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Acronyms and abbreviations.
ABC Acceptable Biological Catch
BRP Biological Reference Point
B_{MSY}, Biomass for Maximum sustainable yield
$B_{THRESHOLD}$, Biomass threshold
CPUE catch per unit effort
F Fishing mortality rate
F_{MSY} Fishing mortality rate (F) at maximum sustainable yield
M Natural mortality rate
MD Maryland
MD DNR. Maryland Department of Natural Resources
NCBO NOAA Chesapeake Bay Office
NCBO GIT Goal Implementation Team
NOAA National Oceanic and Atmospheric Administration
ToR Term of Reference
UMD University of Maryland
VA Virginia
VIMS Virginia Institute of Marine Science
VMRC Virginia Marine Resources Commission
YOY Young of the year or spat

Introduction.

This project began in 2011 as a two-year collaborative effort between partners from MD (MD DNR, UMD), VA (VMRC, VIMS) and federal entities (NOAA Oxford Laboratory and NCBO-NOAA) to complete a bay wide stock assessment for oysters (*Crassostrea virginica*) in the Chesapeake Bay. Included in this effort were five main components:

1. Stock Assessment of public grounds in MD by MD DNR
2. Stock Assessment of sanctuaries in MD by UMD
3. Stock Assessment of public grounds and sanctuaries in VA by VIMS-VMRC
4. A comparison of gear types used in MD and VA studies
5. Disease status of both the endemic Dermo (*Perkinsus marinus*) and non-endemic but now established MSX (*Haplosporidium nelsoni*) in oyster populations in MD and VA with a comparison of historical data on a single evaluation scale.

As the project progressed the option arose to extend analysis into a first attempt at a benchmark stock assessment for oysters in the bay. Terms of Reference (ToR) are required to drive a formal benchmark assessment. ToRs drive a product that, in turn, can be subjected to an external peer review by Center for Experts. Some obvious ToRs were covered in the original project design, others were not, and it was equally obvious that additional expertise would be required to elevate the originally envisaged end product to that of a formal benchmark assessment. None the less we have pursued the production of a draft document driven by the ToRs developed in a discussion lead by Derek Orner, a former CBSAC and then NCBO manager who has been an integral part of the federal-state efforts focused on oysters for much of the past twenty years. Derek's efforts in driving this project are gratefully acknowledged, right down to his day aboard the R/V Miss Kay as "chief buoy deployment officer" on December 13, 2011. The ToRs have been presented to and endorsed by the NCBO Fisheries Goal Implementation Team (GIT)

This is an imperfect document. It is offered not as a definitive end point but more as a starting point. In it we have assembled a state of our knowledge of oyster population biology in the bay, together with the equally important statement of what we do not know and what we need to do in order to develop a sound assessment on which to base future oyster management bay wide. We acknowledge many productive discussions with experts (notably Alexi Sharov at MD DNR, and Rob O'Reilly at VMRC), NCBO personnel (including Peter Bergstrom, Stephanie Westby, Kevin Schabow, Bruce Vogt and Earl Meredith), and the efforts of John Thomas (VIMS ITNS) for patience in assembling and managing databases, who have generously given of their time to this project, even though they may never have been either formally engaged with or supported by the project. We trust that they will remain engaged as future discussions evolve. We also acknowledge the valuable assistance of technical staff at MD DNR, VMRC and VIMS without whose efforts this report would not have been assembled. We welcome a new phase of constructive debate.

Development of the Terms of Reference (ToR)

The ToR's were developed from a draft proffered by Derek Orner in late 2012 and discussed on a multi-participant conference call on January 3, 2013. The participants in that discussion were as follows: Derek Orner, Peter Bergstrom and Stephanie Westby (NCBO), Mitch Tarnowski and Chris Dungan, (MD DNR) Kennedy Paynter and Mike Wilberg (UMD), Howard Townsend (NOAA Oxford), Jim Wesson (VMRC), Ryan Carnegie, John Hoenig, Melissa Southworth and Roger Mann (VIMS). Kevin Schabow, grant manager for NCBO, assumed responsibility of the award when Peter Bergstrom retired during the award period. The summary findings of the conference call provided a ToR listing that included some that had universal agreement, and others that were cause for discussion. The listing is given below. Additional comments are then addressed by ToR where appropriate, for in most instances they underscore weaknesses in current data and/or approaches that require attention in the near future.

1) Characterize the commercial catch including landings, effort, CPUE and discards. Describe the uncertainty in these sources of data.

2) Characterize the survey data that are being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, etc.). Describe the uncertainty in these sources of data.

3) Cross-calibrate MD dredge with VA patent tong methodologies to provide information for total Bay wide population estimation. Describe the methodology and characterize uncertainty.

4) Evaluate status of shell substrate on public reefs Bay wide.

5) Quantify disease prevalence and intensity in all sampled populations Bay wide. Compare age-specific mortality against disease prevalence and intensity.

6) Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and characterize the uncertainty of those estimates.

7) Update or redefine biological reference points (BRPs; estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, and F_{MSY}; rebuilding thresholds, and estimates of their uncertainty). Comment on the scientific adequacy of existing and redefined BRPs.

8) Evaluate stock status with respect to the existing BRPs, as well as with respect to updated or redefined BRPs (from ToR 7).

9) Identify potential environmental, ecological, and fishing-related factors that could be responsible for low recruitment in future years. Develop forward projections?

10) Develop and apply analytical approaches and data that can be used for conducting single and multi-year stock projections and for computing candidate ABCs (Acceptable Biological Catch).
    a. Provide numerical short-term projections (1-5 years; through 2015). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass.
    b. Comment on which projections seems most realistic, taking into consideration uncertainties in the assessment.
    c. Describe the oyster stock's vulnerability to becoming overfished, and how this could affect the choice of ABC.

11) Identify, review, and prioritize future research needs (including to the extent practical, cost estimates).

Comments on ToR #9 (1/3/2013)

- The status of our knowledge of disease impacts on our collective ability to develop an assessment. Current protocols do not provide adequate description of what is happening with *Perkinsus marinus* infections in the fall of the year. There are years when MSX is more active in the spring, or warm springs when *Perkinsus marinus* is also evident. On these occasions early disease may impact reproductive activity, but we do not see this in the fall assessment surveys. We need additional low-level sampling to capture a disease peak early in the year.
- Both Wilberg and Townsend suggested this ToR be revised thus: "Explore potential environmental, ecological, and fishing-related factors on population dynamics."
- The option exists to use data from MD sanctuaries to contribute to this ToR (Paynter and Westby).
- Hoeing supported Paynter's suggestion, noting that it is one way to control for stock abundance impacts. Additionally, he commented that we should be seeking situations that describe "sufficient" conditions, not "optimal conditions". Good recruitment requires everything to be good, modest recruitment requires only one thing to be bad.
- A revision was not agreed upon and thus the original is included in this report.

Comments on ToR #10a (1/2/2013)

- Note that ABC is not a fishery term, it is a regulatory term. In carrying out projections, consider a range of assumptions about the most important uncertainties in the assessments. Given the extreme variability in recruitment and disease, multi-year projections are not tractable (see ToR #9 above). When making an ABC projection consider that the survey(s) overlaps with the fishing season.

- Wilberg discussed a 3-year projection option, and notes a lot of recruitment variability, thus the mean is liable to be difficult to generate with confidence.
- Tarnowski offered another complex example – that of good recruitment and stocks in a year coincident with an increase in *Perkinsus marinus* impacts. The result would be an overfishing situation if we based the quota on just standing stock description in the absence of accommodation of disease data.
- There is no effective quota cap on fishing in either MD or VA. Longer-term projections should be based on a change in management actions.
- As an academic exercise can we examine a thousand simulations attempting 1 year and 5 year projections, using the ToR to direct the computation of a sustainable harvest / target catch? The current support is not for modeling, but that does not mean that we cannot suggest a future modeling effort.

CHESAPEAKE BAY OYSTER STOCK ASSESSMENT TERMS OF REFERENCE (TOR); LISTING AND COMMENTARY.

ToR #1. Characterize the commercial catch including landings, effort, CPUE and discards. Describe the uncertainty in these sources of data.

MD data. The portal to management details for the MD oyster fishery can be found at http://dnr2.maryland.gov/fisheries/Pages/oysters/index.aspx. Historical surveys of the MD oyster grounds began with the commissioning of Lt Winslow (US Coast and Geodetic Survey) to survey Tangier and Pocomoke Sounds in 1875. In 1906 Yates was commissioned to survey all natural bars and barren bottoms, an effort that required 6 years, and defined approximately 250,000 acres of natural oyster beds. The most recent review of boundaries of the historical oyster bars are presented at http://dnr2.maryland.gov/fisheries/pages/oysters/bars.aspx, a 1997 document based on the 1983 Natural Oyster Bar Charts. These boundaries may differ from the current boundaries in that a comprehensive survey of bars has not been made since 1983, prior to the impacts of decimating epizootics in the late 1990s. These differences are critical in estimating current populations in MD and bay wide in that extrapolation from estimates of oyster density (number per unit area) to whole reef and cumulative of all reef values are compromised. This challenge is also addressed later in this document.

Regulations summarizing management of the oyster (indeed all) fishing in MD is given at http://www.dnr.state.md.us/fisheries/regulations/table.asp?c=commercial. MD DNR staff maintains a historical record of commercial oyster landings. An annual summary of oyster landings, but not effort, is provided as a component of the MD Oyster Status Report that is produced following the Fall survey. The individual surveys from 1996 through 2013 can be downloaded at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/reports.aspx.

Minimum size limits for oysters landed in MD are enforced for market oysters. Oysters are culled on deck as part of the daily fishing effort and sub market size oysters are returned to the water for harvest at a later date when larger in size. Catch is subject to inspection by MD Law Enforcement. There are no “discards” in the commercial catch.

The oyster fishery is open to all MD residents who purchase appropriate licenses. A cap exists on the number of licenses, but it has not been reached at this time. There are no control dates in place should there be consideration of limited access in the future.

In addition to fishing on charted public oyster grounds MD residents can apply for commercial shellfish leases. Historically these have been comparatively modest in area and focused on improving otherwise “barren or marginal bottom that does not produce oysters naturally” (Webster and Meritt 1988). This option has recently been expanded by 20111 legislation that offers a joint application to MD DNR and the U.S. Army Corps of Engineers. (http://dnr2.maryland.gov/fisheries/Documents/Shellfish-Lease-Application-

Instructions.pdf) for a permit that covers both on bottom and water column (cages and floats) structures for oyster culture.

The Potomac River resource is managed by the Potomac River Fisheries Commission (PRFC). The history of PRFC is described at http://www.prfc.us/history.html. The resources of the Potomac are managed by a bi-state commission originating with the adoption of the MD and VA Potomac River Compact of 1958. PRFC regulates the fisheries of the main stem of the tidal Potomac River from the MD/Washington D.C. boundary line (near the Woodrow Wilson Bridge), to the mouth of the river at Point Lookout, MD and Smith Point, VA. The oyster resources of the Potomac are surveyed annually as part of the MD DNR effort. For the current document PRFC managed oyster resources are included in the MD data sets. A summary of PRFC regulations pertaining to commercial oystering is given at http://www.prfc.us/commercial/oyster_regulations.html. The seasonal activity limits are available at http://www.prfc.us/commercial/commercial_oyster_seasons_restrictions.html

VA data. General details of the fishery are given in Chapter 4VAC20-720-10 et seq. of the Code of VA. These are revised and updated annually (or more often as required) following management actions of the VA Marine Resources Commission (VMRC). The public oyster grounds of VA were first comprehensively surveyed by Baylor (1896), hence their common description as "Baylor Grounds", and identified 243,000 acres of natural oyster beds in the bay and coastal embayments of VA. The surveys were updated by Haven and colleagues in the late 1970s – early 1980s as part of a comprehensive survey of the VA Oyster industry. A current map can be viewed at https://webapps.mrc.virginia.gov/public/maps/chesapeakebay_map.php. This is equivalent to the MD document at http://dnr2.maryland.gov/fisheries/pages/oysters/bars.aspx. A detailed review of the work by Haven and colleagues illustrates the disparity between the early efforts of Baylor, wherein large swaths of habitat inclusive of prime oyster bars were included with habitat of lesser value, and the records of Haven that discriminate oyster habitat into several broad categories. In sum the total oyster habitat area described by Haven and colleagues is considerably less than that given by Baylor. The nature of the continuing long-term assessment program described herein is a revision of the habitat boundaries by default. The VA surveys employ an estimate of total oyster habitat in survey design; however, this, like the MD survey data, also has limitations in supporting estimates of total population size.

The VA public grounds are open to fishing for market oysters (> 3 inches, 76 mm shell length) from October through April of the following year (thus, for example, the 2012 harvest year extends from October 2012 through April 2013). The annual limitations on opening and closing of specific areas, allowed gear type, daily time limits and catch limits by size, bushel volume, and more (as required) are defined by VMRC as regulation updates. These regulations eliminate bycatch in that the harvest is culled and subject to inspection by VA Law Enforcement. Sub market size oysters are returned to the water and available for harvest at a later date when larger in size. There are no "discards". Areas may be opened and closed on a rotation plan (see for example the Rappahannock River record at http://cmap.vims.edu/VOSARA/VOSARA_Viewer/VOSARA.html). Fisheries are supported for both market and seed (< 3 inches for replanting) oysters. The period for harvest for seed is, again, set by VMRC regulation. VMRC may choose to set a harvest limit (bushels) for the seed fishery as required. Seed oysters are harvested as young of the year (YOY, typically, also termed spat) or sub market size oysters (less typically) attached to shell. Thus they are usually describe in terms of spat per bushel, with higher "spat counts" commanding a premium price. Blank shell devoid of attached oysters is discouraged. The current harvest regulations can be viewed at http://mrc.virginia.gov/regulations/fr720.shtm

In addition to the VA public fishery there also exists a VA "private" fishery, based on the leasing of non Baylor bottom resource by private citizens/corporations, appropriate preparation of that bottom by the lease, the transplant to that lease of seed oysters and/or deployment of cultured oyster spat on shell from hatchery sources, maintenance of the lease until such time that the planted oysters are of size for harvest, and the final harvest of those oysters. Unlike the public harvest effort, there are no date restrictions on harvest from private leases. A map of both active leases and areas currently under application and consideration for lease can be viewed at https://webapps.mrc.virginia.gov/public/maps/chesapeakebay_map.php. Lease fees are very modest at $1.50/acre/y. Leases have a "use it or lose it clause", although exemptions can and are considered to this clause, especially in periods of disease epizootics.

The public fishery is open to all VA residents who purchase appropriate licenses with no limits on access at this time. The oyster fishery is open to all MD residents who purchase appropriate licenses with no limits on access (i.e., this is not a limited entry or ITQ fishery) at this time. There are no control dates in place should there be consideration of limited access in the future.

VMRC staff maintains a historical record of commercial landings from both public and private "lease" oyster fisheries. For completeness, we note that these have recently been supplemented by records from aquaculture production. VA oyster production is now reported as the sum of these three parts. Efforts records have historically been poor in that daily boat counts have not been made. Mandatory reporting by harvesters was initiated in 2007 and these remain as the primary methods for estimating effort. Details of time and gear limitations, and buyer and harvester reports are summarized by area in Appendices A through G (labels correspond with sampling and data presentations given later in the report). Buyer reports were also required for part of this period, although this requirement has now been rescinded. Effort reports should, in theory be available from these reports, but these remain incomplete and are less than desired.

***ToR #2. Characterize the survey data that are being used in the assessment (e.g., regional indices of abundance, recruitment, state surveys, age-length data, etc.). Describe the uncertainty in these sources of data*.**

Survey methods in both MD and VA are driven by the need to survey an extensive spatial region in a limited (by biology and weather) time period with limited resources (one vessel plus crew, limited budget). The methods employed reflect the compromise in effecting such surveys on a continuing basis. Oyster reefs are highly variable in both shell and live oyster density at scales from centimeters to hundred of meters laterally, and present a stratified structure vertically from living overlay, through shell above the sediment water interface (oxic layer), through buried shell below the sediment water interface. All of these components are important in a complete assessment of reef, and thus population integrity. Available survey methods represent inevitable compromises in complete system description.

The following summaries address MD and VA programs in unison, or in isolation depending on subject. Extensive background information is presented at the following web resources:

MD general survey considerations can be explored through the portal at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/index.aspx and the "Monitoring and Assessment Links" listed on that page.

VA general survey considerations are summarized at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/survey_design_field/index.php and the sub links subsumed within that page.

Gear options for quantitative oyster surveys
(http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/survey_design_field/index.php)
All quantitative sampling gear has strengths and weaknesses. MD DNR surveys employ a swept area corrected approach with a dredge. These data are used in the current assessment. In VA there has been an historic (and continuing) oyster survey using a dredge; however, these data are not swept area corrected and are therefore qualitative at best. For the current assessment the VA surveys employ a hydraulic patent tong. For completeness in discussion we offer a brief discussion of the strengths and weaknesses of dredges, mechanical patent tongs, and hydraulic patent tongs.

Dredges.
The base requirement for a dredge to be used in quantitative surveys is that it can be assumed to cover a defined swept area with known capture efficiency on a consistent basis.

If these requirements can be met then a simple division of the number of oysters captured by the area covered gives density (oysters per unit area). Multiply density by the spatial footprint of the habitat, correct for dredge efficiency (this is less than 100%) and a total stock is estimated. Over the past decade the science supporting swept area approaches has been intensively examined and refined by NEFSC NMFS-industry-academic collaborative efforts in support of the surf clam, ocean quahog and sea scallop fisheries. These studies highlight the limitations of gear that was initially employed as a qualitative rather than a quantitative sampling tool. The oyster dredge is such a piece of gear – the challenge in its operation is to sample consistently over non-uniform bottom. Potential problems include the following:

a. The dredge is towed by a flexible line of variable length with variable scope and "hinge points" at either the winch or the passage of the towline over the stern of the vessel. An additional hinge point is the attachment of the line to the dredge. The cumulative design in tow mode functions by alternately digging and releasing, hence the action of a towline over the stern of the vessel during dredging. As such the dredge scoops but does not plane, so it does not sample representatively over the course of a tow, especially when the tow path moves over varying bottom type as would be found on a reef.
b. The dredge fills over the course of the tow to become a plough, after which it does not sample. Thus the only conditions under which a dredge can be used quantitatively are for very short tows (see Powell et al. 2002). The MD DNR surveys correctly employ very short tows with GPS location of deployment and retrieval with rejection/repeat of tows that are overflowing on retrieval. Notably this was NOT the case with historical dredge surveys in VA.
c. A dredge is size selective because it samples the surface more so than the underlying reef. If the Young of the Year (YOY, spat) are near the surface then the sampling is not representative. Bias in favor of live animals over shell has been noted by both Powell at al. (2002) and Mann et al. (2004). We address biased sampling later in this report in the context of dredge versus patent tong comparisons.
d. A single dredge will vary in efficiency depending on scope, speed of towing, size of vessel and even vessel operator, in addition to state of and direction of the tide. With this combination of variables caution must be exercised in transferring calculated efficiencies from one dredge/vessel/operator/location to another. These variables argue that any use of a dredge as a quantitative tool require that it be calibrated for each operator, vessel, bottom type, tidal stage and more. This important point is consistency to insure repeatable results. Again, this consistency is noted in the current MD DNR protocols.
e. Oyster dredges are less than 100% efficient in retention. There are no published depletion based efficiency estimates for oyster dredges. There are for surf clam and ocean quahog dredges (NEFSC-NMFS assessments), but the latter operate in uniform substrates and do not sample in an oscillatory manner when towed - they slide on wide runners and exhume the target species with hydraulic jets.

f. A strong ASSET of dredges is that they can cover a considerable area within a single tow, and thus integrate over that area. This is in stark contrast to the areal sampling problem presented by tongs (see below).

Mechanical patent tongs.
Mechanical patent tongs, like classic grabs or cores, sample from a known area, so the swept area at less than 100% retention efficiency concerns associated with dredges are moderated(redundant). The challenge is to assess the efficiency of sampling in the area enclosed by the tong opening as it sits on the bottom. This is influenced by tong weight, length of tong teeth, bottom type and deployment protocol (that collectively determine how far the teeth initially penetrates the bottom) and by retrieval protocol. A typical mechanical patent tong is designed to close as it is recovered – both actions occur simultaneously. Herein lies its weakness as a sampling tool in that a well operated patent tong in fishing mode both sorts and retrieves in one action. It is selective by design, especially so when bottom penetration is limited. This is problematic where natural reefs retain their base structural integrity, such as in the James River where exploitation has been limited to hand tongs with their limited bottom penetration ability. Thus mechanical patent tongs sample the surface layer with greater consistency than underlying layers; the latter are poorly sampled if at all. As will be addressed in later discussions related to brown (oxic region above the sediment water interface) versus black (buried, anoxic) shell data, the inability to simultaneously sample the underlying shell habitat limits the use of mechanical patent tongs in comprehensive studies. Finally, most mechanical tongs have limited covers and are thus susceptible to spillage of material during retrieval – mostly small material that is of limited interest in fisheries with minimum size limits. This material is however, often critical in stock assessment.

Hydraulic patent tongs
Hydraulic patent tongs separate the actions of closing from retrieval. Thus each can be optimized in design rather than compromised. The hydraulic tong is heavier than a mechanical tong of comparable opening allowing both deeper initial penetration of the bottom, and insuring that the tongs continues to "dig" during the closing action. The same arguments apply in the design of certain grabs that also separate closing from retrieval. The result is a deeper sampling into the aforementioned vertically stratified structure of the reef. Once closed the hydraulic patent tong is then retrieved. The hydraulic tong used in VA studies has the optional cover to retain surface material, and the integrity of the surface in the retained sample. Total volume retained in a single sample can regularly exceed 50L with an intact surface layer. Penetration through the live animal – oxic shell layer to the underlying black anoxic shell layer illustrates complete sampling of the layered reef crust.

Both mechanical and hydraulic patent tongs sample a small footprint, typically on the order of one square meter (the design of the hydraulic tong used by both MD DNR and VMRC-VIMS). Thus spatial variation in the reef environment is a critical problem in sampling employing tongs. This will be addressed later in the current report.

Survey design: coverage of the spatial footprint of interest.

The desired end point of an assessment survey is to provide a defensible quantitative estimate of oyster populations, on a river and/or region specific basis if required, for both the MD and VA portions of the Chesapeake Bay. The assessment must minimally include demographics of the live population by size class as traditionally used in fishery management. A longer term and desirable goal is to extend the assessment to include age class structure and describe the status of the underlying shell substrate (reef) structure. Current surveys meet the minimum requirements described above and include data that portrays absolute densities and demographics; progression to the desirable goal(s) are in progress and will be discussed later in this document.

MD survey design is described at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/fall-survey.aspx and http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/methods.aspx. The following is distilled from those sources.

The MD annual dredge based survey began activity in 1939. These surveys provide data on oyster abundance, recruitment (spatfall intensity), mortality, and more recently on parasitic infection status. Monitored sites have included natural oyster bars, seed production and planting areas, dredged and fresh shell plantings, and sanctuaries. The survey design has evolved since inception but with care being taken to insure continuity of the long-term data set. In 1975, 53 sites and their alternates, referred to as the historical "Key Bar" set, were fixed to form the basis of an annual recruitment spatfall intensity index. These sites were selected to provide both adequate geographic coverage and continuity with data going back to 1939. An oyster parasite diagnosis component was added in 1958, and in 1990 a 43-bar subset (Disease Bar set) was established for obtaining standardized parasite prevalence and intensity data. Thirty-one of the Disease Bars are among the 53 spatfall index oyster bars (Key Bars). A map of the locations of both the Disease Bars and Key Bars in presented at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/fall-survey.aspx

Surveys of MD sanctuaries are supported in part by this award. These are regions that are very modest in terms of their contribution to the total area under consideration, but is disproportionate in terms of dollar investment and monitoring intensity. Sanctuary surveys were completed under the supervision of Dr. Kennedy Paynter of the University of MD. Given the unique nature of this effort the report describing sanctuary assessment is appended to this report in its entirety as Appendix UMD. Notably the report includes description of coordinated use of side scan sonar and patent tong sampling on targeted reefs. Such knowledge is important as a contribution to future survey design as addressed in ToR#11.

VA survey design follows that employed in prior surveys funded by NCBO-NOAA (then NOAA-CBSAC) and EPA. As in MD there is a long standing dredge based annual qualitative survey of oyster bars in VA (summaries included in annual reports at http://www.vims.edu/research/units/labgroups/molluscan_ecology/publications/reports/annual/index.php); however, these are not defined swept area and thus do not provide per unit area values for oyster density. They provide per bushel data only. To remedy this situation a quantitative patent tong survey began in fall 1993 for a subset of the current locations, with serial improvements being made in field methods through 1998. Since that time methods have been constant and are as described in peer publications by Mann et al. (2009), Southworth et al. (2010) and Harding et al. (2010), and under section 2 through 6 at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/index.php. The surveyed areas were originally based on prior designations of public oyster grounds by Haven and colleagues in the early 1980s. These delineations include a variety of bottom types deemed suitable for oysters including oyster reef (also termed oyster rock) through shell-mud and shell sand mixtures that were either originally marginal to more compact reef habitat or are the product of decades of disturbance by fishing and other anthropogenic activity. The survey design adopted in 1993 was based on the approach employed by NEFSC-NMFS in its offshore clam surveys; essentially treat each area as a stratum within which sampling will be effected on a random basis. In 1993 the approach was to mark the corners of the defined region, overlay a grid with the grid points being given progressive numbers, then sample grid points in the order determined by a random number table. The procedure of Bros and Cowell (1987) is then employed to assure adequacy of sampling within each strata – basically a plot of standard error of the running mean versus the number of samples collected within a strata, the desired minimum number of samples being determined by the point at which the plot levels and indicates decreasing information for each additional added sample. We continue to add to the survey footprint as shell planting in support of fisheries and restoration activity dictates.

This approach has both strength and weaknesses. All surveys where distribution of target species within a boundary is unknown are a compromise of time invested in mapping to determine sampling on the one hand, versus time and resources on the other. The VA survey attempts to cover approximately 174 distinct sampling areas covering approximately 8,900 acres in one calendar month with a vessel and crew that can sample up to 100 individual sites per day with a hydraulic patent tong under optimal weather conditions. Twenty calendar days in the field provides for approximately 1600 sites, or approximately one site (one sq. meter) every 5.2 acres (21,000 m^2). It remains clearly impractical to attempt a detailed mapping at scales finer than that provided by Haven and colleagues for the vast area at hand (notably Haven and field crew spent 4 years in the field producing their most recent generation maps, and the distance between their transect swaths was still of an order greater than certain reef footprints). Thus the employment of the above described approach. Retrospectively, the option exists to cumulatively add data by annual increments to the database describing the resource within each area (=strata) and re-stratify within the boundaries based on distribution of both oysters and shell substrate. This requires care in that re-stratification redirects the limited resources (1600 samples upper limit) with gains in fidelity in some regions being traded against losses in others. In addition, re-stratification cannot jeopardize continuity of long-term data[1].

MD DNR field sample and data collection methods.

MD DNR annual Fall Survey sample and data collection methods are described in detail at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/methods.aspx. Treatment of the collected samples to generate oyster population data is described at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/sample.aspx. The following is a brief summary of those descriptions.

The typical Annual Fall Oyster Survey visits over 250 discrete oyster bars with upwards of 350 or more samples taken. In addition to the Key and Disease bars (see earlier section on survey design), natural oyster bars, sanctuaries, natural and hatchery seed planting, shell planting, and special project sites are sampled.

