Evaluating Oyster Aquaculture's Cost-Effectiveness as a Nitrogen Removal Best Management Practice – A Case Study of the Delaware Inland Bays

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1.0   INTRODUCTION

1.1   Oysters in Delaware

Once a thriving industry, disease and overfishing have led to a dramatic decline in populations and harvests of the eastern oyster *Crassostrea virginica* in Delaware and other states along the Atlantic Coast since the 1950's. While other states have sought to rebuild their native populations though reef restoration or have sought to farm oysters, Delaware was currently the only state on the Atlantic Coast without a commercial viable wild oyster population or oyster aquaculture industry at the time this research was conducted. Until recently, importation of oysters to grow and harvest in Delaware was in fact illegal, part of an effort to prevent aquatic-borne diseases such as MSX and Dermo from being transported to the state's waters (Ewart, 2013). However, in June 2013, Delaware legislators passed Delaware House Bill 160 authorizing the Department of Natural Resources and Environmental Control (DNREC) to develop and oversee a commercial shellfish industry. After a lengthy public review process, DNREC issued final regulations for the industry in August 2016, including the establishment of 343 one-acre rectangular plots of subaqueous bottom within the Delaware Inland Bay estuary, which includes Rehoboth Bay, Indian River Bay, and Little Assawoman Bay (Figure 1). These areas were carefully chosen to minimize water use conflict, emphasize ease of access, and are eligible to be leased by prospective oyster farmers (10 acres maximum per grower) after the successful application for DNREC and U.S. Army Corps of Engineers (USACE) permits for use of subaqueous lands. As marked by red rectangular icons in Figure 1 and shown in more detail in Figure 2 (produced by DNREC), the 343 acres are divided into six clusters called Shellfish Aquaculture Development Areas (SADA's), including three in Rehoboth Bay (RB-A, RB-B, and RB-C), one in Indian River Bay (IR-A), and two in Little Assawoman Bay (LA-B and LA-D). Note that originally in early 2013, one more SADA in Indian River Bay (IR-B) and two more in Little Assawoman Bay (LA-A and LA-C) were proposed, but withdrawn from consideration after public opposition for water use conflict.

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Figure 1. The Delaware Inland Bays Watershed
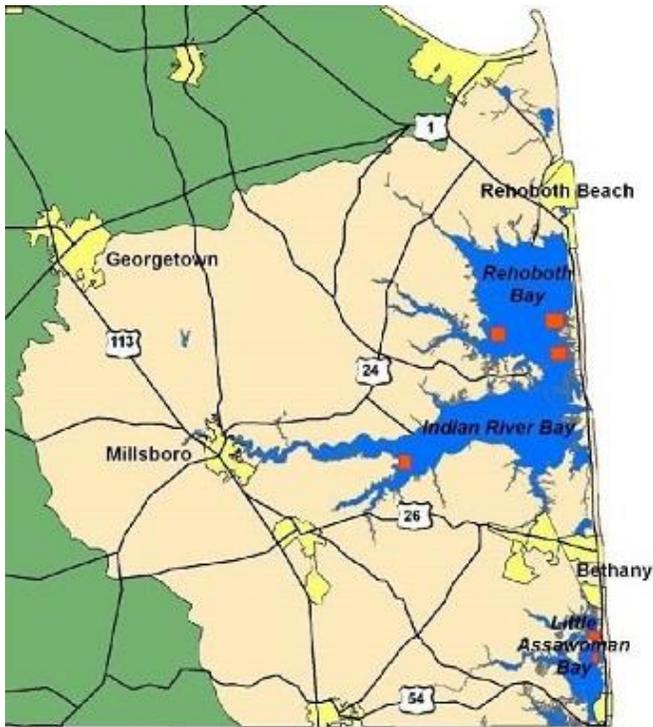
Credit: Delaware Center for the Inland Bays

Figure 2. Map of Leasable SADA's in Rehoboth Bay
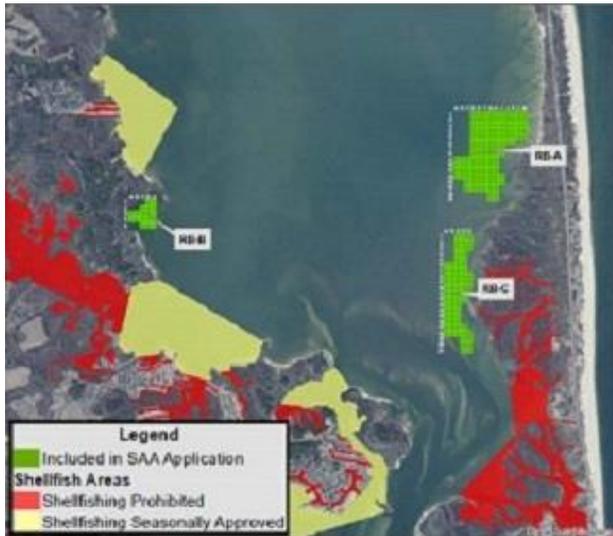
Credit: DNREC Public Workshop presentations 2013 – 2014.

The initiative to grow the commercial oyster aquaculture industry may contribute to the state's economy via potential job creation, reinvestment in working waterfronts, and potentially tapping into consumer preferences for locally-sourced seafood, the initiative to grow the

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commercial oyster aquaculture industry can be assisted by quantifying the potential cost savings of using oysters instead of other currently employed nutrient management strategies to help improve local water quality in the Delaware Inland Bays. These waterbodies, like other estuarine systems in moderate to highly populated areas, are often classified as degraded or impaired due to excessive nutrient loading from land based sources (Ewart, 2013). The majority of these sources in the Delaware Inland Bays are difficult to control as they include "non-point" sources such as runoff of nutrient-rich fertilizer and stormwater containing sediment (Ewart, 2013). The low flushing rates of the Delaware Inland Bays and other similar estuaries, coupled with the presence of such large amounts of nutrients frequently contributes to algal blooms, or excessive growth of phytoplankton in the water column which are stimulated by nutrients delivered from land. These blooms increase turbidity, reducing light available to submerged aquatic vegetation (SAV) which provide critical habitat for juvenile fish and invertebrates as well as oxygen for the water column (Delaware Center for the Inland Bays, 2013). The reduced light inhibits SAV growth and may also lead to mass mortality of SAV populations if such conditions persist. Following the eventual algal mortality, decomposition by bacteria further depletes oxygen levels leading to potential hypoxic conditions incapable of supporting aquatic life (Kellogg et al., 2014). As a result of increased anthropogenic sources of nutrient pollution, estuaries have become severely degraded, leading economic losses from lower fishery landings and reduced tourism (Ewart, 2013).

