ABSTRACT

Title of Thesis: VALUING SHALLOW WATER SYSTEMS IN MARYLAND'S CHESAPEAKE BAY

Megan Munkacsy, Master of Science, 2022

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Oyster aquaculture (OA) activity is sometimes framed as a hindrance to habitat, recreation, property values, and wild oyster harvest in Maryland's Chesapeake Bay. Yet, tradeoffs under OA policies have not been thoroughly analyzed. I applied decision science techniques to capture alternative OA policy effects on users and ecosystem services. Stakeholders helped organize system complexities into management goals and performance indicators, and shared preferences to inform indicator weights. These weights were applied to outcomes from a suite of economic and ecological models, resulting in each scenario's stakeholder-weighted summary score. Results revealed that (1) highly protective habitat policies create risk to future OA production while protecting less than 0.1% of habitat, (2) proposed changes to current OA policies appear less effective at balancing goals, and (3) under no policy does OA impact more than 1.3% of wild oyster revenues. This analysis served to clarify system complexities to inform policy analysis.

VALUING SHALLOW WATER SYSTEMS IN MARYLAND'S CHESAPEAKE BAY

by

Megan Munkacsy

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2022

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Dedication

This thesis is dedicated to all the other queer children of immigrants working hard for a better tomorrow, especially the women of aquaculture.

Acknowledgements

I want to thank my committee members, Dr. Michael Paolisso, Dr. Matthew Fitzpatrick, and Dr. Jeremy Testa, without whom this project would not have been possible. Additional thanks to Dr. Michael Wilberg who offered guidance on various oyster metrics.

I also want to acknowledge three women who, maybe unknowingly in some cases, kept me going when I felt lost in this degree process.

First, my advisor Dr. Wainger, who saw that I could be held to a higher standard than I saw in myself. She never gave up on me, even when I had no plan and no funding.

Secondly, my Sea Grant mentor Shannon Hood, who has shown me for the past five years how to be gracious and tenacious in the world of aquaculture.

Finally, Claire Nemes, for setting an example of how to persist when your plans change out of your control. She exemplifies how to find humor and community in the field.

Above all else, though, I want to acknowledge my parents and grandparents. My mother, Teresita Munkacsy and her parents Katherine Fitzsimmons and Joseph Ryan; and my father Christopher Munkacsy and his parents Marie Melroy and Mihály Munkacsy.

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Chapter 1: Introduction

Economics is the study of how limited a resource is through valuation and relative comparison. The value of an ecosystem service, or something society values from the ecosystem around it, represents how willing we are to trade-off something else for the preservation of that service. The economic valuation of ecosystem services provides information to policymakers regarding how scarce a service is, helping inform the policy making process to avoid a misallocation of resources and thus harms to society. However, policy integration often lacks explicit evaluation of a full range of ecosystem effects on human wellbeing beyond monetary values (Chan et al., 2012; Kenter et al., 2015; Saarikoski et al., 2016a). Monetizing ecosystem services to quantify their importance to society can lead to justifying policy decisions that exclude cultural values or fail to represent collective meanings (Balmford et al., 2002; Costanza, 2006; Gómez-Baggethun and Ruiz-Pérez, 2011; Wainger and Mazzotta, 2011).

Therefore, methods that are able to quantify stakeholder concerns for multiple ecosystem services, and recognize the complex motivations and preferences people have related to those services, have become useful to inform ecosystem service evaluations (Spash, 2008; Turner, 2007). Since ecosystem service valuations are often cited to justify policy decision making, producing ecosystem service valuations which incorporate both monetary and non-monetary values are critical. With such an approach, policies can better protect the myriad ways in which society benefits from ecosystems.

One particular region in which more robust stakeholder values need to be captured are along our coastlines, which host both increasing human populations and increasing uses, and thus an increasing need for well-informed policies (Kannen, 2014). For example, over the past decade aquaculture (coastal and inland, collectively) has been the fastest growing agricultural sector in the world (FAO, 2020). Aquaculture is a way of growing water-based food sources such as fin-fish, shellfish, and kelp. The expansion of marine aquaculture along coastlines has led to a requirement for more robust marine spatial planning (Douvere, 2008).

Proponents of the continued growth of aquacultural coastal uses cite global nutritional needs, nutrient pollution reduction, and improving livelihoods as reasons to support such a system (Bricker et al., 2017; Ferreira and Bricker, 2016; Gephart et al., 2020). Opponents mention the aesthetic impacts, disease risk, and inhumane working conditions as reasons why coastal aquaculture disrupts the values important to coastal systems (Dempster et al., 2002; Marschke and Betcherman, 2016; Shafer et al., 2010). These concerns come up at different scales throughout the world, but all of them frame how complex and multifaceted societies use and non-use values associated with coastlines are. As such, the common application of monetary valuation is inappropriate. Coastal aquaculture and marine spatial planning requires a more systemic and inclusive understanding of how society values coastlines.

Multi-criteria decision analysis

One way to ensure that a range of values are incorporated into ecosystem services valuation is to apply a multi-criteria decision analysis approach to help inform the decision-making process. Multi-criteria decision analysis (MCDA) is an approach to policy evaluation that utilizes a stakeholder-defined assessment framework to incorporate stakeholder values and biophysical, quantified outcomes to inform decisions (Belton and Stewart, 2002; Keeney and Raiffa, 1976). MCDA is particularly useful in systems thinking that involve (1) incomplete information and uncertainty, (2) competing interests and lines of evidence and (3) invested stakeholders (Huang et al., 2011). This process breaks complexities and competing values down into core qualities to reveal preferences within a system. MCDA then helps quantify several dimensions of a system into scores representing alternatives and outcomes. Those scores are then translated to a linear weighted sum of scores across several criteria (Huang et al., 2011).

MCDA makes extensive use of stakeholder input, allowing them to incorporate multiple definitions of value – including moral, environmental, economic, and cultural – to enlarge the representation of stakeholder values typically considered in an ecosystem services valuation project (Banville et al., 1998). MCDA's ability to incorporate multiple, sometimes competing, stakeholder values and ecological science outcomes at varying levels of robustness makes it well suited to evaluate alternatives to coastal policies and marine spatial planning in the context of coastal shellfish aquaculture.

There are several types of MCDA analysis that can be conducted (Table 1).

Table 1: Common multi-criteria decision analysis approaches, details, and citations.

MCDA Approach	Details	Citation
Analytic Hierarchy Process (AHP/ANP)	Criteria are ranked against each other via pairwise comparison in order to form a hierarchy.	Saaty TL. Fundamentals of decision making and priority theory with the analytic hierarchy process.

		Pittsburg: RWS; 1994.
Multi-Attribute Utility Theory (MAUT/MAVT)	Develops utility functions to evaluate which scenarios best utilize set criteria.	Keeney RL, Raiffa H. Decisions with multiple objectives: preferences and value tradeoffs. New York: John Wiley & Sons; 1976.
Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)	Outranking and voting approach that utilizes flow scores. Does not aim to arrive at an answer but rather engage stakeholders in a process.	Brans, JP., De Smet, Y. (2016). PROMETHEE Methods. In: Greco, S., Ehrgott, M., Figueira, J. (eds) Multiple Criteria Decision Analysis. International Series in Operations Research & Management Science, vol 233. Springer, New York, NY. https://doi.org/10.1007/978-1-4939-3094-4_6
ELimination and Choice Expressing Reality (ELECTRE)	Similar to PROMETHEE.	Ghosh, Anindya & Mal, Prithwiraj & Majumdar, Abhijit. (2019). Elimination and Choice Translating Reality (ELECTRE). 10.1201/9780429504419-4.
Technique for Order Preference by Similarity (TOPSIS)	Ideal negative and positive solutions are determined and criteria scores are compared to those extremes to select the scenario closest to ideal and furthest from least ideal.	Uzun, B., Taiwo, M., Syidanova, A., Uzun Ozsahin, D. (2021). The Technique For Order of Preference by Similarity to Ideal Solution (TOPSIS). In: Uzun Ozsahin, D., Gökçekuş, H., Uzun, B., LaMoreaux, J. (eds) Application of Multi-Criteria Decision Analysis in Environmental and Civil Engineering. Professional Practice in Earth Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-64765-0_4

Of the MCDA approaches, AHP is the most commonly used in environmental sciences – particularly geospatial analysis – though all MCDA approaches to environmental science issues have been growing in popularity since the beginning of the 21st century (Huang et al., 2011).

MCDA methods are not a problem-solving method, but instead a problem structuring method that aids decision makers to more fully understand an issue and the potential consequences of a decision (Marttunen et al., 2017).

A significant strength of the MCDA approach is that it expands the decision criteria that can be quantified, compared to economic analysis. Instead of only using monetary values to assess options, MCDA uses quantitative measures of changes, weighted by stakeholder concern for those changes. Methods such as cost-benefit analysis (CBA) have been criticized for ignoring values and culturally important aspects of decision making, although a thorough CBA will describe aspects that cannot be valued in monetary terms (Saarikoski et al., 2016b).

MCDA is not a cure-all though, and critiques include the oversimplification of trade-offs, the impact that quantification choices can have on outcomes, and the risk that stakeholders rely too heavily on a leader's opinion rather than representing their own (McDaniels et al., 1999; Steele et al., 2009). To address quantification challenges, criteria or the value a criteria represents must be understandable to a non-expert stakeholder, and practitioners must keep criteria weights proportional to the relative importance of the criteria during the final score calibration step (Steele et al., 2009). To address challenges associated with a single loud voice influencing others opinions, MCDA can be coupled with other social science methods such as the modified Delphi technique, which helps prevent groupthink (Kiker et al., 2005).

The ideal opportunity for applying MCDA methods to the decision making process will have a variety of informational inputs (quantified information, expert opinion, stakeholder opinions, and risk considerations), trade-offs or conflicts between values, and incomplete information about a system (Kiker et al., 2005). The issue of oyster aquaculture siting in Maryland's Chesapeake Bay has all of these concerns, rooted in over a century of social debate and facing the unknowns of a wild population decline and the relative beginning of realizing climate change impacts.

Maryland's Oyster Aquaculture Conflicts

Maryland's Chesapeake Bay regional history has been associated with the Eastern oyster (*Crassostrea virginica*) and its harvesting dating back long before the settlement of the state by English colonists (Keiner, 2009). Wild oyster harvesting in the Chesapeake Bay peaked in the late-1800s, as harvest methods became more efficient and wild stocks were still abundant (Cronin, 1986; Rothschild et al., 1994). As early as the 1870s, state managers and oyster harvest practitioners recognized the opportunity to develop agricultural practices that rear oysters, also known as aquaculture in Maryland, and began passing legislation seeking to promote oyster aquaculture (Kennedy and Breisch, 1983; Winslow, 1884). Harvesters in the wild catch industry, regionally referred to as watermen, continuously opposed efforts to normalize oyster leasing in the Bay. Their political actions stalled social acceptance of oyster bottom leasing in Maryland, and so aquaculture remained an untapped resource in the state until the late 20th and early 21st century (Kennedy and Breisch, 1983; Webster, 2018). This anti-leasing sentiment was first recorded around the time of the passing of the 1906 Hamon Oyster Bill, which allowed private leasing of up to

30 acres of “barren bottom” submerged lands in county waters, and up to 100 acres in non-county waters. While groups such as the Nationalist Club of Baltimore equated leasing to enslavement, the majority of arguments against leasing were born of three main beliefs: (1) that natural oyster beds belong to the people of Maryland at large and should not be privatized, (2) that this practice could lead to the monopoly of Maryland oysters by some corporate entity, and (3) that oysters could not be successfully reared on any bottom that was not a natural oyster bed (Green et al., 1916). In response to watermen’s protests in the early 1900s, the state agreed to survey all natural oyster bars (NOBs) in Maryland’s Chesapeake Bay so as to exclude them from consideration for lease applications (Yates, 1913). Though leased acreage exceeded 30,000 in the first quarter of the 20th century, it fell to 9,000 by the 1930s and remained there for the remainder of the century (Kennedy and Breisch, 1983; Webster, 2018).

Through disease and overfishing, the state had lost 80% of the natural oyster beds over the last 30 years leading to a 75% decline in harvesters and an 80% decline in oyster processing companies (Figure 1) (Cronin, 1986; Rothschild et al., 1994; Winslow, 1884). At the same time, Virginia aquaculture had become well-established and was a multi-million dollar industry, bringing in tax revenue for the state, local coastal economic success, and providing a local example for Maryland to aim for.

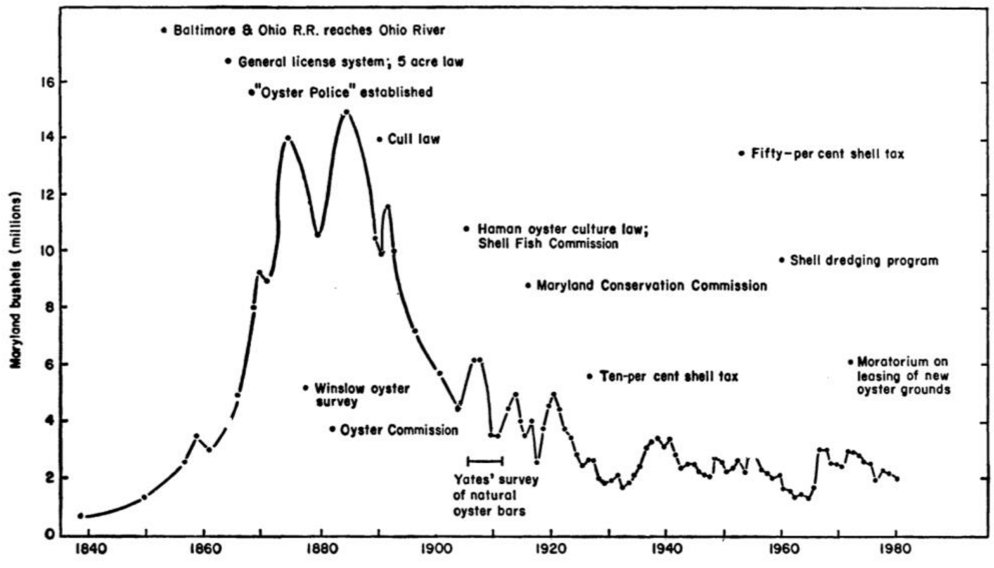

Figure 1: Figure from Kennedy and Breisch, 1983: "Reported landings of oysters in Maryland over the past 14 decades, in millions of bushels (approx. 1-3 times standard U.S. bushel).The harvest period for oysters begins at the end of the old year and extends into the new.The time line refers to the new year (for example, 1961 denotes the 1960-1961 harvest period). Important events in the history of management in Maryland are noted. (After Grave 1912, modified.)"

In 2009, Governor Martin O'Malley's Oyster Restoration and Aquaculture Development Plan, authorized by Maryland Ch. 173, Acts of 2009, was implemented, requiring the Maryland Department of Natural Resources (MD DNR) to streamline the oyster aquaculture leasing process. Two motivations for this change are cited in the policy: the failure of the wild fishery, and the desire to rebuild an oyster-based economy to a globally competitive level. This legislation opened new areas to shellfish leasing and provided alternative economic opportunities to the wild harvest watermen (Webster, 2009).

Since the passage of the 2009 bill, the oyster aquaculture industry has grown an average of 24% annually, providing over 100 jobs and $8.1 million in economic benefits (Senten et al., 2019). Over 7,000 acres of Maryland's tidal waters are now leased across over 430 sites in 10 Bay counties and one ocean-side county (MD DNR). The actions of the 2009 change in legislation put 95,000 acres of wild oyster bars that were no longer harvested by the aquaculture industry into the leasable areas pool. It also re-named NOBs to public shellfish fishery areas (PSFAs). The distinction between a NOB and a PSFA is the new potential for leasing expired NOBs. Additionally, leasees interested in developing aquaculture in a PSFA can petition for the designation to be changed, an option previously unavailable under NOB designation. This policy also dictates that PSFAs are reviewed every 3 years by MD DNR for harvest activity and density of oysters in the area. Over a decade after this forward movement of aquaculture in the state, watermen are pushing back. A current debate puts this density designation into question. Watermen are organizing for any PSFA supporting 1 oyster/m^2 or more to be defined as a PSFA unavailable for leasing (Wheeler, 2020).

In 2020, COVID-19 introduced new uncertainty into the future of the oyster industry that we have yet to understand. Markets for oysters declined due to closure of restaurants, where the majority of oysters are consumed (Senten et al., 2021). However, the industry is expected to continue to grow, and throughout the 2020 and 2021 seasons new lease applications continued to be submitted.

Waterman protests of oyster aquaculture leasing persist to this day, but the industry faces two new sources of social conflict as well. First is conflict with other uses of shallow waters such a riparian homeownership enjoyment, recreational boating and other powered watercraft activities, and recreational and commercial fishing activities. Though leased areas are not off limits to the public other than to leave gear unharmed and in place, recreationalists have complained that they cause a burden to access and enjoyment.

A recent case of use conflict arose in St. Mary's County along the Southern Western shore of Maryland's Chesapeake Bay. In late 2018, homeowners in the region successfully protested to restrict aquaculture activity from using commercial docks for 6 months. During a public comment period, 353 comments were submitted in favor of the moratorium, and 27 were opposed. Those in favor mostly cited frustrations that aquaculture operations affect their ability to safely boat, swim or hunt in the waters off their property. Leases also need approval from local riparian homeowners in order to be approved, a common source of contention as waterfront homeowners are often hesitant at best to allow an aquaculture farm into their viewshed.

It should be noted that oyster aquaculture leases are not the only floating gear in the Chesapeake Bay. It is common to see crabbers set trot lines that float via recycled milk gallon containers, pound nets made of a series of bamboo sticks that run perpendicular to channel flows, and wild harvest oyster and clam harvesters that dredge bottom area repeatedly, leading to plumes of sediment. These activities are rarely protested.

The second major conflict arising in Maryland's Chesapeake Bay in regards to oyster aquaculture siting is the recovery of submerged aquatic vegetation (SAV) beds. In the Chesapeake Bay, SAV beds occur in the same habitat as shellfish beds. This is a critical spatial conflict under the Magnuson-Stevens Act (MSA), which established protections for Essential Fish Habitat (EFH) in 1976. EFH is defined as areas without which fisheries would not be able to survive – such as mangroves, coral reefs, wetlands, seagrasses, deep sea, kelp forests, bays and rivers. EFH, such as submerged aquatic vegetation (SAV) beds, are not stationary and can appear in regions where they previously were not present.

