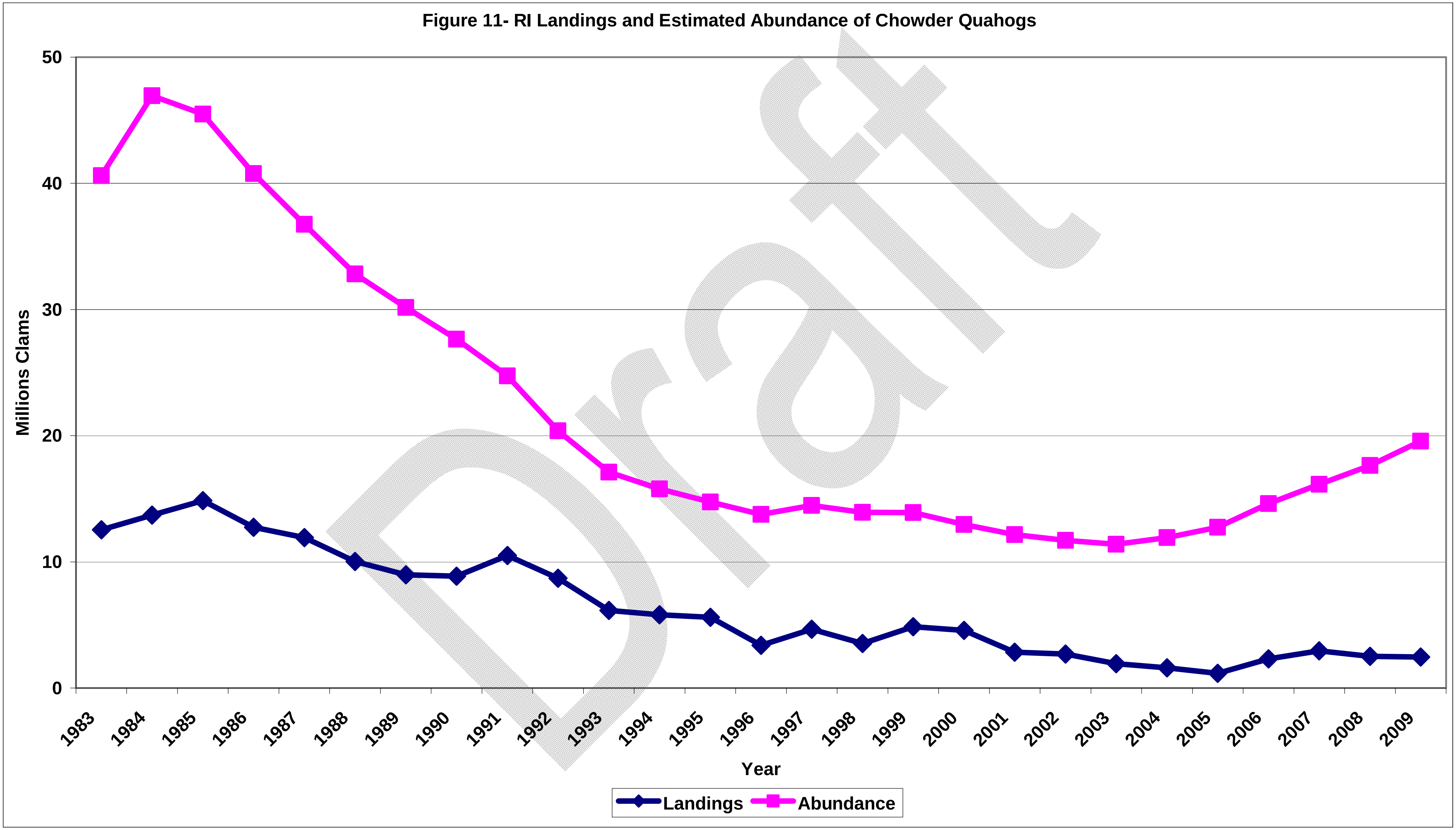


Figure 11- RI Landings and Estimated Abundance of Chowder Quahogs
Millions Clams
50
40
30
20
10
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Landings
Abundance
Draft