Samples are acquired by towing a 32 inch-wide standard oyster dredge. At each of the 53 Key Bar sites and the 43 Disease Bars, two 0.5-bushel subsamples are collected from replicate dredge tows. On seed production areas, five 0.2-bushel subsamples are taken from replicate dredge tows. At all other sites, one 0.5-bushel subsample is collected. Since 2005 tow distances have been recorded for all samples using the odometer function of a global positioning system unit. A proviso for all samples is that the dredge is not full and has thus sampled for the entire length of the two. Thus swept area is estimated and the total volume of material in the dredge represents that area. Quantitative per unit area estimates are thus facilitated. One half bushel subsample are taken and processed as follows: live and dead oysters are separated, live oyster are carefully examined for the presence of YOY (spat), and oyster are measured for maximum dimension from the hinge to the growing edge. This is correctly termed shell height, although commonly described as shell length in most literature. We adopt the common convention and refer to shell length (SL) in this text.

Representative samples of 30 oysters older than one year are taken at each of the 43 Disease Bar sites. Additional samples for disease diagnostics are collected from seed production areas, seed planting areas, and areas of special interest. Oyster parasite diagnostic tests are provided by staff of the Oxford Laboratory. Data reported for *Perkinsus marinus* (Dermo disease) are from rectal Ray's fluid thioglycollate medium (RFTM) assays. Prior to 1999, the less sensitive hemolymph assays were performed. Data reported for *Haplosporidium nelsoni* (MSX disease) have been generated from tissue histology since

[1] A related project has been initiated (July 2014) as a supplement to a current NSF award to Eric N. Powell and Robert Leaf (Gulf Coast Research Laboratory, University of Southern Mississippi), and Roger Mann (VIMS) to compare, as a retrospective exercise on a virtual population developed by overlaying the entire geo-referenced Virginia historical data set on a single GIS layer, options for random, fixed station and adaptive sampling regimes to develop oyster population estimates.

1999. Before 1999, hemolymph cytology was performed, while histology samples were examined for *H. nelsoni* only from selected locations.

Data presentation in the Fall Surveys includes elements that cover the entire MD bay, and others that are location specific as required on an annual basis.

VA field sample and data collection methods.

These are summarized under sections 2 through 6 at the following: http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/index.php. Oysters are collected from the 43-ft long VMRC vessel *J.B. Baylor* with a hydraulic patent tong. The open dimensions of the tong are such that it samples one square meter of bottom. Upon retrieval of each sample (= patent tong grab), oysters are counted and measured (mm), and the volume of shell material (L) recorded. The recorded dimension for each oyster, as in MD procedures, is the longest from the hinge to the shell margin. This is correctly termed shell height, although commonly described as shell length in most literature. We adopt the common convention and refer to shell length (SL) in this text. A count of the number of oysters per tong was made in all years sampled (1993 through the most recent survey in 2013). Prior to 1998 a representative subsample (n > 100) of oysters was pooled across individual samples for a given reef and measured and classified into 5 mm size bins. From 1998 to 2002, for each sample, all oysters were measured and classified into 5 mm size bins. Beginning in 2003, for each sample, individual lengths were recorded to the nearest mm. Distinction is also made between Young of the Year (YOY) or spat, and older oysters. Spat, are generally closely attached to the substrate for their entire length when examined in the fall after recruitment to the benthos whereas older animals develop a cupped shape in the attached valve. Since 1998, samples with > 20 L of shell have typically been subsampled (1/2, 1/3 etc.) to facilitate processing. An appropriate subsample factor was then applied to the resulting counts and length frequency distributions to estimate density and size distribution on a per m^{-2} basis when subsampling was necessary. All dead oysters with articulated valves, commonly termed boxes (and termed boxes throughout the remainder of this document), were similarly counted and measured. The VA survey has collected quantitative shell data (L volume) for both brown (oxic exposed) and black (anoxic buried) shell since 2002, 2000 in some cases, back to 1993 for a combined measurement of both where brown and black were not separated.

The VA oyster resource may have been considered as a series of contiguous sub populations in the rivers and bays in the time of Baylor, but these resources were fractured spatially by the actions of both MSX and Dermo with the resultant restriction of oysters to discrete populations in low salinity sanctuaries from disease. The definition of discrete versus metapopulations within the Bay, together with sources and sinks, remains a subject of investigation and debate. Thus for the current report the population is considered as a series of adjacent stocks with no presumptions as to the levels of connectivity. These stocks are coincident with subdivision of the surveyed area in a north-south direction as follows: (A) Pocomoke and Tangier Sounds, (B) Great Wicomico River, (C) Rappahannock River, (D) Piankatank River, (E) Mobjack Bay, (F) York River, (G) James River, and (H) Elizabeth and

Lafayette Rivers (H). In addition there are a modest number of stations in the Bay main stem adjacent to both not enclosed by various of estuary mouths. Unlike the previously described MD surveys the number of stations visited by the VA surveys the overall number of stations sampled has gradually increased since 1993, although in some instances the number is certain locations has increased then decreased as (a) statistical analysis suggests only modest information return in some locations and (b) effort has expanded to include new locations. The following tables summarize area surveyed (acres and m^2) and number of individual patent tong collections by region/river within each year from 1993 through 2013.

Table 2.1. Number of samples collected by region/river and year

	A	B	C	D	E	F	G	H	TOTAL
1993							825		825
1994							800		800
1995		31		62			816		909
1996				62			822		884
1997		59		0			751		810
1998		71		78			801		950
1999		38		42			422	14	516
2000		49	173	59			409		690
2001		49	195	68			415		727
2002	28	49	287	75			405		816
2003	80	49	287	73			418		827
2004	101	49	301	73			421		844
2005	110	49	301	73			421	21	865
2006	151	49	301	72	21		527	21	991
2007	151	56	385	72	21		527	21	1082
2008	151	70	385	72	21		527	21	1096
2009	148	77	385	72	21	54	527	21	1157
2010	148	77	395	79	21	76	527	21	1196
2011	148	77	395	128	21	76	518	21	1236
2012	148	77	395	128	21	76	518	21	1236
2013	193	77	397	131	30	77	519	21	1252

Table 2.2. Area sampled by region/river and year: data in both acres (top) and m^2(*bottom*)

	A	B	C	D	E	F	G	H	TOTAL
1993							5650.5		5650.5
1994							5950.3		5950.3
1995		114.8		173.6			5955.6		6244.0
1996				173.6			5955.6		6129.3
1997		161.8		0.0			5955.6		6117.4
1998		174.4		173.6			5955.6		6303.6
1999		161.8		93.2			5955.6	16.3	6226.9
2000		70.7	276.8	166.0			5955.6		6469.1
2001		70.7	280.4	173.6			5955.6		6480.4
2002	33.0	70.7	497.7	180.3			5955.7		6737.3
2003	197.0	70.7	497.7	180.3			5935.0		6880.7
2004	222.0	70.7	509.3	180.3			5955.7		6937.9
2005	254.3	70.7	509.3	180.3			5955.7	29.3	6999.5
2006	310.0	70.7	509.3	180.3	23.2		6800.5	29.3	7923.3
2007	310.0	73.9	568.7	180.3	23.2		6800.5	29.3	7985.9
2008	310.0	104.2	571.7	180.3	23.2		6800.5	29.3	8019.2
2009	310.0	108.2	571.7	180.3	23.2	208.5	6800.5	29.3	8231.8
2010	310.0	108.2	571.7	182.3	23.2	208.5	6767.9	29.3	8201.2
2011	310.0	108.2	571.7	204.3	23.2	208.5	6767.9	29.3	8223.2
2012	310.0	108.2	571.7	204.3	23.2	208.5	6767.9	29.3	8223.2
2013	496.6	108.2	571.6	204.3	45.3	208.5	6767.9	29.3	8431.8
1993							*2.29E+07*		*2.29E+07*
1994							*2.41E+07*		*2.41E+07*
1995		*4.64E+05*		*7.03E+05*			*2.41E+07*		*2.53E+07*
1996				*7.03E+05*			*2.41E+07*		*2.48E+07*
1997		*6.55E+05*		*0.00E+00*			*2.41E+07*		*2.48E+07*
1998		*7.06E+05*		*7.03E+05*			*2.41E+07*		*2.55E+07*
1999		*6.55E+05*		*3.77E+05*			*2.41E+07*	*6.60E+04*	*2.52E+07*
2000		*2.86E+05*		*6.72E+05*			*2.41E+07*		*2.62E+07*
2001		*2.86E+05*		*7.03E+05*			*2.41E+07*		*2.62E+07*
2002	*1.34E+05*	*2.86E+05*		*7.30E+05*			*2.41E+07*		*2.73E+07*
2003	*7.96E+05*	*2.86E+05*		*7.30E+05*			*2.41E+07*		*2.79E+07*
2004	*8.98E+05*	*2.35E+05*		*7.30E+05*			*2.41E+07*		*2.80E+07*
2005	*1.03E+06*	*2.86E+05*		*7.30E+05*			*2.41E+07*	*1.19E+05*	*2.83E+07*
2006	*1.25E+06*	*2.86E+05*	*9.38E+04*	*7.30E+05*	*9.38E+04*		*2.75E+07*	*1.19E+05*	*3.21E+07*
2007	*1.25E+06*	*2.99E+05*	*9.38E+04*	*7.30E+05*	*9.38E+04*		*2.75E+07*	*1.19E+05*	*3.23E+07*
2008	*1.25E+06*	*4.22E+05*	*9.38E+04*	*7.30E+05*	*9.38E+04*		*2.75E+07*	*1.19E+05*	*3.25E+07*
2009	*1.25E+06*	*4.38E+05*	*9.38E+04*	*7.30E+05*	*9.38E+04*	*8.43E+05*	*2.75E+07*	*1.19E+05*	*3.33E+07*
2010	*1.25E+06*	*4.38E+05*	*9.38E+04*	*7.38E+05*	*9.38E+04*	*8.43E+05*	*2.74E+07*	*1.19E+05*	*3.32E+07*
2011	*1.25E+06*	*4.38E+05*	*9.38E+04*	*7.94E+05*	*9.38E+04*	*8.43E+05*	*2.74E+07*	*1.19E+05*	*3.33E+07*
2012	*1.25E+06*	*4.38E+05*	*9.38E+04*	*8.27E+05*	*9.38E+04*	*8.43E+05*	*2.74E+07*	*1.19E+05*	*3.33E+07*
2013	*2.01E+06*	*4.38E+05*	*1.83E+05*	*8.27E+05*	*1.83E+05*	*8.44E+05*	*2.74E+07*	*1.19E+05*	*3.41E+07*

Development of population estimates: numbers, biomass, age structure, and mortality in state surveys.

MD surveys

Mean oyster density (number m^{-2}) can be estimated for each oyster reef from the known swept area and total number of oysters collected by the individual tow. These data can be hind cast to 2005 when swept area estimates were first incorporated into survey design.

Shell volume (L m^{-2}) can also be estimated from the swept area collections for the 2005-present time period given that total dredge content is recorded and the dredge is not full when retrieved. These values will; however, underestimate total shell resource because the dredge samples across the surface of the reef as discussed earlier, rather than penetrating to and through the base of the reef below the sediment water interface. The values will therefore be lower than those estimated in the VA survey by hydraulic patent tong methods. Nonetheless the long-term records of shell data offer the opportunity to generate a shell or habitat index in MD that is presented in partnership with the live oyster biomass index described below.

Biomass in MD surveys is presented as a time series ***Biomass Index***. The index is designed to include the processes of recruitment, growth and mortality (both M and F) in one descriptor. The Biomass Index is based on the oyster size-weight relationships described in Jordan et al. (2002) where y is dry meat weight (DW, g) and x is shell length (SL, mm) and the exponential relationship is described by $y = 0.0002x^{2.0626}$. In that study oyster shells were measured (SL, mm) and the meats were removed, oven-dried, then weighed to generate individual biomass or dry meat weight (DW, g). Average dry-meat weights were calculated for oysters in each 5-mm grouping used in the field measurements. Those standards are used to this day to calculate the annual Biomass Index from size-frequency data collected from Fall Survey field samples. For each of the 43 disease monitoring stations, the number of small and market oysters (= post-spat or 1+ year classes) in each 5 mm size class was multiplied by the average dry-meat weight for that 6 size classes to obtain the total weight for each size grouping. These weights were summed to estimate total dry-meat weight of a 1 bu. sample (composite of two 0.5 bu. subsamples) from a disease monitoring bar. The average biomass value for all 43 sites is then estimated. For long term trend purposes the annual average biomass values are compared to the biomass value for 1993 (which is set at 1.0 because the baseline data are from the 1993 Fall Survey, corresponding to the year with lowest oyster harvest on record to that date). The Biomass Index is calculated by dividing the year's average biomass value by the 1993 average biomass value. This approach provides a Biological Reference Point (BRP) in the 1993 value. BRP's are also discussed under ToR #7 and ToR #8 later in this text.

The MD Annual Fall Survey has an attendant statistical framework for analysis. Friedman's Two-Way Rank Sum Test, a non-parametric treatment, is used (Hollander and Wolfe 1973). This procedure, along with an associated multiple-range test, allows among-year comparisons for several parameters. Additionally, mean rank data can be viewed as annual indices, thereby allowing temporal patterns to emerge. Friedman's Two-Way Rank Sum Test, an analog of the normal scores general Q statistic (Hájek and Šidák 1967), is an expansion of paired replicate tests (e.g. Wilcoxon's Signed Rank Test or Fisher's Sign Test). Friedman's Test differs substantively from a Two-Way ANOVA in that interactions between blocks and treatments are not allowed by the computational model (See Lehman 1963 for a more general model that allows such interactions). The lack of block-treatment interaction terms is crucial in the application of the test to the various sets of Fall Survey oyster data, since it eliminates nuisance effects associated with intrinsic, site- specific characteristics. That is, since rankings are assigned across treatments (in this report - years), but rank summations are made along blocks (oyster bars), intrinsic differences among oyster bars are not an element in the test result. All Annual Reports employ Friedman's Test with $\alpha=0.05$.

To quantify annual relationships, a distribution-free multiple comparison procedure, based on Friedman's Rank Sum Test, is used to produce "tiers". Each tier consists of a set of annual mean ranks that are statistically similar to one another. This procedure (McDonald and Thompson 1967) is relatively robust, very efficient, and, unlike many multiple comparison tests, allows the results to be interpreted as hypothesis tests. Multiple comparisons are evaluated using "yardsticks" developed from experimental error rates of $\alpha=0.15$.

Age structure has not been examined in MD oyster stocks.

Mortality in MD surveys is estimated as the percentage of total small and market oysters as boxes. This is reported as "Total Observed Mortality."

Recruitment in MD surveys reported by a Spatfall intensity index is estimated as arithmetic mean of spat per bushel for "Key Bars."

Surveys of MD sanctuaries are supported in part by this award. These are regions that are modest in terms of their contribution to the total area under consideration, but is disproportionate in terms of dollar investment and monitoring intensity. Sanctuary surveys were completed under the supervision of Dr. Ken Paynter of the University of MD. Given the unique nature of this effort the report describing sanctuary assessment is appended to this report in its entirety as Appendix UMD. Notably the report includes description of coordinated use of side scan sonar and patent tong sampling on targeted reefs. Such knowledge is important as a contribution to future survey design as addressed in ToR#11.

VA surveys
Methods for the VA surveys are described at
http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/population_estimates/index.php

Mean oyster density (number m^{-2}) was estimated for each oyster reef by averaging the number of oysters collected from all samples on a reef within a year. These data are available back to 1993 depending on location (see Table 1).

Shell volume (L m^{-2}) has been collected since 1998 coincident with the measurement of all boxes (articulated valves of dead oysters). Since 2002 shell has additionally been categorized as brown shell that was exposed to oxic water above the sediment water interface, and black shell that was exhumed during the collection process.

Biomass estimation (DW, g) : Data from a size range (30-139 mm shell length) of live oysters (n= 73) collected from Swash in the James River (Reef 13, Figure 1 in Mann et al. 2009) in November 2004 (n = 24), 2005 (n = 24) and 2006 (n= 25) were used to estimate the relationship between oyster shell length (SL, mm, see earlier note on convention with shell height and length) and biomass or dry tissue weight (DW, g). After the oysters were measured to the nearest mm, the tissue was removed and dried to constant weight (DW, g) at 80°C (72 hrs). The resulting relationship is:

$$\text{Biomass (DW, g)} = 7.12 * 10^{-5} * \text{Shell length (SL, mm)}^{2.15}; \text{(James)}$$

Additionally shell length to biomass relationships were developed for the Great Wicomico and Piankatank River oyster populations. These were as follows:

$$\text{Biomass (DW, g)} = 9.63 * 10^{-6} * \text{Shell length (SL, mm)}^{2.743} \text{ (GWR)}$$

$$\text{Biomass (DW, g)} = 4.92 * 10^{-5} * \text{Shell length (SL, mm)}^{2.299} \text{ (PR)}$$

Biomass calculations were made for (YOY, small at <75 mm SL, and market at SL >75 mm), for each 5 mm size class, and for each age class (see below) across all data as required (see later discussion in stock versus recruit relationship). The biomass values were estimated for each reef and river system/area as required.

Wet shell weights (WSW, g) were collected from the same 73 oysters used in biomass determinations in the James River after the tissue had been removed and before the shells had air-dried. The relationship between SL and WSW is described in Mann et al. (2009) as follows:

$$\text{Wet shell weight (WSW, g)} = 0.002374 * \text{Shell length (SL, mm)}^{2.21}; r^2 = 0.64, n = 73$$

This relationship was used to estimate the amount of live shell (g) observed in each patent tong on the basis of the available live oyster and demographics. Note that the exponents in equations describing (a) biomass versus SL and (b) wet shell weight versus SL are remarkably close, indicating that a traditional meat weight: shell weight condition index (e.g., Walne and Mann, 1975; Mann, 1978) is approximately constant with size.

Wet shell volumetric conversion: a volumetric conversion was also estimated by weighing 1 L shell samples, including a range of shell types from whole shells to shell hash, collected from five reefs in the James River in November 2006.

1 L of wet James River shell = 587.3 g +/- 22.6 g

Biomass to shell volume conversion: Combining the above relationships allowed estimation of shell volume of live oysters from biomass using the relationship:

$$\text{Volume (L)} = 7.66 * 10^{-2} * \text{biomass (DW, g)} - 0.0014$$

This final relationship allowed comparison of live animals associated shell to oxic brown shell at any chosen location.

Age structure has been investigated in VA oyster populations. Age structure provides running quantitative indices of both recruitment and mortality. Unlike the vast majority of bivalves oysters do not have typical symmetry in their growth form, indeed the aggregated growth in reefs generally insures a variety of final growth shapes. Signature growth increments in the shell matrix, as seen in sections of the shell and/or hinge, are also variable and require care in interpretation. The approach described here uses predominantly demographic analysis bolstered by very large n values. It is, notably, in agreement with blind testing using both growth signature and isotope analysis (for discussion see Harding et al., 2008, 2010b). As an historical note, demographic plots prepared for each year in the 1998-2006 period for each reef surveyed in the James River for both live oysters and boxes using 5 mm bins provided limited guidance on age versus length relationships. Distinct year classes of live oysters that could be followed for a minimum of three years were rare in these plots. The period of recruitment to the benthos (spatfall) in the James results in a broad size range within each year class such that interannual junctions are not distinct with a 5 mm size bin. Data for 2004 –2006 were, as mentioned earlier, available in 1 mm size bins. All data for these years for reefs with densities exceeding 100 oysters m^{-2} are in close proximity to each other and were aggregated on a single size frequency plot with 2 mm bins. The individual cohorts (not year classes, there being one or more cohorts in a single year class) were identified by the method of Bhattacharya (1967). The range and modal length of each cohort was identified by counting cohorts and relating the cohort settlement dates to long term recruitment patterns developed from annual spatfall reports for the James River over the study period (annual reports by Southworth et al, available at http://www.vims.edu/mollusc/publications/mepubamr.htm), The cohorts were thus assigned to years and a linear age at length relationship fit to the data (y = mx + c). This gave a good fit for James River observations (Mann et al. 2009, Figure 6) thus:

$$y = 30.22 + 21.6x;\ r^2 = 0.93,\ n > 22{,}000$$

Using a July 1 birth date and noting that current data is for a fall survey then lengths on November 1 represent ages of 0.33, 1.33, and so on with annual increments, although for clarity throughout this text these are referred to as age classes 0 (= YOY = spat), 1, 2, 3 and >3 or year olds. Corresponding lengths are 37.3 mm at 0 yrs, 58.9 mm at 1 yrs, 80.5 mm at 2 yrs, 102.1 mm at 3 yrs and 123.7 mm at 4 yrs. This age at length model was used to recast the length demographic as an age demographic and to estimate age specific mortality. Mann et al (2009) argue that a linear age versus length fit is appropriate for early years given the life expectancy of an oyster (10-15 years in undisturbed populations, Cummings and Powell 1985), given the previously mentioned plastic form and lack of adherence to isodiametric form (Powell et al in preparation) with allometric b values generally nearer 2 than 3 (including those presented above). James River oysters are also distinctively long and thin rather than typically cupped in shape – they have been locally described as "pencils". Such a form approximates to a tube rather than a sphere, again allowing for a linear fit. The adoption of an age-at-length plot using the von Bertalanffy (1938) model is not considered appropriate for the these oysters. In addition to the linear (best fit) model for James River data a quadratic length versus age descriptor was developed for oysters in the Great Wicomico River by Southworth et al (2010) and the Piankatank River by Harding et al (2010). In both instances the quadratic fit gave a higher R^2 value than the linear fit. Unlike the James River oysters individuals collected from both the Great Wicomico River and the Piankatank River tend to a more cupped shape (not "pencils") and a non-linear age versus length fit is supported. The quadratic fit is of the form $SL = a*(Age)^2 + b*(Age) + c$.

For the Great Wicomico River: included years are 2003-2009. Values of a, b and c are as follows: a =-3.76, b = 38.077, c = 8.51. The corresponding SL values are 17.5 mm at 0 yrs, 52.1 mm at 1 yrs, 75.4 mm at 2 yrs, 87.4 mm at 3 yrs, 98.25 mm at 4 yrs.

For the Piankatank River: included years are 2003-2009. Values of a, b and c are as follows: a =-2.947, b = 32.6565, c = 14.456. Corresponding lengths are 24.9 mm at 0 yrs, 52.7 mm at 1 yrs, 74.5 mm at 2 yrs, 90.5 mm at 3 yrs. 100.4 mm at 4 yrs.

The age at length estimates for the Great Wicomico and Piankatank rivers are slightly lower than those for the James River linear fit. Caution is required when extrapolating these fits in that the very nature of linear and quadratic fits are that they will diverge with increasing age. In this report the river specific fits are used to estimate age structure from demographic data for only those specific locations except when otherwise stated. At this time we have not yet developed age at length estimators for the Rappahannock River, and Pocomoke and Tangier Sounds, although these are tractable goals by the method of Bhattacharya (1967) given the increasing volume of data on hand (they are listed as future research needs in ToR# 11). These locations are not, however, visited as part of the ongoing spatfall reports, and therefore the luxury of double blind testing of cohorts in both spatfall and length demography is not available.

Estimating mortality in VA data: natural and fishing rates, and the use of "box counts".

Mann et al (2009) use the age-at-length estimator described above to recast length demographic plots as graphs of year classes for each year and reef in the James River for the period 1998-2006. Where live cohorts could be followed for more than two successive years, the number of individuals per m^2 was recorded in successive year classes. Survivorship and mortality were thus estimated by the following relationships as a proportion with values ranging from 0 – 1.0:

(1) Survivorship = #Live (t+1)/#Live(t)
(2) Mortality = #Live(t) – #Live (t+1)/#Live (t)

where #Live(t) equals the number of live oysters at time t (t, units of 1 yr). Thus mortality can be estimated provided $\geq$2 successive years of data are available, and as an alternative to box count data provided (see below). An error inherent to the approach of using just year class data is assignment of the animals to the wrong year class (too old or too young) from the age-at-length estimator. The error cascades through the demographic, and in some instances where #Live(t+1)>#Live(t), gives nonsense negative mortality values in the simple proportion estimator; however, the incorrect assignment to year class may not be the only causative agent in the proportion estimator. Under-counting of small size and/or bias in gear collection against small sizes, and thus age classes can give similar errors. The possibility exists that both spat and spat boxes are underestimated by this sampling method, the latter being physically separated during collection. One of the challenges in the James River, where recruitment can occur as late as September (Southworth et al. 2002, Southworth & Mann 2004, Southworth et al 2006), is to count spat in October-November patent tong surveys. Underestimation of spat in patent tong surveys is cause for concern.

So why not use the traditional and widely used approach of counting boxes? In response – this method also has limitations. Box-length demographics can be converted to age demographics employing the assumption that all boxes are $\leq$1 year old in order to categorize the boxes into the same age classes as the live animals (that is valves disarticulate within one year of the death of the oyster). Thus live oysters with lengths x through y and boxes with lengths x through y are assumed to represent the same year class and are only counted once. If December is the end of the growing season and the surveys are in the preceding October-November, then all boxes represent mortality in that calendar year with the bulk of mortality being in the warmer months (predation, especially on the smaller individuals) and in the late summer (disease). This assumption is central to the approach that all boxes can be used in mortality estimation, although the longevity of undisturbed hinges in articulated valves has not been critically examined, and there is no requirement to estimate the "age" of new boxes as proposed by Volstad et al (2008). Thus employing spat box densities may underestimate mortality in small oysters range because of both the fragility of the articulated box (it disarticulates quickly) and that predation related mortality does not leave an intact box in very small oysters (this is embodied in a research need in ToR #11).

If boxes are assigned to year classes and only counted once then mortality can be estimated by a second relationship as follows, again expressed as a proportion with values ranging from 0 – 1.0:

(3) Mortality = #Box(t) / [#Box(t) + #Live(t)]

The two mortality estimators are related by use of the #Live(t) value. A comparison of data from both estimators is presented in Figure 9 of Mann et al (2009). There is a notable disparity between these two estimators with box counts providing consistently lower estimates. So both methods have limitations. We acknowledge the widespread use of box count data when no other data are available, and offer the MD Annual Survey of the value of such data when it is collected consistently and presented as an index of mortality..

The age based demographic approach does not distinguish the contributions of natural (M) versus fishing (F) mortality. Thus generated mortality estimates are (M+F). For management purposes both are desirable in that F can be controlled, M generally cannot. Box counts include articualted valves as an estimate of M, but do not include F. Estimates of F require fishery reporting as mentioned in discussion of ToR #1. Converted efforts have been made in recent years in both MD and VA to improve self reporting of catch (see earlier comments in ToR#1 on CPUE). MD in particular willl move to entirley digital reporting in the coming year, and these efforts will undoubtedly improve our abilities ot povide sound estimaytes of F.

A commentary on natural mortality rates of oysters based on life history and longevity

Estimates of both M and F are valuable to fishery management, and are challenged for Chesapeake Bay oyster populations by the fact that stocks have been decimated by well over a century of intense exploitation, habitat degradation, and the cumulative impacts of two diseases. The diseases in particular have resulted in age truncation of the extant stocks. Thus it is reasonable to ask what should we expect for values of M in "pristine" populations versus extant populations?

