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REVIEW ARTICLE

Guidelines for evaluating performance of oyster habitat restoration

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Restoration of degraded ecosystems is an important societal goal, yet inadequate monitoring and the absence of clear performance metrics are common criticisms of many habitat restoration projects. Funding limitations can prevent adequate monitoring, but we suggest that the lack of accepted metrics to address the diversity of restoration objectives also presents a serious challenge to the monitoring of restoration projects. A working group with experience in designing and monitoring oyster reef projects was used to develop standardized monitoring metrics, units, and performance criteria that would allow for comparison among restoration sites and projects of various construction types. A set of four universal metrics (reef areal dimensions, reef height, oyster density, and oyster size–frequency distribution) and a set of three universal environmental variables (water temperature, salinity, and dissolved oxygen) are recommended to be monitored for all oyster habitat restoration projects regardless of their goal(s). In addition, restoration goal-based metrics specific to four commonly cited ecosystem service-based restoration goals are recommended, along with an optional set of seven supplemental ancillary metrics that could provide information useful to the interpretation of prerestoration and postrestoration monitoring data. Widespread adoption of a common set of metrics with standardized techniques and units to assess well-defined goals not only allows practitioners to gauge the performance of their own projects but also allows for comparison among projects, which is both essential to the advancement of the field of oyster restoration and can provide new knowledge about the structure and ecological function of oyster reef ecosystems.

Key words: ***Crassostrea virginica*, criteria, eastern oyster, ecosystem services, monitoring, Olympia oyster, *Ostrea lurida*, reefs**

Implications for Practice

- Requests from restoration practitioners for a set of specific monitoring guidelines tiered to account for limitations in budgets and expertise in oyster restoration projects have been fulfilled by a panel of scientific experts and restoration practitioners.
- Oyster restoration projects should monitor established universal metrics primarily focusing on structural attributes (vertical relief of oyster reefs, oyster density, and spatial footprint over time); specific minimum requirements for timing of monitoring are essential.
- Measurement of broader ecosystem-based metrics would allow for more thorough examination of specific ecological benefits of restoration projects.
- Detailed methodology provided publicly through a workshop report gives restoration practitioners access to training material and reporting information.

Introduction

Marine biogenic habitats such as salt marsh (e.g. Kennish 2001), seagrass (Orth et al. 2006; Waycott et al. 2009), oyster (e.g. Beck et al. 2009, 2011), and mangrove (Alongi 2002;

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Spalding et al. 2010) habitats have suffered significant declines on national and global levels. The degradation and loss of these habitats is a serious conservation threat as it impairs vital ecosystem functions such as providing nursery habitat for ecologically and economically valuable fish and invertebrates, regulating nutrients, stabilizing shorelines, and increasing biological diversity (for a recent review, see Powers & Boyer 2014). Among these threatened habitats, the decline of oyster habitats in the United States, as well as globally, has been well documented (see Beck et al. 2009, 2011; Wilberg et al. 2011; zu Ermgassen et al. 2012), with degradation primarily driven by factors such as overharvest, changes to hydrology and salinity regimens, pollution, and disease. Oyster restoration efforts have historically focused on oyster fisheries enhancement; however, in recent decades, there has been an increasing recognition of a broad array of ecosystem services provided by oyster habitats. These services include the production of fish and invertebrates of economic and ecological significance, water quality improvement, removal of excess nutrients from coastal ecosystems, and stabilization and/or creation of adjacent habitats such as seagrass beds and salt marshes (e.g. Peterson & Lipcius 2003; Grabowski & Peterson 2007; Grabowski et al. 2012). This has prompted many agencies and conservation organizations to change their focus to restoring oyster habitat for these broader ecological functions as the primary or exclusive goal(s) of oyster restoration projects (e.g. Coen et al. 2007; Beck et al. 2011).

