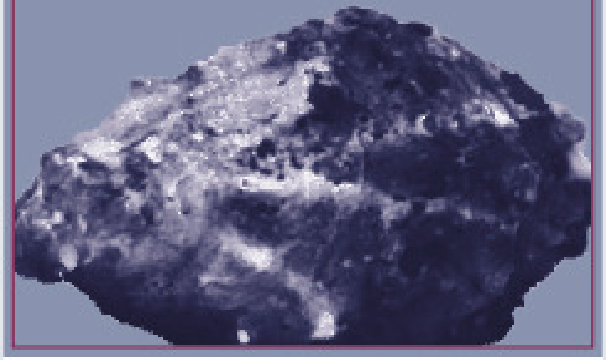
Estimating Net Present Value in the Northern Chesapeake Bay Oyster Fishery



Prepared for
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
CHESAPEAKE BAY OFFICE
GRANT # NA05NMF4571231

By
MAIN STREET ECONOMICS
Independent Economic Analysis

ESTIMATING NET PRESENT VALUE
in the
NORTHERN
CHESAPEAKE BAY
OYSTER FISHERY

Prepared for

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

CHESAPEAKE BAY OFFICE

NON-NATIVE OYSTER RESEARCH PROGRAM

GRANT # NA05NMF4571231

Robert Wieland

Main Street Economics

PO Box 11 • Trappe, Maryland • 21673

www.mainstreeteconomics.com

and

Steve Kasperski

University of Maryland

Department of Agricultural and Resource Economics

Submitted: June 20, 2008

Revised: November 7, 2008

Acknowledgements

This paper was funded by the NOAA Chesapeake Bay Office's Non-native Oyster Research Program. Special thanks are due Jamie King, who managed that program. Her support for this work was essential to its accomplishment. The authors also thank Chris Dungan and Doug Lipton who read and commented on earlier drafts of the paper and the Non-native Oyster EIS Review Panel for their comments on the final draft. While these and other reviewers have provided useful comments, any errors and omissions that remain are the responsibility of the authors.

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1. Introduction

Oyster stocks in the Chesapeake Bay provide value to people in several ways. In the most obvious sense as a fishery resource, they generate value along a market channel that begins with harvesters[1] and continues through wholesalers, processors and retailers up to their ultimate consumption. In a somewhat less apparent sense, oysters play an important role in the ecosystem of which they are a part, and those services work through to people in such benefits as improved fishing, improved water clarity, and greater ecological diversity. Although markets for these ecological services do not exist, there are methods for imputing values for them as described in Hicks and others (2004).

Given the decline in oyster harvests over the past 26 years, the current fishery is clearly worth much less than it used to be. In simplest terms, the 1982 Maryland harvest of 2.309 million bushels had a value in constant 2000 dollar terms of $36.55 million. The 2007 harvest of 0.165 million bushels had a value (in 2000 constant dollars) of $4.27 million. Considering these endpoints for gross sales, the harvest value has declined by 88 percent over the period. But this does not capture the full loss of value, even with respect to only the commercial value of oyster stocks.

Because oyster stocks are a renewable resource, their commercial value does not reside solely in the current year's harvests. Future harvests are implicit in the resource, and these form part of the value of oyster stocks. In renewable resource markets with well-defined property rights, optimal harvests are typically imagined as periodic withdrawals that maximize the net present value of the resource. Net present value of oyster stocks (ignoring for the moment environmental benefits) is just the sum of present harvest value, net of harvest costs, and the discounted expected net returns of future harvests.

Net present value is largely dependent on the interest rate, stocks, and the rate at which stocks grow. Product prices and harvest costs also enter into the calculation but, for a biological resource that grows fairly rapidly and is highly fecund, net present value is largely determined by how much of the stock can be taken in the current period without undermining the stream of value anticipated from future harvests.

Although the maximization of net present value of commercial harvests is a useful conceptual starting place, since the Chesapeake Bay oyster fishery is managed in large part as an "open-access" resource, market incentives do not drive outcomes in that direction. Rather, because profits can be had harvesting even a diminished oyster stock, and because whatever one harvester does not take, another may, the harvest industry is burdened with an unfortunate incentive to fish away the natural resource rents (profits) inherent in a maximum net present value of the fishery. In the discussion that follows we will assume an alternative management regime for our estimates of the net present value of the commercial fishery.

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[1] While this market channel could be argued to start prior to harvest, to the extent that public sector entities invest in the production of oysters on the bottom for watermen to harvest, the present paper does not account those production costs. For a discussion of those costs see Wieland (2008)

In addition to the watermen who harvest oysters, firms that aggregate, process, and retail oysters have suffered from the decline in the oyster resource. To the extent that oysters can be gotten from other sources, the impacts of reduced Chesapeake Bay harvests on consumers, processors and retailers are mitigated, somewhat. But it is clear from the decline in the Chesapeake Bay oyster packing industry (Lipton and Kirkley, 1994) that the decline in the local fishery has significant negative effects on that part of the market. Firms that sell and service the equipment necessary to harvest and process oysters have also suffered losses from the decline in oyster harvesting. Oysters harvested elsewhere do not help these support industries.

A complete measure of the value of oyster stocks needs to also account contributions from the ecological services provided by those stocks. Cerco and Noel (2007) address potential environmental gains from a ten-fold increase in existing oyster biomass and project that such an increase would generate a reduction of system-wide summer surface chlorophyll by about 1 mg per cubic meter of water; increase deepwater dissolved oxygen by 0.25 g. per cubic meter; add 2,100 kg of carbon to summer submerged aquatic vegetation; and remove 30,000 kg of nitrogen per day through denitrification. These benefits could substantially improve ecosystem function in regions of the Bay, generating benefits to people with respect to fishing, water quality and ecological diversity.

