Restoration Goals, Quantitative Metrics and Assessment Protocols for Evaluating Success on Restored Oyster Reef Sanctuaries

A Strawman Proposal from the Oyster Metrics Workgroup as convened by the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program.

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1. Introduction

Concerted efforts over the past two decades to restore oyster reefs to the Chesapeake Bay have met with mixed success (1-4). A recent review of oyster restoration activities in Virginia and Maryland pointed to the lack of clear goals, established metrics of success, consistent sampling protocols and sufficient monitoring as contributing to our uncertainty surrounding their success (5). Monitoring activity has generally not been well coordinated with restoration activity, and different entities involved in the monitoring have used different sampling gear, monitoring approaches and assessment protocols. Despite explicit objectives of restoring ecological functions and ecosystem services provided by oyster reefs, few measures beyond the number of market-sized oysters have been used to judge success.

Executive Order 13508 *Strategy for Protecting and Restoring the Chesapeake Bay Watershed* established a goal of restoring oyster populations in 20 tributaries of Chesapeake Bay by 2025, further adding to the need to develop clear restoration goals, quantitative metrics and assessment protocols. This document represents an effort by state and federal agencies directly involved in oyster restoration in the Bay to develop clear and consistent objectives, definitions, sampling protocols and assessment techniques pursuant to achieving this goal and evaluating success.

To address these issues the Sustainable Fisheries Goal Implementation Team (GIT) established a technical workgroup comprised of representatives from NOAA, USACE, MDNR, VMRC and academic scientists from UMCES and VIMS. The specific charge to the group was to develop common bay-wide restoration goals, success metrics and monitoring and assessment protocols for sanctuary reefs that include progress toward achieving a sustainable oyster population that ultimately will provide increased levels of ecosystem services. The charge for the group specifically excludes fisheries-specific metrics since it is limited to sanctuary reefs, though the oyster population metrics are certainly germane to fisheries management. It is also important to point out that the group was tasked with identifying a minimum suite of metrics that should be measured across all sanctuary reefs, particularly for the purpose of assessing progress toward the Executive Order oyster goal. We recognize that some sanctuary reefs will need to be monitored more intensely to address specific issues (research priorities, ancillary goals, etc.). The minimum suite of metrics laid out herein should in no way be seen as limiting such additional monitoring and research activity. The workgroup recognizes that future research will inform oyster restoration practices, and strongly encourages adaptive management in the restoration arena. We view this report as a science-driven consensus document meant to establish clear success metrics, sufficient monitoring levels and consistent sampling protocols given currently available technologies and scientific information. We expect that these goals will evolve as more information becomes available.

2. Restoration Goals

The overarching goal of restoring a large oyster population, capable of supporting a vibrant fishery and providing other valued ecosystem services throughout much the Chesapeake Bay drives specific management actions and targets, such as those set forth in E.O. 13508. The crucial fact remains, however, that oyster populations in the Bay have undergone a dramatic regime shift over the past half century and that high natural mortality rates associated with disease, predation and siltation, along with negative shell budgets (i.e. shell loss rates > shell accretion rates) in many areas, pose significant challenges to achieving a greatly expanded oyster population. Implicit in the goal of restoring 20 tributaries is the notion that working on a tributary scale will be necessary to achieve sufficiently large changes in oyster populations. Moreover, the cumulative effects of restoration activities are unlikely to be linear; that is, there is an expectation that it will be necessary to exceed several threshold values (e.g. in shell volume, larval supply and survival, disease tolerance, etc.) to achieve a regime shift that supports greater population abundance. Figure 1 provides a simplified depiction of this condition graphically and helps to make the point that restoration of oyster populations and the ecological functions that they provided to a higher level may require exceeding threshold improvements in environmental conditions.

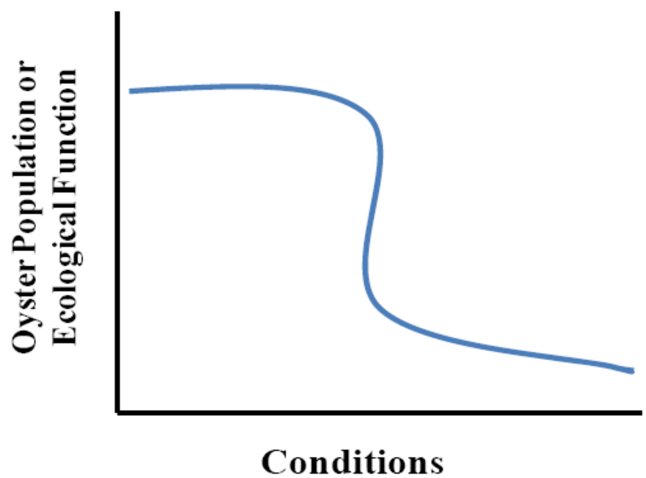

Figure 1. Generalized representation of multiple stable states and regime shift in which improvement in conditions (towards the left) must exceed a critical value to return the system to a stable improved state (upward).

2.1. Tributary-level restoration – Central to our task of developing clear goals and measures of success is establishing what constitutes restoration at the level of a tributary. Is the end product a population of a certain size? Or, is it a percentage of historical oyster habitats occupied by restored reefs? Are we seeking an operational definition related to the amount of restoration activity (shell, alternative substrate or seed planting) or a functional one in which a tributary is not restored until a greatly expanded, sustainable oyster population is achieved? These are not trivial issues to resolve. The workgroup spent substantial time considering these issues and it is important to review a number of caveats before setting final targets.

It seems evident that the intent of setting a goal of restoring oysters to 20 tributaries by 2025 is to undertake restoration at a sufficiently large scale to dramatically increase oyster populations and realize enhanced ecosystem services at a tributary-wide scale. The workgroup discussed this intent at length, defining it as a functional goal. *Specifically, the goal of oyster restoration at the tributary-level is to dramatically increase oyster populations and recover a substantial portion of the ecosystem functions provided by oyster reefs within the tributary.* In effect the goal is to return to the higher plateau represented in Figure 1. As restoration proceeds, the workgroup believes that it is essential that these functional goals remain the primary target.