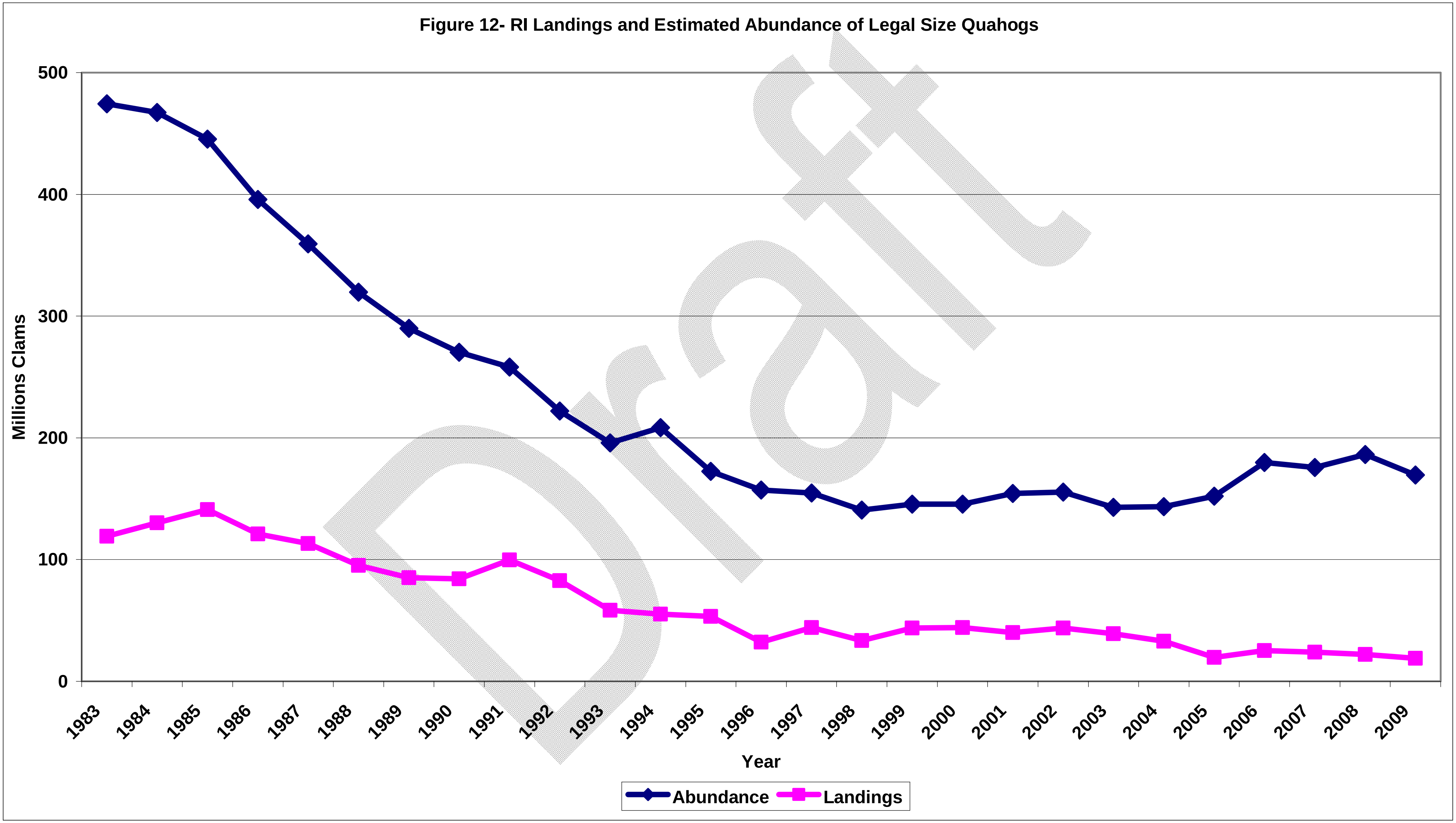


Figure 12- RI Landings and Estimated Abundance of Legal Size Quahogs
Millions Clams
500
400
300
200
100
0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Abundance
Landings
Draft

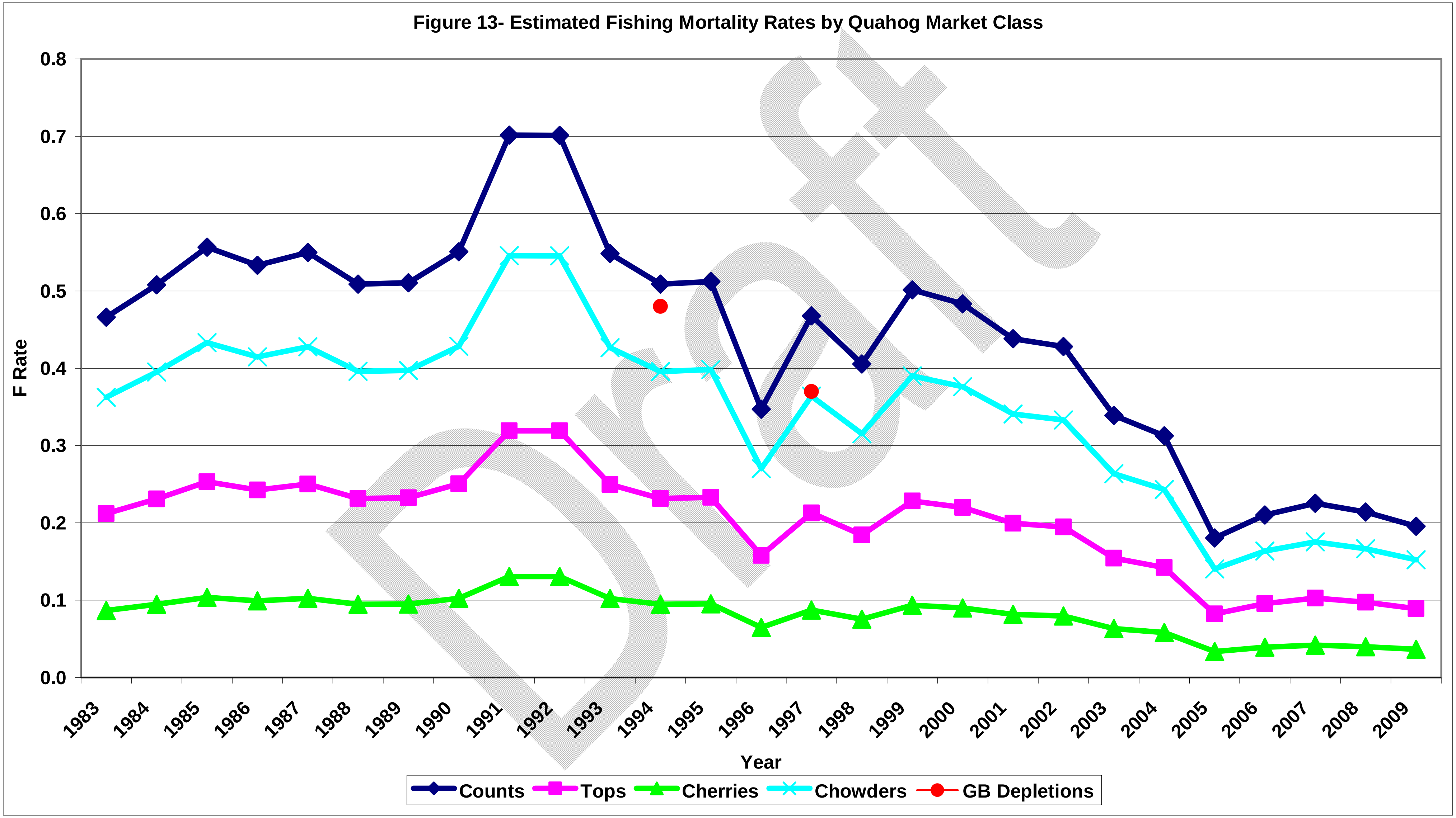


Figure 13- Estimated Fishing Mortality Rates by Quahog Market Class
F Rate
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Year
Counts
Tops
Cherries
Chowders
GB Depletions
Draft