The goal of this paper is to address the net present value of oyster stocks with respect to commercial and environmental benefits under different management scenarios. This objective is complicated by several factors. Pre-eminently, neither oyster stocks nor stock change are precisely known. Several estimates have been made for oyster stocks in the Chesapeake Bay[2] but, because of the practical difficulty of accounting a large amount of Bay bottom that can only be imperfectly sampled, there is a lot of uncertainty in those estimates. Secondly, oyster stocks in the Chesapeake Bay are now in a state of collapse. Hence, whatever uncertainty there might have been about stocks and stock change under normal conditions is likely amplified under the current, exceptional circumstance.

While limitations in the scientific understanding of oyster stocks and their change over time are important to recognize, recent empirical and analytical research has extended the understanding of some of the factors that drive stock change, with particular respect to habitat, disease and recruitment. Moreover, commercial prices are fairly stable, as are production costs. Interest rates are known. An economic estimate of the net present value of the oyster fishery requires a growth rate for stocks and one is proffered in the discussion below. If, as is hoped, better estimates for stock growth become available in the future, the economic model developed in this paper provides a basis for estimating the net present value implications of that improved science.

The following section describes in general terms estimates for oyster stocks and elements of the change in oyster stocks in recent history. After reviewing recent findings with respect to natural (disease) mortality, habitat constraints, spawning and recruitment, and

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[2] Newell (1988); Jordan and others (2002); Greenhawk, O'Connell, and Barker (2007); Volstad and others (2007).

management issues, a counterfactual is proposed for the estimated history of oyster stocks in Maryland's portion of the Chesapeake Bay in the absence of harvests. This counterfactual provides the basis for an estimate of the natural growth rate of oyster stocks in the northern Chesapeake Bay under recent conditions.

In **Section 3**, a model is proposed for using the estimated oyster stock growth rate along with literature values for the carrying capacity of the northern Chesapeake Bay, to estimate a net present value for the fishery with respect to commercial harvests. This model considers a 100 year time horizon and is further developed to accommodate closures (harvest moratoriums) of varying lengths. The model also takes up ecological values in the measurement of net present values and considers its own sensitivity to different stock growth rates, carrying capacity estimates, and discount rates. **Section 4** discusses the model findings with respect to their political economy and institutional issues inherent in shifting to a net present value maximizing approach to managing the oyster resource. In our conclusion, we summarize our modeled findings and suggest a shift in the mandate under which oyster managers operate. We recommend targeting a higher net present value for the oyster resource.

2. Estimating Stocks and Stock Change

2.1 Estimating Oyster Stocks

Basing his estimates on long-term harvest data, Newell (1988) suggests that standing stocks of oysters in Maryland's portion of the Chesapeake Bay might have been as high as 229 million bushels prior to 1870. He converts those bushel abundance estimates to dry-weight biomass by a fixed factor and extends the consequent abundance and biomass estimates to Virginia's portion of the Bay, treating Virginia's standing stock as a percentage of the Bay-wide harvest. Newell estimates a total oyster biomass of 188 million kg dry-weight for the entire Chesapeake Bay, prior to 1870. He estimates total oyster biomass in 1988 to have been 1.9 million kg dry-weight; roughly one percent of what might be taken for the carrying capacity population maximum. Error bands were not attempted for these estimates.

Due in large part to a commitment by Virginia and Maryland to increase 1994 Chesapeake Bay oyster stocks 10-fold, efforts to develop more robust estimates for standing stocks have been joined over the past decade. Jordan and others (2002) undertook a detailed estimate of stock abundance and biomass in Maryland's portion of the Chesapeake Bay, based on fisheries independent and fishery dependent data. Fishery independent data were generated from sampling at 43 sites, surveyed each fall from 1990 to 2000[3]. Harvest data were obtained from DNR's commercial shellfish harvest dataset.

Jordan and others (2002) used dredge survey sample data to estimate length-to-weight ratios and indices of relative abundance at those sample sites. Those resulting (fisheries

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[3] See Smith and Jordan (1993).

independent) abundances were then regressed on harvests to determine how well the former predicted the latter. Finding a significant fit, they made the assumption that the difference between actual harvests and their predicted harvests in any given year is caused by different rates of fishing mortality. They further assumed that fishing mortality in their base year (1991) was 53 percent. From these assumptions and parameter estimates, they estimated mean total oyster abundance in Maryland's portion of the Bay from 1991 to 2001 at 478 million. Estimates for individual years range from 266 million to 629 million oysters. The mean total biomass over this period was estimated at 574 million g dry weight and ranged from 241 to 864 million grams dry weight.

Most recently, Maryland Department of Natural Resources units at the Cooperative Oxford Laboratory, and the University of Maryland Marine Estuarine and Environmental Studies Program[4] have undertaken annual estimates of oyster biomass in Maryland's waters, based dredge surveys on harvest bar sampling sites. Through the Virginia Institute of Marine Science Department of Fisheries Science Molluscan Ecology Program and the Virginia Marine Resources Commission Conservation and Replenishment Division, Virginia is undertaking a similar stock assessment in its waters. These efforts to assess stock abundance and biomass in both Virginia and Maryland are aimed at providing consistent estimates for the entire Bay. Estimates of total abundance and biomass for the last 13 years are reported in **Table 1**.