Exactly what will be necessary to achieve these functional goals is unknown. Simply stated, it has not been done previously. We lack both an empirical and theoretical basis for knowing how much oyster reef restoration is necessary within a given tributary to reach our functional goals. Our underlying assumption is that achieving this goal will require the *successful functional restoration* of a significant proportion of the historical oyster reefs within a tributary. As discussed in the following section, many years of post restoration monitoring will likely be necessary to determine successful functional restoration at the reef level. Additionally, there are several practical limitations on the scale of restoration that can be undertaken within a given tributary, including available restorable areas, the extent of private leases and designated fisheries bars, the availability of shell, and limits on the amount of spat-on-shell production. Each of these is discussed briefly below.

Despite the ultimate goal of functional restoration success, restoration goals at the tributary level will need to include *operational goals*, e.g., the amount of shell planted or the quantity of spat-on-shell or the number of bars planted. The agencies and organizations involved in restoration must set operational targets for planning and staging their work. It is necessary, therefore, to establish target levels for restoration activity within a tributary that constitute operational or intermediate measures of success that facilitate restoration planning and implementation. Unfortunately, there is no clear answer to how much oyster reef habitat within a tributary should be targeted for restoration. Comparing detailed surveys by Winslow in Tangier Sound (6) and by Moore in the James River (7) with the more general Yates (8) and Baylor (9) surveys in Maryland and Virginia, respectively, USACE estimated that approximately 40% of the areas included in the Yates and Baylor surveys were hard oyster habitat. Further, typical Marine Protected Areas range from 20-70% of a species home range (10). As sessile organisms, oysters would likely fall on the low end of this range, 20-40%. Combining these two pieces of information, USACE has projected that 8-16% (40x20% to 40x40%) of historic (Yates and Baylor) habitat needs to be restored in a tributary to affect a significant change.

"Restorable areas" are considered to be areas of hard bottom that will support shells or alternative substrates deposited on the bottom in a restoration effort (i.e. they will not sink into mud or silt) and appropriate water quality. The amount of reasonably restorable area varies considerably among tributaries. Surveys of oyster bars conducted during the late 19th and early 20th Centuries provide our base maps for historical oyster distributions (6-9). The most recent comprehensive survey of the condition of the Maryland Bay Bottom was conducted between 1974 and 1983. More recent surveys (11, 12) have attempted to characterize the currently-viable habitat and estimate habitat loss. In Maryland, a recent estimate suggested that less than 10% of the areas formerly classified as supporting oysters currently have suitable substrate for oyster restoration (12). In Virginia, surveys conducted in the 1980's suggested that only about 20% of areas formerly classified as oyster bars were viable (11, 13). These estimates do not necessarily precisely characterize the amount of bottom area that is suitable for restoration, but they do make the point that conditions at many of the historical oyster bars are not currently favorable for conducting oyster restoration. In Virginia, an Oyster Restoration Atlas (14) has been developed by VIMS and VMRC, which incorporates the most recent substrate maps, the boundaries of public and leased oyster grounds, bathymetry and salinity in relation to current and potential restoration sites on a tributary by tributary basis. These maps not only target areas that are suitable for restoration, but make it quite clear that many areas are either not suitable or not available by nature of being privately leased. For instance, the Piankatank River has only a very limited area that is included in the public oyster grounds and much of the shallow-water habitat is held in private leases. Other areas, like the upper James River, have extensive public oyster reefs but have a long-standing role as part of the public fishery and are unlikely to be included within a sanctuary for restoration. In Maryland, the Native Oyster Restoration and Aquaculture Development Plan designates some areas to be established as sanctuaries and others for aquaculture development, with other areas open to fishing. The combination of these factors results in widely varying restoration potentials among tributaries, ranging from tributaries such as the Piankatank River where all of the potential areas that can reasonably be restored have already been planted with shell, to Harris Creek on the Choptank that looks like a strong candidate for targeting intensive restoration, to others where perhaps planting shell on a significant portion of the historical bars or all of the sites identified as suitable for restoration would require more shell than is available throughout the region. It is clear that tributaries will need to be selected for restoration based upon numerous criteria, including the amount of area suitable for restoration and how this area compares to the historic extent of oysters. Those with too little suitable area offer little chance for improvement, and those with too much are likely intractable.

These considerations lead us to recommend that tributaries slated for oyster restoration be carefully selected as those adequate in size to be meaningful, but not of a scale that is so large as to exceed reasonable expectations with available resources. Large-scale, tributary based oyster restoration is in its infancy. Techniques and methods are only beginning to be identified and are largely untested at this scale. With this in mind, as well as recognized funding and resource limitations, it is recommended that small tributaries (creeks and small rivers) receive initial focus. (See Appendix A for Chesapeake tributaries that fall into this size category). Thus, tributaries on the scale of Harris Creek and the Honga River in Maryland or the Great Wicomico and Piankatank Rivers in Virginia provide a better starting point for tributary-level restoration than, say, the entire Choptank, Potomac or James Rivers. However, it may be reasonable to target geographically distinct sub-segments of such larger tributaries for focused oyster restoration and still be consistent with the E.O. goal. Tributaries need to be further evaluated on the amount of available habitat that is suitable for restoration and the reality of establishing and maintaining the restoration sites as sanctuaries (See Appendix B for an example analysis)
In accordance with this analysis, the workgroup suggests that an operational goal of restoring a 50 -100% of currently restorable oyster habitat represents a reasonable target for tributary-level restoration. In selecting a tributary for focused restoration, it is also essential to consider its historic oyster bottom. As mentioned previously, USACE has projected that 8-16% of historic oyster bottom habitat needs to be restored in a tributary to affect a significant change. *Thus, an ideal candidate tributary is one where 50-100% of the currently restorable bottom is equivalent*

to at least 8% of its historic oyster bottom. Appendix B shows an example of how a target tributary may be analyzed toward these criteria.

Final judgments about the ultimate success of these activities in catalyzing a regime shift to greatly enhanced, sustainable oyster populations may not come until many years after the actual restoration activities are completed. Functional success metrics for gauging the ultimate success of these efforts are discussed in sections below.

