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SUSTAINABLE OYSTER AQUACULTURE, WATER QUALITY IMPROVEMENT, AND ECOSYSTEM SERVICE VALUE POTENTIAL IN MARYLAND CHESAPEAKE BAY

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ABSTRACT The United States has a $16 billion seafood deficit that the U.S. Department of Commerce and states are attempting to close by legislative policies, encouraging expansion of aquaculture in the United States. One of these policies, the 2011 National Shellfish Initiative, recognizes the benefits to water quality of cultivation of bivalve shellfish aquaculture in addition to the provision of seafood product. More recently, research addressing these policies has resulted in approval of the use of harvested oysters as a nutrient best management practice in the Chesapeake Bay region. Also discussed, but not yet fully implemented, is the inclusion of oyster growers in nutrient credit trading programs where economic compensation is provided to oyster growers for the nutrient removal ecosystem service that their oysters provide. This study used field sampling and a local-scale oyster production model to compare water quality, oyster production, and oyster associated nitrogen removal at two bottom and four water-column Maryland Chesapeake Bay oyster farms. Objectives were to highlight differences in water quality (i.e., oyster food), resultant differences in oyster production, and differences in estimated oyster-associated nutrient removal among farms. An avoided, or replacement, cost economic valuation analysis was performed to also compare the potential payment to the oyster growers for the nutrient removal service if they were included in a fully developed nutrient credit trading program. Production at the six sites varied from 1.78 to 25 metric tons of harvestable oysters acre^{-1} y^{-1}. Oyster filtration–related N removal was estimated to be at a range of 28–457 kg N acre^{-1} y^{-1}. The potential economic value of the total N removed by a farm was estimated to be at a range of $\$0.56 \times 10^3$–$\$12,446 \times 10^3$ y^{-1} among farm sites, depending on the alternative management measure used to assign the value.

INTRODUCTION

The United States had a $16 billion seafood trade deficit in 2016 (NOAA Fisheries 2017). The 2011 Department of Commerce and National Oceanic and Atmospheric Administration (NOAA) Aquaculture Policies and the National Ocean Policy provide federal guidance for marine aquaculture activities. One such policy is the NOAA National Shellfish Initiative that has established partnerships with shellfish farmers and shellfish restoration organizations with the goal to increase populations of bivalve shellfish (oysters, clams, and mussels) in United States national coastal waters through both sustainable commercial production and restoration activities. The NOAA is targeting the expansion of shellfish aquaculture to help close the gap while also recognizing water quality benefits of increased oyster populations (NOAA 2011). As a result of NOAA and state of Maryland activities to promote aquaculture (i.e., revision of leasing laws, streamlined permit processing, investments in training and education programs, and low-interest loans), the number of oysters harvested by aquaculture in Maryland Chesapeake Bay has increased 10-fold since 2010 (Kobell 2017, Parker et al. 2020). The primary reason for the increase in production is the expansion of permitted oyster aquaculture leases, which have increased from 3,674 to 6,803 acres between 2013 and 2018 (Maryland Aquaculture Coordinating Council 2013, 2018).

In addition to provision of seafood, oysters are well known for their ability to effectively remove nutrients from the water column through filtration and assimilation of phytoplankton and detritus into tissue and shell (Bricker et al. 2014, 2018, 2020). Denitrification from sediments associated with cultivation is an additional oyster-related nitrogen (N) removal method (Kellogg et al. 2013), but was not considered in this study. Recognition of these water quality benefits has led to the approval of harvested oyster tissue for use as a nutrient best management practice (BMP) in the Chesapeake Bay region (Cornwell et al. 2016) to help jurisdictions meet mandated nutrient reductions. There has been interest in compensating oyster growers for the nutrients removed through the Maryland Nutrient Trading Program established in 2010; however, the regulations to allow such compensation have not yet been fully implemented (MDA 2010, Weber et al. 2018). With the approval of the oyster tissue BMP and the recently developed payment mechanism, payment to growers within the Maryland Nutrient Trading Program is now possible.

This study was designed to evaluate the following: (1) differences in water quality and aquaculture practices and resultant production among study site locations to highlight the range of (potential) production in Maryland Chesapeake Bay, (2) the range in potential N removal *via* sustainable oyster aquaculture among the farm sites, and (3) the economic value of the removed nutrients, representing potential payment to growers within a nutrient credit trading program for the nutrient removal service their oysters provide.

STUDY SITES AND CULTIVATION PRACTICES

The focus of this study was oyster farms in Maryland Chesapeake Bay and tributaries; 11,600 km^2 area of the bay is shared by Maryland and Virginia. Study sites were located in the West and Wicomico rivers, Calvert Bay, and Potomac River on the western shore, and Chester and Honga rivers on the eastern shore of Chesapeake Bay (Fig. 1). About 50% of freshwater enters Chesapeake Bay through the Susquehanna River at the head of the bay with an additional 20% accounted for by freshwater inflow from the Potomac River in Maryland and the James River in Virginia. The average depth

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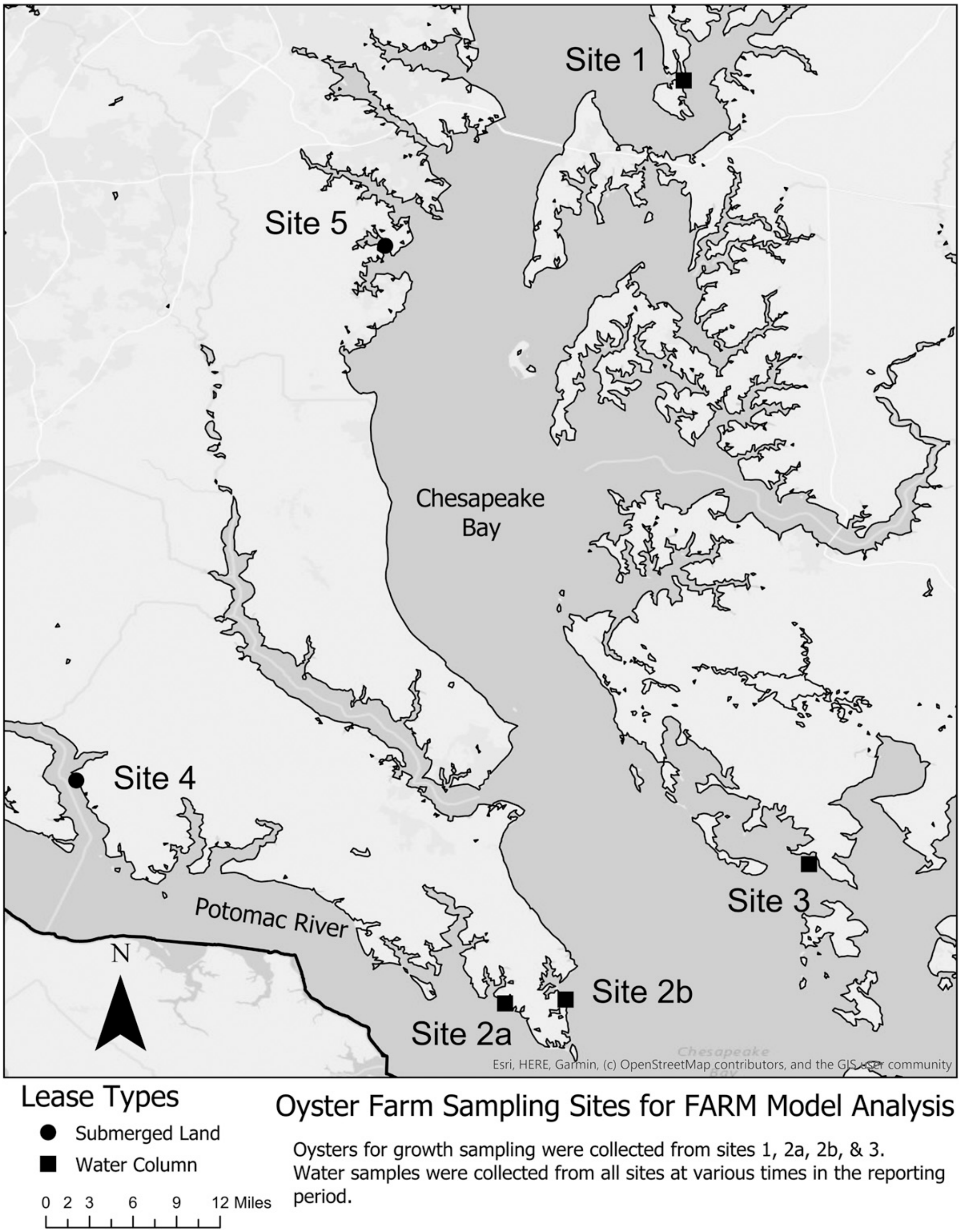