Table 1: Oyster Abundance (million oysters) and Biomass (million g dry tissue weight) By State & Year

Year	Maryland Population	Virginia Population	Total Bay Population	Maryland Biomass	Virginia Biomass	Total Bay Biomass
1994	589	1404	1942	705	514	1218
1995	505	1926	2431	668	513	1180
1996	514	1781	2296	657	683	1340
1997	496	1164	1660	732	475	1207
1998	635	1606	2241	782	587	1369
1999	586	1973	2559	823	590	1413
2000	528	1820	2348	731	682	1414
2001	430	1717	2147	591	710	1301
2002	157	4193	4350	247	571	818
2003	286	2367	2653	317	587	904
2004	227	2311	2538	308	787	1095
2005	241	2144*	2385	368	1052*	1420
2006	201	1824*	2025	339	855*	1193
2007	179			258		

Source: Chesapeake Bay Oyster Population Estimates: http://www.vims.edu/mollusc/cbope/index.htm
* Provisional estimates

These abundances are based on sampling in the major basins of both states, factored by the projected area of available habitat in each basin. As an indication of the potential measurement error for Maryland's estimates, a recent reconsideration of the length of tow

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[4] With funding from NOAA's Chesapeake Bay Stock Assessment Committee and the EPA Chesapeake Bay Office.

for dredge samples resulted in changes in abundance estimates that ranged from 26 percent to 1 percent of the original estimates.

Recognizing that any practical attempt to count oysters in the Bay will entail some measurement error, the Chesapeake Bay Oyster Population Estimates (CBOPE) provide a somewhat standardized calculation of stocks over time. The Maryland CBOPE estimates are not radically different from Jordan and others' (2002) estimates, even though they are based on different methods of calculation (though largely the same sample sites). Moreover, Newell's much simpler model, while applied to a year (1988) outside the CBOPE range, generates a whole-Bay biomass estimate that is not drastically different from the CBOPE estimates.

To the extent that these estimates mirror what is actually happening on Chesapeake Bay bottom, it is interesting to note that Virginia's population estimates, which show consistently greater abundance than Maryland's stock, had less total oyster biomass than Maryland until 2001. This outcome is in keeping with the generally held view that, in Virginia's higher salinities, stocks recruit better but are cropped by disease more completely at larger sizes. From 2001 onward, however, Maryland's stocks fell to such small numbers that, even with oysters that are on average smaller, Virginia's total oyster biomass began to exceed that of Maryland's.

Maryland's oyster numbers and biomass are on a clear downward trend with the most recent year's abundance diminished by two thirds from abundance at the start of the period. Based on either their provisional estimates or the last year for which they have certified estimates, Virginia's oyster biomass increased over the same period.

As described in the introduction, current stocks are only one part of the measurement of net present value; albeit an important part. Some idea of the stock effects of harvests and other determinants of stock change is needed in order to estimate expected net returns from future harvests. While the idea that lower current harvests might allow stocks to grow faster carries intuitive appeal, other mortality factors and limits to growth (i.e., habitat constraints and spawning and recruitment issues) must be considered.

2.2 Factors Affecting Stock Change

Since it is difficult to know oyster abundance in the Chesapeake Bay with certainty at any given point in time, it is also difficult to know stock abundance at two points in time. On the other hand, when harvests decrease drastically or when sampling efforts turn up large numbers of recently dead oysters, it is reasonably deduced that stocks have declined. Below, we consider some of the environmental conditions, including disease, habitat and spawning and recruitment issues that are thought to be important factors for stock change.

2.2.1 Disease Mortality:

Two diseases have decimated Chesapeake Bay oyster stocks over the past fifty years. MSX (*Haplosporidium nelsoni*), is thought to be an imported disease (Burreson and others 2000) of fairly recent origin to the Bay. It requires higher salinities and exhibits maximum pathology at temperatures around 20 degrees centigrade and salinities of 30 parts per thousand (ppt) (Dungan 2007). No one yet knows how this disease is transmitted, and its agent has not yet been cultured *in vitro*. Some evidence exists that domestic oyster stocks can achieve some tolerance to this disease over several generations of exposure (Mann and Powell)[5].

Dermo disease (*Perkinsus marinus*) has been observed in the Bay for at least 50 years, though its epizootic effects have manifested in recent decades. *Perkinsus marinus* is transmitted between hosts, surviving for some time and distance in the water column and it can tolerate lower salinities than MSX (3 ppt). It is, however, most virulent at higher salinities (>9 ppt) and temperatures (>25 degrees centigrade). Dermo disease affects between 60 and 98 percent of oysters in the Chesapeake Bay (Tarnowski, MD Fall Survey 2006). Brown and others (2005), report diminished disease effects in cohorts of oysters from different populations, indicating some genetic-based disease tolerance, and Dungan (2007) reports evidence of resistance among some wild Virginia oysters.

Both diseases tend to kill oysters of older year classes, and both can be chronic in local stocks. Tarnowski, 2006 reports non-fishing (disease) mortalities in Maryland that in drought years range from 40 to almost 60 percent, are nine years out of 22 greater than 30 percent, and only eight years out of 22 less than 20 percent. Mann and Powell (2007) report age-specific local mortalities in excess of 70 percent in Virginia.