Restoration efforts in various other marine habitats have yielded important insights about ecological function of those habitats. For example, restoration projects in salt marsh and mangrove habitats have demonstrated the importance of species interactions and the need for diverse species assemblages, and seagrass restoration projects have demonstrated the importance of genetic diversity in transplants (Hughes & Stachowicz 2004; Reusch et al. 2005; and as discussed by Beck et al. (2011) and Powers and Boyer (2014)). Despite these advances in restoration practices, many oyster habitat restoration efforts suffer from a lack of clearly defined goals and are often not monitored post-construction to an extent that allows for adaptive management, determination of whether stated goals have been successfully achieved, and/or comparison between projects. Studies that have revisited previous restoration efforts are often hindered by a lack of basic descriptive information (location, original configuration) and have only been able to examine rudimentary performance metrics (e.g. Powers et al. 2009; La Peyre et al. 2014). Kennedy et al. (2011) demonstrate the pervasiveness of these problems in their recent review of available data from oyster restoration activities conducted by state, federal, and non-governmental agencies from 1990 to 2007 in Chesapeake Bay. This review found that the restoration goals of the projects were often ill-defined and that monitoring was performed for relatively few of the restoration projects (Kennedy et al. 2011). In addition, after analyzing the available data, Kennedy et al. (2011) were unable to answer basic questions concerning the overall success of restoration projects, the influence of scale on success, long-term trends in success, and the occurrence of oyster disease resistance in natural and selectively bred stock used in restoration efforts. They stressed the need for oyster habitat restoration projects to include clearly stated goals as well as quantitative prerestoration and postrestoration monitoring with adequate replication and sample sizes.

To address the lack of consistency and limited extent of monitoring of oyster habitat restoration projects, a working group of restoration scientists, practitioners, and funding agencies was formed with the goal of developing monitoring guidelines, including standardized metrics, well-defined performance criteria, and recommended monitoring techniques. The working group was led by a steering committee composed of scientists from the University of South Alabama (USA), Florida Atlantic University (FAU), The Nature Conservancy (TNC), and the NOAA Restoration Center (NOAA RC), and included broader participation by staff from TNC, the NOAA RC, as well as restoration scientists from universities from the Atlantic, Gulf, and Pacific coasts. A working group convened in 2011 in Silver Spring, Maryland, provided valuable input on drafts of the resultant guidance handbook (Baggett et al. 2014; available at www.noaa.gov, www.oyster-restoration.org, and www.conservationgateway.org). The efforts of previous workshops of various federal, state, and local organizations (e.g. Coen et al. 2004; NOAA RC 2007; OMW 2011; Boswell et al. 2012) and previous restoration guidance documents (e.g. Thayer et al. 2003, 2005; Coen et al. 2004; Brumbaugh et al. 2006; CSCC 2010) served as the basis for discussions at the 2011 workshop and provided an important foundation for the 2014 handbook. Although previous efforts had produced more general recommendations or site selection guidance, or were specific to a particular region or species, participants at the 2011 workshop endeavored to identify those metrics and associated performance criteria that would be sufficiently general to provide national guidance for monitoring oyster restoration projects across an array of construction methods, tidal elevations, oyster species (i.e. *Crassostrea virginica* or *Ostrea lurida*), and regions. The ultimate goal of this national guidance is to enable the comparison of restoration projects within and across tidal elevations, regions, and construction types, and to provide practitioners with valuable information that would aid in future restoration efforts as well as in the adaptive management of ongoing restoration projects. A draft of the handbook was presented at several national and regional conferences, and posted online for broad review and comment. Subsequent drafts benefited greatly from the valuable input received from restoration scientists and practitioners, fisheries managers, and scientists and policymakers from local, state, and federal entities. An overview of the recommendations developed by the working group and presented in the national "Oyster Habitat Restoration Monitoring and Assessment Handbook" is presented here.

Recommendations

Assessing the performance of a restored oyster habitat involves evaluating the persistence of the restored habitat as well as the effectiveness of the restored habitat in meeting any explicitly stated ecosystem service-based restoration goals. Therefore, the working group developed a set of universal metrics to be monitored for all restoration projects, regardless of their stated goals. Monitoring of the universal metrics would allow for the assessment of the basic performance (i.e. habitat persistence, and oyster recruitment and abundance) of all oyster restoration projects. In addition, restoration goal-based metrics were developed specific to commonly cited ecosystem service-based goals of oyster restoration projects. A set of universal environmental variables were also developed that should aid in the interpretation of data collected during both preconstruction and postconstruction monitoring. Guidance is also provided for an optional set of ancillary monitoring considerations that may further aid in data interpretation and provide supplemental and/or more detailed information concerning project performance and could possibly be beneficial to future restoration efforts (readers are referred to Table 1 for descriptions of the categories of recommended parameters to be monitored and related terms, and Tables 2 and 3 for a listing and brief description of the universal metrics and universal environmental variables, respectively, and Table S1 (Supporting Information) for a listing and brief description of the restoration goal-based metrics). In general, it is recommended that the metrics be assessed at both the short-term (1–2 years postconstruction) and mid-term (4–6 years postconstruction) time frames. In addition, prerestoration monitoring of appropriate metrics and variables should be conducted when applicable.