Figure 1. Study sites in Maryland Chesapeake Bay. Sampling of oysters and water quality variables was conducted from May 2016 to August 2018. Data were used to develop oyster growth curves to calibrate the FARM model to Maryland Chesapeake Bay to estimate oyster production and nitrogen removal associated with Maryland oyster farms (Ferreira et al. 2007, Cubillo et al. 2018). Nitrogen removal estimates were used to calculate the value of avoided or replacement costs for oyster aquaculture at each location.

of Chesapeake Bay is 7.3 m, with average depth of the study tributaries ranging from 3.3 to 5.1 m. Tidal range among the study sites ranges from 0.45 to 0.67 m (Bricker et al. 2007, 2008).

Study sites included two bottom and four water-column oyster farms (Fig. 1) that were selected to provide a suitable representation of oyster culture practices currently used by private aquaculture operations in Maryland. In 2019, there were 455 shellfish leases with a total of more than 7,100 acres under cultivation; 93% of lease acres were for bottom and 7% were for water-column (cage) operations (MD DNR 2019). In addition, the distribution of sites was made to highlight production across all of Maryland Chesapeake Bay, including tributary and mainstem sites. The leases in this study varied in size from 4 to 22 acres, compared with a range of 0.1–100 acres per lease in all of Maryland Chesapeake Bay. The Maryland Department of Natural Resources (MD DNR) reported the mean lease size for bottom-culture operations was 18.5 acres, median lease size was 9.15 acres, and mode was 5.00 acres in May 2017. At the same time, the MD DNR reported the mean lease size for water-column operations was 4.69 acres, and the median lease size was 4.10 acres, with the mode being 5.00 acres for all farms in Maryland Chesapeake Bay (Parker et al. 2020). The annual average salinity at the study farms ranged from 8.98 ± 2.48 to 13.9 ± 2.94 during the years of the study (2016 to 2018). All of these sites have high-level impacts from nutrient loads including moderate to high levels of chlorophyll (CHL; range among all sites of highest annual CHL concentrations was 10–32 μg L^{-1}; Bricker et al. 2007, 2008). These concentrations suggest that additional nutrient management measures are needed, given the association of seagrass die off, changes in the diversity of phytoplankton community, and low bottom water dissolved oxygen (DO) concentrations observed at 15 μg CHL L^{-1} and higher (US EPA 2001, Bricker et al. 2003).

All six oyster farms cultivate the eastern oyster *Crassostrea virginica* (Gmelin, 1791) subtidally; there are no intertidal oyster operations in Maryland. Private oyster cultivation practices included two bottom spat-on-shell operations with no gear—the traditional and still the dominant oyster growing practice in MD; 80% of lease holders use this method (Maryland Aquaculture Coordinating Council 2018). Compared with the highly variable cage operations, the practices used by bottom growers are similar among all farms. Growers using this practice spread spat-on-shell oysters, produced using remote setting techniques (Meritt & Webster 2013), on their lease at a typical density of 247 oysters m^{-2} (1×10^6 $acre^{-1}$) or greater to assure success due to observed mortality of 75%–80% during the 36-mo growing cycle (Congrove 2008, Kingsley-Smith et al. 2009, Abbe et al. 2010, Parker et al. 2020). After planting, there are periodic checks to monitor growth but no regular handling of oysters during the growing cycle. Oysters grown on bottom in Maryland are primarily diploid and generally take 36 mo to reach market size (7.6 cm, 3 inches; Parker et al. 2020); however, some growers use triploid oysters when they are available. In this study, all bottom-cultured oysters were diploid oysters. Diploid oysters can reproduce, and triploid oysters are used for aquaculture because they cannot reproduce, and thus grow faster.

Very little literature exists for a complete growth cycle of oysters, under commercial production conditions, for water-column operations in Maryland. The lack of available data along with higher variability among typical cage grower operations and the high level of interest by cage growers in project participation allowed us to include more cage than bottom farm operations in the study. Furthermore, due to the difficulty in measuring growth for bottom-culture operations, data from restored reef sites were used to represent the growth of bottom-grown oysters because both restoration and bottom-culture operations use spat-on-shell planting methods. The four growers using cage operations (bottom or floating) have more variable seeding densities than bottom-growing oyster operations; in this study, seeding densities ranged from 20 to 160 oysters m^{-2} (83×10^3–650×10^3 $acre^{-1}$) depending on the number of cages and number of oysters per cage in the lease area. Typically, juvenile oysters are raised in a nursery to prevent losses from predation until they are about 15 mm when they are placed into mesh bags inside cages. As the oysters grow, they are split into multiple bags or cages with larger mesh sizes to prevent overcrowding and allow for better water flow (i.e., food delivery) through the cages. Cage-grown oysters are handled several times during the 18- to 24-mo growing cycle, with an overall reported mortality of 30%–50% at the study sites. In areas that have low wave energy, a tumbler may be used to cull oysters when they are sorted into larger mesh size bags; this tumbling encourages the shell to develop a deeper cup. In high wave energy areas, oysters in cages are tumbled naturally and do not need additional tumbling. Oysters grown in the water column in cages are typically triploid and generally take 18 to 24 mo to reach 3 inches (7.6 cm; Parker et al. 2020). In this study, all oysters grown in bottom or floating cages were triploid oysters.

