Appendix E: Literature Review Summaries by the Oyster Recovery Partnership (ORP)

Previous Efforts:

The efforts of two main activities to evaluate nutrient removal efficiencies by oyster practices and their potential application in Chesapeake Bay are summarized below:

2013 Workshop—Quantifying Nitrogen Removal by Oysters:

- Two-day workshop (January 10-11, 2013) sponsored by the NOAA Chesapeake Bay Office that resulted in a report that included a comprehensive review of literature on nitrogen removal via nitrogen assimilation and denitrification by the Eastern oyster (*Crassostrea virginica*) related to intensive on bottom and off bottom aquaculture and restored oyster reef practices.
- 30 oyster-related experts attended the workshop, including resource management agency personnel, restoration practitioners, and scientists.
- Existing published and ongoing studies were evaluated to determine the capacity of oysters to remove nitrogen from coastal waters. Total of studies evaluated for the different nutrient cycling processes and oyster practices are summarized below:
    - Nitrogen assimilation in oyster tissue:
        - Off bottom aquaculture—1 publication.
        - On bottom aquaculture—3 publications.
        - Restored oyster reefs—1 publication.
    - Nitrogen assimilation in oyster shell:
        - Off bottom aquaculture—1 publication.
        - Restored oyster reef—1 publication and 1 unpublished data.
    - Enhanced Denitrification by Oysters:
        - Off bottom aquaculture—2 publications.
        - Restored oyster reefs—3 intertidal publications, 1 intertidal ongoing study, and 2 subtidal publications.
- Relevant key findings include:
    - Concerning nitrogen assimilation, nitrogen content should be reported as a percentage of dry weight for oyster tissues and shell.
    - Most accurate estimates of nitrogen assimilation will be from using length to biomass relationships from oyster populations of interest at the time of interest because of variability in environmental conditions, food quality, and oyster reproductive state and health.
    - Low variation in the nitrogen content of tissues and shells for a range of sites and environmental conditions along the mid-Atlantic and northeast coasts of the U.S. supports the use of the mean of these values for oysters in these regions.
    - Due to variability in the enhancement of denitrification, reference site information should be collected before assigning nitrogen removal rates for oyster reefs.
- Relevant gaps in knowledge include:
    - Percentage of nitrogen in the tissues and shells of intertidal oysters (available studies only investigated oysters growing in aquaculture cages or on subtidal reefs).
    - Generalized relationships for estimating enhanced denitrification associated with oyster reefs under varying conditions.
    - Denitrification rates for other forms of aquaculture (available data only existed for sediments below floating cages).
    - Nitrogen removal via burial of biodeposits or shells (no data existed during evaluation).
    - Nitrogen removal via nitrous oxide release.

- Reference:
    - Kellogg, M.L., M.W. Luckenbach, B.L. Brown, R.H. Carmichael, J.C. Cornwell, M.F. Piehler, M. S. Owens, D.J. Dalrymple, C. B. Higgins and A.R. Smyth. 2013. Quantifying nitrogen removal by oysters. Workshop Report. NOAA Chesapeake Bay Program Office, Annapolis, MD.

2013 STAC Review—Evaluation of the Use of Shellfish as a Method of Nutrient Reduction in the Chesapeake Bay:

- The Chesapeake Bay Program's Management Board requested the Scientific and Technical Advisory Committee (STAC) to review the paper, "Shellfish Aquaculture: Ecosystem Effects, Benthic-Pelagic Coupling and Potential for Nutrient Trading" by Roger Mann and Roger Newell and other relevant studies related to the use of shellfish as a method of nutrient reduction and advise how it could be applied in the Chesapeake Bay TMDL watershed model.
- STAC leveraged the review conducted by the 2013 workshop, "Quantifying Nitrogen Removal by Oysters."
- Key findings included:
    - Nitrogen content of oyster soft tissue and shell can reasonably be estimated as 8.2% and 0.2% of dry weight, respectively.
    - Phosphorus content of oyster soft tissue and shell can reasonably be estimated as 1.07% and 0.06% of dry weight, respectively.
    - Due to variability in predicting oyster growth and survival, nutrient removal BMP efficiencies should be based on actual harvest data (oyster dry weight) multiplied by the nutrient percentages above.
    - Nutrient removal rates for shell only apply to shell which is not returned to the Bay.
    - Burial rates for nutrients associated with biodeposits are not currently known.
    - Measured denitrification rates associated with oyster aquaculture have not revealed any enhancement above background levels.
    - Denitrification rates associated with oyster reefs typically exceed background levels, but are highly variable among locations and seasons.
    - Lack of data on other grow-out methods (e.g., oyster grown in cages near the bottom and cage-less, spat-on-shell grown on the bottom) on denitrification rates.
    - Oyster aquaculture has the potential to reduce nitrification (and hence coupled nitrification-denitrification) if rates of biodeposition by the oysters coupled with low flushing rates cause oxygen depletion. Modeling tools that provide site-specific guidance on oyster stocking densities should be developed to avoid this negative effect.

