The potential for nutrient credit trading or economic incentives to expand Maryland oyster aquaculture

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FINAL REPORT
The potential for nutrient credit trading or economic incentives to expand Maryland oyster aquaculture

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Contents

Abstract 1

Introduction 2

Aquaculture in the Chesapeake Bay 2

Policy effects on aquaculture industry growth 3

Nutrient trading policy 4

Potential for aquaculture business sector to produce credits in Maryland 5

Baseline reductions 6

Additionality 6

Uncertainty 7

Methods 7

Scenario development 8

Baseline scenarios 8

Policy Scenarios 9

Nutrient credit prices 9

Loans 10

Hatchery Production Efficiency 11

Production function model 11

Modeling industry growth based on profit 14

Running scenarios in the production function and industry growth models 15

GIS analysis of available lease areas 16

Results & Discussion 18

Scenario Comparisons 19

Nutrient Credit price effects 23

Effect of potential half-shell market saturation on container culture 23

Sensitivity analysis of profits to costs of production and prices received 25

Conclusions 26

Acknowledgements 29

References 29

Appendix A. Estimates of potential willingness to pay for nitrogen credits in Maryland A-1

Chesapeake Bay policy conditions affecting cost analysis A-1

Cost Analysis Methods A-1

Using CAST to generate nutrient removal efficiency per practice A-2

Estimating practice costs A-3

Cost-effectiveness applied to estimate value of N reduction A-3

Comparison of cost analysis to published fixed credit prices A-4
References A-5
Appendix B. Analysis of suitable aquaculture area using spatial data B-1

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Abstract

Oyster aquaculture is thought to have the potential to maintain commercial production of this iconic species by counteracting long-term declines in the wild population. In addition, a thriving aquaculture industry may be able to support goals to preserve cultural values associated with watermen livelihoods and communities and create benefits derived from improved water quality and fish habitat. We developed a model to estimate industry growth under alternative policy scenarios. We adapted an existing production function model of the aquaculture industry and created supplemental models that created industry entry in response to firm profit. The scenarios covered a range of conditions including the presence of a nutrient credit trading market (nitrogen only) with high or low credit prices, in which credits serve as price supports. Other scenarios evaluated effects of policies that reduced one or more costs associated with loan payments or inputs to production. We evaluated scenario performance in terms of oyster production, sales, profits, jobs, and nitrogen removed, relative to baseline conditions without policy changes.

Of the scenarios tested, nutrient credit trading showed the greatest potential to increase industry growth compared to scenarios that reduced individual costs. However, trading only increased production substantially when credit prices were relatively high and trading rules for additionality were set to allow all production after a fixed year to be eligible for trading (Additionality A rules). A high credit price of $190/lb for nitrogen (estimated using a risk-adjusted replacement cost for practices proposed to meet the Chesapeake Bay Total Maximum Daily Load) increased oyster aquaculture production by 59% over a constant growth trend baseline. In contrast, a low credit price scenario ($10/lb) created less than a 4% increase in production over the baseline rate, even with Additionality A rules. Industry growth rates were one-tenth of these values when additionality rules only allowed new production activity to be eligible to trade (Additionality B). Credit prices would need to be on the order of $160/lb to increase growth 50% above baseline growth trends and use Additionality A rules. Scenarios that reduced costs of production had substantial, but lower effects than the trading scenarios. Investments in hatchery research to reduce the cost of spat and seed oysters yielded an estimated 23% increase in growth and a scenario of reduced loan rates yielded an estimated 15% growth.

In all scenarios, gross sales and profits increased proportionally more than oyster production. For example, the high nutrient credit price increased production by 59% over baseline, but sales increased by 75%, and profits by 188%. The public return on investment was characterized by the number of jobs created and the amount of nitrogen removed from waterbodies, since these outcomes represent goals for economic development and Chesapeake Bay restoration. We found that high value nutrient credit trading with Additionality A rules generated the largest increase in jobs at 50% (98 more jobs/yr) and nitrogen removal at 59% (6,900 more lbs/yr) above baseline. Loan rate reductions and research investments also increased jobs by 14% and 22% and nitrogen reductions by 15% and 23%. All results were sensitive to assumptions about future growth and policies had lower influence under reduced baseline growth.

Introduction

Oyster aquaculture is growing rapidly in Maryland and is considered by many to have the potential to align goals for business development, cultural preservation and environmental improvements in the Chesapeake Bay. Growth in the industry was made possible by new rules to allow aquaculture leasing of bottom and water column areas and has been supported by Maryland state with loan and outreach programs. The industry is seen as desirable to support because it may provide opportunities to maintain production of this iconic species despite long-term declines in the wild population. It is further hoped that aquaculture can create opportunities for watermen who might otherwise be forced to leave the industry, thereby preserving cultural values associated with watermen livelihoods and communities. Other benefits are derived from the ecological functions (also called ecosystem services) that oysters provide such as nutrient sequestration, water filtration, and food web support that have social value to the extent that they reduce costs of meeting pollution caps, create aesthetic amenities from cleaner water, and increase fishing quality, among other benefits.

Future growth in the industry will depend on a wide variety of factors and the central goal of the study is to estimate the impact on oyster aquaculture of alternative economic incentives or policies that may indirectly create incentives. Nutrient credit trading is a policy that may indirectly create economic incentives for the industry because aquaculture has been approved for use in generating nutrient credits (expert panel report) and trading regulations have recently been established in Maryland (Maryland Code 2018 45:14 Md. R. 698; Agriculture Article, §§8-901 and 8-904; Environment Article, §§9-313, 9-315, 9-319, and 9-325) as an approach to reducing the costs of meeting the Chesapeake Bay Total Maximum Daily Load (TMDL) for nitrogen, phosphorus and sediment. Other policies may be specifically oriented to help aquaculture such as low-interest loan programs, as are currently offered by the Maryland Agricultural and Resource-Based Industry Development Corporation (MARBIDCO).

Aquaculture in the Chesapeake Bay

Two broad classifications of oyster aquaculture occur in Maryland. The first, bottom culture, is the more traditional method. Growers manually reseed their oyster beds, primarily with spat-on-shell, for later harvest. Bottom culture on leased state land is different from wild harvest areas that are open-access fishery locations. Bottom culture oysters are predominantly sold by the bushel to a shucking house for canning. The second type of oyster aquaculture is referred to in this report as *container culture*. Container culture is primarily conducted in Maryland using submerged cages resting on the bottom, but floating cages or cages suspended from other structures may also be used. Container culture requires more capital investment per oyster but sales prices are higher, since the oysters are typically sold for consumption in the restaurant half-shell market.

Maryland oyster aquaculture has been increasing rapidly for both cultures since lease regulations were revised in 2010 (Maryland Department of Natural Resources, n.d.). Harvest lags industry activity since it typically takes several months to secure a lease and a minimum of 1-3 years, depending on the culture method, to grow oysters that are large enough to legally harvest. Since 2012, average aquaculture harvest has increased more than 8,000 bushels per year for bottom culture, and more than 5,000 bushels per year for container culture (Figure 1).

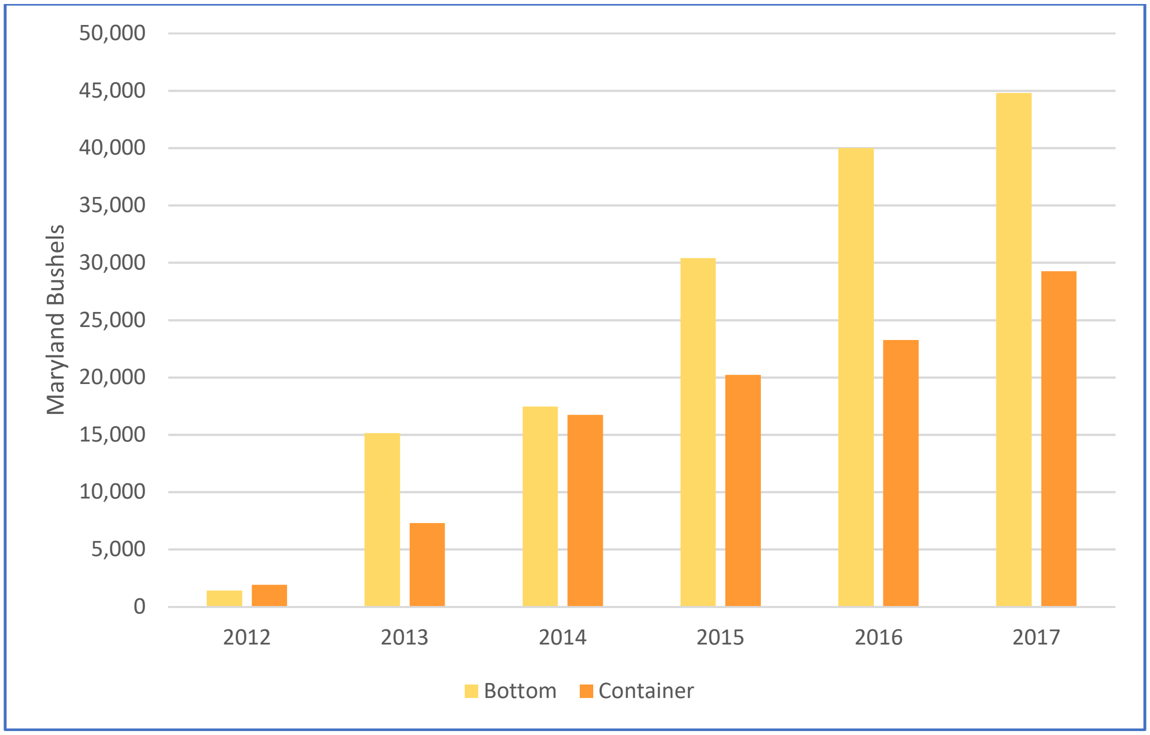

Figure 1. Maryland oyster aquaculture harvests
Source: Maryland Department of Natural Resources.
Bushels of production can be converted to an estimate of individual oysters using the ratio 275 oysters/bushel (Maryland Department of Natural Resources 2008; pg. C-4).

Virginia has a longer record of aquaculture production than Maryland and therefore, may provide some clues about the future of Maryland's industry. A trajectory of strong growth in container culture (floats and off-bottom cages) began after 2005 in Virginia, with an average increase of almost 13 million more single oysters harvested per year until a peak of 135 million oysters harvested in 2015. The trend has levelled off in the last couple of years. Virginia bottom culture harvests (planted directly on bottom) grew from approximately 2,000 bushels in 2009, to a peak of over 42,000 bushels in 2016. As with floating container culture, growth in bottom culture appears to have levelled off in recent years. Federal monies had been supporting large-scale spat-on-shell production, but those subsidies are no longer offered (Hudson, 2018).

Although aquaculture has been practiced for over 150 years in the region, Maryland's industry is still young. There are numerous unanswered questions about what future growth will be. The recent surge in growth may be an artifact of pent-up demand for leases by relatively few parties or represent a trend that will continue. Bottom culture harvests in Maryland are already on par with Virginia, whereas Maryland container culture harvests are less than 10% of those in Virginia.

Policy effects on aquaculture industry growth

Continued growth of the aquaculture industry in Maryland will depend on many conditions including ensuring adequate supply chains, avoiding market saturation, managing water user conflicts, and creating and/or maintaining reasonable business profits to attract new entrants. Several possible constraints on the supply chain include production levels of seed oyster or spat on shell, which are the main input to most businesses. There are some concerns that the shell needed for producing spat on shell may become constrained, but that constraint does not appear imminent and may be overcome with technological innovations for alternative substrate (Wheeler, 2017). User conflicts remain an issue in Maryland (e.g., Deville, 2018).

Any industry growth will be influenced by profits and the size of current profits in the industry is not clear. However, it would be typical to find highly variable profits in a new industry, particularly one relying on a natural resource (Bockstael and Opaluch, 1983). To help the industry grow, several types of economic incentives might be considered to provide time for entrants to refine their operations to become profitable and to support growth during the lag period between initial investment and first harvest. To reduce costs, we considered the use of low-interest loan programs (for capital or operating expenses), which already exist but might be expanded or restructured for maximum effect. We also considered investments in scientific research to improve efficiency of seed or spat production or technological investments that could lower costs of operations. Finally, we considered the potential to expand half shell markets under conditions of market saturation (and decreasing prices with increasing production), through marketing or branding campaigns, or other investments. However, Maryland wild harvest data show that oyster prices in the shucked market are not highly responsive to total harvest levels (C. Hayes, pers comm.), suggesting that market saturation is not an imminent concern in that market. Anecdotal information suggests that prices in the half shell market are similarly generally unresponsive to supply and that market saturation may only occur after substantial growth in the industry.

Nutrient trading policy

Although it was not designed to be an economic incentive for aquaculture, Maryland's nutrient trading program offers the potential for aquaculture producers to sell nutrient credits and supplement their income stream. Before rules of credit production trading had been established, DePiper et al. (2010) explored the effects of this opportunity on firm survival, finding a small potential effect. Trading rules were established in 2018, and other changes in permit conditions have potentially altered trading conditions, warranting a new examination of whether additional oyster production may result from trading.