1.2 Oysters and the Estuarine Environment

In addition to providing habitat for juvenile fish and value as shoreline buffers to erosive wave action (Grabowski et al., 2012), oysters both wild and cultured filter algae, sediments, and other suspended particles from the water column, a process by which they capture and consume particulate food necessary for metabolism and growth (Newell et al., 2004). After ingesting the plankton, bivalves assimilate the nutrients into their tissue and shell, a process also known as bioextraction if the oyster biomass is permanently removed from the ecosystem via harvest. Oysters' metabolic processes may also excrete dissolved nitrogen directly back into the water column or create solid waste products called biodeposits, including feces and pseudofeces. When deposited in the adjacent sediments, the biodeposits may enhance microbial activity that transforms nitrogen through a series of reactions to a biologically inert form (N_2 or dinitrogen gas), unavailable for uptake by phytoplankton (Carmichael et al., 2012). Due to the multiple ways oysters serve as natural biological filters, they perform an important ecological function in maintaining water quality in estuaries. As such, policymakers have been intrigued by their potential to be included as a best management practice (BMP) in the effort to restore historically eutrophic areas such as Chesapeake Bay and the Delaware Inland Bays.

1.3 Oysters as a New Nutrient Management Strategy

In order to grow the industry and increase the increase the quantity of environmental and social benefits provided by oysters, policymakers are interested in different means to compensate producers (growers) for the ecosystem services their oysters provide. In Delaware, DNREC has

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investigated the potential of allowing regulated point source dischargers in the Inland Bays watershed to experiment with oyster aquaculture as a method of lowering the cost to comply with the United States Environmental Protection Agency (EPA)'s restrictions on nutrient discharges. While the City of Rehoboth Beach's wastewater treatment plant (WWTP) is currently the only significant permitted point source discharger within this watershed, all of the approved BMP's listed in DNREC's official Pollution Control Strategy (PCS) for the Delaware Inland Bays watershed will be used in an effort to determine if using oyster aquaculture as a new BMP is a more cost-effective option for both point and non-point source nutrient management.

The Town of Lewes, Delaware also discharges wastewater to the Atlantic Intracoastal Waterway, which is connected to the Delaware Inland Bays, but it is estimated that the vast majority of the nutrients contained in its discharge volume drains north into Delaware Bay. As such, the City of Rehoboth has been considered the sole point source discharger in the Inland Bays watershed for the purpose of this study. The Lewes WWTP, a point-source nutrient discharger, currently purchases credits from farmers using several of the agricultural BMP's to control non-point source nutrient discharges in order to offset the WWTP's unavoidable remaining nutrient discharge. While only the Lewes WWTP has confirmed their use of the BMP's listed in the PCS, it has been assumed that the Rehoboth WWTP is also using these BMP's, as they are state-approved.

Therefore, these BMP costs represent the best available and most localized data for comparison to the cost of employing oyster aquaculture as a new and innovative alternative BMP. However, the BMP calculations within the PCS report contain several inconsistencies that require clarification upfront. First, subcategories of costs such as capital and labor are not separated in the PCS calculations. This prevents a true side-by-side comparison of subcategories for the oyster aquaculture industry. Second, the lifetimes of the BMP's and the schedule of maintenance required for their upkeep, while listed in the cost descriptions, were similarly not adjusted for the final annual side-by-side cost comparison. Third, while the PCS is an official report written by DNREC, the sources of the data used in the calculations were not listed, preventing independent calculations to standardize the data units for better comparisons to oyster industry data. Finally, several BMP cost calculations have significant caveats that render them nearly impossible to compare to oyster costs. For example, the cost of planting of cover crops to stabilize agricultural soils and prevent nutrient runoff and groundwater infiltration is only temporary, as the farmer is allowed to harvest and sell the crops after the soil has been stabilized by root matter, therefore recouping his or her initial costs. Given the estimated harvest delay of only a few months, the discount rate of foregone interest accruing in the bank from the sale of the crops is considered insignificant and the cost of the BMP is therefore close to zero. Other BMP costs are eligible to be shared with local soil and water conservation districts, resulting in unknown, but likely much lower costs than those listed in the PCS. Due to these significant inconsistencies, the cost-comparison framework created herein should therefore be considered a foundation from which to build further analyses rather than a final and precise calculation of what prices WWTP's face when choosing to offset their discharges.

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When such data does become available and as oyster industry growing methods (and therefore costs) become more standardized, policymakers may use the framework to generate more realistic and watershed-specific water quality outcomes.

Regarding previous studies on the subject of oysters as an alternative BMP, it should be noted that Newell et al. (2005) and Bricker et al. (2014) estimated that the cost savings for nitrogen removal realized by a standing stock of oysters in the Choptank River and Potomac River is approximately $3.1 million over 10 years and that oyster growers within the Potomac River would receive approximately $157 million in added revenue with a nutrient trading program, respectively. However, Newell et al. (2005) calculated the *average* annual marginal cost ($/kilogram) of nutrient discharge reduction from a wide range of agricultural BMP's, while Bricker et al. (2014) used only the annual marginal cost ($/kilogram) of constructing a new WWTP to remove nutrients compared to using oysters. Both studies establish an innovative approach to addressing nutrient pollution, but were located in a different watershed and do not offer a side-by-side comparison of multiple BMP's annual marginal costs versus employing oyster aquaculture as a nutrient removal strategy specific to the Delaware Inland Bays. In addition, since the annual marginal cost of using oyster aquaculture appears to not have been subtracted from the overall cost-savings of not employing traditional BMP's in either study, oysters' cost-effectiveness may have been overestimated. As such, this study attempts to create a standardized side-by-side comparison of multiple BMP's and explore the cost savings after "business-as-usual" oyster industry production costs are accounted for.

2.0 MATERIALS AND METHODS

2.1 Estimates of Nitrogen Removal by Oysters

Before addressing the industry costs of simply growing a given number of oysters, it is necessary to understand the scale of nitrogen removal that is possible using the multiple biochemical pathways previously studied. First, it was assumed for the purposes of this study that the entire oyster stock would grow at an even rate and be ready for harvest (and thus, permanent removal of nitrogen stored in shell and tissue) after 2 years on the lease area. This conservative estimate also takes into account the fact that not all oysters will be triploids (possessing 3 chromosomes instead of the usual 2), which have been selectively bred and genetically modified to become sterile and use energy otherwise devoted to gamete production to instead grow to harvest size within 18 months. According to Higgins et al. (2011), an individual harvest-sized oyster is capable of storing approximately 0.13 grams of nitrogen collectively in its tissue and shell and that approximately 7.7 million oysters would be required to remove one metric tonne of nitrogen per two-year harvest rotation cycle. Adjusting this value to U.S. Standard units for comparison to alternative BMP's provided by the Lewes WWTP produces an estimate that each harvest-sized oyster would be capable of removing approximately 0.0002866 pounds of nitrogen and that approximately 3,489 oysters would be required to remove one pound of nitrogen.