The designation of an area as EFH is often where the conflict with aquaculture develops. Due to the protections awarded EFH, the establishment of SAV beds can result in the termination of aquaculture leases with little warning, justified by the assumption that oyster aquaculture causes harm to the habitat.

In order to protect SAV, MD DNR has established that no oyster aquaculture leases can be sited within an area that has hosted SAV at any point in the most recent five years of the Virginia Institute of Marine Sciences (VIMS) aerial survey data. MD DNR also holds the right to revoke or adjust leases that overlap with SAV after the operation has been established, and has used that right to require re-siting of oyster aquaculture operations. In the peer reviewed literature, the impacts of SAV and shellfish on each other are not well understood, with studies showing both positive and negative interactions (Fales et al., 2020; Ferriss et al., 2018). Oyster farmers anecdotally claim oyster farms create increased habitat suitability for SAV, aiding in the recovery of SAV in the Bay.

However, EFH protection is not the only policy goal that SAV beds are tied to in Maryland’s Chesapeake Bay. SAV beds are sentinel species for characterizing water quality due to their sensitivity to nutrient and sediment loading. As such, SAV density and abundance have become key indicators for the impact that policies such as the Total Maximum Daily Load have on Chesapeake Bay water quality and overall health (Orth et al., 2017, 2010; Wainger et al., 2017).

In 2018, the Maryland Legislature passed MD HB 841 requiring the state to develop a better understanding of SAV and oyster aquaculture interactions over the next five years. During those five years, how acceptable oyster lease and SAV bed spatial overlaps are is up to MD DNR's discretion. MD DNR's change in SAV/oyster aquaculture lease siting policy is contemporary with a broader national conversation about the impact that shellfish aquaculture has on SAV beds, and vice-versa.

Though not officially stated anywhere, MD DNR has expressed limited concern for leases that overlap with SAV. The department has implemented an unofficial policy that oyster aquaculture leases with SAV cannot harvest SAV areas during the SAV growing season, from April to October.

However, my analysis comparing Maryland oyster aquaculture leases as of March 2021 and VIMS SAV data found that the majority of leases experiencing SAV overlap are within the smaller 50% of oyster leases by acreage, indicating that mostly smaller leases actually overlap with SAV. Due to size restrictions, this leads to a question of whether this interim policy is effective as many leases may not have significant regions of their leases available to harvest when SAV is growing.

It should also be noted that in Maryland, submerged land leaseholders often switch seasonally between wild harvest and aquaculture. Since wild harvest is only available October through March, oysters from submerged land leases typically are harvested and go to market from April to October. This time frame, April to October, is also the SAV growing season that MD DNR has suggested restricting. This could mean that oyster aquaculturists cannot produce aquacultured oysters during the only season in which they typically harvest such oysters, making their businesses obsolete.

Project Aims

My research explores the social and ecological benefits and harms stakeholders identify with oyster shellfish aquaculture in Maryland's Chesapeake Bay, and integrates those into policy scenarios to quantify how values are impacted under different regulatory approaches. Marine spatial planning for Maryland's oyster aquaculture industry has always been contentious, and yet little has been studied about how oyster aquaculture citing policies may impact the values cited by stakeholders who often raise concerns. Though background work has established that oysters and the lifestyles associated with their harvest are critical to Maryland's Chesapeake Bay culture, no work has explored how to measure the impact that expanding oyster aquaculture might have on those values (Adriane K. Michaelis et al., 2021; Adriane K Michaelis et al., 2021; Michaelis et al., 2020; Paolisso and Dery, 2010). Similarly, there is little literature on how policy changes may impact the profitability of the oyster aquaculture industry in Maryland's Bay (Engle, 2016; Senten et al., 2020; Weber et al., 2018). Furthermore, we know that conflict between wild oyster harvest and leasing are not the only values that are perceived to be impacted by oyster aquaculture sitting in Maryland's Chesapeake Bay, as previously outlined in the section on conflict in St. Mary's County.

Due to these unexplored and complex sources of value and wellbeing in the shallow waters of Maryland's Chesapeake Bay, the application of a multi-criteria decision analysis is highly appropriate and necessary to understand how policy changes may impact the oyster aquaculture system at large. This work aims to provide decision making support for marine spatial planning and decision making regarding which policies maximize societal wellbeing in the context of shallow water uses of Maryland's Chesapeake Bay.

Chapter 2: Site Description

Study Area: Maryland's Chesapeake Bay

This study focuses on Maryland's portion of the Chesapeake Bay, which encompasses the lands of the Nacotchtank, Piscataway, Nentego, Pocomoke peoples. Maryland's portion of the Chesapeake Bay covers 1,726 square miles and 16 of the state's 23 counties have Bay tidal waters.

The Chesapeake Bay in its entirety is the largest estuary in the United States of America and the third largest estuary in the world. It spans the eastern portion of Maryland, Virginia, and all of the District of Columbia, though the watershed is spread throughout the states of New York, Pennsylvania, West Virginia and Delaware as well (Figure 2).

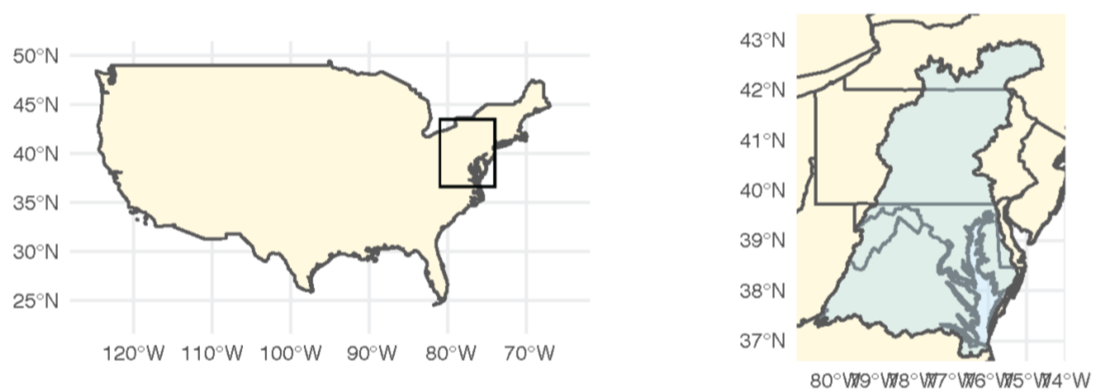

Figure 2: Chesapeake Bay watershed relative to the United States (left) and across the state boundaries (right).

The entirety of the Bay has 11,684 miles of tidal shoreline and an average depth of 21 feet. Today, the Bay region is home to an estimated 18 million people.

Leasing and Oyster Aquaculture in Maryland

Oyster aquaculture siting in Maryland is managed by the Maryland Department of Natural Resources (MD DNR). There are two different types of oyster aquaculture leases that applicants can apply for: a bottom culture lease and a water column lease. Applications for either lease cost $300. Water column leases are required to maintain insurance at the leasees expense. Annual rental rates are $3.50/acre for bottom culture leases and $25/acre for water column leases.

Leases are for a maximum of 20 years, with the potential for renewal once more for an additional 20 years. All leases in Maryland are required to be actively used to have their status maintained. Lease applications are subject to a mandatory 30-day public notice period, wherein the applications are listed online and all local residential and commercial enterprises are notified of the application. Protestors do not need to be local to the lease to submit a request for a public hearing. Protested lease applications have been elevated to the courts in some cases. Siting considerations and limitations can be found listed out in Table 2.

Table 2: Maryland Department of Natural Resources oyster aquaculture lease siting regulations.

Parameter	Criteria
Outside of Maryland Artificial Reef Initiatives Sites	Remove artificial reef sites from consideration.
Buffered Public Shellfish Fishery Areas (PSFAs)	150' Buffer of area.
Buffered Oyster Harvest Reserves	150' Buffer of area.
Buffered Pound Net Sites	150' Buffer of area.
Buffered Historic Oyster Bottom	150' Buffer of area.
Outside of Oyster Plantings	Remove oyster planting sites from consideration.
Buffered Shoreline	50' Buffer of shoreline.
Outside of Submerged Aquatic Vegetation (SAV) 5-year Area	Consider most recent 5 years of VIMs SAV data and remove from consideration.
Buffered Federal Navigational Channel	150' Buffer of area.
Buffered Yates Bar within Oyster Sanctuary	150' Buffer of area.
Outside of Potomac River Fisheries Commission Area	Remove the Potomac River from consideration.
Maryland Department of the Environment Closures	Remove the non-shellfish waters from consideration.
Federally Protected Lands	Remove Federally Protected Lands.
Marinas	Remove 70' Buffer around Marina

Leases can be found in the waters of 11 Maryland counties (Figure 3).

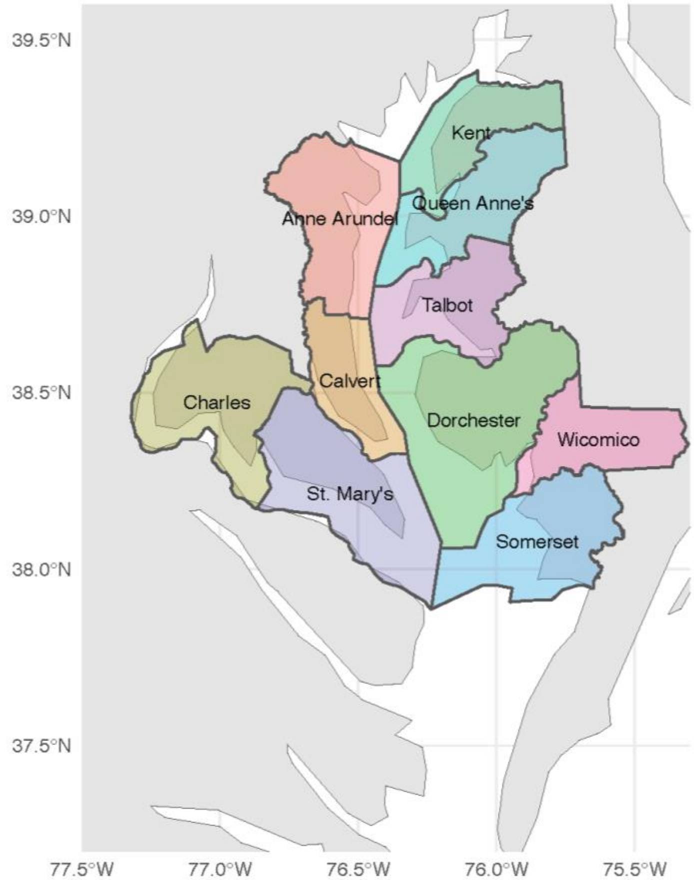

Figure 3: Counties in Maryland's Chesapeake Bay that host oyster aquaculture leases in their Bay waters.

Chapter 3: Methodology

Multi-Criteria Decision Analysis (MCDA)

Multi-criteria decision analysis (MCDA) is an iterative method of preference elicitation and decision analysis used to evaluate alternative actions in terms of their ability to deliver benefits, minimize risk, or otherwise address management needs (Scarlett and Boyd, 2015). MCDA is a family of methods in decision making that can be applied in cases of uncertainty and competing values by helping inform two aspects of complicated decisions (Velasquez and Hester, 2013):

(i) what criteria are important to consider

(ii) how to structure and synthesize those criteria to identify a preferred course of action

MCDA requires the participation of diverse stakeholders in order to identify the variety of values, opinions, and concerns. It further requires making use of expert judgment and systems models to inform the potential courses of action and evaluate which outcomes are preferred (Belton and Stewart, 2002).

Multi-criteria decision analysis (MCDA) involves several stages of methodology broken into two phases (Marttunen et al., 2017; Saarikoski et al., 2016b). Phase one is the Framing Phase. Through a process of co-development and iterative question asking with stakeholders, practitioners identify policy alternatives, define quantifiable indicators of value, and ensure that metrics are robust. Phase two is the Valuation Phase. In this phase, scientists use models to inform biophysical responses to policy. These responses are weighted by stakeholder criteria, scores are aggregated, and a hierarchy of policies relative to the explored values are shared with decision makers to help inform the policy-making process (Martin and Mazzotta, 2018).

This MCDA framework involved stakeholder participation at every step, connecting stakeholder values to ecosystem services and proposed policies, evaluating the impact of those policies on indicators of ecosystem services, and quantifying the value weights for policy outcomes. These weights, representing an aggregation of biophysical and stakeholder preference weights, will inform a set of policy alternatives ranked by how well they protect values and services. These policies and associated value weights will be presented geospatially to stakeholders and policymakers to help inform policy making processes.

In my project we applied a modified MCDA process due to time and resource limitations. We break this process down into the following stages:

1. Problem Identification
2. Problem Structuring
3. Model Assessment and Building
4. Model Application
5. Scenario Outcome Comparisons

Problem Identification

To help reveal a broad spectrum of interests and values associated with oyster aquaculture leasing, I made use of the substantial recent research on the social dimensions of oyster aquaculture that had been funded by National Sea Grant. I searched the awards database to identify projects funded in coastal management and oyster aquaculture within the last three years (2017-2020) that involved policy conflict, geographic siting and/or analysis, and social sciences, including economics. From this review, I identified stakeholders for semi-structured interviews and relevant literature of in-water spatial policies that exist or are under consideration in the United States.

Further exploration of these resources helped fill in structural details and points of contention or tradeoff within my issue system. I conducted semi-structured interviews with researchers and extension agents from Washington, California, Massachusetts, Connecticut, New Jersey, Maryland, Georgia, Mississippi and Alabama. I complemented these interviews with literature reviews of shellfish aquaculture siting conflict management along the United States coasts, which expanded my background research to include Alaska, Maine, Rhode Island, Virginia, and Florida.

Problem Structuring

A critical stage in MCDA is the development and fine-tuning of a decision hierarchy for the system. Structuring the complex systems which MCDA is specialized to address helps clarify where points of tradeoff are, as well as where groups with different values may actually align based on goal criteria. Finally, the decision hierarchy clarifies relationships between values held by stakeholders and areas where policy can adjust criteria relevant to those values.

I conducted semi-structured interviews with researchers, policy makers, and practitioners familiar with shellfish aquaculture siting challenges throughout the United States. After talking with representatives from 11 states I reached information saturation and was able to identify common oyster aquaculture siting policy objectives and points of contention throughout the United States and in Maryland. The policy and literature review that accompanied these interviews addressed how different systems managed such conflicts. A comparison of these goals and criteria was conducted to identify existing models or modeling approaches that are relevant to quantifying Maryland's Chesapeake Bay decision criteria. All of this work culminated in a draft decision hierarchy to present to Maryland stakeholders (Figure 4).

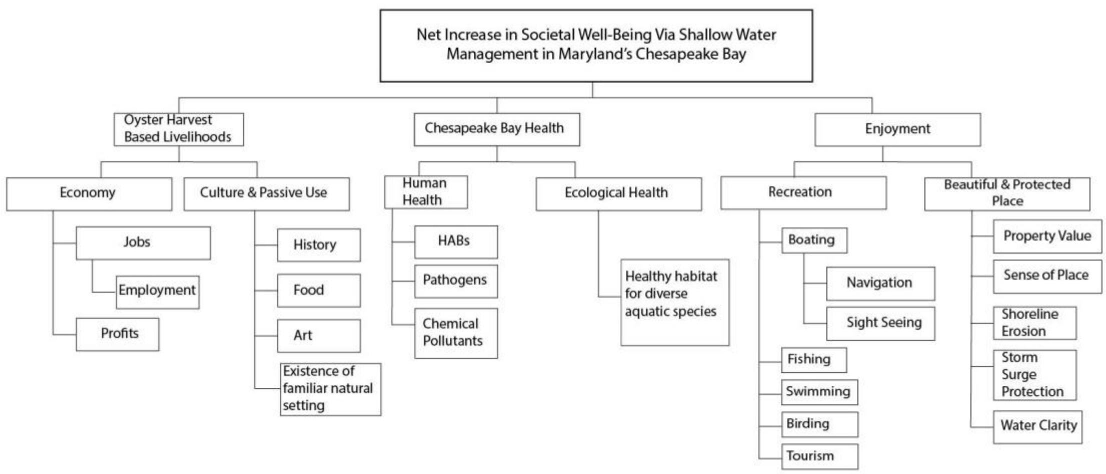

Figure 4: Decision hierarchy for oyster aquaculture lease siting and policy making. Values in Maryland associated with the system include: the balance and protection of oyster harvest based livelihoods, Chesapeake Bay health, and the enjoyment of the Bay. Beneath are listed examples of criteria that might be directly impacted by changes in policy.

Using the decision hierarchy framework, I developed a suite of policy changes that could be applied to Maryland's Chesapeake Bay to directly impact values in the system. My proposed policy alternatives are based on approaches used in other states, approaches proposed but not enacted in Maryland, or spatial management approaches applied in other regions with shellfish aquaculture spatial conflicts. Policy changes were bundled based on the particular interests of aquaculturists, wild harvesters, boaters, riparian homeowners, and habitat concerned stakeholders in order to frame how different policies favoring different values would affect the system at large. Policy scenarios and their details for this project are listed in Table 3.

Table 3: Policy scenarios for oyster aquaculture siting in Maryland's Chesapeake Bay. Some policies add or subtract areas available to lease according to their spatial relationship to socially important areas such as shorelines, housing, or public boat launches. Others adjust areas available to leases according to their relative ecological productivity such as areas of submerged aquatic vegetation, public harvest, and public investment.

Policy Scenario	Policy Events	Description
Business As Usual (BAU)	Standard Policies (See Figure X)	Reference Point (0)
Proposed BAU Adjustments	Standard Policies Lessened SAV Restrictions 150' Distance from Shoreline Buffer	Adjustments currently being considered by MD DNR
SAV Protection	Standard Policies Projected SAV Habitat Restricted from AQ Use 1500' Distance from Shoreline Buffer	Spatial conflicts between SAV and oyster aquaculture leases minimized
Public Access	Standard Policies Lessened SAV Restrictions 150' Distance from Shoreline Buffer 1500' Distance from Public Boat Launches	Spatial conflicts between water recreators and oyster aquaculture leases minimized
Habitat + Aquaculture Production	Standard Policies High Suitability SAV Area Restricted from AQ Use 150' Shoreline Buffer	Spatial conflicts between SAV and oyster aquaculture leases reduced but not avoided
Wild Harvest	Standard Policies 150' Shoreline Buffer 300' PSFAs Buffer Oyster Sanctuaries Restricted from Leasing	Wild harvest areas, or areas where public monies have been invested in oyster recovery, completely removed from lease availability
Wild Harvest + Aquaculture	Standard Policies No SAV Restrictions Regions with Public Monies Reserved for WIld Harvest Eastern Bay reserved for Wild Harvest Only	All regions open to aquaculture except anthropogenic bottom, harvest reserves, oyster sanctuaries (2010-present), oyster sanctuaries (pre-2010), state-funded oyster plantings
Aquaculture = Wild Harvest	No Standard Policies No PSFA Limitations Oyster Sanctuaries Restricted from Leasing Public Health Restrictions Remain in Place	Oyster aquaculture lease restrictions completely equivalent to wild harvest restrictions. Health restrictions remain (conditional harvest approval, etc).
Unlimited Aquaculture	No Limitations on Aquaculture Siting, Including Removal of Standard Policies	No spatial limitations on oyster aquaculture lease siting.

