Ecosystem Effects of Oyster Restoration in Virginia Habitat and Lease Areas

A Report to the Maryland Department of Natural Resources

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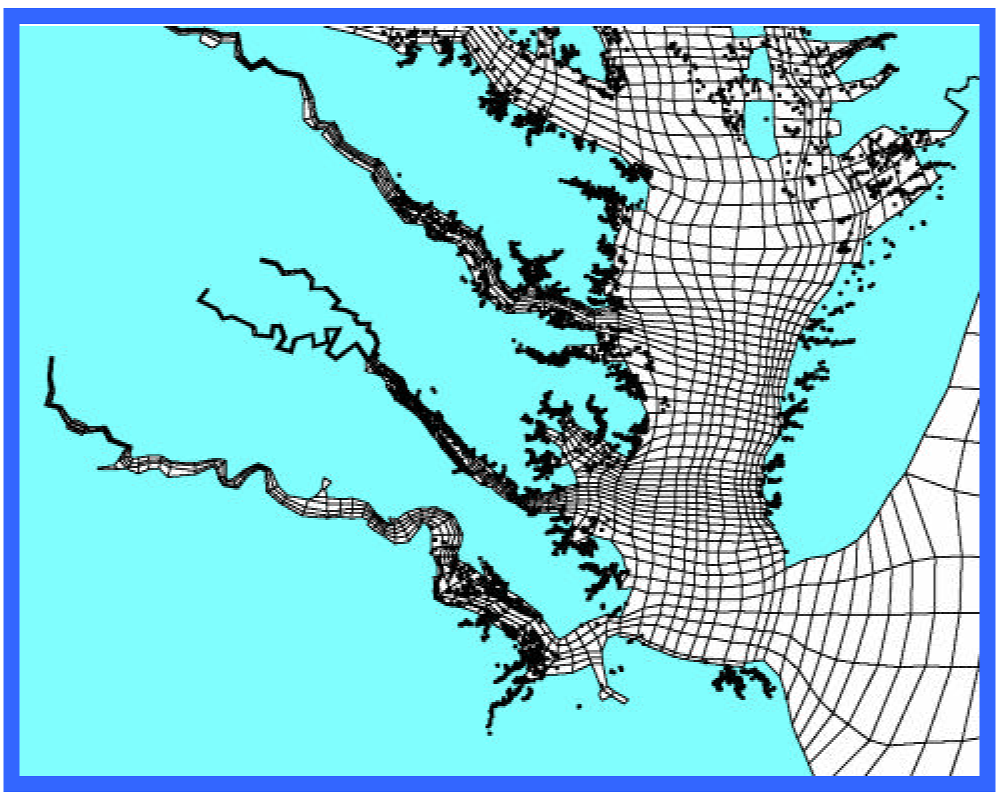

Abstract

This report is the third in a series in which the Chesapeake Bay Environmental Model Package was used to assess the environmental benefits of oyster restoration in Chesapeake Bay. Here, the effects of oyster restoration to all potential Virginia oyster habitat were investigated. Three scenarios were completed with oyster mortality rates corresponding to 1994 base rates, to rates which allow a ten-fold biomass increase in regions that presently support oysters, and to rates consistent with 1920-1970 biomass in regions that presently support oysters. Benefits of establishing oysters in new areas were negligible for 1994 base mortality rates. Maximum benefits were computed for mortality rates consistent with 1920-1970 population levels. The maximum benefits from restoration to all potential Virginia habitat, compared to existing habitat, included: 0.44 µg/L reduction in summer-average surface chlorophyll, 0.04 mg/L increase in summer-average deep-water (d > 12.9 m) dissolved oxygen, 0.06 /m reduction in summer-average light attenuation, 687 tonnes C (11%) additional SAV, and 5301 kg/d nitrogen removal.

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1 Introduction

The present report is the third in a series that examines ecosystem effects of oyster restoration in Chesapeake Bay. All investigations were conducted through the inclusion of an oyster module into the Chesapeake Bay Environmental Model Package (CBEMP), a comprehensive mathematical model of physical and eutrophication processes in the bay and its tidal tributaries (Cerco and Noel 2004). The first report (Cerco and Noel 2005a) examined the effect of a ten-fold increase in the native oyster population. The second report (Cerco and Noel 2005b) expanded the range of oyster biomasses examined. A common feature of both investigations was that oysters were restricted to their present locations (Figure 1). The present distribution covers a wide area, albeit at low biomass density, in the Maryland portion of the Bay. In Virginia, the present distribution is restricted to a much smaller area with concentrations in the James and Rappahannock Rivers. Historic surveys and existing lease holdings indicate the potential for oyster restoration to widespread areas of Virginia. The present report examines ecosystem effects projected to result from oyster restoration to Virginia oyster grounds and lease holdings that do not presently support oyster populations.

Potential Virginia Oyster Distribution

The existing Virginia oyster biomass was based on information provided by Dr. Roger Mann of Virginia Institute of Marine Science. Patent tong samples were averaged according to cells in the model grid and provided to us as g DW m^{-2} per model cell. Estimates were provided for one to five individual years in the interval 1998-2002.

The potential distribution was based on a GIS file provided by Kelly Greenhawk, Maryland Department of Natural Resources, in January 2006. The file contained bar location and area for four habitats:

- Maryland Habitat (MH)
- Maryland Lease (ML)
- Virginia Habitat (VH)
- Virginia Lease (VL)

All oyster bars listed in the GIS file were mapped to the model grid (Figure 2). A significant number of bars were located in tidal creeks too small to distinguish on the grid. These were mapped to the nearest model grid cell. The potential distribution introduced oyster bars along the lower eastern and western shores of the Bay, in the York River, and in Virginia Potomac embayments. Oyster habitat in the James and Rappahannock Rivers was greatly expanded. The total area of VH and VL bars was 128.5 km^2 compared to 42.2 km^2 of oyster bars in model cells that presently support oysters. The area of Virginia model cells that contain VH and VL bars was 1491 km^2 compared to 377 km^2 of cells that presently support oysters.

