# A Guide to Olympia Oyster Restoration and Conservation

**ENVIRONMENTAL CONDITIONS AND SITES THAT SUPPORT SUSTAINABLE POPULATIONS**

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Smithsonian Institution
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Coastal Conservancy
National Estuarine Research Reserve System
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# Contents

## Synopsis

*This guide identifies key environmental conditions that affect Olympia oysters. A qualitative evaluation of 28 embayments along much of the range of the species identifies the areas at risk due to low population sizes or unreliable recruitment, and characterizes patterns of exposure to stressors. The most frequently encountered stressors were sedimentation and predation. Competition, cold water temperatures, warm air temperatures, and freshwater inputs were also common concerns at many bays. Quantitative site evaluations incorporating oyster attributes and environmental conditions were conducted at six estuaries in California and Oregon to prioritize sites for conservation value and restoration potential. Development of an online site evaluation tool allows end-users to conduct similar evaluations in new regions, thereby guiding future restoration and management efforts.*

## Executive Summary

*High densities of Olympia oysters at China Camp State Park, San Francisco Bay, California.*

The Olympia oyster *(Ostrea lurida)* has declined at many estuaries in its native range along the Pacific coast from Baja California to British Columbia. In the past decade, efforts have begun to conserve, enhance or restore Olympia oyster populations. The purpose of this guide is to inform these initiatives, with emphasis on environmental conditions that will foster success.

Sustainable oyster populations exhibit a suite of attributes, including large adult population size, high density on hard substrates, high and reliable rate of juvenile recruitment, diversity of size classes, and high survival rate.

Numerous environmental factors affect these attributes of sustainable oyster populations. Based on results from field monitoring and laboratory experiments, combined with a thorough literature review and our own expert opinions, we determined how sensitive Olympia oysters are to a variety of potential stressors. We found that Olympia oysters are highly sensitive to sedimentation and freshwater inputs, and moderately sensitive to excessively cold water temperature, high air temperature, food limitation, predation, and hypoxia. In contrast, sensitivity to a variety of other environmental factors currently appears to be relatively low; these factors include high water temperature, contaminants, competition, acidification, sea level rise, pathogens and diseases.

In addition to examining sensitivities of Olympia oysters to a variety of environmental factors, we characterized their exposure to these stressors. This is an important distinction, because oysters may be quite sensitive to an environmental factor and yet this is not relevant for management if they are rarely exposed to this factor in a given location. We solicited assessments by local experts of exposure to stressors in 28 embayments across much of the range of the species.

*Researcher examining oysters in Nootka Sound, Vancouver Island, British Columbia.*

Sedimentation was by far the most commonly encountered stressor, affecting populations in 71% of the embayments examined. Predation by drills and by other species was the next most common, identified as significant at 43% of embayments. Competition, cold water temperatures, warm air temperatures, and freshwater inputs also frequently pose threats to oysters (at 25–39% of embayments). Other stressors appear to be less common across this broad range; hypoxia, food limitation, contaminants, disease, warm water temperatures and acidification were identified as important at fewer than 20% of embayments, although at these places they may play a significant role.

This evaluation of 28 embayments provides an unprecedented synthesis of stressors faced by Olympia oysters across much of the range of the species. This comparison also yields insights into the status of oyster populations. The regional comparison identified that 21% of embayments experience many years with zero or near-zero recruitment of juveniles, which poses a threat to their long-term sustainability. Adult population sizes were also estimated. At 39% of embayments, there are estimated to be more than 1 million oysters present. While this is perhaps still a fraction of historical population sizes, these larger populations are likely to be fairly stable. At 43% of the embayments, populations were estimated at between 10,000 and 1 million individuals, which may raise some concern for their sustainability without management intervention. At 18% of embayments, estimates indicated that fewer than 10,000 oysters were present. These areas are excellent candidates for additional conservation and restoration efforts.

**Into the cold bay**
**Place oysters where they can best**
**Survive stressful times**

In addition to the broad comparisons among embayments, we also conducted much more detailed evaluations of sites within some of them. We incorporated quantitative field data on oyster attributes and environmental conditions into tables that served to prioritize sites for oyster conservation or restoration. We conducted such site evaluations at six estuaries in Oregon and California. We also developed an online site evaluation tool (available at www.climate-and-oysters.org) that can be applied by any user to assess other sites with new data.

This approach to quantifying the relative conservation value and restoration potential of multiple sites can be used to inform management actions. Agencies, nongovernmental organizations, community groups, or others considering the launch of a new restoration project can determine whether a particular site is likely to yield success. Funding agencies can use scores to help evaluate multiple restoration proposals and regulatory agencies can use the scores to direct policy protecting valuable existing populations.

In summary, this guide supports Olympia oyster conservation and restoration by enhancing the understanding of the attributes of sustainable oyster populations, the environmental conditions that most strongly affect them, and the embayments and specific sites that best support them.

# Background

## *Purpose and development of this guide*

*Top: dense oyster recruitment on the San Francisco Bay Living Shorelines Project. Above: spreading shell for restoration in Netarts Bay, Oregon.*

The purpose of this guide is to inform restoration and conservation of Olympia oysters *(Ostrea lurida)*. It was prepared by an interdisciplinary team funded by NOAA's National Estuarine Research Reserve Science Collaborative from 2011 to 2015. We first completed a guide for Central California in close collaboration with stakeholders and with substantial new data from field monitoring and laboratory experiments (Wasson et al. 2014). The current guide is an update of the earlier one, including evaluation of embayments along much of the range of the species, and incorporating input from oyster researchers and literature from other regions to increase generality. The intended audience includes oyster restoration practitioners, restoration scientists, and organizations involved in planning, funding, or permitting restoration and conservation.

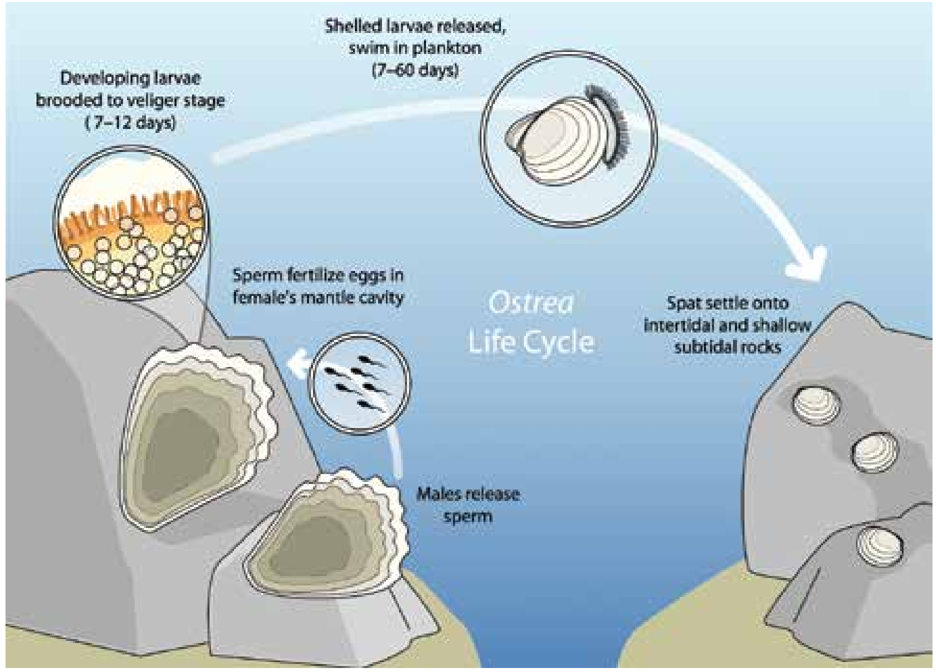
We characterized oyster populations and environmental factors that affected them at two spatial scales. Most broadly, we compared oysters and environmental stressors across much of the range of the species, to identify key opportunities and threats. At a much narrower spatial scale, but with greater depth, we also conducted site evaluations intended to aid end-users in prioritizing sites within particular embayments. We conducted site evaluations in Central California (Wasson et al. 2014), Southern California (Appendix 1) and southern Oregon (Appendix 2).

This is not a "how to" manual for field restoration methods, nor does it address the human processes that are essential for restoration and conservation (permitting, community support, public outreach, etc.). Guides that address these issues are sorely needed and would complement the current effort.

## *Olympia oysters: challenges and opportunities*

### LIFE-CYCLE AND ECOLOGY

Olympia oysters are primarily estuarine and generally not found on the open coast (Baker 1995). In Central California, they are most abundant around the 0-meter tide mark, Mean Lower Low Water (MLLW), and in Southern California at –0.3 m (authors' unpublished data), but have been reported from as high as 1 m above MLLW to depths of 10 m (Baker 1995). They require hard substrate on which to settle. They are sequential hermaphrodites—typically, but not always, starting out as males—and may switch sexes twice within the course of a year (Moore et al. in prep.). Females brood larvae in their mantles for 7–12 days (Coe 1931, Hopkins




*Schematic of Olympia oyster life cycle. Adult males release sperm that is taken up by nearby females. Eggs are fertilized within the mantle cavity and developing larvae are brooded to the veliger stage, released into the plankton, and transported with tides and currents. Larvae settle irreversibly onto hard substrate as juvenile oysters and grow to sexual maturity within months to a year. (Julia C. Blum)*

1936, Strathmann 1987), after which they are released to swim in the plankton for 5 days (authors' personal observations) to 4 weeks (Breese 1953).

*Large adult oysters sharing space with bay mussels at the Berkeley Marina, San Francisco Bay.*

### TRENDS IN DISTRIBUTION AND ABUNDANCE

Olympia oysters range from Central Baja California, Mexico, to British Columbia, Canada (Polson and Zacherl 2009). Abundance varies enormously from scant, but persistent, populations consisting of a handful of individuals, to locations with nearly 100 percent cover of oysters on hard substrates at MLLW (authors' personal observations). In most locations, the size of the pre-European-contact population is unknown. However, there were sufficient populations in many locations, including San Francisco Bay prior to the Gold Rush, to support a commercial fishery (Conte and Dupuy 1982; reviewed in Zu Ermgassen et al. 2012). Based on a review of the former extent of commercial oyster grounds from the earliest available records (mid-1800s to early 1900s), Zu Ermgassen et al. (2012) estimated oyster grounds in Puget Sound, Humboldt Bay, San Francisco Bay, Elkhorn Slough and Mission Bay to be at 1% of historic levels.

### CONSERVATION AND RESTORATION

The earliest efforts to restore Olympia oysters began in Puget Sound in 1999 (Peter-Contesse and Peabody 2005) and included seeding oyster shell and large-scale deployment of Pacific oyster shell for natural set. Current smaller-scale projects in Oregon and in Central and Southern California range from deploying small structures to assess recruitment patterns and best methods, to larger-scale mixed-species restoration projects with both physical and biological objectives in a "living shorelines" model.

*Rocky substrate with oysters in San Francisco Bay.*

It is worth noting that the term "restoration" is used rather broadly, to describe efforts to increase regional numbers of Olympia oysters, back towards levels that were presumed to be considerably higher historically and prehistorically along the entire coast (Zu Ermgassen et al. 2012). At the level of specific sites, there is usually no information about historic oyster densities. Moreover, human activities have changed conditions such as sedimentation and freshwater inputs so that the best locations for oysters today may differ from the best historic sites. Thus, at the level of an individual site, a project may more accurately be described as oyster "enhancement" rather than "restoration".

Sedimentation rates have also increased at many estuaries, such that oysters can no longer survive on tiny bits of natural hard substrate on the bottom or the low-relief oyster reefs that Olympias may have once made. Thus, some restoration efforts provide large artificial hard substrates raised above the sediments, which result in quite different oyster habitat than was historically present.

**Winter storm, downpour**
**Bay oysters shut their valves tight**
**Long wait to exhale**

Climate change is a challenge that must be understood and addressed as a part of restoration. Current model projections suggest rising air and water temperatures, acidification of surface waters and more frequent and severe flood events. These are likely to affect both existing oyster populations and restoration efforts. Climate change stressors may interact with and perhaps act synergistically with each other and with other anthropogenic stressors such as invasive species (for example, predatory oyster drills and potential space competitors such as the Pacific oyster *Crassostrea gigas*), high nutrient levels, and pathogens and disease. Climate change effects are not likely to be the same in all locations, nor are other anthropogenic stressors equally important everywhere. Conservation and restoration efforts require a better understanding of the importance of local environmental factors, both now and in the future.

*Intertidal community with oysters.*

## *Information sources for this guide*

*Stressor experiments on oysters at Bodega Marine Lab, California.*

### IDENTIFICATION OF KEY OYSTER ATTRIBUTES AND ENVIRONMENTAL STRESSORS

We relied heavily on our earlier guide (Wasson et al. 2014) for assessments of oyster attributes and environmental stressors. That in turn was based on extensive new field data collection and analysis at sites in central California, and laboratory experiments on stressors, both of which are described in detail in the original guide and associated appendices (Wasson et al. 2014), as well as a recent publication (Cheng et al. 2015). Both the original and current guide also involved syntheses of the existing published literature, unpublished data and observations of the authors, and personal communications from colleagues. Earlier reviews (Couch and Hassler 1989, Baker 1995, White et al. 2009) provided an excellent base for identification of key environmental factors. Many of the oyster attributes and environmental factors we included are the same as the "universal metrics" recommended for oyster restoration monitoring (Baggett et al. 2014), though we emphasize those most relevant to Olympia oysters.

### EXPERT ASSESSMENTS OF WEST COAST EMBAYMENTS

We invited oyster researchers working along the entire range of the species to evaluate embayments with regard to oyster populations and environmental conditions. The assessments were not quantitative, but rather involved determining whether oyster attributes or stressors fell into "high," "medium" or "low" categories. Broad definitions of these categories (see Table 1) helped provide consistency among assessments by different experts. These expert assessments provide a basis for examining geographic patterns in status of Olympia oyster populations and in expression of stressors.

### SITE EVALUATIONS

The data and approach used for site evaluations of Southern California and southern Oregon are detailed in Appendices 1 and 2, respectively. Our earlier site evaluations of Central California are detailed in Wasson et al. 2014.

*Azevedo Pond in Elkhorn Slough, California.*


*Location of embayments where experts conducted assessments of oyster attributes and environmental stressors. Note that multiple regions within San Francisco Bay, Puget Sound, and the Strait of Georgia were assessed.*

*Field monitoring at the Berkeley Marina, San Francisco Bay.*

# Attributes of Sustainable Oyster Populations

### OVERVIEW

Successful Olympia oyster populations exhibit a suite of biological attributes that we characterized and describe below. These are attributes that can be assessed at the level of individual sites, as a part of site evaluations. Two of these attributes (population size and reliability of recruitment) are also included in our comparison of entire embayments.

The attributes we have focused on include two "universal metrics" recommended for oyster restoration monitoring (Baggett et al. 204), oyster density and size frequency distribution. However, other metrics that apply to larger, reef-forming oysters such as reef height and area are not useful for Olympia oysters and were not included. Conversely, we included metrics not part of the universal recommendations, but very important to Olympia oysters such as recruitment—recruitment failure is common in this species, perhaps because of relatively low population sizes.