Some existing policies were kept constant across all scenarios (Table 4).

Table 4: Current policy restrictions for oyster aquaculture lease siting. These spatial policy restrictions are already enforced by MD DNR. In all scenarios explored in this project, these restrictions remained unchanged.

Parameter	Criteria	Data Source
Outside of Maryland Artificial Reef Initiatives Sites	Remove artificial reef sites from consideration.	Maryland iMap
Buffered Oyster Harvest Reserves	150' Buffer of area.	Maryland iMap
Buffered Pound Net Sites	150' Buffer of area.	Maryland iMap
Outside of Oyster Plantings	Remove oyster planting sites from consideration.	Maryland iMap
Buffered Federal Navigational Channel	150' Buffer of area.	Army Corps of Engineers
Buffered Yates Bar within Oyster Sanctuary	150' Buffer of area.	Maryland iMap, DNR
Outside of Potomac River Fisheries Commission Area	Remove the Potomac River from consideration.	Maryland iMap
Maryland Department of the Environment Closures	Remove the non-shellfish, restricted, and conditionally approved waters from consideration.	Maryland iMap
Federally Protected Lands	Remove Federally Protected Lands.	Maryland iMap
Marinas	Remove 70' Buffer around Marina	ArcGIS Online

While some policy scenarios may not be realistic for Maryland, providing extreme scenarios and their resulting impacts helps clarify tradeoffs that result from policies. Quantifying such scenarios can help clarify for decision makers both intended and unintended consequences of a spectrum of policy options.

Following policy identification, I built out causal chains connecting each event to its expected biophysical outcomes (Table 5). These connections reflect a synthesis of field data, literature review, expert opinion, and model evidence that an event (e.g., preventing oyster aquaculture from existing in projected SAV habitat) is likely to change an ecological or social outcome of interest.

Table 5: Causal chain of connecting values through to their indicators.

Measure of Wellbeing	Model	Metric
Growth potential of aquaculture industry	Enterprise Budget, Industry Growth Model (Weber & Wainger 2018)	$, Net Revenue
Conservation of sensitive species and their habitats	SAV Habitat Suitability Model (Munkacsy, MaxEnt – Fitzpatrick reviewed)	% of SAV Acreage (2020) Covered by Projected Leases
Riparian property value protection	Hedonic Pricing Model (Stump 2019, Virginia Tech)	$, Value Loss (Sum, 2020 USD)
Wild oyster industry value	Harvest Revenue Option Value	$, Lost Revenue
Safe boating access to the Bay	Spatial Buffer	Count of Impacted Sites

Model Assessment and Building

At this stage of decision structuring, stakeholders beyond subject experts were invited to co-develop project outcomes. Early involvement of stakeholders familiar with the issue and system helps ensure that research is relevant and the framework is applicable to real-world solutions (Gamper and Turcanu, 2007). This process provides an avenue for stakeholder agency and familiarity with project outcomes critical for its potential application. It also ensures that critical measures of wellbeing associated with the system are fully captured. A team of 12 stakeholders participated in a questionnaire and workshop to review the drafted decision heircharcy and proposed policy scenarios. Through this process, stakeholders could provide feedback, suggest areas of exploration, and critique approaches.

Workshop Logistics

Stakeholders represented state, federal, and private sectors and specialized in field practices in Maryland oyster aquaculture, ecology of submerged aquatic vegetation, and socio-cultural issues surrounding aquaculture, such as real estate, to represent experts in each respective field of identified actors in the system. As the majority of participants are public servants, we made clear to participants they were being asked for their professional opinion to represent the values of Marylanders at large. The stakeholder workshop was conducted virtually via video conferencing software.

Modified Delphi Technique

A concern that arises with MCDA analysis is the influence of a single or few loud voices in the room to define or derail collective decision making, also known as groupthink. Reducing groupthink is critical to ensuring that stakeholders feel comfortable to voice novel or conflicting ideas to the conversation at large (Janis, 1991). The modified Delphi Technique is a survey-style approach for eliciting stakeholder values that aims to minimize groupthink when asking stakeholders to consider options presented to them (Curtis, 2004). For this project, we applied a modified version to elicit preferences on goals and criteria laid out in the decision hierarchy.

A Likert-type questionnaire (approved by the UMCP institutional review board) was provided to host a virtual workshop with participants to elicit the relative strength of preferences for alternative goals (Appendix 1). Participants were sent a three-question questionnaire electronically and asked to complete it within the week before we met virtually for a stakeholder workshop.

During the workshop, participants engaged in a facilitated discussion about the relevance of the decision hierarchy to outlined goals and criteria of the oyster aquaculture system in Maryland. Stakeholders were also guided to consider how indicator values may change under proposed policy options. This conversation was framed around the initial responses to the questionnaire they completed. After walking through the questionnaire and general response trends as a group, participants were asked to retake the questionnaire.

The Delphi technique allows stakeholders to hear others' points of view on a topic and then explicitly revisit their own opinions on the discussed topics privately by reissuing a questionnaire before and after group consultation. Therefore, post-meeting scores are expected to reveal more complete opinions about values. Stakeholder values in this case were rescored to a 100 point scale for question 2, which asked respondents to divvy up 100 points of policy effort across the five identified impacted aspects of wellbeing: wild harvest options, aquaculture profits, riparian home values, public water accessibility, and habitat protection. These rescaled values represent the relative importance of each value to stakeholders in Maryland.

Model Application

All models described in this section are limited to the Maryland section of the Chesapeake Bay.

Submerged Aquatic Vegetation Habitat Suitability Model

In order to understand policy impacts on SAV habitat, I developed a habitat suitability model to project SAV habitat suitability based on environmental covariates. I chose a maximum entropy model approach for presence-only SAV data (MaxEnt, version 3.4.1). MaxEnt methodology and theory is well described in the literature (Elith et al., 2011; Jaynes, 1956; Merow et al., 2013; Phillips and Dudík, 2008).

The MaxEnt algorithm is implemented in the dismo package in R Studio (version 1.1.456) (Hijmans et al., 2017). The model quantifies the relative suitability of habitat for a species based on presence-only data, distributed across geographical space (Guillera-Arroita et al., 2014). Based on the environmental covariates listed in Table 6, the program identified a range of probability (summing to 1) that each raster cell could host any salt-tolerant SAV species based on the characteristics of presence sites (f_1) compared to characteristics across the entire environment (f), including both presence and background points. This ratio, f_1/f, represents how probable it is to find the species at any given site on a relative scale (Elith et al., 2011; Merow et al., 2013; Phillips et al., 2006; Phillips and Dudík, 2008).

In order to capture more complex relationships between covariates and presence data, MaxEnt provides the log of the relative probability that SAV is found in a single raster cell compared to all others. This calculation clarifies how each cell ranks on a 0 to 1 scale of suitability. This score is then calibrated with covariate intercepts to parameterize the "average" conditions for the species considered. It is common for MaxEnt users to report this logistic value. MaxEnt controls for trade-off between model fit and model complexity via regularization, in order to avoid overfitting (Guillera-Arroita et al., 2014).

There are at least three assumptions for the application of MaxEnt, 1) sample data are unbiased; 2) data are presence-only; and 3) background data (or randomly or regularly selected sample points selected across the extent being modeled) are a reasonable representation of the range of a species (Elith et al., 2011).

I chose MaxEnt because of the nature of my species data, which were available as presence-only data. Although the VIMS survey covers the majority of the Bay, not all locations are able to be sampled due to turbidity, which can lead to failure to detect. Due to this concern, I chose not to apply species distribution models that can handle presence-absence data, such as generalized linear models (GLMs) or generalized additive models (GAMs). MaxEnt is less sensitive to problems associated with pseudo-absence, biasing the analysis not to assume unsuitable conditions at locations without presence points (Guillera-Arroita et al., 2014).

The SAV habitat suitability model was built using geospatial data of SAV distribution and water quality conditions by location (Table 7). I used a 7-year composite of the recent distribution of SAV in order to apply parallel data to the pre-developed raster interpolations of water quality that I used as data for my environmental covariates.

Raster cells that were below 5 salinity 80% of the time or more were masked out for all features in order to improve model performance for salt tolerant species of SAV, which are the relevant species that overlap oyster aquaculture leases. The waters of the Chesapeake Bay host several species of SAV that inhabit a range of salinity, depth, and water clarity parameters (see Table 6).

SAV data were encoded as the maximum density of each polygon of SAV data from VIMS aerial surveys from 2012 to 2019 (VIMS, n.d.). 10,000 randomly generated background points from throughout the Bay extant and 8,734 presence points were used to fit and evaluate my model. I used bootstrapping methods to evaluate model performance wherein 20% of occurrence data were withheld from the model to test results against.

Table 6: Common species of SAV in the Chesapeake Bay. Scientific names on the left, common names on the right. Courtesy of (Orth et al., 2017).

Species	**Common name**
Ceratophyllum demersum	coontail
Elodea canadensis	common elodea
Heteranthera dubia	water stargrass
Hydrilla verticillata	hydrilla
Myriophyllum spicatum	Eurasian watermilfoil
Najas guadalupensis	southern naiad
Najas gracillima	slender waternymph
Najas minor	spiny naiad
Potamogeton crispus	curly pondweed
Potamogeton perfoliatus	redhead grass
Potamogeton pusillus	slender pondweed
Ruppia maritima	widgeongrass
Stuckenia pectinata	sago pondweed
Vallisneria americana	wild celery
Zannichelia palustris	horned pondweed
Zostera marina	eelgrass

Table 7: Data inputs to oyster lease suitability models.

Data Name	Source (*Access Date*)	Treatment
Submerged Aquatic Vegetation VIMS Aerial Survey	VIMs SAV Database (*December 2, 2020*)	Polygon shapefile. 2012-2019 Virginia Institute of Marine Science (VIMS) at William and Mary University multispectral aerial survey of the Bay, conducted on an annual basis. These data are collected from an altitude of 13,200 feet along predetermined flight paths that were chosen to account for most, if not all, of the Bay tidal region. Ground sampling distance is 24 cm and resolution is 1m2. Controls exist within the methodology to account for tidal stage, plant growth, sun angle, atmospheric transparency, turbidity, wind, sensor operation, and land features at the time of collection.
Percent of time with salinity below 5	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Geographically weighted regressions were built to spatially predict hourly salinity within Maryland Chesapeake Bay segments from 2012 to 2019. Proportion of hours below 5 salinity were predicted using the best performing model. Cells with values ≥ .8 were removed.
Bathymetry	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Areas with a depth greater than 5m were masked out
Percent of Sand	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Data were extracted from the Chesapeake Bay Program's benthic databases and percentage of sand, silt, and other sediment were interpolated from non-fixed stations using co-Kriging and Dirichlet regression.
Fetch	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Exposure at 200m resolution was calculated using the fetchR package (Seers 2017) and then resampled at the 1 hectare resolution. Fetch N and SW were found to have the greatest influence and so only these exposure directions were used.

All spatial rasters have a 1 hectare resolution.
All spatial data are projected to NAD83 / UTM zone 18N in R Studio.

Potential weaknesses of this approach include that presence-only data can be subject to sampling bias, and that the prevalence of a species cannot be determined.

However, due to the collection method used for SAV in the Chesapeake Bay, sampling bias concerns are minimized because all tidal Bay waters are scanned for SAV annually (VIMS, n.d.).

SAV presence is highly correlated with light attenuation in the water. However, data limitations prevented me from using this variable, and fetch and bottom type were used as a proxy for light attenuation. Both fetch and bottom type are reasonable proxies for light attenuation, as each is an environmental measure of the wave or flow energy at a site. Low energy environments, indicated by smaller sediment particle size such as silt or mud, are met with less mixing energy from fetch, the water column experiences less light attenuation. Therefore, an ideal site for SAV must have sand-sized particles or finer for SAV establishment and lower fetch energy to avoid mixing.

The MaxEnt output was used to build the mask for SAV exclusion for policies that required SAV exclusion. To calculate SAV impact from lease placements, we used the VIMs composite SAV shapefile representing any presence from 1978 to 2020. Freshwater areas were again masked out and the projected leases were overlaid onto the SAV composite map. Acreage of overlapping leases with historic SAV coverage was summed per alternative. Acres of overlapping area were then compared to 2020 SAV coverage in Maryland’s saltwaters to evaluate the magnitude of effect on SAV coverage baywide, given a potentially low coverage year.

Oyster Aquaculture Leasing Model

To estimate the potential regions where oyster aquaculture leasing might expand, I built two additional MaxEnt habitat suitability models: one that projected oyster aquaculture submerged land lease coverage and one that projected oyster aquaculture water column lease coverage. I chose MaxEnt (MaxEnt, version 3.4.1) to model oyster lease suitability because lease data are presence data, leasing likelihood can be determined by location-derived conditions, and all other model assumptions were met (see SAV model section). Oyster lease data are presence-only data, and not presence-absence data, as areas of absence could exist due to the oyster aquaculture not being saturated rather than an area being inappropriate habitat for leasing, or due to policy adherence removing highly valuable leasable area from production (Weber et al., 2018). Furthermore, spatial lease restrictions have changed over time, with existing leases continuously grandfathered in to the industry, meaning that even leases as they exist today do not exclusively adhere to today's spatial requirements.

Unlike SAV habitat, oyster lease sites are determined by a combination of environmental and social covariates. Based on conversations with Maryland Sea Grant extension agents that specialize in Maryland oyster aquaculture lease siting, I determined that predictive covariates for lease applications by aquaculturists in Maryland were not only influenced by environmental factors important to oysters but also by social factors relevant to access. These conversations revealed that most aquaculturists launch their boats, rather than store them at marinas, and so we added distance from public boat launches as a covariate to inform our model. Covariates for this model can be found in Table 8.

A sensitivity analysis was also run on a suite of relevant available biophysical rasters in order to avoid model overfitting. Northwest fetch was found to have the greatest importance of all the cardinal and intercardinal fetch directions according to variable contribution estimates produced by model runs testing variable sensitivities, and therefore was the only fetch direction applied. The lease data were rasterized so that any cell that overlapped a polygon became a presence point ("1"). 10,000 randomly generated background points and 2,293/150 presence points (submerged land/water column, respectively) were used to fit and evaluate my model. We used bootstrapping methods to evaluate model performance wherein 20% of occurrence data were withheld from the model to test results against.

Assumptions for these models are the same as listed in the SAV section.

Table 8: Data inputs to oyster lease suitability models.

Data Name	**Source (*Access Date*)**	**Treatment**
Oyster Aquaculture Leases in Maryland	Maryland Department of Natural Resources (*March 11, 2021*)	NA. Leases were split into two data sets: (B) for submerged leases and (WC) for water column leases. Each set was run with its own model.
Salinity below 5	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Geographically weighted regressions were built to spatially predict hourly salinity within Maryland Chesapeake Bay segments from 2012 to 2019. Proportion of hours below 5 salinity were predicted using the best performing model. Cells with values ≥ .8 were removed.
Bathymetry	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. NA
Fetch	Dr. Dong Liang, personal communication (*April 23, 2021*)	Raster data. Exposure at 200m resolution was calculated using the fetchR package (Seers 2017) and then resampled at the 1 hectare resolution. Fetch NW was found to have the greatest influence and so only this exposure direction was used.

Public Boat Launches	Chesapeake Bay Foundation (*August 7, 2021*)	Raster data. Distance accumulation raster was built in ArcGIS Pro v 2.9 using the Distance Accumulation tool set to true surface distance.

All spatial rasters have a 1 hectare resolution.
All spatial data are projected to NAD83 / UTM zone 18N in R Studio.

Lease Placement Projections

Lease amounts and placement by scenario were estimated in two stages. First, to estimate how many oyster aquaculture leases would be added to Maryland Chesapeake Bay waters into the future, I conducted a 15-year projection of leases based on the average rate of lease increases between 2010 and 2021 in Maryland. Using historic leasing data (MD DNR Aquaculture and Industry Enhancement Division, March 2021), I calculated the average annual number of leases successfully applied for and sited from 2010 to 2021, broken down by lease type (Table 9). Leases were divided into Western and Eastern Shore categories, as determined by the county specified in each lease application, per the data from MD DNR. Anne Arundel, Calvert, St. Mary's, and Charles Counties represented the Western Shore. Kent, Queen Anne's, Talbot, Dorchester, Somerset, and Wicomico Counties represented the Eastern Shore.

I evaluated the modeled lease suitability for existing leases that were granted from 2010 to 2021 by intersecting lease location polygons with the lease suitability model spatial output, by gear type. I used the extract function from the Raster package in R to identify the maximum lease suitability value (of all raster cells) that fell within each lease polygon (Hijmans and Etten, 2012). Maximum values were chosen to represent each lease's realized growing conditions, as interviews revealed that some lease holders expand the spatial extent of their leases into known areas of poor suitability to create a spatial buffer that prevents leasing by others in close proximity (MD DNR, personal communication).

The lease suitability values of existing leases were then used to identify natural breaks in the data distribution (Figure 5). I found that historically 64.58% of submerged land leases and 66.18% of water column leases occurred in high-quality habitat. Also, 34.42% of water columns and 33.82% of submerged land leases were in variable quality habitat, according to the lease suitability model. Any leases that fell outside of these categories were rounded into the high-quality habitat bin to represent industry actors learning to favor better conditions with industry maturity. Future projected leases were then binned in these same proportions.