<u>Oyster BMP Request Memo from Steve McLaughlin, City of Virginia Beach:</u>

Steve McLaughlin from the City of Virginia Beach sent a formal request to consider sanctuary oyster reefs as a BMP to James Davis-Martin, the Water Quality Goal Implementation Team Vice Chair (Virginia Department of Conservation and Recreation). The full memo can be found in Appendix D. This request is summarized below:

- Proposes that the creation of "sanctuary oyster reefs" in the Lynnhaven River be considered an acceptable method to remove nitrogen from a watershed and credited in the Chesapeake Bay TMDL.
    - Phosphorus removal is not included in the request since studies showed that oyster reefs had little to no effect on soluble phosphorus dynamics.
- Emphasizes that these sanctuary oyster reefs will not replace traditional stormwater BMPs or appropriate land use planning within the Chesapeake Bay watershed, but instead support the

removal of pollutants, such as nitrogen, that reach the Bay when traditional stormwater BMP practices do not remove 100% of the pollutant they receive.

- Proposes that sanctuary oyster reefs be given a provisional denitrification removal rate of 20 lbs/acre/month or 240 lbs/acre/year until further measurements are taken to refine this number.
  - Request only includes nitrogen removal via denitrification because oyster harvesting would not be allowed on the sanctuary reefs.
  - The City of Virginia Beach proposes to monitor the sanctuary reefs for overall health and viability and replace spat-on-shell as needed.
  - The City of Virginia Beach also proposes to measure denitrification rates at selected reef sites for a period of 15-18 months to help refine the provisional denitrification removal rate, if needed.
- Describes the methodologies and results from the following studies that were previously considered during the 2013 STAC Review to support their request:
  - Sisson et al. 2011, "Assessment of Oyster Reefs in Lynnhaven River as a Chesapeake Bay TMDL Best Management Practice."
  - Kellogg et al. 2013, "Denitrification and Nutrient Assimilation on a Restored Oyster Reef."
  - Piehler and Smyth 2011, "Habitat-Specific Distinctions in Estuarine Denitrification Affect Both Ecosystem Function and Services."

<u>Related BMP Efforts:</u>

The Oyster Recovery Partnership (ORP) searched and found 2 related BMP efforts that helped inform recommendations for the oyster BMP expert panel. These efforts are summarized below:

International Workshop on Bioextractive Technologies for Nutrient Remediation Summary Report

- This 2009 workshop was sponsored by NOAA and the Long Island Sound Study (a partnership of federal and state agencies, user groups, concerned organizations, and individuals dedicated to protecting and restoring the Sound).
- This workshop brought together a panel of policy, industry, and science subject matter experts to discuss new and innovative bioextractive technologies (i.e., shellfish and seaweed cultivation to remove nitrogen and other nutrients from the water) to address the management of eutrophication and hypoxia in the Long Island Sound.
- Goals of the workshop included:
  - Increase awareness of alternatives for nutrient management by federal/state/municipal agencies and coastal managers.
  - Assess the local feasibility of bioextractive technologies.
  - Provide recommendations for pilot projects and locations.
  - Identify opportunities for economic incentives for nutrient bioextraction via nitrogen credit trading or other practices.
- Discussions resulted in the following identified strategies:
  - Include definition of Nutrient Bioextraction into draft legislation to reauthorize the federal Long Island Sound Restoration Act.
  - Consider the incorporation of nutrient bioextraction into the revision of the Long Island Sound TMDL.
  - Implement a pilot study in Long Island Sound to examine the effects of large-scale deployment of shellfish and macroalgae on local water quality.
  - Evaluate the value of ecosystem services and identify economic incentives for increased aquaculture activities.

- Reference:
    - Rose, J.M., M. Tedesco, G.H. Wikfors, and C. Yarish. 2010. International workshop on bioextractive technologies for nutrient remediation summary report. US Department of Commerce, Northeast Fisheries Science Center Reference Document 10-19.