Nutrient trading is an approach to cost-effectively achieve a cap on nutrients entering a water body by allowing those with high costs of reducing nutrient emissions to trade with those who have low costs of reducing nutrients. Regulated entities (e.g., counties, wastewater treatment plants) that lack reasonably priced or feasible options for reducing pollution can pay for low-cost reductions by others and thereby reduce total costs of permit compliance (Ribaudo and Gottlieb, 2011). For trades to be accepted as contributing to compliance of the Chesapeake Bay TMDL, models are used to judge the equivalency of pollution emissions at different locations so that the effect on Chesapeake Bay water quality will be the same regardless of where reductions occur.

The impetus for water quality trading in Maryland, are the nutrient caps established for the Chesapeake Bay TMDL on nitrogen, phosphorus and sediment. A legally enforceable pollution cap is the minimum criterion necessary to motivate credit buying. Additional enabling conditions include structuring pollution permits to enable trading, removing other policy impediments, and creating tools to lower transaction costs of trades, which have been or are being done to a large extent in Maryland. Demand for nutrient credits is currently expected to come from economic entities with permits to emit nutrients (MS4 jurisdictions and wastewater treatment plants) but who have not yet reached their permit-mandated reductions. However, wastewater treatment plants are also potential sellers of nutrient credits, since emission from the major plants are below their waste load allocations and they have opportunities to further reduce nutrient emissions through additional management interventions. Another potential credit buyer is the Bay Restoration Fund (BRF) which has set aside funds to bids for cost-effective nutrient reduction projects. Using the BRF can be considered *administered trading* (Hanson and McConnell, 2008) in which collected fees are used to buy nutrient reductions, rather than having individual entities trade with each other, which is referred to as *bi-lateral trades*.

A potential impediment to bi-lateral trading is created when entities that are unregulated with respect to nutrient emissions are responsible for nutrient reductions for which a regulated entity is legally liable. In most markets where pollution credits have been successfully traded, both the sellers and buyers of pollution credits were regulated entities (Wainger and Shortle, 2013) with emission permits that allowed for monitoring and other types of regulatory oversight. However, water quality trading markets that are being established in some Chesapeake Bay jurisdictions generally allow regulated entities, typically point source (PS) entities, such as wastewater treatment plants or MS4 permit holders, to buy from *unregulated* nonpoint source (NPS) entities, such as farm or aquaculture businesses. States must modify pollution emission permits to enable trading but such modifications do not transfer legal liability for reductions away from the regulated entity. As a result, buyers who are willing to trade despite the risks will require a "risk premium," meaning that the savings from trading must be sufficient to compensate for the added legal risk of putting their compliance in the hands of an unregulated entity. Such risk premiums have been observed in carbon credit trading where projects with higher risk receive lower credit prices than projects with lower risk (Peters-Stanley et al., 2013).

Credit sellers may also perceive legal risks of trading and require their own version of risk premiums (i.e., sufficiently high credit prices) to enter into credit trading contracts. Non-regulated entities are potentially motivated to trade by desires for enhanced revenues, to avoid future regulation, or to promote environmental stewardship, rather than legal requirements. However, they incur risks if credit production adds regulatory oversight to their operations in the form of credit verification inspections by government entities and additional paperwork. Even businesses that carefully follow regulations may be reticent to allow on-site inspections because of the potential for inspectors to notice unintended legal violations. Credit aggregators, which would be distinct entities that would manage trades, are often suggested as an approach to managing legal liability concerns and handling regulatory paperwork but must become trusted entities, if they are to attract risk-averse buyers and sellers.

In addition to legal concerns, a variety of technical challenges are present in creating PS-NPS trades that will meet regulatory approval. In Maryland, software is used to calculate the equivalence of nutrient emissions by location and other factors that affect bi-lateral trading details (Maryland Department of Agriculture (MDA), 2008). For example, an entity that emits nutrients in the upland of Maryland will generally be delivering low levels of nutrients into the Bay tidal waters (per pound emitted at the source) than an entity emitting nutrients directly into tidal waters. If these two entities were to trade, a trading ratio would be used to make the nutrient emission equivalent from the perspective of their effect on bay water quality. The software also screens for additional rules requiring that trades occur within one of the three trading areas in Maryland (Maryland Department of Agriculture, 2018), meet local TMDL requirements, and that baseline requirements are met, among other rules. Farms in Maryland must achieve site-specific nutrient reductions before being allowed to sell credits that reduce nutrients below that baseline (Maryland Department of Agriculture (MDA), 2008).

Potential for aquaculture business sector to produce credits in Maryland

The current Maryland trading rules allow aquaculture businesses to offer nutrient reduction credits, however, some details of the rules remain to be clarified by the Maryland Department of the

Environment. What is known is the quantity of nitrogen reductions that can be claimed from aquaculture operations in credits and that the location of in-water operations will be associated with the nearest shoreline, for the purposes of judging equivalence of trades (Cornwell et al., 2016). However, other issues, such as baseline requirements, uncertainty ratios, and whether nitrogen and phosphorus credits can be sold separately, have not yet been specified in Maryland rules, although some issues were discussed in Cornwell et al. (2016).

Baseline reductions

An issue that is unresolved is whether aquaculture businesses will need to meet any baseline reduction requirements before being allowed to offer credits. Since the sector has not been assigned a reduction goal, as is used to calculate baselines for agriculture operations offering credits (see Text Box1), a baseline would not be expected and has not been required in Virginia (Virginia Department of Environmental Quality, 2017).

Baselines used in nutrient credit trading for Maryland agriculture

In Maryland, baselines are used to achieve load allocations that have been assigned to a particular nutrient-emitting sector (Maryland Department of Agriculture (MDA), 2008; Wainger, 2012). Specifically, the agricultural sector has been assigned a cap on nutrient emissions that is necessary to achieve the Chesapeake TMDL caps. However, the state does not have the legal ability to enforce those caps. As an alternative to regulation, they require that all farms that offer credits for sale first reduce nutrients to a baseline level. The baseline level is calculated per farm to represent that farm's portion of the sector's reduction. Only practices that lower the farms emissions below the baseline can be used to create sellable credits.

Additionality

Additionality reflects the concern that payment for credits should result in a net nutrient decrease that would not have happened otherwise (Ribaudo and Savage, 2014). Requiring additionality in trades ensures that pollution caps are met because the entity buying the credit will emit pollution in excess of its permitted cap and the trade must create an equivalent offsetting reduction to maintain a cap. Since the Chesapeake Bay model does not explicitly include aquaculture as a source of nutrient reductions, any reductions created from aquaculture production can reasonably be seen as new reductions, within the TMDL accounting framework. However, from a cost-effectiveness perspective, it is inefficient to pay for a nutrient reduction that would have happened regardless of the payment. The concern is that paying for activities that would have occurred without payment, prevents that money from being used to generate additional reductions.

Therefore, two additionality questions to be addressed in trading rules are 1) Should credit be given for all production or only the growth induced by credit sales?; and 2) Can nitrogen and phosphorus credits be *stacked*? Stacking credits meaning that the same oyster could be sold to two different buyers, one for the nitrogen credits and one for the phosphorus credits.

Credit payments can reasonably be expected to induce new aquaculture production because, as a general rule of market behavior, when the price being offered for a good increases, production increases proportionally, all else equal. However, giving credit to all aquaculture production or allowing stacking would tend to reduce the cost-effectiveness of a trading program since it is likely that much of that production (and the byproduct of nutrient reductions) would have happened without payments. Therefore, if policy makers wanted to maximize the cost-effectiveness of trading programs, they would need to establish a rule that only the induced growth of the industry could be used to create credits for trade. However, such an approach would be difficult to implement since it would require calculating a baseline trend without the credit and separating out the growth above trend. Such an approach is technically possible to calculate for an existing business or for the industry as a whole by using historic growth data. However, such an approach would have high error and create uncertainty about returns to investments in growth, which would tend to suppress investment in business expansion. In other words, businesses are more likely to invest in expansion, if they can be assured of a certain price being paid for production. Similarly, allowing stacking of credits would tend to increase credit value to growers and reduce uncertainty about being able to recoup costs associated with business growth.

Uncertainty

The issue of uncertainty has been discussed in the expert panel report (Cornwell et al., 2016) and among Virginia stakeholders (Virginia Department of Environmental Quality, 2017). Since aquaculture directly removes nutrients from the water column, the uncertainty surrounding the in-water reduction is negligible compared to using upland BMPs to create nutrient credits. Further, since nutrient credits can only be generated by aquaculture for the oyster tissue, the accuracy of the information being used to estimate nutrient removal is high relative to other practices. As a result of these conditions, a Virginia panel concluded that "It is expected that credits generated by [aquaculture operation] will be more accurately quantified than stormwater loads from an MS4 system and therefore could be traded at a 1:1 ratio." (Virginia Department of Environmental Quality, 2017).

Methods

In order to evaluate the effect of economic incentives or nutrient trading on the aquaculture industry, we built an industry growth model in which average profits determined growth. The model was built using information on current aquaculture industry growth trends and production functions. The model was used to examine potential effects of policies on industry growth and evaluate which policies were likely to have the largest effects. Policy incentives can either reduce costs or increase prices to increase profits and thereby induce industry growth, as measured by new oyster production. In addition to production, we also calculate sales, profits, jobs, and nutrients sequestered to compare policy performance.

Production function models were developed for bottom and container culture. The models consisted of detailed information on industry costs per unit of production and estimated profit for a given price per bushel and per half-shell oyster. The models were adaptations of spreadsheet tools developed by Parker et al. for bottom culture (2013) and container culture (2016). These detailed spreadsheets were designed to assist new and existing growers in predicting profits under innumerable combinations of inputs, such as varying the proportion of oysters sold to the half-shell market, varying the price received per oyster, varying the cost of each item of equipment.

We developed an industry growth model by building on these production function models. We constructed a model relating recent data on observed production (2012-2017) and estimate profits by comparing revenues to costs. We then modeled industry growth as a function of profit. The methods section describes development of these three models 1) nutrient credit market and policy scenarios, 2) production function models, and 3) industry growth model. The subsequent section explains how the model was exercised to represent scenario outcomes. Last in methods, are details of a GIS analysis to evaluate the potential geographic limits to aquaculture growth.

Scenario development

We developed four main types of policy scenarios and compared them to two alternative baseline scenarios representing alternative future trends. The scenarios explored the potential effect of policies on aquaculture industry growth, net revenues and other economic and environmental outcomes, relative to a future with no changes in policy. The baselines that were used for comparing policy effects represented two alternative growth scenarios for the bottom culture industry.

Baseline scenarios

We used two baseline scenarios to represent oyster growth in the absence of new policies. For both baseline scenarios, we assumed that existing policies would continue, but we projected different expected future growth for bottom culture. The first baseline scenario extrapolated growth trends for container and bottom culture from 2012 to 2017 into the future (as shown in Figure 1). In this baseline (referred to as "constant trend") we assumed that the profit levels of the past would continue to be more or less the same, and that the rate of new growth attracted by that profit would also remain the same. The second baseline (referred to as "reduced growth") used a lower growth rate for bottom culture. We continued to assume that profit levels of the past will remain more or less the same in the future - but we reduced the rate of new growth in bottom culture attracted by that profit.

As will be described later, bottom culture growth has been stronger than container culture growth in recent years, although profits appear to be less. The reduced growth baseline uses the same response to profit for bottom culture as for container culture, which has the impact of greatly reducing the projected increase in bottom culture over time. Although, we revisit this assumption during analysis. The container culture baseline is the same in either the constant trend or reduced growth baseline but the potential for growth to be suppressed through market saturation is explored via an alternative analysis.

The rationale for including a reduced growth baseline specific to bottom culture was that the oyster aquaculture industry is relatively young in Maryland, and investments would be expected to migrate towards the higher-return form of oyster aquaculture, all else equal. Our initial data suggest that container culture yields greater returns per dollar invested, and growth rates in bottom culture vs. container culture may still be adjusting. New unreleased survey data on enterprise budgets for bottom culture vs. container culture in Maryland may eventually allow improved comparison of costs and returns (Engle and van Senten, 2018). We can also look to Virginia’s more mature aquaculture industry to project future trends, where data suggest that bottom culture growth has been substantially slower than container culture production (Hudson, 2018).

Additional factors could constrain bottom culture in the future, more than container culture. Leasable area that meets preferred criteria may be more constrained for bottom culture than container culture. We explored this possibility using GIS analysis, as detailed below. Another factor potentially limiting bottom culture in the future is availability of oyster shell, since it is used to stabilize the ground for bottom culture and promote productivity (pers. comm. D. Webster). Oyster shell is already becoming scarce for use in public shellfishing bed restoration. Bottom culture uses shell for spat-on-shell production, but the shell supply is not currently considered the limiting factor on production (W. Slacum, pers comm.). Container culture also uses shell in producing seed oysters, but small fragments can be used, and alternative substrates appear feasible. Finally, the limited capacity of local shucking houses could become a problem if bottom culture production were to increase markedly. Capacity limits have the potential to decrease prices in the shucked market, if they are exceeded.