### MODERATE-TO-HIGH ADULT DENSITIES (importance: *very high*)

The density of adult oysters at a site can serve as a cumulative indicator of its appropriateness for conservation or restoration; moderate to high adult densities result from one or more years of significant recruitment and survival. Current oyster density data are important for prioritizing conservation areas, yet some populations fluctuate from year to year and it is better to have multiple years of data for greater confidence. High oyster densities on existing substrate can be used to assess suitability for restoration at that site, provided there is existing hard substrate to begin with. In a survey of 24 locations across the species' entire range, Polson and Zacherl (2005) recorded a wide range of densities from one individual to 146.8 /$m^2$ , but we recorded much higher densities at several sites in San Francisco Bay in 2012–13, up to 961/ $m^2$ in San Francisco Bay. Densities in Newport Bay and San Diego Bay are generally much lower (up to 55/$m^2$ and 219/$m^2$, respectively). Similarly, Coos Bay sites we evaluated were generally lower (up to 76.4/$m^2$), although recent survey work at a mitigation site found densities as high as 1000/$m^2$ (S. Groth personal communication).

### TOTAL ABUNDANCE AT SITE (importance: *very high)*

An order-of-magnitude estimate of the total number of oysters living at a site is a good indicator of its relative conservation value. In some cases, adult density per square meter of hard substrate may not represent density at larger scales (e.g., hectares), because there is very limited hard substrate. A site that has a million oysters within a hectare should have greater conservation value than a site that has a thousand oysters per hectare, and far greater than one that has ten oysters per hectare, even if all those sites have the same density per square meter. Therefore, it is important to establish where to draw the line around a site of interest and whether or not to include the full tidal range encompassing all colonized hard substrate. For assessments in Central California, we limited the total

*Monitoring a remarkably dense population of Olympia oysters in Nootka Sound, Vancouver Island, British Columbia.*

area for each site calculation to a 1-m wide band extending 300 m alongshore and centered around study transects at the tidal elevation of maximum oyster density. We were then able to use our density measurements (above) to generate order of magnitude estimates of total population. Site-level oyster population estimates in all California study bays ranged from fewer than 100 to 10,000s of individuals, with a high of estimate 100,000s of individuals at a single site in San Francisco Bay.

Broad assessments of abundance at the level of entire embayments are also useful for comparisons. Table 1 reveals that in 39% of embayments assessed, Olympia oyster populations are estimated to be above 1 million individuals. At 43%, populations are estimated at between 10,000 and 1 million oysters. However, at 18%, abundance of Olympia oysters is estimated at fewer than 10,000 individuals, which is of concern for long-term stability and persistence.

### OYSTER SIZES: BROAD SIZE DISTRIBUTION (importance: *high)* AND LARGE SIZES (importance: *medium)*

The presence of oysters distributed among a broad range of size classes is a good indicator of a healthy population, indicating a combination of recent recruitment, growth, and long-term survival. Each is an important aspect of a sustainable population, but it is time-consuming and sometimes logistically challenging to measure each separately. Because recruitment can vary from year to year, the best estimates of size distribution will include several years of data. At the very least, estimates ought to be made after the recruitment season, to include newly settled juveniles. Consistent absence of particular size classes does suggest potential limitations for populations. For example, absence of small sizes might suggest recruitment limitation or absence of large size classes might indicate a lack of long-term survival. However, although a broad range of sizes is regularly seen at high quality sites in Central California, not all Olympia oyster populations show persistent evidence of previous recruitment, particularly if growth to adult size happens very quickly and subsequent growth of those same individuals is limited. We measured oysters in quadrats

*Top: measuring oysters. Above: multiple age classes.*

along our study transects, categorized these into 10 mm size classes, and generated a size-class diversity index using a formula typically used to compare species diversity, the Gini-Simpson index. Our sites ranged from an index of 0.25 at a location in Elkhorn Slough where all oysters were from a single recruitment event, so that size diversity was very low, to an index of 0.876, at a site in San Francisco Bay where there were many oysters in multiple size classes. Newport Bay and Southern Oregon sites were all between 0.50 and 0.77.

In addition, when we included data on the largest oysters, the table was more accurate in ranking sites that we know from previous research have had consistent recruitment and moderate to high densities of oysters over time periods longer than the current study. We used the mean of the upper quartile of oyster sizes measured in our quadrats. Across study sites, the average sizes of the largest oysters ranged from 12 mm—a site in San Francisco heavily impacted by oyster drill predation—to 66 mm at an Elkhorn Slough site. Across all bays, largest oysters were typically between 30 and 50 mm, although oysters at most Elkhorn Slough sites tended to be above 50 mm.

### RECRUITMENT RATE: HIGH RECRUIT DENSITY (importance: *high)* AND RELIABLE RECRUITMENT (importance: *medium)*

Recruitment is absolutely necessary for a site to support a sustainable oyster population in the long run. Several factors influence whether or not there is high and reliable recruitment at a site, including processes affecting larval transport and retention, and the number and proximity of other colonized sites that could serve as larval sources. Estimating recruitment rate may be especially important for sites without adults where restoration actions are being considered. However, potential restoration sites that exhibit low recruitment may not need to be eliminated if seeding those sites with settled oysters is a viable option, and if this can be done at a large enough scale that a new, self-sustaining population can be formed, producing and retaining sufficient larvae. In central California, we counted recruits to standardized settlement tiles, deployed and retrieved quarterly, to arrive at a measure of recruits/unit area/day. We also calculated the coefficient of variation (CV) quarterly per site to generate a measure of reliability of recruitment; a low CV indicates a relatively consistent rate while a large one inconsistent recruitment. In Central California, quarterly average recruit density ranged from 0 at several Elkhorn Slough sites to 88 recruits/m$^2$/day at a San Francisco Bay site. In Southern California sites, where recruitment rate was calculated between June and October, rates ranged from 24–42 recruits/m$^2$/day in Newport Bay and from 136–1349 recruits/m$^2$/day in San Diego; measurements from southern Oregon calculated for a similar time period ranged from 3–39 recruits/m$^2$/day. Recruitment CV ranged from 0.5 at a Newport Bay site to ~3 at several Elkhorn sites and one in San Francisco Bay, all of which had recruitment in only one of two study years.

## Table 1: Synopsis of Oyster Population Attributes and Stressors Across Range of Olympia Oyster

| | OYSTER ATTRIBUTES | | STRESSORS[3] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | POPULATION SIZE[1] | RECRUITMENT[2] | SEDIMENTATION | PREDATION BY DRILLS | PREDATION BY OTHER SPECIES | WATER TEMP. TOO LOW | COMPETITION BY PACIFIC OYSTERS | COMPETITION BY OTHER SPECIES | AIR TEMP. TOO HIGH | LOW SALINITY | FOOD LIMITATION | DISEASE/ PATHOGENS | ACIDIFICATION | WATER TEMP. TOO HIGH | CONTAMINANTS | HYPOXIA | SOURCES |
| **CALIFORNIA** | | | | | | | | | | | | | | | | | |
| San Diego Bay | green | green | green | green | light green | green | light yellow | light green | light green | green | light green | green | light green | light green | light green | light green | S. Briley & H. Henderson, personal communication |
| Newport Bay | yellow | green | yellow | green | light green | green | light green | light green | light yellow | green | light green | green | light green | light green | light green | light green | S. Briley & D. Zacherl, personal communication |
| Alamitos Bay | yellow | green | yellow | green | light green | green | light green | light green | light yellow | green | light green | green | light green | light green | light green | light green | S. Briley & D. Zacherl, personal communication |
| Elkhorn Slough | red | red | red | green | green | light yellow | green | light green | green | green | light yellow | green | green | green | light green | red | Wasson 2010, Wasson et al. 2014, Wasson, personal communication |
| SAN FRANCISCO BAY | | | | | | | | | | | | | | | | | |
| South Bay | green | yellow | red | yellow | light green | green | green | light green | green | yellow | light yellow | green | green | green | green | green | Grosholz et al. 2008, Zabin et al. 2010, Wasson et al. 2014 |
| Central Bay | green | yellow | red | green | light green | light green | green | light green | green | yellow | light yellow | green | green | green | green | green | Grosholz et al. 2008, Zabin et al. 2010, Wasson et al. 2014 |
| North Bay | green | yellow | red | green | light green | light yellow | green | light green | green | red | light yellow | green | green | green | green | green | Grosholz et al. 2008, Zabin et al. 2010, Wasson et al. 2014 |
| Tomales Bay | yellow | red | green | yellow | green | light yellow | green | green | green | green | green | green | yellow | green | green | light green | Kimbro et al. 2009, E. Grosholz, personal communication |
| Humboldt Bay | yellow | light yellow | red | red | light yellow | light yellow | green | green | light green | light yellow | light yellow | light yellow | light green | light green | light green | light green | D. Couch & K. Ramey, personal communication |
| **OREGON** | | | | | | | | | | | | | | | | | |
| South Slough | red | light red | light red | green | light green | green | light green | light green | green | light green | light green | light green | light green | green | light green | light green | A. Helms & B. Yednock, personal communication |
| Coos Bay | green | light yellow | light yellow | green | light green | light green | light green | light green | green | light yellow | light green | light yellow | light green | green | light green | green | A. Helms & B. Yednock, personal communication |
| Yaquina Bay | yellow | yellow | yellow | light yellow | light red | light yellow | light yellow | light red | green | light yellow | light yellow | light red | light yellow | green | yellow | green | D. Vander Schaaf, personal communication |
| Netarts Bay | yellow | red | yellow | light yellow | light red | light yellow | light yellow | light red | green | green | light yellow | light yellow | red | green | green | green | D. Vander Schaaf, personal communication |
| **WASHINGTON** | | | | | | | | | | | | | | | | | |
| Willapa Bay | green | green | yellow | yellow | yellow | light yellow | yellow | yellow | light yellow | green | green | green | light green | green | green | green | Trimble et al. 2009, J. Ruesink, personal communication |
| PUGET SOUND | | | | | | | | | | | | | | | | | |
| Henderson Inlet | red | yellow | yellow | yellow | yellow | light green | green | yellow | light green | green | green | green | light green | light green | light green | light green | B. Allen, personal communication |
| Totten Inlet | green | green | yellow | yellow | yellow | light green | green | yellow | light green | green | green | green | light green | light green | light green | light green | B. Allen, personal communication |
| Noth Bay, Case Inlet | green | green | green | light green | light yellow | light yellow | green | light green | light yellow | green | green | green | light green | green | green | green | White et al. 2009, J. Ruesink, personal communication |
| Belfair, Hood Canal | light red | light yellow | yellow | yellow | yellow | light yellow | yellow | light green | light yellow | green | green | light green | light green | green | green | green | J. Ruesink and S. Valdez, personal communication |
| Dabob/Quilcene, Hood Canal | light red | light green | light green | light green | light red | light yellow | yellow | light green | light yellow | green | green | light green | light green | green | green | green | J. Ruesink and S. Valdez, personal communication |
| Port Gamble Bay | yellow | light green | light yellow | light green | light green | light green | light yellow | light yellow | light green | green | light green | light green | light green | light green | light green | light green | B. Allen, personal communication |
| Discovery Bay | yellow | light green | light yellow | light yellow | light yellow | light green | light green | light yellow | light green | green | green | green | light green | light green | light yellow | light green | B. Allen, personal communication |
| Dyes Inlet | green | green | yellow | yellow | yellow | light green | green | yellow | light green | green | green | green | light green | light green | light green | light green | B. Allen, personal communication |
| Liberty Bay | green | green | yellow | yellow | yellow | light green | green | yellow | light green | green | green | green | light green | light green | light green | light green | B. Allen, personal communication |
| Fidalgo Bay | yellow | red | light green | green | green | light red | green | light green | green | green | green | green | green | green | green | green | P. Dinnel, personal communication |
| **BRITISH COLUMBIA** | | | | | | | | | | | | | | | | | |
| STRAIT OF GEORGIA | | | | | | | | | | | | | | | | | |
| Victoria area | light green | light yellow | yellow | green | green | light green | green | light yellow | green | yellow | green | light green | light yellow | green | green | green | J. Carolsfeld, personal communication |
| Nanaimo area | yellow | yellow | green | green | green | light green | green | green | yellow | green | green | green | green | yellow | green | green | S. Dudas, personal communication |
| Baynes Sound area | yellow | yellow | green | green | green | light green | green | green | yellow | green | green | green | green | yellow | green | green | S. Dudas, personal communication |
| Quadra/Cortes Island area | yellow | light red | light green | light green | light green | light green | light green | light green | light green | light green | green | light green | light green | light green | light green | light green | S. Dudas, personal communication |

1. Population size estimate for estuary/region (intertidal and subtidal combined, even though latter is very uncertain)
   - red: <10,000
   - yellow: <1 million
   - green: >1 million

2. Recruitment assessment
   - red: many years with zero or near zero recruitment
   - yellow: occasional years with zero or near zero recruitment
   - green: no years with zero or near zero recruitment

   (for entire estuary/region)

3. Stressor assessment: negative effects include low recruitment, dieoffs of adults, or absence of oysters at otherwise favorable sites
   - red: stressor affects >10% of population every year or >25% every 5 years
   - yellow: significant problems, but not regularly or affecting much of the bay
   - green: no evidence of significant problem

Lighter colors indicate lower levels of certainty.


*From top to bottom: life stages of the oyster: gonads, brooded larvae, free-swimming veligers, "spat"—settled young oysters.*

Across the range of the Olympia oyster, there is reliable recruitment at some embayments (Table 1). However, at 61% of them, there are at least some years with zero or near zero recruitment. At Elkhorn Slough, Tomales Bay, South Slough, Netarts Bay, Fidalgo Bay and in the northern Strait of Georgia, there are many years with zero recruitment. Such populations may be at risk of local extinction, particularly if changing climate conditions lead to increased numbers of consecutive years with zero recruitment. The sites with unreliable recruitment were ones that did not have large (over 1 million oysters) population sizes (Table 1).

### HIGH JUVENILE SURVIVAL RATE (importance: *high)*

Juvenile stages are particularly susceptible to predation and other stressors that could lead to mortality. Survival to the adult stage is critical for reproduction and the overall sustainability of a population. In many cases, high rates of juvenile survival will be reflected in a broad range of oyster sizes present at a site (with the abovementioned exceptions). Thus, while survival rates are not critical to measure *in situ,* doing so allows for a more precise understanding of why certain size classes might be missing at a site. In central California, we allowed oysters to recruit to tiles in the field and then tracked the survival and growth of these oysters. For locations that did not have natural recruitment, we deployed tiles from nearby locations that had recruitment. Across embayments measurements of survival were made on oysters of different ages and over different time scales, making direction comparisons impossible. Early survival was high in San Diego (typically 99.9%/day for 90 days) and at most Central California sites (99.9% to 99.45%/day). Survival of juveniles on tiles in Coos Bay ranged from 45 to 79% at three sites across a study period of six months (January to July) (Rimler 2014). The methods used for the site evaluation table were too different to compare among embayments.