2.2. Reef-level restoration – Oyster restoration activity (planting of substrate or spat-on-shell) takes place at the level of an oyster bar (=reef). Again, however, we lack clear definitions of either operational or functional success at this level. Complete failure is easily observed as a lack of recruitment to planted shell, high mortality of planted seed, or the degradation and burial of shell before a population becomes established. Success, on the other hand, can be harder to define and quantify. Do we define operational success in restoring a reef only after 100% of that reef area has been planted with shell, alternative substrate or spat-on-shell? Or, is some lesser coverage sufficient? Is functional success achieved only when a threshold abundance of oysters (e.g., 100 oysters m^{-2}) is established, or a target value of an ecosystem service (e.g., 500 kg N removed $hectare^{-1}$ yr^{-1}) is reached? And, what is the time course over which this success is to be judged? Each of these requires some resolution if progress towards achieving the goal set forth in the E.O. is to be tracked in a consistent manner. We attempt to provide some clarity on these issues below.

Establishing operational success metrics is an imperative. Restoration activity on an individual bar must have a target value at the implementation phase. Do we target planting shell, alternative substrate or spat-on-shell on 100% of the bar before we consider our current activity at that bar complete or do we target planting 50% of the area, for instance? A relevant consideration here is that in their unexploited state oyster beds in the Chesapeake Bay did not exist as vast uniform reefs, but rather varied considerably in shape, size and degree of bottom coverage (6, 7, 15-17) with "hard-rock" and "mud-shell" areas occurring within an oyster bed (18). Practical considerations of planting techniques in current restoration practices also play a role in variable coverage of oysters on a reef. Thus, it seems apparent that restoration of an oyster bar should target planting something less than 100% of the historical bar area. Unfortunately, we have only limited information on which to base specific recommendations for the amount of coverage that should be targeted with shell, alternative substrate or spat-on-shell plantings. Figure 2A shows an aerial view of intertidal oyster reefs in the coastal bays along Virginia's Eastern Shore. Individual patch reefs, typically 2 – 3 m^2 in area are separated by 1 – 4 m and larger scale patterns of reef distribution appear to the reflect flow patterns. We do not suggest that this pattern is typical of all subtidal reefs within Chesapeake Bay, but use it to illustrate that in a natural, seemingly healthy and stable oyster population that oysters do not cover 100% of the bottom within an area that might reasonably be termed a reef. Historical accounts from subtidal reefs in the Chesapeake Bay indicate that "reefs", even during the early phase of heavy exploitation, were not uniformly covered in oysters, but included extensive areas without oysters (6, 7). A lack of complete coverage of the bottom is also evident in planting techniques currently in use (Fig. 2B, C) for planting shell and spat-on-shell in Virginia and Maryland, respectively. There are two distinct reasons to establish minimal planting coverage operational targets – (1) to provide guidance on how much planting should be planned for a particular reef and (2) to establish a consistent approach to reporting the aerial extent of operationally restored reefs.

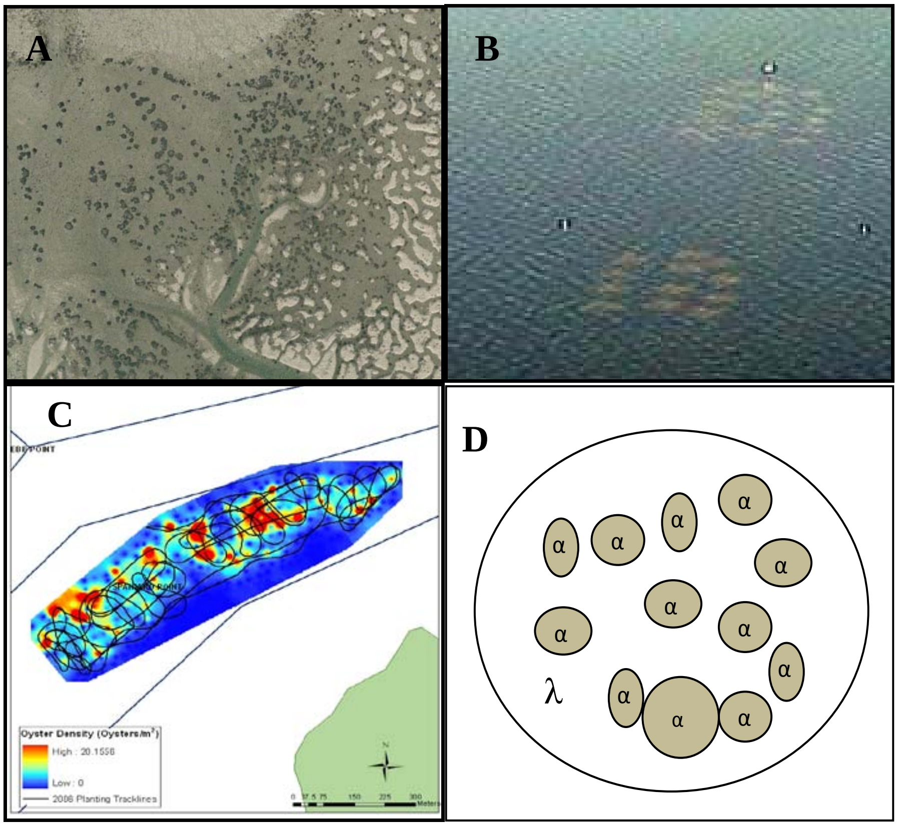

Figure 2. Shell and oyster coverage on natural and restored reefs: (**A**) Intertidal patch reefs in the VA coastal bays; (**B**) Shell plants in mounds in the Rappahannock River; (**C**) Track lines from seed planting and oyster densities on a restored reef in the Chester River; (**D**) Idealized reef of area λ

Figure 2D depicts an idealized situation in which **λ** represents the area targeted for restoration and the α_i's represent the areas in which oyster shell or spat-on-shell have been planted. Thus, we suggest that some value of $(\sum_{i=1}^{n} \alpha_i)/\lambda$ greater than 0 and less than 1 should be the target of restoration activity on a reef. In lieu of a more rigorously defined value, we suggest that at this time a minimum target of 0.3 for this ratio or 30% coverage of a reef be set as an operational practice. *That is, shell planting and spat-on-shell should result in a minimum of 30% of coverage of the restoration reef*[1].