Policy Scenarios

We formulated five different policy scenarios for testing effects on aquaculture industry growth and profitability (Table 1). They cover existing policies for nutrient credit trading, and potential future policies for loan programs and research and technology investments. We developed these policies in consultation with numerous professionals in the oyster aquaculture field to find policies that were achievable and the most likely to have a discernible effect on industry profits and growth.

Nutrient credit prices

Market prices for credits are a function of many variables and since no nutrient credit trades have taken place in Maryland at the time of writing, it is impossible to predict prices for nutrient credit with any confidence. Many questions remain about whether a nutrient credit market will develop (Ribaudo and Gottlieb, 2011; Stephenson and Shabman, 2017). If a market did develop, we would expect prices to change over time as the market equilibrates or as supply and demand conditions for credits changes, rather than remain a static price. For example, low cost credits might be used up first, causing price to increase through time. Alternatively, an active market could create incentives for new cost-effective approaches to develop, lowering costs overtime.

In addition to available technologies to reduce nutrients, nutrient credit prices are affected by a myriad of details that are established in permits and trading rules and regulations (Ribaudo and Gottlieb, 2011; Shortle, 2013; Stephenson and Shabman, 2011). For example, the size of the trading area strongly affects price since larger areas tend to reduce credit prices by increasing the number of potential suppliers and thus competition among suppliers (Wainger, 2012). Prices could increase over time if trading becomes robust and credits become scarce. Alternatively, major policy changes could eliminate or reduce demand for credits, for example, by providing dedicated funding streams for permittees to meet permit requirements with their own nutrient reduction projects.

To overcome this data gap on price expectations for our scenarios, we estimated a potential range of nutrient credit prices by using available data on the costs of generating nutrient reductions in Maryland (Appendix A). The cost of producing nutrient reductions through management practices other than aquaculture provides some insight into what competing suppliers might charge for a credit. Credit suppliers will need to recoup project costs, cover administrative or transaction costs, and be compensated for taking risks (as discussed in the introduction). The cost data also provide insights into what buyers might be willing to pay, since the practices include only those that were included in the county watershed implementation plans (WIPs, Phase II) and county governments are potential buyers for credits to meet their MS4 permit requirements, particularly in the short term.

We compared costs of nutrient reductions to published credit prices for programs in which nutrient credits are offered for fixed prices that are calculated by program administrators. These values do not represent market prices as established through supply and demand conditions. Instead, these reflect prices that have been paid under conditions that differ substantially from the market for aquaculture credits. Credits are all part of government-supported programs, are subsidized in one way or another, and generally have low transaction costs because they are purchased through an existing structure. We used these prices to suggest a low-end willingness to pay for credits, since more representative prices, as generated through markets, were generally not available.

We used two credit prices for scenarios based on our cost analysis and a review of credit prices paid in administered programs (not competitive markets). Neither price was based on a detailed analysis of market conditions in the Chesapeake Bay and thus should be considered rough approximations of credit prices, should a market for credits develop in Maryland. A survey of water quality trading programs generated a range of $3 - $20 per credit and we chose $10/lb/N credit price as a value to test in our scenario. The cost analysis yielded an average cost of $280/lb N/year, after removing unrealistically high and low cost options (explained further in Appendix A). This value reflected what counties suggested that they would be willing to pay to reduce nutrients in projects they funded. We reduced that average value by 30% to cover transaction costs (see Chesapeake Bay Commission, 2012) and the risk premium (discussed in introduction) to generate $190/lb N / year as a potential high value of credit price. Although this value seems high, it is well below the WIPs' marginal cost of nitrogen abatement (or highest cost per pound that was specified in the WIPs used, Appendix Table A1), suggesting that counties are potentially willing to implement practices with much higher costs per pound. We applied the two prices at a 1:1 trading ratio (Virginia Department of Environmental Quality, 2017).

Credits from aquaculture are generated via harvest and only the nutrients in the tissue and not the shell can be used to generate credits. The amount of nitrogen sequestered per oyster was recently estimated by Cornwell et al. (2016) as part of BMP recommendations for nutrient reductions due to oyster aquaculture. We selected the 2.5 to 3.49 inch size class as indicative of market size oysters, based on the minimum harvestable size of wild-harvested oysters being 3 inches (Cornwell et al., 2016, p. 55) although aquaculture sizes can vary. The default grams of nitrogen for that size category are 0.09 and 0.13 for diploid and triploid, respectively (Cornwell et al., 2016, p. 61). We applied these default triploid values for container culture oysters and the diploid value for bottom culture oysters. Under the BMP recommendations, growers would have the option to submit data to petition for different (e.g., larger) sequestration rates per oyster for their operation.

We considered two additionality rules in the analysis that were applied to the two price scenarios, effectively creating four scenarios representing nutrient credit trading under alternative market conditions and trading rules. For the first rule, credits were paid to growers for all new leases and harvests in perpetuity, which is equivalent to labeling all production above a given year as additional (referred to as *Additionality A*). For the second rule, only the first harvest for a new entrant (new operation or expansion of an existing operation) received the credit price (referred to as *Additionality B*). A grower can only generate nutrient credits in successive years if they continuously expand their operation.

In the model of credit price changes, Additionality A was a permanent change to growers' profit, and so had a recurring effect on industry entry year after year. Additionality B was modeled as a one-time payment for the first harvest of a new grower or an expanded area of operation and was spread out over 10 years to be consistent with model accounting on investment costs.

Loans

The third scenario was a policy to reduce loan-related costs to growers. The cost of servicing loans used to cover equipment, operating capital and payroll are a substantial proportion of business costs. To lower this burden on the aquaculture industry, the state could insure business loans, so that banks would be able to offer lower loan rates. MARBIDCO currently offers some types of low interest loans sometimes combined with principal forgiveness. Our scenario represents a simplified case in which loans are reduced for all new growth, by applying a discount to typical loan rates (reported in Engle and van Senten (2018)). For the typical 10% rate on operating capital, we reduced it 7%; for the typical 7% rate on equipment, we reduced it to 4%.

Hatchery Production Efficiency

The fourth scenario represented a hypothetical state investment in research and operations to improve survival in hatcheries and thereby reduce the costs of spat and seed oysters. Spat and seed oyster costs are large components of operating (variable) costs. These costs might be reduced by investing in research to modify hatchery operations to increase the survival rate in hatcheries of spat on shell and seed oysters. To guide our scenario, we applied some initial research suggesting that epinephrine can increase survival by a factor of 3 - 4, with minimal added cost (pers. comm. T. Miller, University of Maryland). Direct injection of epinephrine in hatcheries is currently illegal in the U.S., but hatchery systems could be developed to mimic the effect using natural sources. Assuming that hatchery cost savings were passed on to producers via selling price of spat and seed oysters, we applied a 50% reduction to current selling prices from Horn Point Hatchery (2018).

Table 1. Policy scenarios examined

Policy Description	Baseline	Policy Change
1. Low price nitrogen credits. Additionality addressed in two different ways: a) All production above year zero b) New production only	No nutrient market	$10/lb payment per lb nitrogen sequestered.
2. High price nitrogen credits. Additionality addressed in two different ways: a) All production above year zero b) New production only	No nutrient market	$190/lb payment per lb nitrogen sequestered.
3. State fund to back aquaculture loans, allowing reduced loan rates.	Operating capital loan rate at 10%; Equipment loan rate at 7%	Discount capital loan rate to 7%; Discount equipment loan rate to 4%
4. Investment in research to reduce the effective cost of spat and seed oysters by increasing hatchery survival rates	Cost of spat at $3,500 per million; Cost of seed oysters at $17.00 per thousand	Costs reduced by 50%: spat at $1,750 per million; Cost of seed oysters at $8.50 per thousand

Production function model

Our goal of characterizing how economic incentives and nutrient payments might affect oyster aquaculture required estimating the costs of production for bottom culture and container culture. The production functions were intended to represent costs and revenues of an average firm but may not be representative of any particular operation. Operations differ in techniques used, degree of outsourcing, operator skill, and the proportion of product sold directly to restaurants or consumers vs seafood buyers, among other details that affect profits.

Numerous sources of information were used to build our versions of the aquaculture production functions: preliminary survey information of Maryland aquaculturists (Engle and van Senten, 2018), University of Maryland Extension information (Parker et al., 2016, 2013), Virginia Institute of Marine

Science research (Hudson et al., 2012), and expert judgement. Selected values used in the model and their sources are shown in Table 2. Some variables are omitted from Table 2 because data were provided as a courtesy but were unpublished at the time of writing (Engle and van Senten, 2018).

Table 2. Key budget items and sources

Bottom Culture		
Parameter	**Value**	**Source**
Price per bushel (2018 $)	50.00	Engle and van Senten (2018)
Price per half-shell (2018 $)	0.49	Engle and van Senten (2018)
% sold to bushel market	90%	M. Parker
% sold to half-shell market	10%	M. Parker
Production Level Unit: bushels/yr	2,000	Engle and van Senten (2018)
Spat needed (million)	3	Parker et al. (2013)
Spat cost (2018 $, per million)	3,500	Horn Point Hatchery (2018)
Labor needed per year	Supervisory: 1 FTE General Labor: 0 hrs	M. Parker
Labor cost (2018 $/hr)	Supervisory: $20.00 General Labor: $12.50	M. Parker
Interest on operating costs	10%	Engle and van Senten (2018)
Interest on capital expenditures	7%	Engle and van Senten (2018)
Other costs	Various	Various sources
Container Culture		
Key parameter	**Value**	**Source**
Price per bushel (2018 $)	50.00	Engle and van Senten (2018)
Price per oyster (2018 $)	0.49	Engle and van Senten (2018)
% sold to bushel market	95%	M. Parker
% sold to half-shell market	5%	M. Parker
Production Level Unit: oysters/yr	1,000,000	Engle and van Senten (2018) Parker et al. (2016)
Seed needed (million)	2	Parker et al. (2016)
Seed cost (2018 $, per thousand)	17.00	Horn Point Hatchery (2018)
Labor needed per year	Supervisory: 1 FTE General Labor: 9,920 hrs	Hudson et al. (2012) for total of 12,000 hrs needed
Labor cost (2018 $/hr)	Supervisory: $20.00 General Labor: $12.50	M. Parker
Interest on operating costs	10%	Engle and van Senten (2018)
Interest on capital expenditures	7%	Engle and van Senten (2018)
Other costs	Various	Various sources

The budgets were based on a production level of 2,000 bushels per year for bottom culture and 1 million oysters per year for container culture. We assumed that costs prepared for these production levels scaled linearly with size. We did not assume every operation had those levels of production, only that costs would be proportionate. For model simplicity, we omitted costs of running nursery operations, i.e., without remote setting for bottom culture, and without upwellers for container culture. Bottom culture growers were assumed to purchase <5mm diploid spat-on-shell, at bulk-order pricing comparable to Horn Point Hatchery (2018). Container culture operators were assumed to purchase 5-10mm triploid, disease resistant oyster seed at pricing comparable to Horn Point Hatchery (2018).

Upfront and recurring investments in equipment were a substantial cost for bottom and container culture operations. We simplified loan terms for capital costs by annualizing loan payments over the useful life of each line-item. For example, for a $20,000 pickup truck with useful life of 20 years, we calculated the yearly payment over a period of 20 years, with an interest rate of 7% to represent annual operating costs.

Our estimates of the production function model suggested that the single largest source of operating costs was labor for both bottom and container culture, although this will vary by operation. In addition, variable costs generally were much higher than fixed costs for both types of production (Figure 2). Besides labor, spat/seed, and interest on operating capital were the highest costs. Fixed costs were mainly in annualized capital payments (boats and trucks). However, the largest annualized equipment cost for bottom culture was bottom stabilization, and the largest annualized equipment cost for container culture was oyster cages.