### HIGH JUVENILE GROWTH RATE (importance: *low to high)*

As noted above, juvenile oysters are generally more susceptible to predators and environmental stressors than are adult oysters, suggesting the clear benefits of growing quickly after settlement. High juvenile growth rates indicate favorable conditions (such as available food and sufficiently high salinity and dissolved oxygen) and should lead to healthy adult populations. However, sites with high food resources and warm water, which can promote growth, may also suffer from low dissolved oxygen. Additionally, low juvenile growth rate does not necessarily indicate poor field conditions. Growth may be limited by high recruitment densities rather than by a lack of food or by other unfavorable conditions. Marking and remeasuring oysters is time-consuming. Size-class distribution calculations, as mentioned above, provide indirect measurements of growth and survival. Such calculations could be substituted for direct measurement in sites with existing oyster populations. For sites without oysters or with few oysters, deploying settled oysters on tiles, as we did, to observe growth and mortality, can indicate whether conditions at a site are appropriate for restoration with seeded oysters. Across embayments growth

*Top: tracking survival and growth of oysters on monitoring tiles. Middle: Olympia oyster spat on Pacific oyster shell. Above: juvenile Olympia oysters on eelgrass.*

measurements were made on oysters of different ages and over different time scales, making direction comparisons impossible. For Central California, growth ranged from 0.037 mm/day at one San Francisco Bay site to 0.11 mm/day at four Elkhorn Slough and one San Francisco sites across six quarters. At San Diego Bay sites, growth of ~30 day old oysters was 0.24 to 0.39 mm/day over a two month period. In Southern Oregon growth ranged from 0.03 to 0.14 mm/day from April to July.

### HIGH LARVAL CONTRIBUTION TO REGION (importance: *medium to high)*

Sites that support significant adult populations also might export larvae and be of particular conservation value to the regional population. Ideally, this information would be included in evaluating sites for conservation. Measurements of fecundity and larval connectivity can help to identify what sites might most contribute to regional larval supply, but a thorough understanding of larval sources and sinks also requires an understanding of tidal currents and other transport processes around and between sites. At present this represents a major data gap in consideration of specific sites for restoration as well as for understanding the importance of oyster populations within regions.

Using shell chemistry analysis, we were able to evaluate the relative contributions of larvae produced in regions within San Francisco Bay to other regions in the Bay in 2012. Due to low adult densities and/or low fecundity at some sites, only six sites were evaluated in this portion of our research. For the locations we evaluated, our estimates ranged from 3 million larvae exported from a South Bay site to more than 26 million exported larvae from a North Bay site (Wasson et al. 2014). Carson (2010) used shell chemistry analysis to determine the origin of newly settled spat and thus the connectivity between sites in San Diego Bay, Mission Bay, and Agua Hedionda and Batiquitos in north San Diego County. Over the course of the whole recruitment season, sites in San Diego Bay and North County supplied more than half of their own recruits, while newly settled spat in Mission Bay were almost all from the other locations. However, Carson noted that the proportions of self-recruits and the relative contributions from each bay varied between the first and second half of the summer. Source and sink dynamics also likely vary between years, so the results of these two studies should not be considered definitive.

**Larvae floating free**
**Attach to hard surfaces**
**Forever settled**

# Environmental Stressors

### OVERVIEW

The distribution and abundance of Olympia oysters are affected by numerous environmental factors. We identified those environmental factors most important to Olympia oysters. Three of these—temperature, salinity, and dissolved oxygen—are ones considered "universal metrics" to monitor for any oyster restoration project (Baggett et al. 2014).

Through our data from field monitoring and laboratory experiments, combined with a thorough review of the literature and our team's expert opinion, we determined the *sensitivity* of Olympia oysters to a variety of potential stressors. Sensitivity is the degree of responsiveness to a realistic level of the environmental factor, for instance, high mortality rates or high recruitment failure in response to a potential stressor is considered high sensitivity, while limited sublethal effects would represent low sensitivity. Below, we explain how we determined sensitivity, highlighting the data or literature used to make the assessment. However, this categorization of sensitivities should not be considered final and comprehensive; as new studies are conducted our understanding will evolve. For instance, as a result of collaboration with colleagues from a broader geographic area, our evaluations of sensitivity have already been updated from our earlier efforts for Central California (Wasson et al. 2014).

In addition to assessing sensitivity of Olympia oysters, we also evaluated their *exposure* to environmental stressors. Exposure is the actual experience that oysters have with the stressor in the field. The distinction between sensitivity and exposure is important. For instance, Olympia oysters are quite sensitive to

**Table 2: Overview of Olympia Oyster Sensitivity and Exposure to Different Stressors**

| STRESSORS | SENSITIVITY | EXPOSURE |
|---|---|---|
| Sedimentation | High | High |
| Low salinity | High | Medium |
| Predation | Medium | Medium |
| Water temperature too low | Medium | Medium |
| Air temperature too high | Medium | Medium |
| Food limitation | Medium | Medium |
| Hypoxia | Medium | Low |
| Competition | Low | Medium |
| Water temperature too high | Low | Medium |
| Acidification | Low | Medium |
| Sea level rise | Low | Medium |
| Contaminants | Low | Medium |
| Disease/Pathogens | Low | Medium |

KEY: LOW | MEDIUM | HIGH

HIGH: For sensitivity, this indicates teh stressor can have strong negative effects on oysters; for exposure, indicates it was considered a concern at ≥50% of surveyed bays

MEDIUM: For sensitivity, this indicates the stressor can have moderate negative effects on oysters; for exposure, indicates it was considered a concern at ≥25% of surveyed bays

LOW: For sensitivity, this indicates the stressor has few negative effects on oysters; for exposure, indicates it was considered a concern at <25% of surveyed bays

*Sensitivity* assessments were based on literature review, field data, and laboratory experiments. *Exposure* assessments were based on the evaluation of 28 bays by local experts (Table 1).

*Top: large cobble provides hard substrate in Elkhorn Slough, California. Above: oysters in muddy conditions in Alamitos Bay, Southern California.*

prolonged periods of low salinity. However, this is only relevant to those places that receive significant freshwater input, such as northern San Francisco Bay. The interannual variation in the amount of freshwater flow leads Olympia oyster populations to expand upstream in dry years into areas that are then inundated with fresher water in wetter years, causing mass mortality. Patterns of exposure at 28 embayments are characterized in Table 1. A summary of both sensitivity and exposure is provided in Table 2. We considered overall exposure to be high if concerns were identified (yellow or red colors) at ≥50% of embayments that were assessed; medium if ≥25% of embayments identified concerns, and low if <25% of embayments identified concerns.

Below, we review a series of environmental factors relevant to oysters. For each we first discuss sensitivity, then methods for quantifying stressor levels, and then exposure.

### SEDIMENTATION (sensitivity: *high;* exposure: *high)*

*Sensitivity:* Olympia oysters cannot survive extended durations of burial in soft sediments. Exact tolerances to burial are not known for this species, but sedimentation has been identified as a stressor (Blake and Bradbury 2013). Other oyster species have been shown to be able to survive short-term burial (Hinchey et al. 2006), but longer-term burial can reduce recruitment and increase mortality (Lenihan 1999). Grain size is an important aspect of sedimentation (Thrush et al. 2004); while significant accumulation of fine-grained sediment could limit water circulation and challenge feeding and respiration, even complete sediment burial in coarser-grained sands may not be detrimental. Sediment types and deposition and movement rates interact with availability of larger hard substrates at a site. If the only hard substrates available to oysters at a site are limited numbers of shells of other oysters, then they cannot survive much deposition of fine sediments. However, at sites with large hard substrates, such as natural boulders or artificial rip rap, oysters can be raised above the sediment sufficiently to avoid burial. For instance, the majority of Elkhorn Slough consists of mudflats with deep fine sediments. Oysters are entirely absent from these areas, except where artificial hard substrates are available for attachment, allowing them to avoid burial (Wasson 2010). In Willapa Bay, removal of extensive accumulated shell mounds during harvesting of Olympia oysters a century or more ago may continue to hamper recovery of Olympia oyster populations, because oysters that settle on smaller, less stable substrates are more prone to burial (Trimble et al. 2009). Oysters are thus highly sensitive to sedimentation, and generally absent from areas with deep fine sediments, but this sensitivity can be mitigated with sufficiently large hard substrates. Many restoration efforts provide hard substrate for oysters through addition of bare Pacific oyster half shell, reef balls, and other techniques. One example is the Coastal Conservancy's San Francisco Bay Living Shorelines Project, which constructed reefs in 2012 with mounds of clean Pacific oyster shell, and with artificial reef methods such as structures made from cement mixed with mined oyster shell and sand. Up to 3 million native oysters have settled onto these shell bags and cement structures.

*Constructed reefs with Pacific shell bags provide hard substrate in San Francisco Bay.*

*Assessment method:* To determine potential negative effects of sedimentation on oysters at a site, both sediment depth and availability of hard substrates at the appropriate tidal elevation must be assessed. Wasson (2010) plotted the relationship between sediment depth and substrate size needed to sustain live oysters for Elkhorn Slough, but this relationship probably differs somewhat among embayments. As a general guide, the diameter of hard substrates available should be comparable to the depth of fine sediments. For example, if there are 2 cm of fine sediments at a site, then small bits of shell 2 cm in size probably can support oysters. However, if the mud is 50 cm deep, rocks 50 cm in size are needed to prevent burial and support live oysters. Other dynamic factors, such as seasonal deposition or strong currents that can turn rocks, can complicate this rule of thumb.

**In stormy winters**
**Many oysters do perish**
**Empty shells linger**

*Exposure:* Table 1 reveals that exposure to sedimentation is high, with moderate or high stressor levels reported at 71% of embayments. Thus sedimentation limits the potential distribution and abundance of oysters at many embayments. However, at some estuaries, such as San Diego Bay, there is such extensive man-made hard substrate (armored shores, cobble, rip rap) that sedimentation is not considered an important threat at many sites. In the northern part of the range, oysters are often found in less muddy habitats where they can survive on small bits of natural hard substrate.

### LOW SALINITY (sensitivity: *high;* exposure: *medium)*

*Sensitivity:* Salinity places basic physiological constraints on all marine and estuarine organisms (Hochachka and Somero 2002), and is a fundamental determinant of where species can live in an estuary (Remane and Schlieper 1971). Although Olympia oysters tolerate a range of salinity levels, low salinity exposure is stressful, can reduce reproduction (Oates 2013), and cause death in severe cases (Gibson 1974). In a laboratory experiment, we found that juvenile Olympia oysters suffered significant mortality when exposed to salinity levels below 10 for five or more days (Cheng et al. 2015). However, our field data from Central California showed a strong negative correlation between exposure to salinity below 25 and several oyster attributes, including average size, recruitment rate, and growth (Wasson et al. 2014). Thresholds may show local adaptation and vary across regions.

*Die-off of oysters at China Camp, San Francisco Bay, after prolonged heavy winter rains in 2006.*

*Assessment method:* Salinity can be best measured with *in situ* sondes continuously collecting data, but can also be assessed with less frequent spot samples (weekly or monthly). The salinity data must then be related to thresholds relevant to oysters, which could potentially vary between locations.

*Exposure:* Low salinity limits the distribution or abundance of oysters at about a quarter of embayments (Table 1). For instance, in San Francisco Bay, high freshwater flow in wet years following precipitation events and snowmelt can lead to low salinity conditions and subsequent massive die-offs in oyster populations that settled during dry years (Zabin et al. 2010). In Coos Bay, oyster reproduction was lower at a site with lower salinity (Oates 2013). However other estuaries, such as Elkhorn Slough and Humboldt Bay (D. Couch, personal communication) oysters are found in strongly marine-influenced areas, with rapid flushing of freshwater and thus little exposure of oysters to prolonged salinity stress. In other embayments, spatial salinity patterns may be fairly consistent across years, such that there are brackish or freshwater areas where no oysters occur, and consistently higher salinities in the areas where oysters do occur.

### PREDATION (sensitivity: *medium;* exposure: *medium)*

*Sensitivity:* Olympia oysters may be quite sensitive to some types of predation. In particular, studies from West Coast estuaries have shown that introduced species such as Atlantic oyster drills *(Urosalpinx cinerea)* and Japanese oyster drills *(Ocenebra inornata)* can have substantial local impacts on oyster populations (Willapa Bay, Buhle and Ruesink 2009, Tomales Bay, Kimbro et al. 2009, Humboldt Bay, Koeppel 2011, Puget Sound, Blake and Bradbury 2013). However, the importance of drill predation within a bay appears to be highly variable, due at least in part to variability of drill abundance (Buhle and Ruesink 2009, Kimbro et al. 2009, Koeppel 2011). For example, *U. cinerea* is well established in some parts of San Francisco Bay, and appears to impact populations where it is especially abundant, but it is present in low abundance or absent from many other locations. Additionally, recent work at one site in San Francisco Bay found that drill predation varied with tidal elevation: drills killed ~60% of adult oysters at +7 cm MLLW within two months, while oysters at +37 cm were not preyed upon (Kiriakopolos et al. 2014).

Crabs, particularly larger cancrid crabs, may also prey on native oysters, and pose a significant source of mortality in some locations. Koeppel (2011) reported evidence of crab predation (chipped/crushed shells) from two study sites in Humboldt Bay; in follow-up feeding trials in the laboratory *Cancer productus* readily consumed oysters attached to tiles while *Romaleon antennarium* did not. In contrast, positive effects of crabs on oysters have been found elsewhere as crabs prey on oyster drills, reducing predation pressure on oysters (Buhle and Ruesink 2009, Kimbro et al. 2009). Seastars can also exert high predation pressure in fairly marine sites (Ruesink, personal communication) Other predators, such as rays, birds and small mammals may also prey on native oysters, but to our knowledge such predation has not been quantified. Human collection of Olympia oysters is likely not a major factor in most locations, but this might

Monitoring at Elkhorn Slough, California.

change if native oyster populations become more abundant in easily accessible locations and may occur occasionally (anecdotal information reported to Zabin at Elkhorn Slough 2012).

*Assessment method:* Oyster drill abundance can be quantified in field transects of oyster beds. Drill densities may not correlate exactly with per capita effects on oysters, because these are also affected by availability of other prey types and potential predators of drills, as noted above. Predation by crabs, rays, birds and small mammals is harder to quantify. Manipulative experiments—such as comparing mortality in caged vs. uncaged oysters—are needed to shed light on strength of predation effects at a site.

*Exposure:* Significant effects of drills on oysters have been noted in 43% of embayments assessed, but drills are entirely absent from others, such as many Southern California bays, Elkhorn Slough, South Slough and Coos Bay in Oregon, and at British Columbia sites (Table 1). Predation by other species is also considered significant at 43% of embayments, with a variety of predators involved, although in many cases these impacts have not been experimentally tested or quantified. Ray and duck predation have been frequently observed at Humboldt Bay (D. Couch, personal communication); predation by crabs has been observed in Netarts Bay (D. Vander Schaaf, personal communication) and extremely high predation pressure from seastars has been observed at one site in Puget Sound, Dabob/Quilcene in Hood Canal (J. Ruesink, personal communication). Elsewhere in Puget Sound, predation by the crabs *Cancer productus* and *Cancer gracilis* and the sea stars *Pisaster brevispinus* and *Evasterias troschellii* has been observed (B. Allen, personal communication). In Totten Inlet, Henderson Inlet, and Port Gamble Bay and other historic Pacific oyster culture sites in Puget Sound a predatory

Non-native oyster drills prey on native oysters.