[1] This recommendation is not intended to suggest that restoration activity should select a region of the target area that is only 30% of the total and concentrate shell or spat-on-shell planting only in that region. Rather, it is a recognition that even a natural or fully restored reef is not a monolithic structure fully covered in oysters and shell. 30% is intended only as a minimal acceptable coverage within the area that was actually planted.

Operational targets for the oyster population size and structure within these planted areas also need to be established. Again, however, we lack a clear empirical or theoretical basis for setting these targets. We follow a few guiding principles in developing some tentative recommendations in this area. The first, and most compelling, is that our concept of a reef as a biogenic structure is unlikely to be achieved at very low densities of oyster (< 10 and perhaps 20 adult oysters/m^2). Indeed, the persistence of the reef itself is dependent upon densities above some minimal level. A positive shell budget will require sufficient numbers of oysters accreting at a rate that exceeds current sediment deposition and shell degradation rates, a condition that Mann and Powell (2) have pointed out is not currently achieved with many restoration efforts. In a successful modeling study of oyster populations in the James River, Mann and Evans (19) assumed, based upon a previous empirical study (20), that at a density of 100 oysters/m^2 fertilization efficiency was still less than 10%. Because oysters are largely protandric hermaphrodites, with most larger, older individuals being females, achieving high reproductive success may require that multiple ages classes are present to ensure adequate numbers of males and females. A second area of guidance in developing oyster density or biomass targets comes from studies of ecosystem services provided by oyster reefs. Though we lack quantitative relationships between oyster density and the various ecosystem services that we are seeking to recover via restoration, the studies to date that have documented such services have, to our knowledge, done so on reefs with densities well above 20 adult oysters/m^2 (e.g., 21-35). Though a firm basis for establishing density and age structure targets is lacking, *the workgroup tentatively recommends that a density of 50 oysters/m^2 and 50 grams dry weight /m^2 containing at least 2 year classes, and covering at least 30% of the reef area provides a reasonable target operational goal for reef-level restoration.* An oyster density of 50 adults/m^2 over 30% of the bottom is comparable to the median oyster density in Maryland 100 years ago, 10-15 oysters/m^2 (and 10-15 g dry wt/m^2) over an entire oyster bar (36).

However, even reefs with much lower densities than this target may still be viable, provide some level of ecosystem services, and could serve as spat settlement substrate in out years. Thus, for the purpose of consistently tracking progress toward the E.O. goal, the *workgroup recommends a <u>minimum</u> threshold for a successful reef as a density of 15 oysters/ m^2 and 15 grams dry weight/ m^2 containing at least two year classes, and covering at least 30% of the reef area.* Reefs that meet this minimum threshold will be considered minimally successful for the purposes of track E.O. goal progress, although the higher target density is greatly preferable. For reference, it is helpful to note that one gram of dry weight is approximately equivalent to one three-inch oyster.

As noted above, a viable oyster reef must maintain a non-negative shell accretion rate (2). The basic tenet here is that structure should at a minimum be maintained, or ideally grow, from a post-restoration baseline to allow for continued reef persistence. Restored structure to date generally consists of either shell mounds or alternative substrates (rock, crushed concrete, reef balls, etc.). Tracking the height, aerial extent, and shell budget on these areas over time is critical to understanding whether the structure is growing, maintaining, or subsiding. Factors contributing to structural growth include natural spat set, oyster growth, set and growth of other hard-shelled organisms, and maintenance plantings of shell or seed oysters. Factors contributing to subsidence include initial construction on unsuitable bottom (ie, post-construction subsidence into muddy bottom), shell dissolution in excess of accretion, illegal harvest and improper dredge activity. Thus, the workgroup recommends as *a structural goal that shell accretion, reef height, and reef aerial extent should remain neutral or increase from a post-restoration baseline.*

Meeting operational targets does not, of course, ensure functional success of the restoration. The reality exists, however, that it may not be possible to determine functional success until several years after the initial restoration activity. The ultimate goal of restoring a reef is that it will persist as part of a larger *self-sustaining* population, with new substrate accruing or keeping pace with shell loss and providing desired ecosystem services. Limited success at achieving this goal at a greatly enhanced population level on a system-wide basis has led to the new emphasis on a tributary-scale approach to the problem with the hope that this will overcome some of the problems in the past. In the near-term an intermediate goal of *sustainable* reefs (for which some ongoing intervention, such as shell or spat plantings may be repeated every few years) is more realistic than entirely self-sustaining reefs. *On a time horizon of 2 – 10 years following restoration activity, we suggest that a stable or positive shell budget, stable or increasing oyster biomass and multi-year class age distributions represent reasonable goals.* Monitoring, employed in an adaptive management approach, can inform the need for additional restoration activity on specific reefs following initial restoration activity to meet this intermediate goal. NOAA's Chesapeake Bay Office houses a database called the Oyster Data Tool. The workgroup recommends that all monitoring data collected toward tracking the reef-level and tributary-level goals laid out herein be reported into this Bay-wide tool as a mechanism of tracking progress toward the E.O. goal of restoring 20 tributaries.