Potential Virginia Oyster Biomass

Model scenarios are based on baywide total oyster biomass, quantified as a ten-year (1984-1995) autumn average. Baywide biomass is attained through specification of a uniform mortality coefficient that represents the combined effects of predation, disease, and harvest. Biomass on the local scale of model cells (˜ 2 km x 2 km) is computed within the model and is influenced by food availability, salinity, suspended solids concentration, dissolved oxygen concentration, and other factors (Cerco and Noel 2005a). Scenarios were previously completed based on 1994 baseline biomass, a ten-fold increase in biomass, and restoration to biomass characteristic of the period 1920-1970 (Cerco and Noel 2005b). For the present investigation, mortality coefficients characteristic of these biomass levels were retained but oysters were placed in all model cells coded as VH or VL. The Maryland oyster distribution was unchanged from previous model runs. The additional area roughly doubles computed Virginia biomass (Table 1) under 1994 baseline mortality rates. The projected biomass more than triples under mortality rates that correspond to a ten-fold biomass increase and 1920-1970 population levels.

Table 1
Oyster Biomass Estimates

Run Code	Mortality Rate, 1/d	Maryland, kg DW	Virginia (previous), kg DW	Virginia (new), kg DW	Total, kg DW	
OYS36	0.028	821,902	239,680	451,906	1,273,808	Mortality corresponding to present biomass levels
OYS37	0.0236	8,356,620	1,785,170	6,439,024	14,795,644	Mortality based on ten-fold biomass increase
OYS38	0.019	18,238,940	4,218,842	13,349,828	31,588,768	Mortality derived from 1920-1970 biomass levels

References

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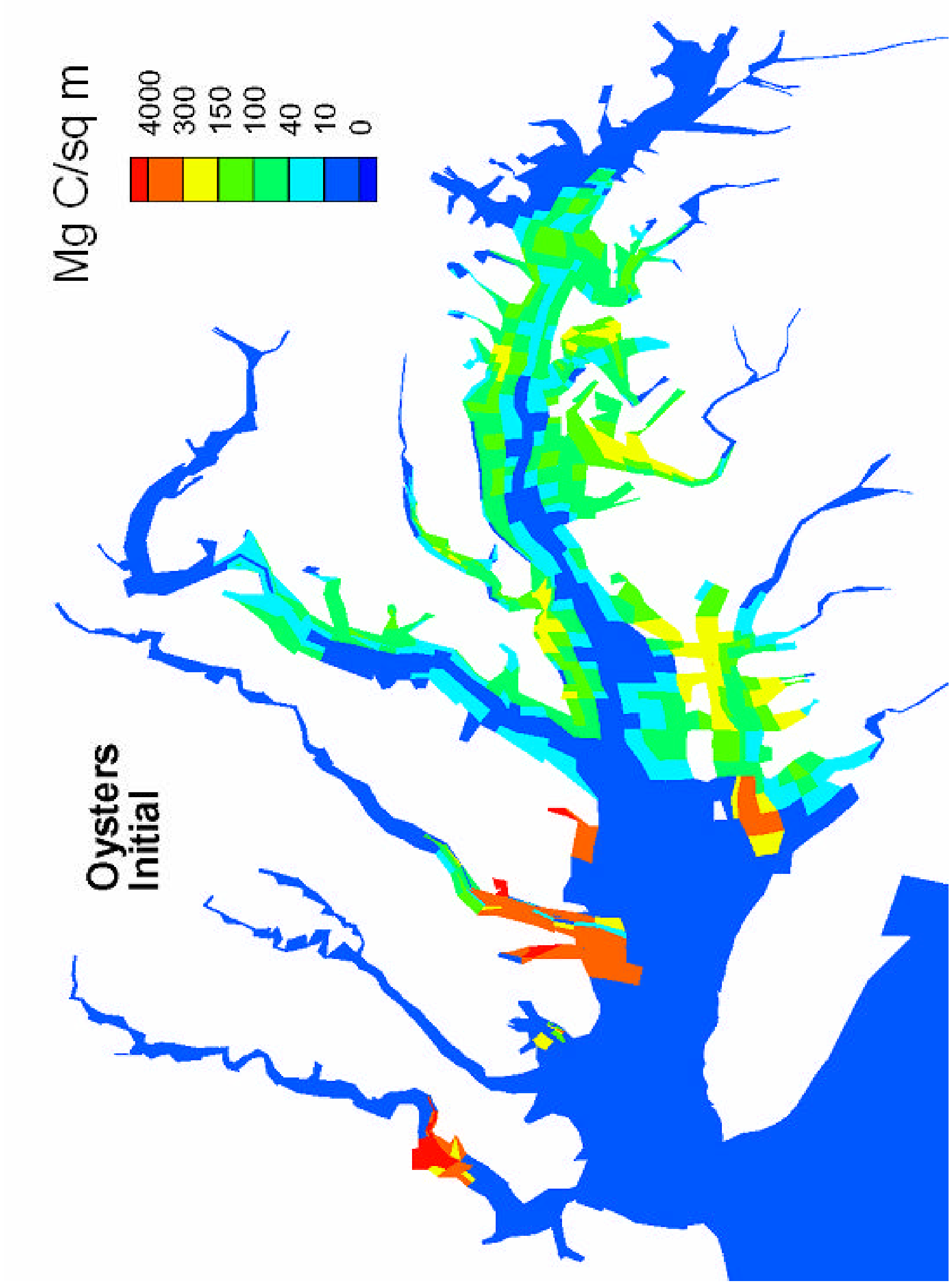

Figure 1. Present oyster density in Chesapeake Bay (Cerco and Noel 2005)