2014 Urban Stream Restoration BMP Expert Panel's report—Recommendation of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects:

- This expert panel was formed to provide recommendations to the Chesapeake Bay Program Office on the nutrient and sediment removal rates for stream restoration projects.
- This panel conducted an extensive review of recent research on the impact of stream restoration projects in reducing sediment and nutrient delivery to the Chesapeake Bay.
- This panel decided that the assignment of a single removal rate for stream restoration was not practical or scientifically defensible because projects are unique with respect to its design, stream order, landscape position and function.
- This panel developed four general crediting protocols based on available data as of November 2013 to define pollutant load reductions associated with individual stream restoration projects, including:
    - Protocol 1: Credit for prevented sediment during storm flow—defines an annual mass reduction credit for projects that prevent channel or bank erosion.
    - Protocol 2: Credit for instream and riparian nutrient processing during base flow—defines an annual mass nitrogen reduction credit for projects that enhance instream denitrification.
    - Protocol 3: Credit for floodplain reconnection volume—defines an annual mass sediment and nutrient reduction credit for projects that reconnect stream channels to their floodplain.
    - Protocol 4: Credit for dry channel regenerative stormwater conveyance as an upland stormwater retrofit—defines an annual sediment and nutrient reduction rate for projects that treat stormwater upland.
- Protocols are additive and individual stream restoration projects may qualify for credit under one or more of the protocols, but aggregate load reductions from a practice should not exceed loads in the Watershed Model for any given land-river segment.
- Reference:
    - Schueler, T. and Stack, B. 2014. Recommendations of the expert panel to define removal rates for individual stream restoration projects. Available at http://www.chesapeakebay.net/documents/Final_CBP_Approved_Stream_Restoration_Panel_report_LONG_with_appendices_A-G_02062014.pdf.

<u>Oyster Literature Not Previously Considered:</u>

The ORP did a literature search for oyster-related studies that were not considered or available during the 2013 STAC Review. This search identified 12 studies that would be beneficial for the oyster expert panel to review. These individual studies are summarized in Table 1 below:

Table 1: Summary of individual studies not considered during the 2013 STAC review.

ID #	Lead Author(s)	Publication Date	Publication/Project Title	Lead Author Organization	Coauthors/ Partners	Scientific Information Type	Summary of Project	Geographic Location(s)	Researched Species	Oyster Practice(s)	Nitrogen (N)	Phosphorus (P)
1	Ayvazian, Suzanne and Fulweiler, Robinson W.	Ongoing	N Cycling Processes Across an Oyster Aquaculture Chronosequence	US EPA, Office of Research and Devlopement, Atlantic Ecology Division and Boston University, Boston, MA	Boze Hancock (The Nature Conservancy/ U. of RI) Steve Brown (The Nature Conservancy, RI Chapter) Robinson W. Fulweiler (Boston University)	Ongoing study from 2013-present	Use of novel in-situ benthic chamber experiments to quantify the influence of oyster aquaculture, oyster reef restoration, and cultch placement on N_2 and N_2O fluxes across the sediment-water interface.	Shallow (~1m) estuary in southern New England, US	Eastern oyster, C. virginica	Aquaculture and reef restoration	Denitrification	-
2	Bricker, Suzanne B.	2014	From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River Estuary	National Oceanic and Atmospheric Administration, Silver Spring, MD, USA; e-mail: Suzanne.Bricker@noaa.gov	Rice (U. of VA); Bricker (USGS)	Peer-reviewed publication in Aquatic Geochemistry, DOI 10.1007/s10498-014-9226-y	Model analysis of the nitrogen contribution of headwaters, nontidal, and estuarine portions of Potomac River watershed to total nitrogen loads to Chesapeake Bay. Used eutrophication model to evaluate nitrogen loading changes since 1990s. Used FARM model to determine oyster aquaculture potential to mediate eutrophication impacts.	Mid Potomac River mainstem, USA	Eastern oyster, C. virginica	Extensive on bottom, spat on shell aquaculture	Removal of assimilated N (via harvest)	-
3	Cerco, C.F.	2007	Can oyster restoration reverse cultural eutrophication in Chesapeake Bay	U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS	Noel, M.R. (U.S. Army Engineer Research and Development Center)	Peer-reviewed publication in Estuaries and Coasts, 30(2): 331-343	Applied an oyster module to a predictive eutrophication model to investigate the hypothesis that effects of cultural eutrophication can be reversed through natural resource restoration.	Chesapeake Bay	Eastern oyster, C. virginica	Oyster Restoration	Denitrification	-
4	Ferreira, J.G.	2007	Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model	IMAR — Institute of Marine Research, Centre for Ecological Modelling, IMAR–DCEA, Fac. Ciencias e Tecnologia, Qta Torre, 2829-516 Monte de Caparica, Portugal	Hawkins (Plymouth Marine Lab); Bricker (NOAA)	Peer-reviewed publication in Aquaculture 264: 160-174	Describes model for assessment of coastal and offshore shellfish aquaculture at the farm-scale and presents results from several case studies. Model allows (i) prospective analyses of culture location and species selection; (ii) ecological and economic optimization of culture practice, such as timing and	N/A (scenario-based)	C. gigas	On bottom and suspended aquaculture	Assimilation and excretion of ingested particulate organic N	Assimilation and excretion of ingested particulate organic P (results are not shown, but model can compute this)