2.3. Ecosystem services and ecological function – Oyster restoration efforts in the Chesapeake Bay and elsewhere in the U.S. have been motivated over the past two decades as much by the desire to recover lost ecological functions and ecosystems services provided by oysters and the reefs they build as by the desire to rebuild fisheries. Several studies over the past few years have demonstrated that healthy or restored oyster reefs provide enhanced ecosystem services over unrestored or non-reef habitats, including the growth rate of seagrasses (28), the abundance, biomass and diversity of reef resident organisms (24, 25), the abundance, biomass and diversity of nekton (22, 29-33), water quality improvement (26, 37, 38), nutrient cycling (27, 38, 39) and shoreline stabilization (35). Setting specific targets for any of these ecosystem services or ecological functions as quantifiable goals for oyster restoration face several practical constraints. First, we lack both a historical basis and appropriate current reference sites to set targets for most ecological functions of interest. We currently do not know, for instance, how much fish production or denitrification was associated with historical oyster reefs in the Chesapeake Bay or how much would be associated with fully restored reefs in the present. Second, we cannot quantify the level of any of these services provided by a restored reef by sampling on reefs alone. The quantity of an ecosystem service (e.g., increased water clarity or enhanced blue crab populations) provided by a reef or a series of reefs in a tributary cannot be determined from sampling only on restored reefs, but requires comparisons to appropriate references areas in a well conceived BACI (Before-After-Control-Impact) design. Even in the uncommon situation when appropriate reference sites are available, the effects of restored oyster reefs on ecosystem services may be confounded by many other factors in the watershed and water body. We nevertheless appreciate the importance of evaluating the ecosystem services provided by oyster restoration activities and including these in our determinations of success. Thus, we outline an approach in the sections below on Assessment Protocols for estimating the ecological services provided by restored oyster reefs based upon combining the findings from experimental and/or modeling studies with routine reef monitoring.

3. Assessment Protocols

Evaluating reef-level restoration success minimally requires the determination of several parameters: (1) structure of on of the restored reef (aerial extent, reef height and shell accretion), (2) population density (as individual abundance and biomass) and (3) a total reef population estimate (biomass). Although measurement of the first two and calculation of the third parameters are straightforward, they have been the source of some consternation in the past, so we will first clarify the issues before making specific recommendations.

3.1. Reef area, height, shell accretion, and surface complexity – Original reef boundaries in the Chesapeake were mapped in the late 19th Century by using techniques such dragging a chain or probing the bottom with a pole (6-9). These techniques were adequate for coarse identification of broad areas with shell and oysters; however, it was recognized at the time (6, 7) and has been subsequently verified that these approaches did not accurately represent either the boundaries of the reefs or the heterogeneity within a reef. The practical implication of this today is that neither the Yates nor the Baylor surveys serve as appropriate benchmarks for scaling restoration targets.

Current-day techniques for assessing reef structural metrics include acoustic mapping, patent tong samples and aerial imagery. Acoustic mapping is a powerful tool for obtaining detailed topographic and textural information about bottom habitats, thus it is ideal for measuring reef height, area and structural complexity consecutively and with the highest resolution. However, it cannot be used in shallow areas and needs to be combined with groundtruthing to distinguish shell from live oysters. Patent tong samples coupled with high resolution GPS data can be used to map reef perimeters, but large samples numbers are required to accurately define the reef perimeter. Additional survey methods would also need to be utilized to acquire reef height and surface complexity. For shallow water reefs where acoustic mapping may be inefficient or impossible, aerial photography can provide an accurate means of assessing reef area (see Fig. 2B or the Google Earth image of the Hume Marsh reefs in the Lynnhaven River at 36°53'26.47"N, 76° 5'6.15"W), though this approach requires groundtruthing as well. On these reefs height can be obtained using a rod and level method and surface complexity can be determined via string or chain transects.

Quantitative samples taken for oyster population measures by patent tong or diver can be used to measure volume. Recommended assessment methodology for measuring and tracking shell accretion on subtidal reefs is by patent tong. During surveys for oyster populations, retrieved shell volume can be measured in each tong grab. Shell quality can also be subjectively judged in several ways including an estimation of 'anoxic' or black shell vs. 'oxic' or brown shell. Expectations would be that shell volume surveyed in this way would reflect general decline, maintenance or increase over time.

The most appropriate method or combination of methods for assessing reef area will vary by region and reef types. The important point is that accurate determination of total reef area is, in particular, critical to estimating the amount of restored area, oyster population abundance and ultimately the quantity of ecosystem services provided by oyster restoration. *Determination of reef area, height, and shell accretion should be an integral part of the assessment of restoration success on sanctuary reefs.*

3.2. Quantitative density estimates – There is historical precedent in portions of Chesapeake Bay for estimating oyster abundance based upon timed dredge tows and there are widely recognized limitations to this approach including unknown sample area and a dependence of gear capture efficiency on sample volume (39,40). Density estimates obtained in this manner are usually expressed as numbers of live oysters per bushel of shell, but conversion to numbers of live oysters per unit bottom area have also been developed by Rothschild and colleagues (42). It was not in the purview this workgroup to design sampling protocols for oyster fisheries assessment, so we will leave it to others to determine the appropriate of sampling technique for that use. *However, we categorically recommend oyster density estimates on sanctuaries and other protected reef restoration sites be obtained from quantitative grab samples*. These samples may be obtained from quadrat samples excavated by divers or obtained by patent tongs or, in shallow-water and intertidal sites, by direct access. We point out, however, that the capture efficiency of quadrat grabs and tongs is less than 100% and that there is the need for careful calibration of these techniques.

Monitoring costs by any of the methods above can be high, especially when there are large areas to be assessed. Thus, there is often pressure to keep sample replicates to a minimum. Accurate estimates of mean abundances in highly patchy populations nevertheless can require large sample sizes. Determining the relationship between sample number and sample variance will aid in determining the optimal number of samples that should be collected on each reef. It is important to keep in mind that without reasonably accurate population estimates on each restored reef, parameters such as growth, mortality and recruitment cannot be followed over time allowing the analysis of trends toward improvement or degradation, nor can any insight be discerned as to the causes of degradation such as disease, poor water quality or sedimentation.

Greater confusion has occurred in recent years regarding the inclusion of grab samples that do not include oysters into estimates of mean density. This uncertainty arises because oyster reefs (even natural healthy ones) are not monolithic structures with oysters located everywhere within what we would define as the reef perimeter (see Fig. 2 and discussion in Section 2.2). Thus, as we assess progress towards restoring (and conserving) reefs, we need to come to grips with the fact that restored area does not precisely match the area with oysters. This situation is particularly well is illustrated in Figure 2A which shows an area with intertidal patch reefs. The currently available information suggests that this represents a fully developed reef complex which is comparable in aerial extent and density (though perhaps not oyster size and biomass) to historical reefs in the region. Estimating the mean density of oysters on these individual patch reefs (which average 2 – 3 m^2 in area) is straightforward, requiring only that we obtain adequate numbers of quantitative samples from randomly-selected individual patch reefs over the area. The point of disagreement that has arisen is over how one determines either the total population size or the total area of restoration from these samples.