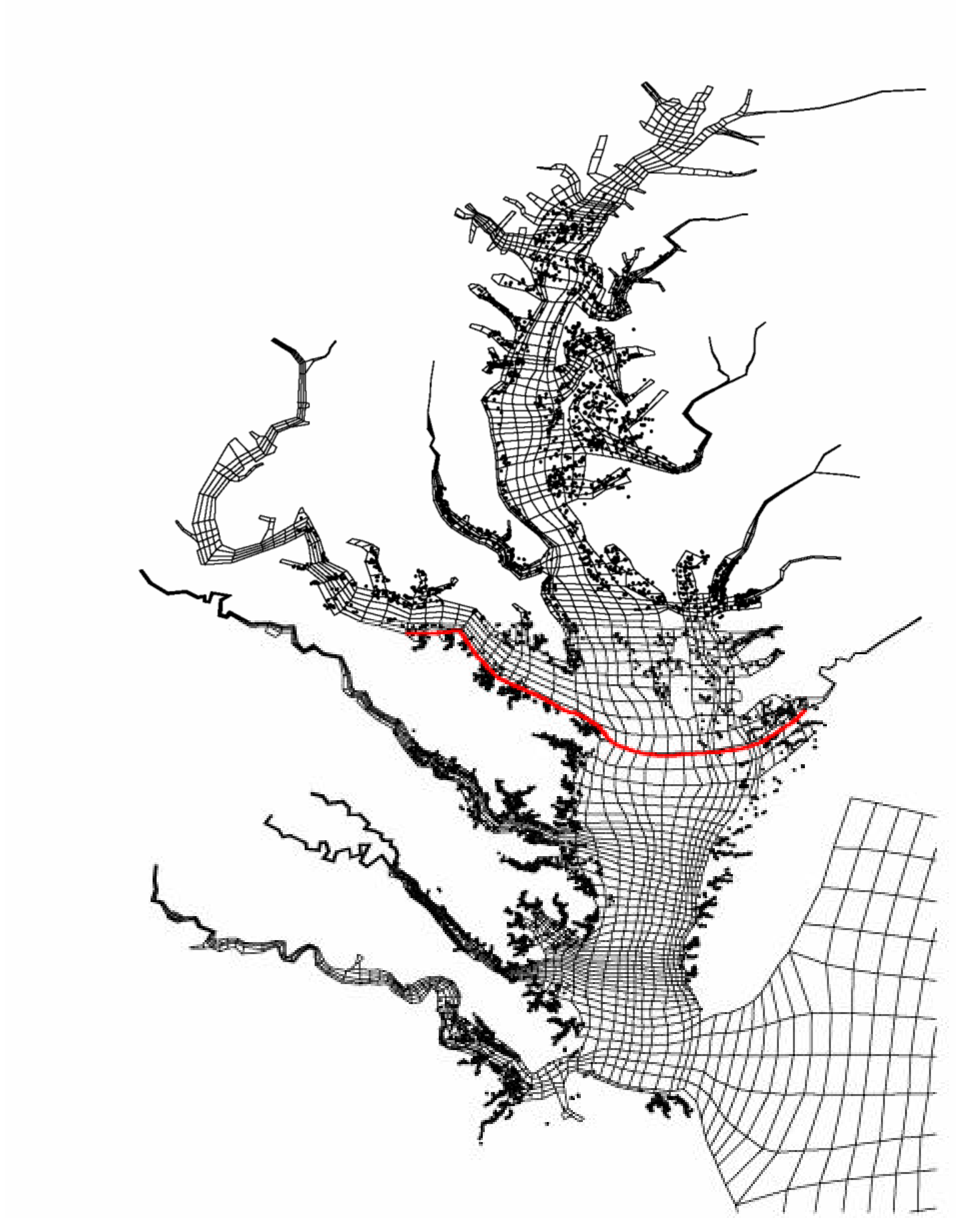

Figure 2. Existing and potential oyster bars superimposed on model grid. Red line shows approximate Maryland-Virginia boundary.

2 Local-Scale Effects

A significant finding of the initial investigation (Cerco and Noel 2005) was that benefits of oyster restoration depend on local geometry and circulation. Oyster restoration was projected to be most beneficial in shallow regions with limited exchange rather than in regions of great depth, large volume and spatial extent. Greater potential was projected for restoration to influence submerged aquatic vegetation (SAV), which co-occurs with oyster beds, than for bottom-water hypoxia, which occurs in locales far removed from shallow-water oyster bars. These results are consistent with previous investigations (Officer et al. 1982, Gerritsen et al. 1994) and form a hypothesis for the expected effects of oyster introduction into regions in which they are presently not found. That is, we expect greater benefits in shallow, semi-enclosed, regions and we expect greater influence on SAV rather than dissolved oxygen.

Five regions (Figure 1) were selected for examination of local-scale effects:

- Lower Chesapeake Bay polyhaline (CB7PH)
- James River polyhaline (JAMSPH)
- Mobjack Bay polyhaline (MOBPH)
- York River mesohaline (YRKMH)
- Pocomoke Sound mesohaline (POCMH)

These were selected to provide a range of geometry (Table 1) and oyster biomass. At one extreme, CB7PH represents an extensive, deep, mainstem bay segment with only a small fractional area subject to oyster restoration. At the other extreme, Pocomoke Sound represents a shallow environment fully subject to restoration. Three segments, CB7PH, JAMSPH, YRKMH, support no oysters at present (Figure 2). MOBPH and POCMH presently support small populations. While dissolved oxygen standards are violated at times and locations, anoxia or severe hypoxia are not problems in the segments selected. Only MOBPH is subject to problematic dissolved oxygen concentrations; summer average bottom dissolved oxygen (depth > 12.9 m) is less than 4 g m^{-3}. Summer-average bottom dissolved oxygen exceeds 4 g m^{-3} in the remaining segments.