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Nitrogen removal measurements by Newell et al. (2005) included 0.52 grams per oyster via tissue and shell bioassimiliation, 0.50 g via biodeposits, and 0.25 g via denitrification by microbes within sediments enhanced by biodeposits. The tissue and shell estimates were obtained for harvest-sized oysters, representing a time period comparable to oyster aquaculture's harvest cycle, while the biodeposition and denitrification value were annual estimates. When doubled to account for the continuous nitrogen removal estimated over 2 years, oysters' biodeposits and role in denitrification accounted for an additional 1.00 g and 0.50 g of nitrogen removed, respectively. As such, the total nitrogen removed by all biological pathways over a two-year harvest cycle equaled approximately 2.02 grams per oyster, compared to the approximately 0.13 grams per oyster using only tissue and shell bioassimilation measurements for cultured oysters by Higgins et al. in 2011. Assuming that these additional pathways are as consistent as bioassimilation, the resulting nitrogen removal efficiency is nearly 16 times greater when all forms of nitrogen removal are considered.

However, there are several issues with including all possible nitrogen removal pathways as currently documented in the scientific literature. First, as demonstrated by the diversity of scientific peer-reviewed literature cited herein and compiled by Kellogg et al., 2013, volumes and rates have been highly variable. Second, studies by Smyth et al. (2013 and 2015) and Kellogg et al. (2013) found that these additional nitrogen removal pathways are habitat-specific and more research is required to better understand these processes. Higgins et al. (2013) concluded that "aquacultured oyster biodeposition did not have a ubiquitously enhancing effect on nitrogen removal rates via denitrification gas production and is therefore unlikely to be effective as a policy initiative for eutrophic mitigation. In addition, "sediment denitrification gas production is costly and difficult to measure, and to applicable as a practical policy initiative for Chesapeake Bay eutrophication mitigation, oyster cultivation would likely need to elicit a ubiquitously enhancing effect on nitrogen removal, an effect not observed in this study." Third, in attempting to extrapolate these findings to on-bottom oyster aquaculture, it should be noted that routine disturbance of subaqueous sediments associated with equipment and maintenance as well as the potential cost of sampling by DNREC or the grower may render expectations of permanent nitrogen sequestration unrealistic. Likewise, assuming the continued abundance of denitrifying microbes within the sediment as well as measuring the amount of their nitrogen removal is difficult and would represent additional costs. Finally, Kellogg et al. (2013) formally acknowledged the limitations of the current understanding of these nitrogen fluxes and advocated a cautious approach toward inclusion in any nitrogen removal policy going forward. As such, only the bioassimilation of nitrogen into oyster shell was included in this study because of the reliability of measurement – the oyster and therefore nitrogen is completely removed from the waterbody.

Another limitation of this study is the intentional exclusion of phosphorus removal by oysters. While this nutrient has also historically been a key pollutant in estuaries, there are several reasons why phosphorus is not considered in more depth in this analysis. First, based on removal rates measured by Higgins et al. (2011) and Newell et al. (2005), cultured and wild oysters are

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only capable of bioassimilating 0.019 g and 0.16 g of phosphorus per year, respectively. As such, it would require approximately 25,000 cultured oysters to remove one pound of nitrogen annually. As with nitrogen, the higher rate of P removal by wild oysters observed by Newell is not considered in order to maintain the consistency of the analysis of cultured oysters' nutrient removal capabilities. In addition, the literature available to date does not contain studies on microbial removal of phosphorus from oyster biodeposits. As such, the lower efficiency and diversity of phosphorus removal pathways compared to nitrogen make the latter a more feasible nutrient removal alternative to consider.

2.2 Economic Theory

Before pursuing a direct comparison of oyster industry costs to existing BMP's, it is necessary to discuss the economic theories being applied and how the resulting framework can be used to quantify oysters' ecosystem services via potential cost-savings in nitrogen removal. In Figure 3 below, per oyster marginal costs and price are shown as a function of oysters supplied by the market under business as usual conditions. The supply curve is upward sloping, reflecting the concept that as more and more oysters are grown, the per-unit cost of production increases. Generally, this is due to changing aspects of production, but as discussed in more detail below, Delaware oyster aquaculture costs are projected to increase as a function of higher travel costs to lease areas which are further away from marina locations. These include higher fuel costs and the opportunity cost of time spent passively working (i.e. riding on a boat). The current market price per oyster is depicted as being constant at P*, reflecting an assumption that consumers' demand is inelastic. This means that for any increase in price, the quantity of oysters demanded will not increase. The quantity of oysters supplied at market equilibrium is denoted by Q*, where the supply and demand curves intersect. This point represents where the marginal cost of producing an oyster equals the price consumers are willing to pay for the oyster, the most efficient market outcome under the circumstances considered thus far.

Inversely to how inelastic consumers will respond to a higher price by not demanding a higher quantity of oysters, producers are assumed to be price-takers, only able to charge the market equilibrium price, but nothing higher. As such, the oyster industry will not supply additional oysters beyond Q* at market equilibrium if the per oyster marginal cost is higher than P*, which is implied by the upward sloping marginal cost curve. This inability to charge a higher price to offset higher marginal costs presents an obstacle for expanded industry production. Therefore, any increase in price, whether through an increased willingness-to-pay (WTP) for oysters on behalf of consumers or a form of a publically-financed subsidy, would in theory incentivize higher levels of production by compensating growers for the higher marginal costs incurred at those levels. This idea of payments for ecosystem services (PES), specifically nutrient removal by shellfish, is not new, as Lindahl et al. (2005) explored the idea of improving marine water quality in Sweden using mussel farming. However, this is the first research done to address whether a marginal PES to oyster growers would be a cheaper method of nutrient reduction than the marginal cost of BMP's currently available. Furthermore, the concept of additionality, also used by Lindahl et al. (2005)

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minimize PES to mussel farmers by subtracting the marginal revenues from marginal costs to avoid double counting ecosystem services already being provided ("business-as-usual") will be employed here.