3.3. Oyster population assessment – In the intertidal situation represented in Figure 2A, the total population size of oysters in the reef complex is easily estimated as the product of the mean density on patch reefs and the total area of the individual patch reefs, because we can clearly count and measure the individual patch reefs within the area. Similarly, if the parameter of interest is the mean density of oysters over the entire flat that contains the reef complex, then we need only divide this total population estimate by the area of the entire reef complex (including those barren areas between the patch reefs). The challenge emerges in subtidal reefs were obtaining a clear picture of the distribution of oysters prior to sampling is more difficult and costly. High resolution side-scan sonar, coupled with extensive groundtruthing samples has the potential to provide this information. *If current, verified maps of fine-scale reef distribution are available prior to quantitative density sampling, then sample allocation may be directed at those locations only and total population size estimated as in the intertidal example above*. In the more generalized case in which predetermined high precision maps of oyster density or habitat quality are available, Wilberg (pers com) has shown that stratified random sampling (STRS) provides a more accurate estimate of total oyster abundance than a simple random sampling (SRS) across the region. In the STRS scenario, areas within the reef that are devoid of oysters (like the intertidal situation discussed above) are not sampled and regions within the reef of high, medium and low habitat quality are sampled in a stratified random design (see Fig. 2C for a map of a reef exhibiting these conditions). This approach provides the most accurate estimate of the true population abundance with the fewest required sample replicates (Wilberg, pers com). The problem, of course, is that this method is dependent upon the available of high resolution maps reflecting the current reef conditions prior to sampling. Although ideally these maps would be available, to date such detailed knowledge about the underlying distribution of oysters on a reef have not always been available to guide sampling. When the underlying distribution of oysters (or even oyster habitat) within a restored reef are unknown or not known with sufficient accuracy, then a stratified sampling design is not possible. In this case two approaches have generally been used: systematic and random sampling. A systematic survey will provide information on both the population and its distribution across the target area. If distribution is not important, an SRS will suffice for population estimate and coverage. The number of samples required will be determined by the variance of the grabs and should be adjusted to reduce the variance of the sample population to the point where additional grabs will only minimally affect the variance.

The data from either systematic or SRS surveys can be treated in different ways to calculate population size on the reef. In one the mean density of oysters in all grab samples (including zeros) taken within the target restoration area is multiplied by the entire target area. In the other, the percentage of grabs containing oysters can be used as a simple estimate of reef coverage (i.e. if 50% of the grabs contain oysters, the target area would be considered to be 50% covered by the restoration effort) and the total abundance of oysters on the reef computed the mean density of oysters in the samples (exclusive of zeros) multiplied by the percent coverage and the target area. The two approaches are mathematically equivalent.

The workgroup is recommending that at least of 30% of the target area be covered by 15 oysters/m^2 <u>and</u> 15 g dry weight/m^2 three years after restoration as a minimum threshold goal.[2] Higher coverage with lower mean densities does not qualify. Higher abundances without 15 g

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[2] Note that this calculation is based upon average density of only those samples which contain oysters. In the case in which zeros are included and oysters are present in only 30% of the samples the minimal target values would be 5 oyster and 5 g dry weight for the means over the entire area.

dry weight/m^2 does not qualify, nor does >15 g dry weight/m^2 with fewer than 15 oysters/m^2. The workgroup believes the literature supports the establishment of a combination of minimum biomass, abundance and coverage for restoration to be deemed successful.

3.4. *Assessment Frequency*- The question ‘At what point in time can we call a reef restored?’ is not an easy one, but the workgroup believes it is an essential part of our initial charge to come to consensus on this for the purpose of tracking progress toward the E.O. goal.

The recommended minimum assessment intervals for reef-level goals is established at 1) post-restoration activity to establish baseline (within 6 to 12 months of restoration activity); 2) again at three years post-activity; and 3) again at 6 years post-activity. More frequent/ intensive monitoring will likely be required, and is highly encouraged, on some restoration projects to facilitate, for example, research projects or ancillary goals. The above intervals are established only as *minimum* frequencies for assessment, and are in no way meant to preclude more frequent monitoring. The initial post-restoration assessment is essential for establishing a baseline against which to evaluate future project success. The three-year point is critical to allow for adaptive management. If, for example, a project shows at this point signs of needing additional seed or shell, a management decision can be made to do so to increase the likelihood of success. Conversely, the decision may be made that the project was poorly constructed, poorly sited, used inappropriate materials, etc., and that continued investment is ill advised. By consensus, this workgroup establishes the six-year assessment as a reasonable point at which to determine whether a reef is ‘successful’ for tracking progress toward the E.O. goal.

3.5. *Ecosystem services and ecological function* – In Section 2.3 we indicated that monitoring alone would not be sufficient for assessing the level of ecosystem services provided by a restored oyster reef. Because this is an important concept, we will explain this assertion further and then recommend an assessment strategy that we believe is appropriate. Most of the ecological functions and ecosystem services that we desire from a restored oyster reef are affected by a great many other factors. For instance, water clarity is affected by terrestrial inputs, phytoplankton dynamics and meteorological conditions, among other things. Thus, measuring changes in water clarity in a tributary and attempting to link those changes to oyster restoration success is highly problematic. Indeed, even as an increasing oyster population filters more water, changing land use practices could cause water clarity to decline. Similarly, measuring utilization of a restored reef by finfish does not account for numerous other factors (e.g., recruitment, natural mortality and fishing mortality) that may be affecting regional population size. Comparisons to a nearby non-reef control sites may overcome some of these uncertainties; however, such a monitoring scheme quickly becomes intractable to do at all restoration sites.

