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

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Abstract

Disease and overfishing have led to a dramatic decline in wild populations and subsequent harvests of the eastern oyster *Crassostrea virginica* over the past few decades in Delaware and other states along the Atlantic Coast. However, in addition to their value as food to consumers, oysters, whether wild populations or cultured stocks, can provide ecosystem services such as nutrient removal, which may result in localized water quality improvements. Consequently, recent policies in Delaware have sought to establish and grow an oyster aquaculture industry. However, a key challenge to achieving efficient levels of industry growth and water quality improvements is that current market prices for oysters in other states and those projected for a Delaware market do not account for the value of these additional ecosystem services. In my analysis, I consider the present market value of oysters, estimate the additional value of their nutrient removal benefits, and propose a framework of financial incentives needed to increase the supply of oysters and therefore improved water quality. I then conclude with a brief discussion of how this incentive program could be financed as well as a sensitivity analysis of how oysters' nitrogen removal capacity may fluctuate as new data emerges from the scientific literature.

Could Oyster Aquaculture be an Effective Nutrient Management Tool?

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 leasable subaqueous bottom within the Delaware Inland Bay estuary, which includes Rehoboth Bay, Indian River Bay, and Little Assawoman Bay (Figure 1). As marked by red star icons in Figure 1 and shown in more detail in Figure 2 below, 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). As will be discussed in greater detail below, the unique locations of each lease area will significantly impact the projected costs and benefits of oyster production in Delaware.

In addition to providing local economic development and job creation, policymakers in Delaware also have a few other good reasons to rebuild the shellfish aquaculture industry. Beyond providing habitat for juvenile fish and value as shoreline buffers to erosive wave action (Grabowski et al., 2012), oysters existing on both wild reefs and those cultured by growers (Figure 3) 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 may 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, which when deposited in the adjacent sediments 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). These processes are shown in Figure 3 below. Due to the multiple pathways by which oysters serve as natural biological filters, they perform an important ecological function in maintaining water quality in estuaries. As such, Delaware policymakers have been intrigued by the potential cost savings of using oyster aquaculture as a best management practice (BMP) in the effort to restore the historically over-eutrophied Inland Bays.

For the purposes of this study, only N removal rates from the literature were used (oysters removed Phosphorus less efficiently) to project the ability of large-scale oyster farms to improve water quality in the Inland Bays. Several assumptions were made regarding oysters' ability to do so, including that growth rates would be even and that all surviving stock (50% mortality accounted for) would remove N at an equal rate at all lease locations. This conservative estimate also takes into account the fact that not all oysters will be triploids (possessing three chromosomes instead of two), 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 N collectively in its tissue and shell. As such, approximately 7.7 million oysters would be required to remove one metric tonne of N per two year harvest rotation cycle. Adjusting this value to U.S. Standard units for comparison to alternative BMP's provided by the Lewes sewage treatment plant (STP) produces an estimate that each harvest-sized oyster would be capable of removing approximately 0.0002866 pounds of N and that approximately 3,489 oysters would be required to remove one pound of N. Thus, it is important to note that per literature N removal estimates, oysters' value as a BMP is only realized at higher levels of production. As will be discussed shortly, marginal costs of production may also be higher at those levels. To account for oysters' best case N removal capacity (and therefore cost effectiveness), a sensitivity analysis incorporating N removal rates via other pathways described in the literature is performed later in the Results section.