**Figure 3. Market for Oysters**
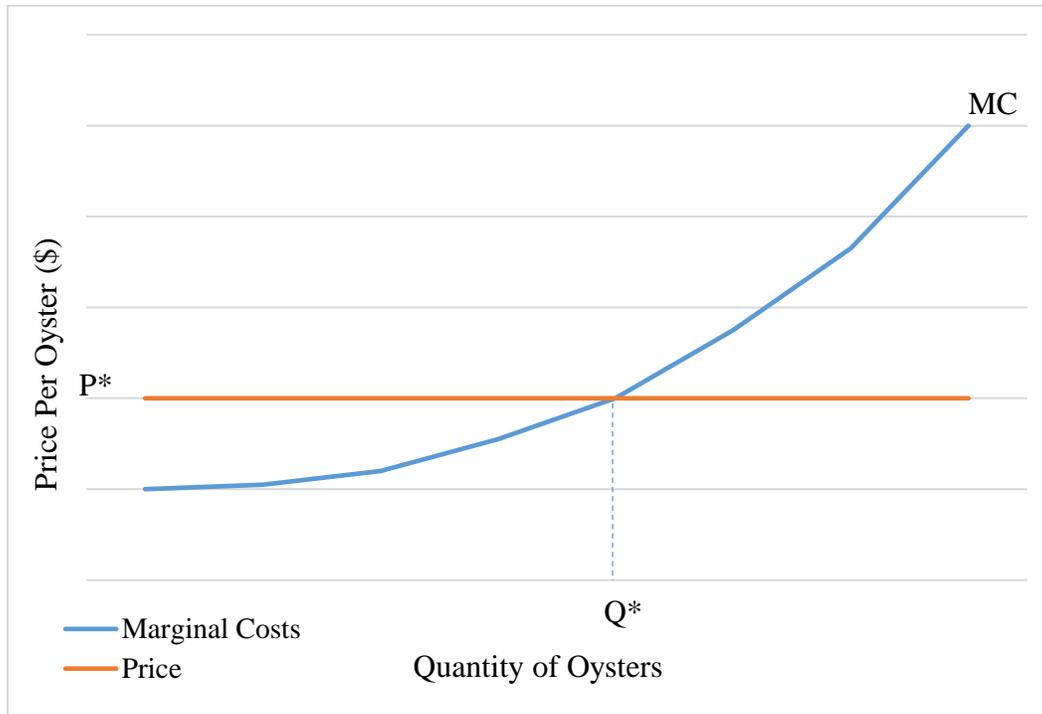
2.3 Ecosystem Services, Positive Externality, and Market Failure

As shown in Figure 4, at a market equilibrium the supply and demand curves for a given good or service intersect at price P* and quantity Q*. However, the value of oysters' ability to remove nitrogen and therefore improve water quality is greater than the market price paid by consumers, otherwise known as the consumptive value. Thus, since society as a whole receives more benefits than they individually pay for, the value of oysters' ecosystem services is external to the market and is deemed a market failure. In addition, because no private markets for the ecosystem services from oysters exist, too few oysters are supplied to the market and therefore too few ecosystem services are provided to society (Pigou, 1920). Furthermore, since oyster growers do not receive a higher price that captures the added benefits of their stock, there is no incentive to increase production in order to provide more of these services. By quantifying the added benefits society receives from oyster aquaculture and adding that value to the current levels of compensation at Q* the producer receives from the market equilibrium price P*, the producer may be incentivized to provide more services Q** at new higher price P**, thus growing the industry and resulting in more benefits to society. As will be discussed below, this mechanism should be careful to avoid providing redundant compensation to producers for the services already provided

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and solely target expanded production by only compensating them for the difference between the current market price (P*) and the total value of oysters' ecosystem services (P**).

Figure 4. Oysters as a Positive Externality
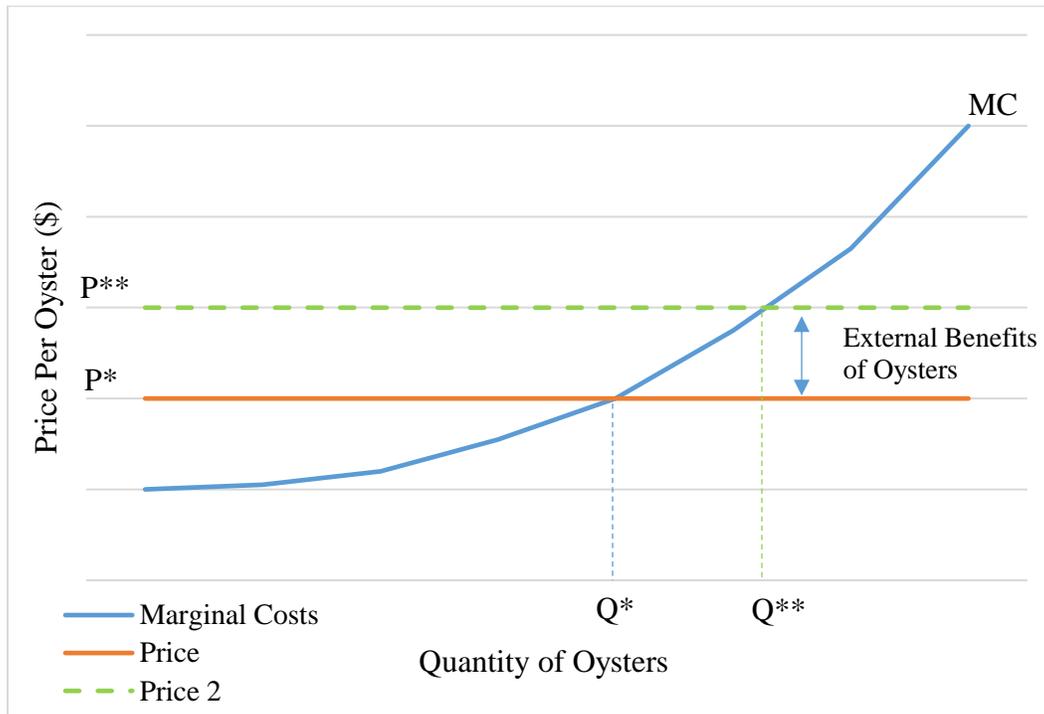
Prior to constructing Figure 5, the marginal cost per pound of nitrogen removed was first calculated from the per oyster marginal cost and scaled up to reflect oysters' limited nitrogen removal capacity – recall that an estimated 3,489 oysters required to remove one pound of nitrogen. The price per oyster was also multiplied by this number of oysters to model the constant revenues received by growers, regardless of rising marginal costs of nitrogen removal. To avoid double counting the value of oysters to consumers as reflected by the market equilibrium price (additionality), the constant price was subtracted from the marginal costs associated with nitrogen removal by oysters at each level of production. The resulting difference between these values thus represents the additional cost to society for increasing the supply of oysters to the market and therefore what society would have to pay to increase the amount of nitrogen removed via increased oyster production. These cost differences are plotted in Figure 5 as their own supply curve. As noted previously, the cost of compensating growers for higher and higher quantities of oysters supplied is the same as this difference and will be used to compare oyster to other BMP's. As will be described in the Results section, this comparison simply consists of comparing the per-unit costs of nitrogen removal and can be graphically depicted by constructing an aggregate supply curve which includes the costs and removal capacity of oysters plotted with the other BMP methods. Before considering the currently available cost data of the oyster aquaculture industry

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below, it is important to note that even at a hypothetical minimum PES of $0.01 per oyster, after additionality is accounted for would yield a minimum annual per pound nitrogen removal cost of $34.00. This sum is noteworthy and will appear again in the results section, after the following effort to ground-truth oyster production costs per the best available industry data.