Hoenig (1983) provides a reasoned argument for the estimation of natural mortality rates based on species longevity. These are discussed for oysters by Mann et al (2009), who both review historical records of oyster age (10-20 y, Powell and Cummins 1985) and size (up to 450 mm, DeBroca 1865) prior to the impact of harvest and, more recently, disease epizootics. Under a scenario where life expectancy is matched with a constant mortality for age classes >1y (to avoid the complication of density dependent YOY predation loss and include the predation refuge size of 25+ mm (Eggleston 1990)) we can describe annual mortality rate, M, as a proportional value between 0.0 (all survived) and 1.0 (all died). Survival, S, is (1-M) for a period of one year or $(1\text{-}M)^q$ for a period of q years. Recalling that the plot of S versus time is exponentially declining, a 2% value for S is reached with the corresponding values for age and M: 5 y at M= 0.55, 7 y at M= 0.45, 9 y at M = 0.35, 13 y at

M = 0.25, >20 y at M = 0.15. Note that longevity values approaching 20 years are not unreasonable for pre-colonial oyster population in that the maximum length of 450 mm SL from DeBroca (1865) corresponds with and age 19 y and SL of 433 mm using the modern growth curve from Mann et al. (2009). Oyster life history traits are the product of 50 million years of selection (see discussion in Mann et al 2009 with respect to the role of longevity in shell production and reef accretion through positive shell budgets). Individual longevity approaching 20 y is a product of that selection, yet this is not commensurate with observations of extant populations. Both Dermo (*Perkinsus marinus*) and MSX (*Haplosporidium nelsoni*) can typically kill their hosts within the first 2-3 years of life, thus massively truncating the age demographic of the population. Such disease-compromised populations cannot, unfortunately, be modeled using mortality estimators developed from the life history based arguments discussed above.

So what drives the mortality observations of recent (approaching 50 years) studies and how are the mortality estimators from the above discussion of use? Numerous studies have used tray held oysters to assess mortality over time in conjunction with disease assays in the experimental populations. In addition studies have examined the temporal and spatial variability in disease prevlance and intensity in field populations. With the advent of age structure description, we can estimate age specific mortality, and thus compare the observed mortality data with parallel disease date. This approach remains limitation by an inability to subtract the impact of harvest removal (F) on a site and time specific basis and thus correct the estimate of disease related mortality. This subject is revisited in discussion of current disease status for the MD and VA oyster stocks in ToR #5.

Projecting standing stocks and demographics from assessment data.

Oyster density and demographic data provides a basis for estimation of standing stocks in defined sampling strata where the areas of the latter are known. This is the case for the current assessment with VA data within the limitations described earlier for habitat area. A forward prediction of standing stock is possible with an age structured demographic and a stock-recruit (S/R) relationship and/or a predictable range of M and F to apply to current standing stock. The S/R relationship for oysters has not been comprehensively examined in the literature. A variable S/R is a common feature of long-lived bivalve populations (notable also in sea scallop and surf clam assessments). In the absence of a robust S/R relationship an alternative approach is to estimate upper and lower bounds for age specific mortality (M+F) based on prior experience and data, and project the current age structure forward open year with those upper and lower bounds. This is a relatively crude model for fishery purposes, but it does allow the critical estimation of the number of sub market (small) oysters in year t that will survive to market size oysters in year (t+1). Such estimates have been made for the upper James River (Burwell Bay – the reefs described by Mann et al. 2009) for multi-year periods post 2000 (Mann, unpublished data). The VA public fishery is not limited by total stock quota, but rather by gear type (hand tongs), a per day bushel limit per license and per boat with additional time limits (seasonal by area and time of opening and closing each day). The forward projections have not been employed in fishery management

The current project provided the impetus for development of demographic descriptors in terms of biomass for young of the year (YOY, spat) and all age classes using the equations provided earlier in this text. Thus spawning stock biomass (all ages >YOY) in year *t* can be compared to biomass of age 1 in year (*t*+1). This comparison is a S/R relationship that avoids the inherent high and density dependent loss of YOY to predation before they reach age class 1. The first year class discrimination based on length has some modest error associated with the applied age 1 to age 2 boundary as discussed earlier; however, this boundary is much less problematic than, for example the age 3 to age 4 or even the age 4 to age 5 boundary. For the purposes of developing a biomass based S/R relationship the latter boundaries are inconsequential because the ratio includes all age classes >YOY as a single unit in the S component. Thus definition of area and year specific values of both S and R are tractable. Additional details are provided in presentation of S/R data in ToR#6.

ToR #3. Cross-calibrate MD dredge with VA patent tong methodologies to provide information for total Bay wide population estimation. Describe the methodology and characterize uncertainty.

There are prior published studies that attempt to compare the data obtained from dredges and tongs (Chai et al. 1992, Mann et al. 2004 as examples). They are not in uniform agreement as to the possibility of developing correction functions that allow estimation of absolute density estimates (tong data) from semi-quantitative (per bushel but not per unit area) dredge data. Such a comparison is however, critical to the development of a single population estimator for Chesapeake Bay oyster populations based on combined MD and VA survey data. To this end a series of side-by-side gear comparisons were made of the dredge and hydraulic patent tongs operated in survey mode. These are described in chronological sequence.

On December 13, 2011 a comparison study of the two gear types was completed on four sites on three distinct reefs in Great Wicomico River, VA: two sites on Shell Bar reef (# 135 on Figure 3.1), with differing substrate, plus one site each at Sandy Point reef (# 133 on Figure 3.1), and Cranes Creek reef (# 137 on Figure 3.1). The study design identified regions of "uniformity" from prior surveys by VMRC/VIMS using a hydraulic patent tong. Within each region four parallel dredge tows were made across the reef in swept area mode using the MD DNR dredge operated from the MD DNR vessel R/V Miss Kay, and processed as per the described standard MD protocol. On the same reef and within the polygon boundaries set by the dredge tows ten hydraulic patent tong deployments were made from the VMRC vessel R/V Baylor and the retained samples processed as per the standard VA protocol.

Absolute estimates of density at Cranes Creek are in good agreement (Table 3.1), but there are notably higher estimates by tong at the Sandy Point and Shell Bar sites, thus posing the question "why the observed variability?" The hydraulic tong samples through the reef surface to the underlying anoxic shell/sediment complex, but the dredge samples the surface layer (no black shell). The depth of the shell layer is thus implicated. As noted earlier mechanical tongs are both lighter and, by their simultaneous closing and lifting action do not sample underlying layers as well as hydraulic tongs. Note the higher absolute shell density estimates at Sandy Point and Shell Bar sites. Cranes Creek was subject to intense fishing effort on the day of our study, possibly providing a "loose" shell base that was equally sampled by tong and dredge, whereas other sites had well consolidated shell that was difficulty to penetrate in one dredge tow but not a tong deployment (the tong weighs in excess of 70 kg). When the data is expressed as oysters per unit volume of shell the values are generally in good agreement at all stations as can be seen by examining the dredge efficiency estimates in the lower section of Table 3.2.

Figure 3.1. Great Wicomico River: public reefs examined by VA surveys. Reef numbers 135 (Shell Bar) 133 (Sandy Point) and 137 (Cranes Creek) site were the sites of 2011 comparison studies (see text).

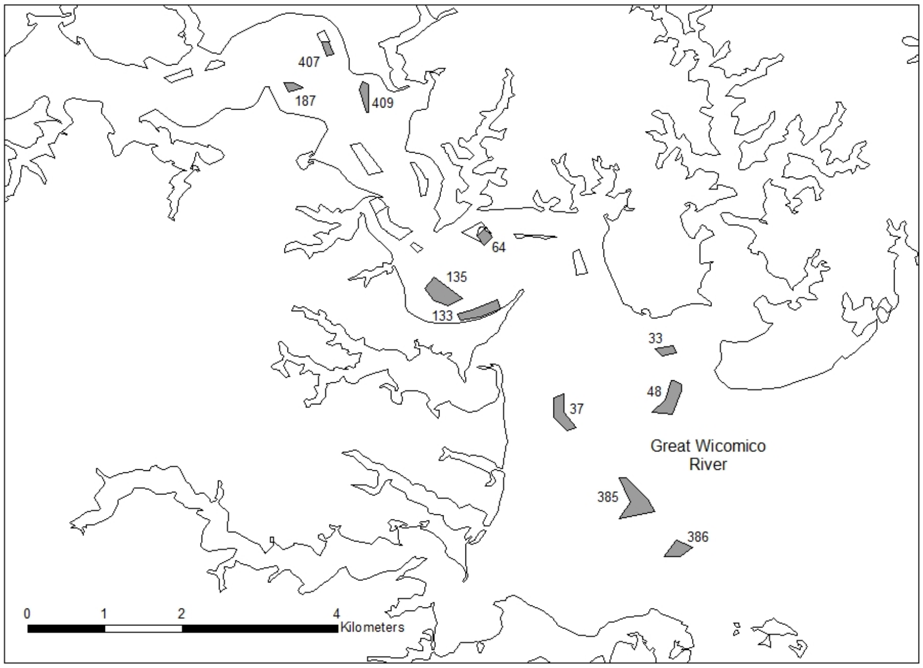


Table 3.1: Mean and standard deviation density estimates for shell, spat, small, market and total oysters: dredge and patent tong.

		DNR dredge data, n = 4					VMRC patent tong data, n = 10				
		shell	spat	small	market	total	shell	spat	small	market	total
Cranes Creek	mean	10.5	6.6	25.7	6.2	***38.6***	11.1	7.8	34.2	4.9	***46.9***
	sd	2.1	0.9	5.4	2.1	***7.7***	7.9	6.4	17.3	4.5	***25.9***
	per L shell	0.0	0.6	2.5	0.6	***3.7***	0.0	0.7	3.1	0.4	***4.2***
Sandy Point	mean	4.0	7.8	10.4	2.3	***20.5***	12.1	17.3	44.8	5.2	***67.3***
	sd	1.4	2.5	5.4	1.0	***8.8***	5.2	9.6	22.7	2.5	***32.1***
	per L shell	0.0	2.0	2.6	0.6	***5.1***	0.0	1.4	3.7	0.4	***5.6***
Shell Bar (shell)	mean	1.8	5.0	6.0	1.3	***12.2***	17.4	31.5	68.7	5.8	***106.0***
	sd	0.7	2.5	3.0	1.1	***5.7***	7.4	29.3	51.5	3.4	***74.6***
	per L shell	0.0	2.8	3.3	0.7	***6.8***	0.0	1.8	3.9	0.3	***6.1***
Shell Bar (shell+mud)	mean	2.2	5.2	6.2	1.8	***13.1***	17.1	20.3	57.1	6.5	***83.9***
	sd	0.9	3.3	2.7	1.1	***6.0***	2.8	11.2	16.8	3.7	***23.8***
	per L shell	0.0	2.3	2.8	0.8	***5.9***	0.0	1.2	3.3	0.4	***4.9***

Table 3.2. Dredge v patent tong estimates expressed as dredge efficiency:
by absolute "***density***": (dredge density.m^{-2}/tong density. m^{-2}) x 100%
corrected by "***per L shell***": (dredge density per L shell/tong density per L shell) x 100%

	shell	spat	small	market	total
density					
Cranes Creek	94.4%	85.0%	75.3%	126.8%	***82.3%***
Sandy Point	33.0%	45.1%	23.3%	43.5%	***30.4%***
Shell Bar	10.4%	15.8%	8.7%	21.7%	***11.5%***
Shell Bar Mud	13.1%	25.6%	10.8%	27.5%	***15.7%***
per L shell					
CranesCreek		90.0%	79.7%	134.3%	***87.1%***
Sandy Point		136.9%	70.6%	132.1%	***92.4%***
Shell Bar		152.1%	84.0%	209.3%	***111.1%***
Shell Bar Mud		195.3%	82.4%	210.1%	***119.6%***

The Great Wicomico River is noted for its robust reefs with substantial shell resources (see Southworth et al. 2010). For comparative purposes on a "typical" MD survey site a two day field survey was completed in April 2013 at five sites on the bay side of the MD Eastern Shore. The R/V Miss Kay was the survey vessel and the crew consisted of personnel from MD DNR, VIMS and Rutgers University[2]. The R/V Miss Kay is equipped with both a 32-inch dredge and a patent tong identical to that used on the R/V Baylor. Thus all collections for the April 2013 studies were made from this one vessel.

The five locations chosen for April 2013 study were Clay Island (Fishing Bay), Drum Point and Georges (Manokin River), Haines and Turtle Egg (Tangier Sound). These can be viewed at www.dnr.state.md.us/fishries/oyster/monitor/image/keybar.jpg. The Manokin locations (Georges, Drum Point) were on shell mounds. Georges in particular has a softer based substrate. Tangier Sound (Haines, Turtle Egg) sites were on hard sand bottom. All field studies were completed on 4/16 and 4/17/2013. At each location four dredge hauls were completed using MD DNR protocols. Tow length was recorded by differential GPS. A prerequisite for an acceptable haul was that the dredge not be full on retrieval. Total volume of material collected was recorded and a subsample (typically 0.5 bu or approximately 25L) taken for further examination. All oysters were measured and categorized, as were boxes. Total brown shell volume (blank, devoid of attached oysters) and live oyster volumes (both in L) were examined and recorded. At each dredge location twenty patent tong samples were collected, with sample locations being chosen along the dredge tow lines (five patent tong samples per dredge tow line). Data collection for each sample was as for VA assessment: respective per square meter values for number of spat (identified as YOY), small oysters ≤75 mm, market oysters >76 mm, new and old boxes (articulated valves), brown shell volume in L and black shell volume in L. All live oysters and boxes were measured to the nearest mm longest dimension to allow examination of possible size bias selection by the gear types.

A summary of field data providing a comparison of the performance of the two gear types is given in Table 3.3. Mean values for dredged area varies by location between 14.6 and 43.5 m^2. Associated standard deviations are modest within each location. When corrected to comparable area (one m^2) shell values for dredge samples are notably lower than brown shell values obtained by the patent tong. Dredge samples were also consistently devoid of the black shell that underlies the brown oxic layer. Oyster densities by size class were consistently higher by patent tong when expressed on an absolute per m^2 basis; however, when expressed on a density corrected to both area and per unit shell volume as a ratio of PT/D values the result is consistently <1.0 with only one exception. This ratio illustrates both the "layering" of shell and biota in the sampled structure with the biota being aggregated at the surface of the mix. Across all locations there is a notable linear

[2] The presence of the two Rutgers team members on the *R/V Miss Kay* was to familiarize the Rutgers crew with methods employed by both MD DNR and VIMS/VMRC. The annual Delaware Bay oyster survey is completed by staff of the Haskin Shellfish Research Laboratory of Rutgers University aboard commercial vessels using dredges. They had expressed interest in comparing their dredge methods with patent tong methods, and a comparison study with the VMRC vessel *R/V Baylor* was made in late 2013 in Delaware Bay.

relationship (y=mx + c) between mean density as estimated by dredge (y) and mean density as estimated by patent tong (x) as follows:

Spat (YOY): $y = 0.32x - 0.74$, $r^2 = 0.96$, $n = 5$
Small: $y = 0.45x - 1.92$, $r^2 = 0.98$, $n = 5$
Market: $y = 0.54x - 0.90$, $r^2 = 0.95$, $n=5$.

The presence of a linear relationship between dredge and patent tong estimates is encouraging for development of a conversion function; however, the presented data is from a plot of mean values, an examination of biases by gear remains to be completed (essentially starting with a comparison of demographic data from each sample), and sensitivity to low absolute densities must be acknowledged. The slope value (m) increases from spat to market oysters (0.32, 0.45, 0.54 respectively). The intercept value (c in y = mx +c) on each of the fitted regressions is of note: for spat it is comparable to mean values at Clay Island, Haines and Turtle Bay sites, all of which exhibited low spat densities; for both small and market oysters it is exceeded (often by very large values) at all locations except Haines.

Subsequent to the described field effort further data analysis was pursued as a collaborative effort with Dr. Howard Townsend at the NOAA Oxford Laboratory and Ms. Rebecca Scott of NCBO. The extensive graphical presentation following Table 3.3 is from the data review by Ms. Scott. Annotations and comments are by Roger Mann.

Table 3.3. Summary comparison of patent tong (PT) and dredge (D) performance at 5 locations in MD waters: Clay Island (Fishing Bay), Drum Point and Georges (Manokin River), Haines and Turtle Egg (Tangier Sound). Tow area is mean of four tows. Values for L all (total live and shell material volume), L shell (shell volume devoid of oysters), Brown shell (that above sediment water interface), Black shell (buried shell), Spat (YOY oysters), Small (oysters <75 mm), and Market (oysters >76 mm) are all per square meter.

Location	gear		tow area (m^2)	L all	L shell	Brown Shell	Black Shell	Spat	Small	Market
Clay Island	PT	mean				3.63	0.88	2.10	10.35	3.90
		s.d.				1.99	0.48	1.94	5.12	2.67
	D	mean	19.97	1.72	1.06			0.59	5.21	1.67
		s.d.	0.92	0.40				0.23	1.67	1.13
Drum Point	PT	mean				6.20	2.75	12.35	33.90	12.80
		s.d.				3.93	1.21	9.72	26.87	7.36
	D	mean	25.98	1.65	0.33			3.79	9.95	4.51
		s.d.	1.29	0.44				1.78	3.15	1.58
Georges	PT	mean				11.55	1.95	25.80	93.70	19.60
		s.d.				4.08	2.08	18.42	59.05	10.18
	D	mean	14.57	5.15	1.00			7.62	41.63	10.59
		s.d.	0.51	0.42				2.01	3.65	1.71
Haines	PT	mean				5.30	1.95	4.30	4.10	2.85
		s.d.				1.75	1.49	2.05	2.29	1.98
	D	mean	43.47	0.66	0.38			0.42	0.78	0.93
		s.d.	4.09	0.07				0.20	0.08	0.17
Turtle Eggs	PT	mean				4.10	2.81	7.00	11.10	4.40
		s.d.				1.48	2.02	4.34	4.18	3.39
	D	mean	41.67	0.87	0.46			0.63	2.27	1.37
		s.d.	5.46	0.21				0.24	0.64	0.15
Clay Island	PT/D							0.92	0.51	0.60
Drum Point	PT/D							0.15	0.16	0.13
Georges	PT/D							0.25	0.16	0.13
Haines	PT/D							0.64	0.33	0.19
Turtle Eggs	PT/D							1.10	0.48	0.32

Figure 3.2. Great Wicomico gear comparison, December 2011, oyster density

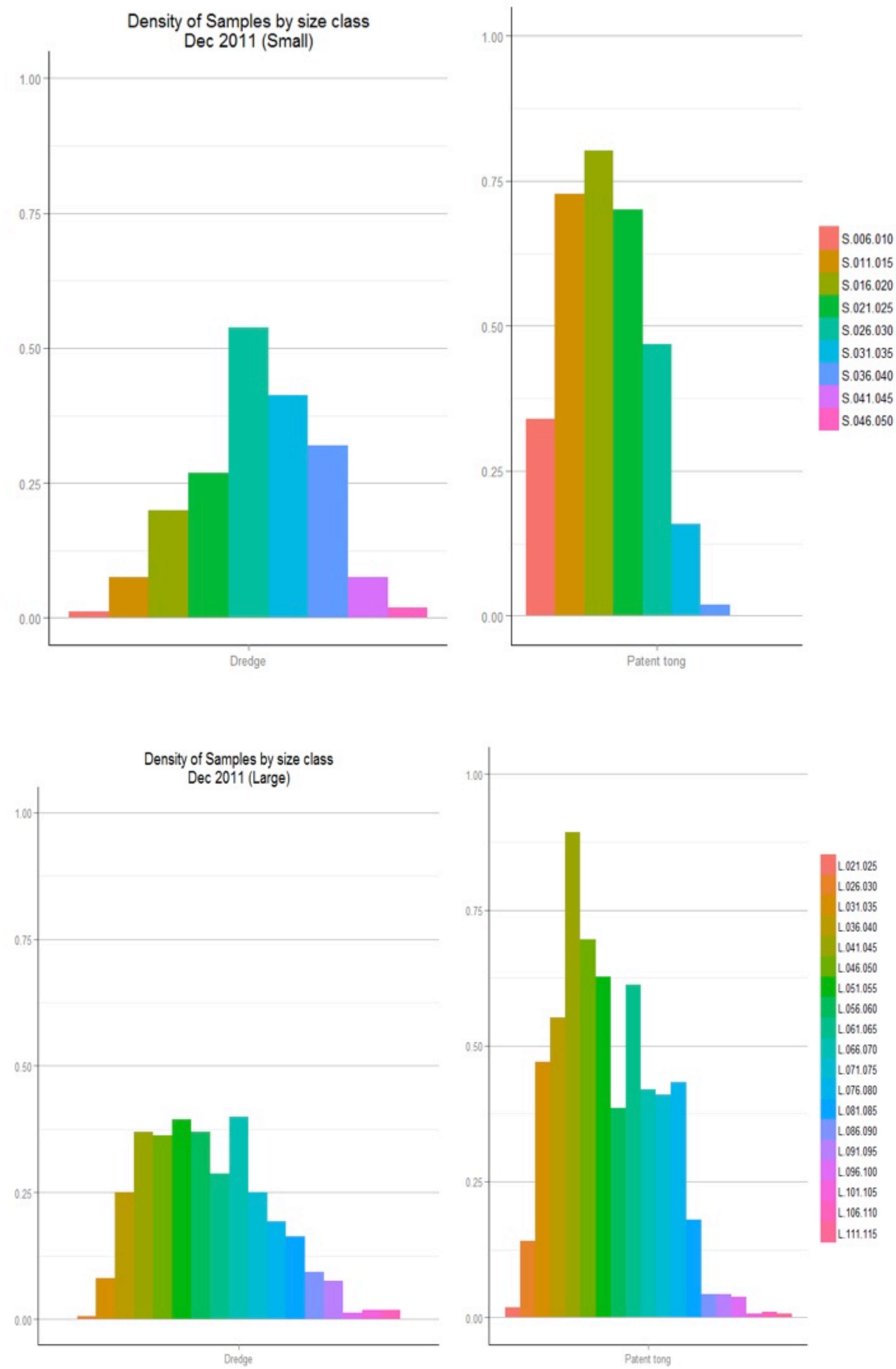
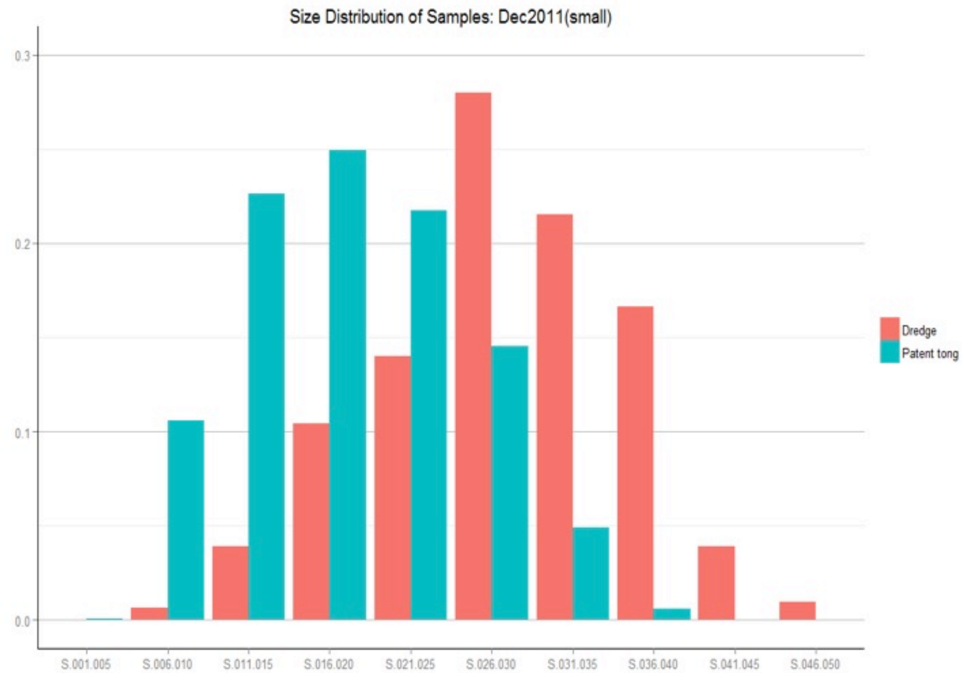


Figure 3.3. Great Wicomico gear comparison, December 2011, oyster size distribution



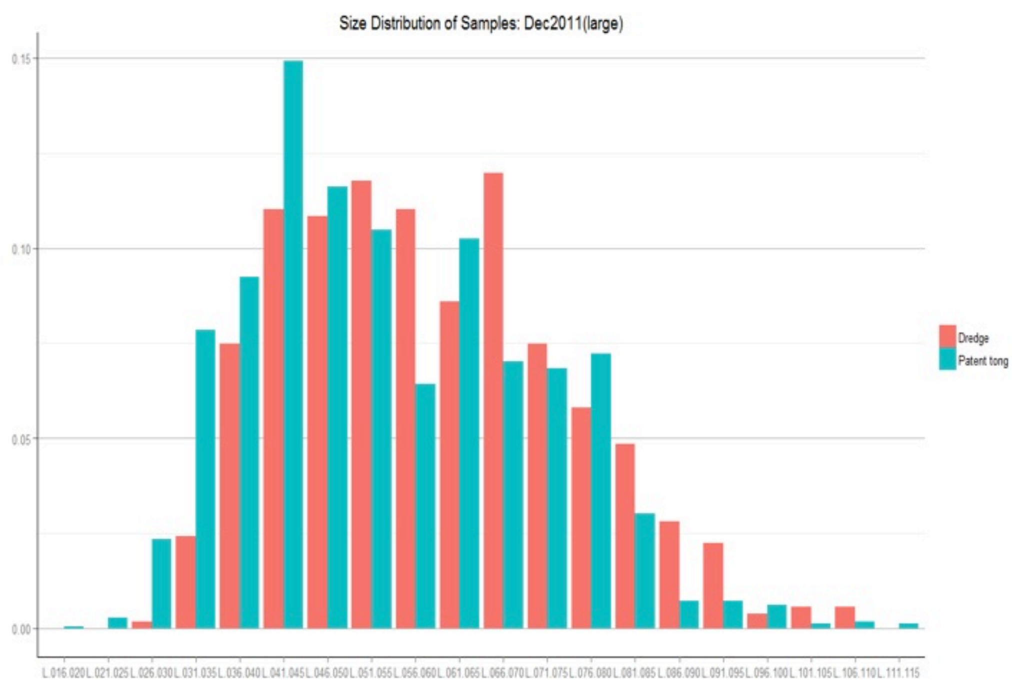


Figure 3.2 provides a comparison between the two gear types for two size classes: YOY oysters (spat) density in the upper panel and small plus market oyster density (all ages 1 and above) in the lower panel. Figure 3.3 provides the accompanying size distribution data in upper and lower panels respectively. Differing retention by size class of the two gear types is evident for this sampling location. The patent tong collects the smaller YOY (spat) with greater efficiency than the dredge, but the larger size classes are collected with less bias.

For the YOY size class the three length classes of 11-15, 16-20 and 21-25 mm SL, are similar and dominate numerically in the tong data; however this is not the case for the dredge data where the three most abundant size classes are 26-30, 31-35 and 36-40 mm SL. By comparison the tong samples smaller YOY with greater efficiency. The smallest YOY size class of 6-10 mm SL is very poorly represented in the dredge data being the least abundant, yet in tong data it falls below the YOY 26-30 mm SL class, but well in excess of the YOY 41-45 and 46-50 mm SL classes. The YOY 11-15 mm and 41-45 mm size classes are approximately equal in representation in the dredge data, yet by contrast the YOY 11-15 mm oysters are approximately twice as abundant in the tong data.

The small plus market panel (ages 1 and above) covers 5 mm SL increments from 21-25 mm through 111-115 mm. The dredge data illustrate a demographic with comparable abundance of size classes from 36-40 mm through 61-65 mm with slightly lower values in the 56-60 mm interval. A steady decline in abundance is noted with each increasing size class after 61-65 mm SL. The tong also records the highest abundance in the 36-40 through 50-55 mm SL and 61-65 mm size classes with a lower abundance in the 56-60 mm interval. The differences between classes in the 36-40 through 50-55 mm intervals are more marked in the tong data. The 61-65, 66-70 and 71-75 mm SL size classes are comparable in the tong data, followed by rapid decline in relative abundance in larger size classes.