Definition of Restoration

For the purposes of these recommendations, restoration was defined as “the process of establishing or reestablishing a habitat that in time can come to closely resemble a natural condition in terms of structure and function” (modified from Turner & Streever 2002). Activities involving the construction of new oyster habitats of various materials (natural or man-made) and/or those that seek to return degraded natural or previously restored oyster habitat to its prior condition are covered under this definition. Restoration conducted solely for the purpose of harvest (e.g. put and take placement of cultch; Coen & Luckenbach 2000) is not included in this definition. For ease of use, the terms “restored reef” and “oyster reef” include both intertidal and subtidal oyster habitats, as well as habitats consisting of oyster reefs (as with *Crassostrea virginica*) or low-relief oyster beds (as with *Ostrea lurida*). An oyster habitat (i.e. an oyster reef or bed) is defined as patches of living and nonliving oyster shell (or reef substrate with and without live oysters).

Universal Metrics and Rationale

Of the many questions related to restored oyster habitat performance, perhaps the two most basic, and the most important, questions are as follows: (1) is the restored habitat persisting over time? and (2) are there sufficient densities of living oysters present in the restored habitat? Without living oysters and the structure provided by them (or project construction material), the project cannot truly be viewed as having achieved “success” or providing one or more of the desired ecosystem services. Based on these two fundamental requirements of a functional oyster habitat, four universal metrics are proposed to be sampled for every oyster restoration project, regardless of the stated restoration goal(s): (1) reef areal dimensions, (2) reef height, (3) oyster density, and (4) oyster size–frequency distribution. The reef areal dimension metric has two components: project footprint (a measure of the maximum areal extent of the footprint of the reef) and reef area (the total actual area of patches of living and nonliving oyster shell or substrate with and without live oysters located within the project footprint). The reef areal dimension metric, along with the reef height metric, allow for the assessment of the development and persistence of the reef structure through time and provide valuable information as to the realized habitat provided for associated resident and transient vertebrate and invertebrate species. The oyster density and size–frequency distribution metrics provide information on the size of the oyster population, recruitment, and survivorship occurring on the reef at the time of census. It is important to note that some states include oyster biomass as a target metric for restoration projects, and practitioners should be aware of and adhere to any monitoring requirements specific to their state. For a brief description of methodology, preferred units, and sampling frequency for each universal metric, refer to Table 2.

Restoration Goals/Associated Metrics and Rationale

Based on the ecosystem services provided by oyster habitats (Coen & Luckenbach 2000; Grabowski & Peterson 2007; Grabowski et al. 2012) and those commonly cited as oyster restoration goals, monitoring and performance assessment guidance was provided for the following ecosystem service-based restoration goals: (1) brood stock and oyster population enhancement (on nearby nonrestored reefs); (2) habitat enhancement for resident and transient species; (3) enhancement of adjacent habitats; and (4) water clarity improvement. For a brief description of methodology, preferred units, and sampling frequency for each restoration goal-based metric outlined below, refer Table S1.

Brood Stock and Population Enhancement. The deployment of oysters, either as spat-on shell or individual larger juvenile seed oysters, is a common component of oyster restoration projects meant to jumpstart restoration efforts or to help alleviate recruitment limitation (Brumbaugh & Coen 2009). The aim is to increase brood stock, thus enhancing initial oyster populations and ultimately increasing the larval supply to nearby oyster habitats (e.g. Southworth & Mann 1998; Lipcius et al. 2008). Another aspect of brood stock and population enhancement is the deployment of disease-resistant strains with the intention that the oyster populations will have lower mortality from diseases such as MSX and Dermo and contribute potentially disease-resistant progeny to the larger landscape. Because the effects of brood stock enhancement on the restored reef are measured by the oyster density and size–frequency distribution universal metrics, this restoration goal focuses on the effects of brood stock enhancement on nearby nonrestored reefs. Although connectivity between restored and

Table 1. Categories of recommended parameters to be monitored and related terms.