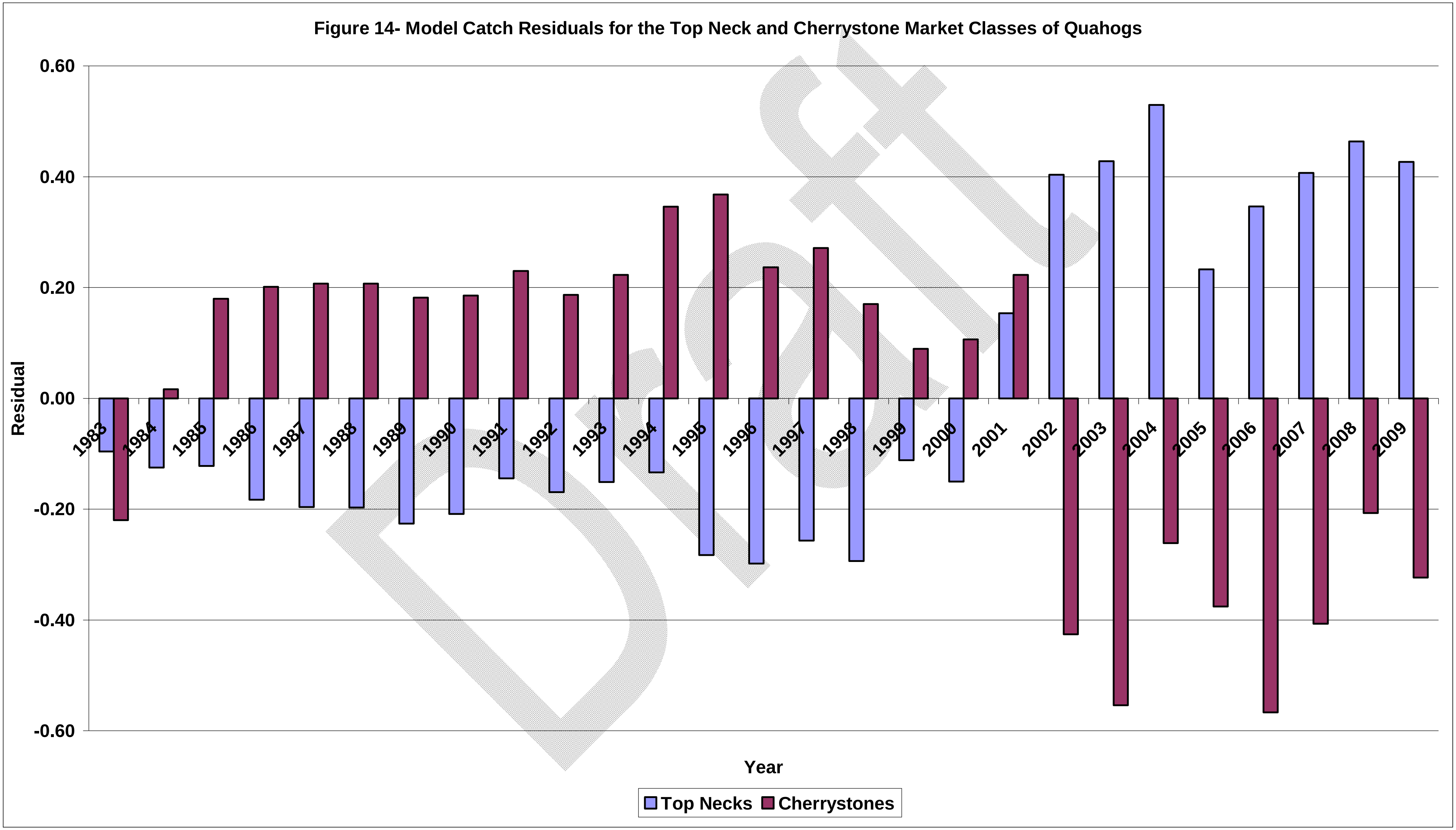


Figure 14- Model Catch Residuals for the Top Neck and Cherrystone Market Classes of Quahogs
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
Residual
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Top Necks
Cherrystones