Figure 5. Accounting for Additionality in Nitrogen Removal
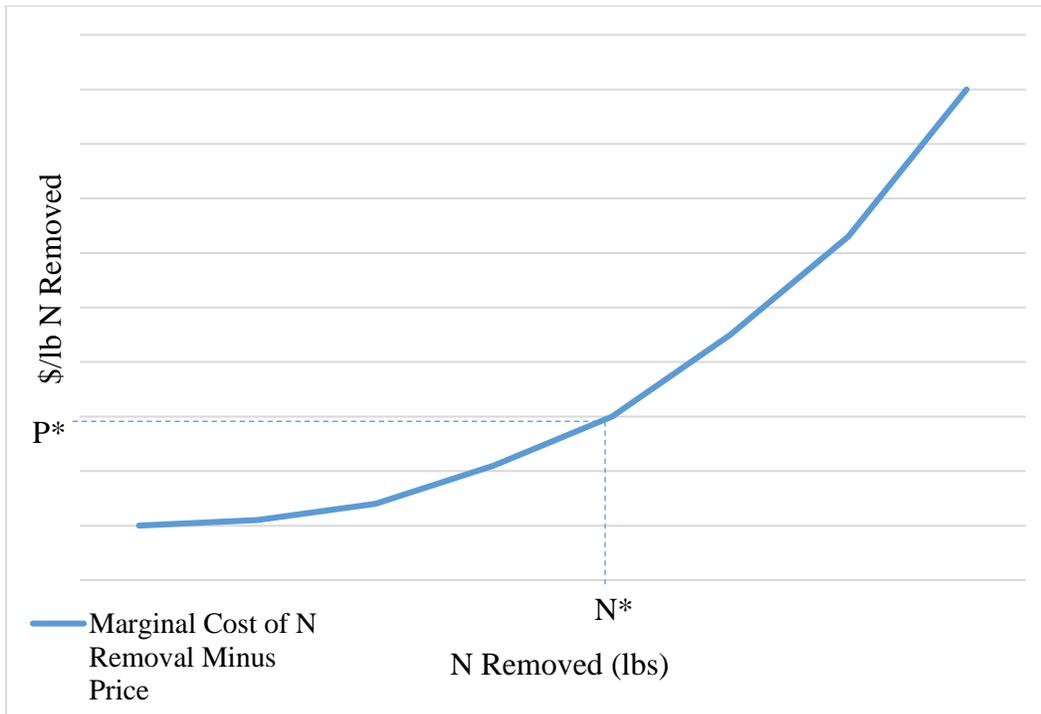
2.4 Production Cost Estimates

In order to create an oyster aquaculture industry supply curve, the production costs (and therefore indirectly the cost of nitrogen removal) were estimated using the Oyster Enterprise Budget, produced by the Virginia Institute of Marine Science (VIMS) and Virginia Sea Grant staff in 2012-2013. The data represents the best available estimate of industry costs, marketing excluded, and has been adapted slightly to model future Delaware industry production and nitrogen removal costs. The budget includes itemized expenses spread over the two-year period during which one-year-old juvenile oysters ("seed") are transferred from a nursery lab setting to bags and cages located on the bottom of a given lease area. Fixed and variable costs are separated and certain items are depreciated as necessary. However, for the purposes of this study, only variable costs such as wages for laborers, workers' compensation, and yearly gear expenses are drawn from the VIMS budget. Other costs such as fuel and opportunity cost of travel are unique to Delaware's lease locations and are thus new data.

According to the VIMS budget, a stock density of 100,000 oysters per acre is both optimal and typical. While other per acre density estimates in the literature (Higgins et al., 2011 per square meter projects to be approximately 1,157,402 oysters per acre) and policy papers (Delaware Center

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for the Inland Bays (2013), 700,000 oysters per acre) are higher, the VIMS density was chosen in order to set a conservative baseline for nitrogen removal, while not endangering the health of the stock. The specific reasons are thus: prevent excess sediment deposits capable of smothering the oysters, the reality that the entire substrate within each lease area might not be suitable for placement of cages (firm bottom substrate required), and the possibility of a learning curve for new growers regarding optimal cage placement.

According to the VIMS budget, labor represents the greatest annual expense category for growers. At the aforementioned stock density of approximately 100,000 oysters per acre, approximately 6 workers are required to work 10 acres of lease area per year, with each individual working 40 hours a week for 30 weeks per year (28 weeks during the growing season, plus 2 weeks total for winter monitoring and maintenance needs), or 1,200 hours apiece. Total hours worked are thus 7,200 per year, or 14,400 hours per harvest rotation. Per the VIMS budget, an hourly wage of $10.00 per hour was assessed and worker's compensation of $4.00 per $100.00 of labor expenses were assessed on the wage total of $144,000, equaling to $5,760 (Table 2). Opportunity costs of travel to and from lease areas are discussed in the travel section below.

To simplify distance calculations, boat access the Inland Bays was restricted to two centrally located public areas, Massey's Marina and Assawoman Bay State Wildlife Area. Massey's Marina is located at the junction of Rehoboth and Indian River Bays, while Assawoman Bay State Wildlife Area contains two launch areas located on the north and south sides of the property, equidistant to LA-B and LA-D, respectively. Using shapefiles made publically available by DNREC projected in Google Earth for SADA locations, distances from Massey's Marina to the closest and farthest corners of RB-A, RB-B, RB-C, and IR-A were measured and averaged. A similar procedure was used to measure distances between the Assawoman Bay State Wildlife Area ramps and LA-B and LA-D (Table 1). These distances were used to calculate fuel expenses based on a 4.5-miles-per-gallon fuel economy (at a speed of 20 mph) for a typical Carolina Skiff typically used by the industry and diesel fuel prices of $3 per gallon (Table 2).