Category/Term	*Definition*
Metric	A measurement used to quantify a characteristic of a habitat.
Variable	A physical or environmental factor that is subject to change and may impact the area of study.
Universal metrics	Metrics that should be sampled for every restoration project, regardless of its restoration goal.
Universal environmental variables	Variables that will aid in data interpretation and should be measured for every restoration project.
Restoration goal-based metrics	Metrics that are specific to ecosystem service-based restoration goals and are not sampled for every project. They may be considered for projects citing a particular restoration goal.
Ancillary monitoring considerations	Optional metrics that may be monitored to obtain additional beneficial information associated with restoration performance.

Table 2. Universal metrics. dGPS = differential Global Positioning System.

Metric	*Methods*	*Units*	*Frequency*	*Performance Criteria*
Reef areal dimension				
Project footprint	Measure maximal aerial extent of reef using dGPS, surveyor's measuring wheel or transect tape, or aerial imagery; subtidal, use sonar or SCUBA.	m^2	Preconstruction, within 3 months postconstruction, minimum 1–2 years postconstruction; preferably 4–6 years. After events that could alter reef area.	None
Reef area	Measure area of each patch reef dGPS, surveyor's measuring wheel or transect tape, or aerial imagery; subtidal, use sonar or depth finder with ground truthing. Sum all patches to get total reef area.	m^2	Preconstruction, within 3 months postconstruction, minimum 1–2 years postconstruction; preferably 4–6 years. After events that could alter reef area.	None
Reef height	Measure using graduated rod and transit, or survey equipment; subtidal, use sonar or depth finder.	m	Preconstruction, within 3 months postconstruction, minimum 1–2 years postconstruction; preferably 4–6 years. After events that could alter reef area.	Positive or neutral change
Oyster density	Utilize quadrats. Collect substrate to depth necessary to obtain all live oysters within quadrat, and enumerate live oysters, including recruits. If project involved the use of seed oysters, enumerate all seed oysters present in quadrat.	ind/m^2	Immediately after deployment if using seed oysters. Otherwise, annually at the end of oyster growing season (will vary by region), 1–2 years at minimum; preferably 4–6 years.	Based on short- and long-term goals developed using available regional and project-type data, as well as current and/or historical local/regional densities.
Size–frequency distribution	Measure shell height of at least 50 live oysters per oyster density sample.	mm (size), number or % per bin (size dist.)	Annually at the end of oyster growing season (will vary by region) in conjunction with oyster density sampling, at a minimum.	None

nearby reefs can be difficult to demonstrate without large-scale hatchery deployments and related genetic analysis, two metrics are proposed that could provide some insight into possible connectivity when compared with off-reef preconstruction data: (1) off-reef oyster density and associated size–frequency distributions; and (2) off-reef large oyster abundance. The first metric provides information about the possible contribution of spat to nearby habitat by the restored habitat; however, caution must be exercised in the interpretation of these data when attempting to draw direct connections without more extensive genetic analysis or modeling of local larval supply dynamics. Densities of large oysters are often of interest because of their increased contribution to reproduction (i.e. size–fecundity relationships) and because they represent a possible source of larval recruitment to the restored habitat. For *C. virginica*, the large designation (>76 mm in shell height) is based on the

Table 3. Universal environmental variables.

Metric	*Methods*	*Units*	*Frequency*
Water temperature	Measure above substrate close to reef using in situ instrumentation, a thermometer, or other handheld instrumentation.	°C	Continuous (preferred), otherwise as often as possible.
Salinity	Measure above substrate close to reef using in situ instrumentation, a refractometer, or other handheld instrumentation.	ppt or psu	Continuous (preferred), otherwise as often as possible.
Dissolved oxygen (subtidal only)	Measure above substrate close to reef using in situ instrumentation or handheld instrumentation.	mg/L	Continuous (preferred), otherwise as often as possible.

commonly used market size of 3 inches, whereas the large designation for *O. lurida* is defined as greater than 35 mm in shell height.