Draft

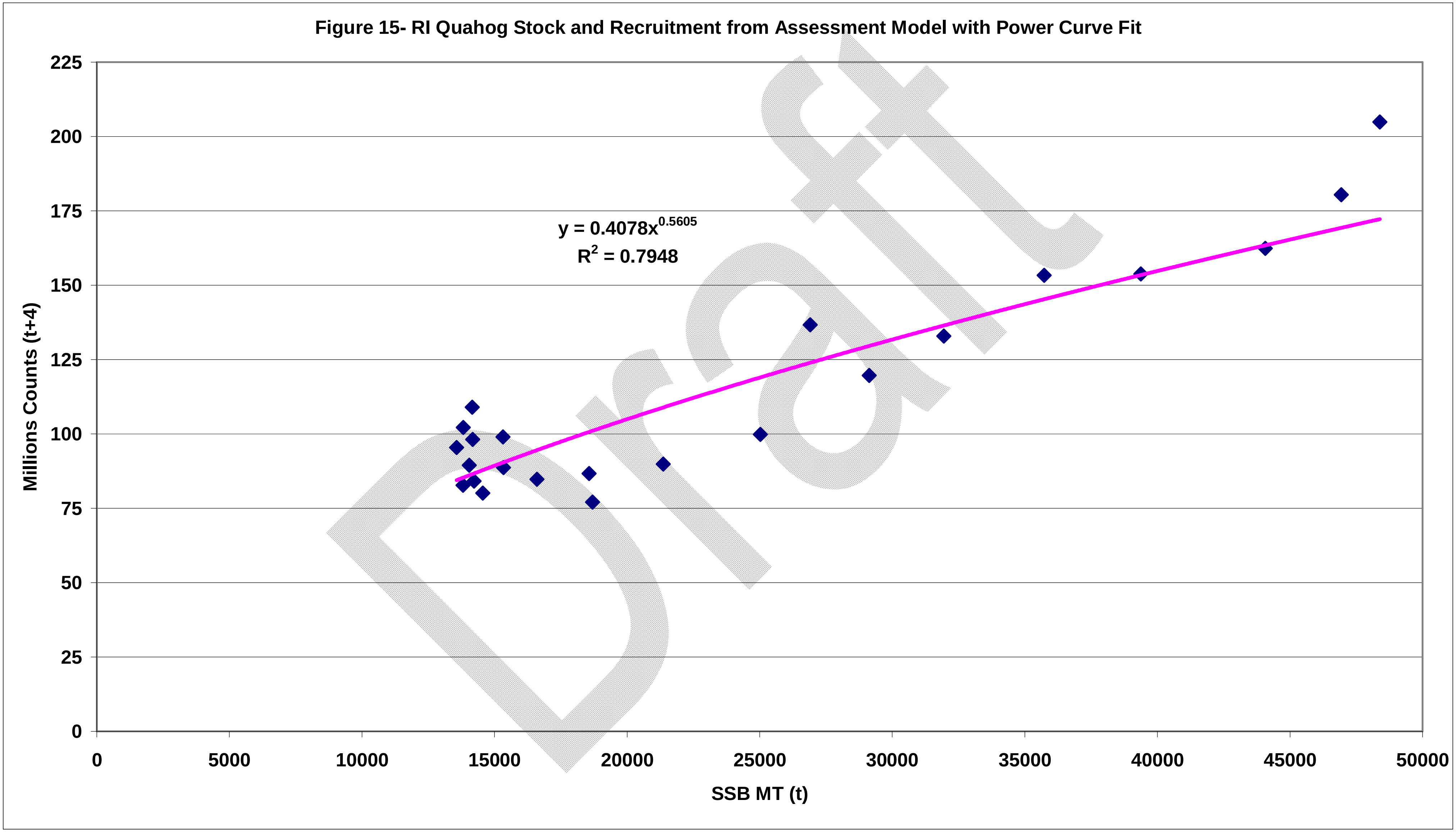


Figure 15- RI Quahog Stock and Recruitment from Assessment Model with Power Curve Fit
y = 0.4078x^0.5605
R^2 = 0.7948
Millions Counts (t+4)
225
200
175
150
125
100
75
50
25
0
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
SSB MT (t)
Draft

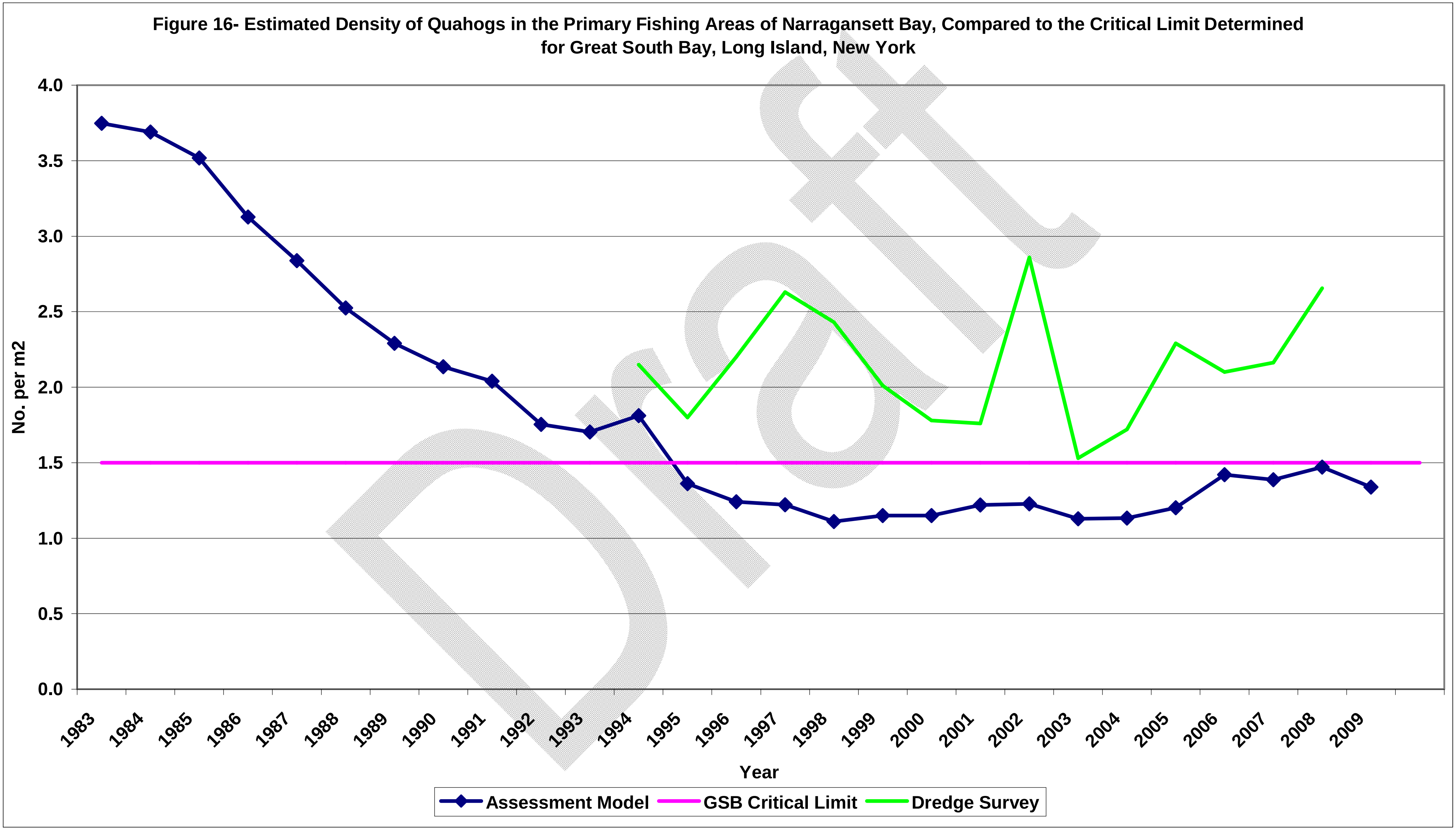


Figure 16- Estimated Density of Quahogs in the Primary Fishing Areas of Narragansett Bay, Compared to the Critical Limit Determined for Great South Bay, Long Island, New York
No. per m2
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year
Assessment Model
GSB Critical Limit
Dredge Survey
Draft