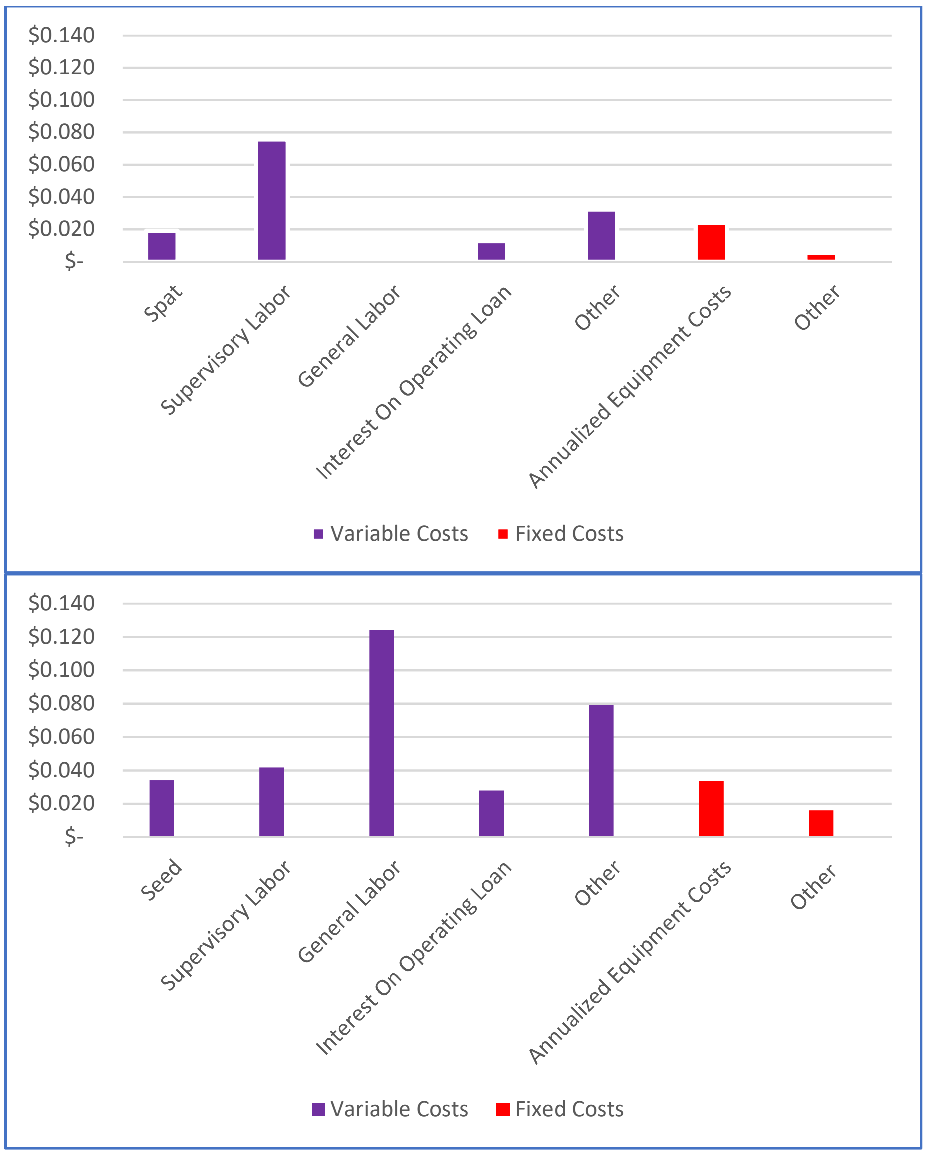

Figure 2. Bottom culture operating costs per oyster (top) and container culture operating costs per oyster (bottom)

Modeling industry growth based on profit

Economic theory suggests that any enterprise returning an economic profit will attract entry into the market. Simply put, the higher the profit, the higher the expected industry growth. The approach of using profits to estimate industry growth has a long history (Duetsch, 1975; Geroski, 1995; Orr, 1974; Peneder, 2008; Rosenbaum and Lamort, 1992; Scarpetta et al., 2002; Siegfried and Evans, 1994). The basic model of linear industry growth is summarized by Geroski (1995):

$$E = \beta(\pi^e - F) + \mu \quad (1)$$

Where E = entry or expansion metric (such as total production or number of firms), π^e = *expected post-entry profit*, F = *costs of entry*, β = fitted coefficient, and μ is an intercept. Authors have statistically estimated the β coefficient representing the rate of expansion using data on profits across industries, as reported in cross-sectional industry census data.

Theoretically, a model could be fit to estimate a comparable β coefficient for the Maryland oyster aquaculture industry, using time-series rather than cross-sectional data. However, few years of data are available. Further, evidence suggests that factors other than profit are needed to describe propensity to work in bottom culture vs. container culture. For example, many bottom culture aquaculture operations are run by watermen who also harvest wild oysters, presumably because the gear requirements and type of work are similar. Conversely, container culture industries include many entrepreneurs who have not worked in the wild oyster fishery.

Lacking data to conduct a robust regression, and desiring separate β coefficients for bottom culture and container culture, we opted for a reduced form model that omits costs of entry and the intercept term:

$$E_{type} = \beta_{type}(\pi^e_{type}) \quad (2)$$

where the E representing additional production of oysters per year, is a function of β_{type}, a measure of the strength of the profit motive, and is estimated separately for *type* of culture, bottom or container. By dropping the intercept, we imply that zero profit per unit operating cost invested would yield zero growth. Note that zero profit does not mean that producers do not make money, only that returns do not exceed their annual pay, set at the opportunity cost of their labor. The model is not intended to make predictions when π^e falls below zero.

The π^e variable is profit per unit operating cost and is calculated with:

$$\pi^e_{type} = (Revenue_{type} - Operating\ Costs_{type})/Operating\ Costs_{type} \quad (3)$$

where operating costs are the sum of fixed costs and variable costs per unit of production. Constructing the profit variable in this way measures profit per dollar invested, as opposed to a measure of profit per bushel or per oyster. This approach facilitates comparison of the profit motive β for bottom culture and container culture, to reflect clear differences in markets and production methods.

For simplicity, we assume constant returns to scale for both culture types, i.e. operating costs per unit of production as well as price received per oyster do not vary with the amount of oysters produced. Although economies of scale may occur, this simplification isolate the effect of a policy on the 'average' profit per dollar invested, rather than confounding multiple effects. With constant returns to scale, industry growth can be thought of as either expansion within existing operations or new entrants.

We calculated β_{type} directly using data on E_{type} and π^e_{type}. The entry rate was set to the average growth in oyster harvest per year from 2012-2017, for each culture. The profit variable was calculated from operating costs and price received, using the production functions previously described.

Parameters of the entry model calculations are shown in Table 3. The average recent net entry is higher for bottom culture, yet the π^e is smaller, resulting in a larger calculated β. This means that the same change to π^e_{bottom} and $\pi^e_{container}$ would produce a larger impact on bottom culture oysters produced than on container culture oysters produced. Put another way, bottom culture growers appear to be willing to work for lower economic profits than container culture growers. We utilize the β as calculated in Table 3 for the constant trend baseline. For the reduced growth baseline, we use the β calculated for container culture for both container culture and bottom culture, since investments in aquaculture may have still be adjusting to the apparent higher profits in container culture.

Table 3. Entry model values

Parameter	Value
E_{bottom} = Average net entry in Maryland bottom culture, oysters per year, 2012 to 2017	2,386,313
$E_{container}$ = Average net entry in Maryland container culture, bushels per year, 2012 to 2017	1,503,640
π^e_{bottom} = Bottom culture current profit (net revenue minus operating costs) divided by operating costs	0.259
$\pi^e_{container}$ = Container culture current profit (net revenue minus operating costs) divided by operating costs	0.332
β_{bottom} = Bottom culture coefficient on π^e	9.21 E+06
$\beta_{container}$ = Container culture coefficient on π^e	4.53 E+06

As a final note on the growth model, we modeled net entry, or the final difference between total new production minus outgoing production. The underlying data used to build the model were aggregated, i.e., the growth in production evident in Figure 1 did not specify how much production was lost from year to year, only the net gain. Consistent with our aggregated approach, we modeled firm entry in units of oysters, rather than in businesses. This masked individual firm behavior of business entry and exit. We did not conduct a subsequent survival analysis for the net entry in each year, but simply maintained all prior growth going forward. This was a relatively benign assumption if conditions remained favorable for growers, but could become problematic if long-term profits became negative, since we treated entry as a one-way door. We did not model scenarios of negative returns in this report.

Running scenarios in the production function and industry growth models

We extensively modified the production function models to track the effects of scenarios on production costs and prices received. Essentially, every policy changed one or more costs or prices in these spreadsheet models. These changes in turn affected profits by industry (π^e_{type}), thereby updating the dependent variable entry rate (E_{type}) through the relationship in Equation 2. The ultimate impact of a large variety of specific budget items (individually or in combination) on π^e_{type} and thus E_{type} could then be quantified. A dashboard was used to adjust multiple budget factors simultaneously, for example, nutrient credit price, spat price, loan rate, etc.

In order to see how impacts of a policy accrue over time, we ran the model for a 15-year timeline. With any entry or expansion, growers had a period of time in which they were making investments without harvest, while oysters grow to marketable size. This delay affected the timing of production and substantially affects profits. A policy incentive that affects production costs will take a few years to affect production levels or industry growth in our model, because of the time between oyster placement and harvest. We assumed it would take time to secure lease area for a new entrant or to expand an existing operation and to grow oysters, with a longer growing period assumed for bottom culture. Thus, impact of a policy implemented in year 1 would be seen in total production for model year 4 for bottom culture, and in model year 3 for container culture.

GIS analysis of available lease areas

Bottom culture is likely only economically feasible when conditions are favorable, as represented by locations with hard bottom, adequate salinity, and relatively shallow water for ease of access. Conversely, container culture is feasible over a broader range of bottom conditions, although user conflicts may be more severe with container culture since the floats are visible on the water surface, raising concerns of aesthetics and interference with boating. We explored whether space would likely be a constraint on either culture type, using a spatial (GIS) analysis (further described in Appendix B).

We estimated the suitable area of bottom, caged, and floating oyster aquaculture in the Maryland portion of the Chesapeake Bay (caged and floating culture being two types of container culture). We identified suitable areas for aquaculture by considering appropriate growing conditions, legal limitations on leasable areas, and logistical factors that would limit locations of aquaculture businesses. We gathered spatially georeferenced data (GIS shapefiles) from various resources, including the Maryland GIS Data Catalog (iMap), and the Virginia Institute of Marine Science (VIMS) to evaluate suitability conditions.

Our analysis was modeled after the Carlozo (2014) report that analyzed established areas of opportunity for bottom, caged, and floating culture aquaculture using available spatial data. We replicated that analysis to a large degree but chose conditions most suitable for aquaculture to narrow the analysis to prime locations. We used many of the same variables to define the most suitable oyster production areas as Carlozo (2014) (Appendix Table B1). Criteria included environmental parameters and legal restrictions to avoid artificial reef initiative sites, oyster harvest reserve areas, historic oyster bottom, historic and cultural recreational use areas, 5-year SAV presence data and excluded the entire Potomac River mainstem. We also eliminated active fishing areas from consideration including active pound net sites, public shellfishery areas, and oyster plantings.

Our analysis differed from Carlozo's by picking ranges of environmental conditions to identify the most suitable aquaculture areas rather than all potential areas. A primary difference in our analysis was that we used a narrower range of salinity (8-25 ppt compared to 5-25 ppt in Carlozo's General Targeting Results) as a limiting factor. Although oyster aquaculture is possible in salinities greater than 5 ppt, a greater threshold for salinity can produced preferred conditions for prime oyster growth (Carlozo, 2014). Further, we used a shallower depth range for bottom and cage on bottom culture of 0-3 meters but retained the 0-8 m (0-25' in Carlozo) for floating culture (anecdotal information and inspection of leased areas within the VIMS VA Oyster Lease Siting Tool). We also choose different bottom types by including cultch, hard bottom, mud with cultch, and sand with cultch as the bottom types most suitable for bottom and caged culture and an unrestricted bottom type most suitable for floating culture, based on work by Webster and Meritt (1988).

An additional difference between this analysis and that of Carlozo (2014) is that we did not include data on dissolved oxygen, temperature and bacteria. We acknowledge the importance of these criteria, but oxygen and temperature fluctuate to a large degree and are changing as progress is made on the Total Maximum Daily Load for the Chesapeake Bay. Bacteria conditions are a severe limitation and more likely to be persistent problems, but we could not obtain spatial data on areas of bacteria concentration.

The results of our analysis to find the combination of conditions best suited for aquaculture suggest that substantial areas are suitable for bottom and container culture in the Chesapeake Bay, but the area of prime conditions is constrained (Table 4). Options are spread throughout the Bay mainstem for bottom and container culture (Figure 3). The total area identified for production is smaller than Carlozo's because of the different choices we made regarding suitability of salinity zones and bottom type. Area for bottom culture and cage on bottom culture was calculated in total as 42,800 acres (Table 4) while Carlozo calculated 81,170 acres. We calculated 103,710 acres for floating culture (or 89,150 acres if production is sensitive to bottom type) compared to 432,490 acres by Carlozo. The amount of productive area is sensitive to which bottom type is considered suitable for production (Appendix B, Table B2 and B3).

Table 4. Suitable aquaculture production area estimates for the Maryland portion of the Chesapeake Bay by oyster aquaculture type.