Volstad and others (forthcoming) use Maryland DNR fall oyster survey data to estimate mortalities somewhat differently than had been done, previously. They use numbers of recent boxes (dead oysters whose shells remained articulated and were not fouled with sediments), old boxes (dead oysters that were fouled) and live oysters to establish short-term estimates of mortality. They treat the ratio of recent boxes to live oysters as a rate of mortality per "one to two weeks" and then factor this by the length of time over which oysters are vulnerable to disease mortality (20 weeks from June to October) to arrive at an annual likelihood that any given oyster will die.

The mortality estimates arrived at in this fashion have the desired characteristic of tracking reasonably with expectations, given what is known about the relationship between salinity and disease virulence. Specifically, if oyster bars are disaggregated into three salinity classes (high, medium and low) and years are rated by disease intensity[6] across all bars from Tier 1 (highest) to Tier 3 (lowest), basing disease mortality estimates on recent boxes tracks more closely to empirical salinity and disease intensity rates than

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[5] While local stocks suffering consistent exposure to the disease may adapt over several generations, genetic contributions from unexposed and therefore susceptible populations can mask the benefit of that adaptation.

[6] As defined in Tarnowski (2003): Tier 1 (high dermo intensity greater than 2.85), Tier 2 (dermo intensity between 2.85 and 2), and Tier 3 (dermo intensity less than 2).

earlier methods. The annual mortality likelihoods for the whole Bay derived by this method are somewhat higher than earlier estimates. They are reported in **Table 2**.

Table 2: Annual Natural Mortality for Market Sized Oysters

Salinity Class	Disease Tier 1	Disease Tier 2	Disease Tier 3
High	.79	.51	.23
Medium	.59	.43	.13
Low	.34	.22	.10

Source: Volstad and others, 2007.

A demographic model developed by Volstad and others (2007) uses these mortality rates to predict probabilistic outcomes based on historical weather patterns and the salinity prospects for each of the oyster bars in the Bay and its tributaries. In that model, on any oyster bar experiencing high salinity (>15 ppt), one of three mortality outcomes will obtain in a year; one tracking high disease intensity, one tracking medium disease intensity and one tracking low disease mortality, and so on for medium and low salinity bars. The demographic model randomly assigns a disease tier to the salinity class chosen, based on empirically determined probabilities.

2.2.2 Habitat Constraints

Because oyster recruits need hard substrate to affix to, and because there is very little hard substrate in the Bay other than live oysters and oyster shells, oysters can be seen as creating their own habitat. Dense assemblages of oysters can keep themselves free of silt and accrete shell under amenable conditions, but sparse populations and shell without live oysters will silt over through time, reducing available habitat. Concomitant with diminished oyster stocks, oyster habitat in the Chesapeake Bay is significantly degraded.

Smith and others (2005) report that 90 percent of Maryland’s productive oyster bottom as defined by the Yates surveys (1913) has degraded to mud, sand or heavily sedimented oyster shell. Of the portion of their sample that was identified as unsedimented shell, 70 percent was from areas that had been replenished with shell at some time over the past 40 years. They found in the statistical analysis of their survey data that improvements to habitat (i.e., shell planting) appear to be short-lived; around five years. Their sample was composed primarily of open-harvest oyster bottom in Maryland’s portion of the Bay.

Powell and Klinck (2007) develop a model for the relationship between habitat and stocks based on the eastern oyster’s evolutionary strategy for success. Under that strategy, recruits depend on the shell that survives for a period, after older oysters die. If a given stock loses its natural age structure, either through harvests or disease, this strategy fails because habitat requirements can not be met.

The apparent inability of current oyster stocks to create sufficient habitat for stock maintenance or increase can be addressed by shell replenishment up to a point. But, Mann and Powell 2007 estimate that restoring 11,000 acres of Virginia’s Bay bottom would require 110 million bushels of shell – over 200 times more than is being planted under restoration activities, currently. Moreover, because of expected disease mortality and gradual shell loss, such habitat restoration is argued to require continuing infusions of shell if it is to be maintained over time.

Currently, shell replenishment suffers from constrained supply in both Maryland and Virginia. In earlier years, Maryland shellfish managers were able to dredge shell from deposits in the northern part of the Bay's main stem for shell replenishment on harvest and seed bars. Between 1985 and 2005 shell plantings composed primarily of dredged shells averaged 3.16[7] million bushels a year in the State. However, the sites from which shells were obtained have been closed since 2006 and replenishment from that source has been suspended. Virginia's shell replenishment is preponderantly dependent on shucked shell from packing houses. While shells remain available from this source, the volume of the resource is limited to between 350,000 and 500,000 bushels per year[8].

Available habitat (hard substrate) is a necessary but not sufficient condition for oyster recruitment. If there are no spat to settle or if other environmental conditions are not appropriate, then recruitment will be constrained. Still, for any given number of spat disbursed across the Bay's water column under given environmental conditions, less substrate is taken to imply lower recruitment and commensurate stock growth.

The demographic model proposed by Volstad and others (2007) treats available habitat as a fixed amount of either "high quality" or "low quality" oyster cultch on historical oyster bottom. The estimate of extant oyster bottom is based largely on Smith and others' (2007) reported decline from the recent (1978 – 1984) Maryland Bay Bottom Survey (MBBS) acreage and the earlier Yates delineations of oyster bottom. Mappings of MBBS and Yates bars are reduced by factors derived from Smith and others' findings. The remaining area is then evaluated as being 92 percent low quality substrate and 8 percent high quality substrate[9]. This initial base of habitat is retained throughout the ten years of model runs.