Cultivated oysters can be harvested from cage operations all year, and from bottom-growing operations outside of the public harvest season, with a minimum harvest size of 5.08 cm (2 inches). Legal harvest size for oysters from the public (wild) fishery is 7.6 cm (3 inches) and occurs from October 1 to March 31. The first seeding day for bottom- and cage-grown oysters in this study is mid-April to mid-May dependent on water temperature (>15°C). Mortalities reported for bottom-grown oysters are higher (75%–80%) than those reported for cage-grown oysters, although cage-grown oysters have high mortalities during the initial setting process within the nursery. Here, reported mortalities were provided by growers, note that mortalities reported for cage-grown oysters are post-nursery. Monthly harvest records provided to the MD DNR indicate most of the oysters harvested from bottom leases are harvested between March and October when the wild capture fishery is closed. Additional harvest from bottom-culture operations also occurs in November and December because of seasonal increases in demand (Parker et al. 2020). For this study, it was assumed all farms harvest 7.6 cm (3 inches) oysters that each weigh 35 g (triploid) or 40 g (diploid; weights measured in this study).

MATERIALS AND METHODS

This study used analysis of field-collected water and oyster samples and the local-scale Farm Aquaculture Resource Management (FARM; Ferreira et al. 2007) oyster production model to compare water quality, oyster production, and oyster-associated N removal *via* assimilation into tissue and shell at two bottom and four water-column Maryland Chesapeake Bay oyster farms. Here, the focus is on N because it is, globally, most often the limiting nutrient in estuarine waters such as Chesapeake Bay and has been the focus of coastal nutrient management (Malone et al. 1996, Howarth & Marino 2006). An avoided or replacement cost economic analysis was performed to assign an economic value to the estimated N removal. A similar approach was used previously in Potomac River

(Bricker et al. 2014), in Long Island Sound (Bricker et al. 2018), and in Great Bay Piscataqua River Estuary (Bricker et al. 2020).

Farm FARM Model for Production and Nitrogen Removal Estimates

The FARM model combines physical and biogeochemical models, bivalve growth models, and screening models for determining shellfish harvest and for eutrophication assessment at the farm scale (Ferreira et al. 2007). The FARM model is well described and has been tested in the United States, European Union, China, and elsewhere (Bricker et al. 2014, 2015, 2018, 2020, Ferreira et al. 2007, 2009, 2011, 2012, Nobre et al. 2010, Nunes et al. 2011, Saurel et al. 2014; www.farmscale.org). Briefly, the model calculates the phytoplankton and detrital carbon removed by shellfish as water and ''food'' passes through the lease area, and then converts those values to N and deducts losses due to pseudofeces, feces, excretion, mortality, and spawning. The mass balance, for a single cultivation cycle, provides a value for net removal of N from the water column by the population of cultivated oysters, which effectively equates to a drawdown of phytoplankton (represented as CHL in the model), that is, of one of the primary symptoms of eutrophication. The model also provides an estimate of production (harvest) for one cultivation cycle (e.g., 18–24 mo; Ferreira et al. 2007). The model is useful for decision support for aquaculture siting (Silva et al. 2011, Ferreira et al. 2012, Bricker et al. 2016) because it evaluates both harvest and ecological carrying capacity (e.g., changes in dissolved and particulate concentrations due to aquaculture activity) without the financial cost (e.g., for seed, cages, lease fees, insurance, boat and boat maintenance, and fuel) and time (i.e., one cultivation cycle is 18–24 mo) required for implementation of a shellfish farm.

The FARM model has recently been calibrated to Chesapeake Bay oyster farms, which is the model used for this study (Cubillo et al. 2018). An individual model for eastern oysters was developed for Maryland Chesapeake Bay from measured oyster data from the four cage operation farms in this study and was incorporated into the FARM model to simulate oyster population growth. Additional modifications were made to account for the high particulate matter environment within the bay, and an option was included that can turn off spawning so that growth of both diploid and triploid oysters can be simulated (Cubillo et al. 2018).

Data inputs required for simulation of oyster growth using the FARM model include monthly measures of temperature, salinity, concentrations of total suspended solids (TSS), total volatile solids (TVS; which represent the organic part of suspended solids, also called particulate organic matter), and phytoplankton (represented as CHL; Ferreira et al. 2007). Other measures, DO, nitrite nitrate (NO_{23}), and ammonia (NH_4) are not required for growth simulations but rather are used to determine changes in water quality that occur that are attributable to the oysters as the water moves across the oyster farm. These are also indicators of nutrient enrichment, and it was of interest to evaluate the changes in these indicators that could be attributed to the oyster farms. Additional inputs needed for the simulations are current speeds (taken from the NOAA buoy closest to each study site), oyster seeding density, size of oyster seed and harvestable oysters (3 inches, 7.6 cm), and typical mortality over the cultivation cycle (reported by the growers). The model outputs of interest to this study were oyster production and the net mass of N removed through uptake of phytoplankton and detritus (i.e., food for the oysters). The removal of N estimated by the FARM model is a result of the balance of shellfish filtration, assimilation into tissue and shell through physiological growth processes, and return of the remaining N to the environment through pseudofeces and feces, natural mortality, and excretion (Ferreira et al. 2007). Eight model simulations were made at Site 1 in Chester River using different mortalities (20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) to represent the potential range of production and N removal at a farm, given the range of mortalities reported by all growers (20%–90%). This was the only site for which harvest data were made available (320×10^3 oysters harvested in 2016) and, thus, was the only site for which a comparison of reported harvest and model results was possible.

Water Sampling and Analysis

Data to drive FARM model simulations were collected monthly, from bottom-culture production operations (Sites 4 and 5) from May 2016 to August 2017, and from water-column (cage) production sites (Sites 1, 2a, 2b, and 3) from May 2016 to August 2018, as producer schedules allowed. The difference in sampling schedules was determined based on the growing time (i.e., time to reach harvest size) for oysters produced by each method, and the available information in the literature on the growth of oysters in restored oyster reefs, which are representative of bottom culture (Kellogg et al. 2014, Cornwell et al. 2016). Sampling efforts were focused on water-column production methods to capture water quality parameters throughout the entire culture period.

At each site, monthly measures of DO, water temperature, and salinity were measured in the field with a YSI Pro2030 and recorded. Water samples were collected monthly from each site and prepped in the field for analysis by the Nutrient Analytical Services Laboratory located at the University of Maryland Center for Environmental Science Chesapeake Biological Laboratory, Solomons, MD. Water samples were filtered through GF/F glass microfiber filters (0.7 micron pore size) in the field, wrapped in aluminum foil, put on ice, and transported to the laboratory. The samples were analyzed for TSS, TVS, NH_4, NO_{23}, and CHL components using standard laboratory practices (Table 1).

Oyster Sampling and Analysis

In addition to water samples, oyster samples were collected from a single cohort from each water-column production location to provide accurate growth estimates for calibration of the FARM model to Chesapeake Bay (Ferreira et al. 2007, Cubillo et al. 2018). Oysters were not collected from bottom-culture operations because of the small size of oysters at deployment and the difficulty of obtaining accurate measurements from clusters of oysters. In addition, it was assumed diploid bottom-culture spat-on-shell oysters would have similar growth patterns to wild diploid oysters (Kellogg et al. 2014, Cornwell et al. 2016). Therefore, growth data from restored reef sites were used as a proxy for spat-on-shell aquaculture oyster growth.

Each month, 50–100 live oysters were collected from the four water-column production sites and transported to the Quantitative Fisheries Ecology Laboratory at the University of

TABLE 1.