Type of Oyster Aquaculture	Salinity Range	Depth Range (meters)	Bottom Culture Type	Area (ha)	Area (acres)
Floating Culture	8-25	0-8	No restrictions.	41,970	103,710
			Only Cultch, Hard Bottom, Mud With Cultch & Sand With Cultch.	36,080	89,150
Bottom & Cage on Bottom Culture	8-25	0-3	Only Cultch, Hard Bottom, Mud With Cultch & Sand With Cultch.	17,320	42,800

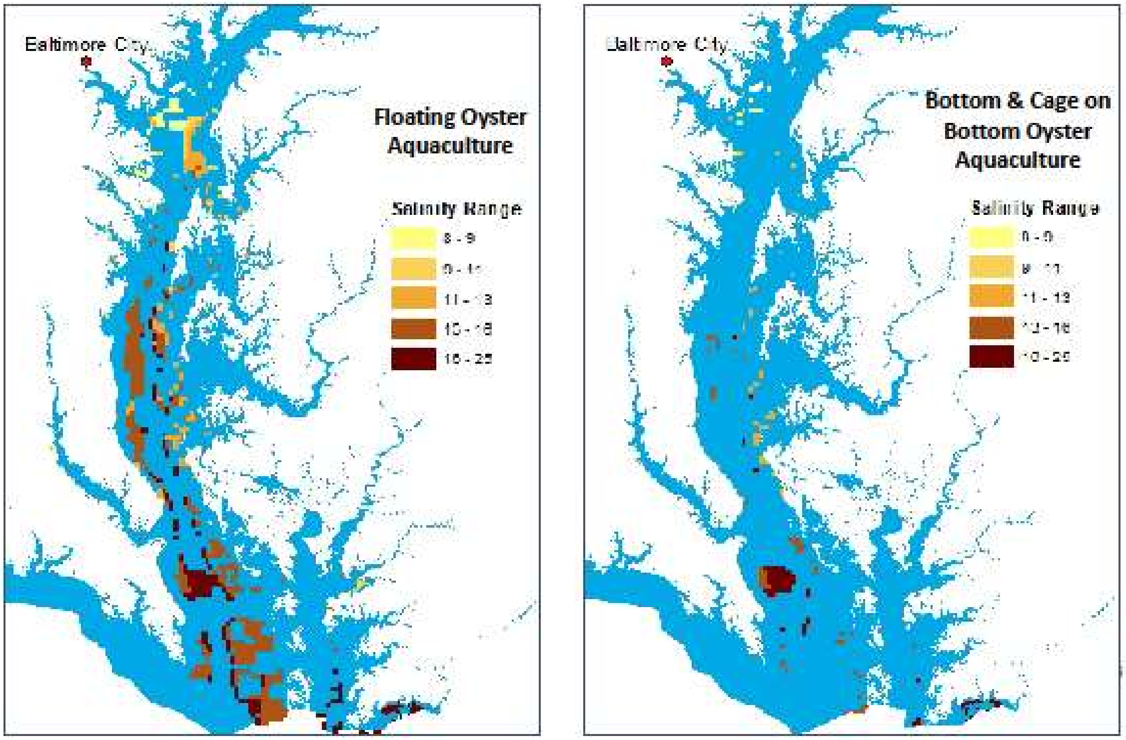

Figure 3. Potential suitable areas for different types of aquaculture by salinity zone in the Maryland portion of the Chesapeake Bay.
Results of a spatial analysis to evaluate areas with the most suitable habitat conditions and no legal restrictions on leases. Areas have not been screened for economic feasibility criteria, such as distance to commercial ports. Many of the data layers used for GIS analysis were developed prior to 2003 and may be out of date; some data layers did not cover the full area of the Chesapeake Bay. Therefore, maps are not necessarily accurate at fine scales and may omit suitable sites in tributaries.

Results & Discussion

Our GIS analysis indicated that space was not likely to be limiting for either bottom culture or container culture over the 15 year modeled timeline. We found that existing operations had a relatively small footprint compared to the space available. However, our results were dependent on relatively old data and conditions on the ground may not be as favorable as suggested by static maps that do not reflect daily or seasonal variability. Nonetheless, we used these results to eliminate the need to incorporate space constraints on future growth.

For all scenarios, we compared production to the two alternative estimates of baseline growth to generate an estimate of the change in production due to the policy scenario. We used several performance metrics to compare scenarios including relative production in bottom vs. container culture, market sales, profits, jobs, and nitrogen sequestered. Since industry growth (or net entry) was driven by profit, the results depended on the relative effect of policies on costs and revenues.

Scenario Comparisons

Results for bottom culture varied substantially for the two baseline trends that we examined and we first discuss results under the *constant trend* baseline. Policy scenarios produced a range of two orders of magnitude difference in the percentage of baseline growth by the end of the 15-yr modeled timeline (Table 5). The scenario with the largest incentive for growth was Scenario 2a, the $190/lb nitrogen credit price with Additionality A (payments for all production above a base year). In this scenario, annual production grew by 59% for bottom and container culture combined, over baseline at year 15 (almost 35 million more oysters/yr). This growth was far more than the 3.1% additional oysters/yr at year 15 that occurred with the low credit price of $10/lb in Scenario 1a (1.8 million more oysters/yr) (Figure 4). For perspective on the size of the price effect, the $10/lb credit price (Scenario 1) increased the price per bushel by $0.55 (or an additional $0.0020 per oyster), and increased the half-shell price by $0.0029 per oyster. The $190/lb credit price (Scenario 2) increased the price per bushel by $10.37 (or an additional $0.038 per oyster), and increased the half-shell price by $0.054 per oyster.

The effect of additionality rules was striking. While Scenario 2a (high price credits, all production eligible for credits) produced the largest effect on production and profits, Scenario 2b (with Additionality B of only new annual production eligible for credit) was one of the least influential policies (Table 5). Similarly, Scenario 1b (low credit price with Additionality B) barely registered a difference from baseline at a 0.4% increase (0.2 million more oysters/yr) over baseline at year 15. The two extremes of credit price and the large differences in outcome suggested that the industry could be induced to grow in response to a credit market, if prices were large enough and if additionality was measured relative to a specific year rather than requiring constant new growth.

The second largest effect on industry growth was Scenario 4 (50% reduction in spat and seed costs). This scenario generated a 23% increase in oysters/yr over the baseline at year 15 (13.6 million more oysters/yr), mostly in bottom culture. Scenario 3, reduction in loan rates, also had a significant impact, with a 15% increase in oysters/yr over the baseline at year 15 (8.4 million more oysters/yr).

Similar to the effects on production, the impacts on sales and profits were highest for Scenario 2b, but they increased at a higher percentage than production since they generated a 75% increase in sales and a 188% increase in profits, above baseline, at year 15. The profit estimates assumed that net entry (as estimated from equation 2) did not include significant firm exit from the industry. In other words, industry profit was reduced when firms entered the industry but exited the market before harvesting. However, this effect was not represented in the model because we did not have data on exit during startup to estimate this effect. Further, although the model represented the lag between initial costs and revenues due to harvest, we did not have data on startup labor costs and therefore used operating labor costs to inform estimates of the startup period.

The public return on investment in any given policy incentives can be characterized by the number of jobs created and the amount of nitrogen removed from waterbodies, since these outcomes represent goals for economic development and Chesapeake Bay restoration. Jobs and nitrogen removal were correlated with oyster production, therefore, results were similar to results for change in production. For bottom culture, Scenario 2a resulted in the largest increase in jobs at 50% (98 more jobs/yr) and nitrogen removal at 59% (6,900 more lbs/yr) above baseline. Scenarios 3 and 4 also produced respectable job increases of 14% and 22%, and nitrogen reductions of 15% and 23% (Table 5).

Table 5. Policy scenario results showing percentage change from *constant trend* baseline at year 15

	Production (Oysters/yr)	Sales (2018$/yr)	Profits (2018$/yr)	Jobs (FTE/yr)	N sequestered (lbs N/yr)
Bottom Culture					
Baseline Annual Total (yr 15)	35,794,688	7,611,252	704,134	65.1	7,102
% Changes from Baseline at year 15					
Scenario 1a: Low Price Credits, Additionality A	3.8%	4.8%	13.6%	3.8%	3.8%
Scenario 1b: Low Price Credits, Additionality B	0.4%	0.5%	1.3%	0.3%	0.4%
Scenario 2a: High Price Credits, Additionality A	72.0%	103.8%	394.1%	71.9%	72.0%
Scenario 2b: High Price Credits, Additionality B	7.2%	9.2%	26.4%	7.2%	7.2%
Scenario 3: Reduce Loan Rates	15.8%	15.8%	56.2%	15.8%	15.8%
Scenario 4: Hatchery Production	25.8%	25.8%	94.4%	25.8%	25.8%
Container Culture					
Baseline Annual Total (yr 15)	22,554,593	10,704,205	2,082,180	130.1	4,475
% Changes from Baseline at year 15					
Scenario 1a: Low Price Credits, Additionality A	2.1%	2.7%	5.1%	2.1%	2.1%
Scenario 1b: Low Price Credits, Additionality B	0.2%	0.3%	0.5%	0.2%	0.2%
Scenario 2a: High Price Credits, Additionality A	39.3%	55.0%	118.5%	39.3%	39.3%
Scenario 2b: High Price Credits, Additionality B	3.9%	5.1%	9.8%	3.9%	3.9%
Scenario 3: Reduce Loan Rates	12.4%	12.4%	28.0%	12.4%	12.4%
Scenario 4: Hatchery Production	19.3%	19.3%	44.2%	19.3%	19.3%
Bottom Culture & Container Culture Combined					
Baseline Annual Total (yr 15)	58,349,281	18,315,457	2,786,314	195.2	11,577
% Changes from Baseline at year 15					
Scenario 1a: Low Price Credits, Additionality A	3.1%	3.6%	7.2%	2.7%	3.1%
Scenario 1b: Low Price Credits, Additionality B	0.3%	0.4%	0.7%	0.3%	0.3%
Scenario 2a: High Price Credits, Additionality A	59.3%	75.3%	188.1%	50.2%	59.3%
Scenario 2b: High Price Credits, Additionality B	5.9%	6.8%	14.0%	5.0%	5.9%
Scenario 3: Reduce Loan Rates	14.5%	13.8%	35.2%	13.5%	14.5%
Scenario 4: Hatchery Production	23.3%	22.0%	56.9%	21.5%	23.3%

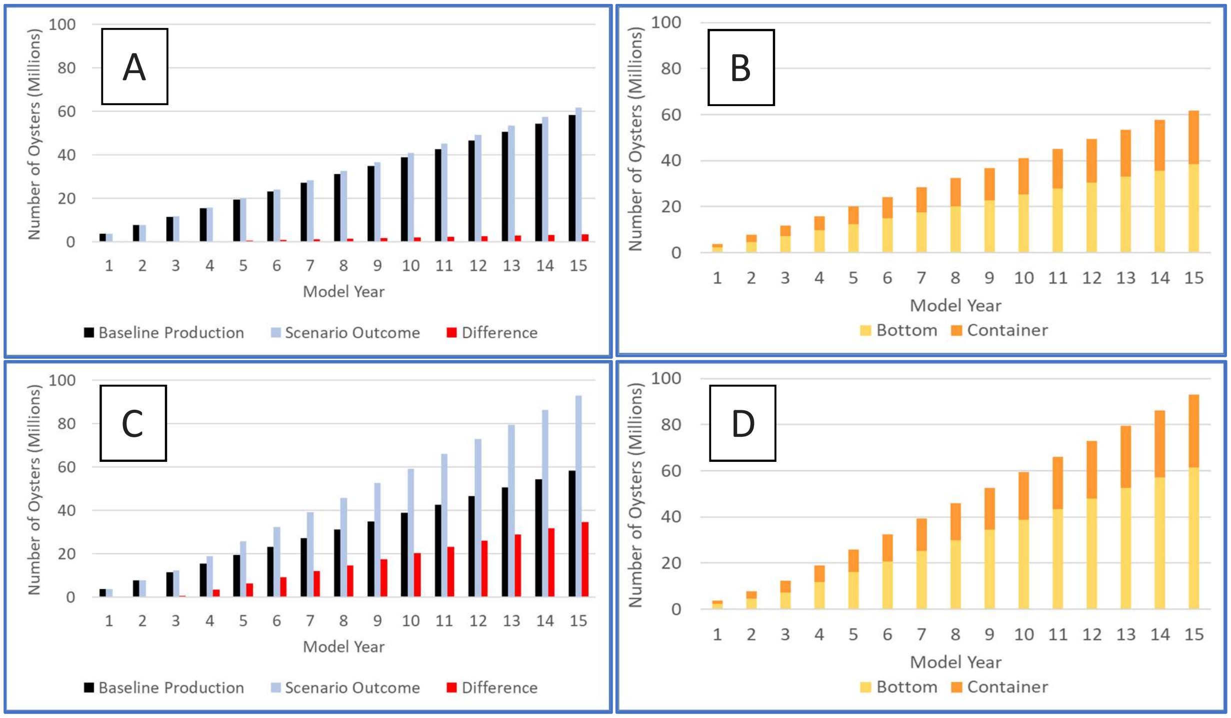

Figure 4. Effects on oyster production of Scenario 1a (low nutrient credit price, panels A and B) and Scenario 2a (high nutrient credit price, panels C and D) by model year. *In both scenarios pictured, all new growth receives the credit payment in perpetuity (Additionality A) and baseline growth reflects the historic trend. The low credit price is $10/lb nitrogen (Scenario 1a) and the high price is $190/lb (Scenario 2a). Panels A and C show growth relative to baseline growth and include a delay before policy impacts on production occur (red bars). Panels B and D show the breakdown of all new growth into bottom and container culture.*

The effect of changing to the reduced growth baseline dramatically reduced growth in bottom culture over 15 years, and likewise greatly reduced total industry growth. Total new growth at 15 years was 58.3 million oysters/yr (roughly 212,000 bushels) under the constant trend baseline (Table 5), and 40.2 million oysters/yr under the reduced growth baseline (Table 6), a decrease of over 30%. Scenarios also showed reduced response in terms of bottom culture entry. Percentage increases for bottom culture were the same in Table 5 and Table 6, since the effect of each policy on profit and entry changed proportionately, by using a different *β* coefficient (see Equation 2). However, scenario percentage impacts for bottom culture and container culture combined were markedly lower in Table 6 (lower half) as compared with Table 5 (lower third). Scenario 4, for example, showed a total effect of 15% increase in production after 15 years (Table 6), while with the constant baseline had a 23% impact (Table 5). Under the reduced growth baseline and the revised effect of Scenario 4, container growth slightly outpaces bottom culture growth (Figure 5), in contrast to the *constant trend* baseline (Figure 1).