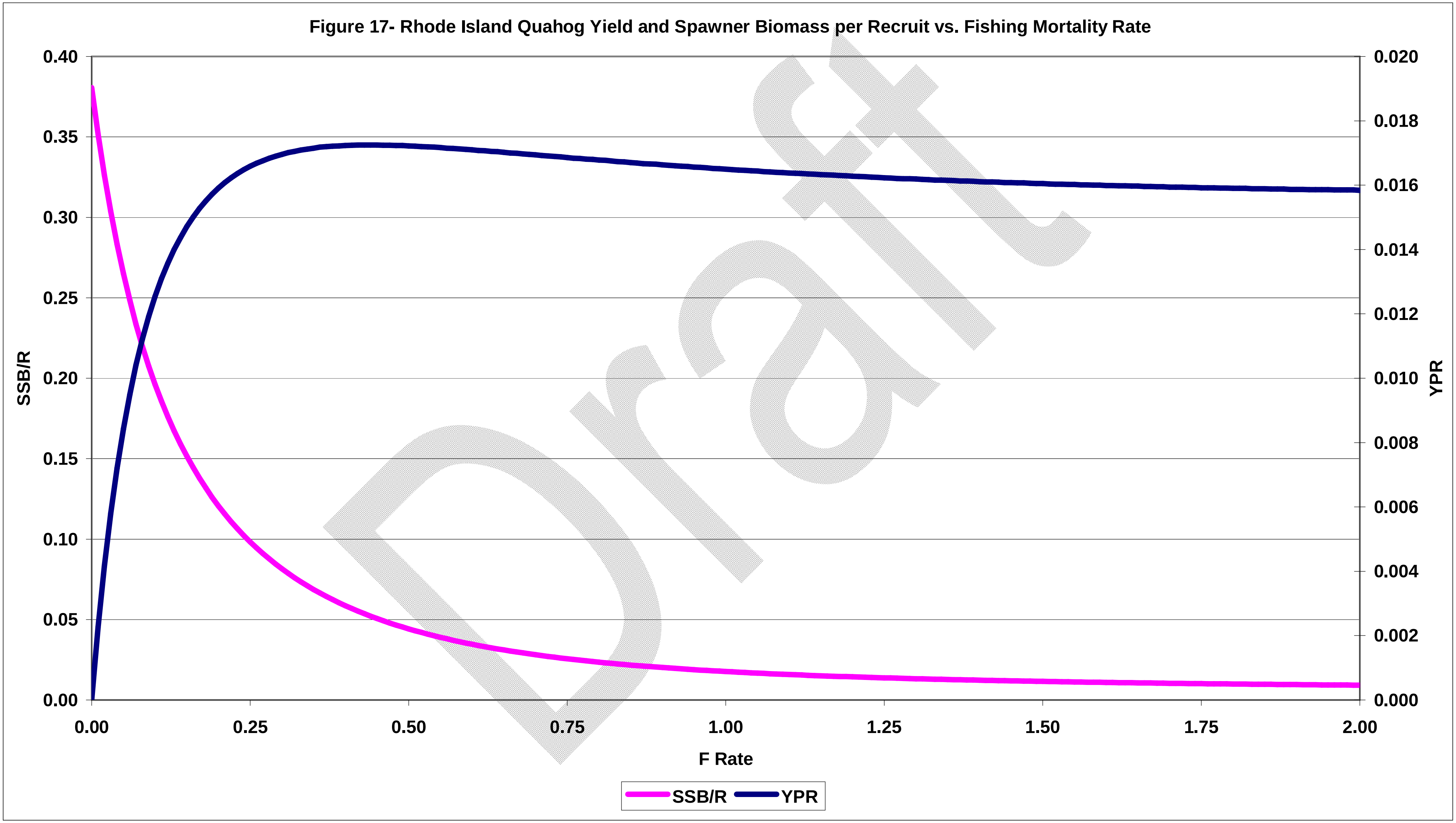


Figure 17- Rhode Island Quahog Yield and Spawner Biomass per Recruit vs. Fishing Mortality Rate
SSB/R
YPR
F Rate
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
SSB/R
YPR
Draft

Figure 18- Phase Plot for Rhode Island Quahog Abundance vs. Fishing Mortality Rate