Figures 3.4 and 3.5 illustrate corresponding plots to Figures 3.2 and 3.3 for the April 2013 studies in MD locations in Fishing Bay, Manokin River, and Tangier Sound. The upper panel of Figure 3.4 (density of YOY) shows strong similarity to the upper panel of Figure 3.2 with a greater efficiency of collection of smaller size classes and higher density estimates overall for the patent tong. The lower panel of Figure 3.4 (ages 1 and above) shows generally good agreement with respect to relative contributions by size class although tong data again is higher than that for dredge samples. When size distribution is considered in the absence of density, as in the upper panel of Figure 3.5, there is generally good agreement between size distributions of YOY for MD data irrespective of collection gear. This is in contrast to the same comparison for VA data (upper panel in Figure 3.3) where the patent tong showed bias towards the smaller size classes within the YOY demographic. For ages 1 and above, the distribution of data in the lower panel of Figure 3.5 is similar to that of the corresponding panel in Figure 3 that is there appears to be comparable retention bias by both gears for these larger oysters.

Figure 3.4. MD locations gear comparison, April 2013, oyster density

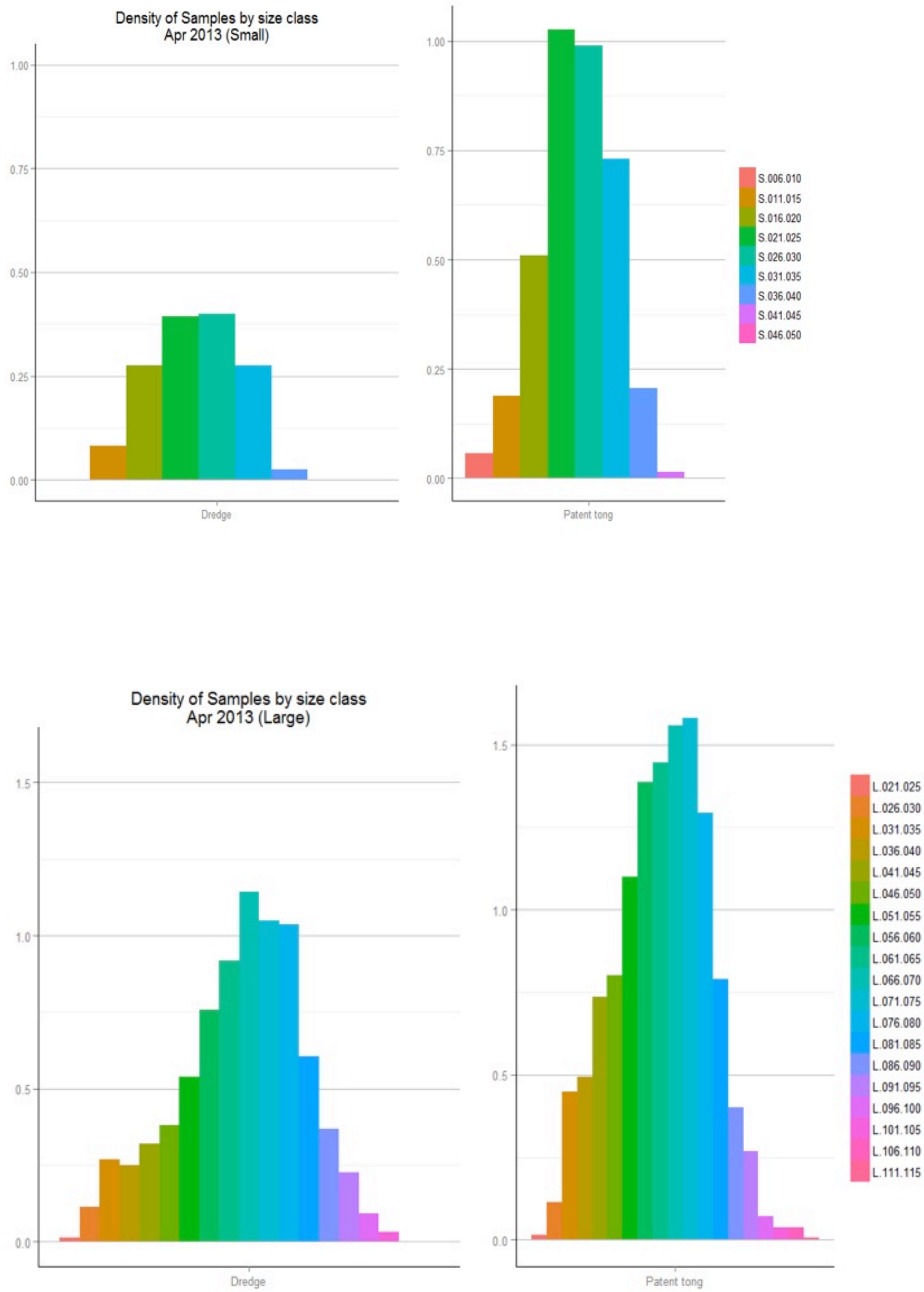
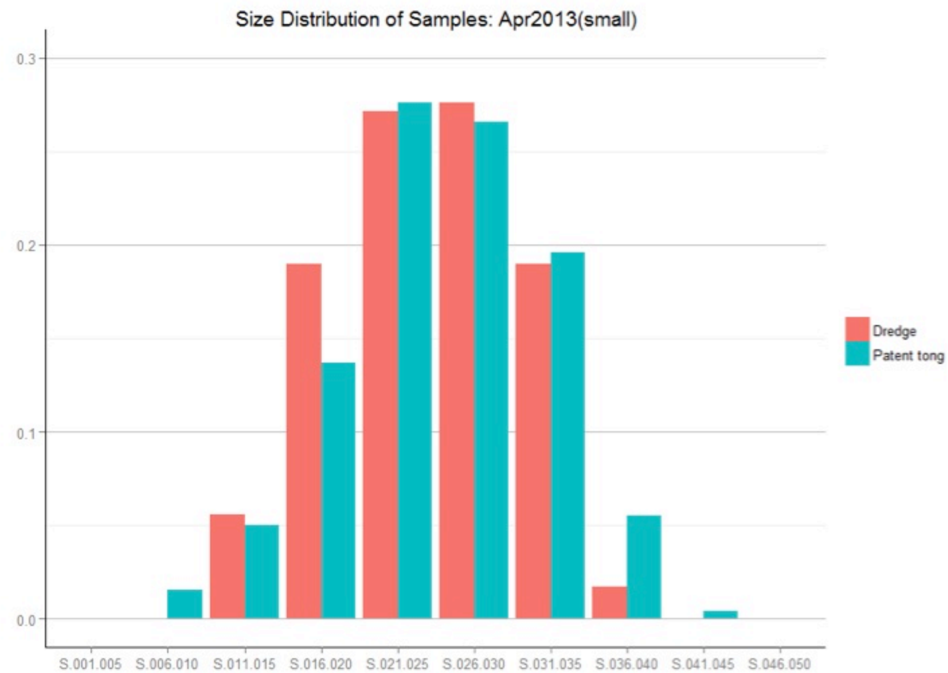


Figure 3.5. MD locations gear comparison, April 2013, oyster size distribution



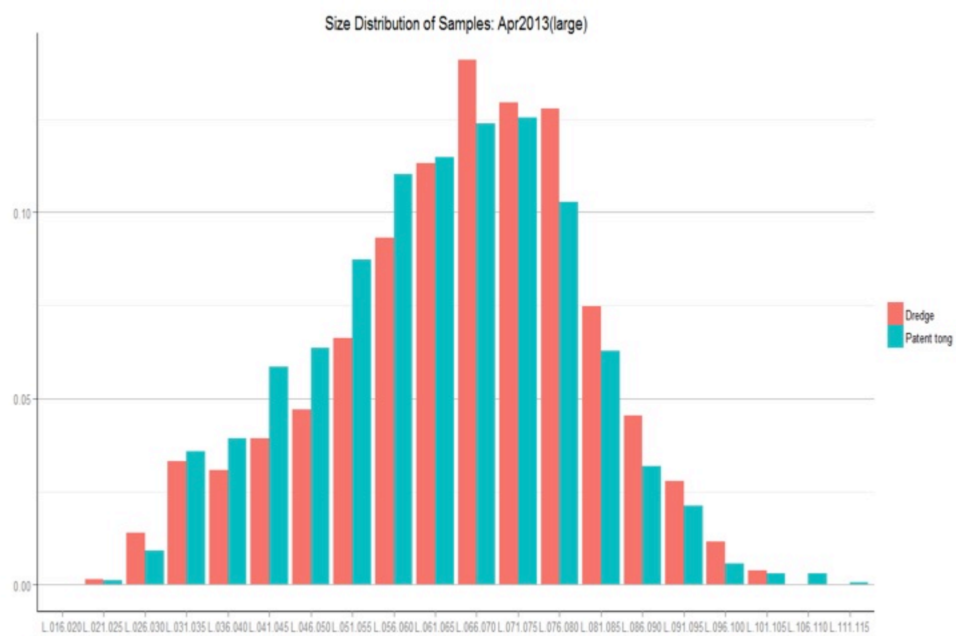


Figure 3.6 Correlation of sample density by location for gear types within the Great Wicomico for oysters greater than YOY, December 2011.

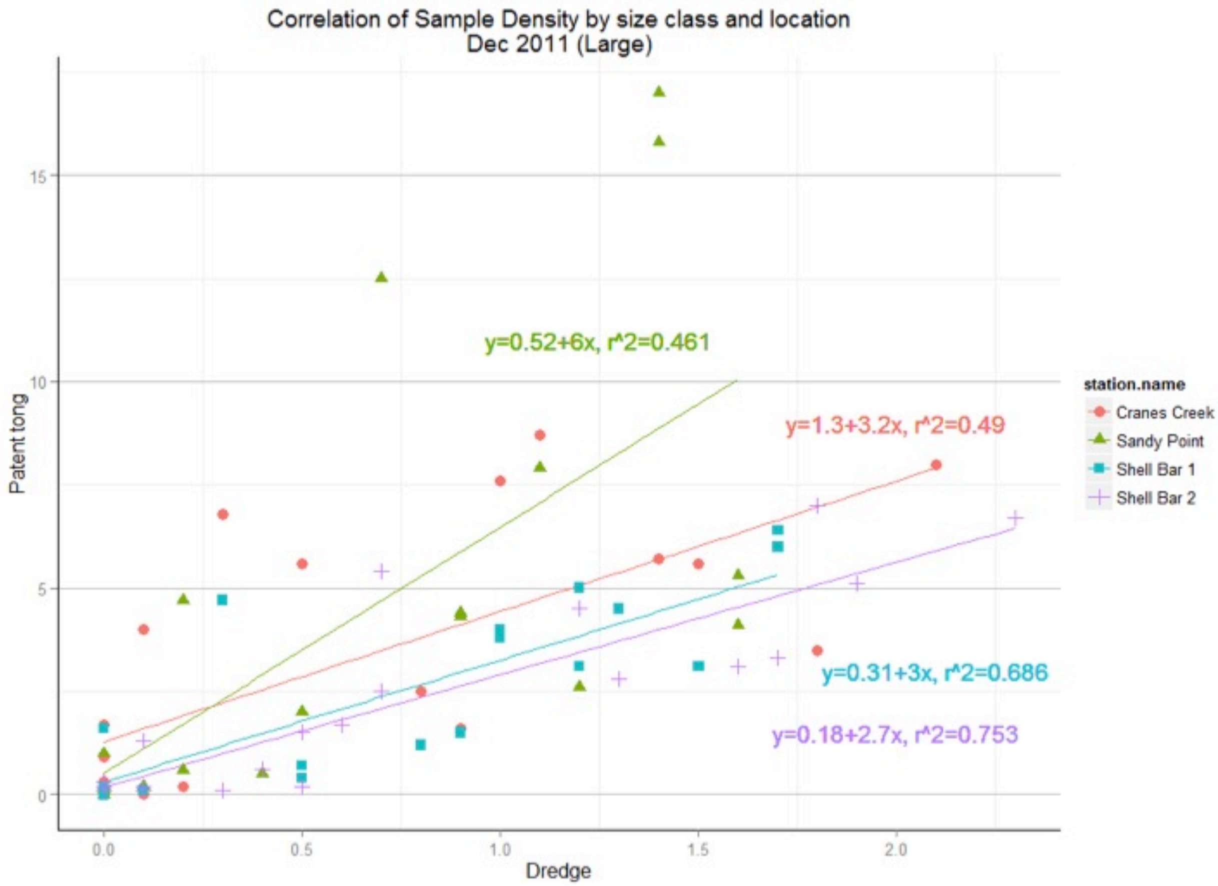


Figure 3.6 illustrates the correlation by size class and location within the four Great Wicomico sites for the oysters of one year and greater age. These correspond to the lower panels in Figures 3.2 and 3.3. A generally good agreement is observed on density versus density plots for all locations (slope values between 2.7 and 3.2) except Sandy Point, where a higher slope value of 6 is evident. The accompanying values for r^2 vary between 0.49 and 0.753. The plot suggests a reasonable ability to predict oyster density (not including YOY) as assessed by tongs from dredge data and vice versa in these dense, shell rich reef habitats. Figure 3.7 illustrates the comparable plot for the five MD locations. Again, a good agreement in slope values (3.3 -4.1) with a marginal exception at Haines where a lower slope (1.8) is observed. The MD data exhibit remarkable values for r^2 which vary between 0.74 and 0.922. Again the plot suggests a reasonable ability to predict oyster density as assessed by tongs from dredge data and vice versa in these lower oyster densities where reef habitats are less abundantly supplied with shell. A summary of correlation data is given in Table 3.4.

Figure 3.7 Correlation of sample density by location for gear types within MD sampling locations for oysters greater than YOY, April 2013.

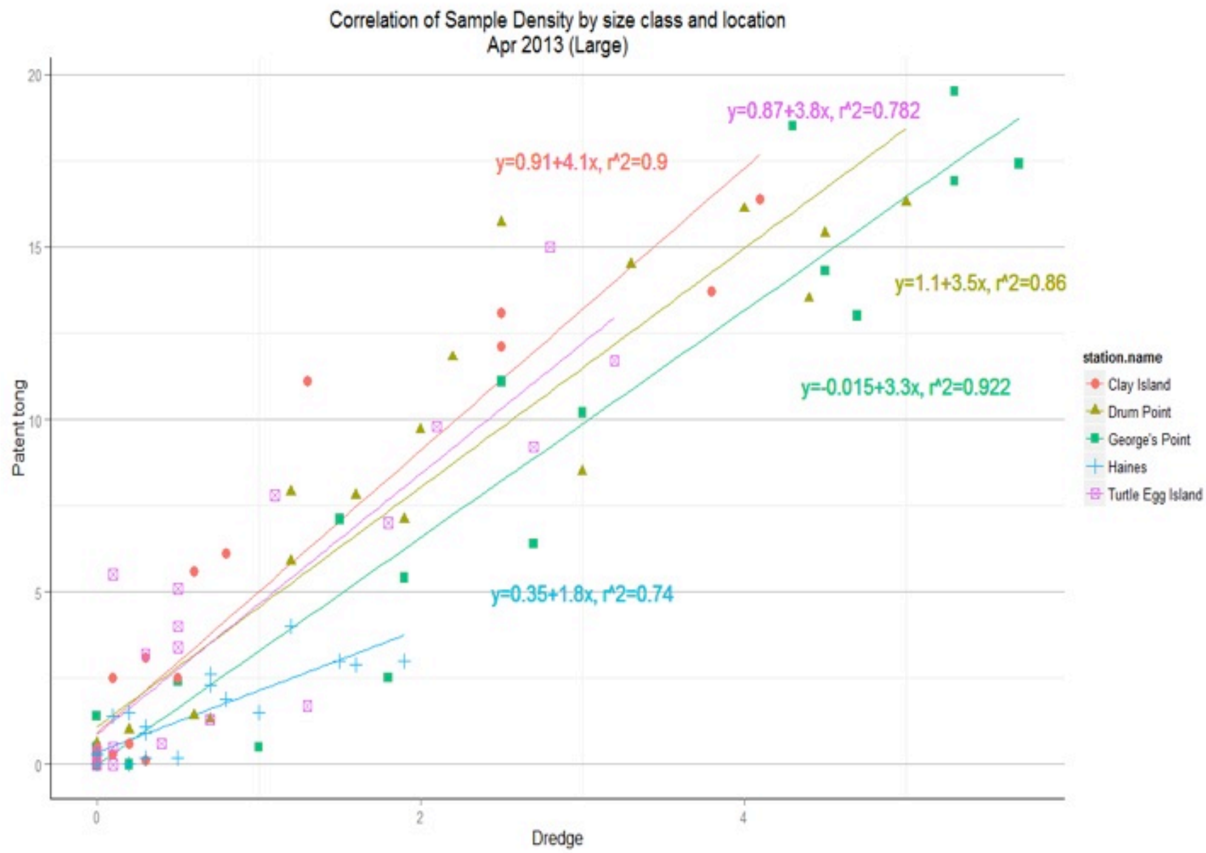


Table 3.4. Summary of correlations between oyster density for age classes >YOY by location. Data is presented in the form y = a + bx where y = density estimated by patent tong, a = location specific constant, x = density estimated by dredge.

Great Wicomico	a	x	r^2
Cranes Creek	1.3	3.2	0.49
Sandy Point	0.52	6	0.461
Shell Bar 1	0.31	3	0.686
Shell Bar 2	0.18	2.7	0.753
MD			
Clay Island	0.91	4.1	0.9
Drum Point	1.1	3.5	0.86
Georges Point	0.015	3.3	0.922
Haines	0.35	1.8	0.74
Turtle Egg Island	0.87	3.8	0.782

ToR #4. Evaluate status of shell substrate on public reefs Bay wide.

Shells are mixed with sediment below the sediment-water interface and form reef structures that persist over geological time periods. Above the sediment water interface (the oxic region) is a mix of shells from recently dead oysters plus the demographic of living oysters. Oysters recruit to the substrate offered by both living oysters shells and exposed dead shell. Through their growth these recruits add to the shell substrate above the interface and the carbonate mass of the reef structure as a whole. But shells also are lost over time (otherwise estuaries would be full of shells) through a combination of biological and chemical processes. These have been termed taphonomic processes (Davis et al. 1989) and the region containing shells and live animals above the sediment water interface the taphonomically active zone. Reef accretion occurs when rates of shell addition exceed taphonomic loss and burial. When loss exceeds accretion reefs will eventually be lost. The importance of shell budgets to reef maintenance and perpetuation has, surprisingly, received substantial study only in recent years (Powell and Klinck 2006, Mann and Powell 2007, Mann et al. 2009, Southworth et al. 2010, Harding et al. 2010 Powell et al. 2012). Shell is critical to the alkalinity budgets of estuaries and thus habitat maintenance for all benthic forms (Waldbusser et al. 2011, 2013). Over the 1985-2008 period water pH has decreased across polyhaline sections of the Chesapeake Bay, although not the mesohaline, with current average values driving net shell dissolution in some estuaries (Waldbusser et al 2011). Shell budgets have been described for the James, Great Wicomico and Piankatank Rivers (Mann et al. 2009, Southworth et al. 2010, Harding et al. 2010) using a simple accounting system in concert with estimate of rates of shell loss. Reliable budgets are best developed using multiple years of serial observations. For each sequential year shell addition through recruitment and growth is balanced against shell loss to mortality and taphonomic processes. For the current VA survey requisite input to the calculation is provided by estimates of brown (oxic) and black (buried) shell, population demographics by year class matched with growth and shell mass values for each age class.

The VA survey has collected quantitative shell data for both brown and black shell since 2002, 2000 in some cases and back to 1993 for a whole shell measurement. The dredge survey in VA was not collected on a defined area per tow and thus data cannot be described quantitatively. The shell resource record in MD collects almost exclusively brown shell as part of the protocol described earlier. The MD dredge collected data will thus generally underestimate total shell, it is however a long term quantitative estimator of considerable value for the purpose of describing habitat stability. At this time both surveys generate data on shell as density (shell volume per unit area, MD data since 2005 when known swept area dredge tows were implemented), but there is also need to consider areal extent of cover. Side scan sonar has been promoted as a method to resolve this question. Side scan sonar can define where oysters are absent, but ground verification is required where hard bottom is identified to eliminate false positive interpretation. Side scan sonar has utility as a tool to focus survey activity, however, it cannot as yet be used as quantitative substitute. We suggest additional investigation of side scan as a quantitative tool in ToR#11.

In this section we describe the status of the shell substrate. The relationship between the shell and live oysters is presented in ToR#6 when addressing recruitment and stock biomass.

Status of shell substrate on MD reefs

The Annual Fall Surveys do not at this time include specific descriptions of the status of the MD shell resource: however, as noted under ToR#2 under the sub section entitled "Development of population estimates: numbers, biomass, age structure, mortality in state surveys", the survey protocols since 2005 include defined swept area tows and the recording of two volumes. These volumes, inclusive of both shell and oysters, allow the quantitative estimation of shell, and hence habitat, on the MD bars on a regular basis. A research recommendation under ToR#11 is to effect a retrospective examination of tow volumes as an index of shell status as a sister data set to the ongoing biomass index values.

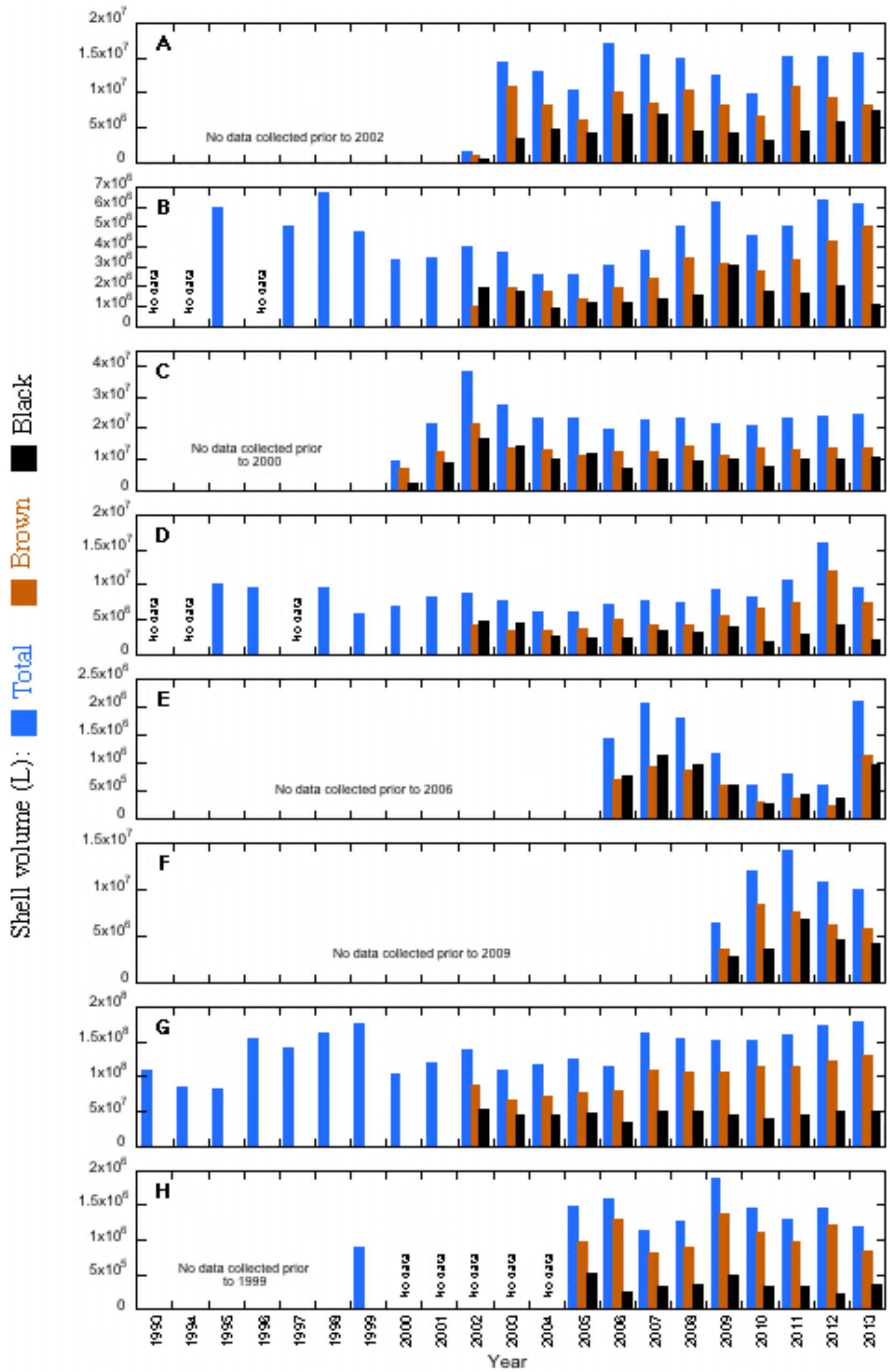
Status of shell substrate on VA public reefs

The VA survey has collected quantitative shell data for both brown (oxic exposed) and black (anoxic buried) shell since 2002 (2000 on some reefs), in some cases back to 1993 for a whole shell measurement. The current survey generates data on shell as density (shell volume per unit area), but there is also need to consider areal extent of cover. Possible employment of side scan sonar in reef assessment has been addressed earlier in this text.

The VA shell resource is summarized in Figure 4.1 as total, brown and black shell, by region/river since the initial dates of data collection. This data is also available at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/shell/status_shell_substrate/index.php. The time series is longest for the James River and is generally descriptive of the status of the whole oyster stock in three time periods: prior to the late 1990s epizootic, during the epizootic and the post epizootic recovery. The first and third periods have comparable shell volumes. The Great Wicomico and Piankatank data also cover the approximate period of that for the James and have comparable patterns of signal magnitude. Both include periods of shell planting in the post epizootic recovery period. The Rappahannock data set begins with a very large-scale shell planting effort as part of the VA Oyster Heritage Program in the late 1990s and early 2000s, followed by a modest decline and stability for the past decade. In all instances the observed stability of the data in the absence of major epizootic impacts suggests we have arrived at a default BRP for "no net shell loss" under current practice. Future management actions must consider shell planting to offset losses incurred by harvest scenarios. The critical advice here is the continued availability of shell in sufficient volume and at a reasoned cost to maintain this balanced approach.

The Pocomoke/Tangier and the Elizabeth/Lafayette data sets show modest variation but in general suggest stability over time. By contrast the Mobjack Bay and York River data sets illustrate temporal variability but are generally too short to draw conclusions as to long-term stability under present management protocols. These are both areas of recent restorative actions and caution must be strongly advised not to compromise gains that have been made. Both regions are managed on a rotational basis, an approach that has been successful in rebuilding the Rappahannock resource to the extent that it now supports a healthy fishery. A conservative approach to exploitation is advised for the near future.

Figure 4.1. Absolute volumes (L) of shell by VA region/river and year.



ToR #5. Quantify disease prevalence and intensity in all sampled populations Bay wide. Compare age-specific mortality against disease prevalence and intensity.

While use of Ray's fluid thioglycollate method (RFTM) to detect *P. marinus* is routine nearly everywhere this parasite is found, there is more than one scale in use to score infection intensities (i.e., the abundance of the parasite in oyster tissues)(Table 5.1). Estimates of *P. marinus* infection prevalences are calculated identically in data from Maryland and Virginia surveys.. Comparing *P. marinus* infection levels between MD and VA has long been complicated by use of different infection intensity rating scales in the two states, MD using a 1 to 7 integer-intensity scale (following Quick 1972) and VA scoring intensities as 0.5 to 5 (per Mackin 1954).