Table 2. Spatial Attributes of Lease Areas

SADA	Leasable Acres	Miles Per Trip	Lease Area Width (Mi.)
RB-C	1 to 71	1.78	0.72
RB-B	72 to 89	2.62	0.12
LA-B	90 to 107	2.61	2.22
RB-A	108 to 227	2.98	1.75
LA-D	228 to 252	3.90	0.59
IR-A	252 to 343	5.66	1.19

Per DNREC regulations, oysters and gear are not permitted to be cleaned or processed within the lease site. As such, it is estimated that growers must make two round trips to the lease

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area per day, calculated by multiplying the average distances to each SADA by four. The number of trips was capped at this amount due to uncertainty regarding travel time due to weather conditions and the general lack of industry data available for time required to fully inspect and remove biofouling material from the stock. As such, a VIMS "reasonable estimate" of 50,000 oysters per day was obtained for processing efficiency (Karen Hudson pers. Comment). However, it should also be noted that this study was confined to water-dependent operations and dockside maintenance and land travel time from places of business to wholesalers and associated truck fuel costs were not calculated. In addition, increased maintenance efficiency resulting from the use of power washers, mechanized tumblers, and overnight freezer storage on land is not considered due to the aforementioned exclusion of fixed costs in this analysis. It was also assumed that growers would travel to the public access point closest to each SADA regardless of where their place of business or personal residence was located. Accordingly, the order of which acres are chosen by growers is strictly based on ranking the distances from each marina to the closest SADA in that respective Bay from shortest to longest. In addition to travel fuel costs, idling time spend navigating through a SADA was calculated, using a speed of 0.5 mph and the width of each SADA cluster (Table 1). Total fuel costs (travel and idling through congested lease area) ranged from approximately $15,975 for RB-C to $49,963 for IR-A per harvest rotation (Table 2). The opportunity cost of travel was a function of distance travelled and ranged from approximately 1,281.60 hours to 4,068 hours per harvest rotation. Multiplied by the same wage of $10 per hour, these costs ranged from approximately $12,816 to $40,680 per harvest rotation. However, opportunity costs were not included in the aforementioned workers' compensation calculations, as they are not likely to be listed on a "real world" payroll submitted for tax purposes.

Seed are anticipated to be obtained from the Haskin Shellfish Lab's hatchery, owned and operated by Rutgers University in the Cape May area in New Jersey (Ewart, 2013). Currently, there are no commercial hatcheries in Delaware and seed must be imported. DNREC requires a rigorous screening process to ensure that the oysters are not contaminated or diseased and this cost has been listed as $600, although it is presently unclear the number of oysters inspected this fee covers. As such, this amount has been added as a flat rate cost to the seed purchase calculation, which consists of the number of oysters per acre being multiplied by the individual price of seed ($0.03). A VIMS estimate of 50% mortality over the two-year harvest rotation was used to account for the uncertainty of natural conditions (including extreme winter weather, possibility of disease, and predation) as well as a new grower learning curve for optimal production. As such, twice as much seed would need to be purchased (200,000) than oysters harvested (100,000), for a total cost of $6,000 per acre or $60,000 for ten acres (1,000,000 oysters harvested from 10 acres). While the metal cages typically used for holding oysters were considered to be fixed costs due to their durability, plastic mesh bags were considered less durable and included as an annual expense of approximately $1200.10 per acre or a total of $24,002 for ten acres over the two-year harvest rotation.

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An additional category included in the production cost calculations is the renting of a boat to transport oysters and laborers to and from the lease area on a daily basis, set at 5 days per week. Averaging the per diem (8 hour) rental rates of two local rental venues, Rehoboth Bay Marina and Dewey Beach Watersports, the subsequent cost came to approximately $130,500 per harvest rotation cycle. While no comparison to a payment for a purchased boat is included in this study, the rental rate can be viewed as a variable cost in that each additional acre of production would require usage of a boat. It should be noted that since the other cost categories are based on an 8-hour workday, the marginal cost of boat usage does not increase with more time spent on the water i.e. travel costs to further lease areas.

Table 2. Variable Costs for Each SADA Cluster

SADA	Acres	Boat*	Wages*	Work. Comp.*	OC*	Fuel*	Gear*	Seed/ Test*	Total Cost*	Per Oyster
RB-C	1 - 71	130	144	5	12	15	24	60	393	0.393
RB-B	72 - 89	130	144	5	18	23	24	60	407	0.407
LA-B	90 - 107	130	144	5	18	24	24	60	407	0.408
RB-A	108 - 227	130	144	5	21	27	24	60	413	0.413
LA-D	228 - 252	130	144	5	28	34	24	60	427	0.427
IR-A	253 - 343	130	144	5	40	49	24	60	455	0.455

*In thousands of USD (rounded down to the nearest thousand)

2.5 Oysters' Current Market Price

In terms of price estimates, a value of $0.397 per oyster was chosen. This value represents the average price between 2014 and 2015, as listed in the VIMS 2016 Virginia Shellfish Situation and Outlook Report. The 2014 and 2015 prices were based on survey data for those years, as reported by approximately 67 Virginia oyster growers. It should be noted that any consideration of future price changes would need to be compared to future marginal cost data, which would be calculated based upon future labor wage rates, gear costs, among other categories listed in Table 2 to provide a consistent analysis.

3.0 RESULTS

3.1 Marginal Costs, Price, and Incentivized Industry Expansion

When per oyster marginal costs and prices for each SADA cluster are graphed, in order of closest to farthest from the respective boat launch area (Figure 6), it is found that the cost curve is predictably upward sloping due to increasing travel costs to farther lease areas. To account for additionality, the marginal revenue was subtracted from the marginal cost at each SADA, with the resulting differences ranging from $-*13.95* to $202.37 per pound nitrogen removed. The *negative* value represents the marginal cost ($0.393) of nitrogen removal by oysters within SADA RB-C as being less than the marginal revenue ($0.397) received by producers growing oysters in this lease area. Once within the next farthest lease area, SADA RB-B however, the marginal per-unit