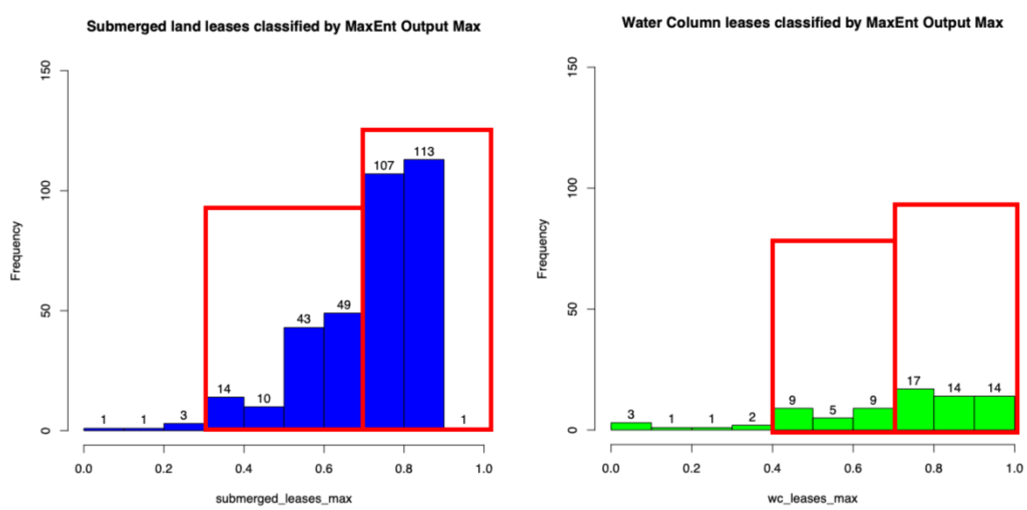

Figure 5: MaxEnt oyster lease suitability model spatial classification of existing oyster leases (as of March 2021). Classification defined by the maximum cell value overlapping an existing lease polygon. Numbers over columns represent count.

Based on these data, we determined lease counts by shore and gear type (Table 9).

Table 9: Number of oyster aquaculture leases, by shore and lease type, projected to 2036. Projection based on the average number of leases added annually from 2010 to 2020 per MD DNR lease data.

Shore	Lease Type	Average Number of Leases Added Annually (2010-2020)	Projected Number of Leases Added (2021-2036)
Eastern Shore	Submerged Land	14.8	222
Eastern Shore	Water Column	6.4	96
Western Shore	Submerged Land	4.8	72
Western Shore	Water Column	4.6	70

Using R (V 2021.09.1) and the function genRandomPoints, lease points, in the proportion previously determined, leases were placed randomly according to the following rules (Knevels et al., 2019):

1. No placed lease can overlap an existing lease as of March, 2021 (MD DNR).
2. Each lease must fall within its respective habitat suitability category.
3. Each point must be buffered to an area of 17 acres, the average lease size in Maryland as of 2021 regardless of gear (MD DNR).
4. The entirety of a lease must fall outside of a policy restriction's full, buffered area.
5. Restricted areas will always include those in Table 10.
6. Further spatial restrictions are determined by policy adjustments in Table 3.
7. Once a lease is placed, that area cannot have another lease placed on it for the scenario being run.

8. Submerged land leases must be placed before water column leases.
9. Leases are placed randomly within specified zone (Eastern or Western shore and habitat suitability bin).
10. If the placement of high habitat suitability leases is space restricted, the lease count left to be placed is added to the variable suitability. If lease placements still cannot be completed due to space limitations, remaining leases indicate a loss in potential industry size.

Table 10: Static policy restrictions for oyster aquaculture lease siting. These spatial policy restrictions are already enforced by MD DNR. In all scenarios explored in this project, these restrictions remained unchanged.

Parameter	Criteria	Data Source
Outside of Maryland Artificial Reef Initiatives Sites	Remove artificial reef sites from consideration.	Maryland iMap
Buffered Oyster Harvest Reserves	150' Buffer of area.	Maryland iMap
Buffered Pound Net Sites	150' Buffer of area.	Maryland iMap
Outside of Oyster Plantings	Remove oyster planting sites from consideration.	Maryland iMap
Buffered Federal Navigational Channel	150' Buffer of area.	Army Corps of Engineers
Buffered Yates Bar within Oyster Sanctuary	150' Buffer of area.	Maryland iMap, DNR
Outside of Potomac River Fisheries Commission Area	Remove the Potomac River from consideration.	Maryland iMap
Maryland Department of the Environment Closures	Remove the non-shellfish, restricted, and conditionally approved waters from consideration.	Maryland iMap
Federally Protected Lands	Remove Federally Protected Lands.	Maryland iMap
Marinas	Remove 70' Buffer around Marina	ArcGIS Online

Wild Oyster Harvest Opportunity Cost Model

In order to estimate the impact of different siting policies have on the wild oyster harvest industry's profits, we calculated the total dollar value of the areas removed from wild harvest for oyster aquaculture under different scenarios. MD DNR provided time series harvest data by oyster bar ID from the wild oyster industry. These data reported the average annual oyster harvest, in bushels, from the season beginning in the fall of 2009 to the season beginning in the fall of 2019.

The average annual harvest in bushels per m^2 of each publicly harvested oyster bar from spring 2009 to spring 2020 was calculated by simple division and multiplied by the area that each policy removed from public bars to place into private leasing using the sf package's st_intersection function (Pebesma, 2018). The total potential bushels removed were then multiplied by their market value to calculate the value of the area removed from the wild fishery (Equation 1). The average cost of a bushel of wild oysters is $50 2018 USD, or $51.54 in 2020 USD (Parker et al., 2020). Based on average oyster bushel prices provided by MD DNR from 2018-2021 this value likely overestimates the value of the wild oyster industry slightly, which makes losses to the industry seem more extreme.

$$\mathit{Bar\ Area\ (m)}_{\mathit{lease\ overlaps,\ ID}} \bullet \mathit{Average\ Bushel\ Harvest}_{\mathit{sq.m,\ ID}} / \mathit{Years\ Harvested} \bullet \$50 \qquad (1)$$

The output from equation 1 represents the opportunity cost to the industry under different policy scenarios.

I chose to evaluate the impact to the wild oyster industry as opportunity cost rather than option value for a few reasons. First, option value is dependent on willingness to pay. Between 2010 and 2021 there was an average of 943 oyster surcharges issued by MD DNR. A surcharge is required by the department for each waterman actively harvesting oysters that season. Due to this relatively small number, the willingness to pay value would likely be negligible.

Secondly, the literature suggests that you can ignore option value for public investments because 1) the decision is not irreversible and helps to gather information on the productivity of the bar; 2) no proposed policy would result in a lack of future supply of unrestored bars, as there are plenty of bars available for risk-hedging (Barbier, 1994; Costello and Kolstad, 2015). Further, risk avoidance is not necessary for the management of public projects (Arrow and Lind, 1970).

Table 11: Data used to estimate wild oyster harvest opportunity cost.

Data Name	**Source (*Access Date*)**	**Treatment**
Harvest Data	MD DNR *(Sept 2021)*	Joined with Yates Bars data by ID; averaged annual harvest per bar
Yates Bars	MD iMap *(December 2020)*	

All spatial rasters have a 1 hectare resolution.
All spatial data are projected to NAD83 / UTM zone 18N in R Studio.

Oyster Aquaculture Enterprise Budget

In order to determine Maryland oyster aquaculture industry growth under various policy scenarios, I applied a previously built model to estimate average profits of oyster aquaculture farms (Weber et al., 2018). In the Weber et al. model, production functions represent costs and revenues of an average farm operation with considerations of techniques used, outsourcing magnitude, skill, final market value, and other profit-impacting factors.

The enterprise budget uses profit to estimate industry growth linearly, summarized in equation 2:

$$E = \beta(\pi e - F) + \mu \tag{2}$$

Where E = entry or expansion metric (such as total production or number of firms), πe = expected post-entry profit, F = costs of entry, β = fitted coefficient, and μ is an intercept. The β coefficient represents the rate of expansion using data on profits across industries. Due to data limitations, cost of entry (F) and the intercept term (μ) were omitted leading to a simplified model (equation 3):

$$E_{type} = \beta_{type}(\pi^{e}_{type}) \tag{3}$$

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 water column. Variable Π^{e}_{type} was constructed to measure profit per dollar invested, rather than profit per bushel of oyster or individual oyster.

Assumptions

In the production model, production is assumed to scale linearly with farm size and costs are assumed to scale proportionately to size. Nurseries, remote setting, and upwelling container costs are all omitted. Oyster seed is assumed to be diploid for bottom culture and triploid for container culture, 5mm and 5-10mm respectively, and costs equal to Horn Point Hatchery 2018 prices.

The industry growth model assumes all prior growth moving forward, meaning that it assumes no negative long-term profits. It also assumes that there is a policy effect delay temporally. For bottom culture the delay is standardized at 3 years, for container culture the delay is 2 years.

Application

This model was adjusted in several ways to better fit this analysis. See Table 12 for a full description of the changes made and their justifications. The water column model was run four times for leases with the following conditions: shallow vs deep, high suitability (low mortality) vs low suitability (high mortality). A deep lease is any lease deeper than 1.5m (4.9ft), to represent leases that cannot easily be accessed without a boat. Mortality was determined by comparing DNR disease bar estimates of mortality to MaxEnt suitability estimates for each gear type. A significant relationship between average annual mortality and habitat suitability was found by running a t-test comparing MD DNR oyster mortality data to spatially overlapping suitability values from both the water column and submerged land MaxEnt rasters.

Total costs, sales, and net profits were calculated at a farm level under each condition set. The bottom column model was run twice to calculate values for leases with the following conditions: high suitability (low mortality) vs low suitability (high mortality). Water column and bottom culture leases were considered different industries. For each policy scenario, a tally of each lease type was multiplied by its respective representative firm net profit. Those values for each scenario were then summed to represent the industry's net profit.

This approach assumes that all leases considered have recovered from the first two to three years (based on lease type) that leases often turnover a loss in value. It also assumes no net gain or loss in adult oysters to anything other than mortality (i.e. harvest rates equal the rate at which oysters are reaching maturity).

Average net entry value represents the number of adult oysters on water column leases according to equation 4 and submerged leases according to equation 5:

$$\textit{Avg. Net Entry (oys/yr)} = \textit{Known production rate/acre} \bullet \textit{Larval Survival}_{t=1}/100 \bullet \textit{Acres of lease} \bullet \textit{Adult Survival} \bullet \textit{Years spat to market} - 1 \qquad (4)$$

$$\textit{Avg. Net Entry (oys/yr)} = \textit{Known planting rate/acre} \bullet \textit{Larval Survival}_{t=1} \bullet \textit{Acres of lease} \bullet \textit{Adult Survival} \bullet \textit{Years spat to market} - 1 \qquad (5)$$

Table 12: Adjustments to the Weber et al. 2018 oyster aquaculture enterprise budget made in this application of the model.

Variable	Weber 2018 Value	Munkacsy 2022 Value	Justification for Change
Average Net Entry (adult oys/yr)			
Bottom Culture	2,386,313	841,500	Representative of adult oysters. Parker 2020 lists 2M oysters/acre as typical planting density. All leases are assumed to be 17 acres. Assumes 15% survival in year one.
Water Column	1,503,640	3,400,000	Representative of adult oysters. Applied Parker 2020 calculation 1M oysters/2.5 acres as typical harvest density, or 400k oysters/acre. All leases are assumed to be 17 acres. Assumes 50% survival in year one.
Survival % of adults to harvest (post year 1)			
Bottom, low mortality	85%	11%	MD DNR disease bar 15-year average mortality. Bars in MaxEnt high suitability categorization were found to have a statistically different mortality rate than variable suitability bars, at the 95% confidence interval.
Bottom, high mortality		17%	
Water Column, low mortality	50%	11%	
Water Column, high mortality		17%	
Vessel Cost			

Bottom Culture	$25,000	$25,000	
Water Column, Shallow Site	$35,000	$10,000	Hayes and Wainger unpublished survey
Water Column, Deep Site	$35,000	$31,250	Hayes and Wainger unpublished survey
Vessel Lifespan			
Bottom Culture	25	30	Hayes and Wainger unpublished survey
Water Column, Shallow Site	11	30	Hayes and Wainger unpublished survey
Water Column, Deep Site	11	30	Hayes and Wainger unpublished survey
Labor Hours Per Week			
Bottom, Supervisory*	40	30	Hayes and Wainger unpublished survey found the average waterman works 6 hours per trip. Assumes a 5 day work week. *We assume this to be the farm manager, who is not always the same as the farm owner
Water Column, General Labor, Shallow	40	50	General laborers assumed to be additional hired workers during the busy season. Personal Communication.
Water Column, General Labor, Deep	40	50	
Labor Weeks Per Year			

Bottom, Supervisory*	52	32	Typically these workers work as watermen during the wild harvest season
Bottom, General		0	
Water Column, General Labor, Shallow	52	20	Single, half time employee
Water Column, General Labor, Deep	52	40	Two single, half-time employees. Personal communications with water column leasees estimates twice as much labor needed at deeper sites. Identities protected under IRB.
Water Column, Supervisory	52	52	
Average Yearly Fuel Cost			
Bottom	$4,000	$4,000	
Water Column, Shallow	$7,500	$7,657	Dumas et al. 2009 0-29’ boats
Water Column, Deep	$7,500	$11,520	Dumas 2009. Deep sites use more fuel for things other than transport (i.e. stabilization, other motors (cranes, anchor), fighting rougher chop, etc.)
Percentage Of Oysters Sold To			
Half Shell Market, Water Column	95%	100%	Parker et al. 2020
Other Markets, Water Column	5%	0%	

Insurance, annually			
Water Column, Shallow	$7,500	$700	Hayes and Wainger, unpublished survey
Water Column, Deep	$7,500	$7,500	Hayes and Wainger, unpublished survey
Repairs and Maintenance			
Water Column, Shallow	$20,000	$9,004	Engle et al 2021 values for =<6,000 box production. Assuming that lower production means smaller scale gear, workload, etc. which lead to repairs and maintenance needs.
Water Column, Deep	$20,000	$21,658	Value from Engle et al 2021 >6k box production. Assuming that higher production means larger scale gear, workload, etc. which lead to repairs and maintenance needs. Deeper sites also need gear able to handle more action, at approximately twice the cost (personal communications, shellfish grower in MD).
Gear (Cage & Bags)			
Water Column, Shallow	$96,000	$26,657	Value from Engle et al 2021 >6k box production
Water Column, Deep	$96,000	$26,657	Value from Engle et al 2021 >6k box production
Crane/Hoist			
Water Column, Shallow	$0	$0	

Water Column, Deep	$0	$7,850	Value from Engle et al 2021 >6k box production

Hedonic House Pricing Model

Oyster aquaculture is hypothesized to influence riparian home values by infringing on the aesthetic use and enjoyment of properties. To estimate the effects of oyster aquaculture lease visibility, including proximity, on single-family house values, I applied a hedonic house pricing model developed in 2019 to quantify lease proximity and size impacts on Virginia housing values (Stump et al., 2019). Other research uses hedonic models to estimate impacts of aquaculture on housing values, and results from all three studies are mixed (Sudhakaran 2021,Evans 2017). We applied the Stump et al. study due to similarities in housing stock and visual aesthetics between our study and theirs.

The Stump research investigated effects of oyster aquaculture leases on waterfront or water adjacent properties in Virginia's Eastern mainland region. Property sales values from 2012 to 2016 were adjusted to 2016 dollars using the Consumer Price Index, and considered oyster leases included any actively harvested lease and a separate category for any lease with cages on it, most commonly rack and bag. Rack and bag cages sit completely submerged on a lease and thus are only visible if the tide exposes them, though lease activity is visible regardless of gear type. Stump's model controlled for a setof conditions that contribute to housing price, including water clarity.

Stump et al. (2019) found relationships between home value and aquaculture lease type and size at multiple distance buffers from residential, single family parcels within 50m of the shoreline. The percent of the buffer in which aquaculture leases are visible was found to impact home selling price, presumably because the higher proportion of lease per unit of water view, the higher the magnitude of visual effects. Stump provided standardized coefficients such that the coefficient * 100 was equivalent to the percentage change in home value per percentage change in cage gear visibility, at the specified buffer distance (Table 13). Only the 300, 400 and 500 m buffer distance results were used because I screened results by statistical significance and only used results with $p<0.01$. Stump's results for the 50m and 100m buffer showed positive contributions to home value and were significant at the $p>0.10$ level. We omitted those results due to the lower level of statistical significance and because of concerns that there may have been an omitted variable that would explain the positive relationship. For example, homes with short water views could have added value due to the presence of a protected boat anchorage or reduced shoreline erosion risk, which were not represented in the Stump model.

Table 13: Hedonic model adjustments to residential market price due to aquaculture gear visibility. For every percent of water area covered by a lease within a given buffer distance, the percentage shown reflects the modeled change in home value, all else equal.

Buffer Radius (m)	Change in market price per % of visible lease
300	-1.1%
400	-1.3%
500	-1.6%

Hedonic models are a standard model applied in economics to evaluate the degree to which environmental conditions are reflected in housing value. Essentially, hedonic models are regression models in which many characteristics are compared for their ability to explain variation in home selling prices. They are used to isolate and quantify the degree to which each aspect of a parcel or property reflects buyer preferences and willingness to pay for amenities or to avoid disamenities. Hedonic models have been used to estimate the impact that environmental features have on housing value and consumers marginal willingness to pay for specific features of the surrounding landscape, while holding house, parcel and other location conditions constant (Evans et al., 2017; Geoghegan et al., 1997; Mazzotta et al., 2014; Sunak and Madlener, 2012; Walsh et al., 2017). However, hedonic models can be easily misapplied or misconstrued when the full range of characteristics that influence price are not considered. This concern is known as omitted variable bias, and can mislead interpretation of model outputs, suggesting that a single feature accounts for a larger change in value than it truly does, as that characteristic is parallel to another, unmeasured variable.

Originally built for Virginia homes, I transferred the Stump et al. (2019) model to Maryland's Chesapeake Bay counties where active oyster aquaculture leases are present (Anne Arundel, Calvert, St. Mary's, Charles, Kent, Queen Anne's, Talbot, Dorchester, Wicomico, and Somerset). I used a geospatial data set that provided parcel characteristics[1] to identify and compare conditions for homes potentially affected by aquaculture. Following methods similar to Stump et al. (2019), I first identified parcels that fell within 50m of the shoreline. These parcels were filtered for

[1]https://opendata.maryland.gov/resource/ed4q-f8tm.json?property_factors_location_waterfront_mdp_field_pflw_sdat_field_65=Water View (2)

single-residence parcels with structures, using the land use code equal to (R) in the database. Their assessed value for years 2018-2021 was converted to 2020 USD value using the Consumer Price Index average national value. Each parcel was buffered to include a 300m, 400m, and 500m circle, the distances at which Stump et al. (2019) found significant impacts from oyster aquaculture leases. We evaluated the property value effects at each of the three buffer widths using the standardized coefficient for the cagelease variable in Stump for coefficients (Table 13) and then chose the maximum value decrease for each house. Code for these methods can be found in the Appendix 2.