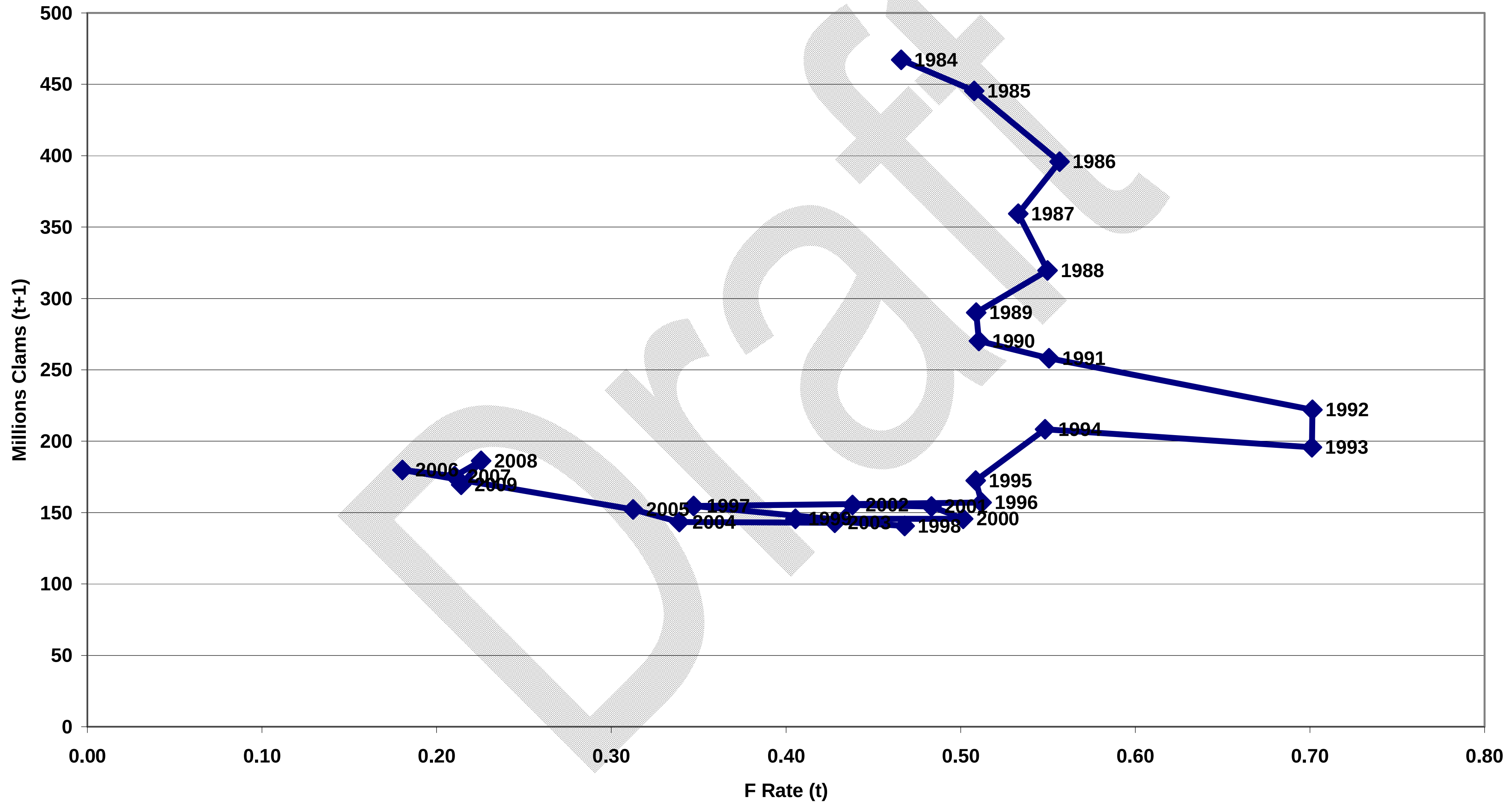
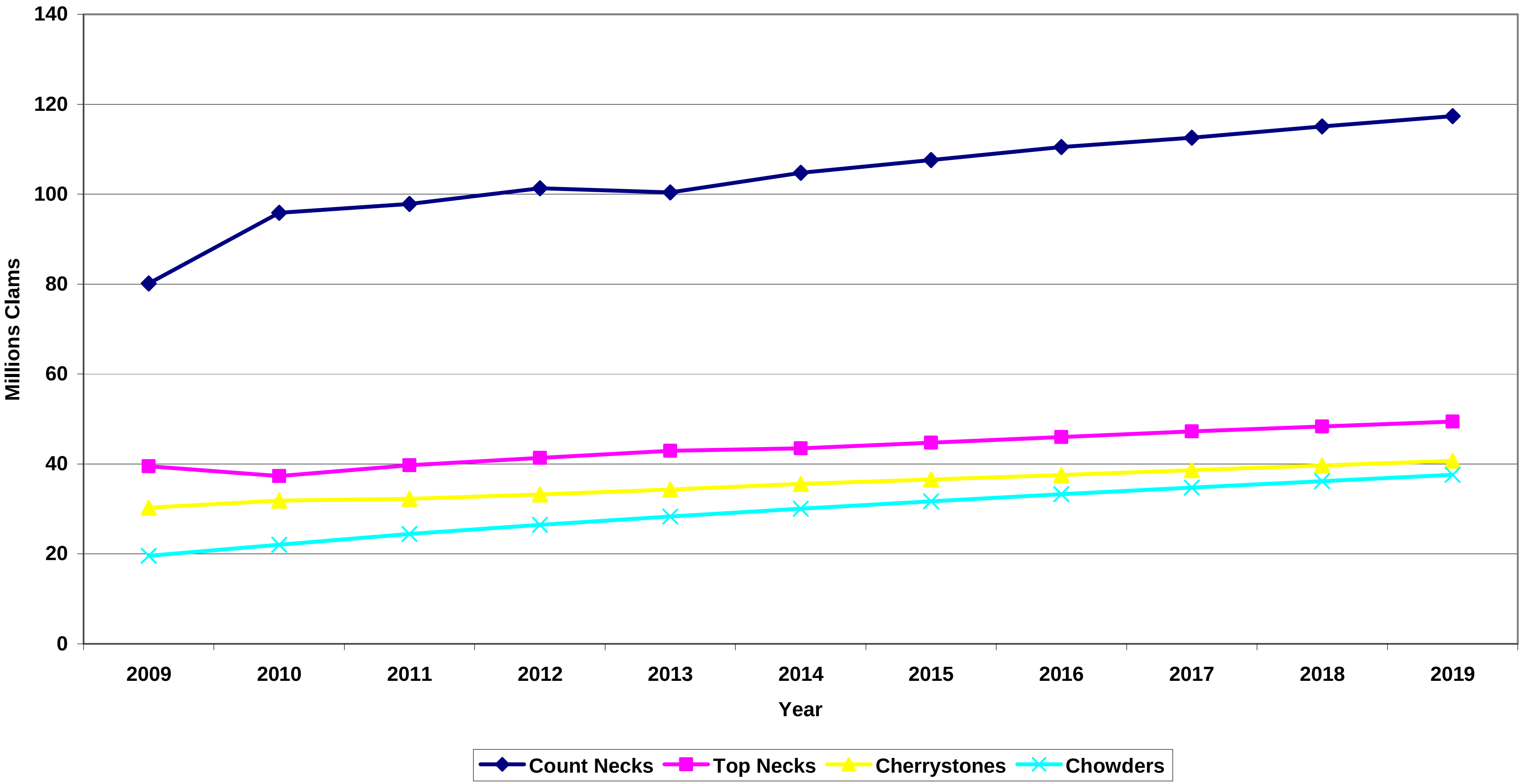