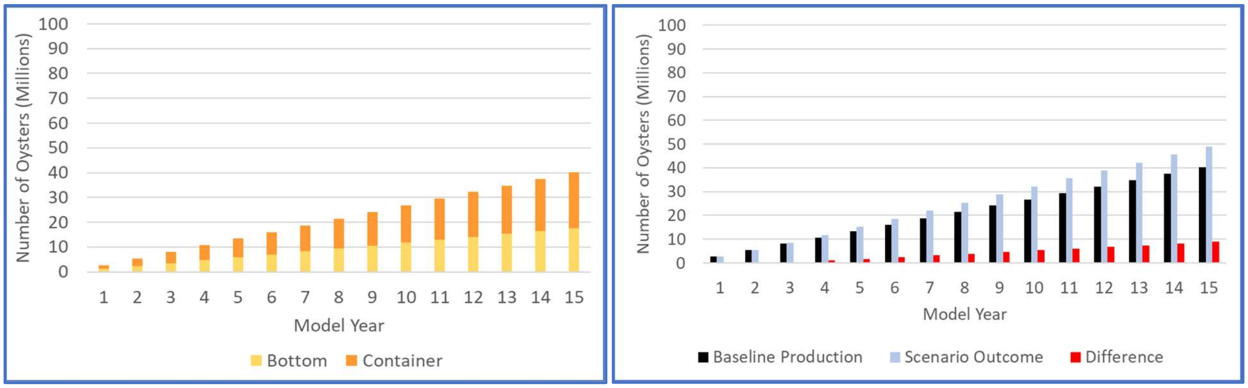

Figure 5. Effects on oyster production of Scenario 4 (increased hatchery productivity) with reduced growth baseline for bottom culture by model year. *The left panel shows the breakdown of bottom culture and container culture. The right panel shows oyster production.*

Table 6. Policy scenario results showing percentage change from *reduced growth* baseline at year 15

	Production (Oysters/yr)	Sales (2018$/yr)	Profits (2018$/yr)	Jobs (FTE/yr)	N Sequestered (lbs N/yr)
Bottom Culture					
Baseline Annual Total (yr 15)	17,608,439	3,744,194	346,384	32.0	4,475
% Changes from Baseline at year 15					
Scenario 1a: Low Price Credits, Additionality A	3.8%	4.8%	13.6%	3.8%	3.0%
Scenario 1b: Low Price Credits, Additionality B	0.4%	0.5%	1.3%	0.4%	0.3%
Scenario 2a: High Price Credits, Additionality A	72.0%	103.8%	394.1%	72.0%	56.2%
Scenario 2b: High Price Credits, Additionality B	7.2%	9.2%	26.4%	7.2%	5.6%
Scenario 3: Reduce Loan Rates	15.8%	15.8%	56.2%	15.8%	12.3%
Scenario 4: Hatchery Production	25.8%	25.8%	94.4%	25.8%	20.1%
Bottom Culture & Container Culture Combined					
Baseline Annual Total (yr 15)	40,163,032	14,448,399	2,428,564	162.1	8,950
% Changes from Baseline at year 15					
Scenario 1a: Low Price Credits, Additionality A	1.9%	2.5%	5.5%	2.0%	1.9%
Scenario 1b: Low Price Credits, Additionality B	0.2%	0.3%	0.5%	0.2%	0.2%
Scenario 2a: High Price Credits, Additionality A	36.9%	53.4%	137.5%	38.0%	36.9%
Scenario 2b: High Price Credits, Additionality B	3.7%	4.9%	10.6%	3.8%	3.7%
Scenario 3: Reduce Loan Rates	9.5%	10.5%	27.9%	10.8%	9.5%
Scenario 4: Hatchery Production	15.2%	16.5%	44.8%	17.1%	15.2%

Nutrient Credit price effects

With few observable nutrient credit prices, it is difficult to predict what price might be offered for nitrogen credits, if a market were to develop. Our analysis showed dramatic differences in industry growth using two end-member credit prices but it is useful to consider what range of credit prices could have a substantial effect on the industry. If we allow credit price to vary between $0 and $200/lb nitrogen, we project that annual oyster production at year 15 increases linearly with price and diverges from the baseline growth (Figure 6). From the graph, we see that the credit price has to be relatively large to add a significant additional percentage of oyster production or nitrogen sequestration, as compared to the baseline rate at year 15. A price of $160/lb is needed to achieve 50% growth above baseline for container and bottom culture combined.

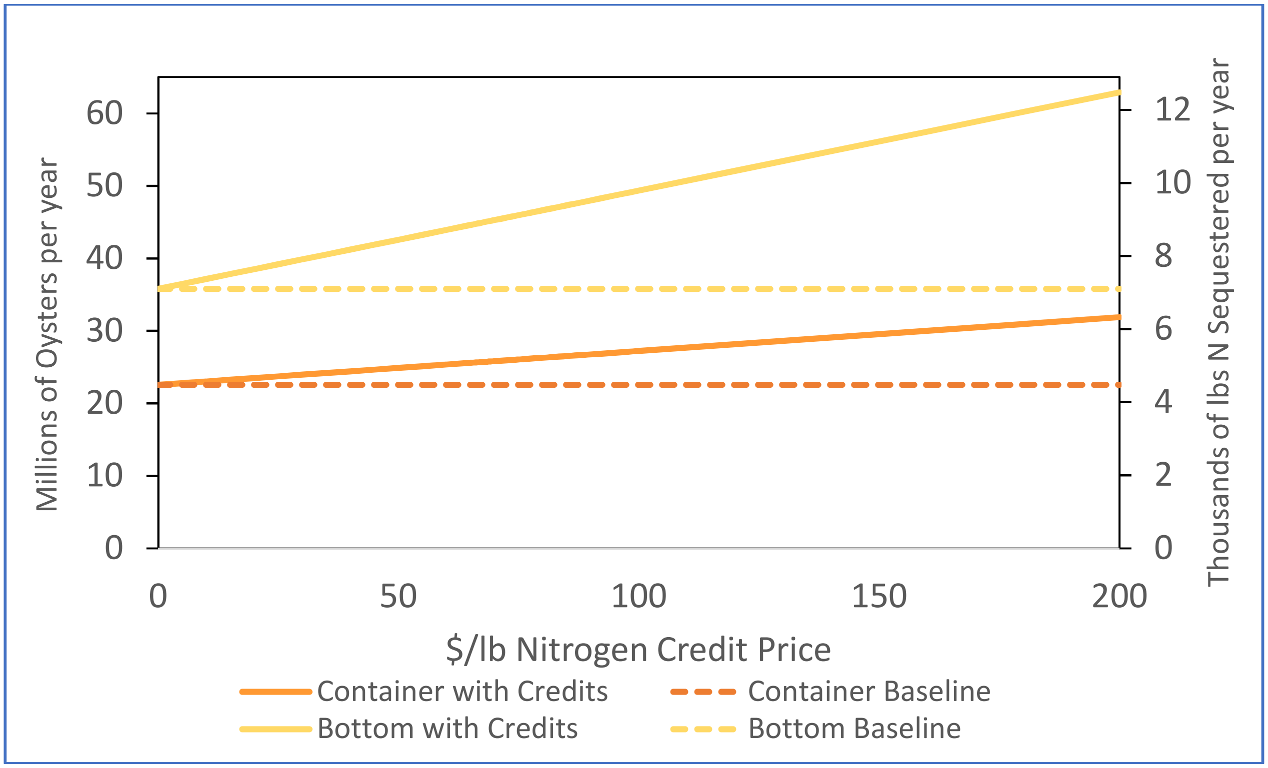

Figure 6. Effect of credit price on total new oyster production and nitrogen sequestration at year 15 by credit price. *Prices are for Additionality A rules. For Additionality B rules, divide prices by 10. Dashed lines show constant trend baseline conditions.*

Effect of potential half-shell market saturation on container culture

Earlier we tested the impact of an alternative baseline for bottom culture. Here we investigate the possibility of market saturation in the half-shell market that would primarily impact container culture via reduced prices. Price damping might also occur in the shucked market due to market saturation in the shucked market. However, the effects of market saturation (e.g., due to harvest exceeding capacity at the shucking houses) on the shucked market would be similar the reduced growth baseline and therefore, this analysis is only for the half shell market. Half shell market saturation will also affect bottom culture since they sell a small percentage of production to the half shell market, but we ignore those effects here.

Currently, there is no evidence that growers are having trouble selling half-shell oysters. Container culture grew more than 25% between 2016 and 2017 (Figure 1), while the population growth rate in Maryland and Virginia is closer to 1%. Continuing the current upward trend of half-shell oyster sales depends on there either being currently unmet demand, significantly increased demand per capita in the region in the future, or relatively low-cost shipping to other markets.

Despite recent growth, the effect of increased oyster production on prices as the aquaculture industry matures is highly uncertain. Data collected by the Maryland Department of Natural Resources on the public oyster fishery suggest that annual average price is fairly inelastic with respect to annual total supply (C. Hayes, pers comm). However, much of the wild harvest goes to the shucked oyster market, which may have different dynamics than the aquaculture industry that supports the half shell market. Half shell oysters are distributed throughout the US and thus, sellers have opportunities to expand beyond the local market as production increases. However, if aquaculture is also growing in other areas, the half shell market could become more competitive, depressing prices.

If prices did decrease as production increases, public or private investments could assist growers in distributing their product more broadly to counteract market saturation. For example, machines that automate shucking and shrink-wrapping could facilitate sales to restaurants without raw bars or directly to consumers in markets, thereby expanding the pool of buyers. Other types of support might be offered to expand markets, such as specialized branding campaigns or alternative transportation infrastructure.

To test the effect of such an investment, we first modified our original model to represent market saturation condition. The original model was parameterized with best professional judgment so that container culture growers sold 95% of their harvest to the half-shell market. To model market saturation, we modified price received over time to be the equivalent of 75% harvest going to the half-shell market by year 15.

When we compared the newly formulated market saturation baseline against the original baseline for container culture, we found that even when reducing the effective proportion sold to the half-shell market by 20 percentage points, container culture still showed strong growth (Table 7; top row). A slight convex shape was observed in the industry growth trend as prices per oyster harvested decreased over time for container culture (Figure 7, left panel). As compared with the original industry baseline of 58.3 million oysters/yr (Table 5), the baseline would now be 52.1 million oysters/yr, a decrease of about 10%. Nonetheless, using investments to bring production up to the constant growth baseline would represent a large jump for container culture, the equivalent of a 38% increase in production at year 15, and a 213% increase in profits (Table 7). The 38% increase would bring container culture production back up to the 22.5 million oysters per year baseline level (shown in Table 5).

Table 7. Market saturation affecting container culture, counteracted by market expansion policies

	Production (Oysters/yr)	Sales (2018$/yr)	Profits (2018$/yr)	Jobs (FTE/yr)	Nutrients Sequestered (lbs N/yr)
Container Culture					
Baseline Annual Total at year 15	16,319,477	6,739,356	664,644	94.2	3,238
% Change from Baseline at year 15					
Market Expansion Measures	38.2%	58.8%	213.3%	38.2%	38.2%

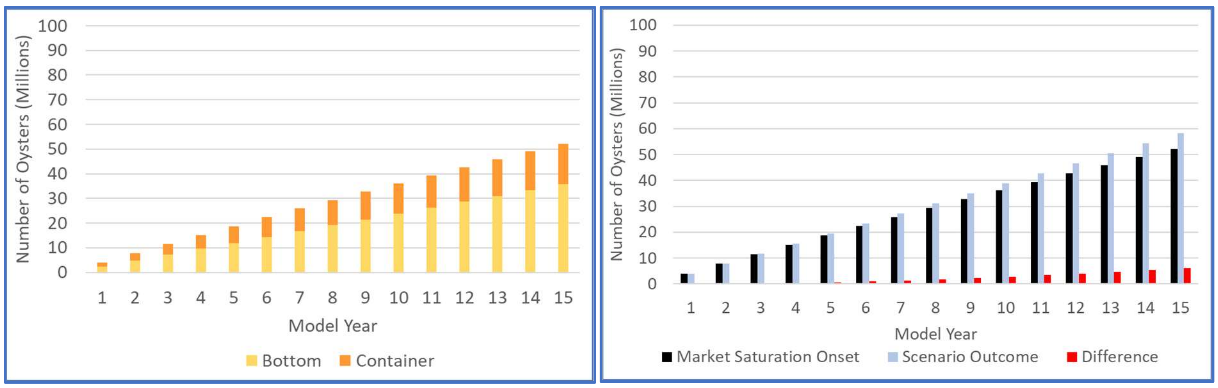

Figure 7. Oyster production in response to market saturation baseline (left) and with market expansion policy impact (right) by year. *The impact of market expansion tactics to counteract market saturation for the half shell market.*

Sensitivity analysis of profits to costs of production and prices received

The scenario analysis provides insights into selected policies but a sensitivity analysis provides insights into which types of interventions are most likely to affect profits and growth in the industry. We tested sensitivity of profits in bottom and container production to various budget factors, as shown in Figure 8. These profit variables (π^e from equation 2) can be thought of as proxies for net revenue in bottom and container culture. All items on the x-axis are changed in a direction to favor increased entry. The changes are either an increase or decrease of 1%.