Methods used for water quality parameter analysis by Chesapeake Biological Laboratory Nutrient Analytical Services Laboratory.

Water quality parameter	Standard method used	Source
NH_4	Standard methods 4500-NH_3 G-1997	University of Maryland Center for Environmental Science Chesapeake Biological Laboratory Nutrient Analytical Services (2019a)
NO_{23}	EPA 353.2 CADMIUM	University of Maryland Center for Environmental Science Chesapeake Biological Laboratory Nutrient Analytical Services (2019b)
TSS TVS	EPA 160.2 SM2540	University of Maryland Center for Environmental Science Chesapeake Biological Laboratory Nutrient Analytical Services (2019c)
CHL-Total	EPA 445.0, SM10200H.3	University of Maryland Center for Environmental Science Chesapeake Biological Laboratory Nutrient Analytical Services (2019d)

Maryland Center for Environmental Science Chesapeake Biological Laboratory for analysis. Oyster measurements included shell height, live whole weight, wet and dry shell weight, wet and dry tissue weight, and the volume of water inside the oyster shell *via* standard laboratory practices. Once shell height and live whole weight were recorded, the oysters were shucked and the volume of water inside the shell was measured. Tissue was separated from the shell to determine wet shell weight and wet tissue weight. After wet weights were recorded, both tissue and shell were placed in an oven to dry for 72 h at 60°C, and dry weight recorded. These data were used to compare growth at the different sites and to calibrate the FARM model to Chesapeake Bay (Cubillo et al. 2018).

Economic Avoided Costs Analysis: Estimated Compensation for Nitrogen Removal Ecosystem Services

An avoided, or replacement, cost approach was used to estimate the value of the nutrients removed by oyster farms in this study. This approach assumes there is equivalency of N removal services by oysters and by alternative removal methods, that the avoided cost good is the least cost for N removal, and that there is willingness to pay because of the inclusion of parts of Chesapeake Bay on the 303d list for N impairment and the requirement of N load reductions to meet water quality goals (Freeman et al. 2014). In this approach, the costs of alternative nutrient management measures (e.g., wastewater treatment plant upgrades, and agricultural and urban stormwater BMPs) are used to represent the potential value of N removed by oysters (e.g., Bricker et al. 2018, 2020, Rose et al. 2015). There continues to be great interest in determining the economic value of oyster-mediated nutrient removal services, given the need for continued nutrient management in most United States coastal waterbodies and worldwide. Harvest of cultivated bivalve shellfish is already being used to fulfill mandated nutrient reductions in several United States jurisdictions and parts of Europe (e.g., Massachusetts, oysters and clams; Town of Mashpee Sewer Commission 2015, Reitsma et al. 2017; Denmark, mussels, Nielsen et al. 2016; Chesapeake Bay region, oyster tissue, Cornwell et al. 2016). Compensation to shellfish growers for the nutrient removal ecosystem service provided by their oysters through a nutrient credit trading program is gaining momentum (Lindahl et al. 2005, Profeta & Daniels 2005, Lal et al. 2009, Miller 2009, Jones et al. 2010, Ferreira & Bricker 2016, Weber et al. 2018).

This is evidenced in the Chesapeake region by the inclusion by the State of Virginia of shellfish aquaculture in their nutrient trading program (§10.1–603.15:2; VA DEQ 2017; VNCEA 2017), and the recent application of the Oyster Company of Virginia to be a credit aggregator under the nutrient trading program of Virginia (VA DEQ 2018). In July 2018, Maryland adopted its Nutrient Trading Program regulations for the agricultural, stormwater, wastewater, and on-site sewage disposal sectors (COMAR 26.08.11.01). Within this program, harvested oyster tissue from aquaculture practices are eligible for consideration as nutrient reduction BMPs where the N (and P) removed in harvested oyster tissue can be credited toward fulfillment of nutrient reduction requirements. The framework has been developed for inclusion of sales of oyster aquaculture credits, but very few sales have been made (Wheeler 2020). The Maryland Department of Environment has developed a marketplace that includes trades of N removed in aquaculture oyster tissue, based on the approved oyster aquaculture BMP (Cornwell et al. 2016). The MD DNR has been designated as the agency that will verify harvests from shellfish aquaculture leases that will be used to generate credits through the Maryland Nutrient Trading Program.

In anticipation of this, one Maryland company has been formed to act as a third-party verifier and aggregator of credits produced from aquacultured oysters (Blue Oyster Environmental n.d.; East Coast Shellfish Growers Newsletter, June 2019; Shockley 2019). This company, in late 2019, was able to broker a voluntary payment of $1,600 (4 lb of N) to an oyster grower for nutrient reduction credits to shrink the environmental footprint of events held at the Baltimore Convention Center, highlighting the Baltimore Convention Center commitment to sustainability and environmental protection. In the second payment to oyster growers in Maryland Chesapeake Bay, Anne Arundel County paid $4,950 (107 pounds of nitrogen and 12 pounds of phosphorus) for nutrient credits to satisfy a regulatory requirement to meet state mandates for treating stormwater runoff—the credits were equivalent to treating runoff from three acres of impervious surface (Wheeler

2020). The two recent trades provide optimism regarding the recognized value of aquaculture-related nutrient removal and the possibility of full inclusion of oyster growers in a comprehensive nutrient management program. In addition, these first payments enhance public awareness of the beneficial impacts of oyster aquaculture on water quality and might help shift attitudes to allow expansion of shellfish aquaculture that will also support domestic sustainable sources of seafood.

Quantification and valuation of N removed through shellfish harvest can be used by policy-makers to assess the available set of nutrient management tools to design a comprehensive nutrient management plan that will most efficiently and cost effectively achieve water quality goals. Assigning an economic value to the N removed *via* oyster bioextraction is difficult (Peterson & Lipcius 2003) and is further complicated by the lack of functioning N trading programs (Stephenson & Shabman 2017). Previously published avoided cost values determined for Virginia Chesapeake Bay (Jones et al. 2010, Stephenson et al. 2010, Rose et al. 2015) were used to calculate economic benefits for oyster harvest in Maryland Chesapeake Bay (Table 2). Those estimates were compared with recent results from Weber et al.'s (2018) evaluation of potential effects of economic compensation for nutrients removed *via* oyster aquaculture. Weber et al. (2018) estimated upper and lower N credit values ($22 and $418 per kg of N removed) that would increase aquaculture production by a small or large amount. This range of costs is representative of the range of costs of providing nutrient removal by oyster aquaculture. Note that the range of costs reported by Weber et al. (2018) overlaps with ranges reported by Bricker et al. (2018) and Rose et al. (2015), although at the lower end of those ranges. In addition, published payment rates from the Virginia Nutrient Credit Exchange Association (VA DEQ 2017, VNCEA 2017; Table 2) were also included for comparison. Although the value of the N removed may be provided to growers as compensation for the N removal service their oysters provide within a fully developed nutrient credit trading program, the upper-level values do not represent what expected compensation will be, as noted earlier. In a competitive functioning nutrient market, the expected payments will be closer to the lowest cost alternative (Freeman et al. 2014; e.g., wetlands or agricultural BMPs). If there is a limitation on the lowest cost BMPs available for purchase, other slightly more expensive BMPs will be available, but not the highest avoided cost value. Values of N from recent trades were not evaluated because the value of N from the Anne Arundel County trade was not identified, and the Maryland Department of Environment has not recorded enough trades to determine an average value for N removed *via* oyster aquaculture in the Maryland Nutrient Trading Program.