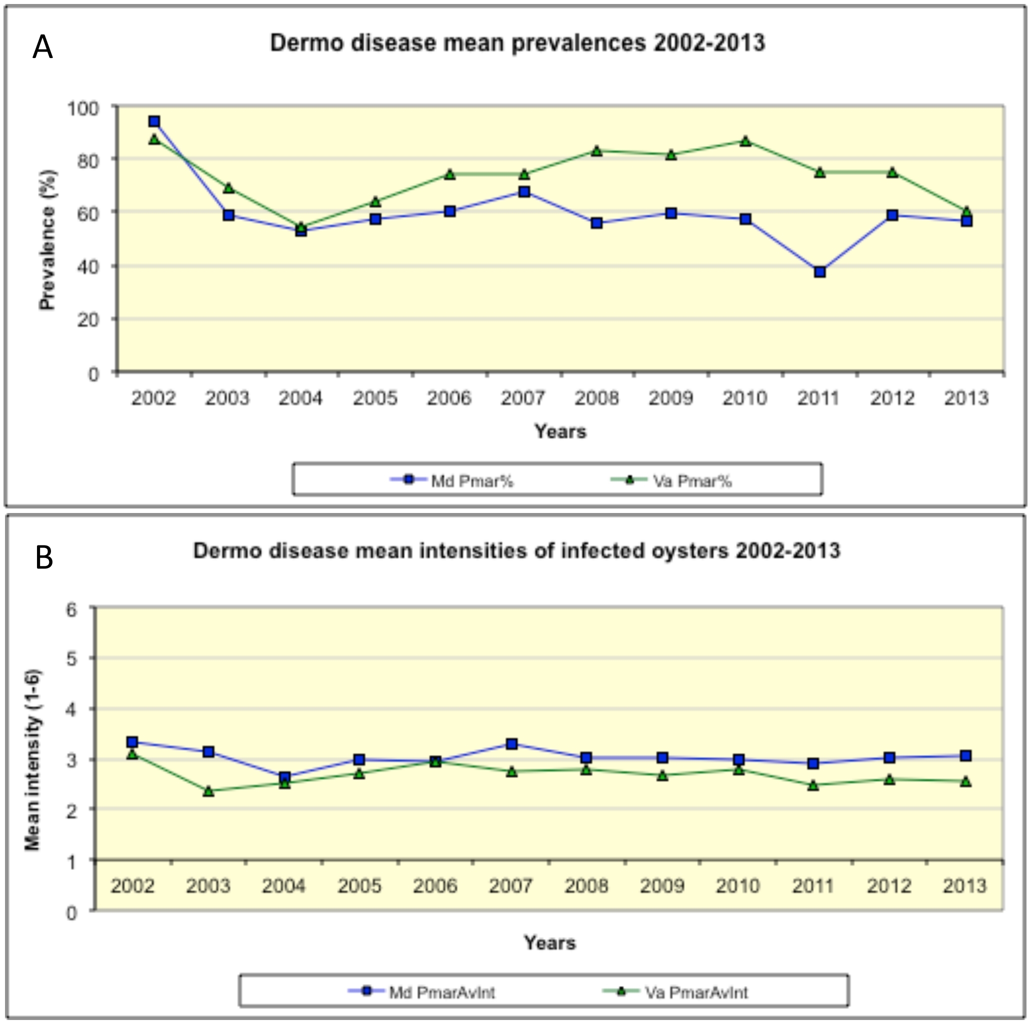
Table 5.1. Four scales for numeric interval rank categories of *Perkinsus* sp. infection intensities estimated by RFTM assays.

Ranking scale	Numeric interval ranks for *Perkinsus* sp. infection intensities					
Mackin (Ray 1954)	0.5	1	2	3	4	5
Quick (1972)	1	2	3	4	5	6
Farley((Calvo et al 1996)	1	2	3	4	5	6 & 7
Craig et al. (1989)	0.33	0.67 1.0 1.33	1.67 2.0 2.33	2.67 3.0 3.33	3.67 4.0 4.33	4.67 5.0

MD and VA data from 2002-2013 have now been integrated into a single dataset with intensities scored on the 1-6 integer scale of Quick (1972), 1 representing the lightest infections and 6 the heaviest. This makes possible bay-wide analyses of Dermo disease epizootiology during the last 12 years, which included the last year of the historically acute 1999-2012 outbreak and the subsequent years of more typical but still interannually variable Dermo disease levels. *H. nelsoni* prevalences are also included in the dataset for the same time period to illustrate the trend in MSX disease.

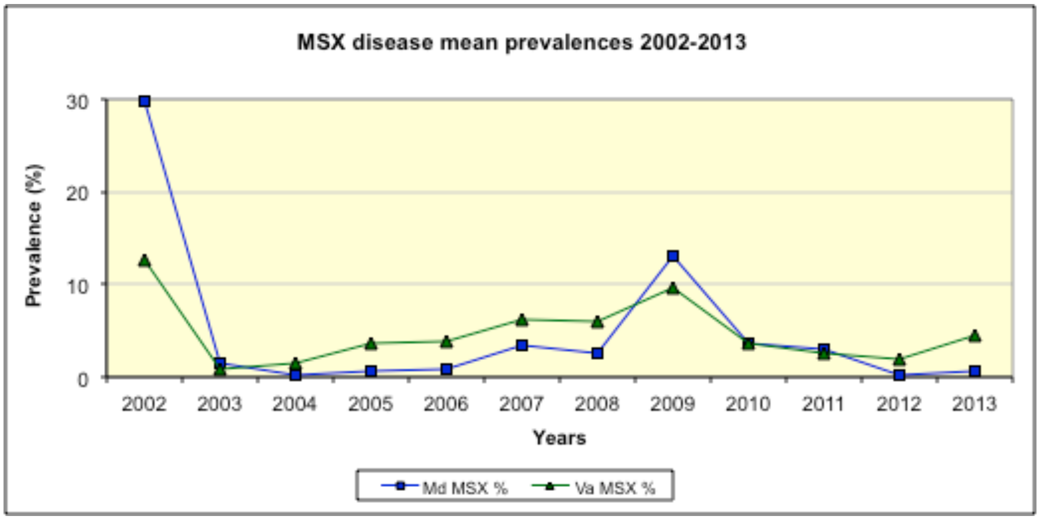
As a first step in analyzing these data, we calculated means for MD and VA for each of the 3 measures; *P. marinus* prevalence, *P. marinus* average intensity, and *H. nelsoni* prevalence, to allow graphical representation of regional trends.

Figure 5.1**.** *Perkinsus marinus* (dermo) infection levels in VA and MD, 2002-2013. **A.** Overall annual mean prevalences of *P. marinus* for each state. **B.** Overall annual mean *P. marinus* infection intensities.



The trend in mean *P. marinus* prevalence over the 2002-2013 period (Fig. 5.1A) reveals both the decrease in prevalences following the end of the 1999-2002 epizootic and the re-establishment of the normal *P. marinus* infection gradient, with prevalences diverging between the states such that the highest levels were routinely observed in VA after 2002. Mean prevalence peaked in MD in the post-2002 period in 2007. In VA, mean *P. marinus* prevalence peaked in 2010. Mean prevalence fell in both states in 2011, with a sharp recovery in MD in 2012 but with *P. marinus* prevalences in VA continuing to decline through 2013. Mean infection intensity was more stable through the period and generally higher in MD than in VA. In both states the average infection was generally light-moderate in intensity (Fig. 5.1B).

Figure 5.2: Overall MSX prevalences in VA and MD from 2002 to 2013.



Haplosporidium nelsoni was present at 39/42 MD stations in 2002 (mean prevalence: 29.7%), and at 27/29 VA sites (mean prevalence: 12.6%), with prevalences in some MD samples exceeding 60%. The far higher MSX peak in MD (Fig. 5.2) may have reflected the greater susceptibility of MD oysters to this parasite, following the argument of Carnegie and Burreson 2011). Following 2002, however, MSX disease fell to mean prevalences < 2% in 2003 and 2004. The subsequent time series displays a gradually increasing *H. nelsoni* prevalence trend in VA, from 2005 to a peak mean MSX prevalence of 9.7% in 2009. Gradually intensifying MSX disease in VA progressed into MD by 2007 and reached a higher peak mean prevalence of 13.1% there in 2009, before MSX levels fell in both states. The higher peak prevalence in MD in 2009 again supports the interpretation that MD oyster populations may be more susceptible to MSX, but the difference was not as great as that observed in 2002. We may hypothesize that, as in Delaware Bay (Ford and Bushek 2012), a strong early epizootic (here, in 2002) produced an oyster population increasingly resistant to *H. nelsoni* parasitism.

The apparent increase in *H. nelsoni* prevalence in 2013 in VA must be viewed with caution, as those *H. nelsoni* data are not complete.

With the VA and MD datasets merged, one of the most important questions we might ask is whether the unified dataset presents indications concerning the distribution of disease resistance to both MSX and Dermo in Chesapeake Bay. As noted earlier, the prevalence data for *H. nelsoni* suggest a level of resistance to MSX disease that has been developing at least since 2002 (see also Carnegie and Burreson 2011), and which may be somewhere better developed in VA where parasite pressure is heaviest. While P. marinus continues to be the dominant pathogen in the region, might there be resistance developing to Dermo disease as well?

First, following the logic Carnegie and Burreson (2011) used in arguing for the existence of *H. nelsoni* resistance, it is instructive to compare disease levels in wild oysters with oysters that we know to be acutely susceptible, the naïve sentinel "Spring Imports" deployed annually to the York River from the disease-free upper Rappahannock River (Ross Rock).

Table 5.2. *Perkinsus marinus* infection levels in wild oysters from the York River and Mobjack Bay compared with sentinel Spring Imports to the York River, 2009-2013.

	York-Mobjack Wild Beds (4)		Spring Imports to the York River	
Year	Prevalence (range)	Mean Intensity (range)	Prevalence (maximum)	Mean Intensity (maximum)
2009	88-100%	2.38-3.33	100%	3.92
2010	92-100%	2.43-3.20	100%	3.74
2011	92-96%	2.26-3.38	100%	4.48
2012	72-96%	1.96-3.04	100%	4.32
2013	76-96%	2.37-3.10	100%	3.68

A comparison of mean *P. marinus* prevalences and infection intensities at wild oyster reefs in the York River, VA, with those in Spring Imports to the York River (Table 5.2) shows that while *P. marinus* prevalences were similar, mean intensities reached markedly higher levels in the Spring Imports, reflecting an increase in the number of heavier infections. In wild oysters, relatively few infections are more than moderate in intensity. The wild oysters, therefore, while clearly not dermo-proof, are relatively more resistant than more obviously susceptible oysters. They are still infected, but many oysters are able to prevent infections from reaching very heavy (and likely lethal) intensities.

The York River and Mobjack Bay reefs are generally representative of more disease-intense VA oyster reefs. As described earlier, oyster samples from MD populations tended to display lower prevalences of *P. marinus* infection than VA reefs in general but somewhat higher mean infection intensities. Most of these oyster reefs may be assumed to have some resistance relative to the most susceptible oyster populations. To mine the data a bit further to determine whether there may be some more or less resistant populations, we calculated 95% confidence intervals for *P. marinus* prevalences and mean intensities for each station's 2003-2013 period—that is, for the period of relatively typical disease levels following the intense 1999-2002 epizootic. By doing so, we systematically defined the lower and upper bounds of what may be considered a "normal" year for each measure in each state and bay-wide. Prevalences of *P. marinus* vary from year to year with changing environmental conditions (especially salinities), and intensities tend to increase with increasing prevalences as indications of increasing disease when conditions are favorable for the parasite. The question we asked was, Are significant increases in prevalence (outside the 95% confidence interval upper bound) more likely to be accompanied by significant increases in mean intensity in some areas than in others? And if so, is there a difference between VA, where *P. marinus* pressure is higher, and MD, where it is lower?

Table 5.3. Mean intensity levels corresponding to prevalences elevated with regard to the 2003-2013 trend. "Low", "normal" and "high" are in comparison with 95% confidence intervals for each measure and site.

	VA	MD
Total number of reefs with high prevalence	85	145
Mean intensity low (%)	10.6%	6.9%
Mean intensity normal (%)	52.9%	50.3%
Mean intensity high (%)	35.3%	42.8%

In both VA and MD, "high" *P. marinus* prevalences were accompanied by "normal" mean intensities half the time. When mean intensities associated with elevated prevalences fell outside the 95% confidence intervals, it was much more frequently in the high direction than in the low in each state. Elevated prevalences were only slightly more frequently accompanied by elevated mean intensities in MD than in VA. While there was generally little geographic pattern with regard to these associations, some few exceptions stand out. In 2007 and 2008, both prevalences and intensities together peaked at several stations in the upper area of MD, including Eastern Bay, Miles River, and Chester River. From 2006-2008, prevalences and intensities tended to peak together in the James River. What these areas have in common is that they are frequently areas of lower salinity where *P. marinus* is inhibited by its physical environment. Because of the inhibition of the parasite, unselected, relatively susceptible oysters may be more abundant in these areas. It is possible that when salinities become more favorable for *P. marinus* in such places the parasite is more likely to proliferate to very high intensities in such susceptible oysters. With the possible exception of these areas in the major rivers and well up the mainstem of the Bay, some level of disease resistance would appear to presently be established in much of the surveyed area.

Annual reports describe disease prevalence and intensity at sentinel stations and in all sampled populations. MD reports are part of the MD Oyster Population Status Reports and can be viewed at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/reports.aspx. Data for 1996-2013 can be accessed from this site. VA reports can be viewed at http://www.vims.edu/research/departments/eaah/programs/shellpath/publications/index.php. Data for 1998-2013 can be accessed from this site. Comprehensive description of methods, data collection and analysis are presented in both report series.

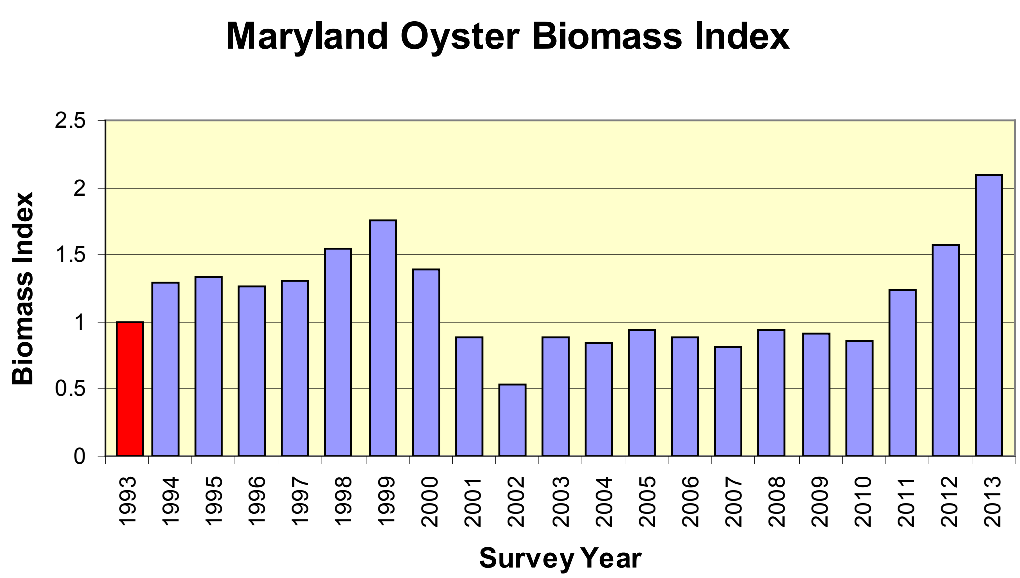
ToR #6. Estimate annual fishing mortality, recruitment and stock biomass (both total and spawning stock) for the time series, and characterize the uncertainty of those estimates.

Population estimates are presented in several formats beginning with biomass indices (MD) or biomass in grams (VA) with all size classes included. The MD data includes a spatfall intensity index as a descriptor of recruitment, and observations of mortality from box counts. The VA population demographic includes identified year classes allowing the biomass data to be further subdivided for examination and presentation as area specific stock: recruit (S/R) relationships, and finally as area specific age specific mortality and survival summaries.

Oyster biomass Index on MD reefs.

Oyster biomass is described with a single statewide index and compared to a unity value for the 1993 survey, commensurate with the lowest annual harvest to that date. Figure 6.1, taken from the 2013 Annual Fall Survey Report, summarizes trends in the index for the period 1993-2013. A gradual increase in the biomass index was observed for the 1993-1999 period, followed by a dramatic, epizootic driven to a value slightly in excess of 0.5 in 2002. The Biomass Index remained below 1.0 for a further eight consecutive years despite low disease pressure and high oyster survivorship over this period. Recruitment during this timeframe was sufficient to maintain the population at this level but not increase it. It was not until the strong recruitment event in 2010 that the population began to grow, bolstered by another good recruitment event in 2012. The 2013 MD Oyster Biomass Index increased for the third consecutive year to 2.09, a 32% gain over 2012, reaching its highest point since the baseline index was established in 1993.

Figure 6.1. MD Oyster Biomass Index 1993-2013.



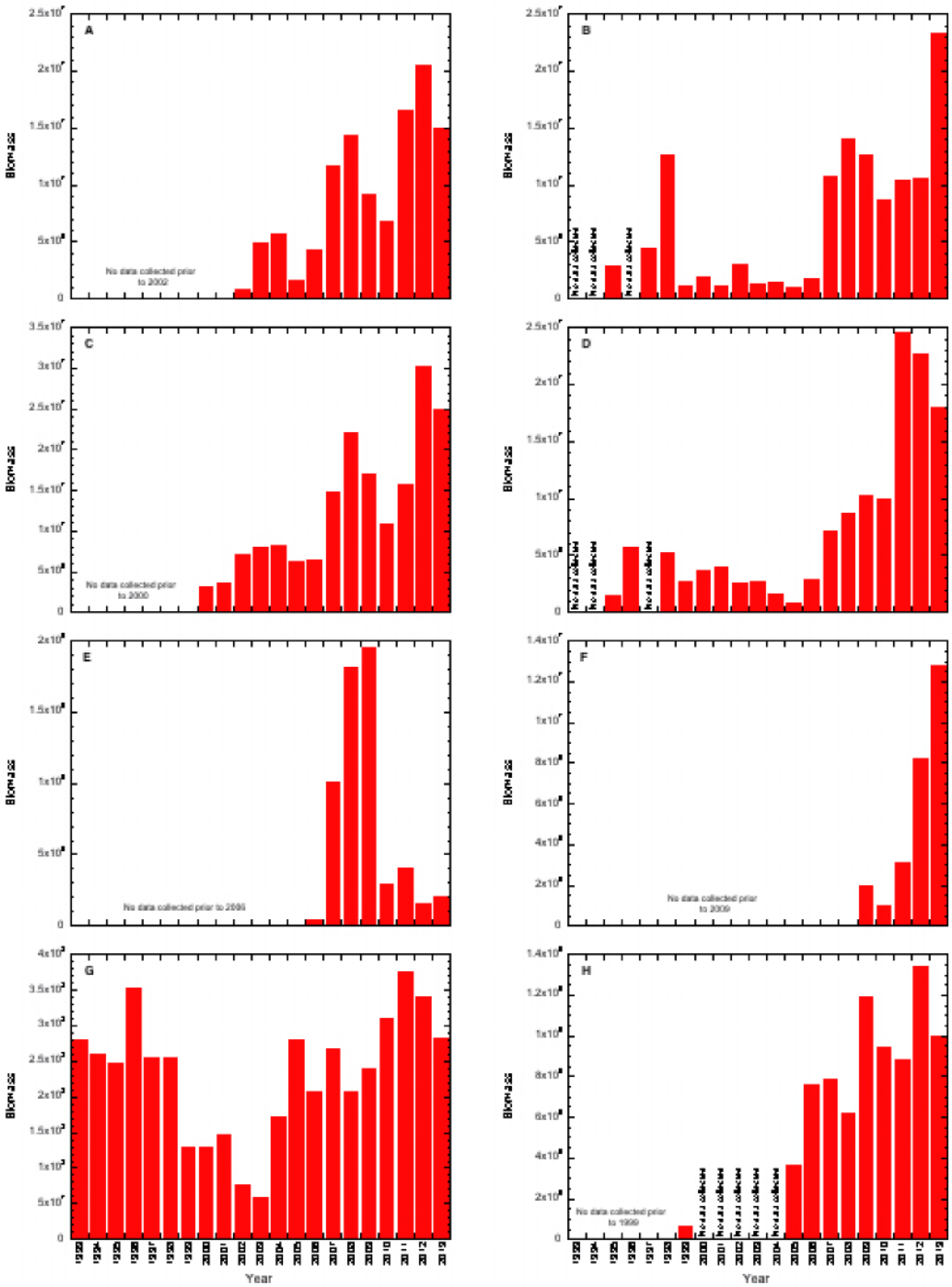
Oyster biomass on VA public reefs.

Oyster biomass data is described for defined stocks and are coincident with subdivision of the surveyed area in a north-south direction as follow: (A) Pocomoke and Tangier Sounds, (B) Great Wicomico River public reefs, (C) Rappahannock River, (D) Piankatank River, (E) Mobjack Bay, (F) York River, (G) James River, and (H) Elizabeth and Lafayette Rivers. Data is summarized in Figure 6.2. This figure is also offered at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/population_estimates/oyster_biomass/index.php with the additional facility to "click on" each river specific panel and obtain enlarged images for the individual plots. Note that the scales of the y-axes are region/river specific. The unit of biomass is grams dry tissue weight. Conversion functions to other metrics are described earlier in this text. All plots begin in 1993 to provide ease of comparison between sites within the plot, even though data collection was initiated at a variety of dates: 1993 for the James River, 1995 for the Great Wicomico and Piankatank Rivers, 2000 for the Rappahannock River, 2002 for Pocomoke and Tangier, 2005 for continuous monitoring of the Elizabeth and Lafayette Rivers, 2006 for Mobjack Bay, and 2009 for the York River.

Of particular note is the long-term pattern of biomass in the James River. Biomass remained between 2.54×10^8 g and 3.52×10^8 g between 1993 and 1998. The 1998-1999 winter was warm resulting in an intense MSX epizootic in 1999. The fall decrease in biomass was exacerbated by the occurrence of tropical storms Dennis and Floyd in September 1999 driving salinities down from mid teen values to ~6 ppt[3] for an extended period. The disease epizootic was followed by a high salinity, high recruitment year in 2002, and a wet low recruitment year in 2003. Fall 2003 was, however, notable for the passage of Hurricane Isabel and the presence, even if only in small numbers and in limited downstream locations, of predatory gastropods that had been absent since being locally extirpated by Tropical Storm Agnes in 1972. The lowest biomass was recorded in 2003 at 5.83×10^7 g before a gradual recovery was observed to 3.75×10^8 g by 2011. The 2006 and subsequent records include stations downriver of Burwell Bay not covered in the pre 2006 surveys, a modest (13%) increase in total area surveyed. A modest decrease in biomass to 2.82×10^8 g has been observed through 2013. The Great Wicomico public reef time series illustrates modest biomass in the 1990s (no samples were collected in 1996) with highest biomass in 1998 at 6.51×10^6 g. Like the James River, the warm 1998-99 winter and high 1999 salinities resulted in a sustained epizootic in 1999. Biomass decreased and remained low through 2006. While this may in part be epizootic related, the cause of this prolonged depression in biomass is not fully understood. From 2007 through 2012 biomass stabilized around 1×10^7 g, with a notable increase to 2.33×10^7 g in 2013. The Piankatank, like the Great Wicomico, exhibited modest biomass in the 1990s, high salinity and an epizootic

[3] We employ the units of ppt for salinity in this text. Over the past decade quantitative descriptors of salinity have migrated from the logical parts per thousand (weight of salt equivalent per weight or water), to "practical salinity units" or psu (thus inferring that ppt is impractical), to current use as a unitless value. This is utterly illogical, an attempt to describe a quantity without quantitative units. Thus we have regressed to units that simple biologists can comprehend.

Figure 6.2. Trends in oyster biomass (dry tissue, g) by region and river for the period 1993-2013.



beginning in 1999, and decreasing biomass in the early 2000s to a low value in 2005, followed by a sustained increase to the highest values in 2011. This increase is commensurate with shell planting and the addition of more reefs into the survey.

The Rappahannock River was the focus of extensive shell planting in the late 1990s and early 2000s. This is evident in both the shell data and increasing biomass in the 2000-2006 period. Sanctuary reefs were added to the survey footprint in 2007. Since 2007 biomass has increased dramatically in parallel with the signal observed in all of the above described river systems, in Tangier and Pocomoke, and in the Elizabeth and Lafayette Rivers.

The data series for Mobjack Bay and the York River are the shortest among those presented. Mobjack Bay biomass increased in the 2006-2009 period only to decrease afterwards. Note also a rise and decrease in shell resources over the same time period. The York River biomass illustrates an increasing trend over a stable shell base, but the time series is too short to offer generalizations.

The long-term trends in the presented data are encouraging. The major resources in the James, Piankatank and Great Wicomico Rivers have recovered following the epizootics of the late 1990s. The large watershed subestuaries James suffered rom low salinities accompanying the passage of Hurricane Isabel in 2003. By contract the impact in small watershed rivers such as the Piankatank and Great Wicomico was modest, and the cause of the low population estimates for this period remain poorly understood in these rivers. Careful management in concert with strategic shell planting has allowed increasing harvest to current high levels while maintaining standing stocks. In a manner similar to that of the shell resource we have arrived at a default BRP that is sustainable with careful proactive management.

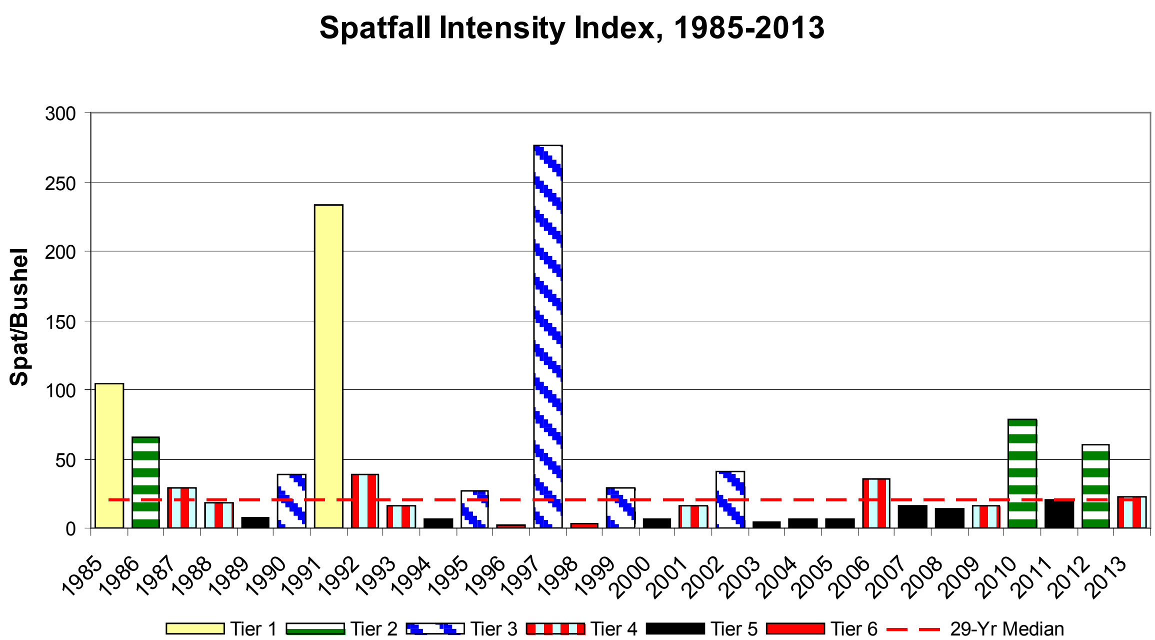
Recruitment of oysters in MD and VA.