Habitat Enhancement for Resident and Transient Species. Numerous fish and invertebrate species, including many that are economically or ecologically important, utilize subtidal and intertidal oyster habitats as sites for shelter, feeding, attachment, and/or reproduction (e.g. Breitburg 1999; Coen et al. 1999; Harding & Mann 2000; Peterson et al. 2003). As such, habitat enhancement is a commonly cited goal for oyster habitat restoration projects (Peterson et al. 2003). Although stated oyster habitat enhancement goals are sometimes specific to a species (e.g. red drum, striped bass, and blue crabs) or faunal group (e.g. finfish, waterbirds, and decapod crustaceans), more often they are broad or vague. As previously mentioned, restoration goals should be specific so that the project's performance in meeting the stated goal(s) can be properly assessed; therefore, one metric, density of selected species or faunal groups, is proposed to assess habitat enhancement goals when compared with measures from control or reference site(s). The selected target species will vary by project and should be based on each project's stated restoration goal(s). For example, if a stated goal was to provide habitat for striped bass, then the practitioner only need to quantify striped bass; however, if a stated project goal was to increase total biodiversity of finfish, then all finfish species present should be quantified. Density data can also be used in conjunction with species-specific growth rates and associated age-specific survivorship data to estimate the per-unit-area enhancement of fish or large mobile decapod crustacean production that can be expected from the restored habitat (see Peterson et al. 2003; Blandon & zu Ermgassen 2014). Practitioners may also measure wet weights (or even body length and width as appropriate for taxa) of target species when collecting the density data. In addition to quantifying desirable target species, practitioners may also quantify other taxa such as non-native species, potential competitors, or predators.

Enhancement of Adjacent Habitats. The ability of intertidal and subtidal oyster habitats to lessen erosive hydrodynamic forces from currents, tides, and natural or anthropogenic-derived waves, and thus protect, stabilize, and even possibly promote the expansion of nearby vegetated habitats, has been documented (e.g. Meyer et al. 1997; Piazza et al. 2005; Scyphers et al. 2011). Because of their shoreline protection benefits, as well as their other ecosystem services, constructed oyster reefs are increasingly incorporated into "living shoreline"-type shoreline protection and restoration projects as breakwaters meant to reduce wave action and promote sediment deposition inshore of the reef. To evaluate the effects of oyster restoration projects on adjacent shorelines, three metrics are proposed: (1) shoreline loss/gain (i.e. change in shoreline position); (2) shoreline profile/elevation change; and (3) density and percent cover of marsh (or mangrove) plants. Together, these measurements provide practitioners with information regarding the degree to which the restoration project may be influencing sediment deposition or erosion on adjacent flats and shorelines. Any impact that the restored reef may have on adjacent marsh or mangrove habitats is quantified by comparison of the marsh plant (or mangrove) density metric with control (without oyster reef present) or reference marsh site(s). Practitioners may also want to consider monitoring the presence/coverage of submerged aquatic vegetation and/or wave energy and tidal water flow when evaluating the impact of oyster restoration projects on adjacent habitats.

Water Clarity Improvement. The improvement of water clarity through oyster (or other bivalve) filtration activities and its potential beneficial impacts on nearby benthic habitats is well documented in the primary literature (e.g. Peterson & Heck 2001; Newell & Koch 2004; Grizzle et al. 2006; Grizzle et al. 2008; Wall et al. 2008; Booth & Heck 2009) and, as such, water clarity improvement is often cited as a goal for oyster habitat restoration projects. Of the various methods used to assess water clarity, the use of one or both of the following parameters are proposed: (1) seston and/or chlorophyll *a* concentration; and/or (2) light penetration. These metrics should be measured up- and down-current of the reef, as well at several points on the reef. Oyster habitats can also affect coastal biogeochemical cycles, and practitioners are encouraged to measure these effects if they have the means and expertise to do so (see Piehler & Smyth 2011; Carmichael et al. 2012; Kellogg et al. 2013).