Dissolved Oxygen

The major issue to be examined is the improvement in dissolved oxygen gained by introduction of oysters to regions in which they presently do not occur. Simulations indicate the improvement in summer-average bottom dissolved oxygen is usually less than 0.1 g m^{-3} (Tables 2 to 6). In one extreme case, represented by restoration to 1920-1970 oyster densities in all potential areas of Mobjack Bay, computed dissolved oxygen improves by 0.15 g m^{-3} (Table 5). An interesting example is provided by Pocomoke Sound (Table 6) in which dissolved oxygen diminishes as a function of oyster restoration. Similar behavior was previously noted at another Eastern Shore embayment (Cerco and Noel 2005). In this case, relatively high dissolved oxygen concentrations are maintained by algal production. Diminished production due to oyster filtration results in lower dissolved oxygen concentration. The projected summer-average dissolved oxygen concentration under the most extreme restoration levels is nearly 7 g m^{-3}, however, so diminished dissolved oxygen induced by oyster restoration is not a concern.

Chlorophyll

Reductions in chlorophyll depend on the level of restoration and the area subject to restoration. Reductions in surface chlorophyll in CB7PH are less than 0.2 mg m^{-3} at the highest restoration levels. Benefits are limited due to the large expanse of this segment and the limited area subject to restoration. The greatest reductions are 2 to 2.5 mg m^{-3} in the YRKMH and POCMH regions. Reductions in the York are associated with the highest levels of computed regional oyster density. Computed oyster densities are lower in the Pocomoke than the York but are compensated by the shallow depth and large restoration area.

Light Attenuation and SAV

Two factors must be considered in judging oyster effects on light attenuation and SAV. The first is the magnitude of improvement. The second is the absolute value of attenuation relative to the criteria for survival of SAV. Criteria call for attenuation less than 1.5 m^{-1} during the growing season for SAV survival at the 1 meter depth (Batiuk et al. 1992).

Minimal improvements in attenuation, 0.03 m^{-1}, occur in CB7PH at the highest oyster restoration levels. Improvements are limited by the same geometrical effects that limit chlorophyll reductions. Since CB7PH is well within the criteria for SAV survival, however, even minimal reductions in attenuation produce enhancements in SAV. Greater reductions in attenuation, up to ~ 0.2 m^{-1} are projected in the JAMSPH, POCMH, and MOBMH regions. Since attenuation in these regions is within criteria for SAV survival, SAV enhancements are projected. Virtually no improvement in SAV biomass is projected for the YRKMH region despite reductions in attenuation. Light attenuation in this portion of the York is well outside criteria for SAV survival and oyster restoration cannot bring attenuation into the desired range. The oyster densities projected for the York are among the highest of all segments examined. This instance emphasizes the importance of geometry. Although oysters are projected to thrive in this environment, they cannot significantly reduce the light attenuation in the open reach of the middle York River.

The greatest SAV biomass improvements are projected for CB7PH. These are attributed to the extensive area of the segment and the presently suitable conditions for SAV survival. In percentage terms, the greatest SAV improvements are projected for POCMH, followed by MOBPH and JAMSPH. No improvement is projected for YRKMH.

Table 1
Characteristics of Selected Regions

Region	Volume, 10^6 m^3	Surface Area, 10^6 m^2	Mean Depth, m	Fraction Oyster Cells (existing)	Fraction Oyster Cells (potential)
CB7PH	14,562	1,312	11.10	0.01	0.10
JMSPH	517	64	8.07	0.00	0.21
MOBPH	1,432	264	5.43	0.02	0.45
YRKMH	322	70	4.59	0.00	0.66
POCMH	617	198	3.11	0.48	1.00

Table 2
Projected Effects of Oyster Restoration in Chesapeake Bay Lower Eastern Shore (CB7PH)

	1994 Base	Base w restoration	Ten-Fold Increase	Ten-Fold w restoration	1920-1970	1920-1970 w restoration
Bottom DO, g m^3	5.16	5.16	5.19	5.21	5.23	5.27
Surface Chlorophyll, mg m^3	5.28	5.27	5.16	5.08	5.08	4.89
Light Attenuation, m^{-1}	0.62	0.62	0.61	0.60	0.60	0.57
SAV Biomass, tonnes C	1172	1186	1289	1359	1285	1489
Oyster Biomass, g C m^{-2}	0.00	0.01	0.00	0.36	0.00	0.83

Table 3
Projected Effects of Oyster Restoration in Polyhaline James River (JAMSPH)

	1994 Base	Base w restoration	Ten-Fold Increase	Ten-Fold w restoration	1920-1970	1920-1970 w restoration
Bottom DO, g m^{-3}	4.74	4.75	4.76	4.78	4.80	4.84
Surface Chlorophyll, mg m^{-3}	5.85	5.85	5.84	5.23	5.83	4.46
Light Attenuation, m^{-1}	1.22	1.22	1.22	1.15	1.21	1.03
SAV Biomass, tonnes C	52	52	52	64	54	74
Oyster Biomass, g C m^{-2}	0.00	0.01	0.00	2.00	0.00	2.32

Table 4
Projected Effects of Oyster Restoration in Mesohaline York River (YRKMH)

	1994 Base	Base w restoration	Ten-Fold Increase	Ten-Fold w restoration	1920-1970	1920-1970 w restoration
Bottom DO, g m^{-3}	4.25	4.27	4.27	4.34	4.31	4.37
Surface Chlorophyll, mg m^{-3}	11.09	11.05	11.07	10.07	11.05	8.58
Light Attenuation, m^{-1}	2.40	2.39	2.40	2.29	2.40	2.13
SAV Biomass, tonnes C	0.04	0.04	0.04	0.04	0.04	0.05
Oyster Biomass, g C m^{-2}	0.00	0.06	0.00	2.21	0.00	4.30

Table 5
Projected Effects of Oyster Restoration in Mobjack Bay (MOBMH)