The two state surveys approach this challenge by differing yet equally valuable approaches. MD employs a Spatfall Intensity Index based on YOY (spat) per bushel for the MD Key Bars as described earlier. The annual Index is compared with entries in the time series that originates in 1985, by the statistical ranking methods described in ToR#2. VA has both a spatfall survey effected throughout the summer months to provide spatial and temporal records of spatfall on provide substrate in three major estuaries (Great Wicomico, Piankatank and James Rivers), and explores the stock-recruit relationship in data from the annual fall patent tong survey. Although the data collection and the size demographic data in the VA fall survey identifies YOY in all samples the data are not typically examined as a recruitment index as for MD surveys. While VA enjoys generally higher YOY recruitments than MD these are also accompanied by higher mortality events of the YOY. A useful exploration would be a common treatment of the VA YOY data with MD methods to complete a bay wide Intensity Index. This is listed in ToR#11. Recruitment events in VA typically manifest as increases in biomass 2-3 y after the event. These events are reflected in Figure 6.2

MD oyster recruitment: the spatfall intensity index

(This section of text is excerpted from the 2013 Annual Fall Survey Report).
The 2013 Spatfall Intensity Index, a measure of recruitment success and potential increase of the population, was 22.7 spat per bushel, a sharp decline from the previous year's index of 59.9 spat/bu. but slightly higher than the 29-year median index of 20.1 spat/bu. Two of the last four years have seen strong year classes that have contributed to the increase in the Biomass Index (Figure 6.1). The 2013 recruitment, while not exceptional, may serve to maintain this population. The 2013 spatfall intensity index ranked in the fourth highest statistical grouping of six for the period from 1985 to 2013 (Figure 6.3).

Figure 6.3. The 1985-2013 MD Spatfall Intensity Index (arithmetic mean of spat per bushel for "Key Bars"), including rakings of statistically similar indices.



The Index is a survey wide arithmetic mean value and does not describe spatial variability. Recruitment was not as well distributed among the Key Bars in 2013 compared with the previous year. In 2013, spat were observed on 33 of the 53 Key Bars vs. 46 bars in 2011. Eight bars contributed 75% of the spat index, while 18 sites were needed to reach 95% of the spat index. In contrast, 14 bars accounted for 75% of the index in 2012. As usual, four of the top-five Key Bars for spat counts were along the Eastern Shore – all in southern Eastern Shore tributaries, although the highest Key Bar spat count in 2013 was 196 spat/bu. on Pagan in the St. Mary's River, the sole Western Shore representative. Locations are described at http://dnr2.maryland.gov/fisheries/Pages/shellfish-monitoring/fall-survey.aspx and in the Annual reports.

Even though the spatfall intensity index does not describe spatial variability the statistical tiers in Figure 6.3 do have a spatial component. For example, the near-record high spatfall intensity in 1997 was limited in extent, being concentrated in the eastern portion of Eastern Bay, the northeast portion of the lower Choptank River, and to a lesser extent, in parts of the Little Choptank and St. Mary's rivers. Over 75% of the 1997 index was accounted for by only five of the 53 Key Bars, while ten contributed nearly 95%. As a result, the 1997 spat index fell into the third statistical tier despite being the second highest index on record and an order of magnitude higher than other Tier 3 indexes. In contrast, the 1991 spatfall, the third highest on record, was far more widespread. Fifteen Key Bars comprised 75% of the index that year, while 28 sites were needed to attain 95% of the spatfall intensity index, placing it in the first statistical tier notwithstanding having a lower spatfall index than 1997.

VA oyster stock-recruit (S/R) relationship as biomass of spawning stock in year t in relation to biomass of year class age 1 in the following year.

Data for each river or region data is presented in separate figures (Figures 6.4A-H). These figures are also available in expandable format at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/population_estimates/stock_recruit_relation/index.php. The number of stations included and areas included are described in Table 2.1 and 2.2. under ToR#2 in this report. Biomass units are in grams dry tissue weight. Fits to the data plots have generally not been attempted. Age 1 biomass is on the y-axis, Age >1 biomass is on the x-axis for all plots.

The Pocomoke and Tangier S/R plots cover the recruitment events from 2004 through 2013 and show a generally increasing trend across the figure. There remains a considerable scatter between 2011 recruitment biomass (7.77×10^6 g) from 2010 broodstock biomass (6.82×10^6 g), and 2013 recruitment biomass (3.91×10^6 g) from 2012 broodstock biomass (2.05×10^7 g). The plot does not indicate a clear asymptote, but suggests density independence.

The Great Wicomico River S/R plots cover the recruitment events from 1999 through 2013. Biomass of Age>1 in the Great Wicomico public reef population is notably depressed in 1999, 2001, and 2003-2005. These correspond to unusual data points in the mortality/survival data discussion later in this text. There is considerable scatter in the S/R plot with low recruit biomass in much of the 1999-2006 period. From 2007 onwards a notable increase is evident in both the recruit and broodstock biomass. 2007 recruit biomass exceeds that of 2006 broodstock biomass by a factor of 4.7! 2013 recruit biomass approximates that of 2012 broodstock biomass. The system exhibits recovery over the study period, complicating any generalized statement on the nature of the S/R relationship.

The Rappahannock River S/R plots cover the recruitment events from 2001 through 2013. The Rappahannock River surveys included an increasing number of stations (173 to 301 in the 2000-04 period and 301-385 in 2006-07) and area (11.12 x 10^6 m^2 to 2.06 x 10^6 m^2 in the 2000-04 period and 2.06 x 10^6 m^2 to 2.30 x 10^6 m^2 in 2006-07) as the study period progressed There is a strong suggestion of density independence in the S/R plot.

The Piankatank River S/R plots cover the recruitment events from 1996 through 2013. The corresponding area increased gradually from 7.03 x 10^5 m^2 to 8.27 x 10^5 m^2 (see Table 2.1, ToR#2) with the exception of 1999 when the sampled area was only 3.77 x 10^5 m^2 . The Piankatank River exhibited low broodstock biomass in 2004 at 1.54 x 10^6 g. The corresponding recruitment in 2005 was comparably low at 2.60 x 10^5 g. This period corresponds with unusual mortality/survival data for the same period as will be discussed later in this report. By contrast a very low broodstock biomass in 2005 (7.98 x 10^5 g) produced a much higher recruit biomass in 2006 (1.56 x 10^6 g). Note this is one year earlier than a similar event in the Great Wicomico River. Like the Great Wicomico record there is a notable increase in broodstock biomass in later years of the survey (2007-2013) including a single data pair (broodstock 2010 at 9.9 x 10^6 g -recruit 2011 at 1.60 x 10^7 g) wherein the recruit biomass exceeded that of the originating broodstock. The S/R plot suggests density independence rather than an asymptote.

The data set for the Mobjack Bay and York River is modest in longevity and not included in the analysis.

The James River data set is extensive in both time (recruitment events from 1994 through 2013) and spatial coverage (increasing from 2.29 x 10^7 m^2 to 2.74 x 10^7 m^2 (see Table 2.2, ToR#2). The reduction in "count" or sample number over time reflects early (pre-2000, see Table 2.1 in ToR#2) efforts to examine sample number versus standard error of the mean relationships as discussed earlier in this text. The lower spawning stock biomass in 1999-2003 (<1.5 x 10^8 g) is epizootic related and post epizootic related.. The 2010-2013 period is notable for both high broodstock biomass (>2.8 x 10^8 g) and recruit biomass (>1.5 x 10^8 g). Variation on the S/R plot in the mid 1990s are probably related to a notable freshet in August 1995. Unlike typical freshets this was not accompanied by a major sedimentation event. It caused considerable mortality in larger oysters (box counts were highest in the >50mm SL size fraction) but the timing of the freshet allowed a post freshet recruitment event on the newly exposed shell with reduced post recruit predation. This recruitment event resulted in a notable increase in the 35-55mm SL size range of small (one year old) oysters in 1996. The overall S/R plot is strongly suggestive of density independence and exhibits no asymptote.

The Elizabeth and Lafayette Rivers are modest in area (6.6 x 10^4 m^2 in 1999, 2.29 x 10^7 m^2 from 2005-2013) and sample number (14 in 1999, 21 from 2005-2013) on an annual basis. Only the 2006-2013 recruitment events are included in the current discussion and figure. With the exception of the "low" 2005 broodstock (3.66 x 10^5 g): 2006 recruit (1.96 x 10^5 g) data point the S/R plot presents a cluster of data. Inclusion of the "low" data point is suggestive of density independence, exclusion of the data point offers no strong relationship in the 7 data points.

In each of the above cases the suggestion has been proffered of density independence in the S/R plot, that is the general absence of some environmental limitation on recruitment within the boundaries of the reported observations. The above plots do not include a shell habitat parameter although parallel data are available as described in the survey methods and reported here under ToR#4. The suggestion that shell habitat may eventually become limiting requires careful attention and will also be addressed in this report following presentation on the relationship of live to dead shell ratios in extant populations.

Consideration of age structure and sex ratio in estimating spawning stock biomass. Oysters are protandric hermaphrodites, maturing first as males and subsequently as females. Thus spawning stock biomass estimates that assumes sexual parity are influenced by population age structure and age of transition from male to female. There is remarkable consistency in the sex ratio with size for oysters in both the Delaware Bay and the VA portion of the Chesapeake Bay as reported by Powell et al. (2013) and Harding et al. (2013) respectively. There is no reason to assume the same transition does not also apply in MD oyster populations. The reports of both Powell et al. (2013) and Harding et al. (2013) suggest that the male to female transition starts at ~60 mm and 1.5 y and that larger oysters are at least 70-80% female. There are no discussions of egg versus sperm limitation in reef forming oysters (although this would be a valuable contribution to both oyster and benthic ecology) so no modification is proffered of the biomass based estimates of broodstock at this time in this report. This does not exclude such a consideration in future discussions (hence inclusion of this subject in *ToR #11*)

Figure 6.4A. Stock recruit relationship for Pocomoke and Tangier oyster stocks

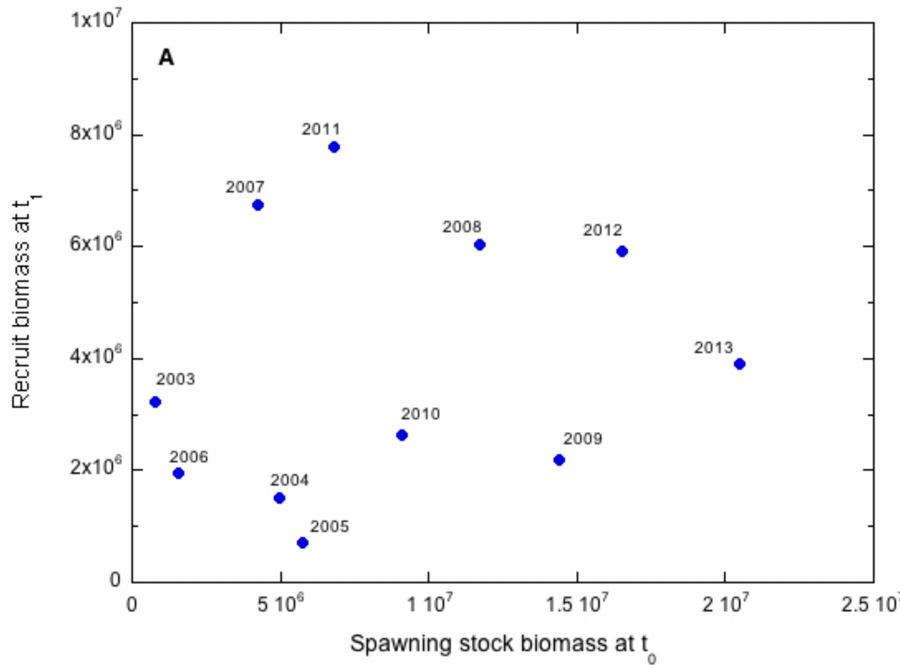


Figure 6.4B. Stock recruit relationship for Great Wicomico River oyster stocks

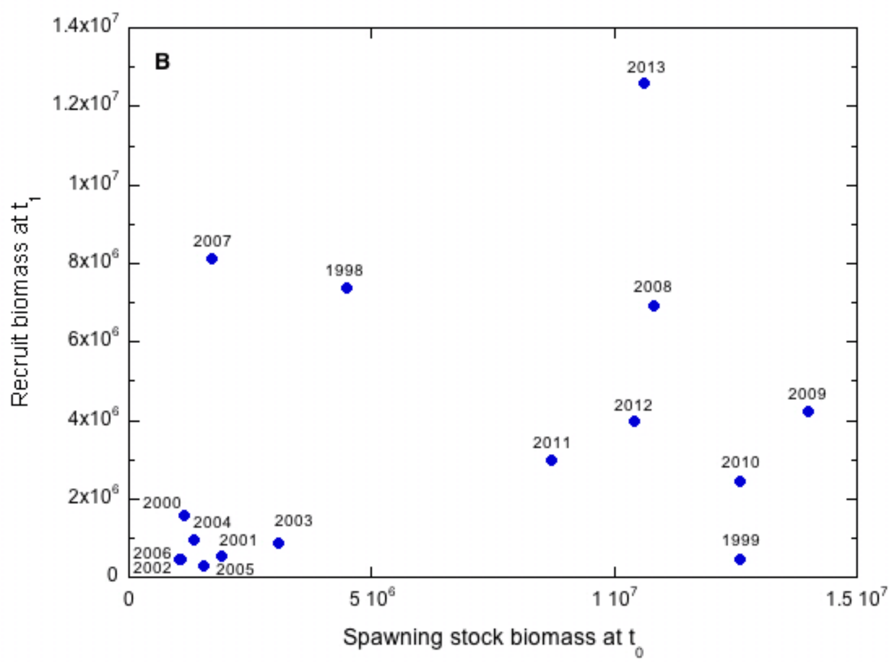


Figure 6.4C. Stock recruit relationship for Rappahannock River oyster stocks

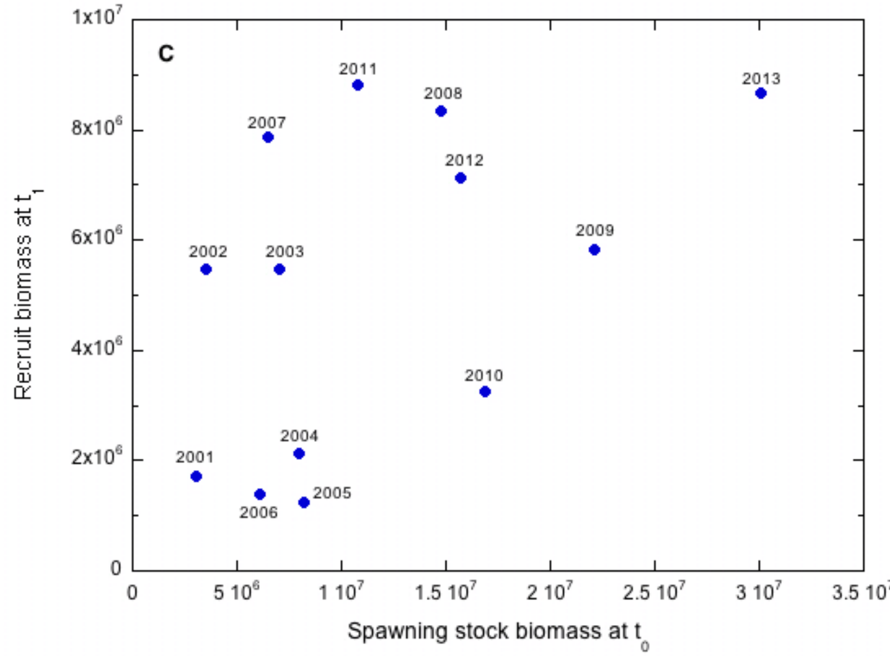


Figure 6.4D. Stock recruit relationship for Piankatank River oyster stocks

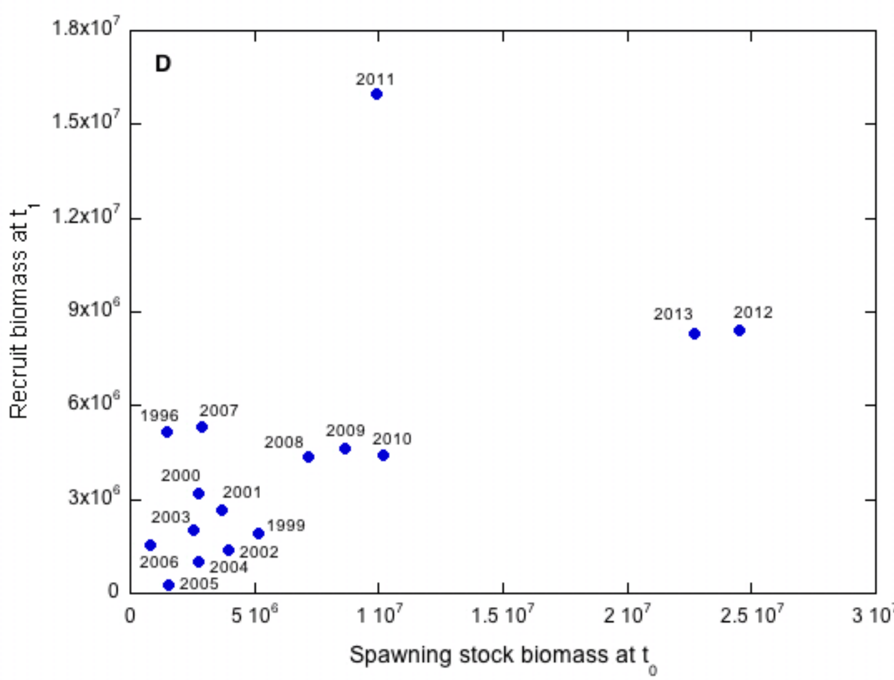


Figure 6.4G. Stock recruit relationship for James River oyster stocks

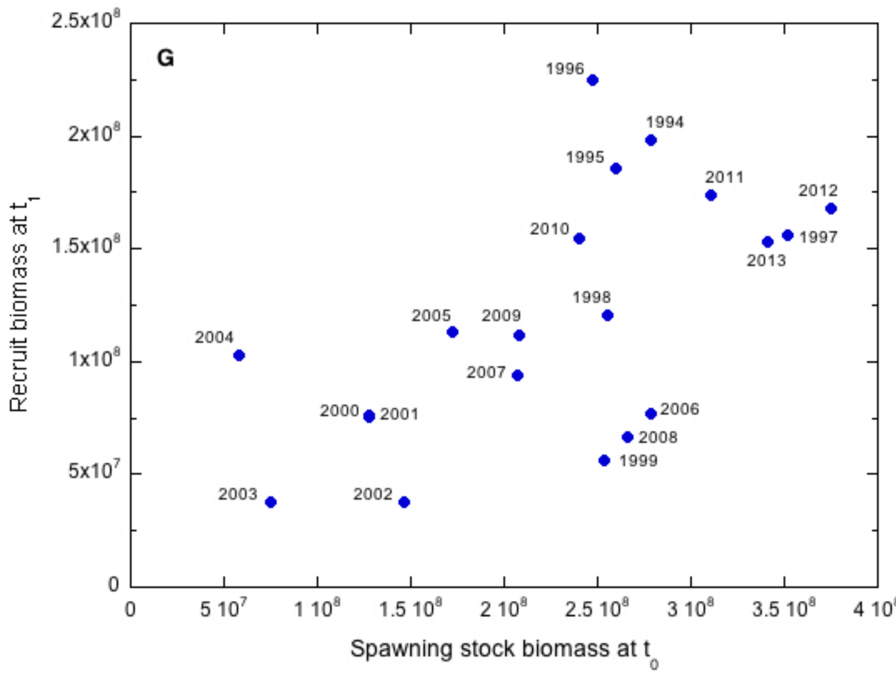
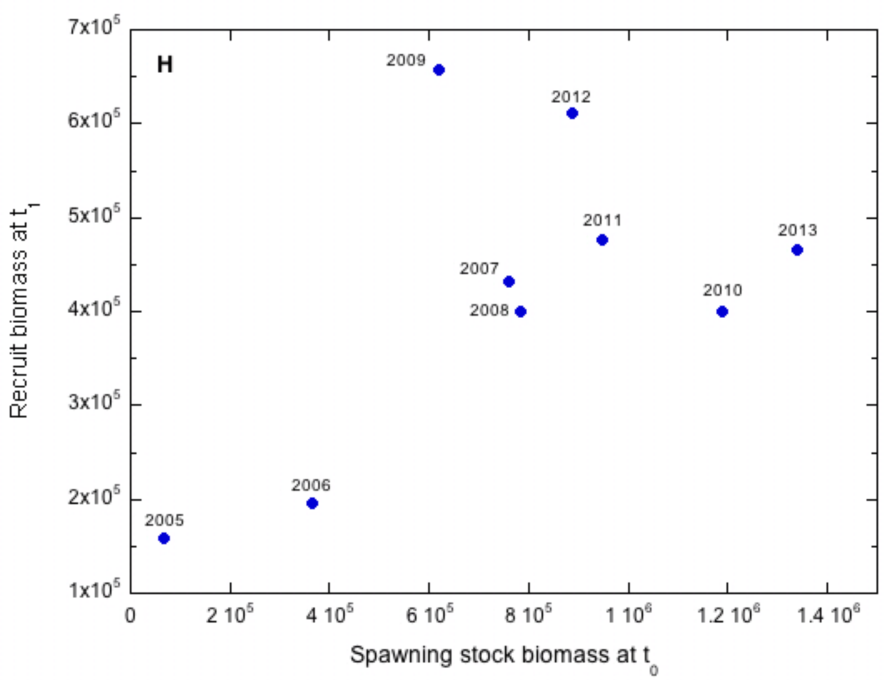


Figure 6.4H. Stock recruit relationship for Elizabeth River and Lafayette River oyster stocks



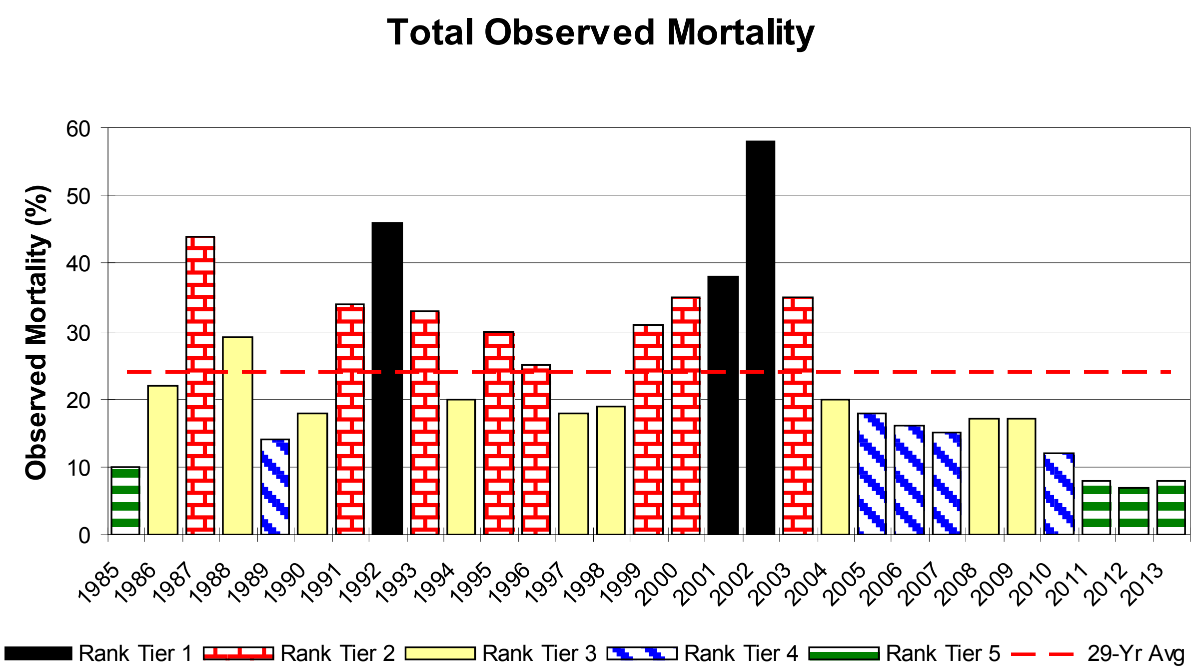
Estimation of Mortality in Oyster Stocks

Surveys in MD and VA estimate and report mortality in differing manners. MD reports total observed mortality based on box counts of small and market oysters. This is reported as a percentage value and while it does not provide age specific mortality rates neither does it suffer the inherent errors associated with distinction of year classes within a demographic distribution. VA dissociates the demographic into estimated year classes and proceeds to estimate age specific mortality and/or survival. This is more complex, subject to greater inherent error but potentially more informative. The VA surveys routinely collect box data as individual lengths within each sample, thus a large database exists. It has not been examined/analyzed by the protocols for the MD data, and a comparison for a bay wide index would be a task worthy of pursuit. It is included in ToR#11.

Observed mortality in MD oyster stocks

(This section of text is excerpted from the 2013 MD Annual Fall Survey Report).