Universal Environmental Variables and Ancillary Monitoring Considerations

The performance of oyster habitat restoration projects may be impacted over both the short term and long term by physical environmental parameters present at a given restoration site. To aid in the interpretation of data gained during preconstruction and postconstruction monitoring, three universal environmental variables (water temperature, salinity, and dissolved oxygen) should be monitored for every oyster habitat restoration project in conjunction with the universal metrics. Data from these variables may help explain trends in the universal metrics data as well as identify any potential impacts on the performance of restored habitats. For a brief description of methodology, preferred units, and sampling frequency for each universal environmental variable, refer to Table 3.

In addition, several ancillary metrics were identified that practitioners may want to consider monitoring to further aid in the interpretation of universal metrics data and the overall trajectory of the restoration project. These metrics are not essential to evaluating the basic performance of a project, but can be important because they provide data that can help to improve subsequent efforts or play a role in adaptive management. These optional ancillary monitoring considerations include (1) presence of predatory, pest, and/or competitive species; (2) disease prevalence and intensity; (3) oyster condition index; (4) gonad development status; (5) sex ratio; (6) shell volume for determination of shell budget; and (7) percent cover of reef substrate (this differs from the reef areal dimensions metric because it is a measurement of the percent coverage, rather than the area, of living and nonliving oyster substrate present and is meant to provide a quick visual estimate of the habitat available for oyster settlement and information concerning smaller-scale patchiness within the larger reef footprint).

Performance Criteria

Performance criteria are generally defined as tangible, quantifiable objectives to be achieved within a specified timeframe and must include a target value and associated time frame for each monitored metric. Setting such specific performance criteria is crucial to evaluating the persistence of the restored habitat and degree to which oyster habitat restoration projects have met their stated ecosystem service-based goals. However, the wide variation in project design (including tidal elevation and reef design), construction materials, and regional and species-specific characteristics and considerations make the adoption of any set of universal performance criteria unfeasible. Specific performance criteria should be set on a per-project basis and based on applicable current and/or historic local and regional data. Because habitat performance will change as a given restoration project develops from early to later stages, it was proposed that habitat performance be assessed at both the short-term (the minimum monitoring period of 1–2 years postconstruction often dictated by funding) and mid-term (the preferred minimum monitoring period of 4–6 years postconstruction) time frames and that practitioners anticipate how the project will be performing at these time frames when setting their goals. Assessing performance at the short-term time frame will provide insight into the establishment of the habitat as well as valuable information concerning the possible need for adaptive management. The mid-term time frame is more of an ecological time frame by which the habitat can be assessed, as the reef should be well established by this point.

Comparison to Control and Reference and BACI. When developing performance criteria for short- and mid-term goals, practitioners should frame their goals as testable hypotheses so that project performance may be determined using appropriate statistical analyses. Data gained from preconstruction and postconstruction monitoring at control and/or natural reference sites allow for the testing of these goal-based hypotheses. Comparisons to control and/or natural reference areas are best performed using a BACI (Before-After-Control-Impact) experimental design (Stewart-Oaten et al. 1986; Underwood 1994; Geraldi et al. 2009), which entails concurrent monitoring at a control and/or natural reference site(s) (i.e. control) and the restoration project site (i.e. impact) both before and after the construction of the oyster habitat. Preconstruction monitoring should be conducted at all sites (the project site and the control and/or reference sites) for at least 1 year prior to project construction, and postconstruction monitoring should be conducted at all sites long enough to encompass the short-term (1–2 years) and mid-term (4–6 years) postconstruction time frames. In general, control sites whose characteristics are most similar to the proposed project site provide the best reference. In areas where healthy unimpacted natural oyster habitat is present, it may be more desirable to compare the restored oyster habitat to a nearby existing natural habitat that is not subject to harvest and has physical characteristics similar to that of the restoration site. Comparison of the restored habitat to control site(s) will allow for determination of the degree of enhancement resulting from the project, and comparison to natural reference sites will determine if the restored habitat is performing at the level of a healthy natural habitat. It is imperative that control and natural reference sites have physical characteristics (e.g. depth, substrate, tidal inundation, current and wave action, salinity, proximity to open water, air and/or water temperature, and freshwater influence) similar to the restored site so that assessed similarities and differences between the project and control and/or natural reference sites can be attributed to the restoration activities as opposed to any physical or environmental differences. When performing preconstruction and postconstruction sampling at all sites, it is important that there is consistency in sampling season (e.g. at the end of the growing season), that there is adequate replication in sampling efforts, and that data are reported using the required units and with a mean and variance so that comparison can be made among projects.