It is clear from both the MBBS and Smith and others' (2005) survey that suitable oyster habitat in Maryland's portion of the Bay is declining over time, up to the present. Shell replenishment has some short-term beneficial effect, and this is captured by Volstad and others' model as a diminishing positive factor (4.5 times the recruitment potential of low quality bottom in the first year, declining to unity at the end of the period) on replenishment sites over five years following their planting. But, as mentioned above, in reality shell replenishment is likely to be much reduced in Maryland's portion of the Bay in the future. Moreover, by using the initial habitat condition as a constant over all the years of the model runs, the model does not capture the constant decline in oyster habitat that appears to be ongoing in the northern Chesapeake Bay.

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[7] MD DNR Seed and Shell Reports, various years.

[8] Jim Wesson, VMRC, personal communication.

[9] There are small differences in the allocations of high and low quality substrate on Yates versus MBBS polygons that are lost in rounding, here.

2.2.3 Spawning and Recruitment

Independent of habitat constraints, recruitment to Chesapeake Bay oyster stocks is difficult to predict. This is in part due to the lack of precise stock estimates. But in another part, it results from the occurrence of episodic large recruitment events (spat sets) in the Bay (Ulanowicz and others, 1980), which confound statistical relationships between spawning stock and recruitment. The causes of these occasional large spat sets are not well understood, but there are indications that it is a "natural" phenomenon in terms of the way that Eastern oysters achieve ecological success (Rose and others, 2006).

Kimmel and Newell (2007) report findings of an inverse relationship between previous years' harvests and current year spat-sets in the Chesapeake Bay from 1940 to 1977. From 1977 to the present, as both stocks and harvests declined far below historic levels, the relationship between previous year harvests and following year spat set is muted. In that period, environmental conditions are the more significant factors predicting recruitment. It is important to note, however, that previous year harvest is a confounding variable in that it contains information about both stock levels (higher harvests imply larger extant populations of market sized oysters) and the number of spawners that were removed from stocks, reducing future spawning potential.

In Volstad and others' (2007) demographic model, spawning is treated as a function of the number of surviving female spawners and their size distribution. Recruitment is estimated using empirical averages[10] of spat per spawners across salinity conditions and available habitat. Episodic large recruitment events are modeled by allowing recruitment to occur at a level defined by the average of outlier (large) spat sets with a fixed probability. At a higher probability, the model uses the ratio of spat to spawners measured by empirically estimated ratios with outliers excluded.

This description simplifies the treatment of recruitment in the Volstad and others (2007) demographic model, and only identifies the fundamental relationships used. A sensitivity analysis undertaken in their report did not show a large stock effect from moderate changes in rates of recruitment. However, the initial condition used for the demographic model in Maryland waters has fewer spat than small and market-sized oysters, signifying recruitment failure. Initializing a model on such an extreme condition could be reasonably expected to generate exceptional results. [11]

2.2.4 Resource Management and Change in Oyster Stocks

There are limited prospects for overcoming the barriers to stock growth (i.e., disease, habitat loss, recruitment failure) described above. By ceasing the movement of diseased oysters from higher salinity waters to lower salinity waters, it is possible that disease

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[10] Principally, MD DNR Fall Survey and disease sentinel site data.

[11] This problem is noted by the authors (Volstad and others (2007) pg. 28).

virulence in some less saline waters may attenuate[12]. But it is not clear how great an effect such a change would have on disease mortality, as both diseases are currently endemic throughout the Bay[13]. The only other means for controlling disease effects on oyster stocks is to obtain a disease-resistant oyster.

Habitat constitutes an important constraint to oyster stock growth under current conditions. Mann and Powell's analysis suggests there is insufficient shell available to meet habitat needs for stock growth as envisaged under the EIS goals, even if the financial resources required to place it were available. On the other hand, those estimates presume continued harvests and Mann and Powell (2007) do not model how long it might take natural stocks to develop sufficient abundance to accrete shell across a larger portion of Bay bottom in the absence of harvests.

With respect to recruitment, the inverse relationship between previous years' harvests and present year spat set identified by Ulanowicz (1980) and extended by Kimmel and Newell (2007) is interpreted as indicating that recruitment was constrained by available spawners before diseases reduced stocks so dramatically in the 1980s and 1990s. Under that interpretation, reducing harvest mortality would be a means for increasing the number of spawners and, *ceteris paribus,* increasing recruitment.

Given current conditions and evidence, harvests are likely to reduce future stocks by reducing available habitat and by removing potential spawners. Reduced harvests would increase disease mortality, as the oyster not harvested has an improved likelihood of succumbing to disease. But the unharvested oyster also has a higher likelihood of surviving and spawning than the harvested oyster. Moreover, in the longer term, constant exposure to disease in the absence of fishing mortality could be expected to speed up the rate at which Chesapeake Bay oysters develop a genetic resistance to either of the two diseases (Ryan Carnegie, Virginia Interagency Oyster Team Memo, February 6, 2008).

Among the available resource management options, limiting harvests is the most promising practical approach for arresting the decline in oyster stocks in the Bay, short of replacing domestic stocks with a disease resistant oyster. The question then becomes, by how much would a cessation of oyster harvests slow the current decrease in stocks in the northern Chesapeake Bay, or increase stock growth in Virginia's portion of the Bay? The estimation of the net present value of the fishery is largely dependent on the answer to that question.