All water column leases in Maryland are assumed to have visible gear for this analysis. Any lease with cage gear on it, including fully submerged on-bottom cages, are classified as water column leases in Maryland. The assumption that all water column leases are visible overestimates the aesthetic impact of water column aquaculture in Maryland but data limitations prevented me from identifying gear visibility. Submerged leases can be unmarked or have visible markers, which are often thin vertical metal or bamboo poles. Water column leases can range from rack and bag systems (which are fully submerged and marked by floating buoys) to floating leases, which have oyster cages strung along floating longlines (these cages are visible at all tides and float about 4-8” above the water).

The sum of housing value effects for each policy scenario and county were calculated as the sum of housing value changes from new leases for all affected homes or residential parcels. Each parcel was evaluated individually to assess the percent of the viewshed impacted by oyster aquaculture leases. To calculate the potential value change, circular buffers were established around each home at 300, 400, and 500m. Within the circle, the land was masked out and total water area was intersected with the previously built geospatial data (see lease placement projections) for projected leases using R's sf package (Pebesma, 2018). See Figure 6 for a mapped example. Buffered area covered by a lease was divided by total water area of each parcel's buffer to produce a percent coverage.

For each residential parcel, the maximum percentage coverage was selected from the set of all buffer distances evaluated. The maximum percent coverage value per residence was multiplied by the calculated dollar value impact per percentage of coverage (Table 13) and summed for each county and scenario.

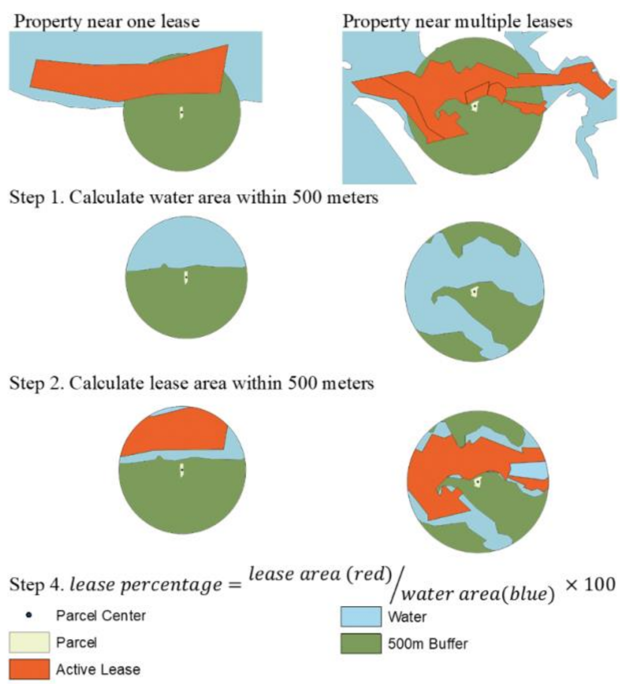

Figure 6: Image from Stump et al. (2016) outlining the process of calculating lease area within distance from single family parcels within 50m of Maryland's Chesapeake Bay.

Table 14: Date used to determine the impact of oyster aquaculture on waterfront home values.

Data Name	**Source (*Access Date*)**	**Treatment**
SHA Shoreline	Maryland iMap (*December 2020*)	50m Buffer
Maryland Housing Parcels	Opendata.Maryland.gov (*January 4, 2022)*	Filter by county, land-use, improvement value >0, shoreline buffer. Adjust pricing. Develop buffers.

Public Water Accessibility Model

Public water access was modeled as a proportion of all public boat launches with oyster leases at specified distances from the shore (Table 15). Public boat launch geospatial data were buffered to 70' and 1500' using R package sf (Pebesma, 2018). The 70' distance represents MD DNR requirements for a minimum setback from private marinas and the 1500' distance represents a European Union requirement for shellfish aquaculture farms setback from high tourism areas (No author 2019). The geospatial information from lease placements were then layered over the public boat launches and evaluated for places of intersection using R's sf package (Pebesma, 2018). The count of leases that intersected each buffer and the sum and percentage of water access points affected was tallied by policy scenario and county.

Table 15: Sum of public access sites in Maryland oyster aquaculture producing counties.

County	**Number of Public Access Sites**
Anne Arundel	29
Calvert	7

Charles	2
Dorchester	4
Kent	12
Queen Anne’s	3
Somerset	1
St. Mary’s	5
Talbot	2
Wicomico	7

Table 16: Data used in analysis of public access sites.

Data Name	**Source (*Access Date*)**	**Treatment**
Chesapeake Bay Potential Public Access Sites	ArcGIS Hub Chesapeake Geoplatform[2]	Only MD AQ counties selected

All spatial rasters have a 1 hectare resolution.
All spatial data are projected to NAD83 / UTM zone 18N in R Studio.

Scaling and Weighting

For each model output, a quantified value that captured the magnitude of impact to each aspect of wellbeing was selected to represent its benefit relevant indicator (BRI) (Table 5). For riparian property value protection, safe public access to the Bay, and maintenance of the wild harvest industry, their BRIs are simple summations of each modeled output for each policy scenario. For conservation of

[2]https://hub.arcgis.com/datasets/52e561ac7d704ad4a1bb45a40c7fa60e/explore?filters=eyJTdGF0ZSI6WyJNYXJ5bGFuZCJdLCJDb3VudHkiOlsiQ2hhcmxlcyIsIkNhbHZlcnQiLCJBbm5lIEFydW5kZWwiLCJRdWVlbiBBbm5lJ3MiLCJLZW50IiwiVGFsYm90IiwiU3QuIE1hcnkncyIsIkRvcmNoZXN0ZXIiLCJXaWNvbWljbyIsIlNvbWVyc2V0Il19&location=38.393347%2C-75.817684%2C8.51

sensitive species and their habitats, I compared how the projected leases for each policy scenario spatially overlap the SAV coverage of a low year (2020) using the sf package in R (Pebesma, 2018). By using a known year of low coverage I am representing enhanced sensitivity to any overlaps between SAV and oyster leases. For the growth potential of the oyster aquaculture industry aspect of wellbeing, I calculated the sum of both water column and submerged land lease industry profits and divided that value by the sum of leases that were projected in each policy scenario. This approach weights the net profits of the industry to also represent how many leases are placed under each policy scenario.

In order to aggregate final values into comparable benefit relevant indicator (BRI) scores, final outcomes had to be rescaled to common units. For all five BRIs, the following scaling calculation was applied (equation 6):

$$\frac{x - x_{Min}}{x_{Max} - x_{Min}} \qquad (6)$$

So, the closer a BRI value was to one, the less that policy scenario protected the measured aspect of wellbeing.

BRI scores were weighted by stakeholder responses to the workshop questionnaire in order to represent the relative importance of each outcome (Table 5). Each BRI score was subtracted from one to reorder policy scenarios on a scale similar to American grading, where 0 is the minimum (lowest performing) and 100 is the maximum (best performing). Those scores were then multiplied by the respective value in Table 17 and all BRIs for each scenario summed to determine the final scoring of each policy scenario.

Table 17: Relationship between each tested aspect of wellbeing in the Maryland oyster aquaculture leasing system and stakeholder-determined weights.

Aspect of Wellbeing	Stakeholder Weight
Growth potential of the oyster aquaculture industry	22.34
Conservation of sensitive species and their habitats	32.57
Riparian property value protection	12.11
Safe public access to the Bay	20.21
Maintenance of the wild oyster industry	12.77

Chapter 3: Results

Results from the project span outputs from seven economic and ecological models, three stakeholder engagement steps, and data summarizing and normalization outputs, culminating in a final dashboard of BRI values.

Intermediate Results: Models

MaxEnt: SAV

MaxEnt outputs from the analysis of SAV presence found that bathymetry (bathy), or depth, were the strongest predictors of a site's suitability for SAV habitat, followed by how long each cell spends below 5 salinity, and how long each raster cell experiences fetch from the north (Figure 8).

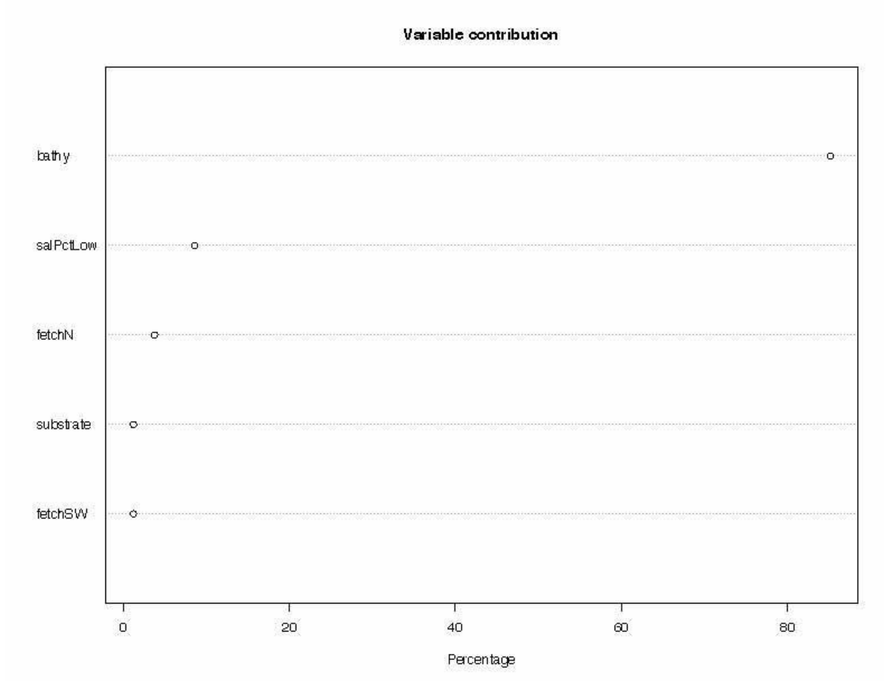

Figure 7: Feature contribution to SAV suitability model output.

Boyce index results for the SAV suitability model can be found in Figure 8. Continuous model values, representing probability of SAV presence, were broken into habitat suitability groups using Fisher-Jinks breaks. Any cell with a habitat suitability value less than 0.02 was considered unsuitable, anything between 0.2 and 0.5 was considered to have variable suitability, and anything greater than 0.5 was considered to have high suitability. These suitability thresholds were then checked against thresholds determined by the threshold function in dismo as a sensitivity analysis (Hijmans 2017). The model performance was not sensitive to changes in this threshold value. A map of these data categories shows a wide distribution of high and variable SAV habitat quality throughout the Maryland portion of the Chesapeake Bay (Figure 9). Higher suitability areas tend to be southeast in the Bay.

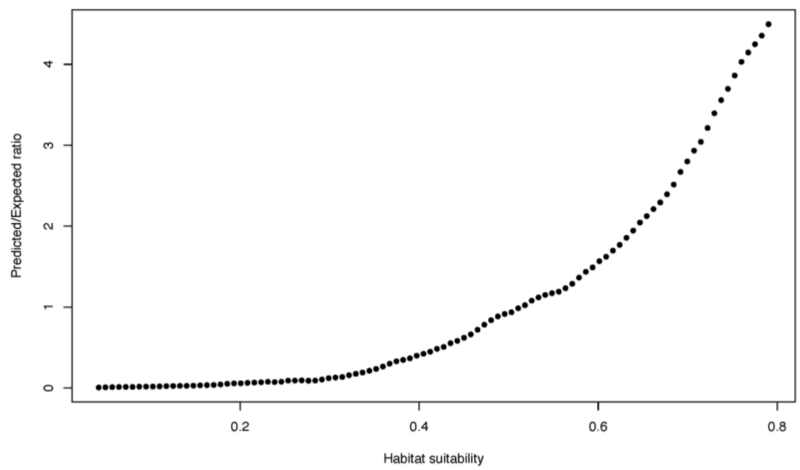

Figure 8: Boyce index for habitat suitability of SAV.

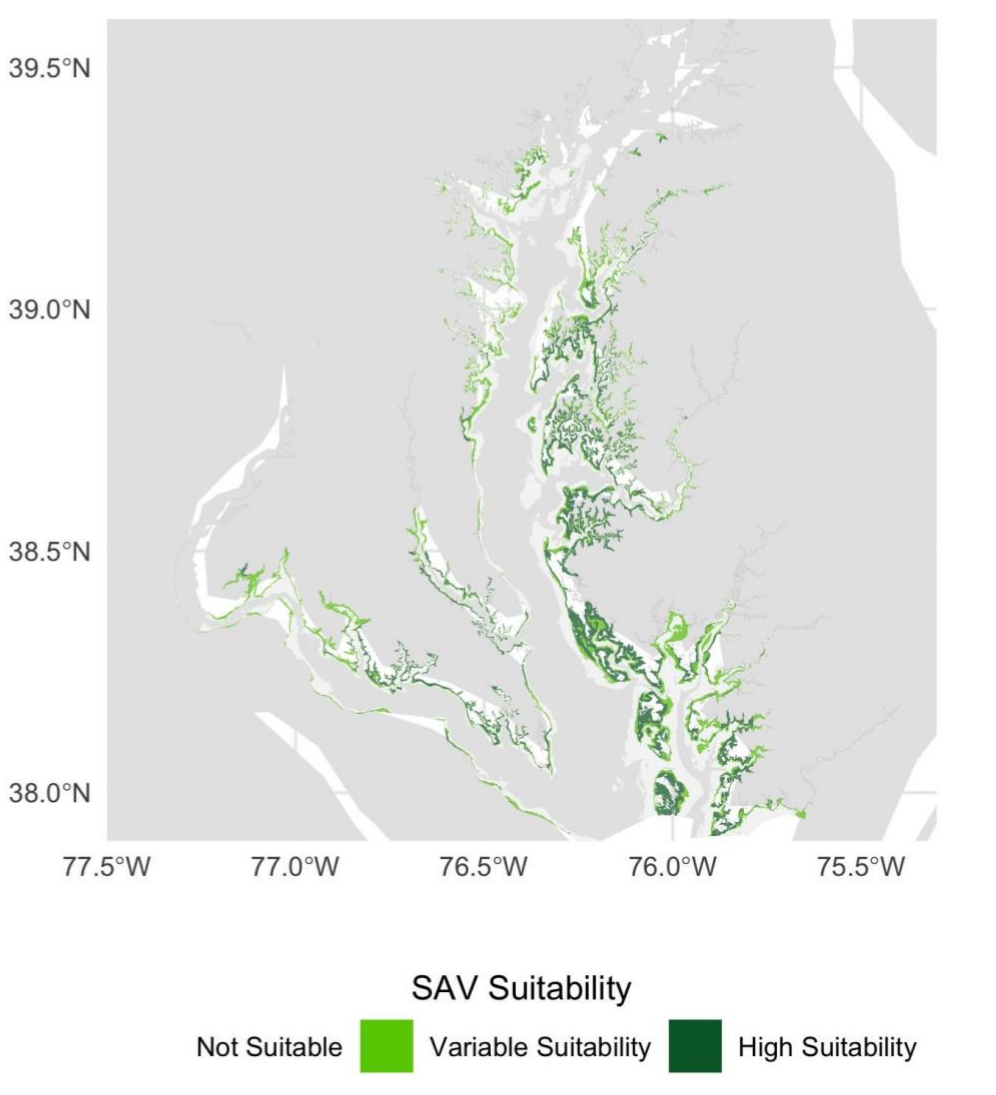

Figure 9: A map of Maryland's Chesapeake Bay submerged aquatic vegetation habitat suitability distribution generated by the MaxEnt analysis and categorized by habitat suitability values.

Table 18: Summary of SAV habitat suitability acreage for Maryland Chesapeake Bay.

Habitat Quality	Acres
Variable Suitability	148,851
High Suitability	123,674

Table 19: Summary of the overlap of projected leases and composite, actual SAV coverage for each alternative policy scenario and the percentage of SAV coverage for 2020, representing a low coverage year.

Scenario	Acres	Percentage of 2020 Acres
BAU	458.7	1.33
Aquaculture = Wild Harvest	1025.1	2.98
Habitat + Aquaculture Prod.	135.4	0.39
Proposed BAU Adjustments	477.7	1.39
Public Access	477.8	1.39
SAV Protection	9.9	0.03
Unlimited Aquaculture	907.5	2.64
Wild Harvest	575.8	1.67
Wild Harvest + Aquaculture	965.9	2.80

MaxEnt: Submerged Land Leases

MaxEnt outputs from the analysis of water column leases presence-background points found that bathymetry (bathy) and salinity (SalPctLow) were leading features determining where water column leases were projected (Figure 10).

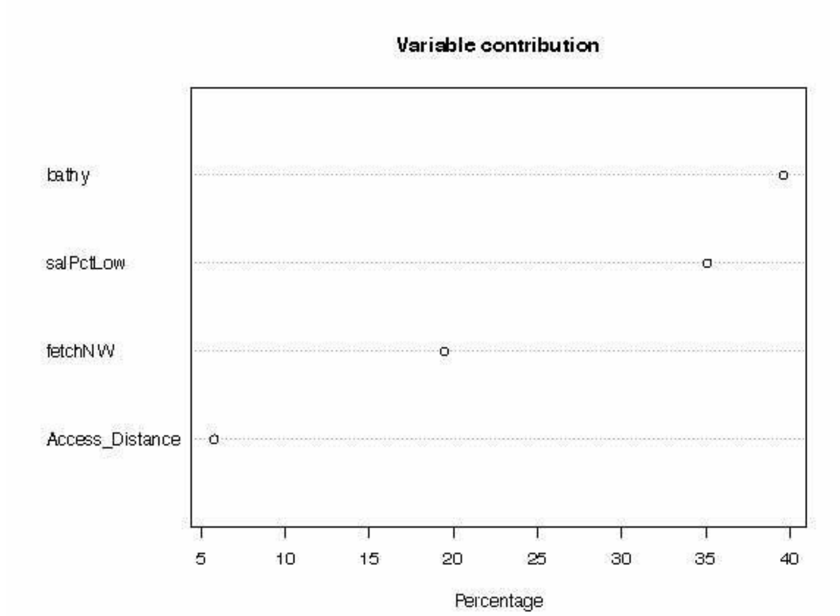

Figure 10: Feature contribution to submerged oyster aquaculture lease suitability model output.