Setting Basic and Goal-Specific Performance Criteria. The proposed universal metrics and their associated performance criteria will permit evaluation of the basic performance of a given restoration project to be assessed based on: (1) the persistence of emergent structure, (2) the density of oysters on the reef, and (3) the evidence of successful recruitment (Coen et al. 2004;

Burrows et al. 2005; Powers et al. 2009). Measurements of reef height (in relation to the natural bottom substrate) and areal dimensions will provide information on the short-term (months) and long-term (years to decades) persistence and condition of the constructed habitat. Restored and natural oyster habitats are subject to a number of factors that may affect their overall dimensions and persistence. Decreases in reef area and height during the months to years after construction may be caused by the spreading of cultch, sedimentation, subsidence, shell degradation by taphonomic sources (e.g. Powell et al. 2006), or a combination of these factors (summarized in Coen et al. 2011). Over the long term, increases in reef height could occur through the accretion of shell material, and would be indicative of an oyster habitat with healthy rates of oyster recruitment, growth, and natural mortality (e.g. Powell & Klinck 2007; Rodriguez et al. 2014). Because of the various factors affecting oyster reef area and height that are not directly correlated with oyster population gain or loss, there are no universal performance criteria for the reef areal dimensions metric, and the performance criteria for the reef height metric is a positive or neutral change in reef height from the original structure. Measurements of oyster density and associated size–frequency distributions can provide valuable information on oyster recruitment, survival, growth, and mortality on restored oyster habitats. Because of the great variation in natural oyster densities among oyster species and along the range of habitats and regions in which oysters are present, restoration goals and associated performance criteria for oyster density must be established on a per-project basis. In addition, potential oyster densities will differ based on the stage of habitat development and, as such, this along with the degree of oyster seeding (if any) should be considered when setting short- and mid-term goals. When establishing oyster density goals, practitioners should consider the full range of available data that are applicable to their particular project location, including current and historical density data from natural, nonharvested habitats (but see cautionary discussion of historical data by Hobbs and Norton (1996), Hobbs and Harris (2001), and Powers and Boyer (2014)). Numerous data sources are available regionally through state fisheries management agencies and practitioners, and consultation with local and/or regional experts can determine target oyster densities that are best suited for their restoration project. In addition, several compilations of regional and national, historic and current oyster density data (zu Ermgassen et al. 2012) are available. There is a high degree of variability in oyster densities among regions and tidal elevations, and interannual and local spatial variability in oyster larval supply and presettlement and post-settlement survival is high. To acknowledge this variability, the performance criterion for recruitment is defined as evidence of successful recruitment during at least 2 years of a 5-year period.

As with the universal metrics, performance criteria for metrics associated with ecosystem service-based restoration goals must be established on a per-project basis, and stated as testable hypotheses with regard to data gained from either onsite preconstruction monitoring or preconstruction and postconstruction monitoring at control and/or natural reference sites. Also, as with the universal metrics, the stage of habitat development will influence the degree to which ecosystem services are provided and, as such, performance criteria should address how the restored habitat is predicted to perform at both the short- and mid-term time frames. A restoration project that had a goal of improving water clarity, for example, could have the following performance criterion: "We predict that seston levels will be significantly lower at the restoration site than at the control site at both the short- and mid-term monitoring milestones under comparable conditions."

The recommendations for metrics and performance criteria contained here and in the related guidance handbook (Baggett et al. 2014) are meant to provide a more standardized way by which to assess performance of oyster restoration projects, and are not meant to discourage practitioners from monitoring any additional metrics deemed important or those required by their state or funding entity. The adoption and widespread application of the monitoring and performance guidelines outlined here, along with any additional monitoring efforts, are necessary to improve the practice of oyster restoration and ensure future investments in restoration are based on a continuously expanding body of knowledge.

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herein. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Metrics for ecosystem service-based goals in oyster restoration projects.

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