Although point estimates for any of the factors of stock change and stocks themselves carry considerable uncertainty, scientists are reasonably certain that disease is a pervasive problem with modulated virulence over seasons and years. Habitat is limiting and shrinking. And, harvests remove some portion of available stocks of both oysters and shell in the fall and winter of each year. Both fisheries-independent sampling data and harvest evidence suggest that stocks in the northern part of the Bay are shrinking in abundance and biomass, while abundance seems to be stable or slightly improving in

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[12] UMCES (2005)

[13] McCollough and others (2007)

Virginia's waters. Although there is uncertainty in these propositions, the trends that they suggest are widely accepted.

Given the uncertainty about both point estimates and the environmental conditions that will obtain in coming years, in the following section we take a simpler approach. We make the simplifying assumption that all of the important factors effecting stock change (e.g., spawning and spat-set effects, shell planting effects, water quality effects, disease effects, harvest effects, etc.) are captured in the record of stocks and harvests over the past 14 years. Using estimated stocks of market sized oysters and reported harvests, we then suggest a counterfactual for stock change, net of harvest effects.

2.3 Market Stocks in the Absence of Harvests

The abundance of market sized oysters is estimated by DNR's Fall Survey which provides a count of market sized oysters at the end of their principal growing, spawning and disease impact period. The count precedes the harvest. And, as the harvest spans two calendar years (i.e., the fall of one year and winter of the next) any given harvest is counted as happening in the year after the count of stock available for that harvest. Thus, with stock estimates and harvest volumes, it is possible to separate out recruitment (to market size) net of disease across the series of annual stock estimates and harvest rates. To see this, consider the accounting relationship: $\text{Stocks}_t = \text{Stocks}_{t-1} - \text{Harvest}_t + \text{Recruitment}_t - \text{Disease}_t$.. With estimates for stock abundance and harvests across periods, we can separate out harvest-adjusted recruitment net of disease mortality as this has transpired over 13 of the 14 years for which MD DNR have data. **Table 3** does this using DNR stock abundance estimates for market sized oysters in Maryland waters of the Bay and DNR commercial fisheries harvest data.

Table 3: Stock Change (Markets)* in the Absence of Harvests

Year	Stocks (Million Oysters >72mm)	Harvests (Million Oysters)	Disease Mortality (percent)	Net Recruits (Million >72mm Oysters)	Net Recruitment Ratio	Stocks Sans Harvests
1994	218.06	23.885	20.42%			218.06
1995	240.90	49.392	25.23%	59.771	27.41%	277.83
1996	235.94	59.939	23.53%	40.875	16.97%	324.97
1997	268.09	53.280	13.45%	78.266	33.17%	432.77
1998	254.10	85.494	15.98%	57.845	21.58%	526.14
1999	289.16	126.966	26.40%	128.508	50.57%	792.23
2000	267.31	114.203	32.05%	55.741	19.28%	944.95
2001	214.89	104.390	39.05%	11.203	4.19%	984.55
2002	81.19	44.447	52.04%	-112.375	-52.30%	469.68
2003	84.52	16.752	36.87%	13.902	17.12%	550.10
2004	101.29	7.941	17.26%	23.341	27.62%	702.01
2005	150.64	21.665	12.81%	68.239	67.37%	1174.95
2006	135.80	46.331	14.06%	24.978	16.58%	1369.77
2007	81.93	49.518	20.65%	-14.572	-10.73%	1222.79

* Oysters greater than 72 mm in length.

In this table we have calculated net recruitment as the annual apparent change in stocks plus oysters that we know were harvested in the year, factored by 1 minus the annual disease mortality rates.[14] Expressed mathematically:

$$\text{Net Recruitment}_t = (\text{Stock}_t - \text{Stock}_{t-1}) + (1 - \text{Disease Mortality}_t) * \text{Harvest}_t .$$

This measure of recruitment minus disease is then divided by prior year stocks to provide an estimate of proportionate change from one count to the next (i.e., Net Recruitment Ratio)[15]. We estimate cumulative market sized stock abundance in the absence of harvests by starting with 1994 stocks and factoring those and each subsequent year by one plus the rate of harvest-adjusted net recruitment. In only two years over the period does disease mortality outweigh harvest-adjusted recruitment, though when it does, as in 2002, it can do so with a vengeance. The projected market-sized population at the end of the period is more than a 4-fold increase above estimated starting stocks, and almost 14 times greater than estimated ending (2007) stocks.

Caution is needed in interpreting these results. The stock estimates, as discussed previously, have considerable uncertainty. Much of this uncertainty is derived from scaling-up sampling results to entire basins. That is, variance in the sampling or error in assumptions about the rest of the habitat in the basin can generate large errors when thought of as actual numbers of oysters in each basin. The harvest figures are also uncertain. Certainly, actual harvests are larger than reported harvests, but it is not known by how much. Since available habitat is thought to be a constraint on stock growth, how likely are increases on the scale suggested in Table 3? Moreover, in a population with a higher percentage of older oysters as implied by this treatment, would net recruitment rates be lower due to higher mortality rates?

With respect to the error inherent in total population abundance estimates, it is not fatal to the underlying argument if these are not actual oysters in the Bay but merely relative abundances, given consistent statistical treatments of samples over time. Obviously, the closer annual total abundance numbers are to actual, the better. But, even if both harvest and stock estimates are relative indexes, using them as we have to distinguish direct harvest effects on stocks is valid as long as they both track their respective variables consistently[16]. Recognizing that reported harvests are less than total harvests, we can claim to have a conservative estimate of the stock effects of harvests[17]. Consistent with this, the rates of harvest estimated with these data are considerably lower than expected

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[14] Mortality rates are from MDDNR Fall Survey data and are specific to market sized oysters.