	1994 Base	Base w restoration	Ten-Fold Increase	Ten-Fold w restoration	1920-1970	1920-1970 w restoration
Bottom DO, g m^{-3}	3.78	3.80	3.83	3.92	3.91	4.06
Surface Chlorophyll, mg m^{-3}	6.23	6.20	6.07	5.31	5.88	4.44
Light Attenuation, m^{-1}	1.00	0.99	0.98	0.86	0.95	0.75
SAV Biomass, tonnes C	504	510	520	608	533	687
Oyster Biomass, g C m^{-2}	0.00	0.03	0.34	1.63	0.61	2.61

Table 6
Projected Effects of Oyster Restoration in Pocomoke Sound (POCMH)

	1994 Base	Base w restoration	Ten-Fold Increase	Ten-Fold w restoration	1920-1970	1920-1970 w restoration
Bottom DO, g m^{3}	7.10	7.09	6.96	6.88	6.91	6.71
Surface Chlorophyll, mg m^{3}	10.27	10.13	8.35	7.49	7.94	5.22
Light Attenuation, m^{-1}	1.50	1.48	1.31	1.27	1.32	1.08
SAV Biomass, tonnes C	291	300	424	435	402	580
Oyster Biomass, g C m^{-2}	0.00	0.03	0.36	1.24	0.86	1.29

References

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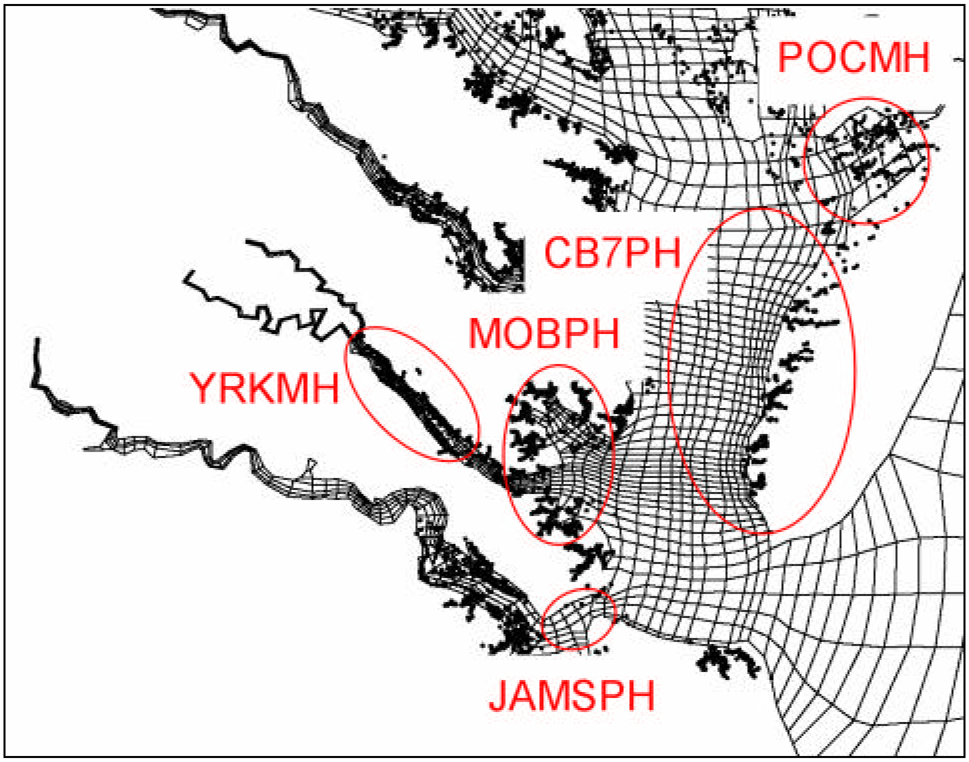

Figure 1. Segments selected for Analysis

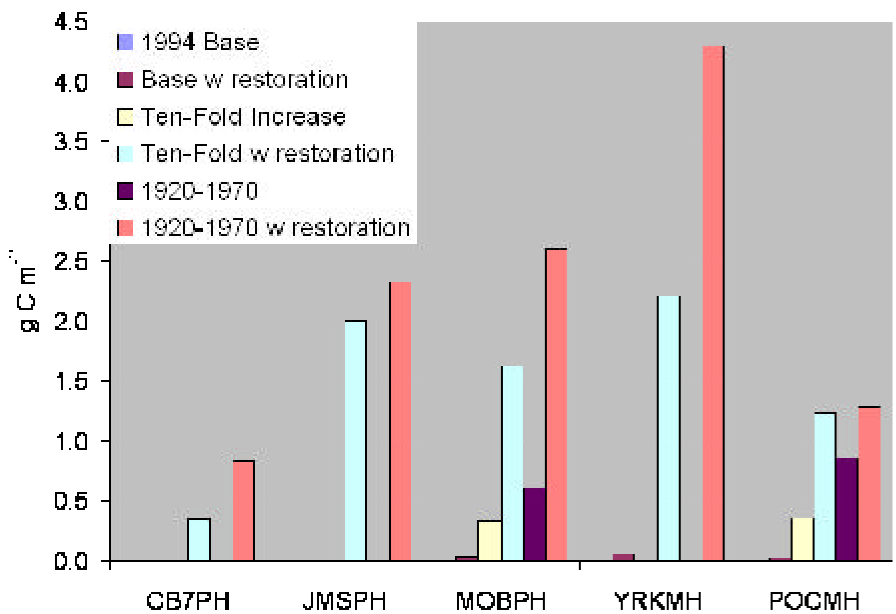

Figure 2. Projected Oyster Densities. Note that the highest oyster densities that presently occur in the bay, averaged over model cell areas, are ~ 4 g C m^{-2}. Computed densities greater than 1 g C m^{-2} are considered to be substantial.

3 Ecosystem Services Provided by Oyster Restoration

Introduction

At the sponsor's request, our previous analyses of ecosystem response (Cerco and Noel 2005) were summarized by state. The summaries included all Chesapeake Bay system waters from tributary heads-of-tide to bay mouth. The analyses are repeated here with the addition of three scenarios that consider oyster restoration to all Virginia habitat and lease areas.