*Non-native green crab with Olympia oysters in Nootka Sound, British Columbia.*

flatworm introduced with Pacific oysters *(Koinostylochus ostreophagus)* has been noted (Blake and Bradbury 2013, B. Allen, personal communication).

**WATER TEMPERATURE TOO LOW** (sensitivity: *medium;* exposure: *medium)*
**WATER TEMPERATURE TOO HIGH** (sensitivity: *low;* exposure: *low)*

*Sensitivity:* Temperature is a major driver of virtually all physiological processes, such as respiration, metabolism, filtration, and excretion (Hochachka and Somero 2002). Excessively cold water can hamper oyster reproduction and growth. Numerous studies have correlated onset of reproduction or larval settlement with particular temperatures; for instance recently Oates (2013) found gametogenesis to occur at temperatures greater than 14.5°C in Coos Bay, Oregon, while other recent studies documented reproduction at a range from 12–21°C, but higher temperatures led to much faster production of larvae following reproductive onset (Santos et al. 1993). However, temperature thresholds for reproduction not only vary across different embayments but also may not show clear patterns within a system (Seale and Zacherl 2009). Our laboratory experiments showed significantly increased growth of juvenile oysters at 24 vs. 20°C (Cheng et al. 2015). Our field data from central California showed positive correlations between percentage of days with temperatures >12°C measured at a site and several oyster attributes, including growth rate, average size, recruitment rates, and adult density (Wasson et al. 2014). On the other hand, excessively warm water can have negative effects on oysters. However, such thresholds appear to occur at quite high temperatures; experiments in central California have shown that Olympia oysters have an LT50 (50% mortality) between 38 and 39°C (Brown et al. 2004, Cheng, unpublished data). Thresholds may vary across the range of the species.

*Assessment method:* Water temperature can best be assessed by continuous measurements taken by *in situ* instruments. To evaluate temperature conditions for oysters, these measurements can be related to thresholds. Such thresholds would probably differ across a latitudinal gradient.

For instance, for our evaluations of sites in Central California, we quantified the percentage of measurements taken that were above 12°C, because this threshold provided most significant statistical relationships with oyster attributes (Wasson et al. 2014). In Coos Bay, 15°C was used based on locally observed thresholds for reproduction (Pritchard 2014). In Newport Bay, temperature was recorded from three study sites only and critical thresholds were not known. We used the average warm-season temperature and ranked lower a site with an average of <17°C compared with others where the average was ~19°C.

*Liberty Bay, Puget Sound, Washington, following enhancement project.*

*Exposure:* Exposure to lower than optimal water temperatures is common across the range of the oyster, since fastest reproduction and growth occurs above 20°C, yet few sites have average temperatures this high. Low water temperatures were listed as a concern for 39% of embayments. One might suspect that these were mostly northern sites, but in fact there is no particular latitudinal pattern. In some more southern embayments such as Tomales Bay, sites near the mouth of the bay can have very cold summer temperatures due to strong oceanic influence and low residence time, while some more northern embayments such as in the Strait of Georgia have less direct marine influence and shallow depths that allow for substantial warming in the breeding season.

Historical data and near-term models suggest that increased sea surface temperatures have occurred and will continue to occur in estuaries worldwide (Cloern et al. 2011). Near-term warming of estuarine waters will probably be beneficial for oyster growth and reproduction, based on existing experimental work. Exposure to greater than optimal water temperatures appears to be rare in most embayments (Table 1).

#### AIR TEMPERATURE TOO HIGH (sensitivity: *medium;* exposure: *medium)*

*Sensitivity:* Air temperatures during low tide can reach and exceed oysters' thermal maximum, while water temperatures rarely reach these high levels. Our lab experiments showed that Olympia oysters can withstand high air temperatures during low tide exposure, with some mortality beginning to occur at 40°C (Wasson et al. 2014). When paired with another stressor, such as low salinity, high air temperature can have more pronounced lethal effects (Wasson et al. 2014). Oysters may also be sensitive to low air temperatures and the northern limit of the species may be set by freezing (Baker 1995), but we lack data on sensitivity and have not included this stressor here. In various bays in Oregon and Washington, significant negative effects of low air temperature have been observed, (B. Allen, personal communication).

*Olympia oysters on hard substrate in Elkhorn Slough, California.*

**Blazing heat and air**
**Meet a patch of oysters bare**
**How will they now fare?**

*Assessment method:* To precisely quantify low tide air temperatures, *in situ* temperature loggers deployed near the oysters are ideal. Percentage of days above a threshold, such as 40°C, can be calculated. Thresholds may show local adaptation and vary across regions.

*Exposure:* In our site evaluations in Central California and Oregon, we found air temperatures rarely to exceed 30°C during low tide exposure. In these areas, the lowest tides (with longest air exposure) mostly occur near dawn or dusk, resulting in low measured air temperatures at low tide. However in Washington estuaries, summer low tides often occur close to midday. In Willapa Bay, exposure to high air temperatures results in significant mortality of juvenile oysters at higher tidal elevations (Trimble et al. 2009). High air temperatures were also identified as a concern at the most southern embayments. Thus in the regional comparison (Table 1), exposure to high air temperature does not follow a clear latitudinal gradient, but rather shows some expression in both southern and northern sites, but not at intermediate ones. Such exposure is projected to increase with climate change.

*Oysters in a high flow habitat in Newport Bay, California, which may enhance feeding and oxygenation.*

### FOOD LIMITATION (sensitivity: *medium;* exposure: *medium)*

*Sensitivity:* Phytoplankton (single-celled planktonic algae) serves as food for filter-feeding oysters. Both food concentration and feeding time can be limiting, for example in intertidal areas with periods of aerial exposure compared with constantly submerged subtidal areas (Kimbro et al. 2009, Deck 2011). Limited food supply can result in reduced growth, shifts in size frequency, and reduced or delayed reproductive ability in other oyster species (e.g. Hofmann et al. 1994, Powell et al. 1995). Food limitation also may lead to reduced growth and weight, and delayed time to settlement in Olympia oyster larvae (Hettinger et al. 2013). Chlorophyll concentrations also correlate with reproduction in the field in Oregon (Oates 2013). Our field data from Central California indicate that levels of chlorophyll *a* are positively correlated with oyster performance (Wasson et al. 2014).

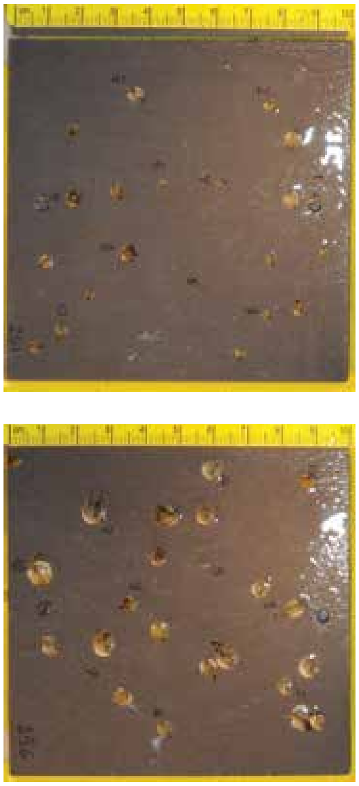
*Assessment method:* To estimate phytoplankton abundance at sites, one can measure the abundance of chlorophyll *a*, a plant pigment that is commonly used as a proxy for phytoplankton biomass. Exact thresholds are not known, but concentrations below 5 µg/L during summer-fall are probably too low, and concentrations >10 µg/L are desirable.

*Exposure:* Little is known about whether food is limiting for Olympia oysters at many sites across their range. In Central California, some sites had levels (<5 µg/L) that may be too low to sustain successful oyster populations (Wasson et al. 2014). Food limitation was identified as a potential stressor at seven embayments in California and Oregon. Exposure to food limitation was not listed as a concern at the other 75% of embayments that were evaluated (Table 1), presumably because productivity is high in these places.

### LOW OXYGEN (sensitivity: *medium;* exposure: *low)*

*Sensitivity:* Hypoxia is the depletion of oxygen from water, typically defined as a dissolved oxygen threshold below 2–5 mg/L (by different standards). Estuaries and near-shore systems often exhibit hypoxia as a result of eutrophication. Eutrophication stimulates the primary production of plants, which then die and are decomposed via microbial consumption, which depletes the water column of oxygen. Overproduction of plants (e.g., algae) can also reduce dissolved oxygen at night when plants respire. Worldwide, hypoxia appears to be expanding in frequency and areal extent (Diaz and Rosenberg 2008). Our experimental results suggest that diel-cycling hypoxia (modeled after the conditions at Elkhorn Slough) is not lethal, but has substantial sublethal effects on growth (Cheng et al. 2015). Periodic die-offs have been observed at Elkhorn Slough at sites with restricted tidal exchange following unusually long anoxic periods (Wasson, unpublished data).

*Assessment method:* Ideally, dissolved oxygen concentrations should be measured with *in situ* sondes collecting data continuously. One can then quantify hypoxia through measures such as the percentage of measurements where



*Oysters raised in the lab, subjected to low dissolved oxygen (top) and normal levels (bottom).*

dissolved oxygen was lower than 5 mg/L. However, many monitoring programs only collect grab samples during the daytime. We have found that variance from 100% saturated oxygen conditions (both increases or decreases) in daytime measurements correlate quite well with duration of nighttime hypoxia. So measures of average variance from fully saturated oxygen conditions (such as 9 mg/L) can be used as a proxy for hypoxia.

*Exposure:* Across embayments, hypoxia was only identified as a high threat for oysters at Elkhorn Slough (Table 1), an estuary very heavily affected by agricultural nutrient loading. Oxygen levels are expected to decrease as climate warms (Levin and Breitburg 2015), so this stressor may increase in frequency and may occur in new locations.

### COMPETITION (sensitivity: *low;* exposure: *medium)*

*Sensitivity:* Other species co-occurring with Olympia oysters on hard substrates may compete with them for space on which to settle or grow, or for food. Our field data from Central California showed no negative correlation between space covered by other sessile species and oyster density, recruitment, or growth at/near MLLW (Wasson et al. 2014). The main groups of species present at MLLW were the green algae *Ulva* spp., red filamentous algae, and barnacles. Many sites were high in bare hard substrate availability. Previous work indicates that the effects of competition are variable, and more likely to have an impact on early life stages of Olympia oysters. The presence of competitors reduced total recruitment in San Francisco Bay and reduced recruit size in Tomales Bay, though effects varied by site (Deck 2011). Competitive effects increased at some sites at lower tidal heights, but this was not consistent across sites or bays. Only minimal effects were observed on other aspects of oyster life stages. Wasson (2010) found no correlation between recruit size or survival and distance to the nearest competitor near MLLW in Elkhorn Slough. However, greater low intertidal and subtidal coverage by fouling species was observed, which could indicate potential effects at lower height. In the Pacific Northwest, Trimble et al. (2009) found that high cover of sessile invertebrate species, mainly barnacles and ascidians, reduced juvenile survival and growth, and tidal height did not affect this. In Puget Sound, barnacles, jingle shells and bryozoans compete for space, potentially limiting oyster recruitment (B. Allen, personal communication).

Competition with the introduced Pacific oyster *Crassostrea gigas* has been demonstrated in Willapa Bay to negatively impact Olympia oyster growth and increase mortality (Buhle and Ruesink 2009, Trimble et al. 2009). Although the potential impacts of *C. gigas* on *O. lurida* are not known for San Diego Bay, concerns about potential competition as well as a desire to not enhance *C. gigas* populations have been a factor in the design of restoration projects there. Indeed, many restoration practitioners are worried about inadvertently increasing populations of nonnative species through the provision of new hard substrates intended for native oysters.

*Tube worms co-occur with oysters in Elkhorn Slough, California.*

*Assessment method:* Percent coverage of potential competing species can be assessed in field transects along with oysters. Another simple proxy for effect of competition is percent coverage by bare space on hard substrates—if this is high, competition is presumably not a major factor. To truly determine the effects of potential competitors on oysters, manipulative experiments are required.

*Exposure:* Multiple factors, including the identity and abundance of potential competing species, environmental stressors, predation, and the timing of recruitment and growth of potential competitors, will determine the degree to which competition is a factor in any given location. Competition with *C. gigas* was identified as being of moderate importance in a number of bays in California, Oregon and Washington, but unimportant elsewhere (See Table 1). Competition with other species was indicated as being potentially of high importance at Netarts and Yaquina, and of moderate importance at various bays in Oregon, Washington, and British Columbia.

**ACIDIFICATION: LOW pH/ALKALINITY** (sensitivity: *low;* exposure: *low)*

*Sensitivity:* One of the better-studied consequences of global change is the increasing acidity of ocean water due to the greater concentration of carbon dioxide ($CO_2$) in the atmosphere. Aragonite is the form of calcium carbonate used by most larval bivalves to build their shells; one aspect of more acidic water is that aragonite is less available to larvae, resulting in small, thinner or malformed shells and/or death (Ekstrom et al. 2015). Experimental studies of Olympia oysters have demonstrated some negative effects of acidification (Hettinger et al. 2012, 2013), though these were mostly sublethal and not as strong as effects demonstrated on other oyster species. Many estuaries, such as San Francisco Bay and Tomales Bay, have relatively large seasonal and diurnal fluctuations in pH and carbonate saturation as the result of inputs from both watershed (river inflow) and nearshore oceans (via upwelling), and the influence of plant metabolism (daily cycles of photosynthesis and respiration)

*Monitoring Olympia oysters among Pacific oysters and mussels in Newport Bay, Southern California.*

(Smith and Hollibaugh 1997). Consequently, organisms in these locations, including oysters, often already experience a very wide range of pH and carbonate saturation conditions, and we are not aware of any evidence to suggest that oysters currently are negatively impacted by these fluctuating conditions in much of the range. At some estuaries, such as Netarts Bay, acidification is a new stressor for *Crassostrea gigas,* leading to lower larval production and growth (Barton et al. 2012), and may also affect *Ostrea lurida* (D. Vander Schaaf, personal communication), although the brooding habits of this species may offer greater protection to larvae.

*Assessment method:* Measurements of pH by water quality instruments provide a reasonable estimate of acidification, but the precision of typical sensors is too low to detect subtle trend changes. Calculations can be made of frequency or duration of low pH events. More precise pH sensors, and at least occasional assessment of alkalinity and dissolved inorganic carbon is ideal, although the required instruments are expensive.

*Exposure:* Across embayments, acidification was currently ranked as a low threat to oysters, with the exception of Netarts Bay where it was ranked high, and Tomales, Yaquina and Victoria, where it was ranked of moderate importance (Table 1). Acidification has been shown to negatively impact growth and potentially increase mortality in larval Pacific oysters in hatcheries in Oregon (see Barton et al. 2012). Although we are unaware of documented impacts to Olympia oysters under current conditions, acidification may impact native oysters more strongly in the future. Potentially, exposure to acidification will increase as increasing atmospheric $CO_2$ results in increasing water-column $pCO_2$, along with future changes in river inflows and upwelling inputs (Cayan et al. 2008, Checkley and Barth 2009), although the complexity of carbonate chemistry in the coastal zone makes predicting impacts difficult (Waldbusser and Salisbury 2014).