This model was analyzed using the Boyce index (see SAV model results for description). A strong model generates a line with positive slopes, as was seen for the submerged land lease suitability model (Figure 11).

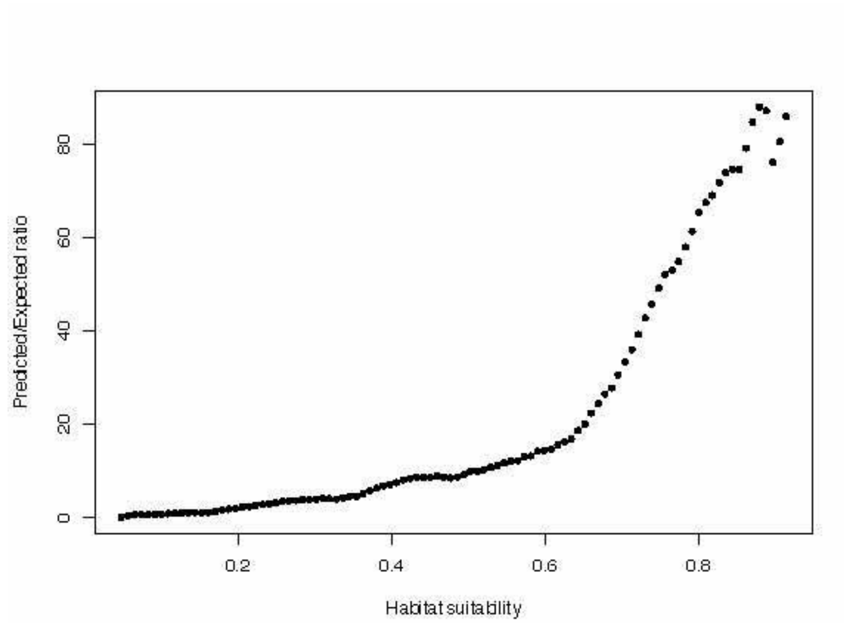

Figure 11: Boyce index for habitat suitability of submerged oyster aquaculture lease suitability model output.

Continuous model values, representing probability of submerged land lease presence, were broken into habitat suitability groups using Fisher-Jinks breaks. Any cell with a habitat suitability value less than 0.3 was considered unsuitable, anything between 0.3 and 0.7 was considered to have variable suitability, and anything greater than 0.7 was considered to have high suitability. These suitability thresholds were then checked against thresholds determined by the threshold function in dismo as a sensitivity analysis (Hijmans 2017). This analysis put the threshold between unsuitable and variable suitability habitat at 0.59. However, the projected leases and presence point leases were placed in the same proportion in/out of habitat (70/30). Further sensitivity analysis should be conducted on these findings.

A map of these data categories shows the spatial distribution of projected submerged land lease suitability throughout the Maryland portion of the Chesapeake Bay (Figure 12). Submerged land lease suitability increases in the further south regions of the Bay, particularly slightly into the mouths of tributaries.

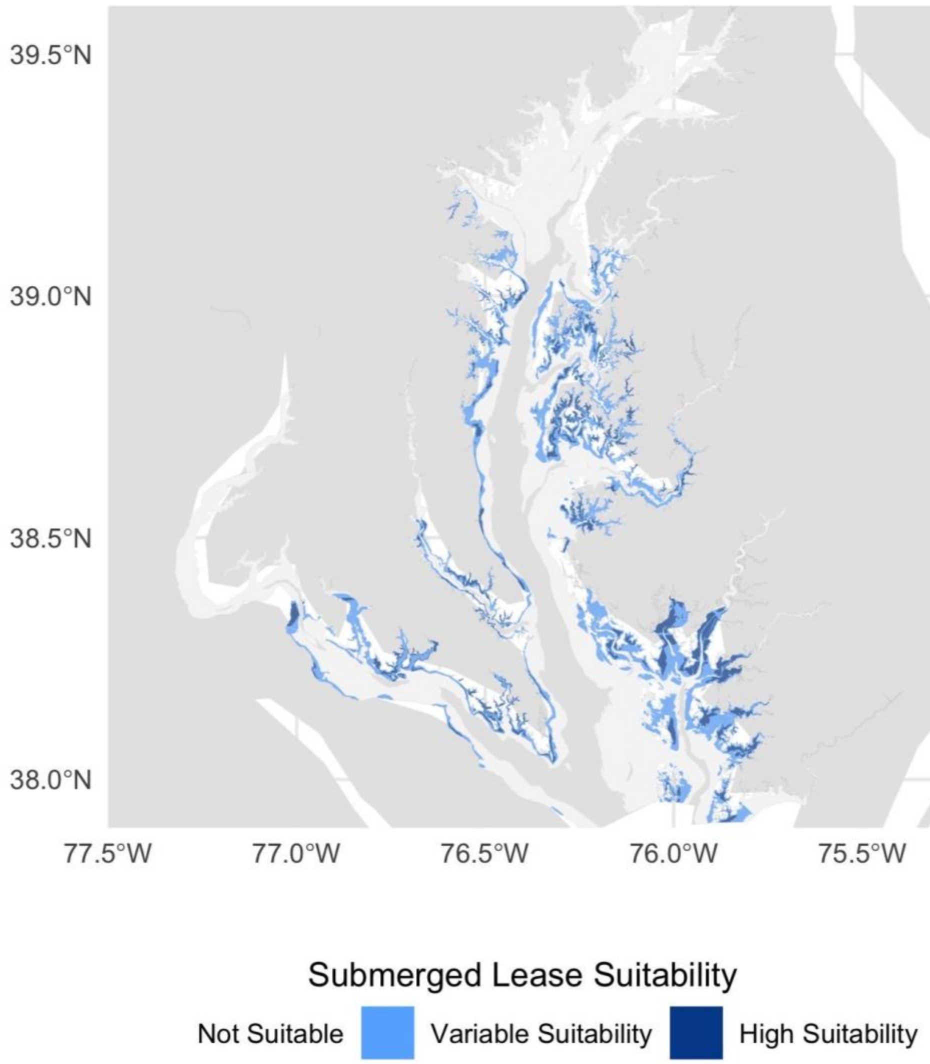

Figure 12: A map of Maryland's Chesapeake Bay submerged land lease suitability distribution, according to the MaxEnt analysis, categorized by habitat suitability value into not suitable (0-0.3), variable suitability (0.3-0.7), and high suitability (0.7-1).

Table 20: Summary of submerged land lease habitat suitability acreage.

Habitat Quality	**Acres**
Variable	251,978
High	71,636

MaxEnt: Water Column Leases

MaxEnt outputs from the analysis of the distribution of water column leases found that bathymetry (bathy) and salinity (SalPctLow) were leading covariates determining where water column leases were projected, with bathymetry being about 10% more important to water column lease suitability than submerged land lease suitability (Figure 13). Fetch direction is about 10% less important to water column leases than it is to submerged leases according to these models.

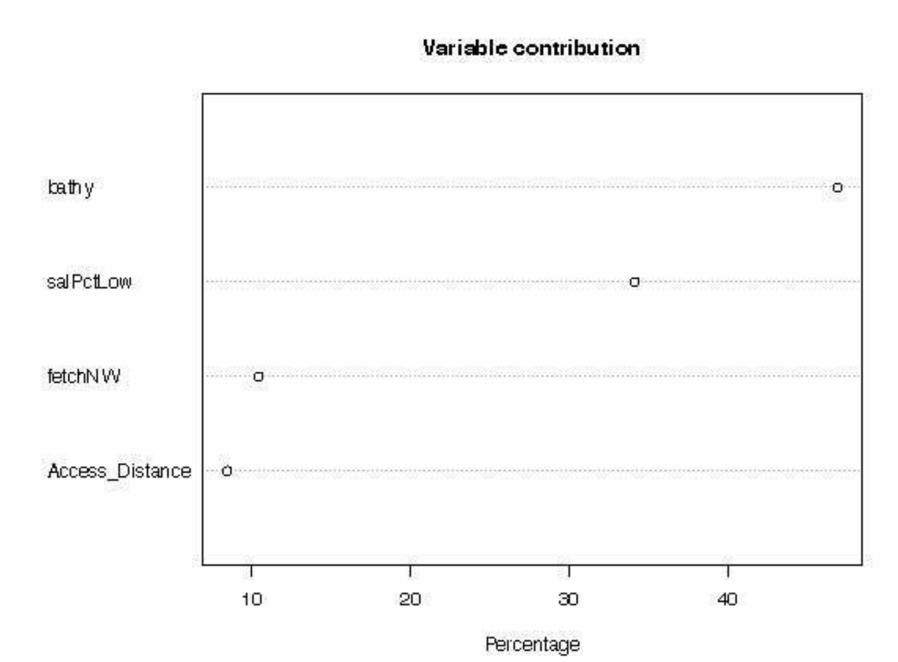

Figure 13: Variable contribution to water column oyster aquaculture lease suitability model output.

This model was analyzed using the Boyce index (see SAV model results for description). A strong model generates a line with positive slopes, as was seen for the water column lease suitability model (Figure 14). This model was less consistently positive than the other two MaxEnt models, likely because there are fewer presence points for water column leases.

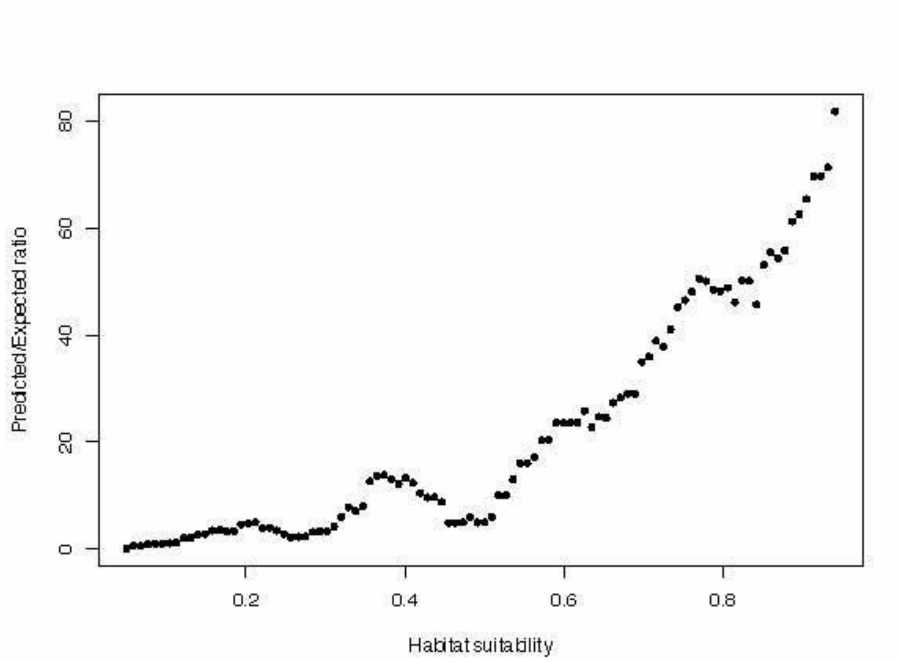

Figure 14: Boyce index for habitat suitability of water column oyster aquaculture lease suitability model output.

Continuous model values, representing probability of water column lease presence, were broken into habitat suitability groups using Fisher-Jinks breaks. Any cell with a habitat suitability value less than 0.4 was considered unsuitable, anything between 0.4 and 0.7 was considered to have variable suitability, and anything greater than 0.7 was considered to have high suitability. These suitability thresholds were then checked against thresholds determined by the threshold function in dismo as a sensitivity analysis (Hijmans 2017). Habitat thresholds were not sensitive to changes suggested by the dismo analysis.

A map of these data categories shows the spatial distribution of projected water column lease suitability throughout the Maryland portion of the Chesapeake Bay (Figure 15). Water column suitability seems to follow depth patterns more than any other distribution.

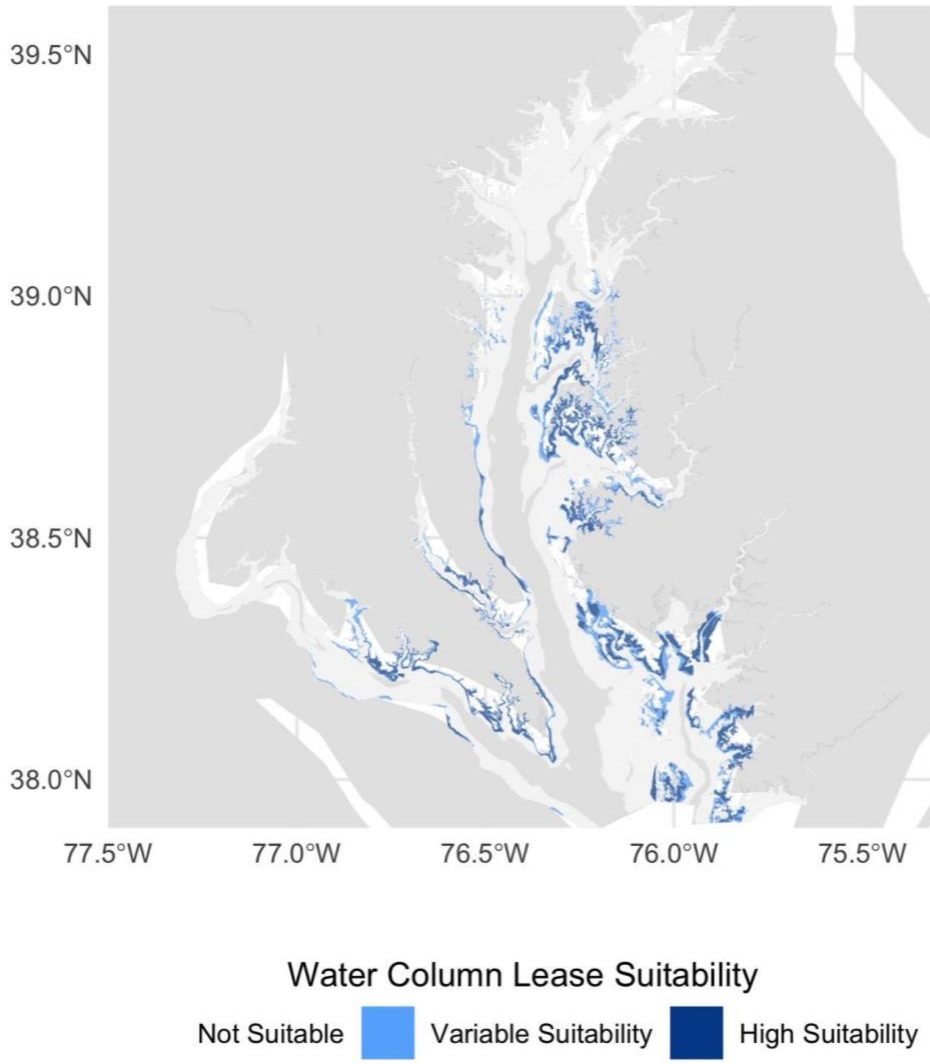

Figure 15: A map of Maryland's Chesapeake Bay water column oyster lease suitability distribution, according to the MaxEnt analysis, categorized by habitat suitability value into not suitable (0-0.4), variable suitability (0.4-0.7), and high suitability (0.7-1).

Overall, my models show 61% more acreage suitable for submerged leases than water column leases (Tables 19 and 20, respectively). Both project more acreage of high quality habitat than variable quality habitat.

Table 21: Summary of water column lease habitat suitability acreage.

Habitat Quality	Acres
Variable	114,375
High	82,978

Random Lease Placement

My random lease placement model found that policy and geospatial conditions support the largest industry by count of leases under the Unlimited Aquaculture policy, and the least under the SAV Protection policy (Table 22).

The only policy scenario under which the industry was reduced due to space limitations was the SAV Protection policy. Under these conditions, wherein aquaculture leases cannot be placed in projected SAV habitat of variable or high suitability, the water column industry essentially fails to exist, with only three water column leases successfully placed throughout all of Maryland's Chesapeake Bay.

Table 22: Count of randomly placed leases by policy scenario.

Policy Scenario		Count of Leases
Business as Usual (BAU)		
	Submerged	295
	Water Column	120
	Total	**415**
Aquaculture = Wild Harvest		
	Submerged	301
	Water Column	127
	Total	**428**
Habitat + Aquaculture Prod.		
	Submerged	297
	Water Column	120
	Total	**417**
Proposed BAU Adjustments		
	Submerged	296

	Water Column	120
	Total	**416**
Public Access		
	Submerged	296
	Water Column	120
	Total	**416**
SAV Protection		
	Submerged	227
	Water Column	3
	Total	**230**
Unlimited Aquaculture		
	Submerged	307
	Water Column	127
	Total	**434**
Wild Harvest		
	Submerged	294
	Water Column	120
	Total	**414**
Wild Harvest + Aquaculture		
	Submerged	306
	Water Column	127
	Total	**433**

Wild Harvest Model

According to the analysis from the wild harvest option value model, three policies result in scenarios where projected oyster aquaculture leases overlap with public shellfish fishery areas (PSFAs) (Table 23). For each scenario this results in about a 1% reduction in industry profits and anywhere from a 9-7% reduction in size. The greatest impact is seen under the policy scenario that allows oyster aquaculture leases to be sited anywhere in the Chesapeake Bay except areas restricted due to health concerns. This shows that oyster aquaculture would likely expand into areas of high value to the wild industry if those regions were available for leasing. However, seeing as this scenario shows greater loss than the Unlimited Aquaculture scenario suggests that there are areas other than PSFAs more suitable for leasing. Further analysis would need to be conducted to explore this.

Table 23: Count of projected leases by policy scenario.

Policy Scenario	**Acres of Bars Overlapped by leases**	**Percent of Total Wild Harvest Bars**	**Wild Harvest Revenue Lost ($)**	**Wild Harvest Revenue Lost (%)**
Aquaculture = Wild Harvest	5,125,452	9.4%	$150,791	1.3%
Unlimited Aquaculture	4,112,449	7.2%	$88,384	0.7%
Wild Harvest + Aquaculture	4,505,061	7.1%	$132,719	1.1%

Oyster Aquaculture Enterprise Budget

The oyster aquaculture enterprise budget found that water column leases in high suitability, shallow areas produce the greatest net profit at the individual farm level, assuming that the average firm is 17 acres and is consistent with the conditions described in the model (Table 24). The least profitable lease according to our model is a submerged land lease in a variable suitability area.