RESULTS

Water Quality Data Model Inputs

Annual averages of monthly measures of water quality parameters at the six study sites from May 2016 to August 2018 are shown in Table 3. Parameter concentrations vary from farm to farm, but annual patterns are similar at all sites. Salinities are lower in summer, and overall concentrations are lower in the river sites, i.e., Chester, Wicomico, and West rivers (Sites 1, 4, and 5) than at farms located closer to the mainstem of the bay (i.e., Sites 2b and 3), highlighting the influence of freshwater and estuarine water masses. Annual average salinities at all sites are within the range of tolerable salinities for *Crassostrea virginica* (5–40, with an optimum of 15–25; Shumway 1996).

Average annual concentrations of CHL for all stations are considered *moderate* according to the range of values in the Assessment of Estuarine Tropic Status (ASSETS, Bricker et al.

TABLE 2.

Estimated value of nitrogen removal as an avoided or replacement cost analysis using costs of alternative nutrient management measures to estimate value for Maryland Chesapeake Bay oyster bioextraction.

Alternative nitrogen management measure	Chesapeake Bay Cost ($/kg N)	Long Island Sound Cost ($/kg N)	Rose et al. (2015) Cost ($/kg N)
Shellfish*	$0–$330	–	$13–$330
Agricultural*†	$7.04–$1,034	$13	$0.22–$1,034
Urban stormwater*†	$66–$4,873	$350	$66–$7,934
Wastewater treatment plant (WWTP) upgrades†	$35–$104	$32–$99	$1.1–$16,742
Wetlands*†	$2.2–$471	–	$1.32–$471
Other (algal turf scrubber and algal biomass harvest)*†	$15–$176	–	$6.16–$480
VNCEA‡ 2018 sales price	$8.33	–	–
Range of threshold costs§ (to increase oyster production by 4%–59%)	$22–$418	–	–

Also included are 2018 N credit sales value within the Virginia Nutrient Credit Exchange and threshold costs that would impact consideration for expansion by grower. Costs estimated for nutrient management measures in Long Island Sound and by a multinational analysis are included for comparison.

* Stephenson et al. (2010).

† Jones et al. (2010).

‡ VNCEA (2017), VA DEQ (2017).

§ Weber et al. (2018); note that Miller (2009) gives a range of $6–$66 per kg N for Virginia oyster growers to realize a 12%–15% 10-y targeted rate of return—adjusted from 2008 to 2018 dollars). Cost ranges represent average and high cost upgrades for WWTPs, various urban stormwater management strategies (i.e., septic retirement, stormwater retrofits, and sand filters), various agricultural strategies (e.g., crop to forest land conversion, conservation tillage, and cover crops), and restored or constructed wetlands.

TABLE 3.

Annual averages and standard deviations of water quality parameters from monthly measures at the six oyster farm study sites in Maryland Chesapeake Bay from May 2016 to August 2018 (Fig. 1 for locations).

			Salinity		Temperature		CHL			TVS		TSS		DO		
Farm site	Type of farm, ploidy	Number of months sampled*	Average	SD	Deg C average	Deg C SD	μg L^{-1} average	μg L^{-1} SD	90th percentile	mg L^{-1} average	mg L^{-1} SD	mg L^{-1} average	mg L^{-1} SD	mg L^{-1} average	mg L^{-1} SD	10th percentile
Site 1	Bottom cage, triploid	23	8.98	2.48	16.7	9.66	14.6	15.1	31.6	4.59	1.70	14	7.77	9.36	2.87	6.22
Site 2a	Floating cage, triploid	19	13.9	2.94	17.2	9.41	7.63	2.66	10.4	3.86	1.17	13.9	7.07	9.42	2.46	6.93
Site 2b	Floating cage, triploid	25	13.7	2.90	17.6	9.36	11.4	5.32	17.5	5.4	1.80	19.3	–	9.14	2.65	5.82
Site 3	Bottom cage, triploid	24	13.8	2.35	18.1	8.63	7.25	3.03	10.8	4.88	1.03	24.9	41.7	9.38	2.26	6.92
Site 4	Bottom culture, diploid	12	10.1	2.37	20.6	8.27	17.6	11.3	29.8	6.04	1.77	14.3	4.98	7.59	2.78	5.84
Site 5	Bottom culture, diploid	10	9.99	2.40	21.5	9.77	19	16.6	28.8	5.56	1.46	12.7	5.63	8.81	2.49	6.05

For CHL and DO, the Assessment of Estuarine Trophic Status (ASSETS) model assessment criteria (Bricker et al. 2003) are included. The 90th percentile CHL concentrations represent highest concentrations observed over an annual cycle where less than 5 μg L^{-1} = good or low, 5–20 μg L^{-1} = moderate or fair, and greater than 20 μg L^{-1} = poor or high. The 10th percentile DO concentrations represent lowest concentrations observed over an annual cycle where 0 mg L^{-1} = anoxic, greater than 0–2 mg L^{-1} = hypoxic, greater than 2–5 mg L^{-1} = biologically stressful, and greater than 5 mg L^{-1} = no problem.

* Not necessarily consecutive; some farms pull boats from the water in winter, and some months were not sampled because of weather (frozen or small boat warning) or when producers were not available. Bottom-culture production farms were sampled from May 2016 to August 2017, and water-column cage production farms were sampled from May 2016 to August 2018.

2003) model (5–20 μg L^{-1}; Table 3). The 90th percentile of CHL, an ASSETS criterion representing worst-case (highest) concentrations during an annual cycle (Bricker et al. 2003), is in the *high* category for three river farm sites (Sites 1, 4, and 5) and moderate for the other three farm sites (Sites 2a, 2b, and 6). Chlorophyll concentrations at all sites are greater than the threshold supportive of desired growth rates shown in an analysis in Long Island Sound (4.5 μg L^{-1}, Bricker et al. 2016). Dissolved oxygen concentrations indicate no problems with depletion in neither annual average nor 10th percentile concentrations, a criterion representing worst-case (lowest) concentrations during an annual cycle (Bricker et al. 2003).

FARM Model Production and N Removal Estimates

Measured data from the farm sites were used as inputs to the FARM model to estimate production and N removal at each site; results are shown in Table 4. Production, or harvest, ranges from total farm production of 20.1–194 metric tons of harvestable oysters y^{-1} or 1.78–25 metric tons of harvestable oysters $acre^{-1}$ y^{-1}. Oyster filtration–related N removal was estimated to be at a range of 28–457 kg N $acre^{-1}$ y^{-1}, which, put into a water management perspective based on 3.3 kg N $person^{-1}$ y^{-1}, represents water treatment for people equivalents (PEQ) of 8–139 PEQ $acre^{-1}$ y^{-1}. Results showed that CHL, DO, and NH_4 concentrations did not change at any site.