*Monitoring restoration at Netarts Bay, Oregon, a site where Pacific oysters have been threatened by acidification.*

*Live oyster surrounded by oil at Angel Island, San Francisco Bay, following 2009 Cosco Busan oil spill.*

### CONTAMINANTS (sensitivity: *low;* exposure: *low)*

*Sensitivity:* Polluted water, notably the discharge of high amounts of sulfite wastes from paper mills in the Pacific Northwest, once had major impacts on native oysters (Blake and Bradbury 2013), and the dumping of untreated sewage may have harmed oysters in San Francisco Bay as well as shut down oyster farming operations due to public health concerns (multiple reports, reviewed by Baker 1995).

Despite the persistent presence of contaminants at many sites, oysters do not appear to be very sensitive to them, generally. In California, Olympia oyster populations exist in habitats formerly considered "polluted," such as near a wastewater treatment outfall in Humboldt Bay, CA, in marina basins in San Francisco Bay, and in an area formerly contaminated with heavy metals and polychlorinated biphenyls near Stege Marsh, Richmond, CA (Couch and Hassler 1989, Hwang et al. 2013). In many locations, heavy metals and other long-lasting pollutants that are the legacy of now-closed industry may be taken up by oysters. For example, a sample of 20 apparently healthy oysters taken in 2006 from an oyster restoration site in San Rafael (San Francisco Bay) indicated very high levels of copper, suggesting the presence of a substantial source of this pollutant nearby (Gerhart, personal communication). However, oysters continue to thrive at this site and at other restoration sites nearby.

*Assessment method:* Contaminant sampling methods for sediments and oyster tissue differ by the contaminant in question. Many estuaries are contaminated by a range of PAHs, heavy metals and legacy pesticides as well as emerging contaminants. Quantifying the bioavailability and toxicity of these compounds, let alone their interactive effects, is very expensive and technically challenging.

*Exposure:* Current environmental laws have reduced the use and release of contaminants, such as organic biocides (Axiak et al. 1995), polycyclic aromatic hydrocarbons, and heavy metals (Connor 1972), which were previously found to affect oyster populations. Contaminants were considered a low threat across embayments, with the exception of Yaquina Bay and Discovery Bay, where this stressor was ranked a moderate threat (See Table 1).

### PATHOGENS AND DISEASES (sensitivity: *variable;* exposure: *low)*

Sensitivity: Overall, oyster diseases and pathogens currently do not appear to be a major factor influencing native oyster populations in Central California. While individual oysters may suffer from infections, rates are low overall and no observed population diebacks have been linked to disease.

However, it would be unwise to entirely dismiss disease as a potential stressor for Olympia oysters. Eastern oysters in the Chesapeake and Delaware bays were apparently disease-free for decades until the introduction of oysters from the Gulf of Mexico led to emergence of two new diseases in the 1950s. Oyster disease agents are certainly present, having been reported from both commercially grown Pacific oysters and native oysters in multiple bays along the coast, including Elkhorn Slough, and Tomales and Humboldt bays in California, and Netarts, Yaquina, and Alsea bays in Oregon (Mix and Sprague 1974, Friedman et al. 2005, Burge et al. 2007, Moore et al. 2011). Olympia oysters may become more susceptible to disease as restoration moves forward and population density increases. Additionally, disease prevalence and impact may increase as a result of other stressors associated with climate change, such as increasing water temperatures, which have been linked to herpes outbreaks in commercial oyster species in Tomales Bay (Burge et al. 2007).

*Assessment method:* An overview of assessment methods for oyster diseases and pathogens is provided by Baggett et al. (2014). Microscopic examination of stained histological sections and/or genetic analyses are appropriate for detecting various pathogens or diseases. If oyster density is considered too low to sacrifice animals for pre-restoration health surveys at the restoration location, information from the nearest population(s) that can be sampled is useful. Additionally, seed oysters from nearby populations with known health history may be deployed at the proposed site. To understand population-level effects, one must quantify percentage of individuals infected, intensity of individual infections and outcomes for those individuals.

*Exposure:* Overall, exposure to disease appears to be low according to the expert assessments (Table 1). We review highlights of potential disease concerns from south to north.

*Monitoring at Nootka Sound, Vancouver Island, British Columbia.*

Reef balls deployed in Elkhorn Slough (top) and San Francisco Bay (bottom).

From Southern California to Tomales Bay, disease was not considered a significant factor affecting Olympia oysters in any embayment (Table 1). The most recent published surveys of disease in Olympia oysters in the San Francisco Bay Area (Friedman et al. 2005; Moore et al. 2011) reported that potentially pathogenic bacteria, viruses, and protists are present only in a minority of oysters, and typically at levels lower than those associated with disease. These studies showed little evidence for presence of disease except for disseminated neoplasia in Drakes Estero, and Candlestick Point, Oyster Point, and Coyote Point in San Francisco Bay (Friedman et al. 2005, et al. 2008, Moore et al. 2011). The levels measured at these four sites are unlikely to seriously affect oyster populations or negatively affect restoration efforts (Grosholz et al. 2008).

In Humboldt Bay, there is evidence of the occurrence of Denman Island disease, and oyster experts coded this as a moderate concern because of potential mortality in older oysters following cold temperatures (D. Couch and K. Ramey, personal communication). However, there is no evidence from any site that Denman Island disease causes significant population level effects on Olympia oysters (J. Moore, personal communication).

In Coos Bay, disease was considered a moderate stressor because 17% of Olympia oysters tested for diseases showed tissue irregularities, focal hemocytosis, and nuclear degeneration (Rumrill 2010). In Netarts and Yaquina bays concerns about *Vibrio tubyashi* led to scores of moderate and high stressor levels for diseases (D. Vander Schaaf, personal communication).

Disease was not considered an important stressor at any embayment in Washington or British Columbia. While several disease agents were recently identified in surveys of Olympia oysters in British Columbia, these were generally detected at low prevalence and intensity and were not believed to have significant health impacts (Meyer et al. 2010).

San Francisco Bay Living Shorelines Project constructed reefs at the San Rafael Shoreline.

## SEA LEVEL RISE (sensitivity: *low;* exposure: *low)*

*Sensitivity:* Olympia oysters are not very sensitive to projected sea level rise. One potential impact of sea level rise could be increased local resuspension of sediment due to greater wave action and tidal currents associated with deeper waters. This could result in stressors associated with increased sediment burial in shallower areas. However, more hard substrate may be available for oysters as sea levels rise, both because existing hard substrates protecting human infrastructure may become submerged, and due to further shoreline hardening to protect human land uses from sea level rise. Given the drawbacks of traditional shoreline hardening, measures such as living shorelines—creating habitat for multiple species—are increasingly being incorporated into thoughtfully planned nature-based solutions.

*Sunset low tide monitoring at Point Orient, San Francisco Bay.*

*Assessment method:* One can assess hard substrate availability at different elevations to determine potential effects of projected sea level rise on habitat availability for oysters.

*Exposure:* Rates of sea level rise on the northeast Pacific coast have been relatively slow compared to other regions, but are anticipated to accelerate soon (Bromirski et al. 2011). Exposure to sea level rise also depends on change in land surface elevation, which can be affected at a regional scale by factors such as geologic uplift, or at a local scale by factors such as groundwater overdraft leading to subsidence.

## INTERACTIONS BETWEEN STRESSORS

Environmental stressors often occur in combination. It is therefore important to understand not only the impacts of individual stressors but also the effects of combinations of multiple stressors on Olympia oysters. Multiple stressors can produce additive effects (i.e., equal to the sum of the stressor impacts), or interactive ones (i.e., either more detrimental or less detrimental than would be expected by simply adding the effects of the stressors).

We used field studies in Central California, combined with previous work, to measure baseline patterns of potential environmental stressors in relation to oyster demographics. We used several multivariate analyses of a broad suite of environmental variables (including air and water temperature, salinity, and dissolved oxygen) and oyster demographic parameters (density, growth rate, size, recruitment rate) to identify which stressor or combinations of stressors explained the most variation in oyster demography.

We used laboratory experiments to more closely investigate causal relationships between multiple stressors and Olympia oyster survival and performance. In the first experiment, we examined interactions between warm water temperatures and low oxygen levels applied as simultaneous stressors. Following a recovery period, we applied low salinity stress, so that interactions between all three stressors could be examined. Here, we found no evidence for interactive effects, but rather, these stressors were additive (Cheng et al. 2015). In the second experiment, we assessed the effects of low salinity and high air

*Tank experiments examining multiple stressors at the Bodega Marine Lab in California.*

temperature simultaneously, and with different amounts of time between applying the two stressors. When applied simultaneously, we saw synergistic effects (detrimental effects beyond what would be predicted by simply adding the effects of low salinity and air temperature). When oysters were given recovery time between stressors, this synergistic response disappeared (Wasson et al. 2014). Previous studies have found interactive effects to be generally more common than additive effects (Crain et al. 2008, Darling and Cote 2008), but we found that results are dependent on the specific stressors and their timing. Although some stressors like low salinity and high air temperature may co-occur (for example, during springtime in some parts of San Francisco Bay) and produce synergistic effects, realistic recovery time between stressors may lead to effects that are more additive in nature.

Many of the environmental factors discussed above also interact with tidal elevation. For instance, feeding time is longer at lower elevations, so phytoplankton concentrations need not be as high to support subtidal populations as high intertidal ones. Exposure to warm air increases with increasing tidal elevation, while coverage of most sessile invertebrates decreases with increasing tidal elevation. For rigorous comparisons among sites, it is thus important to examine biological and environmental conditions across similar tidal elevations; in our assessments of Central California sites, we focused on Mean Lower Low Water because this is where oyster densities are typically highest. For practitioners elsewhere using our site evaluation tool to rank sites for their restoration potential, it is important to consider the role of tidal elevation. For instance, a site that receives a low score because of frequent high air temperatures may be a fine place to do a subtidal restoration project. Considerations of interactions between environmental factors and tidal elevations is thus essential.

*Rocky intertidal habitat at Strawberry (Brickyard Cove), San Francisco Bay.*

# Site Evaluations

## *Background and Goals*

Resource managers and restoration practitioners indicated a need for tools to help rank sites in terms of their suitability for native oyster restoration and conservation (Wasson et al. 2013). Site evaluations have been conducted by other researchers in some regions, including Puget Sound (Blake and Bradbury 2013) and British Columbia (Stanton et al. 2011). However, there was no quantitative methodology for comparing sites in terms of their restoration potential or conservation value. We thus developed quantitative metrics and report-card style summary tables to evaluate sites. With extensive grant funding, we were able to conduct thorough field monitoring data and evaluate 21 sites in Central California (Wasson et al. 2014). Subsequently, we were able to conduct scaled-back evaluations of sites in Southern California (Appendix 1) and southern Oregon (Appendix 2) using existing data for those regions. Furthermore, we developed an online version of the site evaluation tables as a tool for scientists and practitioners working in other estuaries (available at www.climate-and-oysters.org).

## *Our Approach to Site Evaluation*

The site evaluation tables score sites based on oyster performance and on measurements of key environmental parameters. To create the tables, we used the same oyster attributes described above, and all the environmental stressors with high and medium oyster sensitivities discussed above (with the exception of sedimentation, not relevant to most of our sites, which had ample large hard substrates preventing sediment burial, or would have them as a result of restoration projects).

For each parameter for which data were available, we converted raw data to a score. This conversion was based on thresholds we set using expert judgment. For instance, one parameter was oyster drill density. If there were zero oyster drills per square meter, this was assigned a 100, the best score. If there were more than five oyster drills per square meter, this was assigned a 0, the worst score. Intermediate densities received intermediate scores (25 for 3–5 drills, 50 for 1–2 drills, and 75 for between 0–1 drills per square meter). Thresholds were different for Oregon, Central California, and Southern California, and depended on the range of the raw data and/or knowledge of key thresholds at each location, with the goal being to rank sites relative to one another within each region. We shaded cells in the tables, with light colors for low scores and dark colors for high scores, to make patterns easily distinguishable at a glance (Appendix 1, 2, and Wasson et al. 2014).

We assigned weightings to each parameter in the tables. In particular key oyster attributes such as density and recruitment were weighted highly relative to other parameters, since they are the most reliable indicators of oyster success. Relationships between environmental factors such as temperature and oysters are weaker (and were not quantified for Southern California, Coos Bay or South Slough) and thus were weighted lower. The weightings are clearly shown in the tables so the process of obtaining a total score is transparent. In the online tool, users can adjust the weightings themselves.

We calculated overall scores using all the weighted parameters. The tables include three different overall scores at the bottom: 1) a score indicating suitability of the site for restoration through addition of hard substrates; 2) a score indicating suitability of the site for restoration through addition of hard substrates seeded with juvenile oysters, sufficient to establish a self-sustaining population supplying larvae to this area, and 3) a score indicating value of this area for conservation of existing oyster populations. Details on all the parameters included their weighting, and calculation of the overall scores are included in the notes associated with the tables (Appendix 1, 2 and Wasson et al. 2014 [including their appendices 2,4]).

## Site Evaluation Case Studies

### CENTRAL CALIFORNIA

We evaluated twelve sites in San Francisco Bay and nine sites in Elkhorn Slough (Wasson et al. 2014). On the whole, sites in San Francisco Bay scored higher than those at Elkhorn Slough, generally due to higher scores for oyster parameters. Top scoring sites were Berkeley Marina, Strawberry (Brickyard Cove), Point Pinole, and San Rafael Shoreline in San Francisco Bay and South Marsh and Kirby Park at Elkhorn Slough. Major stressors differed between the two bays, with more sites in San Francisco Bay experiencing periodic low salinity, higher air temperatures, and relatively low chlorophyll *a*; while low dissolved oxygen was the major stressor at Elkhorn Slough, with low chlorophyll *a* and low water temperatures mainly at a few marine-influenced sites near the mouth of the estuary. At both estuaries, mid-estuary sites generally scored higher than other sites, which is consistent with our working knowledge of the sites. Although North Bay sites in San Francisco Bay also scored high during this relatively short study period, these sites are more vulnerable to low salinity events. Over the nearly 10 years we have been working in San Francisco Bay, we have seen populations at these sites decline steeply during years of heavy rain. Sites in the South Bay, which have oyster drill populations and warmer air temperatures, such as Eden Landing and Coyote Point, scored lower. At Elkhorn Slough, several sites with little to no recruitment and/or adult oysters, such as Vierra and Moss

*Urbanized conditions in San Francisco Bay (near right) compared to rural conditions at Elkhorn Slough, California (far right).*

Landing, also received low overall scores, as did some upper estuary and tidally muted sites with low recruitment and poor water quality.

### SOUTHERN CALIFORNIA

Fourteen sites, seven each in Newport Bay and San Diego Bay, were evaluated using data collected between 2010 and 2014 as part of several research projects. Not all data were collected at all sites, but measurements of some critical oyster parameters were similar enough to allow comparisons.