Table 24: Average firm net profit for each lease condition tested. Net profit is multiplied by count in Table 23 to produce industry total net profit in Table 25.

Gear	Suitability	Depth	Gross Total Income	Total Costs	Net Revenues

Submerged	High	NA	$98,397	$59,601	$ 38,796
Submerged	Variable	NA	$85,577	$59,104	$ 26,473
Water Column	High	Deep	$741,370	$335,901	$ 405,469
Water Column	Variable	Deep	$691,390	333,992	$ 357,396
Water Column	High	Shallow	741,370	315,182	$ 426,188
Water Column	Variable	Shallow	691,390	313,274	$ 378,116

Depth and habitat suitability influenced how profitable a water column lease is, while only suitability influenced how profitable a submerged land lease is in our scenarios. A deep lease is any lease deeper than 1.5m (4.9ft), to represent leases that cannot easily be accessed without a boat. Depth is irrelevant for bottom leases because they are all accessed by boat regardless of depth. Oyster lease mortality is 11% for high suitability leases and 17% for variable leases, based on a t-test comparison that found a relationship between MD DNR oyster disease bar mortality was related to habitat suitability with 99% confidence. The associated mortalities are the average annual adult oyster mortality for each categorization. For each policy scenario, the proportion of total leases per condition is given in Table 25. In every scenario, the submerged lease count is nearly double the water column count. Under the SAV Protection policy, the submerged lease industry has 76 times the number of leases that the water column industry has.

Table 25: Count of leases by lease type (gear), depth, and mortality per policy scenario with the net profits per average firm. These values are used to calculate the industry value by multiplying the average firm profits by count. Submerged and water column leases are calculated as separate industries.

Policy Scenario	Gear	Depth Category	Suitability	Count	Proportion of Industry
BAU					
	Submerged	NA[3]	High	193	0.65
	Submerged	NA	Variable	102	0.35
	Water Column	Deep	High	48	0.4
	Water Column	Deep	Variable	32	0.27
	Water Column	Shallow	High	16	0.13
	Water Column	Shallow	Variable	24	0.2
Aquaculture = Wild Harvest					
	Submerged	NA	High	197	0.65
	Submerged	NA	Variable	104	0.35
	Water Column	Deep	High	51	0.4
	Water Column	Deep	Variable	37	0.29
	Water Column	Shallow	High	19	0.15
	Water Column	Shallow	Variable	20	0.16
Habitat + Aquaculture Prod.					
	Submerged	NA	High	195	0.66
	Submerged	NA	Variable	102	0.34
	Water Column	Deep	High	27	0.23
	Water Column	Deep	Variable	20	0.17

[3] NA = Not Applicable. In these calculations, depth was not a condition taken into account for submerged leases

	Water Column	Shallow	High	37	0.31
	Water Column	Shallow	Variable	36	0.3
Proposed BAU Adjustments					
	Submerged	NA	High	195	0.66
	Submerged	NA	Variable	101	0.34
	Water Column	Deep	High	44	0.37
	Water Column	Deep	Variable	31	0.26
	Water Column	Shallow	High	20	0.17
	Water Column	Shallow	Variable	25	0.21
Public Access					
	Submerged	NA	High	195	0.66
	Submerged	NA	Variable	101	0.34
	Water Column	Deep	High	44	0.37
	Water Column	Deep	Variable	31	0.26
	Water Column	Shallow	High	20	0.17
	Water Column	Shallow	Variable	25	0.21
SAV Protection					
	Submerged	NA	High	79	0.35
	Submerged	NA	Variable	148	0.65
	Water Column	Deep	High	0	0
	Water Column	Deep	Variable	0	0
	Water Column	Shallow	High	0	0

	Water Column	Shallow	Variable	3	1
Unlimited Aquaculture					
	Submerged	NA	High	201	0.65
	Submerged	NA	Variable	106	0.35
	Water Column	Deep	High	50	0.39
	Water Column	Deep	Variable	32	0.25
	Water Column	Shallow	High	20	0.16
	Water Column	Shallow	Variable	25	0.2
Wild Harvest					
	Submerged	NA	High	193	0.66
	Submerged	NA	Variable	101	0.34
	Water Column	Deep	High	46	0.38
	Water Column	Deep	Variable	27	0.23
	Water Column	Shallow	High	18	0.15
	Water Column	Shallow	Variable	29	0.24
Wild Harvest + Aquaculture					
	Submerged	NA	High	197	0.64
	Submerged	NA	Variable	109	0.36
	Water Column	Deep	High	52	0.41
	Water Column	Deep	Variable	35	0.28
	Water Column	Shallow	High	17	0.13
	Water Column	Shallow	Variable	23	0.18

Analysis of policy scenarios using the oyster aquaculture enterprise budget shows that the Unlimited Aquaculture policy produces the largest industry net profits, which is expected as this is the scenario with the most leases and net profits increase linearly with lease count (Table 26). The only scenario with a significant loss in value is the SAV Protections scenario. Under SAV Protections, the industry only grows an additional $8M USD (2020), an 86% decrease in profits from the Unlimited Aquaculture scenario.

Table 26: Average firm net profit for each lease condition tested. Net profit (Table 24) is multiplied by count in Table 23 to produce industry net value.

Policy Scenario	**Gear**	**Depth Category**	**Suitability**	**Industry Net Value (2020 USD)**
BAU				
	Submerged	NA	High	7,487,530
	Submerged	NA	Variable	2,700,240
	Water Column	Deep	High	19,462,502
	Water Column	Deep	Variable	11,436,678
	Water Column	Shallow	High	6,819,011
	Water Column	Shallow	Variable	9,074,774
Total				$56,980,736
Aquaculture =				

Wild Harvest				
	Submerged	NA	High	7,642,712
	Submerged	NA	Variable	2,753,186
	Water Column	Deep	High	20,678,909
	Water Column	Deep	Variable	13,223,659
	Water Column	Shallow	High	8,097,576
	Water Column	Shallow	Variable	7,562,312
Total				$59,958,353
Habitat + Aquaculture Prod.				
	Submerged	NA	High	7,565,121
	Submerged	NA	Variable	2,700,240
	Water Column	Deep	High	10,947,657
	Water Column	Deep	Variable	7,147,924
	Water Column	Shallow	High	15,768,963
	Water Column	Shallow	Variable	13,612,161
Total				$57,742,067
Proposed BAU Adjustments				

	Submerged	NA	High	7,565,121
	Submerged	NA	Variable	2,673,767
	Water Column	Deep	High	17,840,627
	Water Column	Deep	Variable	11,079,282
	Water Column	Shallow	High	8,523,764
	Water Column	Shallow	Variable	9,452,890
Total				$57,135,451
Public Access				
	Submerged	NA	High	7,565,121
	Submerged	NA	Variable	2,673,767
	Water Column	Deep	High	17,840,627
	Water Column	Deep	Variable	11,079,282
	Water Column	Shallow	High	8,523,764
	Water Column	Shallow	Variable	9,452,890
Total				$57,135,451
SAV Protection				
	Submerged	NA	High	3,064,844
	Submerged	NA	Variable	

				3,917,996
	Water Column	Deep	High	-
	Water Column	Deep	Variable	-
	Water Column	Shallow	High	-
	Water Column	Shallow	Variable	1,134,347
Total				$8,117,186
Unlimited Aquaculture				
	Submerged	NA	High	7,797,893
	Submerged	NA	Variable	2,806,132
	Water Column	Deep	High	20,273,440
	Water Column	Deep	Variable	11,436,678
	Water Column	Shallow	High	8,523,764
	Water Column	Shallow	Variable	9,452,890
Total				$60,290,797
Wild Harvest				
	Submerged	NA	High	7,487,530
	Submerged	NA	Variable	2,673,767
	Water Column	Deep	High	

				18,651,565
	Water Column	Deep	Variable	9,649,697
	Water Column	Shallow	High	7,671,388
	Water Column	Shallow	Variable	10,965,352
Total				$57,099,299
Wild Harvest + Aquaculture				
	Submerged	NA	High	7,642,712
	Submerged	NA	Variable	2,885,551
	Water Column	Deep	High	21,084,377
	Water Column	Deep	Variable	12,508,867
	Water Column	Shallow	High	7,245,199
	Water Column	Shallow	Variable	8,696,659
Total				$60,063,365

Hedonic Model

Analysis from the hedonic model application found that a total of 6,131 single family residences fall within 50m of the shoreline throughout the counties in Maryland that host oyster aquaculture in their Bay waters (Table 27). The Public Access policy impacts the greatest number of these parcels, with 8% of all considered parcels losing value due to oyster aquaculture lease placements (Figure 16). The SAV Protection policy causes the lease value loss to riparian properties, as it prevents leases from being placed within 500m of the shoreline in every county. Somerset County experiences the greatest number of properties impacted most often (in 4 out of the 8 scenarios), while Talbot County experiences the greatest total loss in residential (R) property value (roughly $18M USD under the Unlimited Aquaculture policy scenario) (Figure 17). This finding holds true even when you convert dollars to percentage of total county parcel worth (Figure 18). The Public Access policy causes the greatest total property value loss in 2020 USD of all policies. Again, SAV Protection causes the least at $0 value lost. The second least value loss occurs under the Wild Harvest + Aquaculture policy in 2020 USD.

Table 27: Count of residential, single-family parcels that fall within 50m of the shoreline.

County	Count of houses within 50m of shoreline
Anne Arundel County	2469
Calvert County	558
Charles County	239
Dorchester County	347
Kent County	296
Queen Anne's County	592
Somerset County	247
St. Mary's County	810
Talbot County	477
Wicomico County	96

Impact of Policy Scenarios on Considered Parcels (By Count)

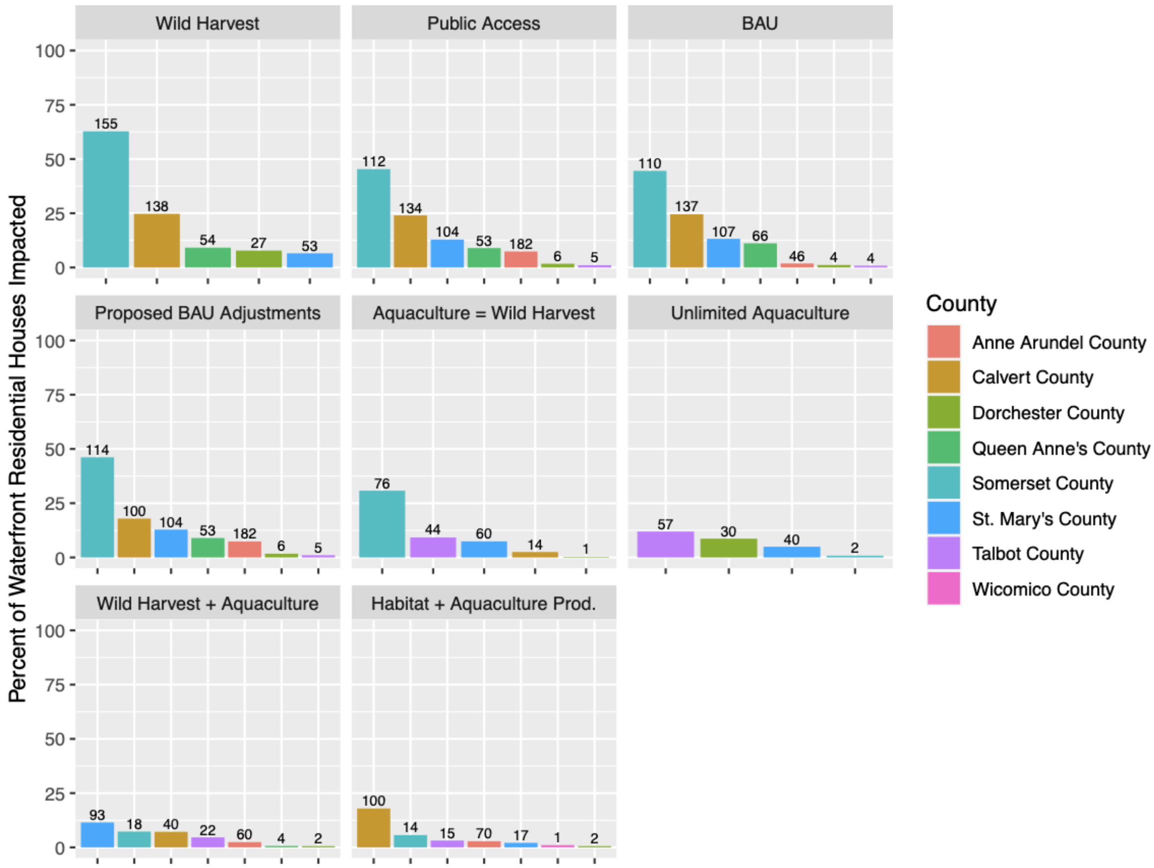

Figure 16: Count (above bars) and percent (Y-axis) of considered parcels impacted by policy, broken down at the county level. Policy facets are ordered from percent of county parcels impacted to least (upper left to lower right). SAV Protection policy is not shown because this policy prevented any considered parcels from losing value due to additional oyster lease siting over the next 15 years.

Impact of Policy Scenarios on Counties (By 2020 USD)

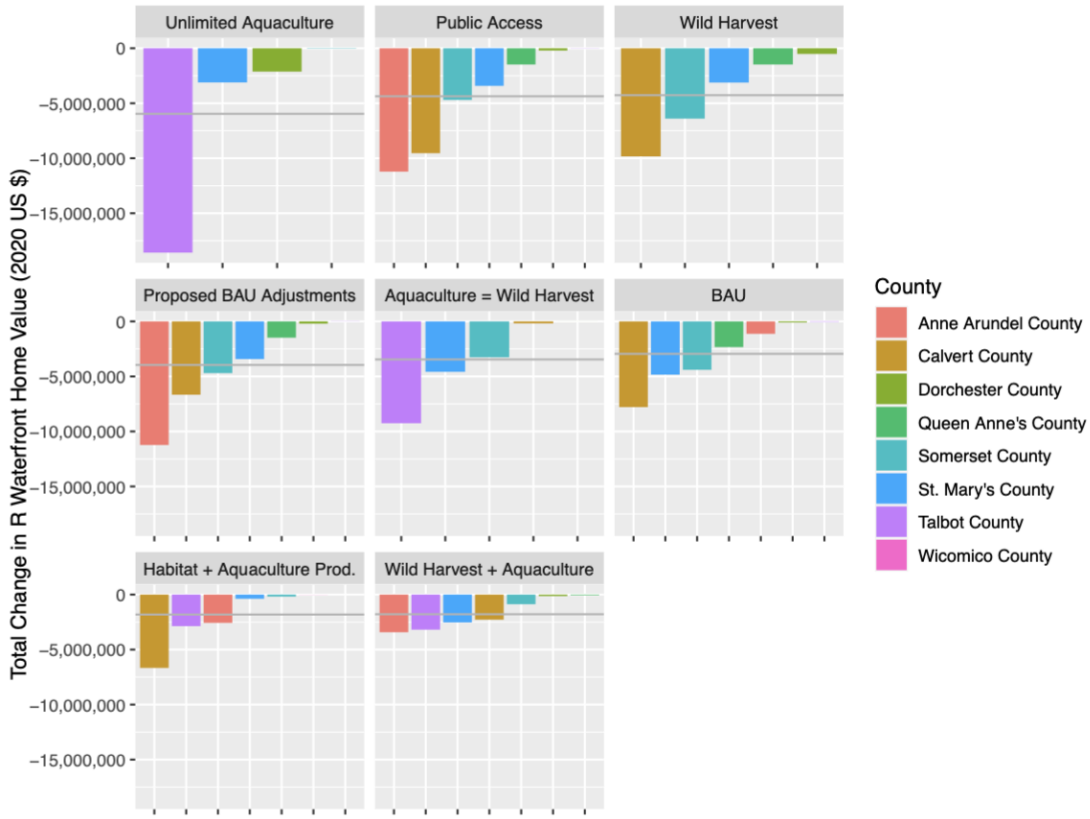

Figure 17: Total change, in 2020 USD, of property value loss by policy, broken down at the county level. Policy facets are ordered greatest single county total loss to least (upper left to lower right). The gray bar represents the average dollar value lost across all counties. SAV Protection policy is not shown because this policy prevented any considered parcels from losing value due to additional oyster lease siting over the next 15 years.

Impact of Policy Scenarios on Total County Housing Value (Percentage)

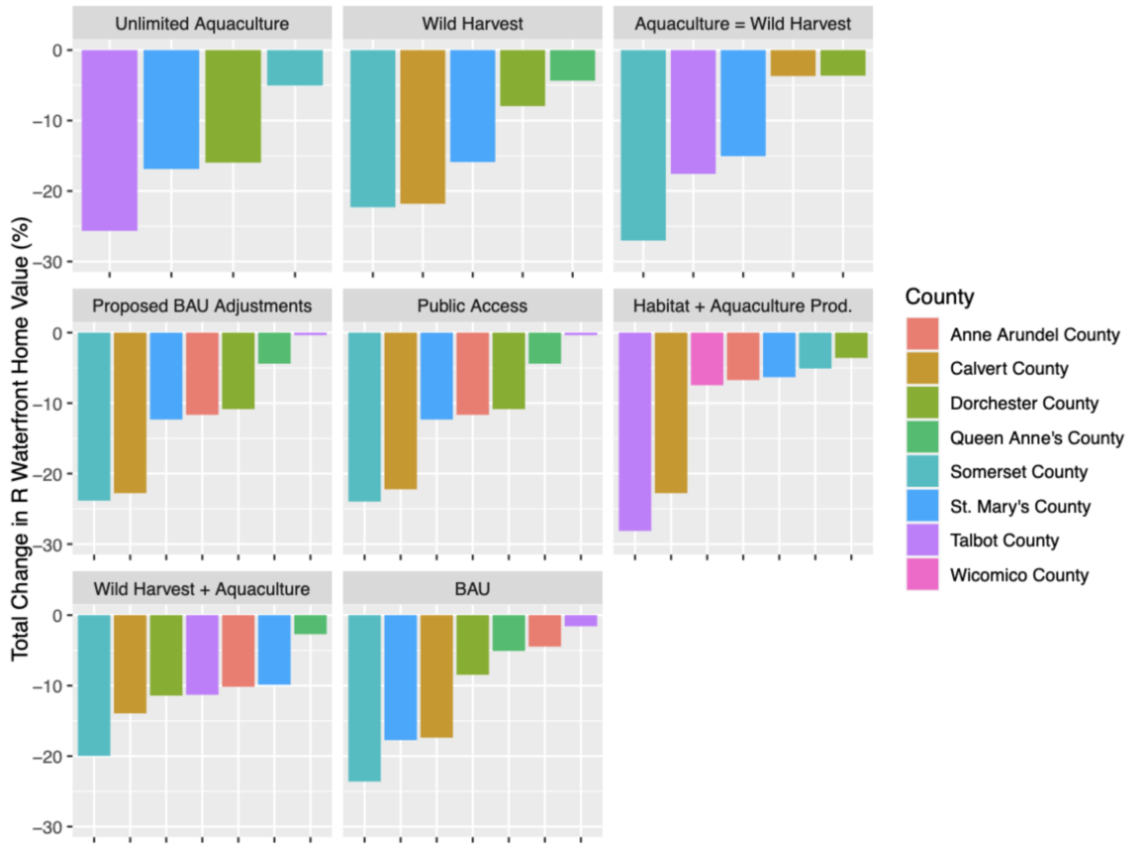

Figure 18: Total percent of home value loss per county by policy scenario. SAV Protection policy is not shown because this policy prevented any home value loss over the next 15 years.