Figure 19- Projection of Quahog Population under F=0.1



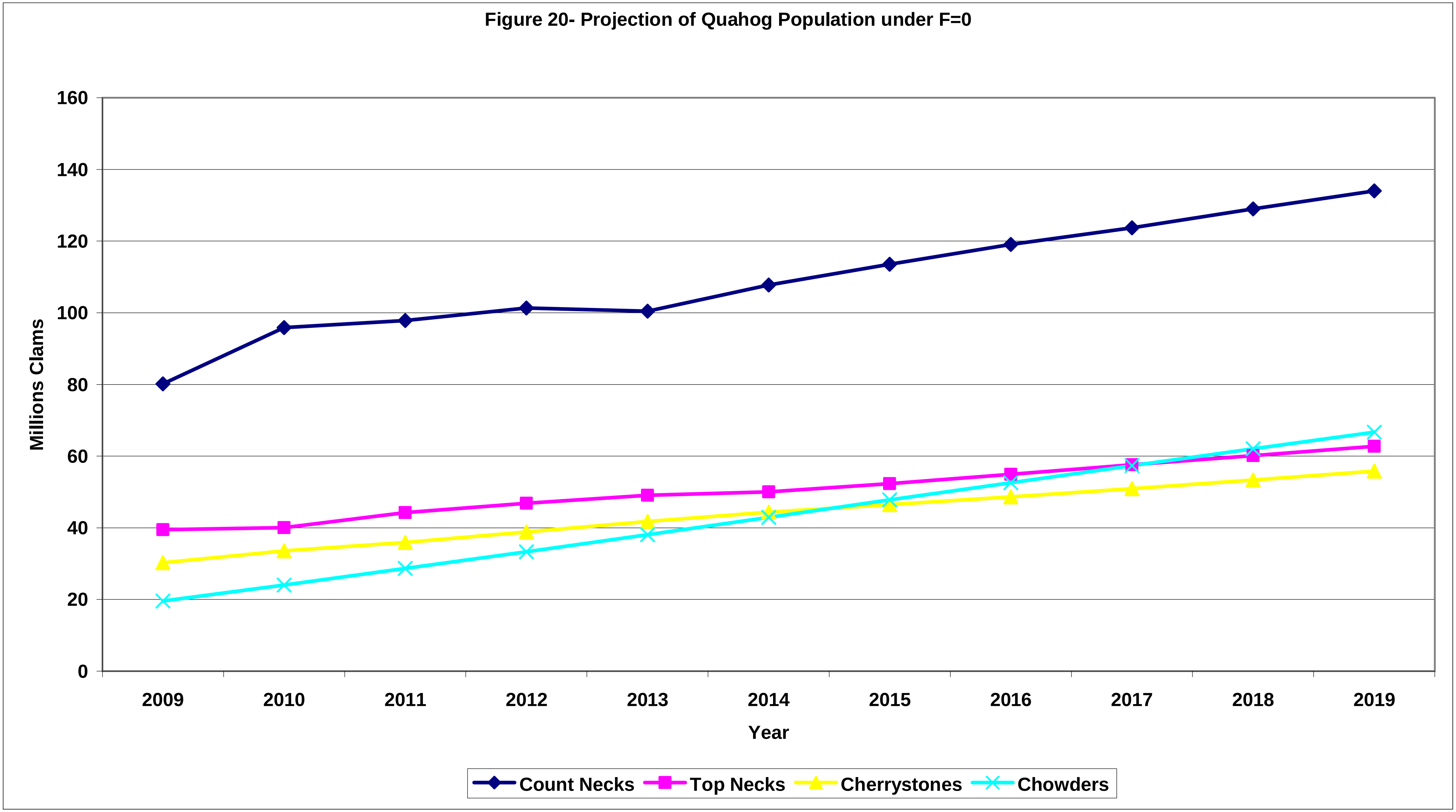
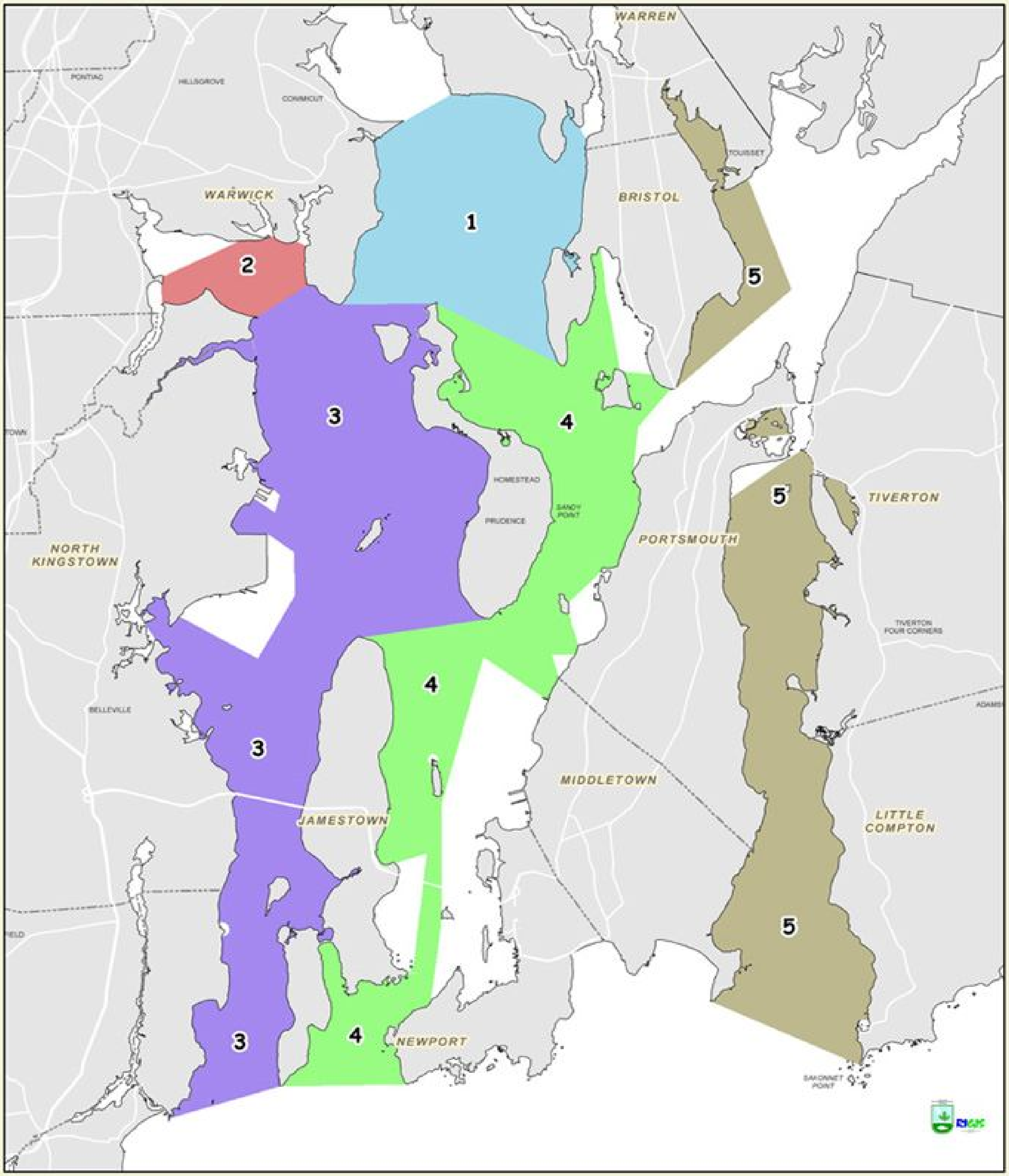