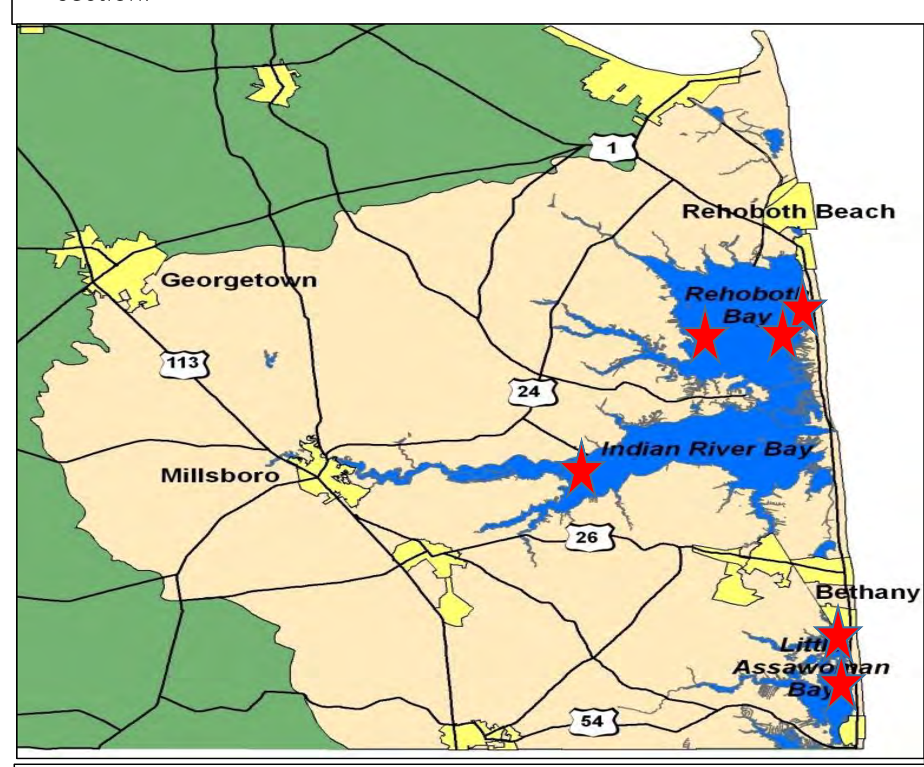

Figure 1. The Delaware Inland Bays Watershed

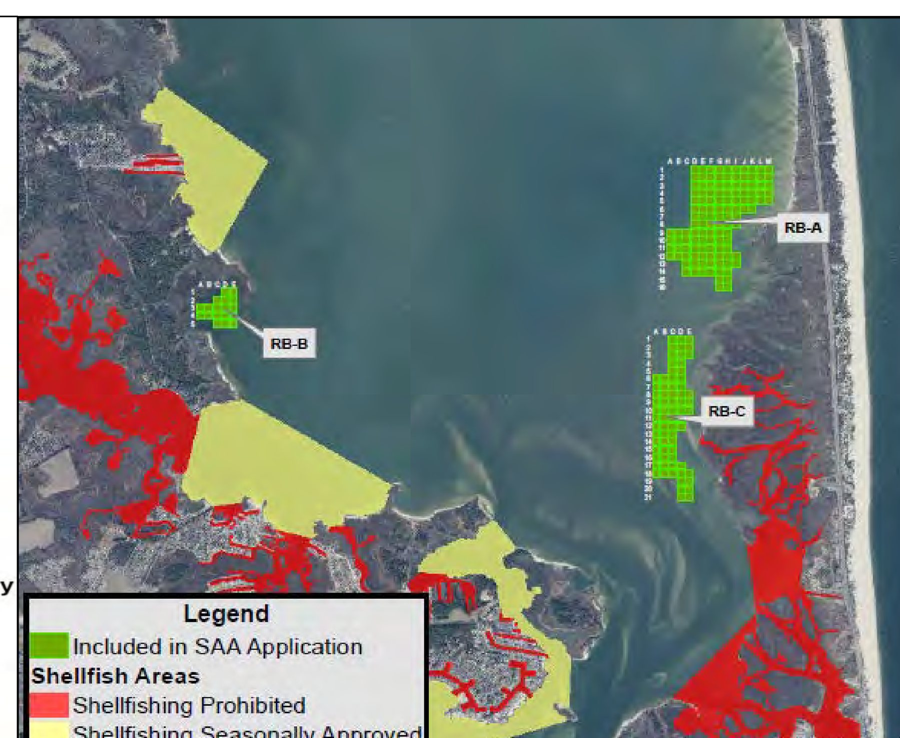

Figure 2. Rehoboth Bay Lease Areas

Figure 3. N Removal Pathways

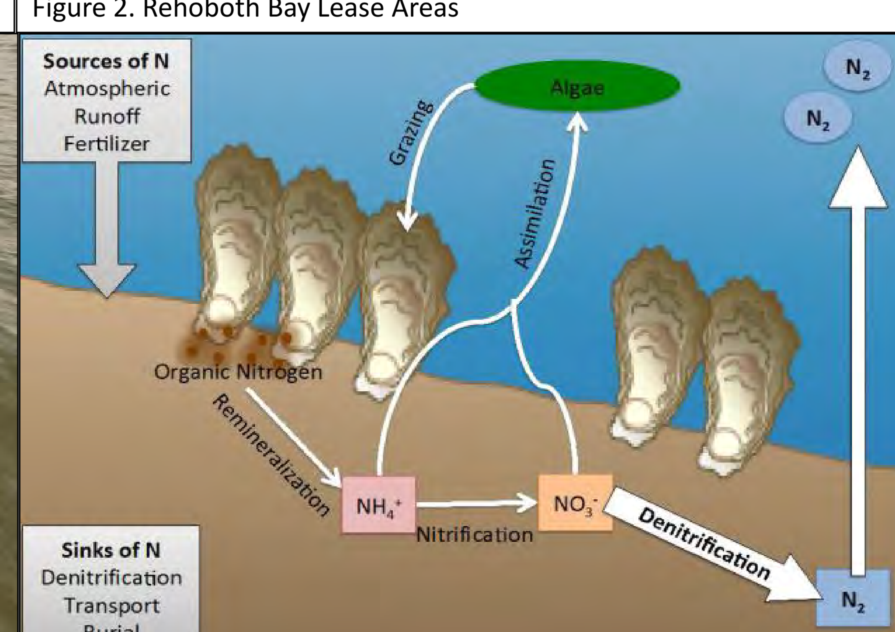

Figure 4. Oyster Bottom Cage Aquaculture

Economic Theory & Industry Costs

In order to grow the industry and increase the quantity of social benefits provided by oysters, policymakers are interested in different means to compensate producers (growers) for the ecosystem services they provide. For example, DNREC has investigated the potential of allowing regulated point sources in the Delaware Inland Bays watershed to invest in oyster aquaculture as a means to meet the United States Environmental Protection Agency (EPA)'s restrictions on nutrient discharges. While the City of Rehoboth Beach's wastewater treatment plant is currently the only significant permitted point source discharger to the Inland Bays watershed, the typical BMP's available for their use will be used to model non-point source management costs for the purpose of this study. These existing BMP's will be compared to the cost of oyster aquaculture in order to determine if the latter could be more efficient at removing excess nutrients.

In order to create this cost comparison framework, it is first necessary to consider two key economic concepts: externalities and additionality. As shown in Figure 5 below, 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 N 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. From an efficiency standpoint however, the issue of additionality, or the redundant compensation to producers for the services already provided is a concern. Therefore, the cost of incentivizing expanded oyster production and therefore N removal beyond market equilibrium levels is limited to compensating growers for the difference between the current market price (P*) and the total value of oysters' ecosystem services (P**). Therefore, the non-redundant oyster supply curve, shown in Figure 8 of the Results section represents the difference between increasing marginal costs and a constant price at each level of production and N removal.

A major challenge in this study was locating consistent and precise economic data measured at the marginal level. The Oyster Enterprise Budget (2012), produced by Virginia Sea Grant (VASG), represents the best available production cost data and does include some per oyster costs. Note that only variable costs such as wages for laborers, workers' compensation, and yearly gear expenses are used in order to model a mature industry with no capital financing costs. Other costs such as fuel and opportunity cost of travel (a function of GIS-measured distances from public boat ramps to SADA clusters) are unique to Delaware's lease locations and are thus new data, adjusted to the marginal level and grouped by SADA clusters in Table 1 below. A market price of $0.397, and average of 2014 and 2015 VASG reports, was chosen to represent marginal revenues (and benefits) to growers.