Figure 6.5 Mean annual observed mortality of small and market size oysters in MD waters combined for 1985-2013. Ranking tiers are based on statistically similar years



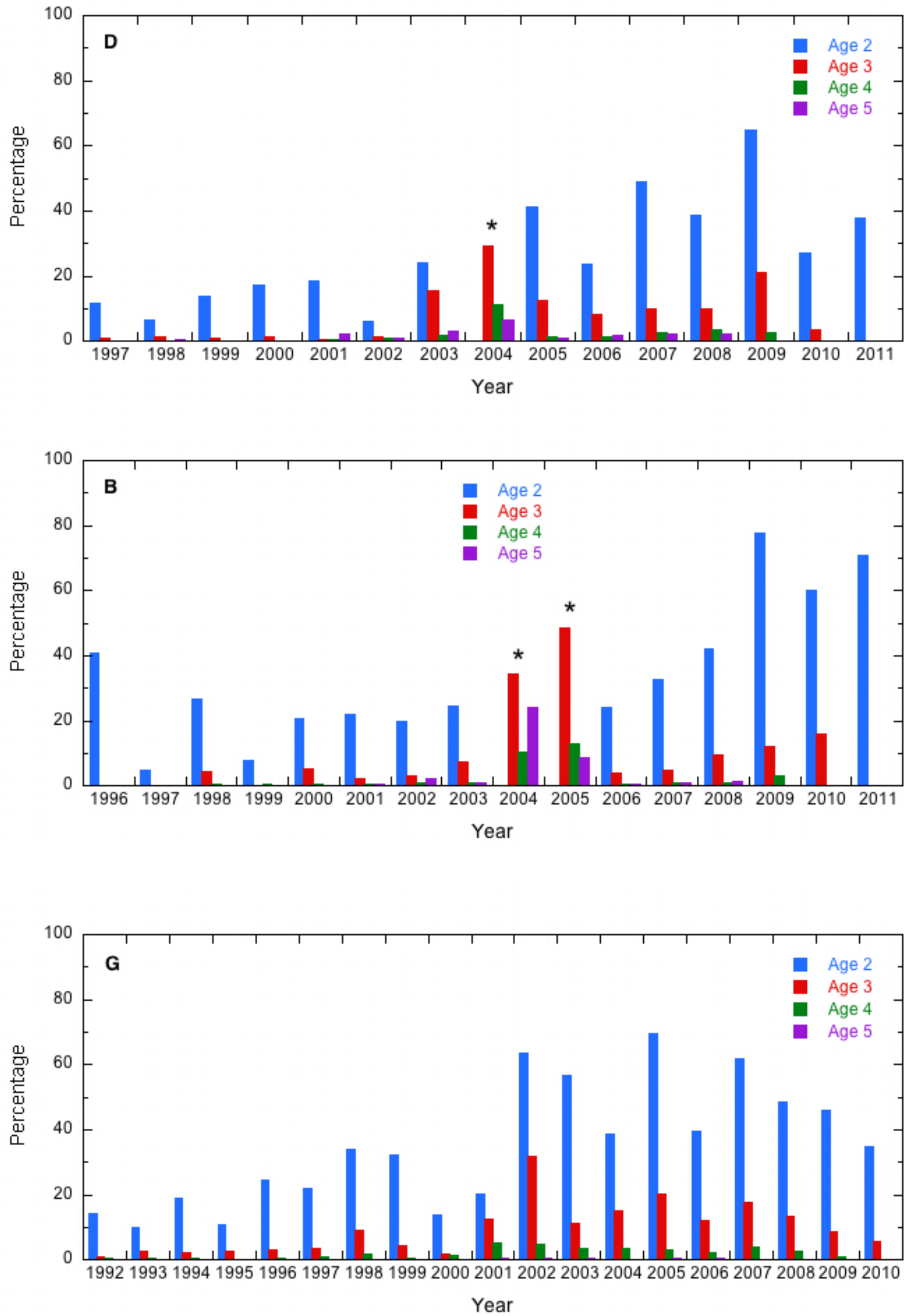
The long-term 29-year average value for observed mortality is 29% (Figure 6.5). Notably high values were recorded in 1987, 1991-1993 and through a 5 year period from 199(?)-2003 coincident with a major epizootic event. The 2004-2013 period is a ten-year period when mortality was markedly below the 29 year mean. For the 43 disease monitoring bar subset, the average observed mortality of 13.8% over the last ten years approaches the background mortality levels of 10% or less found prior to the mid-1980s disease epizootics (MD DNR, unpublished data). The 2013 observed mortality of 8% on the Disease Bars was ranked in the lowest statistical grouping over the same period; the past three years (out of four total) were in this lowest mortality tier (Figure 6.5). This is a remarkable turnaround from 2002 when record-high disease levels devastated MD populations, killing 58% of the oysters. In 2013 there was congruence between recruitment, diseases and mortality with a general north-south gradient in observed mortality rates, with the notable exception of the residual boxes in the Upper Bay from freshets that occurred with spring rains and tropical storms in 2011. This is a rare case where failure of paired valves to disarticulate within a year can result in their being ascribed to the wrong year with respect to time of mortality and thus inflated estimates of observed mortality.

Age specific mortality/survival in VA oyster stocks

Oyster population demographics determine the long term stability of both the live and shell components of reef structures. Age specific mortality and survival (%mortality = 100 - % survival) is reported (Figure 6.6) for the Great Wicomico, Piankatank and James Rivers only, because these are the only rivers where age versus length relationships are available. For the Great Wicomico River the 2004 and 2005 age 2 survival value is driven by very low population totals for year 1 for both year classes (low year 1 in 2005 and 2006 survey respectively) and possible assignment of individuals to incorrect age classes. In the Piankatank River the 2004 age 2 survival value is driven by very low population totals for year 1 in the 2004 year class (low year 1 in 2005 survey) and possible assignment of individuals to incorrect age class. In both instances these periods are noted on the graphics. The cause of the very low abundance in both rivers in this period is not well understood. An “epizootic signal” is also observed in the James River mortality/survival time series; however, the recovery of the oyster population in both the Great Wicomico and Piankatank Rivers occurs later than in the James River.

The current, limited analysis of age specific survival/mortality would clearly benefit from additional age v length relationships to expand the discussion (see expanded discussion in ToR#11). A depressed population census drives error possibilities in the survival estimates for both the Piankatank and Great Wicomico Rivers. The nature of these errors is discussed in ToR#4 in this report. Notably, after these periods of low population census the survival rates post age 1 appear to increase. Is this a fundamental result of heavy selection during the preceding disease epizootic period? Disease monitoring of these major subestuaries (http://www.vims.edu/research/departments/eaah/programs/shellpath/publications/index.php) indicate no decrease in disease weighted prevalence post 2000, so the observed increase in survival estimate is not associated with a decrease in disease pressure.

Figure 6.6. Age specific mortality for oysters in Great Wicomico River (panel B), Piankatank River (Panel D), and James River (Panel G).



A notable trend in the long-term stock assessment data is the observation of earlier recruitment post 2000 in all three systems addressed by the survival data herein (note the temporal pattern of recruitment in annual monitoring reports at http://www.vims.edu/research/units/labgroups/molluscan_ecology/publications/reports/annual/index.php). The earlier recruitment may results in larger YOY at the end of the year. The age versus length estimators presented earlier were developed with post 1998, and predominantly post 2000 data, so the observed "shift" in length demographics should not compromise assigning individuals to the correct year classes.

Relationship of oyster live shell to dead "brown" shell

The relationship of live shell to dead "brown" shell in the oxic region above the sediment water interface can be viewed as a quantitative index of reef health in that shell encourages recruitment and growth of live oysters above the sediment water interface, although we are unaware of any such analysis in the published literature. The individual regions are presented below as volumetric plots with the live animal value being estimated from biomass as described in Figures 6.7A-H of this report. Linear fits, employing a $y = c + mx$ form, are added to each plot. A summary of the descriptive fits (units are in Liters) is as follows:

(A) Pocomoke and Tangier Sounds: $y = 5990.2 + 0.09x$, $r^2 = 0.29$
(B) Great Wicomico River public reefs: $y = 13609 + 0.31x$, $r^2 = 0.64$
(C) Rappahannock River: $y = 5079.7 + 0.07x$, $r^2 = 0.33$
(D) Piankatank River: $y = 33.4 + 0.16x$, $r^2 = 0.68$
(E) Mobjack Bay: $y = 5057.5 + 0.08x$, $r^2 = 0.29$
(F) York River: $y = 31307 + 0.05x$, $r^2 = 0.29$
(G) James River: $y = 69275 + 0.25x$, $r^2 = 0.75$
(H) Elizabeth and Lafayette Rivers: $y = 12409 + 0.04x$, $r^2 = 0.29$

Notable among the descriptors are the slopes for the James and Great Wicomico Rivers in the 0.25-0.31 range, higher than that for the Piankatank (0.16), but all with r^2 values >0.60. The remaining locations exhibited both lower slopes (<0.1) and lower r^2 values (<0.64). The former grouping is generally considered to have the highest standing stock per unit area and consistent history of recruitment. This relationship is not constant across the surveyed systems and is worthy of additional examination with respect to critical values for "healthy" versus challenged reef systems.

Figure 6.7A. Relationship of live shell to brown shell volume in Pocomoke and Tangier Sounds

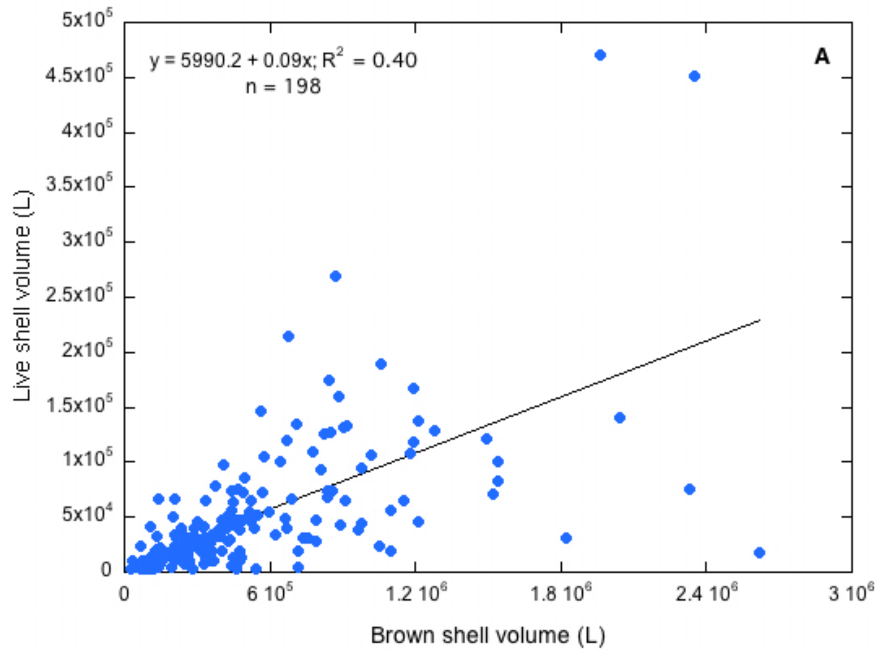


Figure 6.7B. Relationship of live shell to brown shell volume in Great Wicomico River

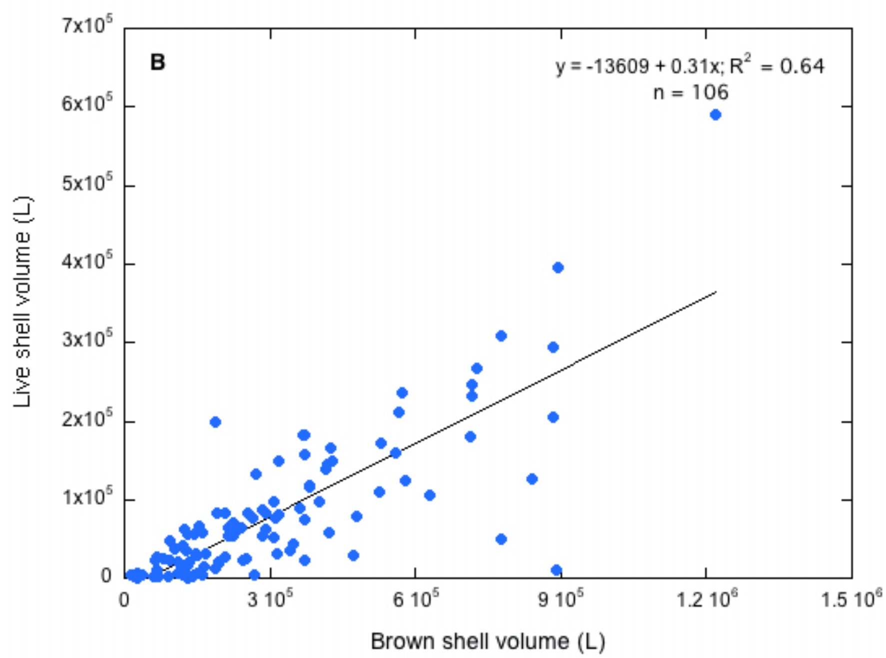


Figure 6.7C. Relationship of live shell to brown shell volume in Rappahannock River

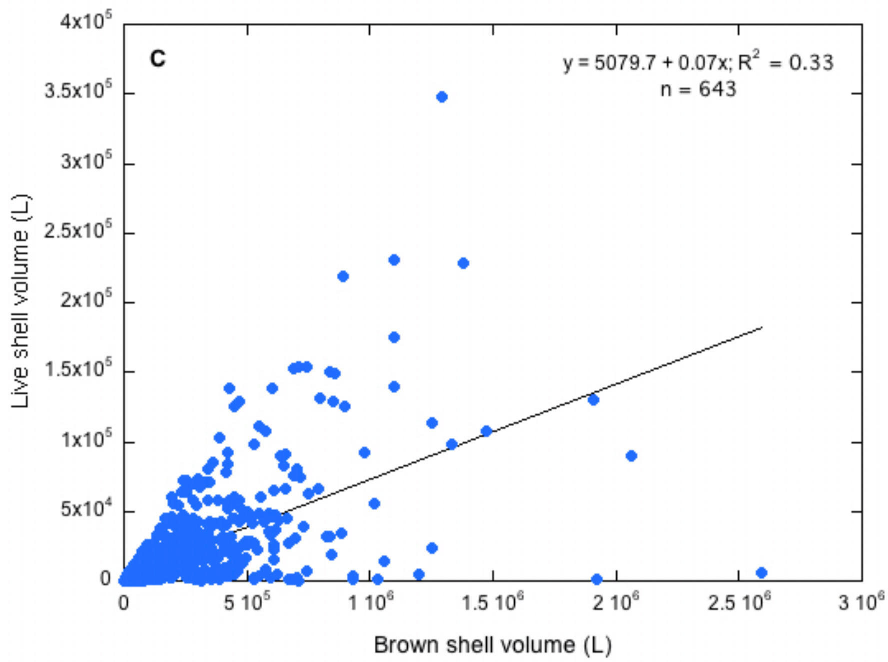


Figure 6.7D. Relationship of live shell to brown shell volume in Piankatank River

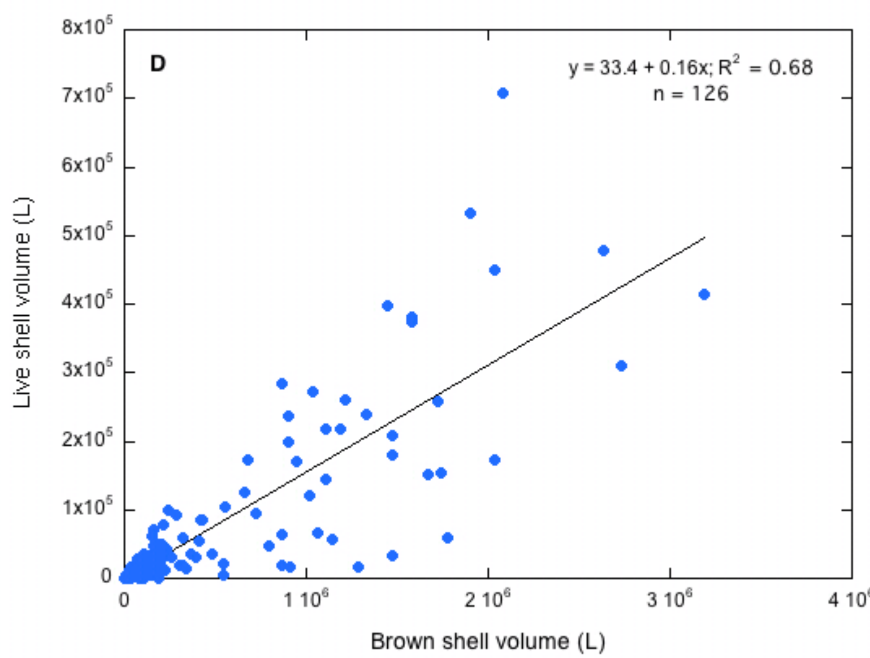


Figure 6.7E. Relationship of live shell to brown shell volume in Mobjack Bay

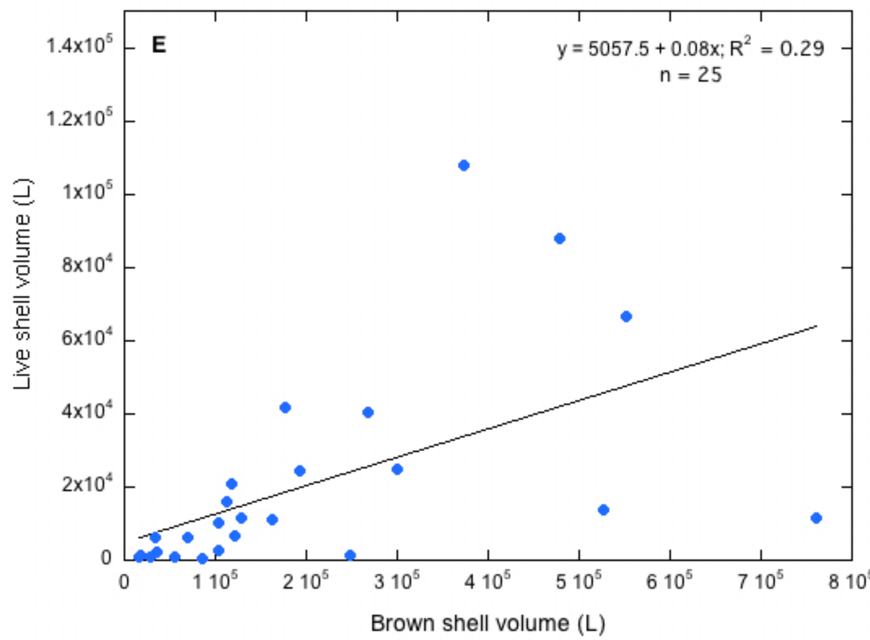


Figure 6.7F. Relationship of live shell to brown shell volume in York River

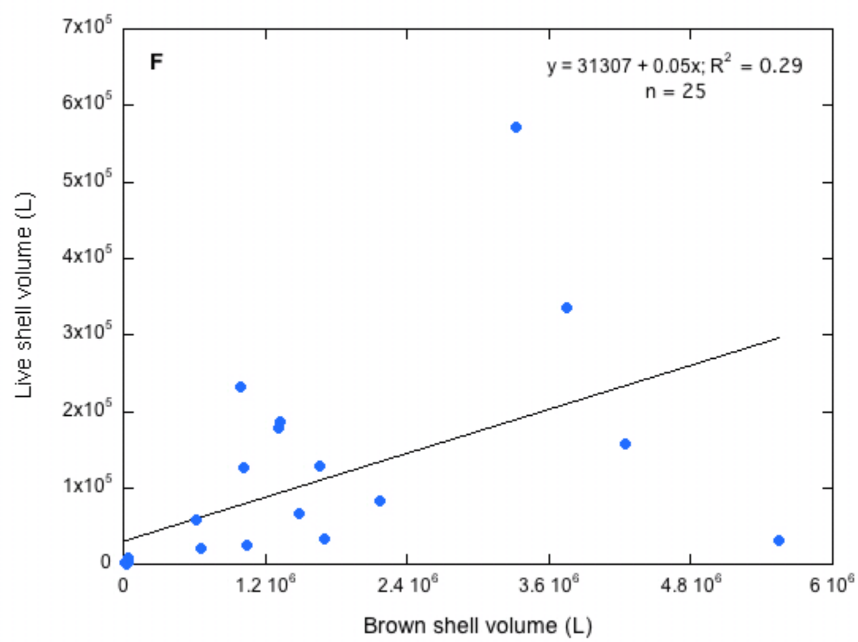


Figure 6.7G. Relationship of live shell to brown shell volume in James River

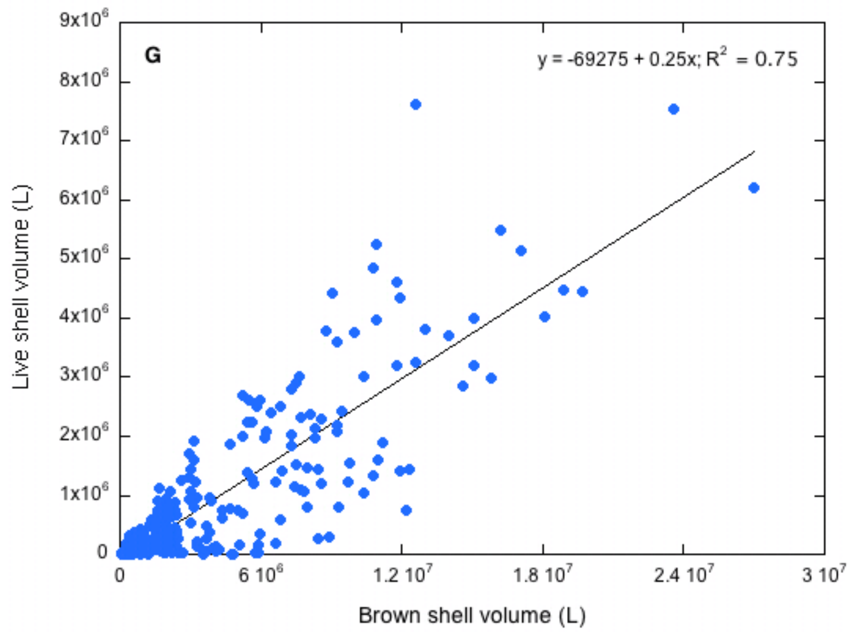
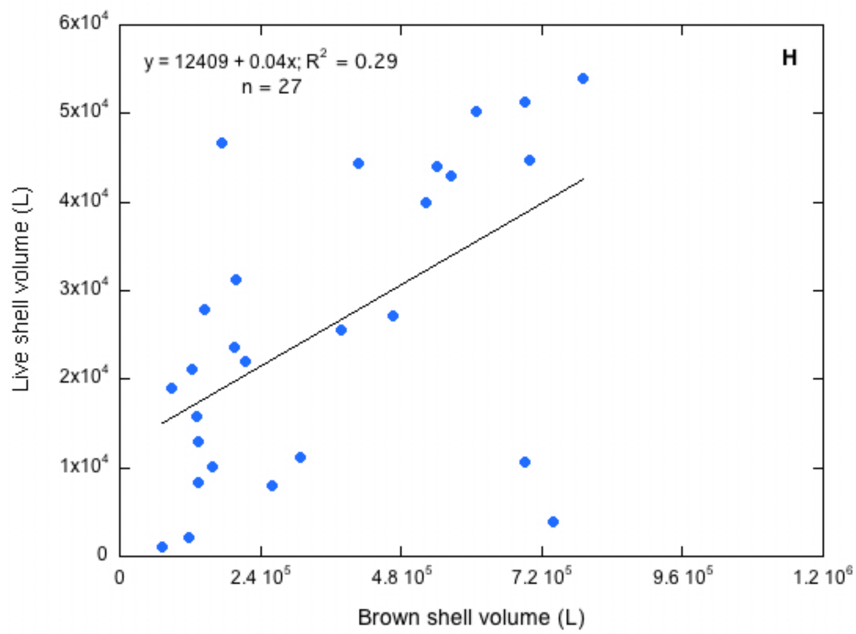


Figure 6.7H. Relationship of live shell to brown shell volume in Elizabeth and Lafayette River



Relationship of recruitment to available shell substrate

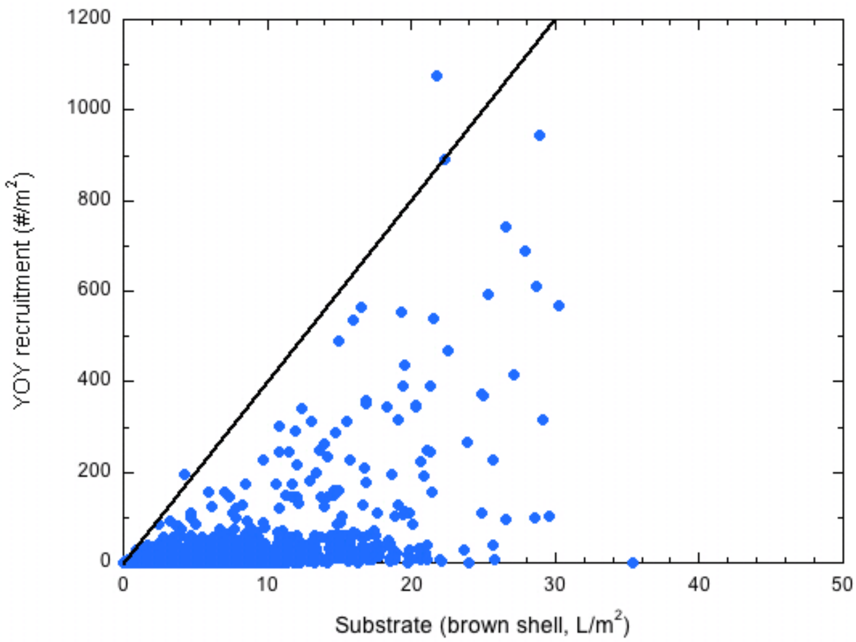
To this juncture the data has focused on recruitment to age 1 in the development of S/R descriptors. There has been a long-standing interest in the recruitment of YOY (spat) on either extant shell substrate or recently added shell (shell planting). Two summary plots are presented for the whole VA data set in Figure 6.8 where individual (year mean for identified region or river) combinations of values for brown shell (upper panel) and live oyster shell (lower panel) versus observed recruitment (YOY) are available. Additionally, the data is presented by area specific plots in Figures 6.9 and 6.10 respectively with areas identified by the letters A through G as for prior figures in this text. .

The summary data set in Figure 6.8 includes 1478 x-y points presented in two plots without discrimination with respect to year or source. In both plots a descriptive line is added suggesting a saturation situation – that is recruitment can occur up to a maximum density per unit volume of substrate. The suggested line approximates to 40 YOY/L for total substrate and 120 YOY/L for live substrate. Recall, however, from the above plots that the brown shell : live shell ratio is region or river specific and that the above values can be expressed as approximate number of spat per bushel as employed in the seed oyster fishery by multiplying the value by 50 (1 VA bushel approximates 50L). Thus a 40 YOY/L for total substrate becomes 2000 spat per bushel. This would be considered an exceptional seed source – 1000 spat per bushel is generally considered very good.

Of concern in both summary plots in Figure 6.5 is the number of points that are far removed from the proposed saturation line. Is this driven by prior fouling of the shell surface or by the lack of available larvae to compete for the substrate? One line of future analysis to clarify this question would be a comparison of specific stations where both assessment stations and shellstring recruitment data (see http://www.vims.edu/research/units/labgroups/molluscan_ecology/monitoring/shellstring_spatfall/index) are available.

When the recruitment versus shell data are considered on an area specific basis striking variation is observed (Figures 6.9 and 6.10). Plots for the Great Wicomico, Piankatank and James Rivers (panels B, D and G) illustrate a scatter of points from close proximity to the x axis to the "saturation line" described for the all area summary plots. The remaining areas (panels A, C, E, F and H) illustrate no such spread in the data points with increasing substrate availability having comparatively modest impact on recruitment. Whether this is the product of limited larval supply, intense early post larval mortality, or a combination of both is worth of additional investigation. The general observation is in agreement with that of Andrews (1979) that the Great Wicomico and Piankatank Rivers are "trap type" estuaries, and that the Burwell Bay area in the James River also experiences retentive circulation

Figure 6.8. Summary plots for all years and stations of brown shell substrate versus observed YOY recruitment (upper panel) and live shell volume versus observed YOY recruitment (lower panel)



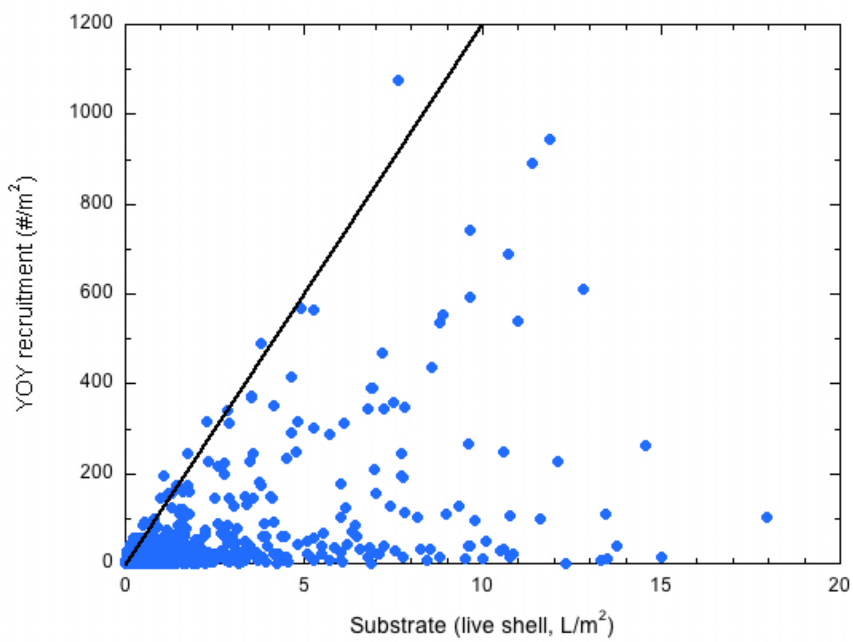


Figure 6.9 Summary plots for all years and stations of brown shell substrate versus observed YOY recruitment.