The sensitivity analysis showed that profits shifted the most in response to a change in selling price (Figure 8). In addition, the percentage of harvest going to the half shell market had a similar effect as price on container profit, since half shell prices were much higher than shucked market prices. Container producers sell to the shucked market as a fallback when half shell market demand is low, among other reasons, but a shift to the shucked market has a relatively large effect on profits.

Decreases in variable costs more strongly affected profits than decreases in fixed costs, reflecting their relative effect on annual costs. The model used annualized fixed costs, which effectively distributed the effects of large purchases over many years. Therefore, variable costs made up the majority of annual costs. Decreases in labor cost/hr had the largest effect on profit of any individual variable cost, since labor was the largest component of variable costs in the model. Profit was also sensitive to spat and seed costs, but the effect was much lower than for labor.

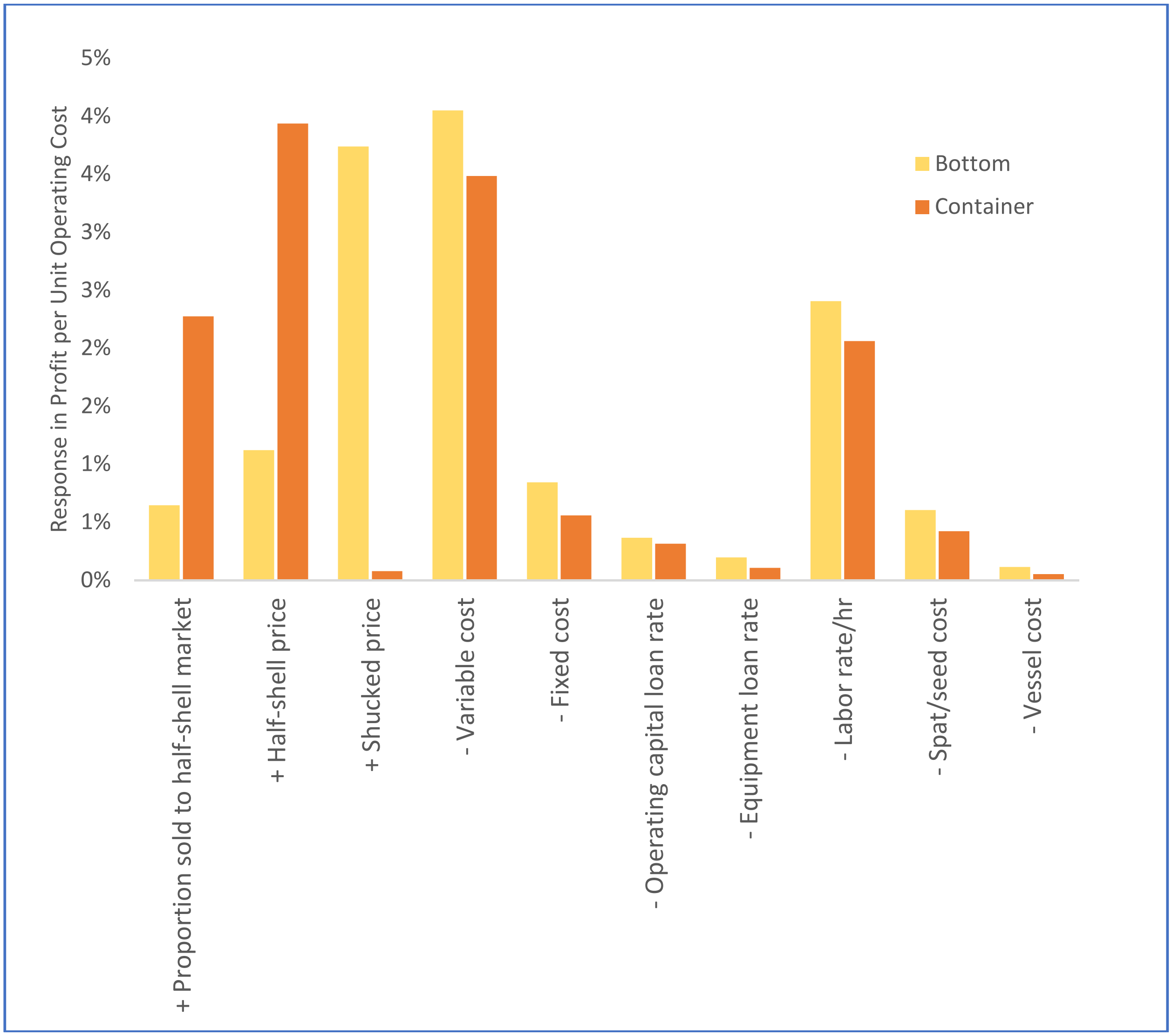

Figure 8. Sensitivity of profit per unit operating cost (π^e) to 1% changes in production function inputs

Conclusions

Our model of firm entry into bottom or container culture showed that a variety of policy scenarios could make a significant impact on the Maryland oyster aquaculture industry by the end of the modeled 15-year timeline, even though the industry is already growing rapidly. Among scenarios tested, nutrient credit trading demonstrated a strong potential to affect growth, increase jobs and remove nitrogen from waterbodies, but results depended strongly on nutrient credit price and additionality rules. Nutrient credit trading impacts varied from the maximum effect of 59% increased growth over baseline in Scenario 2a (high credit price, liberal additionality rules) with a $190/lb price, to the minimal effect of <1% increased growth of Scenario 1b (low credit price and strict additionality rules). These two prices bound a large span of nutrient credit prices and our analysis of response to price suggests that a credit price of $160 would be needed to generate a 50% boost over baseline production, for bottom and container combined.

The importance of credit price for inducing growth is intuitive, but the tremendous influence of additionality rules is less obvious. Essentially, the more liberal additionality rule (Additionality A) creates payments for all harvests and thus adds more years of credit price premiums that a grower could receive, effectively multiplying the price effect over time. The more stringent rule of only allowing new production to be eligible to trade credits (Additionality B) creates payments for the first year of harvest in new areas only. This major difference in firm income yields an order of magnitude difference in growth under the same credit price, as shown by the 59% increase for Scenario 2a compared to 6% increase for Scenario 2b. Neither additionality rule mimics the cost-effective ideal of only allowing credits to be sold for the new growth that would not have occurred without the credit payment. However, such a rule is likely to be impractical to apply. Any estimate of baseline expansion in production that would be used to differentiate incentivized growth would be subject to high error, given the many factors that potentially influence growth in production, which include weather conditions.

Of the policy scenarios other than nutrient credit trading, investing in hatchery research to increase efficiency and reduce the cost of spat and seed (Scenario 4) had the next highest impact, increasing growth 23% above baseline. It appears that production in the state-run hatchery has been supplemented by private efforts, as evidenced by growers running nursery operations on their own, including remote setting tanks for bottom culture, and upwellers for container culture. Since cost of spat on shell or seed oysters is a relatively large input cost, any investment that reduces that cost will influence profits and industry growth. Improved hatchery survival will also improve reliability of supply.

The next largest increase in industry growth of 15% was generated under a scenario in which growers used reduced rate loans (Scenario 3). This scenario was a simple reduction in commercial loan rates and did not include other conditions such as principal forgiveness, as provided by some MARBIDCO loans. If container culture growth is to be sustained, a great deal of new equipment will need to be purchased. Loan rates are also used to cover operating costs in businesses, such as payroll, which is the single biggest cost for either type of culture. Thus, a mature industry would be expected to need access to capital and lower loan rates, which would enable higher profits and growth.

Although bottom and container culture differed in their production functions, all scenarios tended to increase growth for both types and only the magnitude of impacts varied. For example, under the constant trend baseline, research investments that reduced costs of hatchery products had a larger effect (26% increase) on bottom culture than on container culture (19% increase) due primarily to the larger proportion of costs represented by these inputs. A similarity across scenarios was that the percentage increases in profits were always higher than percentage increases in growth. For example, Scenario 2a increased profits by 188% over baseline, more than three times as high as the percentage increase in growth. These magnified effects on profits suggest that even policies having small impacts on production can offer important increased financial viability to the industry.

In terms of public returns of investments, the scenarios showed the potential for policies to encourage job creation and nitrogen removal from waterbodies, to support goals for economic development and Chesapeake Bay restoration. Increases in nutrient reductions were increased proportionally to production, reflecting the linear relationship between oysters produced and nutrient reductions per oyster harvested. Jobs, measured as full time equivalents (FTEs), also increase linearly with total production.

Our results depended strongly on assumptions used to project the growth rate under no changes in policy and revealed some potential differences in the drivers of growth between bottom and container culture. We used two baselines to compare policy effects. The first was a simple baseline in which we projected a trend of current growth for both bottom and container culture. The second baseline addressed our finding that bottom culture grew in response to lower levels of profit than container culture. When we forced future growth in bottom culture to be as sensitive to profit as container culture, bottom culture growth declined substantially. Note that this projection is subject to error if we have overestimated costs to bottom culture and thus underestimated profits. However, declining growth in bottom culture could result from multiple causes such as reduced availability of productive bottom or lack of capacity at shucking houses, making the baseline useful, regardless of whether our specific rationale for the decline was accurate.

When we applied the reduced growth baseline for bottom culture, policies had the same percentage increase on bottom culture output, but since the absolute value of production in the baseline was lower, growth above baseline was also lower. When we explored the potential for reduced growth in container culture due to half-shell market saturation, growth above baseline dropped by more than one-third. This finding illustrates the reliance of container culture on the higher-priced half-shell market to create profits, and the need to expand markets if aquaculture growth continues to outpace population growth in the region.

Although we used a wide variety of data and information sources, our results are conditional on numerous assumptions and data that may not fully represent the scope of industry conditions. Therefore, results should be viewed only as possible futures that may not be realized unless multiple policies and conditions align. A particularly strong assumption was that a robust nutrient credit market would develop, in order to deliver the growth estimated in scenarios 1 and 2. This assumption is not consistent with current conditions of “thin” nutrient credit markets that have only a limited number of buyers and sellers. Nutrient credit trading markets have not generated a large volume of credits bought and sold, and most trades have been among point sources rather than between point and nonpoint sources (US GAO 2017).

If a market to facilitate bi-lateral trading does not develop, nitrogen credits from aquaculture could be cost competitive, if some form of administered trading were used. If the state decided to meet any nutrient reduction shortfalls through a centralized bidding program, nitrogen reduction credits from aquaculture could be provided. The cost would be well below the cost per pound of nitrogen reducing projects that had been proposed by counties in the past, assuming that liberal additionality rules were applied.

Another strong assumption was that firms would stay in the industry despite 4-5 year lag times between initial investment and multiple consecutive years of no profits. Because the industry is relatively new in Maryland, little data on firm exit or consolidation were available to inform this dynamic. If firms have low ability to weather years with no profits, then it will tend to reduce growth, given the dynamics we found while developing the model.

Future growth modeling work could benefit from incorporating a comprehensive survey of current industry conditions and more fully modeling market dynamics and feedbacks. Aquaculture markets are affected by activity around the US and the world. It would be helpful to consider the Chesapeake Bay market share and capacity for product differentiation to better understand future growth potential for the local industry. The model could also incorporate further detail on variability among producers, including aquaculture budgets, any economies of scale, and variety of prices received, as such information becomes available.

Our work to develop the industry growth model suggested that profits rather than any element of the supply chain were the primary limits to growth in the short-term. A spatial analysis suggested that leasable area under current rules was sufficient to support substantial additional growth under current regulations, although the analysis was not comprehensive in terms of including all factors that producers might include in picking economically viable locations. In addition, key informants stated that they had found alternative sources for seed oysters to overcome supply constraints from the state-sponsored hatchery and some producers were creating their own spat on shell from larvae. As a result, our work suggests that short-term future growth can largely be supported by policies that reduce costs or increase prices, while long-term growth may depend on developing comprehensive strategies to prevent local market saturation in the half-shell market or limited capacity at shucking houses.