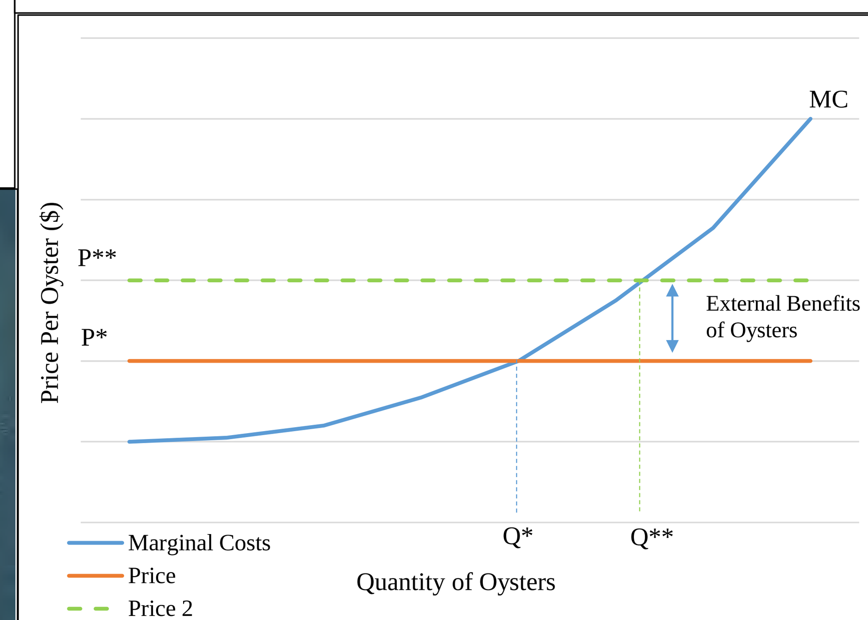

Figure 5. Oysters' N Removal – A Market Externality

SADA	Acres	Boat *	Wages *	Work. Comp. *	O C*	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

Table 1. Projected Delaware Oyster Production Costs (thousands of USD, per unit price in cents)

Oysters vs. Traditional BMP's – Which Removes More N For Less?

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 N removed (Figure 7). The negative value represents the marginal cost of N removal by oysters within SADA LA-C as being cheaper than the marginal revenue received by producers growing oysters in this lease area. Once within the next farthest lease area, SADA RB-B however, the marginal per-unit N 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 N 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 Economic Theory & Industry Costs section, the difference between the marginal cost of N 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.

Oysters' N Removal Efficiency vs. Current BMP's

Using only costs and N removal estimates for shell and tissue bioextraction, the cheapest per pound N removal rate beyond market equilibrium (starting with the first acre within RB-B) would cost approximately $34.89 per pound of N 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 N removal rates of oysters negate the any potential cost advantage over alternative BMP's. Oysters' N removal capacity is plotted (dotted lines) along with the other available BMP's in Figure 8 at right, using costs and capacities listed in Table 2, also at right. In addition, the current non-point source total maximum daily load (TMDL) for the entire Inland Bays watershed is approximately 968 pounds of N (per DNREC regulations), for an annual total allowable amount of approximately 353,320 pounds N. As shown in Table 2, the two cheapest BMP's, manure removal and cover crops, have the capacity to offset this volume of N without even using another method.