Ecosystem Service Valuation

Annualized cost estimates for removal of 1 kg N *via* several different nutrient management methods (Table 2) were applied to the estimated N removed by the oyster farm operations (Table 5). The annual cost to replace the bioextractive removal of N in tissue and shell is estimated to range from \$0.56 × 10^3–\$12,466 × 10^3 y^{-1} among the six Maryland farm study sites depending on the cost of the alternative management measure used for the analysis.

DISCUSSION

Recognition of the United States seafood trade deficit and legislative policies encouraging expansion of sustainable domestic production of seafood was the impetus for this study. There was also interest in addressing the means by which the decimated Chesapeake Bay oyster population and oyster industry might be revived and supported, and to illustrate the range of oyster production (harvest) that might be expected in Maryland Chesapeake Bay. This also provided an opportunity to evaluate the potential improvement in water quality that is recognized as a benefit of the filtering of water by oyster populations as they feed. In fact, Maryland oyster growers have pushed for evaluation of oyster-related nutrient removal capabilities and for inclusion in nutrient management programs

TABLE 4.

FARM model estimates of oyster production and nitrogen removal, and PEQ (PEQ; based on annual average of 3.3 kg N person^{-1} y^{-1}) of water treatment represented by the removal, at oyster farms in Maryland Chesapeake Bay for total farm and per acre.

		Harvestable oyster biomass		N removed		People equivalents	
Farm site	Type of farm, ploidy	M tons oysters y^{-1}	M tons oysters acre^{-1} y^{-1}	Kg N y^{-1}	Kg N acre^{-1} y^{-1}	PEQ y^{-1}	PEQ acre^{-1} y^{-1}
Site 1 (33% mortality)	Bottom cage, triploid	30.1	6.15	399	81	121	25
Site 1 (70% mortality)	Bottom cage, triploid	13.6	2.77	253	52	77	16
Site 2a	Floating cage, triploid	80.2	25.1	986	308	299	93
Site 2b	Floating cage, triploid	194	8.93	1,906	88	578	27
Site 3	Bottom cage, triploid	35.7	1.78	554	28	168	8.00
Site 4	Bottom culture, diploid	41.3	5.90	2,554	365	774	111
Site 5	Bottom culture, diploid	20.4	5.09	1,828	457	554	139

The two entries for Site 1 are for the original grower reported mortality (33%) and actual mortality (70%, determined by FARM model series using varying mortality; see text).

knowing that there is an economic value represented by their aquaculture activities. It was recognized that this evaluation would also be useful to the framing of the nutrient credit trading program under development in Maryland (Cornwell et al. 2016) that will be a model for the development of programs elsewhere.

The Maryland Nutrient Trading Program has formulated a mechanism whereby oyster growers can receive BMP credits for nutrient removal in harvested oyster tissue. As demonstrated in the payment made by Anne Arundel County, the N removal by harvest of oysters can be credited (and sold) to fulfill legally required nutrient reductions within the TMDL in a waterbody (Cornwell et al. 2016, Wheeler 2020). The estimation of production and N removal for the six study sites is illustrated here, and a valuation analysis was also conducted to show the potential economic compensation growers might receive within a fully developed nutrient credit trading program.

Production and N Removal at Oyster Farms in Maryland Chesapeake Bay

Results of modeling of the study farms show variable annual harvest from a low of 14 metric tons at Site 1 to a high of 194 metric tons of oysters at Site 2b. These are total harvests for each farm, which vary in size and culture practices, and are thus somewhat difficult to compare. The range of annual harvests normalized per acre is presented to provide a more standardized comparison, which vary from a low of 1.78 metric tons of oysters acre^{-1} y^{-1} at Site 3 to a high of 25.1 metric tons of oysters acre^{-1} y^{-1} at Site 2a (Table 4). That DO and NH_4 did not change at any site indicates that the farm operations did not have a negative impact on water quality at the farm sites. This means that there is margin for expansion of oyster operations *via* increased seeding densities at these sites, although this must be performed carefully so that other unintended consequences are not created, i.e., drawdown of DO due to overabundance of biodeposits (Lindahl et al. 2005).

The results for these Maryland Chesapeake Bay oyster farms are comparable to FARM-estimated production of *Crassostrea virginica*

TABLE 5.

Estimated annual value of ecosystem service of nitrogen removal by oysters based on FARM model estimates at each site based on costs of several alternative nutrient management measures (the analysis includes only WWTP upgrades, agricultural and urban BMPs, Vance credit sales price, and thresholds that impact aquaculture; see Table 2).

			WWTP		Ag BMP		Urban BMP		Other*			Weber et al.	
		N removed	Low	High	Low	High	Low	High	Low	High	Vance	Low	High
Farm site	Type of farm, ploidy	kg N y^{-1}	Values as \$1,000s y^{-1}										
Site 1 (33% mortality)	Bottom cage, triploid	399	\$14	\$41	\$2.8	\$413	\$26	\$1,944	\$0.88	\$188	\$3.3	\$8.8	\$167
Site 1 (70% mortality)	Bottom cage, triploid	253	\$8.9	\$26	\$1.8	\$262	\$17	\$1,233	\$0.56	\$119	\$2.1	\$5.6	\$106
Site 2a	Floating cage, triploid	986	\$35	\$103	\$7.0	\$1,020	\$65	\$4,805	\$2.2	\$464	\$8.2	\$22	\$412
Site 2b	Floating cage, triploid	1,906	\$67	\$198	\$13	\$1,971	\$126	\$9,288	\$4.2	\$898	\$16	\$42	\$797
Site 3	Bottom cage, triploid	554	\$19	\$58	\$3.9	\$573	\$37	\$2,700	\$1.2	\$261	\$4.6	\$12	\$232
Site 4	Bottom culture, diploid	2,554	\$89	\$266	\$18	\$2,641	\$169	\$12,446	\$5.6	\$1,203	\$21	\$56	\$1,068
Site 5	Bottom culture, diploid	1,828	\$64	\$190	\$13	\$1,890	\$121	\$8,908	\$4.0	\$861	\$15	\$40	\$764

The value is potential revenue to oyster growers if they were to be included in a nutrient credit trading program, although it is likely that the lower values will be those used to calculate compensation.
* Other = wetlands, algal turf scrubber, and algal biomass harvest (see Table 2).

and other oyster species in other locations, although production at Site 2b is highest among sites in all studies (Table 6). Although a more comparable means of contrast, it is important to note that farm production on a per acre basis may not be appropriate because producers typically refer to the number of oysters they harvest per year, rather than an average number per acre. Also, growers may use portions of their lease for nursery production or may have obtained a larger lease than physically necessary to accommodate future production increases. This is important because to standardize the farm practices of the six study sites for use in this study, the total amount of seed was divided by the total lease area, which may not reflect their actual practices. The "ideal" lease size and number of cages placed on a lease are a matter of operator preference and desired production level, as evidenced by the range of lease sizes and stocking densities when measured on a per acre basis. These results, however, still provide insight about the range in potential harvest among Maryland oyster farms.