Overall, greater variability between sites existed within San Diego Bay, whereas the sites in Newport Bay were more similar in all oyster attributes studied. San Diego sites as a rule had much higher recruitment rates (one to two orders of magnitude) than Newport Bay sites, and thus had higher restoration scores overall. San Diego sites also had high juvenile growth rates compared with Central California, although these were somewhat skewed by the short time period (70 days) over which these new settlers were tracked; there was also high survivorship of juveniles over this same time period. These parameters were not available for Newport Bay. Adult densities were low at four sites in San Diego; two sites had no adults and two sites had fewer than 10 individuals/$m^2$. This was due to a paucity of hard substrate at these locations. All sites in San Diego received high to medium high scores for restoration success due to high recruitment rates, rapid juvenile growth and good juvenile survival, although data on potential critical environmental parameters were missing. Three sites—Chula Vista Wildlife Refuge, J Street Marina, and Coronado Cays—received the highest restoration scores, with Chula Vista scoring the highest of the three due to high densities of adult oysters (291/$m^2$). Chula Vista also received the highest conservation score due its large oyster population (estimated in 10,000s).

*Monitoring site in Newport Bay, Southern California.*

*Olympia oyster restoration in South Slough, Oregon.*

None of the Newport Bay sites received a high score for restoration success, but neither did any site rank poorly—rather, all sites scored medium high. All sites had moderate to moderately high scores for adult densities, sizes and size-class distributions, and the three sites for which recruitment was tracked also had moderate scores. Two sites received high scores for conservation, 15th Street, and Newport Aquatic Center, but the latter was evaluated on the basis of its population estimate only (15,000 individuals) as other data were unavailable. Water temperature was the only environmental parameter measured for Newport Bay and only for three sites, so potential environmental stressors for this bay could not be quantified.

### SOUTHERN OREGON

We evaluated three locations in the northeastern portion of the Coos estuary (referred to as Coos Bay), and two sites in South Slough, which comprises the major southern arm of the Coos estuary (Appendix 2). In Coos Bay, large deposits of recent fossil Olympia oyster shells have been found in dredge spoils and American Indian shell middens, but oyster populations became locally extinct prior to European settlement. Only after accidental introductions in the 1980s through aquaculture activities did they become reestablished in the estuary (Baker et al. 2000). The sites in Coos Bay consist of fairly established oyster populations stemming from this re-introduction. In South Slough, Olympia oysters were absent until they were reintroduced through a project that began in 2008. As a result, in general, Coos Bay sites had higher adult densities than the South Slough sites.

The highest scoring site for restoration in Coos Bay was Downtown, although Haynes Inlet received only a slightly lower score. Downtown had the highest adult and recruit densities and larval abundance. For habitat attributes, Downtown also had the highest availability of hard substrate, which was a potential limiting factor for other sites. All Coos Bay sites had substantial freshwater inputs, with daily salinity averages below 25 for up to 76 percent of the year, but this seemed compatible with substantial oyster populations, perhaps due to local adaptation to lower salinity. Coalbank Slough had the highest risk of low pH events, but pH at this site was highly variable. Average chlorophyll *a* concentrations measured at Haynes Inlet and Coalbank Slough were moderate and may contribute to higher oyster performance at these sites whereas average chlorophyll *a* concentrations in South Slough were lower. At nearby weather stations, high air temperature events were rare. Sedimentation in South Slough appears to be high and may impact future restoration seeding operations.

*Top: monitoring tiles at Kirby Park in Elkhorn Slough, California. Bottom: students with The Watershed Project.*

## *Challenges and Limitations to Site Evaluations*

It is important to keep in mind that the site evaluation tables are based strictly on biological/ecological measurements and do not take into account other important considerations in site selection, such as community support, access, funding, and permit procedures.

Even from a strictly scientific perspective, there is still much to learn about native oyster population biology and ecology in our region, and of course there are many unknowns as we project into the future, given a changing climate. In many cases, data are available only for short time spans that likely do not represent the full range of conditions at a site over longer periods, or, particularly for many of the physical parameters, detailed data are only available at larger spatial scales, yet conditions may vary with microclimates at the site level. Many of the physical parameters likely to be important to oysters are difficult and/or costly to measure. Also unknown is the degree to which oysters may display adaptation to local conditions, such that the relative importance of any given physical parameter might vary between embayments. Additionally, we don't yet know the degree to which populations are connected, which could mean that the critical factor of recruitment rate may be partially decoupled from site-level conditions. While oyster attributes, such as size or density, are easily measured, our understanding of the relative importance even of these parameters to the sustainability of oyster populations in a given region is also limited. Thus, in the creation of these tables, we relied on our expert opinion to weigh the relative importance of oyster performance data and the likelihood of extreme climate events at our study sites, particularly in converting raw data into weighted ranks. As such, the tables represent a combination of empirically derived data and judgment calls.

Thus, site scores should be considered advisory only and are intended to provide guidance for restoration by comparing sites within regions, rather than as an absolute ranking across all locations. For some sites, it is also possible that modifications to the restoration approach could help ameliorate stressors. For example, substrates could be deployed in the shallow subtidal rather than in the intertidal zone to reduce heat stress at a site with frequent very-high air temperatures.

## *Online Site Evaluation Tool*

We have created an online site evaluation tool in Excel that allows users to populate a table with their own data (available at www.climate-and-oysters.org). There are separate sheets for assessing conservation value of sites for existing oyster populations vs. restoration potential (with and without seeding). Users can adjust the weight of different parameters as they see fit. The table allows for assessments to be conducted with considerably fewer parameters than we included in our original evaluations (Wasson et al. 2014), which in most locations is likely to be the case.

*Installing monitoring tiles in San Francisco Bay.*

At an absolute minimum, we recommend collecting data on adult oyster densities and diversity of size classes for restoration sites being considered (these are also two of the four "universal metrics" recommended for oyster restoration monitoring by Baggett et al. 2014). To determine a site's conservation value the extent of shoreline with hard substrate at the appropriate tidal height should be assessed. This, together with density, can provide an estimate of abundance of oysters at the site. Data on recruitment rates, derived by deploying clean substrate at the start of recruitment season, should be collected if at all possible; ideally these data should be collected over several years, as recruitment can be highly variable at some locations. Recruitment to deployed substrate and subsequent measurements of growth and survival should be evaluated for sites that do not have hard substrate but are being considered for restoration involving substrate addition. If possible, data on environmental variables should also be incorporated. Across embayments, the most critical factors to assess appear to be: 1) the longer-term risk of low salinity exposure; 2) exposure to high air temperatures, 3) risk of predation by oyster drills and other species, and 4) competition with *Crassostrea gigas* and other sessile organisms. Data from a nearby monitoring station can often be used to determine whether there is a risk of extended freshwater events during wet years, and to calculate maximum daily summer air temperatures (although exposure to air temperatures will be mitigated by tides and influenced by micro-climates at the site level.) Chlorophyll and water temperature data are also regularly available from water monitoring programs and yield important information. Assessing whether oyster drills and other potential predators and competitors are abundant at the site can also be done fairly easily.

*Placing shell bags for restoration at Netarts Bay, Oregon.*

## *Management Applications of Site Evaluation Tools*

The site evaluation tools developed here can be applied to two main types of management questions:

*Student volunteers with The Watershed Project monitor conditions at Point Pinole, California.*

1. **Conservation: Which sites currently support healthy and abundant existing oyster populations that are most likely to be sustainable in the long-term?**

   ***Example of management decisions:*** strategic planners and resource agency staff involved in permitting determine which sites/populations need special protection from development or nearby disturbance; regulatory agency considers oyster needs when designating a new marine protected area.

2. **Restoration/Enhancement**

   a. **Which sites are best for success and long-term sustainability of oyster restoration or enhancement projects?**

      ***Examples of management decisions:*** funding agency decides between competing projects in different locations; strategic planner for estuarine restoration picks target areas; restoration group decides where to propose next project.

   b. **Is an oyster restoration or enhancement project done at site X likely to be successful?**

      (This question is very similar to 2a, but in this case applied to a single site as a "yes/no" question about doing restoration, rather than involving prioritization between multiple sites.)

      ***Example of management decision: r***estoration group decides whether to propose project at a particular site; funder decides whether to fund; conservation land trust or resource management organization decides whether to invest in oyster restoration at a particular property they own.

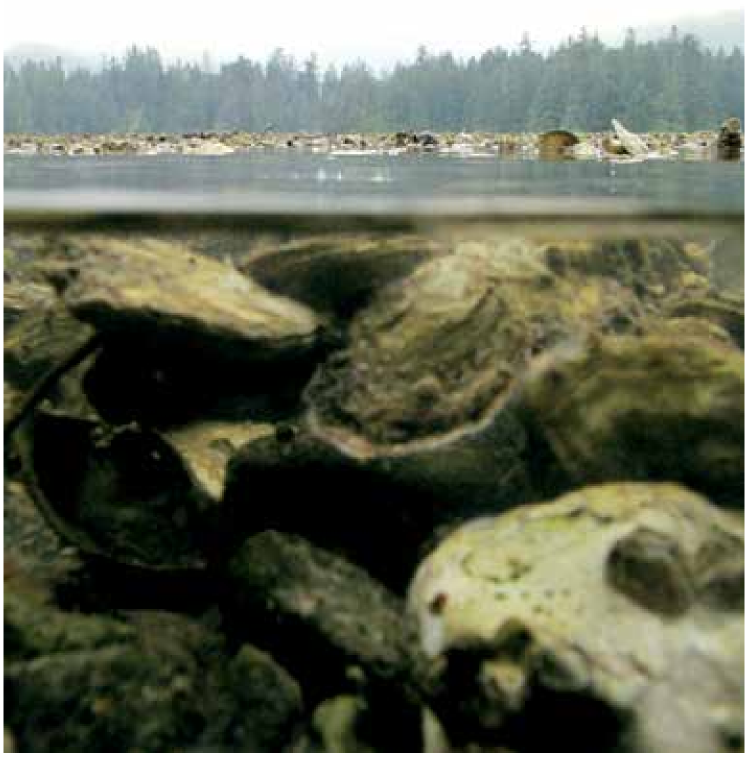
**Elegant oysters,**
**unique history and lore.**
**Habitats prevail!**

## Conclusions

This guide has synthesized data from recent laboratory experiments and field monitoring, and the published literature. We have used this information to characterize the attributes of sustainable Olympia oyster populations, and to identify the stressful environmental factors that affect them most strongly across the range of the species.

Overall, the most frequently encountered stressors across 28 embayments were sedimentation and predation. Competition, cold water temperatures, warm air temperatures, and freshwater inputs were also common concerns at many bays. These types of stressors are natural components of marine ecosystems. However, they have been exacerbated by human activities; for instance, a major predator in some embayments is a non-native snail introduced with aquaculture, and some land uses in estuarine watersheds (hydraulic mining, agriculture) have increased sedimentation rates in some estuaries. Global climate change may also increase exposure to these stressors, for instance increasing storm intensity and freshwater inputs or increasing frequency of exposure to high air temperatures or acidified waters.

We examined interactions between different stressors under laboratory conditions and found that the types of responses observed depended on the stressor and the timing of application. We documented some linear, additive relationships between stressors, and some that were non-linear and synergistic. It is clear that decreasing stressor levels through ecosystem management (such as reducing hypoxia resulting from nutrient loading) will support oysters, but it is hard to predict whether such stressor reduction will increase resilience to other stressors, such as those related to climate change.



*Top: Isthmus Slough, Oregon. Bottom: Olympia oysters in Nootka Sound, Vancouver Island, British Columbia.*

We have developed a site evaluation tool and used it to assess restoration and conservation potential of Olympia oysters in two Oregon and four California estuaries. As more investigations are conducted and restoration projects are implemented, understanding of oyster sustainability will evolve, and these guidelines will need updating. We hope that in the coming years, the recommendations provided here will support improved oyster conservation and restoration.

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From waters unknown
New lives spring into being
Next generation

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*Abbreviations:* T *(top),* M *(middle),* B *(bottom),* L *(left),* C *(center),* R *(right)*

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*Haikus: These originated as a joking response to a request to reduce our research into short, succinct paragraphs. It turned out they were fun to do.*

# Appendices

*Appendix 1*
*Southern California Site Evaluations: Newport and San Diego Bays*

*Appendix 2*
*Southern Oregon Site Evaluations: Coos Bay and South Slough*

## Appendix 1. Southern California Site Evaluations: Newport and San Diego Bays

### Overview

Seven sites in Newport Bay and in San Diego Bay were evaluated using the Site Evaluation Tables. The method of Wasson et al. 2014 was modified for these sites, because few environmental data were available and differences in data collection and the range of key oyster parameters required some revisions to scoring. The site locations and data collection and processing methods are described below, followed by a summary of the site evaluation results.

**Table 1.** List of field sites, site codes, and location by bay.

| *Bay* | *Site Name* | *Site Code* | *GPS Coordinates* |
|---|---|---|---|
| Newport | Highway 1 | HWY1 | 33.6178 -117.9049 |
| Newport | Coney Island | CI | 33.6196 -117.8922 |
| Newport | 15th Street | 15th | 33.6083, -117.9204 |
| Newport | Rocky Point | RP | 33.6295 -117.8859 |
| Newport | Lido Island Site 1 | LI 1 | 33.6131 -117.9157 |
| Newport | Lido Island Site 2 | LI 2 | 33.6113 -117.9119 |
| Newport | Newport Aquatic Center | NAC | 33.6232 -117.8933 |
| San Diego | Chula Vista Wildlife Reserve | CVWR | 32.6143 -117.1138 |
| San Diego | D Street Marsh | DSM | 32.6471 -117.1162 |
| San Diego | Signature Park | SP | 32.6333 -117.1076 |
| San Diego | J Street Marina | JSM | 32.6203 -117.1042 |
| San Diego | Coronado Cays | CC | 32.6264 -117.1294 |
| San Diego | Pond 11 North | P11N | 32.6027 -117.1180 |
| San Diego | Pond 11 South | P11S | 32.6025 -117.1179 |


*Map 1*. Newport Bay field sites.


*Map 2*. San Diego Bay field sites.

### Field Parameters

**Table 2.** List of parameters measured as part of this guide. Please refer to Table 1 for site codes. Timescales: Q = Quarterly, M = Monthly, B = Biweekly, C = Continuous, P = Periodically

| *Oyster Attributes* | *Sites and Timescale* |
|---|---|
| Adult density | Newport sites (P, Oct - Apr); San Diego sites (P, May - Dec) |
| Size | Only Newport sites, except NAC (P, Oct - Feb) |
| Growth rate | Only San Diego Bay sites (~M, May-Sept), except PIIS |
| Survival rate | Only San Diego Bay sites (~M, May-Sept), except PIIS |
| Recruitment rate | All sites (B) except HWY1, LI 1, LI 2, NAC |

**Table 3.** List of environmental factors, sites where data were collected, and the timescale for data collection.

| *Environmental Factors* | |
|---|---|
| Available substrate | All sites (P) |
| Water Temperature | 15th, CI, RP (C) |

## Field Methods

### *Oyster Attributes*

Adult oyster density

We monitored oyster density at Newport Bay sites between October and April from 2010 to 2013 and at San Diego Bay sites between May and December of 2013. At each site, we laid out a 50 X 2 m transect centered near 0 to +0.5 m mean lower low water (MLLW) and then counted the total number of oysters within 30 randomly placed 0.25 $m^2$ quadrats along the transect. Density data were also used in calculations for population estimates on hard substrate over a 2 x 150 m area at each site.