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							sizes for seeding and harvesting, densities and spatial distributions (iii) environmental assessment of farm-related eutrophication effects (including mitigation).					
5	Fulford, R.S.	2010	Evaluating ecosystem response to oyster restoration and nutrient load reduction with a multispecies bioenergetics model	Department of Coastal Sciences, University of Southern Mississippi, Gulf Coast Research Laboratory, 703 East Beach Drive, Ocean Springs, MS 39564	Breitburg, D.L. (Smithsonian Environmental Research Center); Luckenbach, M. (Virginia Institute of Marine Science); Newell (Horn Point Laboratory, University of Maryland Center for Environmental Science)	Peer-reviewed publication in Ecological Applications, 20(4): 915-934	Developed a network simulation model to examine ecosystem-level responses to management. Applied model to compare nutrient load reduction and restoration of the eastern oyster in Chesapeake Bay.	Chesapeake Bay tributaries, Patuxent and Choptank Rivers	Eastern oyster, C. virginica	Oyster Restoration	Did not directly estimate N removal, but instead estimated food web effects of increased oyster biomass resulting from oyster restoration activities (i.e., changes in phytoplankton production from oyster filter-feeding).	Did not directly estimate P removal, but instead estimated food web effects of increased oyster biomass resulting from oyster restoration activities (i.e., changes in phytoplankton production from oyster filter-feeding).
6	Gedan, Keryn B.	2014	Accounting for multiple foundation species in oyster reef restoration benefits	Department of Biology, University of Maryland, College Park, MD 20742, U.S.A.; Smithsonian Environmental Research Center, Edgewater, MD 20137, U.S.A.; Address correspondence to K. B. Gedan, email kgedan@umd.edu	Kellogg (VIMS); Breitburg (Smithsonian Environmental Research Center)	Peer-reviewed publication in Restoration Ecology 22(4): 517-524	Compared temperature-dependent phytoplankton clearance rates and filtration efficiency of Eastern oyster (C. virginica)/reefs with and without hooked mussel (I. recurvum) using lab (with field component) and model results to inform filtration capacity of restored oyster reef at the tributary-scale.	Rhode River, MD, USA	Eastern oyster, C. virginica; hooked mussel, I. recurvum	Reef restoration	Filtration rates could inform N removal rates (not evaluated in study)	Filtration rates could inform P removal rates (not evaluated in study)
7	Grizzle, R.	2014	Nitrogen and Carbon Content of Farmed Eastern Oysters (Crassostrea virginica) In the Great Bay Estuary, New Hampshire	New Hampshire, School of Marine Science and Ocean Engineering, Jackson Estuarine Laboratory, Durham, NH 03824	Ward, K. and Peter, C. (U. of NH); Cantwell, M., Katz, D., and Sullivan, J. (U.S. EPA)	Final report to NOAA	Measured the nitrogen and carbon content in the tissues and shells of oysters of varying age and sizes at six sites over three separate years (2010, 2011, and 2012).	Great Bay Estuary, New Hampshire, USA	Eastern oyster, C. virginica	Intensive Near Bottom Rack-and-Bag Aquaculture	Assimilation	-