Differences in harvest are a result of a combination of factors including size of oyster farm, aquaculture practice (cage or bottom spat-on-shell), seeding density, food quantity and quality, salinity, and natural mortality. A principal component analysis indicated that among all variables, salinity is the strongest identifiable driver of differences in harvest among sites. An example of the different factors that confound the development of any correlations is illustrated by the high mortalities of bottom-grown oysters (75%–80% over the culture cycle) compared with cage-grown oysters (25%–70% over the culture cycle), which suggests that cage-grown oysters might be expected to show greater production. Among these sites, however, seeding density is much higher for bottom spat-on-shell (247 oysters m^{-2} y^{-1}) than for cage-grown oysters (20–50 oysters $meter^{-2}$ y^{-1}), which partially counterbalances the difference in mortality. For example, at Site 1, the food quality (measured as TVS/TSS; Cubillo et al. 2018) and CHL concentrations are highest among the four cage-culture sites, and the 90th percentile CHL (a measure of highest concentrations within the year) is highest among all sites (Table 3). Thus, it might be expected that Site 1 would show the highest production. The seeding density at Site 1, however, is the lowest of all sites, and this location in upper Chesapeake Bay periodically experiences salinities that are below the tolerance of the oysters, which limits their growth. Periodic low salinity may explain why mortality is the highest at this site among the four cage operations (70% compared with 30%–50%).

A series of eight FARM simulations was performed with data from Site 1 to highlight the potential range of harvest that might be expected from year to year, given the range of mortalities reported by growers (20%–90%) and for comparison with reported harvest. This site was selected because it was the only site for which harvest was available for comparison with modeled harvest (see below). The estimated harvest ranged from 4.6 to 36 metric tons y^{-1}, which is the range that might be expected at any site, given variability in mortality due to salinity variations, predation, poor food quality, or other influences on mortality and oyster growth in any given year (e.g., high sedimentation from storms). The corresponding range of oyster-associated N removal in tissue and shell at Site 1 is 147 to 445 (average 308) kg N removed y^{-1}.

Oyster-associated removal of N *via* filtration and assimilation into tissue and shell estimated by the FARM model also shows a wide range among all farm sites. Removal varies among farms from a low of 253 kg N to a high of 2,554 kg N removed per farm per year. On a per acre basis, the range in removal varies from 28 to 457 kg $acre^{-1}$ y^{-1}. The corresponding PEQ represented by total N removal by a farm ranges from a low of eight to a high of 139 PEQ $acre^{-1}$ y^{-1}. As for production, the N removal by Chesapeake Bay oyster farms is within the range of removals reported for oysters in other United States and international study sites (Table 6).

Comparison of FARM Production and N Removal Results to Reported Harvest and Chesapeake Bay Program Nitrogen BMP Estimates (i.e., based on tissue only)

The multiple simulations with differing mortalities at Site 1 also afforded us an opportunity to evaluate the accuracy of the FARM model at predicting harvest. Although previous studies have shown that the FARM model estimates harvest of cultivated oyster and other bivalves reasonably well (Ferreira et al. 2009, Bricker et al. 2020), it would be useful to have reported harvest at all Maryland farm study sites for confirmation of that for the Chesapeake Bay calibrated FARM model. The Maryland industry is young and growing, and there was only one site for which harvest numbers were made available for comparison with model results. As noted earlier, harvest reported for Site 1 was 320×10^3 triploid oysters, which were assumed to be 3 inches in size and weigh 35 g each. There are two results for FARM model simulations for Site 1 in Table 4 for comparison with reported harvest. The original estimate of mortality given by the grower was 33%; however, using this as a model input resulted in model estimated harvest (converted from metric tons) of 860×10^3 oysters y^{-1}, much greater than the reported harvest. The grower reviewed records of seed and harvest to confirm that the actual mortality was 70%. Model simulations using eight mortalities representing the range observed by all growers (20%–90%) were performed to estimate the potential range of harvest and N removal at this site, as an example of the range that

TABLE 6.

Comparative FARM model estimates of oyster harvest and oyster-related N removal *via* sequestration into tissue and shell for Chesapeake Bay (this study), Great Bay Piscataqua River Estuary (Bricker et al. 2020), and Long Island Sound (Bricker et al. 2018).

Location	Harvest (m tons oysters $acre^{-1}$ y^{-1})	N removed (kg N $acre^{-1}$ y^{-1})
Maryland Chesapeake Bay (this study)	1.78–25	28–457
Great Bay Piscataqua River Estuary (Bricker et al. 2020)	0.57–5.27	37–101
Long Island Sound (Bricker et al. 2018)	5.96	125
Multinational study* (Rose et al. 2015)	1.18–8.70	51–345

Also included for comparison are results from a multinational multi-bivalve species study—here, only oyster results are shown (Rose et al. 2015).
* FARM model results for oysters only for eight locations, four countries, and three oyster species (*Crassostrea virginica*, *Crassostrea gigas*, and *Ostrea plicatula*).

might be expected at any site. The range of oyster harvest at Site 1 was 4.6 to 36 (average 20.3) metric ton oysters y^{-1}. The FARM model estimate of harvest at 70% mortality (388×10^3 oysters y^{-1}) was closest of all simulation results to the reported harvest, suggesting that the Chesapeake Bay FARM model reasonably well estimates harvest (Table 4). This highlights that model inputs must be as accurate as possible (e.g., mortality estimates) to make an estimate that is representative of reported harvest.

These simulations also allow for comparison of the FARM model estimates of N removal, which are calculated by a mass balance approach, with an estimate using a per oyster N content as prescribed by the Chesapeake Bay Oyster BMP (Cornwell et al. 2016). The FARM model estimates the total amount of N in shell and tissue removed *via* oysters produced on aquaculture operations, whereas the approved BMP currently includes only the N removed in oyster tissue. To compare results, the FARM estimates were normalized to N removal by tissue only. FARM N removal estimates were normalized to tissue only using results from Cornwell et al. (2016), showing measured tissue N content as 72% of total triploid oyster N content and 47% of total diploid oyster N content. The BMP-based oyster N removal was calculated from the number of oysters (converted from FARM harvest results) and prescribed BMP credit values for harvested tissue of 90 kg N removed with harvest of one million diploid oysters and 130 kg N removed per million triploid oysters (Table 7).

The FARM model resulted in higher estimates of N removal *via* harvested aquaculture oyster tissue (e.g., 182 kg y^{-1} at Site 1; Table 7) when compared with the approved BMP (e.g., 50 kg y^{-1} at Site 1), similar to higher estimates by FARM noted in a previous study (Bricker et al. 2020). This in part reflects the difference between the oysters that are included in the calculations. For example, FARM includes all oysters in the water and uses a mass balance approach where removal is based on filtration and assimilation into tissue and shell minus mortality, excretion, feces, and pseudofeces (values were normalized to tissue as described earlier but is still based on the whole population). The BMP calculation includes only tissue in harvested oysters, although this is unlikely to account for the entire difference; however, the conservative estimate used by the BMP to avoid over crediting does add to the magnitude of the difference. It is interesting to note that the overestimate of removal by triploid oysters is less than the overestimate by diploid oysters. This is likely an artifact of the Chesapeake Bay calibration being based on cage-grown oysters, which grow faster and are lighter than bottom-grown oysters. Ultimately, nutrient credits and economic compensation for N removal by oyster aquaculture will be determined by estimates based on numbers of oysters harvested using the Chesapeake Bay oyster BMP (Cornwell et al. 2016), rather than from modeled estimates. It is useful, however, to have a way to estimate production scenarios, for example, under expanded aquaculture either by higher density planting or added lease acres, and the FARM model can do that without the resources and time that would be required to actually expand the industry. Production estimates from those scenarios could be used with the BMP-based N removal to estimate potential N removal with changes in aquaculture harvest.