Chlorophyll

Oysters effect improvements in the environment by filtering phytoplankton and other suspended solids from the water column. Aside from direct removal, reductions in phytoplankton, quantified as chlorophyll concentration, may also occur via an indirect process: nutrient limitation induced through removal of nutrients, primarily nitrogen. Although phytoplankton require phosphorus and silica (for diatoms) as well, nitrogen limitation is the most significant influence on algal production in the interval when temperature-dependent oyster filtration is greatest (Fisher et al. 1992, Malone et al. 1996).

Within Virginia, the range of densities investigated reduce summer-average surface chlorophyll by up to ˜ 0.8 µg/L, roughly 10% of the 1994 base concentration (Table 1). The greatest potential improvement comes from restoration of all Virginia habitat and lease areas to density levels consistent with the years 1920-1970. The improvement for restoration to new areas ranges from zero, for mortality corresponding to 1994 base levels, to 0.44 µg/L, for mortality corresponding to 1920-1970 levels. Chlorophyll reductions in Maryland range up to ˜ 2.3 µg/L, more than 25% of the 1994 base. One factor that contributes to the disparity is the larger oyster biomass in Maryland, which reflects a larger available area, even with new Virginia habitat. At equivalent mortality rates, computed oyster density is nearly identical for Maryland and Virginia when new Virginia habitat is added (Table 1) but Maryland biomass exceeds Virginia biomass by more than 30% (Table 3).

The range of densities investigated reduced surface total nitrogen concentration by up to 0.05 mg/L in Virginia (Table 1). The concentration reduction computed for restoration to new areas was negligible. The maximum reduction was nearly identical in Maryland, 0.06 mg/L. Under base conditions, net nitrogen removal in Maryland, on an areal basis, is greater than in Virginia, 27 mg N $m^{-2}d^{-1}$ versus 16 mg N m^{-2} d^{-1}. The higher base rate in Maryland reflects deposition of particulate nitrogen below the major fall lines and diffusion of nitrate into bed sediments where it is subsequently denitrified. The difference between the two regions increases with the level of oyster restoration, attributable to the higher densities in Maryland. At the greatest densities examined, oyster restoration removes 4 mg N m^{-2} d^{-1} in Maryland. A fifty-fold biomass increase in existing Virginia areas removes 1 mg N m^{-2} d^{-1}; restoration to 1920-1970 levels in all Virginia habitat and lease areas removes 1.8 mg N m^{-2} d^{-1}. Multiplication by bottom area in each state yields removal rate in mass terms: up to 24,600 kg d^{-1} additional nitrogen removal in Maryland versus up to 5,100 kg d^{-1} additional removal in Virginia for restoration limited to existing areas (Table 1). The Virginia removal rate increases to nearly 8,300 kg d^{-1} for restoration to 1920-1970 levels in all habitat and lease areas. The additional removal rate for restoration to new areas is up to 5,300 kg d^{-1}.

These removal rates can be put in perspective by examining some of the other loads to the system, derived from the 2002 model used for the recent load allocations (Cerco and Noel 2004). The Maryland removal rate corresponding to a fifty-fold increase in oyster biomass is roughly equivalent to the point-source nitrogen load to the Potomac basin (Table 2). The equivalence in loading should not be extended to equivalence in effects, however since the majority of the Potomac load enters in the tidal freshwater reach far removed from oyster habitat. The amount of nitrogen removed by Maryland oyster restoration to 1920 – 1970 levels is equivalent to direct atmospheric loading to the water surface; nitrogen removal from a ten-fold oyster restoration is half this amount.

The Virginia removal rate corresponding to a fifty-fold increase in oyster biomass in existing area is only half of direct atmospheric loading to the water surface (Table 2). Removal rate associated with restoration of oysters to 1920 – 1970 levels in all habitat and lease areas is only a fraction of identifiable loads to the Virginia portion of the bay.

Additional perspective is gained by comparing the nitrogen removal via oyster restoration to nutrient reduction targets (Linker 2005). Recent allocations call for a 24,900 kg d^{-1} reduction in Maryland nitrogen loading. The allocation corresponds to nitrogen removal from a fifty-fold increase in oyster biomass (Table 2). Restoration to 1920 – 1970 levels would accomplish more than half the Maryland nitrogen reduction goal. The Virginia allocation calls for a 34,800 kg d^{-1} reduction in nitrogen loading. This allocation exceeds any feasible reduction from oyster restoration although restoration can still provide a contribution. Restoration to 1920 – 1970 levels in existing areas accomplishes nearly 10% of the Virginia nitrogen reduction goal while addition of all habitat increases the nitrogen reduction to nearly 25% of the Virginia goal. The system-wide allocation calls for a 124,500 kg d^{-1} reduction in nitrogen loading. This allocation also exceeds any feasible reduction from oyster restoration. Restoration to 1920 – 1970 levels plus the addition of all Virginia habitat could, however, accomplish ~ 18% of the system-wide nitrogen reduction goal. Nitrogen removal via oyster restoration can be a valuable supplement to alternate methods but cannot entirely substitute for conventional nutrient controls.

Dissolved Oxygen

Bottom-water hypoxia originates with excess algal production in the surface waters of the bay. Algae and detritus settle to the bottom where they undergo decay that generates oxygen demand and consumption. Density stratification prevents replenishment of oxygen-depleted waters with atmospheric oxygen from the surface.

Within Virginia, the range of oyster densities investigated reduced annual-average net algal production by up to 10%, from 0.68 g C m^{-2} d^{-1} at base levels to 0.62 g C m^{-2} d^{-1}, for a fifty-fold increase in oyster biomass and for oyster restoration to 1920-1970 levels in all Virginia habitat and lease areas (Table 3). Corresponding reductions were greater in Maryland. Annual average net algal production was reduced up to 20%, from 0.74 g C m^{-2} d^{-1} at base levels to 0.59 g C m^{-2} d^{-1}, for a fifty-fold increase in oyster biomass. Under base conditions, annual-average surface algal carbon concentration was equivalent in Maryland and Virginia, 0.5 g C m^{-3} (Table 3). The maximum potential reduction attainable in Maryland, 0.07 g C m^{-3}, was double the potential gain in Virginia, however.