[15] The linear relationship between stocks and growth shown in Table 3 is used only to derive an intrinsic growth rate of the stock (to be used in the logistic growth function in section 3). This relationship is likely linear near the origin (which approximates current conditions). To the extent that the data compiled by MDNR is credible, and to the extent that oyster population growth follows a logistic pattern, our estimate of the intrinsic growth rate is an underestimate since we are fitting the linear relationship at a stock that is (hopefully) greater than the minimum viable population.

[16] It must be noted that if habitat consistently declines in reality but is held constant in basin stock estimates, this condition is not met. However, all of the current demographic models suffer this problem.

[17] Another way in which reported harvests underestimate actual harvest mortality is the number of oysters killed by harvesting equipment but not harvested. Paynter (2007) reports mortalities as high as 50 percent of residual oysters on one of the managed reserves.

(average, 28 percent for the period), implying that either stock estimates tend to the high side or reported harvests understate actual harvests, or both.

With respect to habitat, Mann and Powell (2007) argue that shell stock is a binding constraint on oyster stock growth. However, they also note that natural death of oysters is essential to contributions to habitat and that removal by fishing reduces those contributions. In the no-fishing scenario developed in Table 3, natural (disease) mortality results in additional shell for spat settlement. Spat settlement enters into Table 2 only indirectly, as whatever recruits enter the market size classes had to have set two or more years earlier in order to generate the observed rates of recruitment net of disease.

Whether the larger numbers of spat implied at higher stock abundances could have found adequate habitat in the absence of fishing removals is not known. However, spat do also set on living oysters and, to the extent that the removing fishing effort results in both more living oysters and more empty shell on the bottom, some additional habitat would be available for recruits under the no-fishing scenario.

With respect to whether harvest mortality is additional or compensatory,[18] by focusing on change in market sized oysters, we assume that the oysters harvested in a given year were neither more nor less likely to die of disease in the coming year than those oysters that were not harvested. The seventy two percent of market-sized oysters that (on average) survived harvests each winter went into the next growing season and either died or survived (and spawned) at the rate that is captured obliquely in the net recruitment measure.

Tarnowski (2005) emphasizes the drought period 1999 – 2002 in pointing out that oyster sanctuaries developed the same cropped age structure as harvest bars by the end of that period. Table 3 also indicates that stock growth would have been negative over part of this period. However, as Paynter (2007) reports, oyster sanctuaries that were free of harvests have shown sustained populations over other periods, indicating that some older oysters can survive in some places in normal rainfall years. Certainly, at some point the increased number of older oysters would generate increased old-age mortality. But, given that net recruitment in Table 3 is based on current age distributions that are biased toward younger, less fecund individuals[19], this increased mortality might be compensated by the greater spawning potential of older oysters.

Table 3 is based on the idea that if harvests had not happened, market sized oyster stocks would have changed at the same rate that they changed (net of harvests) from one year to the next in Maryland's portion of the Chesapeake Bay. One cannot know with certainty whether there would have been enough habitat for the increase implied by putting harvested oysters back into stocks, or whether increased numbers of older oysters would change annual net recruitment rates. However, the experiment undertaken by managers over the past 14 years has tested the contention that continued harvests would not affect stocks available for future harvests and this has been shown to not be the case.

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[18] See Klinck and others (2001).

[19] Volstad and others (2007).

Given the prospect that the absence of harvest mortality might permit stock growth, it is reasonable to test the economics of limits on harvest mortality. In the following section, we develop a model to test the effect on the oyster resource's net present value of a range of harvest moratoria based on the underlying growth rate net of harvest mortality that is developed in Table 3. For any given length of harvest moratorium, the model seeks an optimal harvest rate with respect to the maximum net present value of the resource.

3. Modeling the Economics of Stock Change

3.1 The Model

Using the estimates from Table 3, we calculated the rate of growth of the stock in the absence of harvests. There were two negative recruitment years (2002 and 2007) in our sample. We take the average of the positive net recruitment ratios (growth rates) as our estimate for the intrinsic growth rate of the Maryland market sized oyster population (r = .2744). Negative recruitment events are included in the model as described below. We model the population dynamics of the market sized oyster population as partially following a Ricker (logistic) growth function of the population of market sized oysters in the previous period. This model is similar to Jordan and Coakley (2004) and we also use their estimate of the carrying capacity of market sized oysters in Maryland (k = 5,089,200,000)[20]. Using this growth model, we run 1000 simulations of the growth of the stock over a period of one hundred years to determine the harvest rate that maximizes the net present value of the oyster fishery.

These growth parameters remain constant throughout the simulations. However we introduce random population events through the indicator function $\varphi(r, k, q, x(t), \alpha(t), \gamma)$. This function determines if there is a high mortality event as a function of the parameters $\alpha(t)$ and γ. We assume that $\alpha(t)$ is a random number uniformly distributed between zero and one. A new $\alpha(t)$ is generated for each year of the model, and $\alpha(t)$ also varies between simulations. If $\alpha(t)$ is greater than our critical value γ, the stock grows according to its Ricker (logistic) growth function with r = .2744 and k = 5,089 million market sized oysters. However, if $\alpha(t) < \gamma$, this implies that we have a high mortality event, and the stock falls to d % (where $0<d<1$) of last year's stock, minus fishing mortality during that season. We let d equal one minus the average of the two high mortality years in our data (2002 and 2007) which implies that d=.68. Thus when we experience a high mortality event, the oyster abundance falls to 68% of the previous year's stock minus any oysters that were harvested that season. As Maryland's portion of Chesapeake Bay oyster stocks are shown (Table 3) to have experienced 2 years over the past 14 in which natural mortality exceeded recruitment, we set $\gamma = 1/7$.