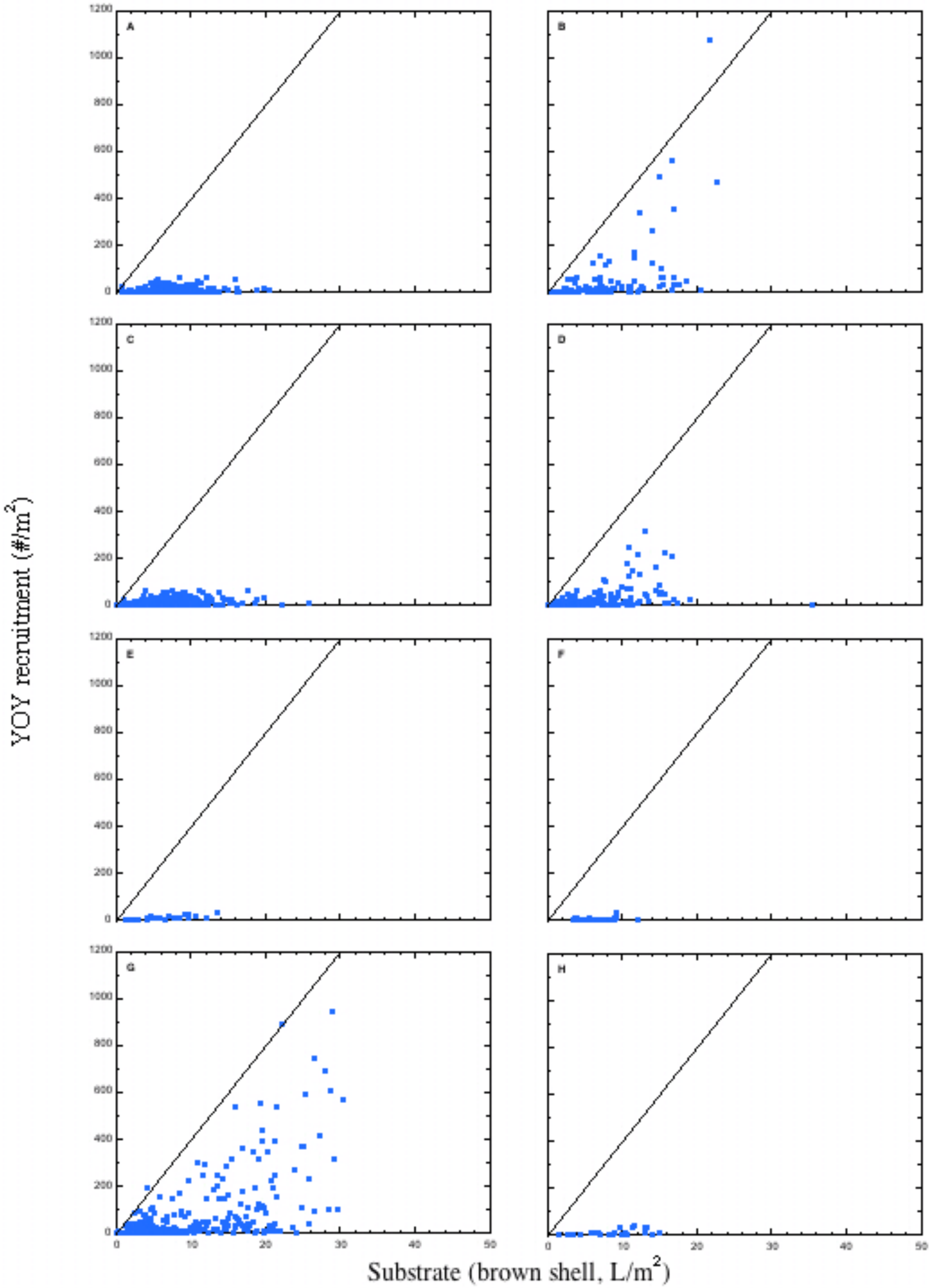
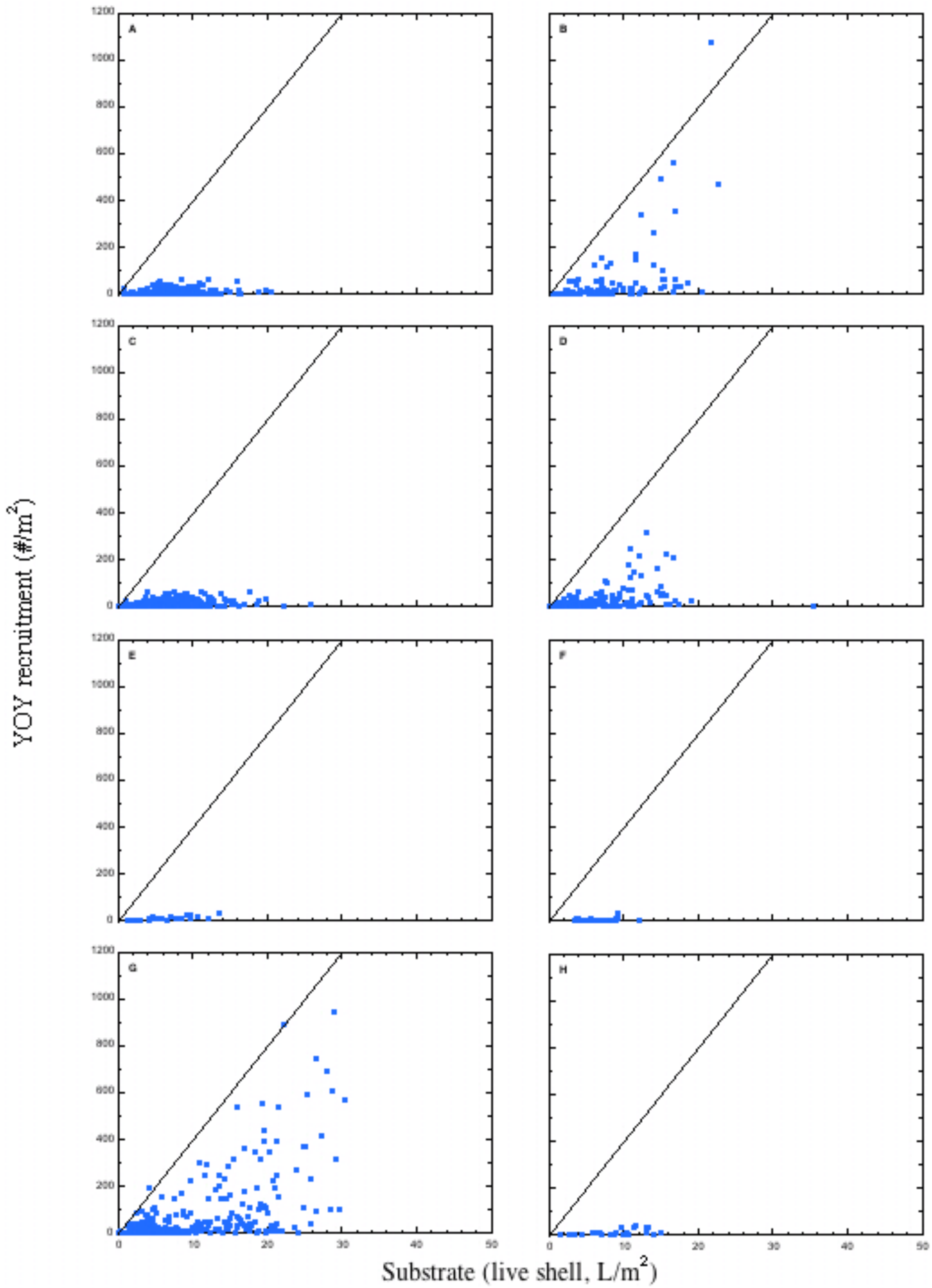


Figure 6.10. Area specific plots for all years and stations of live shell volume versus observed YOY recruitment.



ToR #7. Update or redefine biological reference points (BRPs; estimates or proxies for B_{MSY}, $B_{THRESHOLD}$, and F_{MSY}; rebuilding thresholds, and estimates of their uncertainty). Comment on the scientific adequacy of existing and redefined BRPs.

Biological reference points (BRP's) provide guidance for management actions. Bay wide there are no extant and agreed upon reference points for oyster management. Harvests in both states are not generally managed by quota developed from stock assessment. Rather, they are managed by a mixture of seasonal and aea closure, daily time and gear restrictions (effort control), and daily bushel limits. Over the course of the season however these controls do not typically result in limiting effort, with most areas being fished until so few market sized oysters remain that fishing is no longer cost effective. The development of biological reference points is a useful exercise in consideration of future management actions; however, a consideration of recent historical context is also important.

B_{MSY}, the biomass that supports MSY, maximum sustainable yield, is typically estimated at one half of carrying capacity. At carrying capacity yield is effectively zero. We have no estimates of current potential carrying capacity of the Chesapeake Bay for oysters. There are several discussions of oyster biomass or ecological impacts prior to the fishery associated declines following prolonged exploitation, especially that in the latter half of the 1800s. Newell's (1988) landmark paper estimating that the volume of the Chesapeake Bay could, in pre-colonial times, be filtered in 3.5 days by then extant oysters was a precursor to efforts to develop estimates of biomass at carrying capacity and the ecological benefits of restoring oyster populations to such status. These are of academic interest but i of little immediate practical value in managing the oyster fishery. The Chesapeake Bay bears little resemblance to that of 150+ years ago, and recolonization of the regions from which oysters were extirpated by disease remains challenging to the native oyster without suitable substrates upon which to attach and disease tolerance or, preferably, complete resistance. When food conditions are acceptable, but disease or substrate conditions are not, repopulation from extant oyster populations will not occur. Thus estimates of "whole bay" carrying capacity and B_{MSY} as one half of that value are not reasonable goals in the context of fishery management.

Oysters are unlike finfish in prerequisites for sustainable fishery management because they build their own shell habitat. Mann and Powell (2007) describe the need for sustainable reference points for both live oysters and shell, and that natural mortality must occur to maintain a positive shell balance. This limits exploitation that might otherwise be acceptable in terms of a higher F in relation to M. This relationship has been explored in more detail by Powell et al. (2012) and implemented as a simple no net loss model in practical application (Soniat et al. 2014) by the Louisiana Department of Fisheries and Wildlife. In addition, over longer time frames (hundreds to thousands of years) shell production must be adequate to maintain accretion and reef topography in the face of sea level rise (discussion in Mann et al. 2009). Although now widely acknowledged, comprehensive discussion of dual reference points for live oysters and shell management have not been formally pursued in management of Chesapeake Bay oyster populations.

Given the above background, the question is therefore posed - what are reasonable BRP's for oyster management? Any management plan must accommodate a truncated life expectancy and inter-annual variability in recruitment and survival. While modest single year losses in habitat (see above) may be tolerated prolonged shell loss cannot. The options are either to set very conservative BRP's in order to preserve shell at the risk of lost production (harvest), accept loss of shell in the setting of BRP's with an accompanying commitment to shell repletion (assuming adequate quantities of shell and funds are available to make up the deficit), or develop an interactive management tool that adaptively manages in real or near real time as survey and fishery dependent data becomes available.

Current management practices in both MD and VA do not have formal BRPs that are used in setting quotas or catch limits. Both state fisheries are controlled by time, gear and location limits. This does not mean that the fisheries are without consideration of what are, in effect, proxies for formally developed reference points in management actions. In MD the biomass index and spatfall data are used proactively to inform the management process. In prior periods of abundant shell reserves for substrate enhancement (shell planting) these data were used to guide replenishment efforts. Indeed, we have collectively been in the shell budget and BRP business for over a century without ever examining the underlying quantitative dynamics! In VA the assessment data are used to determine opening and closure dates (especially with respect to rotational harvest regions) and shell data drives the targeted replenishment activity. In both instances the long-term goal is simply "no net loss" – a guiding principle enacted by then VA Commissioner William Pruitt as he addressed rebuilding oyster stocks after the late 1990s epizootics in VA.

The approach of Soniat et al. (2014) is to employ a no net loss calculator for management guidance. Such a calculator is not yet available for management of either MD or VA oyster stocks. To begin to address this inadequacy I (Mann) have developed a simple virtual population estimator in the form of an EXCEL program that allows input and manipulation of recruitment and age specific values of M. It is available for download at http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/biomass_tool/index.php. The output is a population demographic in numbers and biomass, together with serial contribution of shell to the accreting reef structure, offset by shell loss to degradation. Rate functions of growth, biomass estimation from length, shell production and more are taken from long-term James River assessment data, and shell loss to taphonomy is set at a single 30% per year. The tool is set as a 30-year progression with years 1 through 20 having user determined recruitment and years 21-30 as a "decay" period when no recruitment occurs. Shell accretion is one of the outputs. Recall that Mann and Powell (2007) argue for essentially a no net loss of shell habitat as a BRP for shell. The relevant output in the EXCEL tool is accretion rate – is it positive or negative? If the accretion rate is zero then the accompanying value of M sets the no fishing BRP in that M is adequate to supply shell to offset taphonomic loss. If M is below this value then accretion occurs in an undisturbed population. Fishing is permissible until (F+M) reaches the BRP equivalent to zero accretion rate. There is, however, a long term modifier to this scenario that requires attention in that a no net loss of shell or zero (not negative) accretion rate does not address the requirement to match sea level rise (if for example the desire is to maintain the reef relative to that moving standard) and/or sedimentation rates (reviewed in detail by Donoghue 1990, from 1 mm/y to as high as 10 mm/y in the upper bay). Finally, and not included in the EXCEL tool, is the requirement to consider the sediment:shell ratio in accreting reef structure. This is variable but proportionately increases accretion. Smith et al. (2003) describe the sediment – shell mix as a "matrix of **<** 75% loose shell" citing Cuthbertson (1988) and "other fine sediments" citing Bahr & Lanier (1981) and Bouma (1976). DeAlteris, (1988) comments that "The void space in an oyster shell reef is approximately 50% depending on the shell size. This space may be filled with fecal deposits that contribute to reef growth." Thus if the long term accretion rate to match sea level rise is 4.55 mm/y (taken from Mann et al. (2009) using a relative sea level rate of 3.5 mm/y corrected for 30% taphonomic loss), but the sediment:shell ratio in content of the reef substrate is 50:50, then the shell accretion rate as equilibrium with sea level rise is 2.275 mm/yr.

The purpose of the estimator is to provide a simple, framework to begin discussion of BRP's for Chesapeake Bay oysters employing data generated by assessment work to date and summarized in this report. The estimator should be viewed as a mechanism to identify components that are poorly understood quantitatively (for example how shell loss rates vary with (i) exposure versus burial or (ii) over a salinity gradient, and sediment shell ratios in extant reef systems) and appropriate for future investigation (see ToR#11).

ToR #8. Evaluate stock status with respect to the existing BRPs, as well as with respect to updated or redefined BRPs (from ToR #7).

Development of BRP's requires models that link population biology and shell substrate status. Unpublished and somewhat independent initial efforts by Powell in New Jersey for Delaware Bay, by Wilberg for MD and by Mann for James River oyster population suggest a Fmsy of 6-7%. These estimators require rigorous development to be valuable in longer-term projections, and developed tools must be sensitive to spatial heterogeneity.

As mentioned earlier, neither MD or VA have formal oyster BRPs in place, although long term trend data suggest both states have, perhaps by some element of default, arrived at effective management BRP's (gear, time etc. limitations) that provide stability.

ToR #9. Identify potential environmental, ecological, and fishing-related factors that could be responsible for low recruitment in future years.

These have in part been addressed in assembling ToR#11. Several major factors threaten future recruitment.

1. Climate change already influences over winter water temperatures in the Chesapeake Bay, and projections are for this ameliorating trend to continue. Expulsion of Dermo from infected oysters is facilitated by cold winter temperature. Conversely, warm temperatures accelerate proliferation of infected particles in spring months with implications for both reduced fecundity and/or spawning and/or recruitment, and even outright mortality of infected oysters.

2. Watershed activities that contribute to eutrophication of receiving bay waters threaten resident oyster populations. Increased nutrient loads not only drive oxygen depletion but also increased pH, the latter requiring dissolution of biogenic carbonate in benthic environments. Indeed, modest calculations suggest eutrophication far outweighs atmospheric CO2 increase as a driver of increasing acidity in the Chesapeake Bay.

3. The fishing industry has long been supported by shell planting programs in both MD and VA. Traditional sources of shell are from both commercial shucking houses and buried geological reef shells. Both sources are under threat. In MD the geological resource is effectively depleted. Current shell is sourced from geological deposits in Florida and transported by rail to MD shoreline sites for planting. The long-term nature of this arrangement is not assured. In VA there is a modest supply of geological reef shell but access is limited in terms of seasonal time windows to accommodate seasonal passage of anadromous fish. Sources from shucking houses are limited in that (a) shellfish companies are becoming increasingly diversified and participate in not just traditional shell planting on private leases in selected estuaries, (b) some of these companies have adopted substantial commitments to spat on shell operations to support their leased bottom plantings and (c) some companies choose to sell shells to private growers rather than State agencies. Finally, federal requirements for state match of appropriated funds in large-scale restoration efforts have resulted, at least in VA, in use of limited shell resources as "matching funds" for targeted restoration efforts that do not serve fisheries directly. These efforts would be better served by consideration of available alternative substrates that do not degrade by taphonomy. There is at this time a rapidly escalating price structure for shell from shucking houses, with prices having risen from $0.25 per bushel to as much as $3.00 per bushel in a decade. MD currently has a shell policy that directs State purchased shells to remote setting instead of placing shells on public fishery bars. This unquestionably limits shell planting in support of fisheries. As a footnote to this consideration, shell planting costs can generate

substantial revenue in terms of oyster production – current estimates for the Rappahannock River rotational fishery suggest a $7 return for every $1 invested in shell planting.

4. The resurgence of fisheries in both MD and especially VA in recent years has lead to a proverbial rush to obtain harvest licenses. In MD the number of harvest licenses has nearly doubled in five years. Consideration of adopting control dates would be advised simply as a precaution should the need for future implementation of limited access be required. Increasing at the dock prices for oysters in the national market (current prices are in the $40-45/bushel range) can threaten to drive overfishing effort with implications for both broodstock preservation and habitat stability when the latter is disturbed by intensive exploitation.

<u>ToR #10. Develop and apply analytical approaches and data that can be used for conducting single and multi-year stock projections and for computing candidate ABCs (Acceptable Biological Catch). Provide numerical short-term projections (1-5 years; through 2015). Each projection should estimate and report annual probabilities of exceeding threshold BRPs for F, and probabilities of falling below threshold BRPs for biomass.</u>

This is a worthy and lofty goal but illustrates the nascent nature of oyster population dynamics and quantitatively generated BRPs in the Chesapeake Bay fisheries. ABC is not a fishery term, it is a regulatory term. In pursuing the suggested projections there is a need to consider a range of assumptions about notable uncertainties in the assessments. Given the extreme variability in recruitment and disease, multi-year projections may not be tractable. Also, the ABC projection needs to be sensitive to the fact that the current survey implementation overlaps with the fishing season. There is no effective quota cap on fishing in either MD or VA. Thus longer-term projections should be based on a change in management actions.

Can we evaluate management strategies with the current data in hand? The personnel involved in the major part of the effort reported herein are not modelers, and a follow on effort might address the subject of ABC's if we can, for example, develop a model that runs a thousand simulations and takes an average as an academic exercise, then uses this computation to develop an ABC for sustainable harvest or target catch. The current report lists data uncertainties and, perhaps more so, lists data absences (such as age at length or the ability to estimate M and F with confidence) from the required base knowledge to generate BRPs. We need to generate matched BRPs for live oysters and shell, and understand how they will vary over the environmental gradients in the bay as a whole.

Only then can we adequately begin a rational investigation of the bays oyster stock's vulnerability to becoming overfished.

ToR #11. Identify, review, and prioritize future research needs (including to the extent practical, cost estimates).

The following are research needs identified by the assembled summaries. They are not prioritized, and neither should they be considered all inclusive. They are offered as a basis for future discussion and work.

1. Update the surveys for boundaries of the exploited oyster bars in both MD and VA. Without such data total population estimates in terms of both biomass and habitat (shell, carbonate, alkalinity) are compromised.

2. Improve harvester reports to obtain measures of overall catch per unit effort (CPUE) and fishing mortality (F) by location/region/river basin/ management area in both MD and VA. Electronic reporting will shortly become the standard reporting methods in MD, the same goal should be pursued in VA. Note that effort as a reporting metric (hours per day) is distinct from simple days in which catch was taken and landed.

3. Improve assessment methods #1: Develop a formal prospectus/protocol for the evaluation of side scan sonar use in oyster surveys. Extensive data sets already exist for side-by-side data comparisons as a desktop exercise at modest costs.

4. Improve assessment methods #2: An evaluation of random, fixed station and adaptive sampling regimes to optimize assessment data collection in the field in a limited sampling suite. This can be addressed initially as a virtual exercise by generating spatial distribution maps from extant survey data, and then sampling this virtual distribution by the described methods. This is a modest cost investment. Results can then be field tested with the goal of increasing survey precision without (a) increasing vessel time, and (b) compromising long term survey integrity. Analysis should included sensitivity of methods to sample number per designated region.

5. Improve assessment methods #3: The current report includes an encouraging section addressing inter-calibration of survey gear. This is both labor intensive and an ongoing need in that neither MD nor VA is planning to change assessment methods in the near future. The reported comparison purposely chose reefs of differing shell abundance and spatial heterogeneity, yet the resultant comparisons show common trends. Future bi-state efforts should include additional comparisons to include the variety of oyster habitats present in both MD and VA waters. Older

data sets, for example work by Rothschild et al (1991), should be revisited as part of this effort.

6. Explore a common treatment of the VA YOY data with MD YOY (spatfall) methods to develop a bay wide YOY Recruitment Intensity Index.

7. Develop age at length estimators for the Rappahannock River, and Pocomoke and Tangier Sounds in VA and the entire MD stock. Employ these to recast length demographic data as age demographic data. Length at age estimators should be continually revisited and updated as part of ongoing assessments. The current VA protocol employs large n values for demographic analysis that is blind tested against recruitment data. Such blind testing data is not available bay wide. Strong consideration should be given to employing isotope methods to age at length estimation.

8. Implement a regular program of updating the weight – length relationships in both state data sets in support of biomass and biomass index estimators. Both states employ weight - length conversions that are vintage and arguably limited in use. The current effort includes routine but modest collection of samples for biomass: shell comparisons (condition index for a limited suite of stations in VA to compare to disease data. A formal sampling structure with common methods should be developed for survey in both MD and VA. This is not an enormous additional effort but would provide a valuable data stream.

9. Compare box count data for total observed mortality estimates in both states using protocols employed in the MD surveys. The VA data stream exists, it has just never been examined by the proposed approach.

10. Examine age specific growth and mortality rates. Compare age based mortality rates (M) with (a) hind cast disease impact based on a bay-wide 6-point scale for Dermo; and (b) box counts for the above locations and in historic record. This effort should also include a retrospective on MSX, currently very modest in impact. A potential line of investigation is to employ force of infection modeling. MD sanctuary data can provide an estimate of M in the absence of F. The long-term data sets can be used to address such questions as "Can oysters recover or are they considered always diseased?". There is a long-term signal in how populations are responding to the disease challenge with the emergence of resistance. This poses yet another interesting question of where are we in the adaptation process, and how do we consider this moving baseline in a retrospective or even prospective analysis of the contribution of disease to mortality? The challenge is to integrate disease into population data. Note that disease models are much easier to develop when infected animals just get worse, but much harder to develop when animals can recover in any part. Most models assume that if you cannot detect a disease it is not there.

Thus a very low-level intensity but persistent prevalence presents modeling challenges.

11. Continue cross reading of a set number of stations for disease impact annually by MD and VA researchers to maintain a time series of data contributing to the bay-wide 6-point scale for Dermo.

12. Exploration of the stock-recruit relationship: consideration of the role of protandry, sperm versus egg limitation, and size demographics of contributing oysters. Data (mostly unpublished) are available to contribute to this need from prior NCBO awards.

13. Consideration of the roles of habitat dynamics and disease in the S/R relationship. Is this a modified sigmoid rather than a density independent relationship? This question is amenable to modeling using available data within defined environmental limits (mostly salinity), with the model then being used to explore the habitat component in low salinity situations. The impact of epizootics in Figure 6.4 is evident by following the temporal sequence of points. Epizootics influence the rate of shell addition to the underlying habitat; loss from the latter is driven by taphonomy. In the interim period the shell serves as an enhancement for recruitment process.

14. Examine the rates of exposed shell loss rate with respect to salinity in extant reef systems.

15. Explore the shell: sediment ratio in reef substructure and identify the range of taphonomic loss rates in extant reef systems in the Chesapeake Bay. Together with research need #14 (above) this critical to oyster fishery management, restoration activity and development of the alkalinity budget as a buffer to eutrophication induced increases in pH of benthic systems.

16. Develop a BRP for shell equilibrium with the assignment of required shell production rates to maintain reef topography commensurate with sea level rise. What ranges of M and F can support this need when recruitment is variable?

17. Examination of the recruit (YOY) versus total substrate and YOY versus live shell relationship. Why is this so spatially variable?

18. Effect a retrospective examination of tow volumes as an index of shell status in MD survey – this as a sister data set to the ongoing biomass index values.

19. Consider the role of alternate substrates in habitat maintenance and expansion of both harvestable bottom and sanctuaries. In a world of limited substrate availability the question has yet to be evaluated as to the returns in terms of both dollars and

ecological services of long-term investment of shell in either cultivation or restoration. The data in this report allow such debates to proceed in an informed quantitative manner with the understanding that sustainably managed fishery production is commensurate with stable and substantial provision of ecological services.

20. Archive the data in GIS format and a user-friendly format for inclusion in bay wide analysis and management actions. This project has underscored the valued nature of the long term oyster monitoring data sets in both MD and VA, yet this data is rarely requested in terms of contributing to debate on how watershed management actions influence receiving waters. Oysters are arguably the single largest producers of biogenic carbonate in the bay benthos and critical to the bay alkalinity budget (which affects all estuarine biota). The current project has driven review and consolidation of databases in VA. Those in MD are already well archived. While the VA data is web portrayed at two sites (http://www.vims.edu/research/units/labgroups/molluscan_ecology/vorhf/index.php and http://cmap.vims.edu/VOSARA/VOSARA_Viewer/VOSARA.html) it is not in an optimal GIS layer form for use in management processes. Given that the attendant text in the above cited web sites and this document form effective metadata for the overall assessment data sets the option to develop user friendly access should be explored. Finally, this development should include mechanisms for annual update as surveys continue.

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Appendices

Appendices A through G.. Summaries of harvest regulations (open periods), gear type and reported landings (buyer and harvester) by year for the following areas: (A) Tangier and Pocomoke; (B) Great Wicomico River; (C) Rappahannock River; (D) Piankatank River; (E) Mobjack Bay; (G) James River. There are no summaries for York, Elizabeth and Lafayette Rivers, which would have constituted Appendices F and H.

Appendix UMD : Paynter, K. T. Michaelis, SA, Lane, H. et al (2012) Oyster Population and Habitat Assessment, Harris Creek and the Little Choptank River: 2011 report.