Valuation of the Nitrogen Removal Service Provided by the Oyster Aquaculture Industry

Several previous studies have highlighted the economic value of nutrients removed by oysters and other bivalves and the potential economic benefit that bivalves might contribute to a comprehensive nutrient management program (e.g., Lindahl et al. 2005, Miller 2009, Rose et al. 2015, Bricker et al. 2018, 2020). Currently, there are nutrient credit trading programs that allow credits for nutrient removal by oysters and clams. Those credits are being used to help fulfill required nutrient reductions; however, no sales/payments have been documented to growers within any state management program outside of Maryland (e.g., Town of Mashpee Sewer Commission 2015, Cornwell et al. 2016, Reitsma et al. 2017).

Results here, as elsewhere, show that there is a range of costs for removal of N ($2.2–$4,873 per kg N removed; Table 2), which leads to a range of values depending on the alternative management practice used to assign the value to the removed N (Table 5). The range among all the farm study sites is $\$0.56 \times 10^3$–$\$12,445 \times 10^3$ y^{-1} if the total FARM-related N removal is considered, but would be reduced to $\$0.40 \times 10^3$–$\$6,687 \times 10^3$

TABLE 7.

Estimated nitrogen removal by harvested tissue only per farm compared with approved Chesapeake Bay Program oyster BMP credits for harvested tissue.

Location	Culture type, ploidy	Farm model estimate of nitrogen removal (tissue only) (kg y^{-1})	Farm model estimate of nitrogen removal (tissue only) (kg $acre^{-1}$ y^{-1})	Chesapeake bay BMP estimate of nitrogen removal (tissue only in FARM estimated harvest) (kg y^{-1})	Chesapeake bay BMP estimate of nitrogen removal (tissue only in FARM estimated harvest) (kg $acre^{-1}$ y^{-1})
Site 1 (33% mortality)	Bottom cage, triploid	287	59	113	23
Site 1 (70% mortality)	Bottom cage, triploid	182	37	50	10
Site 2a	Floating cage, triploid	710	222	299	93
Site 2b	Floating cage, triploid	1,372	63	722	33
Site 3	Bottom cage, triploid	399	20	133	7
Site 4	Bottom culture, diploid	1,200	171	154	22
Site 5	Bottom culture, diploid	859	215	76	19

The FARM model nitrogen removal estimates were normalized to tissue only based on percent nitrogen represented by tissue (triploid = 72%; diploid = 47% of total oyster nitrogen content; Cornwell et al. 2016). The BMP nitrogen removal values are based on the harvest estimated by FARM, converted to number of oysters and multiplied by the approved nitrogen BMP credit (90 kg per million harvested diploid oysters; 130 kg per million harvested triploid oysters).

if only tissue-related removal was included in the calculation. The value of N removed, based on removal calculated by the BMP-related method, is a range of 0.11×10^3–$3,518 \times 10^3$ y^{-1} among all farms. These ranges describe the value based on the costs of different management alternatives; however, the upper-level values do not represent expected compensation. In a competitive functioning nutrient market, the expected payments will be closer to the lowest cost alternative (e.g., wetland and agricultural BMPs; Table 2). If there is a limitation on the BMP credits at the lower range of costs available for purchase, then other slightly more expensive BMPs will be available, but it is highly unlikely that there will be any purchases of urban BMP credits at the $4,783 per kg N cost.

How Much Nitrogen Is Being Removed by Current Maryland Aquaculture Oyster Harvest and What Is the Value of the Removal?

Knowing the current harvest for Maryland Chesapeake Bay, and using the Oyster BMP method as described earlier, the total N removed and the economic value of the removed N were estimated assuming that bottom-culture cultivates diploid and water-column culture cultivates triploid oysters. In 2017, the MD DNR reported harvest for bottom-grown oysters of 44,805 bushels, and for water-column–grown oysters, harvest was 29,296 bushels. Assuming there are 250 oysters per bushel, the total harvest was 11.2 million diploid (bottom grown) oysters and 7.32 million triploid (water-column–grown) oysters. Based on the Chesapeake Bay oyster tissue BMP crediting guidelines (Cornwell et al. 2016), the estimated N removal by oysters in 2017 was 1,008 kg by bottom-grown oysters and 952 kg by water-column–grown oysters, a total removal of 1,960 kg N. The value of the oyster-related N removal in tissue only, based on the range in costs of alternative management methods, is 4.3×10^3–$9,551 \times 10^3$. This provides insight about the economic value of the N removal ecosystem service that the Maryland oyster aquaculture industry provides and about potential payments that might be made to oyster growers. The compensation to growers will be at the lower end of this estimated range of values, as noted. Growers can already receive credits toward fulfillment of required N reductions for their waterbody through the Maryland Nutrient Trading Program, which has developed a framework that is now allowing sales of credits. This is an optimistic and encouraging development for both water quality concerns and domestic seafood needs. The Maryland Nutrient Trading Program will be an example for the development of nutrient trading programs elsewhere.

CONCLUSIONS

This study shows the range of harvests that might be expected from Maryland Chesapeake Bay oyster farms (1.78–25 metric tons acre^{-1} y^{-1}) that are dependent on a variety of factors, including cultivation practices (e.g., seeding density, cage or bottom grown), and other influences that cannot be controlled (e.g., salinity and/or sedimentation-based mortality).

Nitrogen removal among the oyster farms shows a broad range (28–457 kg N acre^{-1} y^{-1}) that is dependent on oyster growth at each farm site. These results are consistent with oyster-related removal rates reported for other locations in the United States and internationally.

This work supports the ongoing development of nutrient credit trading programs in Maryland and United States that include oyster and other bivalve shellfish (e.g., mussel and clam) farmers. In Chesapeake region and Massachusetts, growers can already be credited with removal of N (and phosphorus). A framework for sales of aquaculture credits has been developed within the Maryland Nutrient Trading Program, which recently announced the first nutrient trades from oyster aquaculture.

Avoided cost analysis shows that growers could expect to receive from $8.33 (Virginia Nutrient Credit Exchange cost) to $7.04 to $1,034 (agricultural BMP cost) to $66 to 4,873 (urban BMP cost) to $2.2 to $417 (wetland and algal strategies) per kg N removed if they were included in fully functioning nutrient credit trading program that compensated them for the N removal ecosystem service their oysters provide. The range of values determined by Weber et al. (2018) to be incentives for aquaculture expansion ($22–$418 per kg N removed) was also included. Depending on sales price, there could be potential revenue for oyster farms for nutrient reductions, with the overall range of values for N removal among sites of 0.56×10^3–$12,446 \times 10^3$ y^{-1}, but in a market-based trading program, the credit price will be at the lower end of this range.

The FARM model is a useful tool but needs continued refinement for Chesapeake Bay.

This approach is transferable to other waterbodies that have nutrient-related degradation and support oyster aquaculture, and is an encouraging development for both domestic shellfish production and water quality concerns.

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