Oxygen improvements are considered for summer-average at depths greater than 12.9 m. This period and depth isolates the time and location of bottom-water hypoxia. Within Virginia, the maximum improvement in bottom-water dissolved oxygen was 0.2 mg/L (Table 3). Within Maryland, the improvement was doubled, more than 0.4 mg/L. The maximum Virginia improvement was attained for a fifty-fold increase in oyster biomass in existing oyster areas. The improvement for restoration to all habitat and lease areas was up to 0.04 mg/L, compared to similar biomass levels in existing areas only.

Water Clarity

Improvements in water clarity are effected by removal of both organic and inorganic solids from the water column. Water clarity is quantified in the model as the coefficient of diffuse light attenuation. The light attenuation coefficient is inversely proportional to water clarity. Lower light attenuation implies higher water clarity. We examined summer-average light attenuation since summer is the critical period for growth of submerged aquatic vegetation (SAV).

Within Virginia, the range of oyster densities investigated reduced summer-average light attenuation by up to 8%, from 1.05 m^{-1} at base levels to 0.97 m^{-1} for a fifty-fold increase in oyster biomass and 0.96 m^{-1} for restoration to 1920-1970 levels in all habitat and lease areas (Table 4). Reductions in light attenuation for restoration to all habitat and lease areas ranged up to 0.06 m^{-1}, compared to similar biomass levels in existing areas only. Percentage increases in summer SAV biomass exceeded percentage reductions in attanuation, up to 23%. Computed SAV biomass increased from 5,627 tonnes C under base conditions to 6,830 tonnes for a fifty-fold oyster restoration and 6,800 tonnes for restoration to 1920-1970 levels in all habitat and lease areas. Improvements in SAV biomass for oyster restoration to all habitat and lease areas were up to 11% more than the SAV biomass obtained for oyster restoration limited to existing areas. Following a pattern established for other benefits, improvements in Maryland exceeded Virginia. Summer-average light attenuation diminished by up to 13%, from 1.39 m^{-1} under base conditions to 1.21 m^{-1} for a fifty-fold increase in oyster biomass. Corresponding percentage improvements in SAV, up to 43%, again exceeded improvements in attenuation. Computed summer SAV biomass increased from 5,227 tonnes C under base conditions to 7,486 tonnes C under maximum restoration.

Discussion

Virtually no benefits, at any scale, local or statewide, are predicted for restoration to new areas under mortality rates employed for the 1994 base run. These results indicate that little can be expected from establishing oysters in new areas unless present mortality rates from disease, harvest, and other factors are reduced. Under reduced mortality rates, corresponding to rates that allow a ten-fold biomass increase or restoration to 1920-1970 levels in existing areas, benefits from establishing oysters in new areas are predicted. The magnitude of the benefits depends on the processes examined, on location, and on spatial scale. Assessment of the benefits also depends on perspective of the reviewer.

Two broad conclusions from our previous work framed expectations for this investigation. First, ecosystem benefits from oyster restoration are emphasized in shallow, semi-enclosed embayments rather than in deep, extensive open waters. Second, greater improvements are seen in the immediate vicinity of oyster bars, e.g. SAV beds, than in locales far removed from oyster bars e.g. deep trenches. This investigation largely reinforced these expectations. The improvement in summer-average, deep trench dissolved oxygen is at most 0.04 mg/L for full restoration to all Virginia habitat and lease areas. Up to 11% improvement in SAV biomass (687 tonnes C) is projected for oyster restoration to the same areas.

Clearly, oyster restoration alone is not going to transform or restore the entire ecosystem although restoration can make a significant contribution. Recent allocations of nitrogen reductions in Virginia, projected to restore the system to living-resource based standards, call for removal of 34,800 kg/d total nitrogen. A fifty-fold biomass increase in existing areas is projected to remove 5,100 kg/d. Oyster restoration to all Virginia habitat and lease areas, at 1920-1970 biomass levels, removes 8,300 kg/d. These are only fractions of the reduction target. Still, a manager faced with the problems and expense of reducing nitrogen loads will welcome any nitrogen reduction effected by oyster restoration. Similarly, the projected SAV restoration is a boost to any that can be obtained through the difficult process of reducing solids and nutrient loads from the watershed.

We previously recommended that oyster restoration be targeted to specific areas with suitable environments and that resulting environmental improvements be viewed on similar, local scales. The present work emphasizes the need for careful selection of locales for restoration. The mesohaline York River is projected to support high oyster densities but concurrent improvements in SAV are nearly absent. Oysters are unable to substantially reduce light attenuation in this highly-turbid, expansive environment. In contrast, projected oyster restoration to new portions of Pocomoke Sound is accompanied by substantial improvements in SAV. The environment in the Sound is such that computed reductions in attenuation bring this parameter into the range that supports SAV survival. Oysters can effect attenuation reductions because large portions of the Sound are (or potentially are) covered with oyster bars and because exchange with the mainstem bay is restricted in this embayment.

Ecosystem benefits associated with oyster restoration can be computed to a high degree of numerical precision. Benefits to be realized in the bay will not be observed at the precise extent to which they are computed, however. In part, uncertainties in the realized benefits are due to environmental variations that are not incorporated in the model simulation. Uncertainties also arise from the assignment in the model of constant numerical values to quantities which are variable or uncertain, such as oyster filtration rate. Uncertainty in the model computations can be examined, to an extent, through the process know as sensitivity analysis. In this process, model parameters are varied and the effects on computations are quantified. Thorough sensitivity analysis in a complex model such as the CBEMP is an extensive, demanding process that is beyond the scope of the present effort. Consequently, the uncertainty in the model results is presently unknown. We are confident, however, that the overarching conclusions of the work are not subject to change as a result of sensitivity to parameter selection. These include:

- Oyster restoration can provide a valuable contribution to Chesapeake Bay restoration. Oyster restoration alone is not sufficient to meet environmental targets for dissolved oxygen, chlorophyll, and water clarity, however.
- Greater benefits from oyster restoration result in Maryland rather than Virginia.
- Oyster restoration has greater impact on the local environment, e.g. in SAV beds, than on distant regions such as the deep bay trench.