Adult oyster size

At all Newport Bay sites except Newport Aquatic Center, adult oyster sizes were surveyed October - November 2010 and January-February 2011. At haphazard points along the transect (see Adult Oyster Density, above), the longest dimension of all native oysters encountered was measured (n = 17 to 57 individuals). These data were used to generate the mean upper quartile. Size distribution data were sorted into 10 mm bins and used to calculate a size-class diversity index:

Gini-Simpson Index = 1 – Simson's index ($D_s$)
$D_s = \sum p_i^2$
$P_i$ = proportion of individuals in each group

Recruitment

We monitored recruitment by deploying four 15 x 15 cm red unglazed ceramic tiles near 0 m MLLW in all San Diego sites from June to October 2013 and at 15th Street, Coney Island and Rocky Point (Newport Bay) year-round from 2006 to 2014. From June to October tiles were collected in each bay approximately every two weeks, and we used these data to calculate recruitment rate. The total number of oysters was counted on each tile using a dissecting microscope to calculate a recruitment rate for each two-week period. The average recruitment rate was determined by averaging the rate from each collection period. The reliability of recruitment over the years was calculated for Newport Bay sites as the coefficient of variation of recruitment rate.

Juvenile growth and survival
At San Diego sites two additional recruitment tiles were deployed (see Recruitment, above), on May 30, 2013 and were collected and returned to the field ~monthly through September 2013 to measure growth and survival rates. Ten oysters per tile were identified after tile collection in June 2013 and their starting lengths were measured. In July and early September 2013, tiles were collected and oysters remaining from the original 10 were measured for growth and survival. Growth and survival rates were averaged between the two collection periods for each site.

*Environmental Factors*
Available substrate
In each bay, we used a 50 cm x 50 cm gridded quadrat along a transect (see Adult Oyster Density, above), to determine habitat percent cover. For each quadrat, we recorded habitat cover at 49 data points (e.g., mud, sand, dead shell, *Mytilus* spp., *O. lurida,* etc.) and from this calculated habitat percent cover. We combined habitat types into hard and soft substrate, and used average percent cover of hard substrate multiplied by oyster density to generate population size estimates.

Water temperature
In Newport Bay, Onset TidbiT temperature loggers were attached to recruitment tees near MLLW at 15th Street, Coney Island and Rocky Point. Loggers collected continuous data every 15 minutes from December 2009 through May 2012. As a rough estimate of water temperature, values above 29°C were excluded to eliminate air temperatures. The average daily warm period temperature was determined as the average of daily temperature means during April – September over each year.

## Modifications to the Site Evaluation Table

We made several modifications to the online version of Site Evaluation Table (Wasson et al. 2014). Because recruitment was recorded only for June-October for San Diego, we used average recruitment rate for that period only for both Newport Bay and San Diego. This resulted in significantly higher recruitment rates than the year-round rate reported for Central California. To reflect this we recalibrated the scoring bins, generally using order of magnitude differences in the raw data. Growth rates were calculated only for new settlers and only over a very short time period (~70 days), during which growth would be expected to be quite high. In contrast, the Central California data included older, larger oysters tracked over longer time periods. We adjusted scores for this parameter, reflecting the spread of the data. We also dropped scores for two sites, Coronado Cays and Signature Park, where fewer than 10 of the individuals being measured survived. We also decided to report water temperatures as the warm period daily average (April – September). We had data on water temperature for only three sites. Based on the assumption that warmer sites are generally better than cooler sites (Wasson et al. 2014), we scored the two warmer sites 100 and the cooler site at 75. It should be noted, however, that there is no indication from the data collected that the cooler site is impacting oyster performance.

## Site Evaluations

Fourteen sites were evaluated in the two Southern California bays. Overall, greater variability between sites existed within San Diego Bay, whereas the seven sites in Newport Bay were more consistent in all oyster attributes studied. Chula Vista Wildlife Reserve scored among the highest in conservation value, largely due to the highest adult density of all the southern California sites surveyed. Other top scoring conservation sites included Pond 11 South and J Street Marina in San Diego Bay and Newport Aquatic Center and 15th Street in Newport Bay, although all Newport Bay sites displayed relatively high conservation scores. However, it should be noted that the high score generated for Newport Aquatic Center is based on two parameters (population estimate and drill predation) and Pond 11 South on three parameters (population estimate, recruitment rate, and drill predation). San Diego sites demonstrate exceptionally high larval recruitment, much higher than Newport Bay sites. High recruitment, along with high juvenile survival and growth rates, resulted in all San Diego sites receiving high or medium high scores as potential restoration sites. All of these can be considered a high priority for restoration through the addition of hard substrate. The top restoration sites in Newport Bay were Newport Aquatic Center, 15th Street, Rocky Point, Highway 1 and Coney Island, with the two Lido sites showing slightly lower restoration scores; generally Newport sites scored lower than San Diego sites for restoration. Newport Aquatic Center already has a large oyster population; on this basis, the other high ranking sites might be preferentially selected for restoration. All sites received a boost in overall scores in the Seeding Score tab, but given the relatively high rates of recruitment in both bays, seeding is clearly not indicated as a restoration method.

However, there are several additional factors present at these sites not incorporated into the site evaluation metrics. First is the amount of available area for potential restoration. Most of the Newport Bay shoreline in particular is heavily armored by man-made substrates including rip rap, sea walls and pilings. Though oysters may perform well at certain sites, there may be little space available for hard substrate addition, particularly Newport Aquatic Center. Another factor of growing concern is the prevalence of the non-native oyster, *Crassostrea gigas*. Densities of *C. gigas* are higher in San Diego Bay than in Newport Bay and in San Diego Bay in particular, densities of *C. gigas* at some sites (Coronado Cays and J Street Marsh) are quite high. It is unclear if high *C. gigas* densities are having a negative impact on native oysters, however, in an effort to reduce potential competition between the two oyster species, restoration practitioners have deployed oyster restoration efforts at tidal elevations lower than the height where *C. gigas* are found in greater abundance (+ 0.75 to 1 m MLLW). Therefore, it is still unclear if high *C. gigas* populations would negatively impact native oyster restoration success or whether restoration plans may be altered to limit any potential negative impacts.

Newport Bay Site Evaluation Table (detailed version available from www.oysters-and-climate.org)

| | Rocky Point | Newport Aquatic Center | Coney Island | HWY 1 | Lido Island Site 1 | Lido Island Site 2 | 15th Street |
|---|---|---|---|---|---|---|---|
| ADULT OYSTER DENSITY | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| OYSTER POPULATION SIZE | 75 | 100 | 75 | 75 | 75 | 75 | 100 |
| ADULT OYSTER SIZE | 50 | | 50 | 50 | 50 | 50 | 50 |
| DIVERSITY OF SIZE CLASSES | 50 | | 75 | 75 | 50 | 50 | 75 |
| RECRUIT DENSITY | 50 | | 50 | | | | 50 |
| RELIABLE RECRUITMENT | 100 | | 50 | | | | 100 |
| WATER TEMPERATURE | 100 | | 100 | | | | 75 |
| DRILL PREDATION | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| **OVERALL SCORES** | | | | | | | |
| **Restoration** (natural recruitment) | 69 | 71 | 68 | 68 | 62 | 62 | 70 |
| **Restoration** (with seeding) | 71 | 80 | 70 | 71 | 64 | 64 | 72 |
| **Conservation** | 71 | 100 | 74 | 75 | 73 | 73 | 89 |

## San Diego Bay Site Evaluation Table (detailed version available from www.oysters-and-climate.org)

| | D Street Marsh | Signature Park | Coronado Cays | J Street Marina | CVWR | Pond 11 North | Pond 11 South |
|---|---|---|---|---|---|---|---|
| ADULT OYSTER DENSITY | 0 | 0 | 25 | 50 | 75 | 25 | 50 |
| OYSTER POPULATION SIZE | 0 | 0 | 50 | 75 | 100 | 25 | 75 |
| RECRUIT DENSITY | 75 | 75 | 100 | 75 | 75 | 100 | 100 |
| SURVIVAL RATE | 100 | 100 | 100 | 100 | 100 | 100 | |
| GROWTH RATE | 75 | | | 75 | 50 | 100 | |
| DRILL PREDATION | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| **OVERALL SCORES** | | | | | | | |
| **Restoration** (natural recruitment) | 66 | 64 | 79 | 78 | 81 | 81 | 82 |
| **Restoration** (with seeding) | 77 | 77 | 87 | 83 | 80 | 90 | 87 |
| **Conservation** | 0 | 0 | 72 | 79 | 91 | 61 | 85 |

# Appendix 2.
# Southern Oregon Site Evaluations: Coos Bay and South Slough

## Overview

We (A. Helms, B. Yednock) evaluated three sites in the northeastern portion of the Coos estuary (referred to as Coos Bay), and one site in South Slough, which comprises the major southern arm of the Coos estuary. The majority of the data used to evaluate the three sites in Coos Bay came from previously published manuscripts (Groth and Rumrill 2009) and student theses (Pritchard 2014, Rimler 2014, Oates 2013). A small amount of unpublished data that were collected in 2014 by staff and interns of South Slough National Estuarine Research Reserve at one of the Coos Bay sites (Coalbank Slough) and at two Olympia oyster reintroduction sites in South Slough were also included in the site evaluation tables. With the exception of South Slough, where oysters were absent until they were reintroduced through a project that began in 2008, the sites in Coos Bay consist of fairly established oyster populations stemming from the reappearance of Olympia oysters to the Coos estuary in the late 1980s. As a result, in general, Coos Bay sites have higher adult densities than the South Slough sites. The site locations and data collection and processing methods are described below, followed by a summary of the site evaluation results.

## Site selection and use of field data in site evaluations

We selected three sites (Downtown Coos Bay, Haynes Inlet, and Coalbank Slough) for restoration evaluations because these sites had data available for both adult oysters and recruits, including growth and survival rates, in addition to larval abundance. Each of these three sites also paired with water quality sonde stations in Coos Bay that were between 1.2 to 3 km away. There were three additional sites from the Groth and Rumrill 2009 study in Coos Bay (Millington, Eastside, Pony Point) where adult density measures were available but no recruitment, growth, or survival measurements were made. From Pritchard (2013) and Rimler (2013), there were three additional Coos Bay sites (Empire, Catching Slough, and Airport) with recruitment and larval abundance data, but adult oyster measurements were not made as part of their work. Therefore, these latter 6 sites were not included in this evaluation.

We selected two reintroduction sites (South Slough-Valino Island and South Slough-Long Island) in the South Slough estuary for evaluating their appropriateness for restoration, based on seeding. The Seeding Score is calculated with a formula that makes recruitment rate less important, to determine if it is appropriate for restoration with seeding by aquaculture spat. Environmental conditions for both sites were characterized by data from the same nearby continuous water quality monitoring station. These two sites do not have naturally established adult oyster populations like the Coos Bay sites that were evaluated for restoration. The adults at these two sites were generated from a reintroduction project that began in 2008 with Olympia oyster cultch from a hatchery along with settled juveniles from the hatchery (2009); both were transplanted to Younker Point in Coos Bay for growth and survival studies. Burial by sediments was responsible for the relocation of the oysters from the reintroduction project site at Younker Point to the two seeding sites, Valino Island and Long Island, located further up the estuary and across from each other separated by the main channel. Oysters were transplanted to the current two locations in 2012 and monitoring began in 2014.

We selected one site, Downtown, to evaluate for its current conservation value based on it having the highest density of adults and recruits and the highest larval abundance of the three sites evaluated for restoration. It also has comparatively more available hard substrate than the other sites, which is an important factor. This evaluation required a new parameter *adult oyster population size*, which had not been quantified for any Coos Bay sites. Based on adult oyster densities from Groth and Rumrill (2009) at this site along with a quick field assessment we conducted in May of 2015, we roughly estimated that there are likely more than 1000 oysters along 300 m of intertidal shoreline. Despite oysters being very patchy along the shoreline, there are areas of higher density including the field site where Rimler 2014 conducted her research.

## Field Sites

**Table 1.** List of oyster field sites, site codes, and locations by sub-basin

| *Embayment* | *Site Name* | *Site Code* | *GPS Coordinates* |
|---|---|---|---|
| Coos Bay | Downtown Coos Bay | DN | 43.37853 N, 124.21559 W |
| Coos Bay | Haynes Inlet | HI | 43.44070 N, 124.22086 W |
| Coos Bay | Coalbank Slough<br>Coalbank-Railroad Bridge<br>Coalbank-Edgewater Hotel | CB<br>CB-RB<br>CB-EH | 43.35590 N, 124.2091 W<br>43.36021 N, 124.20616 W<br>43.36006 N, 124.20689 W |
| South Slough | South Slough-Valino Island<br>South Slough-Long Island | SS-VA<br>SS-LI | 43.30775 N, 124.31962 W<br>43.30716 N, 124.3186 W |

**Table 2.** List of continuous water quality and meteorological stations, station institution, and location by bay.

| *Embayment* | *Station Name* | *Station Code* | *Station Institution* | *GPS Coordinates* | *Distance from oyster field site* |
|---|---|---|---|---|---|
| Coos Bay | Kokwel Wharf | KW | Coquille Indian Tribe | 43.4034055 N, 124.219477 W | 2.9 km (DN) |
| Coos Bay | North Point | NP | NERR, Partnership for Coastal Watersheds | 43.42575 N, 124.222703 W | 1.6 km (HI) |
| Coos Bay | Isthmus Slough | IS | NERR, Partnership for Coastal Watersheds | 43.327808 N, 124.200409 W | 3 km (CB) |
| South Slough | Valino Island | VA | NERR SWMP | 43.3172374 N, 124.3216473 W | 1.2 km (SS) |
| Coos Bay | North Bend Airport | KOTH | Southwest Oregon Regional Airport | 43.4171° N, 124.2460° W | 3.3 km (HI)<br>5.1 km (DN)<br>7.6 km (CB) |
| South Slough | Charleston Met | CM | NERR SWMP | 43.3450 N, 124.3287 W | 4.4 km (SS) |

## Field Parameters

**Table 3.** List of oyster attributes, sites where data were collected, and the timescale for data collection.

| *Oyster Attributes* | *Sites* | *Timescale* |
|---|---|---|
| Adult density | DN, HI<br>CB-RB, CB-EH, SS-VA, SS-LI | 2006<br>2014 |
| Size | DN<br>CB-RB, CB-EH, SS-VA, SS-LI | 2006<br>2014 |
| Size Frequency | DN<br>CB-RB, CB-EH, SS-VA, SS-LI | 2006<br>2014 |
| Growth rate | DN, HI, CB<br>SS-VA, SS-LI | Jan - July 2013<br>Jan – May 2009 |
| Survival rate | DN, HI, CB | Jan - July 2013 |
| Recruitment rate | DN, HI, CB | July-Nov 2012, May-Aug2013 |
| Larval abundance | DN, HI, CB | July-Nov 2012, May-Aug 2013 |

## Environmental Parameters

**Table 4.** List of environmental factors, sites where data were collected, and the timescale for data collection.

| *Environmental Factors* | *Sites* | *Timescale* |
|---|---|---|
| Water temperature | KW<br>NP, IS<br>VA | Sept 2013-March 2015<br>Oct 2013-March 2015<br>Jan 2010-Dec 2014 |
| Dissolved oxygen | KW<br>NP, IS<br>VA | Sept 2013-March 2015<br>Oct 2013-March 2015<br>Jan 2010-Dec 2014 |
| Salinity | KW<br>NP, IS<br>VA | Sept 2013-March 2015<br>Oct 2013-March 2015<br>Jan 2010-Dec 2014 |
| pH | KW<br>NP, IS<br>VA | Sept 2013-March 2015<br>Oct 2013-March 2015<br>Jan 2010-Dec 2014 |
| Air temperature | KOTH, CM | Jan 2013-Dec 2014 |
| Substrate availability | DN, HI, CB | 2012-2013 |
| Chlorophyll a | VA<br>HI, CB | 2010-2013<br>2013 |

## Field Methods

### *Oyster Attributes*

<u>Adult oyster density and size</u>

Means for adult density per $m^2$ for Downtown and Haynes Inlet were used from Groth and Rumrill (2009). Mean adult size for Downtown was also used from Groth and Rumrill (2009) and only included measurements for oysters >20 mm; size data were unavailable for Haynes Inlet. Data for mean adult density per $m^2$ and adult size measurements were collected at Coalbank Slough and South Slough in 2014 as part of an oyster restoration monitoring project. For these surveys, data were collected at 2 m intervals along three 10 m transects at each of the two sites in South Slough and two sites in Coalbank Slough. A maximum of 10 oysters within a ½ $m^2$ quadrat were measured. Five density observations were also made for each transect at 2 m intervals. Data from the two sites in Coalbank Slough (CB-RB and CB-EH) were combined to represent the size and density of adult oysters in Coalbank Slough. The site (CB) where recruitment data were collected by Rimler (2014) is approximately 500 meters from CB-RB and CB-EH.