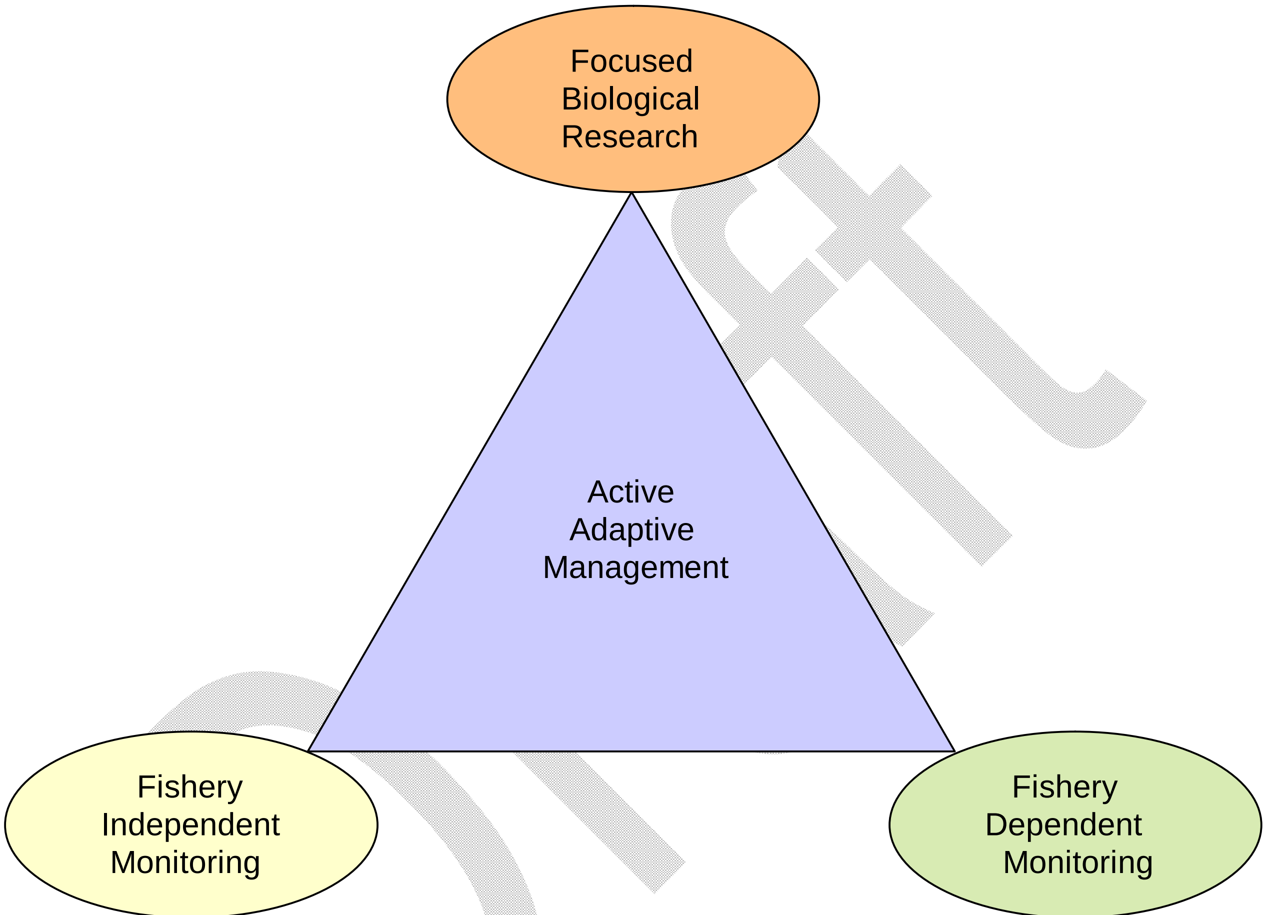
Figure 20- Projection of Quahog Population under F=0
Millions Clams
160
140
120
100
80
60
40
20
0
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year
Count Necks
Top Necks
Cherrystones
Chowders



Narragansett Bay
Shellfish Harvest Areas

RI Dept of Environmental Management
Geographic Information System
2003

Appendix 2- Triad of Information Needed to Support Successful Shellfish Management Program



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