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nitrogen removal cost becomes higher than the price received. For each lease area after RB-B, this is also the case and the sharp increase in per-unit removal costs for oysters within the LA-D and IR-A can be attributed to the significantly greater travel costs to these last two lease areas. As previously detailed in the methods section, the difference between the marginal cost of nitrogen removal at each level of production and the revenues received is the amount that society would have to pay growers to increase their production and therefore provide additional improvements in water quality beyond "business-as-usual." These additional costs can now be compared to alternative BMP's available to Delaware.
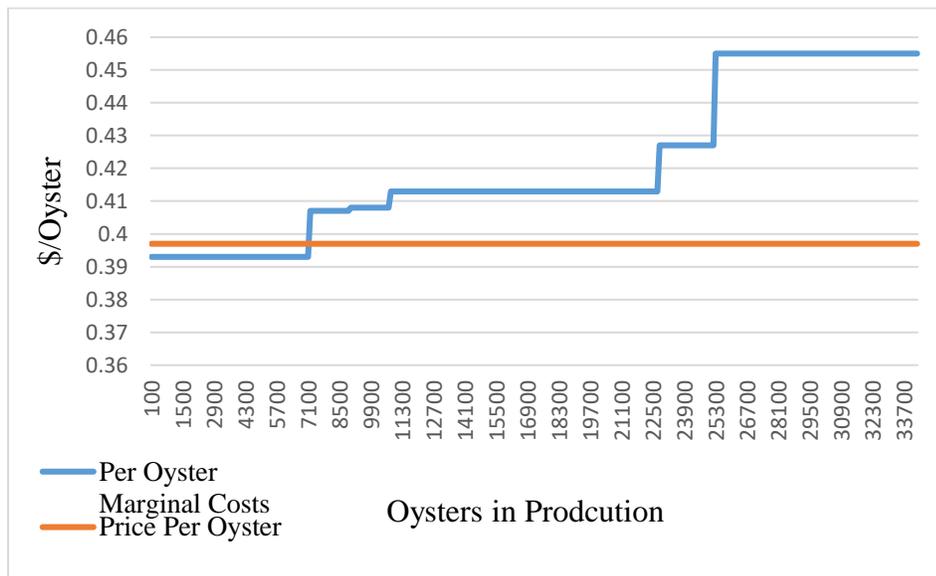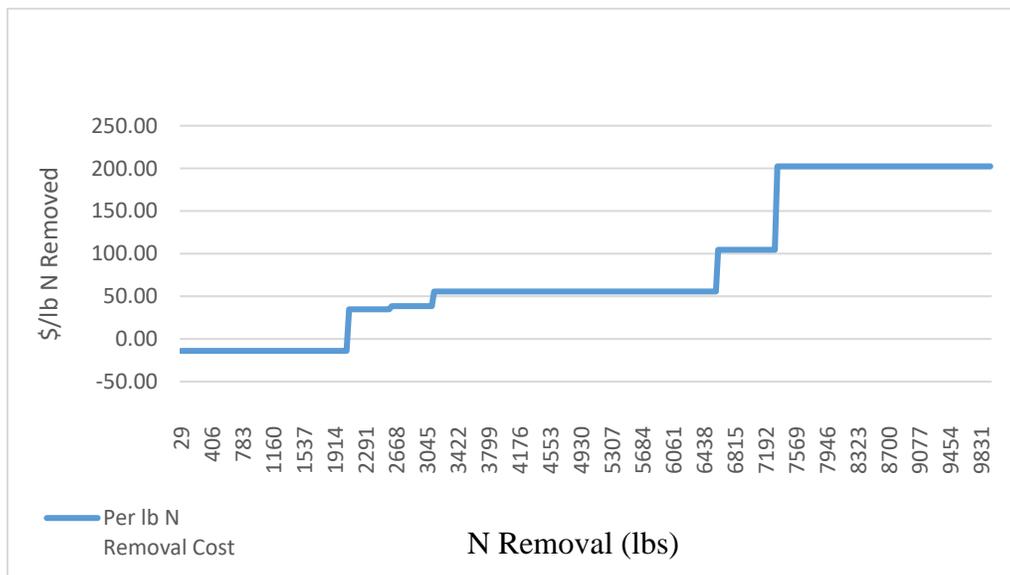
Figure 6. Marginal Costs vs. Price of Oysters

Figure 7. Per-Unit Marginal Cost of Nitrogen Removal, Additionality Accounted For


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3.2 Oysters' Nitrogen Removal Efficiency vs. Current BMP's

Using only costs and nitrogen removal estimates for shell and tissue bioassimilation, the cheapest per pound nitrogen removal rate beyond market equilibrium (starting with the first acre within RB-B) would cost approximately $34.89 per pound of nitrogen removal, the sixth most expensive BMP method compared to the alternatives available. It is clear that even compensating growers approximately one penny per oyster, the inefficient nitrogen removal rates of oysters negate the any potential cost advantage over alternative BMP's. Oysters' nitrogen removal capacity is plotted along with the other available BMP's in Figure 8 below, using costs and capacities listed in Table 3 below. In addition, the current non-point source total maximum daily load (TMDL) for the entire Inland Bays watershed is approximately 968 pounds of nitrogen (per DNREC regulations), for an annual total allowable amount of approximately 353,320 pounds of nitrogen. As shown in Table 3, the two cheapest BMP's, manure removal and cover crops, have the capacity to offset this volume of nitrogen without even using another method. Under the conservative approach taken here, there is no avoiding the issue of oysters' inefficient nitrogen removal and the resulting high PES. If phosphorus removal were to be considered, the per pound cost per 2-year harvest cycle would be approximately $250, even less competitive with traditional agricultural BMP's.

Thus, the cheapest method is currently the "free ride" of water quality improvements provided by business-as-usual. However, payment for these services would violate the additionality concept and not incentivize additional production and therefore nitrogen removal. As stated previously, the PES must start at a minimum of $0.01 per oyster to be considered a realistic sum to the oyster grower.