A much more tractable approach is to make use of the results from targeted monitoring programs, controlled experiments and modeling studies to develop generalizable relationships between characteristics of an oyster reef (e.g., reef size, oyster abundance, oyster biomass, reef complexity or other measures) and the quantity of various ecosystem services. For instance, if a carefully designed study was to estimate:

$$\text{Biodeposition} = f\,(\text{reef size, oyster biomass, background TSS}),$$

then routine monitoring of reefs at other sites together with measurements of TSS could be used to estimate biodeposition provided by those reefs. Similarly, if a controlled, replicated experiment was used to generate a relationship between the numbers (or biomass) of oysters on a reef and the amount of nest sites for resident finfish associated with the reef, then routine monitoring of oyster population characteristics described above could be used to estimate potential finfish production associated with restored reefs in varying conditions. As a final example, if controlled, replicated experiments were employed to quantify nitrogen fluxes from the sediment as a partial function of oyster biomass (as well as temperature and seston concentrations), then routine monitoring data could be used to estimate nitrogen fluxes.

Apart from the obvious benefits of feasibility, this approach towards evaluating success of reef restoration relative to ecosystem services provides a means of estimating the amount of ecosystem services provided by restored reefs that vary in their success. That is, a reef with 100 g dry weight biomass m^{-2} may provide 20-times the nitrogen removal capacity of an unrestored reef, while a reef with only 10 g dry weight biomass m^{-2} may provide 5-times the removal capacity.

Determining such relationships will require carefully designed monitoring, experimental or modeling studies conducted over the next several years. We are careful here not to identify specific ways in which these relationships should be determined acknowledging that it will require creative studies by various investigators. As long as those studies equate absolute or relative values of ecosystem services to quantitative metrics related to the oyster population or reef characteristics that are being measured as part of a routine monitoring program, then they will provide the best means available of assessing success in this area. *Funding these types of studies will be neither cheap nor politically popular, but we emphasize that they are the only reliable means of quantitatively assessing the ecosystem services associated with reef restoration and they are <u>much less expensive</u> than attempting to directly measure ecosystem services on all restored reefs.*

4. Evaluating Success

As stated previously, success in oyster restoration efforts will need to be evaluated on several levels over varying spatial and temporal scales. Targets and metrics of operational success are required to guide restoration activity, such as what percentage of a historical bar or other area should be planted with shell or spat-on-shell. Monitoring of individual reefs following initial restoration activity will be required to determine success at various stages by evaluating recruitment success, early post-settlement or post-planting survival, natural mortality, disease status, growth, reproduction and shell accumulation. Evaluating success at the tributary level likewise will need to involve operational definitions about the amount of area within the tributary that needs to be rehabilitated and functional measures of the status of those areas several years after the restoration activity. Equating reef characteristics to ecosystem services provides a means of estimating the quantity of those services provided; however, success in this regard is probably best determined in a cost-benefit analysis that compares the gain in ecosystem services to the costs of constructing and maintaining the reef at a particular state. Table 1 summarizes the goals, assessment protocols and success metrics that we have discussed above.

Table 1. Summary of goals, assessment protocols, assessment frequency and success measures

Goal	Assessment Protocol	Minimum Assessment Frequency	Success measure
Operational Goals			
Reef-level goal: Shell, alternative substrate or spat-on-shell should cover a minimum of 30% coverage throughout the target reef area.	Patent tong or diver grabs	Within 6-12 months of restoration activity	1. Verify that the appropriate amount of substrate and/or spat-on-shell was planted. 2. Confirm the presence of substrate and/or spat-on-shell within the target area.
Tributary-level goal: A minimum of 50% of currently-restorable area with a given tributary meets the reef-level goals defined above.	GIS-based analysis of restoration activity within the tributary	Annual	1. Verify that the appropriate amount of area within the tributary has met reef-level operational goals.
Functional Goals			
Reef-level goals:			
Significantly enhanced live oyster density and biomass	Patent tong or diver grabs	Minimum 1, 3 and 6 years post restoration	Minimum threshold: An oyster population with 15 oysters and 15 grams dry wt biomass/m^2 covering at least 30% of the target restoration area at 3 years post restoration activity. Target: An oyster population with a minimum of 50 oysters and 50 grams dry wt/m^2 covering at least 30% of the target restoration area at 3 years post restoration activity. Evaluation at 6 years and beyond should be used to judge ongoing success and guide adaptive management.
Presence of multiple year classes of live oysters	Patent tong or diver grabs	Minimum 3 and 6 years post restoration	A minimum of 2 year classes at 6 years post restoration.
Positive shell accretion	Quantitative volume estimates shell (live and dead) per unit area	Minimum 1, 3 and 6 years post restoration	Neutral or positive shell accretion.

Table 1. (cont.)

Goal	Assessment Protocol	Minimum Assessment Frequency	Success measure
Stable or increasing reef height and aerial extent	Multi-beam sonar, direct measurement, aerial photography	Within 6 -12 months and 3 and 6 years post restoration	Neutral or positive change in reef surface complexity from baseline
Tributary-level goals:			
Expanding oyster population beyond the restored reefs	Quantitative assessment of oyster populations throughout the tributary.	Will need to be determined from future assessments.	Will need to be determined as restoration proceeds.
Return of the oyster population within a tributary to an enhanced stable state.	Quantitative assessment of oyster populations throughout the tributary.	Will need to be determined from future assessments.	Specific targets will need to be developed on a tributary-specific basis as restoration proceeds.
Enhanced ecosystem services in the tributary	Determine relationships between structural reef characteristics (e.g., reef size, oyster abundance, or oyster biomass) and the quantity of various ecosystem services via controlled experiments and modeling studies. Then, use measured values of structural metrics to estimate levels of specific ecosystem services.	Currently unknown	Currently unknown. Specific targets will likely be informed by the results of experiments relation ecosystem services to structural metrics.