Table 1
Ecosystem Benefits Associated with Chlorophyll

Designation	VA oyster density[1], g C m $^{-2}$	MD oyster density[1], g C m $^{-2}$	VA Chl[2], ug/L	MD Chl[2], ug/L	VA total N[3], mg/L	MD total N[3], mg/L	VA N removal[4], kg/d	MD N removal[4] kg/d
1994 base	0.01	0.03	6.49	8.42	0.54	0.87	0	0
with restoration[5]	0.02		6.49		0.54		183	
five-fold increase	0.03	0.11	6.45	8.21	0.53	0.87	473	2,812
ten-fold increase	0.08	0.27	6.32	7.90	0.53	0.86	1,575	6,434
with restoration	0.27		6.14		0.52		4,406	
15-fold increase	0.13	0.42	6.23	7.60	0.52	0.85	2,344	6,918
1920 - 1970 level	0.21	0.67	6.16	7.19	0.51	0.84	2,980	13,753
with restoration	0.66		5.72		0.51		8,281	
25-fold increase	0.26	0.87	6.05	6.97	0.51	0.83	3,680	16,091
50-fold increase	0.53	1.83	5.81	6.14	0.49	0.81	5,104	24,644

[1] Annual average across state portion of the system

[2] Summer (June – Aug.) average within surface mixed layer

[3] Annual average within surface mixed layer

[4] Incremental annual average removal compared to 1994 base

[5] Oysters restored to all Virginia habitat and lease areas

Table 2 Nitrogen Loads and Incremental Removal Rates			
Virginia	**kg/d**	**Maryland**	**kg/d**
VA Reduction Target	34,800	Susquehanna Fall Line	169,349
James River Point Source	27,101	System Reduction Target	124,500
James River Fall Line	20,455	Other Fall Line and Distributed	57,876
Distributed Loads	18,580	Potomac Fall Line	55,235
Other Fall Line	13,845	Potomac Point Source	28,811
Atmospheric	10,865	MD Reduction Target	24,900
1920-1970 w Restoration	8,281	50-fold	24,644
50-fold	5,104	Baltimore Point Source	17,217
ten-fold w Restoration	4,406	25-fold	16,091
25-fold	3,680	Atmospheric	14,390
Other Point Source	3,210	1920-1970	13,753
1920-1970	2,980	15-fold	6,918
15-fold	2,344	ten-fold	6,434
ten-fold	1,575	Other Point Source	4,754
five-fold	473	five-fold	2,812
1994 base with Restoration	183		

Table 3
Ecosystem Benefits Associated with Dissolved Oxygen

Designation	VA oyster biomass[1] kg DW	MD oyster biomass[1], kg DW	VA net production[2], g C m^{-2} d^{-1}	MD net production[2], g C m^{-2} d^{-1}	VA algal C[3], g m^{-3}	MD algal C[3], g m^{-3}	VA bottom DO[4], mg/L	MD bottom DO[4] mg/L
1994 base	239,680	981,434	0.68	0.74	0.50	0.50	4.68	2.14
with restoration[5]	451,906		0.67		0.50		4.69	
five-fold increase	699,594	3,867,648	0.67	0.72	0.49	0.49	4.70	2.18
ten-fold increase	1,785,170	8,509,914	0.66	0.70	0.49	0.48	4.72	2.22
with restoration	6,439,024		0.65		0.48		4.75	
15-fold increase	2,808,368	12,482,296	0.65	0.68	0.48	0.47	4.75	2.27
1920 - 1970 level	4,218,842	18,477,200	0.64	0.66	0.48	0.46	4.79	2.34
with restoration	13,349,828		0.62		0.47		4.83	
25-fold increase	5,054,288	22,838,590	0.64	0.64	0.48	0.45	4.80	2.38
50-fold increase	8,583,890	40,593,208	0.62	0.59	0.47	0.43	4.89	2.57

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[1] Autumn (Sept. – Nov.) average

[2] Annual average net phytoplankton primary production

[3] Annual average in surface mixed layer

[4] Summer (June – Aug.) average in depth > 12.9 m

[5] Oysters restored to all Virginia habitat and lease areas

Table 4
Ecosystem Benefits Associated with SAV

Designation	VA oyster biomass[1], kg DW	MD oyster biomass[1], kg DW	VA light attenuation[2], 1/m	MD light attenuation[2], 1/m	VA SAV biomass[3], tonnes C	MD SAV biomass[3], tonnes C
1994 base	239,680	981,434	1.05	1.39	5,548	5,227
with restoration[4]	451,906		1.05		5,587	
five-fold increase	699,594	3,867,648	1.05	1.38	5,637	5,368
ten-fold increase	1,785,170	8,509,914	1.03	1.36	5,985	5,691
with restoration	6,439,024		1.01		6,229	
15-fold increase	2,808,368	12,482,296	1.02	1.33	6,169	5,973
1920 - 1970 level	4,218,842	18,477,200	1.02	1.30	6,113	6,332
with restoration	13,349,828		0.96		6,800	
25-fold increase	5,054,288	22,838,590	1.00	1.28	6,480	6,562
50-fold increase	8,583,890	40,593,208	0.97	1.21	6,830	7,486

[1] Autumn (Sept. – Nov.) average

[2] Summer (June – Aug.) average

[3] Summer (June – Aug.) average

[4] Oysters restored to all Virginia habitat and lease areas

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