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8	Kellogg, Lisa M.	2014	Use of oysters to mitigate eutrophication in coastal waters	Virginia Institute of Marine Science (VIMS), College of William and Mary, P.O. Box 1346, Gloucester Point, VA 23062, USA	Smyth and Luckenbach (VIMS); Carmichael and Dalrymple (U. of S. Alabama); Higgins (Dauphin Island Sea Lab); Brown (Virginia Commonwealth U.); Cornwell and Owens (University of Maryland Center for Environmental Science); Piehler (U. of NC)	Peer-reviewed publication in Estuarine, Coastal and Shelf Science 151: 156-168	Presents and discusses the meta-analysis from the 2013 Quantifying Nitrogen Removal by Oysters Workshop Report. Focused on field studies (laboratory-only studies were excluded).	Varies, includes Chesapeake Bay (see Table 1 in paper)	Eastern oyster, C. virginica	Intensive aquaculture (near bottom and suspended cages); extensive aquaculture oyster reef; restored and natural oyster reefs	Discusses assimilation, denitrification, and long-term N burial from other studies (data previously evaluated during 2013 STAC Review)	-
9	Kellogg, Lisa M.	2014	A model for estimating the TMDL-related benefits of oyster reef restoration	Virginia Institute of Marine Science (VIMS), College of William and Mary, P.O. Box 1346, Gloucester Point, VA 23062, USA	Brush, M.J., (VIMS); North, E.W. (University of Maryland Center for Environmental Science)	Final report to the National Fish and Wildlife Foundation and the Oyster Recovery Partnership	Developed a user-friendly, web-accessible model based on scientifically-defensible data that allows restoration practitioners and resource managers to estimate TMDL-related benefits of oyster reef restoration per unit area.	Chesapeake Bay tributary, Harris Creek	oysters (general)	Oyster Restoration	Assimilation in tissue and shell, denitrification, and burial associated with restored oyster reefs	Assimilation in tissue and shell and burial associated with restored oyster reefs
10	Pollack, Jennifer B.	2013	Role and value of nitrogen regulation provided by oysters (Crassostrea virginica) in the Mission-Aransas Estuary, Texas, USA	Department of Life Sciences, Texas A&M University-Corpus Christi, Corpus Christi, Texas, United States of America; jennifer.pollack@tamucc.edu	Yoskowitz and Montagna (Texas A&M University-Corpus Christi); Kim (I.M. Systems Group)	Peer-reviewed publication in PLoS One 8(6): e65314, doi 10.1371/journal.pone.0065314	Study considered nitrogen regulation by C. virginica in Texas estuary as a function of denitrification, burial, and physical transportation from the system via harvest and development of a transferrable method to value nitrogen removal by oysters. Field data was collected to establish the baseline for water quality (salinity, temp., dissolved oxygen, pH, chlorophyll-a, total suspended solids) and oyster height and biomass variables. Existing field and lab measurements were used to estimate N removal. Value of nitrogen removal was compared to wastewater treatment plant.	Mission-Aransas estuary, Texas, USA	Eastern oyster, C. virginica	Harvested subtidal oyster reefs	Removal of assimilated N (via harvest), denitrification, and burial of N as biodeposits in sediment	-

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11	Rose, Julie M.	2014	Comparative analysis of modeled nitrogen removal by shellfish farms	NOAA Fisheries, Northeast Fisheries Science Center Milford Laboratory, 212 Rogers Avenue, Milford, CT 06460, USA	Bricker (NOAA National Center for Coastal Ocean Science); Ferreira (New University of Lisbon, IMAR)	Peer-reviewed publication in Marine Pollution Bulletin, http:// dx.doi.org/10.1016/j.marpolbul.2014.12.006	FARM model analysis of nitrogen removal at the shellfish farm scale from 14 locations in 9 countries across 4 continents. Model results suggest nitrogen removal from shellfish farms compare to commonly applied agricultural and stormwater runoff BMPs on a per-acre basis.	Potomac River, USA (see Table 1 in paper for other locations)	Eastern oyster, C. virginica (see Table 1 in paper for other species)	On bottom and suspended aquaculture	Removal of assimilated N (via harvest)	-
12	Rose, Julie M.	2014	A Role for Shellfish Aquaculture in Coastal Nitrogen Management	NOAA Fisheries, Northeast Fisheries Science Center Milford Laboratory, 212 Rogers Avenue, Milford, CT 06460, USA	Bricker and Wikfors (NOAA NCCOS); Tedesco (U.S. EPA)	Peer-reviewed publication in Env Sci and Tech, dx.doi.org/10.1021/es4041336	Uses information from other studies to evaluate the potential and challenges in incorporating shellfish aquaculture in nutrient management programs.	Long Island Sound, Chesapeake Bay, Narragansett Bay	oysters (general)	Aquaculture (general)	Discusses assimilation and denitrification from other studies	-