Appendix A: River Size Class (from TNC)

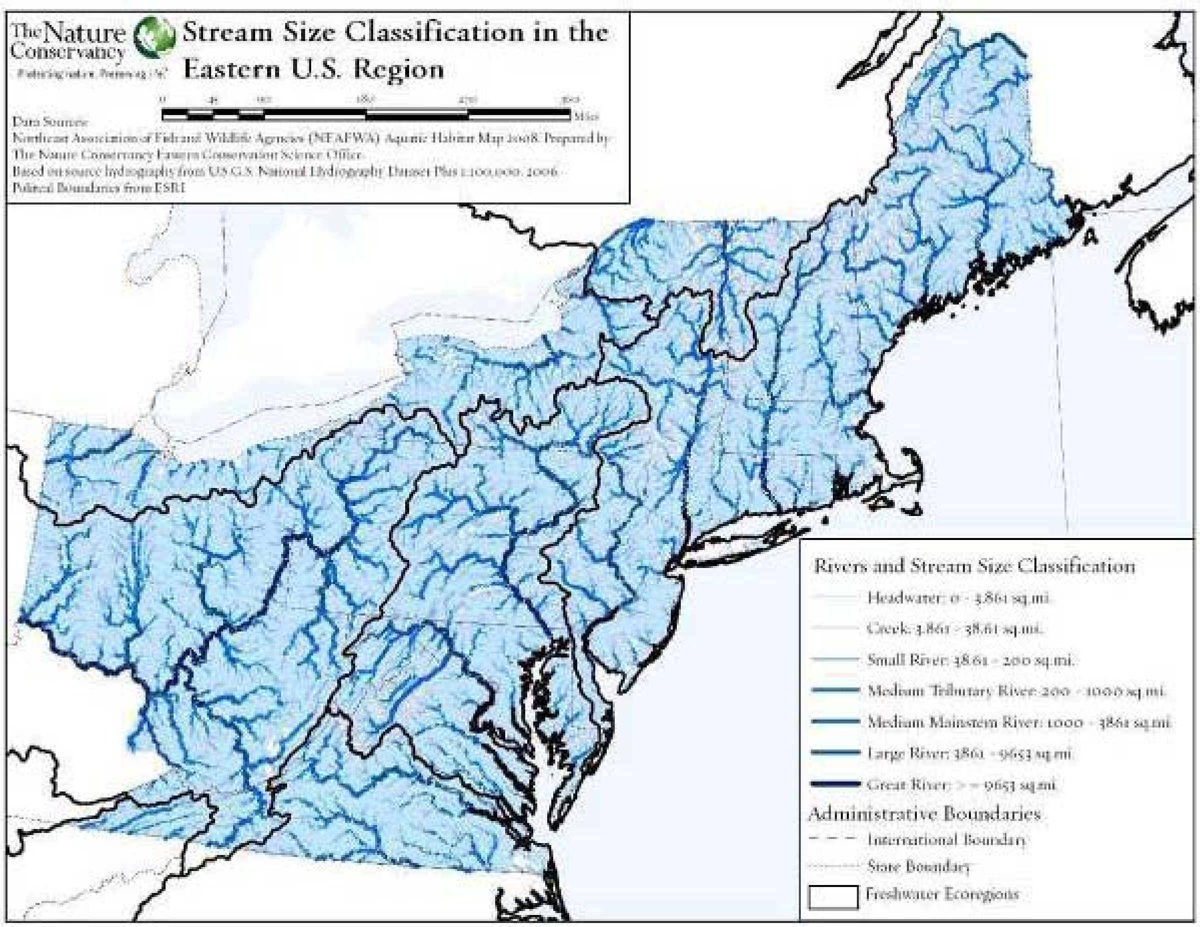
The Nature Conservancy has developed a stream size classification for the eastern U.S. as outlined below:
1a) Headwaters (<3.861 sq.mi.)
1b) Creeks (>= 3.861<38.61 sq.mi.)
2) Small River (>=38.61<200 sq. mi.)
3a) Medium Tributary Rivers (>=200<1000 sq.mi.)
3b) Medium MainstemRivers (>=1000<3861 sq.mi.)
4) Large Rivers (>=3861 < 9653 sq.mi.)
5) Great Rivers (>=9653 sq.mi.)
(measure = upstream drainage area)

The size breaks were initially developed as part of TNC's Northeast Aquatic Stream classification project for the Northeast Association of Fish and Wildlife (NEAFWA) (http://rcngrants.org.spatialData) (See Figure below). The stream classification is regional and is appropriate to apply across the northeast region and within the Chesapeake Bay watershed. All 13 northeast states participated and contributed to its development. According to TNC, the classification has been used in a number of regional projects for planning and reporting. The table below shows the application of the stream classification to the tributaries of the Chesapeake Bay.

Tributary	TNC classification		Tributary	TNC classification
MARYLAND			***VIRGINIA***	
Chester River	medium trib		**James River**	great river
Corsica River	Small river		Elizabeth River	small river
Choptank River	medium mainstem		Nansemond River	medium tributary
Broad Creek	Creek		**Pocomoke Sound**	(medium tributary)
Harris Creek	Creek		**Rappahannock River**	medium mainstem
Little Choptank	Small river		Corrotoman River	small river
Eastern Bay	Small river		**York River**	medium mainstem
Patuxent River	medium trib		Back River	small river
Potomac River	great river		Cherrystone Inlet	small river
St. Mary's River	small river		Cockrell Creek	creek
Tangier Sound	(small river)		Great Wicomico R.	small river
Big Annemessex River	small river		Hungars Creek	creek
Fishing Bay	medium trib		Little Wicomico R.	creek

Little Annemessex River	small river
Manokin River	small river
Monie Bay	(small river)
Honga River	small river
Magothy River	small river
Rhode River	creek
Severn River	small river
South River	small river
West River	creek

Lynnhaven Bay	small river
Mobjack Bay	(small river)
Nandua Creek	creek
Nassawaddox Creek	creek
Occohannock Creek	creek
Old Plantation Creek	creek
Onancock Creek	creek
Piankatank River	small river
Poquoson River	small river
Pungoteague Creek	small river
Severn River	small river



Appendix B: *analysis of Harris Creek under development*

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