N Removal Sensitivity Analysis

In an effort to include an optimistic and flexible scenario for oysters' N removal capacity potential and therefore cost-effectiveness compared to alternative BMP's, a sensitivity analysis was performed using both higher bioassimilation values and incorporating estimate for the N content of oysters' biodeposits and associated denitrification rates found in the literature. These values were not used in the initial analysis due to their uncertainty and habitat-specific variability across different estuarine environments. Nevertheless, the following calculations may serve as a future indicator of oysters' potential as a viable and reliable N management strategy. For this analysis, estimates by Newell et al. (2005) regarding the amount of N found to be in wild oyster shell and tissue (0.52 grams per oyster), biodeposits (0.50 g), denitrification by microbes within sediments enhanced by biodeposits (also containing carbon, a key ingredient to the overall biogeochemical process) (0.25 g) were used. The tissue and shell estimates were obtained for harvest-sized oysters, representing a time period comparable to oyster aquaculture's harvest cycle, while the other two values were estimated to be annual values. When doubled to account for the continuous N removal estimated over 2 years, oysters' biodeposits and role in denitrification accounted for an additional 1.00 g and 0.50 g of N removed. As such, the total N 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 bioassimilation measurements for cultured oysters by Higgins et al. in 2011. Assuming that these additional pathways are as consistent as bioassimilation, the resulting N removal efficiency is nearly 16 times greater when all forms of N removal are considered. Under these circumstances, the previous per-unit N removal cost of $34.89 would be reduced to approximately $2.25 per pound N removed, placing first along the N removal supply from a cost-efficiency standpoint. From a capacity standpoint, the total N removed after the market equilibrium quantity would increase from approximately 7,796 pounds to approximately 121,150 pounds. Despite this increase in efficiency, manure removal's capacity (93,115 lbs N per year) would also have to be employed, as well as some of cover crops' (463,841 lbs N per year), priced at $2.92 and $3.55 per pound, respectively. Nevertheless, oysters' would represent not only a competitive, but the most cost-efficient BMP available for N management in the Delaware Inland Bays if all N removal pathways were to be considered consistent and reliable from both a scientific and regulatory oversight standpoint.