Public Water Access Model

The public water access model found that of the total boat access sites in the evaluated counties (72), none had leases within 70’ of them (21.3m) under any policy scenario and no more than 4 (6%) had leases within 1500’ of them (457m) (Table 28). The Proposed BAU Adjustments and Wild Harvest policies had the greatest impact on public access sites, with each hosting 4 aquaculture farms within 1500’ of them. The SAV Protection policy was the only policy that did not host a lease with 1500’ of a public boat access site.

Table 28: Count of public boat access sites with a lease obstruction at 1500’.

Policy Scenario	Count of Impacted Access Sites	Count of Total Access Sites
BAU	3	72
Aquaculture = Wild Harvest	3	72
Habitat + Aquaculture Prod.	2	72
Proposed BAU Adjustments	4	72
Public Access	3	72
SAV Protection	0	72
Unlimited Aquaculture	2	72
Wild Harvest	4	72
Wild Harvest + Aquaculture	3	72

Intermediate Results: Weighting

Results from our stakeholder workshop and questionnaire show that, on average, stakeholders value the conservation of sensitive species and their habitat more than other considered aspects of wellbeing associated with the shallow waters of Maryland's Chesapeake Bay (32.57) (Table 29). Riparian property value protection scored the lowest (12.11) of all considered aspects of wellbeing. Overall, the aspects considered broke into three groupings (in order of importance): Conservation of habitat; oyster aquaculture potential and safe access to the water; and private homeowner value and wild harvest.

Table 29: The scores of each value according to the post-workshop values submitted by stakeholders on their questionnaire.

Aspect of Wellbeing	Average Weight Score	Maximum Weight Score	Minimum Weight Score
Growth potential of wild oyster harvest	12.77	30	5
Safe boating access to the Bay	20.21	57	5
Growth potential of the oyster aquaculture industry	22.34	58	5
Riparian property value protection	12.11	30	0
Conservation of sensitive species and their habitat	32.57	88	15

Scenario Outcomes

This project finds that policies that conserve sensitive species and their habitat (SAV Protection, then Habitat + Aquaculture Production) outperformed all other considered policies when the average of stakeholder preference weights are used to weight the normalized BRIs to create a composite index score per policy (Table 30, Table 33). Interestingly, while the BAU policy ranks third best, the Proposed BAU Adjustments policy ranks lowest by far. A final summary table of non-normalized criteria values can be found in Table 31, and the impact normalizing had on them is represented in Table 32. Weighting by average stakeholder preferences did not change the order of policy scenario performance relative to a ranking based on the BRI scores. However, weighting by values when aquaculture production is prioritized moves the Habitat + Aquaculture Production to the top position, outranking the next (BAU) by 30 points. This change in weighting aslo pushes the SAV Protection policy down to third to last place. This indicates that a sensitivity analysis needs to be conducted on different weight applications to final indicator metrics.

Table 30: Policy scenario outcomes, ranked by their composite index (normalized, weighted and summed) score, from most protective of wellbeing to least protective. Weights are the average stakeholder group weight.

Scenario	Score
SAV Protection	77.66
Habitat + Aquaculture Prod.	75.50
BAU	61.72
Public Access	57.13
Proposed BAU Adjustments	53.21
Wild Harvest	52.77
Unlimited Aquaculture	43.90
Wild Harvest + Aquaculture	37.78
Aquaculture = Wild Harvest	27.60

Table 31: Policy scenario outcomes, ranked by their composite index scores. Weights are the average stakeholder group weight, except aquaculture production, which is the maximum score in this table. Scores are rescaled from 0-100.

Scenario	Score
Habitat + Aquaculture Prod.	100
BAU	70.07
Public Access	60.40
Proposed BAU Adjustments	52.12
Wild Harvest	51.59
Unlimited Aquaculture	33.58
SAV Protection	30.41
Wild Harvest + Aquaculture	20.51
Aquaculture = Wild Harvest	0.00

Table 32: Summary of raw BRI performance metrics under each scenario.

Scenario	Cover of a Low Year for SAV (2020) Not Overlapping with Leases (%)	Housing Value Changes ($2020USD, M)	Count of Public Boat Launches Impacted	Weighted Average Net Value	Wild Harvest Value Lost
BAU	98.67	20.6	3	137,303	$ 0
Aquaculture = Wild Harvest	97.02	17.3	4	140,090	$ 150,791
Habitat + Aquaculture Prod.	99.61	12.7	3	138,470	$ 0
Proposed BAU Adjustments	98.61	27.7	4	137,345	$ 0
Public Access	98.61	30.6	3	137,345	$ 0
SAV Protection	99.97	0	0	35,292	$ 0
Unlimited Aquaculture	97.36	23.8	2	138,919	$ 88,384
Wild Harvest	98.33	21.3	4	137,921	$ 0
Wild Harvest + Aquaculture	97.20	12.5	3	138,714	$ 132,719

Table 33: Summary of normalized (0 to 1) BRI performance metrics under each scenario. The greater the score, the more extreme the outcome from that policy.

Scenario	Cover of a Low Year for SAV (2020) Not Overlapping with Leases (%)	Housing Value Changes ($2020USD, M)	Count of Public Boat Launches Impacted	Weighted Average Net Value Aquaculture Industry	Wild Harvest Value Lost	Score
BAU	0.44	0.67	0.75	0.03	0.00	1.62
Aquaculture = Wild Harvest	1.00	0.57	1.00	0.00	1.00	3.57
Habitat + Aquaculture Prod.	0.12	0.41	0.75	0.02	0.00	1.18
Proposed BAU Adjustments	0.46	0.91	1.00	0.03	0.00	2.08
Public Access	0.46	1.00	0.75	0.03	0.00	1.93
SAV Protection	0.00	0.00	0.00	1.00	0.00	1.00
Unlimited Aquaculture	0.88	0.78	0.50	0.01	0.59	2.59
Wild Harvest	0.56	0.70	1.00	0.02	0.00	1.88

Wild Harvest + Aquaculture	0.94	0.41	0.75	0.01	0.88	2.93

Table 34: Summary of scaled, weighted BRI performance metrics under each scenario. The greater the score, the better that policy performed at protecting identified aspects of wellbeing associated with Maryland's shallow waters in the Chesapeake Bay. A zero score indicates that it was the minimum value when scaled (Table 30).

Scenario	Cover of a Low Year for SAV (2020) Not Overlapping with Leases (%)	Housing Value Changes ($2020 USD, M)	Count of Public Boat Launches Impacted	Weighted Average Net Value Aquaculture Industry	Wild Harvest Value Lost	Score
BAU	18.22	3.94	5.05	21.75	12.77	61.72
Aquaculture = Wild Harvest	0.00	5.26	0.00	22.34	0.00	27.60
Habitat + Aquaculture Prod.	28.60	7.09	5.05	21.99	12.77	75.50
Proposed BAU Adjustments	17.55	1.13	0.00	21.75	12.77	53.21
Public Access	17.55	0.00	5.05	21.75	12.77	57.13
SAV Protection	32.57	12.11	20.21	0.00	12.77	77.66
Unlimited Aquaculture	3.75	2.66	10.11	22.09	5.29	43.90

Wild Harvest	14.46	3.65	0.00	21.88	12.77	52.77
Wild Harvest + Aquaculture	1.99	7.16	5.05	22.05	1.53	37.787

Chapter 4: Summary and Discussion

Summary of Findings and Comparisons

This research applied an MCDA approach to evaluating alternative policies for oyster aquaculture lease siting in Maryland's Chesapeake Bay. Through this analysis, I found (1) policies intending to conserve SAV have little impact on SAV acreage but risk significant trade offs with the future of the oyster aquaculture industry in Maryland; (2) the proposed adjustment to the BAU oyster aquaculture policy (Proposed Adjustments to BAU) is less balanced than the current policy (BAU); (3) wild harvest bars may be at lower risk from oyster aquaculture expansion than has been historically claimed.

Though the SAV Protection policy was the top performing policy scenario by indicator values, it only protected at most 3% of SAV acreage from oyster aquaculture lease conflicts, while reducing the oyster lease industry by 87% and preventing water column lease placements nearly entirely (Table 26). This indicates that while SAV acreage at large is not sensitive to oyster lease overlaps, the oyster industry is at risk of significant impacts from SAV policy protections.

Seeing as the SAV Protection policy and the Habitat + Aquaculture Production policy scored similarly (Table 30), and both are intended to conserve sensitive species and their habitats at varying levels of compromise with the oyster aquaculture industry, the Habitat + Aquaculture Production policy may be the policy that maximizes wellbeing because it enable aquaculture growth for only an 3% effect on SAV. Differences between SAV Protection and the Habitat + Aquaculture Production policies include a 10-fold increase in the shoreline spatial buffer restrictions under the SAV Protection policy compared to its counterpart, and the detail that in the Habitat + Aquaculture Production policy oyster leases may be sited within SAV variable habitat suitability areas, but cannot be sited in high quality SAV habitat under any circumstances.

Future work exploring the sensitivities of stakeholder preferences under differing magnitudes of benefits, such as through swing weighting, may capture stakeholder willingness to accept small losses of sensitive habitats in exchange for substantial aquaculture industry growth (which was the second highest priority for stakeholders but had a much lower weight). Swing weights are used to examine whether weights vary by the magnitude of change in an outcome. If stakeholders did not consider the magnitude of SAV habitat overlap significant in some scenarios, then the weight on SAV would decrease when effects were small, enabling other weights, such as aquaculture, to increase, thereby changing the policy scenario ranking. Further, the results of using alternative stakeholder weights that prioritized aquaculture (Table 31) caused Habitat + Aquaculture scenario to receive the highest score and indicated that policy rankings are sensitive to weights and they should be further explored Further, this work did not measure potential positive or negative feedbacks between SAV and oysters because applicable models and findings are still in progress through other projects. However, we know that oysters reduce nutrient concentrations in water (Bricker 2017) and that a reduction in nutrients can lead to improving water clarity, which supports SAV expansion (Orth 2010).

A second interesting finding is that the BAU oyster aquaculture policy performed third highest under the defined criteria of this project and average stakeholder weights, while the Proposed Adjustments to BAU scenario performed second to last. Adjustments to the BAU scenario have been proposed to better protect health, recreational, and aquaculture industry concerns, but this analysis shows that they may in fact be inducing more harms, specifically to homeowner values. Though a sensitivity analysis has not been conducted on this finding, a potential explanation for the Proposed Adjustments scenario performance on home values is that, because itimposes a larger shoreline buffer to oyster lease siting, it results in higher housing value impacts due the larger price effects at the larger buffer sizes. A larger impact from visible leases at farther distances is a reasonable expectation for two reasons. First, visual aesthetic studies suggest that the larger a viewshed, the more sensitive a homeowner may be to perceived infractions to it, compared to smaller or more "cluttered" viewsheds where homeowners may be less sensitive to additional visual disruptions (Vukomanovic 2014). Secondly, this result could reflect an omission of elevation analysis in the original model. If riparian houses sit at substantial elevation above the water, they would more easily see infrastructure at a distance rather than close to shore. Until we have a better understanding of why updates to BAU policies are increasing harms across criteria, it is an important consideration to draw out in the context of shifting oyster lease siting policies in Maryland.

That being said, the relatively high ranking of the BAU scenario suggests that the current process of negotiating aquaculture policy largely captures the values of those with access to policy making process. The MCDA similarly captured known concerns of the loudest voices aiming to influence aquaculture siting policy and represented existing power structures, so it is not surprising that it generated a high score for the BAU. Neither method uses a fully representative process to characterize what Maryland residents might value, nor does it examine how minority voices are being represented in the policy process.

Additionally, this study reveals that the wild harvest revenues may be at relatively low risk from oyster aquaculture expansion. As explained in the introduction, a major barrier to the acceptance and implementation of oyster leasing in Maryland has been the concerns of watermen who assert oyster leasing will inundate PSFAs and limit future increases in the wild oyster harvest industry. A key finding of this research that calls that assumption into question is the comparison between the outcome from the Aquaculture = Wild Harvest scenario and the Unlimited Aquaculture scenario. In the former, aquaculture policy restrictions follow those of the Wild Harvest wherein the only spatial restrictions are for oyster sanctuaries and bacterial exclusion zones. In the latter, oyster leases can be placed anywhere except bacterial exclusion zones. When oyster aquaculture has nearly all siting policies removed from it, but still aims to be within reasonable habitat suitability, we see it overlap with the wild oyster industry 2.2% less spatially and captured a 87% smaller impact on wild harvest revenues than when aquaculture is held to the same spatial restrictions as the wild harvest. This suggests that oyster aquaculture siting may not actually be ideal in PSFAs, and thus would not cause much harm to the wild oyster industry. To further explore this, future research should consider both the profitability of each PSFA and the true randomness of the lease placements.

Uncertainties Due to Data or Model Limitations

This research encompasses three stakeholder engagement aspects, seven quantitative models, and normalization and weighting techniques, making it sensitive to data availability and calculations. While the following thoughts are not exhaustive, they do represent some of the significant decisions and conversations that occurred throughout this process. Several of these models have the potential to err on the side of larger effects to non-aquaculture stakeholders, meaning that many outcomes likely represent an overestimate of harms to other Chesapeake Bay uses that may be associated with oyster aquaculture in Maryland's Chesapeake Bay.

In regards to stakeholder engagement and data collection, I recognize that my pool of representatives were nearly exclusively governmental representatives and academics. These voices are meant to represent large groups of individuals through their professional commitment to working as public servants on behalf of the people. Though governmental voices have the professional responsibility to represent the values of their constituents, this duty is met differentially across identities of both individual people and individual institutions and may have biased my results. A slightly larger group with multiple representatives within each institution could have provided this project with replication within institutions, which would have helped capture the range of views on these values. Furthermore, with expanded time and funding resources, stakeholders could have included a greater diversity of backgrounds and identities, as well as a more iterative process. Additionally, this research was not able to capture swing weights which, as stated earlier, would clarify the magnitude of changes in values that stakeholders are willing to accept within a tradeoff. However, we do see that applying different weights to the tested aspects of wellbeing would produce a different hierarchy of alternatives (Tables 30 & 31). Capturing swing weights in future work will help capture the magnitude of tradeoff that differing stakeholder groups are comfortable with.

In regards to model methodology, outcomes from all five indicator-specific models are dependent not only on where leases cannot go, but more specifically where the random lease projections placed leases. This work would be strengthened by further analyzing the randomness of the seeds applied in my randomness code through analysis such as a Monte-Carlo analysis. In a similar vein, few to no sensitivity analyses have been conducted on my final dashboard of findings (Tables 30-32). Finally, this project estimates that all leases regardless of gear type are 17 acres, which is the average size of all leases according to the MD DNR leasing data from March 2021. However, there are no water column leases in Maryland as of 2021 that are that size or larger, and thus many of the production values are only viable as relative comparison points within this study.

There are also data gaps in this analysis that could influence outcomes. I did not find data on recreational boat use on the Bay, and may not be adequately capturing recreational impacts from oyster leasing by examining effects on boat launches. In the public access data that I did use, there was no information on use activity that could be used to estimate site specific impacts, such as how many parking spaces a public launch has to indicate its expected use capacity. Many of the data applied in the enterprise budget are preliminary and estimated from tangentially, but not directly, related studies, particularly regarding operating costs under varying site conditions.

Multi-Criteria Decision Analysis: Abilities and Omissions

As mentioned in the introduction, MCDA is a useful decision support tool but cannot responsibly represent aspects of wellbeing that are inappropriate to trade off with each other, such as the continuation of a culture or existence of a people. In the context of this study that is particularly relevant to impacts on watermen communities that Maryland coastal planning can incur, as their heritage and sense of identity are closely tied to the existence of the wild harvest industry, regardless of its profitability. I also did not capture or attempt to capture spiritual or ancestral values associated with shallow water uses in Maryland's Chesapeake Bay that vary across communities and geographies.

Managing Coastal Use Conflicts

This work captures the consequences of the SAV/oyster aquaculture policy conflict – one which is often discussed among people familiar with the oyster aquaculture industry, but until this study had not been quantified. This project also sheds light on how applying decision science techniques to long-standing policy conflicts, such as how the wild oyster harvest industry could be impacted by oyster aquaculture, quantifies policy outcomes and bounds a problem using data to support decision-making.

While the conflicts explored in this work are contextualized to Maryland, parallel coastal use conflicts occur throughout the country and the world. Ongoing work along the Northeastern and Western coasts of the United States is being explored to understand the impacts that aquaculture scale and practices are having on coastal systems. In the summer of 2020, the Army Corps of Engineers retracted shellfish farming permits in the face of public protest and use concerns, particularly around concerns for eelgrass protections.

As global coastal populations grow and our use of coastal shallow waters increasingly involves novel technologies to address dietary and energy needs, there is an increasing need to implement decision science techniques in marine spatial planning to support data-informed decisions and policies that can account for more than just monetary values.

Appendices

Appendix 1: Stakeholder Questionnaire

Appendix 2: Housing Analysis Code

Appendix 3: MaxEnt Output for SAV Habitat Suitability

Appendix 4: MaxEnt Output for Water Column Lease Habitat Suitability

Appendix 5: MaxEnt Output for Submerged Land Lease Habitat Suitability

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