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Appendix A. Estimates of potential willingness to pay for nitrogen credits in Maryland

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We conducted an in-depth analysis of the costs of meeting nitrogen reductions required for the Chesapeake Bay Total Maximum Daily Load (TMDL) for two counties in Maryland to quantify potential willingness to pay for nutrient credits. We used the Phase II Watershed Implementation Plans (WIPs) for two representative counties that border the Chesapeake Bay mainstem, as the basis for this analysis. WIPs developed under Phase II of the TMDL planning specified the amounts of various practices that would be used to achieve a nutrient cap that had been assigned to the county. This analysis only addresses the potential costs of nutrient reductions and not whether a nutrient credit trading market is likely to develop.

Chesapeake Bay policy conditions affecting cost analysis

The costs of nutrient reductions are not absolutely fixed because they are influenced by the policies, regulations and rules that are embedded in the strategy to achieve the TMDL (Wainger, 2012). Because policies influence costs, our analysis is sensitive to details of the rules in place at the time that the WIPs were developed. In Maryland, counties were given individual reduction caps, allocated by source sector (wastewater, urban, agricultural). Counties responded by creating a proposed set of practices for meeting those reduction targets by source sector, without considering moving reductions among source sectors or Maryland counties. Any changes in the nutrient cap or sector allocations assigned to the county for the upcoming Phase III WIPs will change costs of implementation. Specifically, the lower the cap (the larger the reduction goal), the higher the unit costs. Also, the greater the reduction requirement within the stormwater sector, the higher the average and total costs of implemented practices (Wainger et al., 2013).

Cost Analysis Methods

Our analysis evaluated costs for nonpoint source (NPS) nutrient reduction projects from urban and agricultural sectors that had potential to compete with credits generated by oyster aquaculture. We use the term *practice* to refer to any agricultural best management practice (BMP) or stormwater project. However, the point source (PS) wastewater sector, which was not included here, has the potential to generate low cost credits that could compete with NPS project, as discussed in the main report. We evaluated practices used in the WIPs for Talbot and Dorchester counties (Lackie et al., 2012; Talbot County, 2011). Because these counties border the Chesapeake Bay mainstem, we assumed the nutrient reductions within the counties would require only minimal adjustment to be considered equivalent to aquaculture in adjacent waters. Costs for these counties will be largely representative of projects in counties that border the Chesapeake Bay.

We restrict our cost analysis to nitrogen (N) reductions because this is the only nutrient currently approved for trading in aquaculture. In addition, this choice avoids making assumptions about nutrient stacking, or whether both N and phosphorus (P) credits can be sold for the same oyster. Nitrogen reduction costs for each county were estimated using the specific set of nonpoint source practices documented per county within the Chesapeake Assessment Scenario Tool (CAST, 2016, v 5.2.1; "2025 WIP2" on "2010 baseline") (Archived, Chesapeake Bay Program, 2016). We estimated the cost-effectiveness of each practice in terms of cost per quantity nutrient removed with the following equation:

Annual Unit Cost ($/acre) / Total Nitrogen Removed (lb/acre)

In a few cases, costs were accounted for in units other than acres. Manure transport costs were estimated per ton of manure. To estimate costs per pound of nutrient removed, we converted pounds of N removed to tons of manure using ratios for broiler chicken litter from Chastain et al. (2018).

We estimated the Annual Unit Cost ($/lb/year) of N reduction per practice in two steps 1) *effectiveness* per practice was calculated as the N removed per unit of practice (e.g., lbs N/acre); 2) *cost-effectiveness* of each practice ($/lb N/year) was calculated by dividing the annualized practice cost by effectiveness ($/lb). A *cost function* per county was generated by ordering practices by cost-effectiveness. The cost function is then interpreted to generate the *marginal cost* of compliance ($/lb for the last pound of N removed) and a simple average cost per unit of N removed.

Using CAST to generate nutrient removal efficiency per practice

The N removal effectiveness due to a practice is not a fixed value because it varies by location and as a function of what other practices are installed (Chesapeake Bay Program, 2017; section 6B). We estimated N removal effectiveness using the Chesapeake Assessment Scenario Tool (CAST) (version 5.2.1), which is a web-based model interface and management tool that provides access to the Chesapeake Bay Watershed Model (CBWM) and underlying databases. The CBWM is a calibrated watershed model that uses location-specific data on land use, topography, and hydrology to project the sensitivity of water quality to a change in land use or management (US EPA (Environmental Protection Agency), 2010).

Although nutrient removal rates per management practice are available as a database, those values only represent the *potential* removal rate, since the effective rate used in evaluating management scenarios changes with location and with implementation of other nutrient reduction practices. Location affects practice efficiency because the rate at which nutrients are intercepted during travel from a land parcel (e.g., farm field or residential lot) to a water body depends on vegetation, geology, and runoff flowpaths, among other conditions. Nutrients are removed from water as it flows between the parcel and the edge of stream (EOS), and these effects are captured with location-specific coefficients in the watershed model. Further, the watershed model also includes attenuation coefficients that reflect the quantity of nutrients in streams that eventually reaches tidal waters, creating the edge of tide (EOT) load. EOT nutrient loads serve as drivers to an estuarine model that is used to evaluate whether in-water aquatic habitat goals (largely represented with dissolved oxygen criteria) are being achieved in the Chesapeake Bay.

The second major factor driving effectiveness of any given practice/project is the presence of other management practices. The net removal per practice being added to the landscape depends on the total pool of nutrients available to be intercepted or transformed. In the CBWM, removal is calculated as a percentage of nutrients being acted on by a practice. As nutrient-enriched surface water runoff is leaving an agricultural crop field, the first practice that the runoff interacts with (e.g., cover crops) will encounter a higher concentration of nutrients and have a greater opportunity to remove nutrients than the second practice (e.g., riparian vegetated buffers).

In CAST, practice effectiveness is adjusted to reflect the presence of other practices using a *treatment train* or an ordered list for calculating removal efficiencies (Chesapeake Bay Program, 2017; Section 6B). Practices later in the treatment train are evaluated contingent on implementation of all practices earlier in the treatment train. As a result, practices that appear early in the treatment train will get an efficiency close to the published efficiency, while practices further down the list may have a lower effectiveness than the published value, if multiple other practices are present.

To best represent practice effectiveness, given this model structure, we ran CAST iteratively, removing one practice at a time in the reverse order of the treatment train. The version of CAST that we used allocates a county's practices to sub-areas (referred to as land-water segments) based on the presence of area appropriate for placement. For example, cover crops are apportioned spatially based on the availability of cropland. Thus, the calculation of effectiveness is simultaneously representing effects of expected practices and location factors in a consistent manner.

We used the N removal effectiveness at EOS to provide a conservative estimate of cost per pound removed. Although EOT removal is likely to be more comparable to removal by oysters, the higher load values for EOS (22% higher on average compared to EOS) generate a lower cost per pound. A conservative value is desirable to acknowledge model and future policy uncertainty.

Estimating practice costs

We used cost per unit of practice or per project from the CAST databases, which were developed from multiple sources (Chesapeake Bay Program, 2017). Annualized full costs (in 2011 dollars) are provided and they include capital costs, opportunity costs of land (i.e., market value of land or rental rate for agricultural land), and operation and maintenance costs over the expected lifetime of the project. Through this accounting, some practices have a net negative cost (generate positive returns) since they save implementers money via reduced operation and maintenance costs. High costs per practice typically arise from high capital or land opportunity costs. Costs are average values per state and do not represent variability by location.

Cost-effectiveness applied to estimate value of N reduction

We used cost-effectiveness analysis to generate average and marginal costs of reductions planned in the WIPs for each county and then took the marginal (max) for the two counties and averaged of the two county average values (Table A1). We removed all practices that were less than $1/lb because the low costs were generated using assumptions that are not relevant for the purposes of trading. We also removed all costs greater than $10,000/lb because they did not seem to be realistic investments despite their inclusion in the WIPs. The resulting average cost per pound was $270/lb N.

The cost analysis suggests that counties have an average willingness to pay of $270/lb N/year when implementing their own practices. We reduced that value by 30% to cover transaction costs (Chesapeake Bay Commission, 2012) and the risk premium (discussed in main body of report). Therefore, we used a value of $190/lb N / year as a potential high value of credit price. Although this value seems high, it is well below the marginal cost of nitrogen abatement that was included in the WIPs of $21,400, suggesting that counties are potentially willing to implement practices with much higher costs per pound to meet their TMDL and other requirements.

Comparison of cost analysis to published fixed credit prices

A survey of water quality trading programs with published prices, suggests that credit prices can be substantially lower than the average cost of practice implementation (Table A2). The documented costs that we found ranged from $3 to $20, primarily for trades among point sources. Since we have little market information to guide us, we used the average value of $10/lb/N credit as a sensitivity analysis.

Table A1. Costs per pound N of implementing nutrient management practices

	Talbot & Dorchester counties
Marginal (or Maximum) cost/lb (also marginal cost/lb) (permeable pavement with an underdrain)	$21,400
Average cost/lb (excluding costs per lb <1 or >10,000 $/lb)	$270
Average cost used in scenario 2, representing 30% reduction to adjust for transaction costs and risk premium	$190

Table A2. Documented nitrogen credit prices

Water body	N Credit price (unless otherwise noted)	Notes	Source
Long Island Sound	$6.70 buyer cost $2.66 seller payment	PS-PS sale; Price set by regulators	Connecticut Department of Energy and Environment (2017)
Ohio River	$10 (N and P combined credit; ~2.6 ratio of N:P)	NPS-PS sale; Price fixed by program administrators	Electric Power Research Institute (EPRI, 2014)
Virginia	$3.78 (2018 price)	PS-PS sale; price increases over time	Virginia Nutrient Credit Exchange Association, Inc. (2016 p. 8-17)
Virginia	$20 / lb / year	PS-PS sale between George Mason University and the VA Nutrient Credit Exchange	Arlington County (2015)

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Appendix B. Analysis of suitable aquaculture area using spatial data

Supporting tables and figures for GIS analysis described in report body.

Table B1. Oyster Aquaculture Suitability Criteria Used and Data and Information Sources

Parameter	Criteria Used	Data Source
Outside of Maryland Artificial Reef Initiative Sites	Removed artificial reef sites.	http://data.imap.maryland.gov/datasets/maryland-finfish-maryland-artificial-reef-initiative-sites
Buffered Public Shellfishery Areas	150' buffer of shellfishery areas.	http://data.imap.maryland.gov/datasets/maryland-shellfish-public-shellfishery-areas
Buffered Oyster Harvest Reserves	150' buffer of reserves.	http://data.imap.maryland.gov/datasets/maryland-shellfish-oyster-harvest-reserves
Buffered Active Pound Net Sites	150' buffer of net sites.	http://data.imap.maryland.gov/datasets/maryland-finfish-active-pound-net-sites
Buffered Historic Oyster Bottom	150' buffer of historic oyster bottom.	http://data.imap.maryland.gov/datasets/maryland-shellfish-historic-oyster-bottom
Outside of Oyster Plantings (2000-Present)	Removed oyster plantings.	http://data.imap.maryland.gov/datasets/maryland-shellfish-oyster-plantings-2000-to-present
Outside of Recreational Uses (Historic and Cultural)	Removed recreational uses.	http://data.imap.maryland.gov/datasets/maryland-recreational-uses-historic-and-cultural
Outside of Potomac River	Removed areas from Potomac River. Area not available for leasing.	Carlozo 2014.
Chesapeake Bay Bottom Survey	All cultch selections for bottom culture. No restrictions for container culture.	http://data.imap.maryland.gov/datasets/maryland-soils-chesapeake-bay-bottom-survey?geometry=-78.966%2C37.857%2C-73.797%2C39.359
Maryland Marine Boundaries - Shoreline	Chesapeake Bay outline.	http://data.imap.maryland.gov/datasets/maryland-marine-boundaries-shoreline
Outside 5 Year Submerged Aquatic Vegetation (SAV) Area (2012-2016)	Merged 2012-2016 layers.	http://web.vims.edu/bio/sav/gis_data.html
Chesapeake Bay Salinity (2001-2011)	Salinity range between 8-25 ppt.	Personal Communication: Marcia Berman & Tamia Rudnicky at VIMS
Chesapeake Bay Bathymetry (2003)	Depth between 0-3 meters for bottom culture. Depth between 0-8 meters for container culture.	NOAA
VIMS Aquaculture Lease Tool	Viewed oyster lease locations.	https://webapps.mrc.virginia.gov/public/maps/chesapeakebay_map.php

Table B2. Suitable Area for Bottom and Caged Aquaculture by Bottom Type.

Salinity: 8 - 25 ppt
Depth: 0 - 3 meters

Bottom Substrate	**Area (acres)***
Cultch	10,415
Hard Bottom	20,149
Mud with Cultch	3,645
Sand with Cultch	8,590
TOTAL	42,798

*Area after restricting to salinity 8-25 ppt and depth 0-3 m.

Table B3. Suitable Area for Floating Aquaculture by Bottom Type.

Salinity: 8 - 25 ppt
Depth: 0 - 8 meters

Bottom Substrate	**Area (acres)***
Cultch	17,016
Hard Bottom	37,520
Leased	122
Mud	65,462
Mud with Cultch	11,571
Sand	28,972
Sand with Cultch	23,045
TOTAL	183,708

*Area after restricting to salinity 8-25 ppt and depth 0-8 m.