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Figure 8. Aggregate BMP Nitrogen Removal Supply for the Delaware Inland Bays
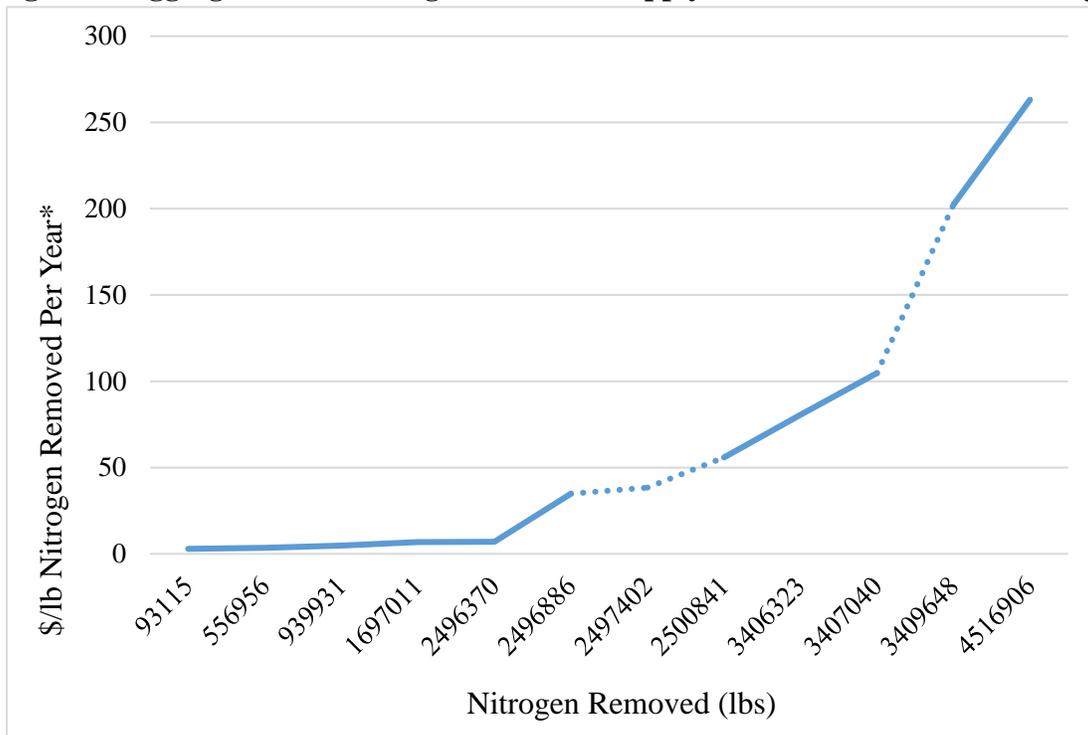
Note: Only nitrogen removal estimates via tissue and shell bioassimilation are plotted and are indicated by the dotted line section of the supply curve.

Table 3. BMP's Available to Lewes WWTP vs. Oyster Aquaculture

BMP Type	Nitrogen Removal ($/lb/2-year harvest cycle)	Nitrogen Removal Capacity (lbs/2-year harvest rotation)
Manure Removal	5.84	186,230
Cover Crops	7.10	927,682
Conversion to Riparian Forest	9.74	1,165,950
Wetlands Restoration	13.70	1,514,160
Grassland Buffers	14.10	1,598,718
Oyster Bioassimilation (Tissue/Shell)	34.89 – 202.37*	7,796
Connect to Sewer Systems	161.30	1,810,964
Bioretention Gardens	526.32	1,814,516

*based on total oyster PES for 2-year harvest rotation, still greater than if alternate BMP's doubled to account for same period, if considering only bioassimilation nitrogen removal pathway

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4.0   DISCUSSION

As stated previously, if only oysters' rate of nitrogen via bioextraction is considered, they are not currently economically competitive with other BMP's due to their inefficient rate of nitrogen removal. However, if all potential nitrogen removal pathways are considered and differences between wild and cultured oyster data are ignored, oysters become a much more cost-effective BMP, even the cheapest compared to the alternative BMP's currently available to point sources in the Delaware Inland Bays watershed. In addition, a flow of payments could be made for in situ nitrogen removal by oysters over the harvest rotation, followed by the aforementioned bioextraction payment at the time of harvest. While these differences in pathways are significant, future scientific research on the degree to which they differ can help clarify the reliability of using and allow of the above approach in incorporating multiple methods of nitrogen removal by oysters into a water quality improvement program. Also, tradeoffs between more reliable bioextraction of nitrogen by harvestable oysters and the placement of oysters in areas closed to harvest in order to continuously removal algae via other pathways past the typical 2-year harvest rotation should also be considered.

Likewise, as the oyster industry emerges in Delaware and continues to grow in other regions, production methods will become more efficient and knowledge more widespread. As the scientific and economic data improve, policymakers develop better oversight practices, target financial obstacles to industry growth, and promote strategies to ease the burden on growers, thereby reducing production costs, streamlining verification of nitrogen removal estimates, and implementing production-incentivizing programs. Specific investigations might include evaluation of seasonality in nitrogen removal, improving growth rates, and measuring nutrients removed via removal of biofouling organisms.

Finally, apart from travel costs unique to the lease areas in the Delaware Inland Bays, the framework may be used by other states to calculate the grower compensation or payment for additional ecosystem services (PES) should they pursue the investigation of such a program. In addition, if oysters become the cheapest method of nitrogen removal by a significant margin, policymakers may choose to ignore the concept of additionality and pursue a lump sum payment to growers.

5.0   CONCLUSIONS

Despite the quantification of the PES performed in this analysis, the implementation of a regulatory program to ensure transparency and reliable accounting of nitrogen removal will inherently incur additional costs. These include any additional fees associated with lab testing for nitrogen in tissue and shell as well as the loss of individual oysters used as representative samples. In addition, the marginal cost of expanding oyster production that formed the central tenet of this analysis may possibly not be recouped by a PES if the sample oyster tested did not meet the nitrogen amount specified by the given program. Furthermore, the opportunity cost of filing reports and hosting regulatory staff for farm inspections is a very real expense as the constant stock

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maintenance and marketing of product leave little spare time. Conversely, the recent recommendations of Cornwell et al. (2016) do not suggest such a burdensome reporting protocol, merely self-reporting sampling for an unspecified time until typical nitrogen removal rates can be established that given location. In either case, a study by the Mississippi-Alabama Sea Grant Consortium and the Louisiana Sea Grant Law and Policy Program investigated an inverse PES in proposing a waiver of regulatory costs for starting any oyster farm instead of a payment for additional ecosystem services. This approach could be used to mitigate the additional costs listed above.

Regardless of what costs are ultimately applicable, members of the oyster aquaculture industry may be able to use the costs of production and projected PES at each level of production developed by this study to develop the business plan required to be included in a DNREC oyster aquaculture permit application, similar to the intent of the VIMS Oyster Enterprise Budget. Likewise, policymakers can budget for and receive estimated returns on investments in water quality improvements using a PES system. One such financing method could be a cooperative agreement between growers, DNREC, and a third party agricultural loan entity to cover the PES costs up front, buying time for public financing to be assembled and allocated. Currently, the Maryland Agriculture and Resource-Based Industries Corporation (MARBIC) offers non-fixed cost loans, which if replicated by a similar Delaware entity, might consider variable costs such as a PES to be eligible for financial assistance. Delaware and other states could also pursue development of publically-financed hatcheries, investing in a steady supply of seed to growers at a discounted rate. Finally, as the oyster market develops in Delaware, a higher WTP on the part of consumers for a local and "green" product such as oysters may render the PES program unnecessary in the future or could offset even greater increases in production within the Inland Bays, planning constraints related to water use conflicts notwithstanding. Indeed, Li et al. (2017) found that Delaware consumers would be willing to pay a higher per-unit price ($0.67) than the Virginia prices reported by Hudson et al. (2016) when educated about oysters' ecosystem services.

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