<u>Diversity of size classes</u>

Data from Groth and Rumrill (2009) were used to evaluate size-class diversity for Downtown. Because only oysters >20 mm in length were measured in the study, this sample represents the largest oysters, so this measurement needs to be interpreted carefully. Size data from the 2014 monitoring surveys at the Coalbank Slough and South Slough sites were used to assess size class diversity for those locations (no size limit was used for those oyster measurements). Oyster sizes were placed into 10 mm bins and used to generate a size-class diversity index (Gini-Simpson).

Gini-Simpson Index = 1 – Simpson index ($D_s$)
$D_s = \sum p_i^2$
$P_i$ = proportion of individuals in each group

<u>Growth and survival</u>

Data for these attributes came from Rimler (2014). For this study 7 to 8 oysters (17.5 – 27.5 mm in height) were epoxied to each of four 10 cm x 10 cm unglazed ceramic tiles that were deployed at each site from 1/10/2013 until 7/10/2013. Tiles were retrieved and oysters were measured and assessed for survival four times during the deployment period. Mean growth rate per day from January to July is reported in the site evaluation tables. A survival rate (% survival from January-July) was calculated from the same data and reported in the site evaluation tables. The growth rate for the South Slough sites shown in the seeding score site evaluation table was calculated from data presented in Rumrill (2010) and based on measurements of oysters growing on shell bags that were sampled four times from January to May in 2009.

<u>Recruitment</u>

Recruitment data also came from Rimler (2014) in which eight replicate 10 cm x 10 cm unglazed tile plates were deployed at each site from 8/3/2012 to 11/14/2012 and 6/10/2013 to 11/18/2013. Plates were retrieved and replaced approximately every two weeks during the deployment period. The number of recruits was counted in a randomly selected subsection of each plate and used to calculate the mean number of recruits per 100 $cm^2$. For the site evaluation tables, we converted the means reported in Rimler (2014) to mean number per $m^2$ per day.

Larval abundance

Mean larval abundance data came from Pritchard (2014). For this study, larval traps were deployed at the same time and adjacent to the settlement plates used by Rimler (2014). Traps consisted of a funnel (7 cm x 5 cm), a PVC tube (61 cm x 5 cm), and a PVC stake fully inserted into the sediment. D-stage, umbo-stage, and settler abundances were counted from each of five replicate traps approximately every two weeks. Peak mean abundance of umbo-stage larvae (reported in the site evaluation tables) was calculated from collections in 2012 and 2013 and averaged across years.

### *Environmental Factors*

Water temperature, salinity, dissolved oxygen, pH

YSI EXO2 or 6600V2 water quality sondes were deployed at permanent monitoring locations in Coos Bay and South Slough. Water quality sondes collect water temperature, specific conductivity, salinity, dissolved oxygen, pH, turbidity, and water depth data continuously every 15 minutes. Data collection and management follow standardized National Estuarine Research Reserve System-wide Monitoring Program (NERR SWMP) protocols (http://cdmo.baruch.sc.edu).

Chlorophyll *a*

For Haynes Inlet and Coalbank Slough, Oates (2013) collected chlorophyll *a* data by monthly grab samples with three replicates averaged for monthly values, however only the highest and lowest monthly values were reported in the thesis. Therefore, we present in the site evaluation table the highest monthly average for chlorophyll *a* at those sites. For the South Slough sites, chlorophyll *a* values were used from the NERR SWMP monthly nutrient program (2010-2014) which collects monthly triplicate grab samples. For comparability with the restoration sites, we also only present the highest monthly average and we only used summer months.

Air temperature

Air temperature data for the Restoration Site Evaluation Table were recorded by the North Bend, OR airport meteorological station (KOTH) and reported as daily maximum mean values. Air temperature data for the seeding sites in South Slough were recorded by the NERR SWMP meteorological station (CM) and were calculated as daily maximum mean values from 15 min averages; the data logger records measurements every 5 seconds and these are averaged over a 15 min interval.

Available substrate

The type and amount of available substrate was qualitatively described in Rimler (2014) for the three sites included in the Restoration Site Evaluation Table: Downtown, Haynes Inlet, Coalbank Slough. Because sites were described relative to each other, qualitative information was used to create categories and related scores for each category.

## Modifications to the Site Evaluation Table

In general, we followed the methods of Wasson et al. (2014) for site evaluations, in terms of parameters included and thresholds used to assign scores. However, we omitted *Reliable Recruitment* and *Larvae Exported* as parameters because data for these parameters were not available for any of our sites. We included *Adult Oyster Size*, *Diversity of Size Classes*, and *Chlorophyll* a as parameters for sites when sufficient data were available. We added parameters for *Larval Abundance*, *Risk of Low pH Events*, and *Hard Substrate Availability* because these are important factors for assessing oyster success and data were available for these parameters for all of our sites. Generally, bins were selected based on the distribution and variability in available datasets to maximize our ability to rank sites relative to one another. For *Survival Rate* and *Low Dissolved Oxygen*, we changed the scoring bin thresholds, because our units of measurement for these parameters differed from those of Wasson et al. (2014). For *Growth Rate*, we reduced all bin thresholds by 50% because data were only available for two quarters (i.e. six months) for our sites, whereas Wasson et al. (2014) averaged growth across all quarters of a year. For the *Low Dissolved Oxygen* parameter, we also used a different assessment metric since we had continuous sonde measurements; percent of data observations where DO fell below 5 mg/L were calculated. Bins for dissolved oxygen were selected to capture large site differences between the number of observations below 5 mg/L. For example, sites had a range including 0, 6, 1,035, and 3,333 instances where DO fell below 5 mg/L; these raw observations were adjusted by total number of observations in the dataset, which varied by site. For *Salinity Range,* we changed the threshold to percent days per year where average salinity was less than 15 ppt (from 25 ppt used in Wasson et al. (2014)). Evidence supports this lower threshold for Coos Bay and South Slough. Gibson (1974) found that salinities of 15 ppt and lower demonstrated deleterious effects on oyster populations in Oregon and Oates (2013) found low salinity effects on various reproductive condition indices at salinities lower than 15 ppt. However, our sites experience a wide range of salinity from 2.7 to 33.3 ppt, primarily from seasonal freshwater inputs, and oyster presence in these low salinity areas indicates oysters may be adapted to local conditions. We also changed the threshold for *Water Temperature* from 12°C to 15°C based on site-specific data on oyster temperature requirements; 15°C is thought to be a critical reproductive temperature; below this temperature spawning may not occur (Pritchard 2013). For the *Chlorophyll a* parameter, we used the highest monthly average concentration from each site because this was a common measure available for all sites.

## Results of site evaluations

### *Restoration potential*

Three sites (Downtown, Haynes Inlet, Coalbank Slough) were evaluated for restoration potential. The highest scoring site for restoration in Coos Bay was Downtown, although Haynes Inlet resulted in only a slightly lower score. Downtown had as much as 16 times higher densities of adults and 3 times the larval abundance as Haynes Inlet and Coalbank Slough. In addition, Downtown had the highest availability of hard substrate (e.g. rip-rap, rock, rubble, pilings), which is a potential limiting factor for other sites. It appears salinity may not be a major stressor for oysters at Coos Bay sites where daily averages were below 15 ppt for up to 39 percent of the year. All of the Coos Bay sites that we evaluated are located in the mid to upper estuary where they can experience long periods of high freshwater riverine input during the rainy season (November– April). In particular, Coalbank Slough had the highest percentage of years with consecutive low salinity events (6 events lasting up to 11 days) followed by Downtown with 1 event (lasting 4 days) over the 1.5 year period; Haynes Inlet had no prolonged low salinity events. Olympia oysters are generally absent from the lower reaches of the estuary where salinities are highest, with the exception of the Charleston Marina and (after reintroduction) South Slough.

Coalbank Slough and Haynes Inlet experienced lower dissolved oxygen (DO) concentrations than Downtown but overall low DO events were uncommon at all sites with < 2.5 % of values falling below 5 mg/L. Water temperatures were higher at Downtown and Coalbank Slough than at Haynes Inlet, most likely due to the location of Haynes Inlet which is lower in the estuary, although all sites had similar scoring for water temperature. Low pH events may be a stressor for oysters in upper estuary/riverine sites, although this stressor needs to be evaluated for local effects in estuaries. Coalbank Slough had the highest risk of low pH events and is located the furthest up the estuary, but pH at this site is highly variable.

Average chlorophyll concentrations measured at Haynes Inlet and Coalbank were moderate and may contribute to higher oyster performance at these sites. At all sites, high air temperature events (> 30°C) were rare (<1% days/yr), therefore this stressor doesn't currently seem to be a concern.

Additional data from three sites in Coos Bay (Airport, Empire, and Catching Slough) are available from the Pritchard and Rimler theses but the data are not presented here as these have more data gaps than the sites we included in our restoration potential evaluation tables. Density data for another location in Coos Bay (Isthmus Slough mitigation site) are also available from the work of Scott Groth (Oregon Department of Fish and Wildlife) where densities of up to 1000/$m^2$ were observed. Including additional sites and filling in data gaps will be an important step for future revisions of the Coos Bay appendix of the Guide.

*Restoration potential with seeding*
We evaluated two reintroduction sites in South Slough to determine the restoration potential of these sites with seeding. Both sites scored similarly overall (56 & 58%). Although Valino Island (SS-VI) had slightly higher adult oyster density and size than Long Island (SS-LI), it had a lower diversity index which resulted in a slightly lower overall score. Since the sites were located very close together and relocated oysters were placed at both new sites randomly, we also considered the averaged metrics from the two sites for a combined score. The environmental factors that may contribute to potential stress for oysters were low chlorophyll levels, some low DO events (2% of observations fell below 5 mg/L), as well as prolonged low salinity events (20% of the year). However, as with the Coos Bay sites, salinity may not be a stressor for native oysters in South Slough since salinity is seasonally variable and can range from 11.3-33.3 ppt. The salinity range metric at Valino Island scored high with only 1 % of days per year averaging less than 15 ppt. Also, there are commercial oyster (*Crassostrea gigas*) operations near Long Island as well as at locations further up the estuary. On the other hand, sedimentation may be a stressor for oysters in South Slough, although it hasn't formally been assessed. The fact that high sedimentation rates required the relocation of outplanted oysters to a new site in South Slough suggests sedimentation may impact future seeding operations.

*Conservation value*
Downtown Coos Bay was evaluated for its value as a conservation site because it has the highest recruitment rates and larval abundances of all the sites that were evaluated. It also has suitable substrate, which would favor recruitment and reduce pressure from sedimentation. The overall oyster conservation score for Downtown (71%) is reasonably high, suggesting it may be an important site to focus conservation efforts. However, it should be noted that the adult oyster population size was a rough estimate from a brief survey to count oyster densities and that more data should be collected at this site. Overall, this site scored fairly high for the environmental parameters, with the exception of prolonged low salinity events. However, as mentioned earlier, the presence of oysters in Coos Bay at locations with low and/or variable salinities suggests native oysters may be locally adapted to these conditions. Similarly, recruits and larval abundances are all high at the Downtown site so they do not appear to be affected by low salinity.

| | COOS BAY | | | SOUTH SLOUGH | | |
|---|---|---|---|---|---|---|
| | Downtown Coos Bay | Haynes Inlet | Coalbank Slough | South Slough combined | Valino Island | Long Island |
| ADULT OYSTER DENSITY | 50 | 25 | 50 | 50 | 50 | 50 |
| OYSTER POPULATION SIZE | 75 | | | | | |
| ADULT OYSTER SIZE | 50 | | 25 | 50 | 50 | 50 |
| DIVERSITY OF SIZE CLASSES | 50 | | 75 | 75 | 50 | 75 |
| RECRUIT DENSITY | 75 | 75 | 50 | | | |
| LARVAL ABUNDANCE | 75 | 25 | 50 | | | |
| SURVIVAL RATE | 75 | 50 | 75 | | | |
| GROWTH RATE | 25 | 75 | 25 | 25 | 25 | 25 |
| WATER TEMPERATURE | 75 | 50 | 75 | 50 | 50 | 50 |
| AIR TEMPERATURE | 100 | 100 | 100 | 100 | 100 | 100 |
| CHLOROPHYLL | | 25 | 25 | 25 | 25 | 25 |
| LOW DISSOLVED OXYGEN | 100 | 75 | 50 | 50 | 50 | 50 |
| SALINITY RANGE | 75 | 75 | 25 | 75 | 75 | 75 |
| RISK OF LOW SALINITY EVENTS | 0 | 100 | 0 | 50 | 50 | 50 |
| RISK OF LOW PH EVENTS | 75 | 100 | 25 | 75 | 75 | 75 |
| HARD SUBSTRATE AVAILABILITY | 75 | 50 | 50 | | | |
| DRILL PREDATION | 100 | 100 | 100 | 100 | 100 | 100 |
| **OVERALL SCORES** | | | | | | |
| **Restoration** (natural recruitment) | 67 | 66 | 50 | | | |
| **Restoration** (with seeding) | | | | 58 | 56 | 58 |
| **Conservation** | 71 | | | | | |

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