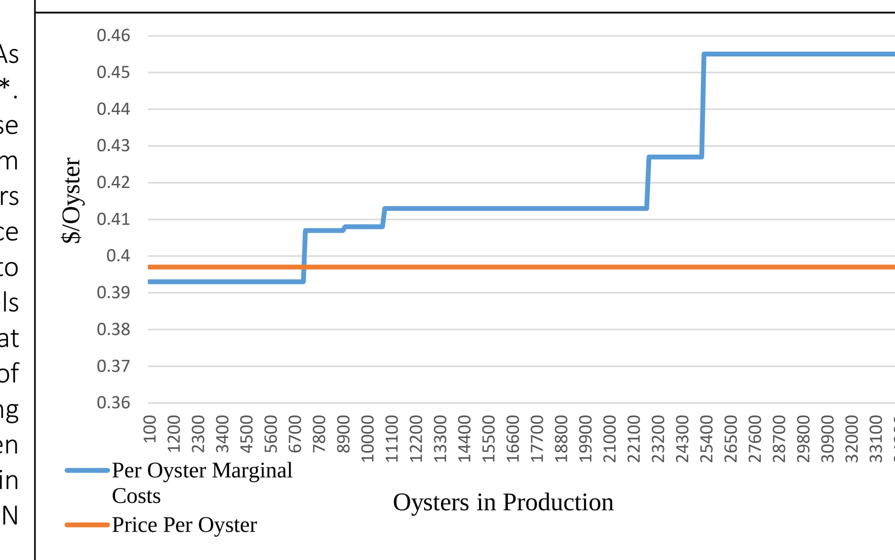

Figure 6. Marginal Costs of Production vs. Price

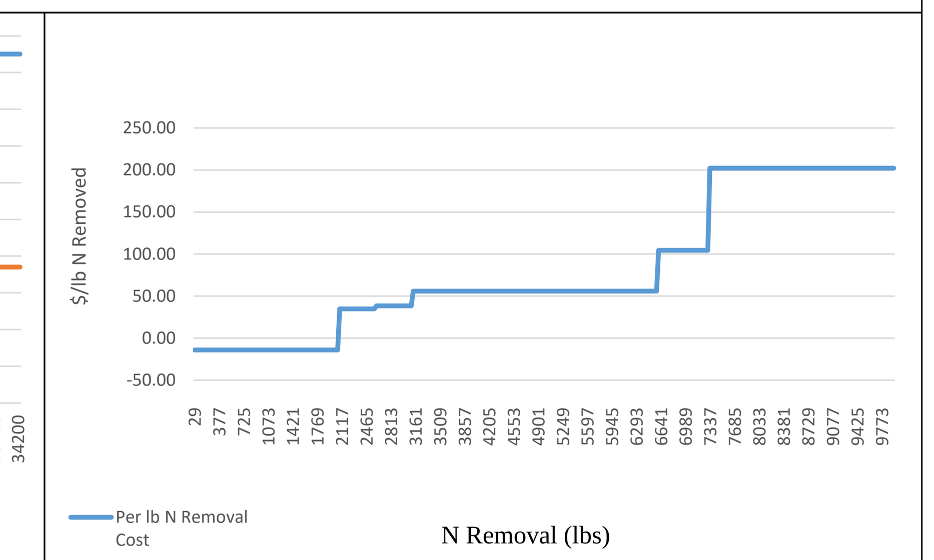

Figure 7. Cost per Pound N Removed – Additionality Accounted For

BMP Type	N Removal ($/lb/yr)	N Removal Capacity (lbs)
Oysters: All N Removal Pathways	2.25*	121150
Manure Removal	2.92	93115
Cover Crops	3.55	463841
Conversion to Riparian Forest	4.87	582975
Wetlands Restoration	6.85	757080
Grassland Buffers	7.05	799359
Oyster Bioassimilation (Tissue/Shell)	34.89 – 202.37*	7796
Connect to Sewer Systems	80.65	905482
Bioretention Gardens	263.16	907258

*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 N removal pathway

Table 2. Oysters vs. Traditional BMP's

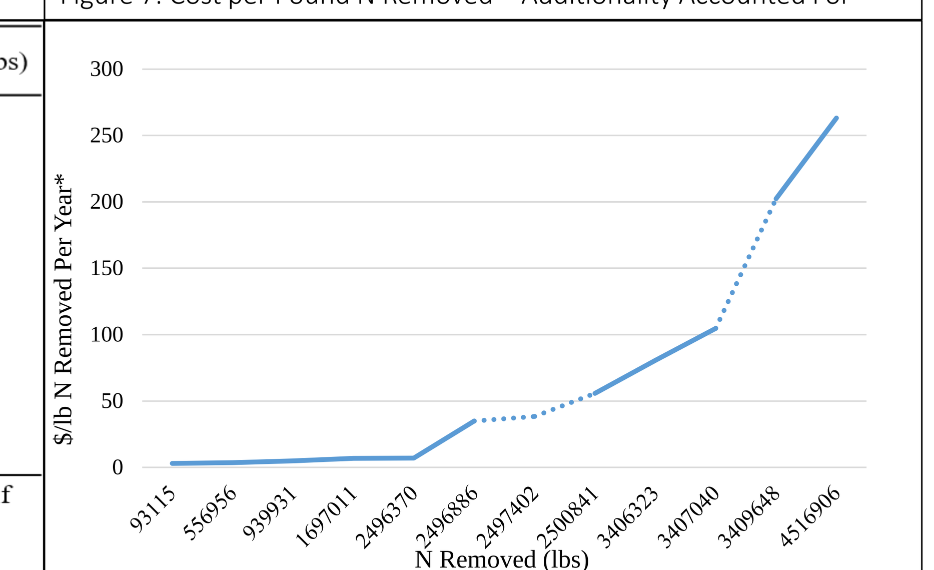

Figure 8. . N Removal Cost Curve – All BMP's

Summary & Future Policy Considerations

<u>If only oysters' rate of N via bioextraction is considered, they are not currently economically competitive with other BMP's due to their inefficient rate of N removal. However, if all potential N 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</u>. In addition, a flow of payments could be made for in situ N 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 N removal by oysters into a water quality improvement program. Also, tradeoffs between more reliable bioextraction of N by harvestable oysters and the placement of oysters in areas closed to harvest in order to continuously remove 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 N removal estimates, and implementing production incentivizing programs. Finally, apart from travel costs unique to the lease areas in the Delaware Inland Bays, <u>the framework may be used by other states to calculate the grower compensation costs compared to traditional BMP methods available in their region</u>.

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