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[20] The estimate by Jordan and Coakley 2004 of the suitable habitat area comes from the MBBS, which indicated that only 10% of nominal oyster habitat actually supported oyster populations (Smith et. al. 2001). For their carrying capacity estimate, they assumed that 10% of cultch areas supported 10 market sized oysters per m^2, and 10% of sand and cultch and mud and cultch areas supported 3 market sized oysters per m^2.

We assume that in normal mortality years the Maryland market sized oysters grow according to a Ricker escapement growth model. The Ricker model is a simple generalization of the logistic growth curve but has some desirable stability properties. We chose to focus the model on escapement for a number of reasons. Firstly, stock estimates (*x*) come from DNR's fall survey and harvests (*h*) occur during the winter months when the stock is assumed to grow very little. However, once the season ends, the remaining oysters are left to grow until the next season when they will again be surveyed in the fall. Those oysters which are reproducing between seasons are only those who have escaped harvest in the past year, and thus an escapement model seems to approximate reality.

Mathematically, the $\varphi(r,k,h(t),x(t),\alpha(t),\gamma)$ function can be described as:

$$\varphi(r,k,h(t),x(t),\alpha(t),\gamma) = x(t+1) = \left(x(\mathrm{t})\text{-}h(\mathrm{t})\right)\mathrm{e}^{\left\{r\left(1-\frac{(x(t)-h(t))}{k}\right)\right\}} \qquad \text{if } \alpha(t) \geq \gamma$$

$$\varphi(r,k,h(t),x(t),\alpha(t),\gamma) = x(t+1) = d\,x(t) - h(t) \qquad \text{if } \alpha(t) < \gamma \quad \forall t = 1,\ldots,T-1$$

$$\text{where } \alpha(\mathrm{t}) \sim \mathrm{U}[0,1]$$

Using this growth equation for Maryland market sized oysters, the problem that we analyze is the maximization of profits from the Maryland oyster fishery over a period of one hundred years. We chose one hundred years arbitrarily, but because our non-stochastic model converged to a steady state after approximately fifty years, the additional years are included to allow for multiple high mortality events. Letting *R*(*p*(*t*),*h*(*t*)) be the revenue from harvest and *C*(*h*(*t*),*x*(*t*)) represent the cost of harvesting, the problem of maximizing the discounted profits from this fishery over the one hundred year time frame subject to the growth of the oyster population can be written as :

$$\underset{h(t)}{\mathrm{Max}} \sum_{t=0}^{T-1} \big(R(p(t),h(t)) - C(h(t),x(t))\big)\left(\frac{1}{1+\delta}\right)^{t} \qquad \text{s.t. } x(t+1) = \varphi(r,k,h(t),x(t),\alpha(t),\gamma)$$

After the end of the model (*T*=100) we assume that there is a salvage value ($\lambda(T)$) to the oyster stock equal to the steady state harvest corresponding with the ending stock size in perpetuity. Let $\lambda(T) = \left(\frac{\big(R(p(T),h(T)) - C(h(T),x(T))\big)}{\delta}\right)\left(\frac{1}{1+\delta}\right)^{T}$ such that $x(T+1) = x(T)$. This implies there is an incentive to keep the stock at a high level at the end of the model so that steady state harvests in the future will be larger. This effect will be countervailed by the fact that these steady state harvests occur after one hundred years and discounting will cause these harvests to be worth less in net present value terms than earlier harvests so there may be some incentive to harvest earlier and not allow the stocks to become too large.

Suppose that the harvest in any season is equal to the percentage of the stock that is taken (*q*) times the stock available at the beginning of the season (*x*) such that $h(t) = q\,x(t)$. We assume that the proportion of the market sized oyster population that is harvested is the same during all periods. It is this fixed harvest percentage that we solve for in the optimization model. The price of oysters each year is a normally distributed random number around the average real price per bushel of oysters over the period 1994-2007 which is $25.72 in 2007 dollars. As prices are likely decline as the supply of oysters increase from Maryland, we truncate the distribution to be no greater than the current real price of $30 per bushel. This allows prices to vary year to year randomly, and also not increase above the current real price with increases in supply[21]. The revenue from harvest is equal to the price times harvest, which can be expressed as: $R(p(t), x(t), q) = p(t)h(t) = p(t)\,q\,x(t)$.

To determine the costs of harvest, we start by estimating the number of active boats in the fishery, given harvest levels. We determine the number of boats active in the fishery each season as equal to the total harvest in bushels divided by each boat's expected seasonal catch. The expected seasonal catch is equal to their expected daily harvest times the season length. We assume that boats use the most efficient method of harvest (dredge), and that operators expect to harvest 50 bushels per day[22] over a season of 100 days. $B(t)$ is a measure of the total direct costs of harvesting. $B(t)$ is equal to the number of boats active in the fishery times the season length, times the boat's daily costs of operation. We assume the daily boat and labor costs with dredge gear to be $375/day of a 100 day season, which is Wieland 2006's high-end estimate for dredges. Using these parameters, $B(t) = 25,000\,h(t)$ where $h(t)$ is measured in millions of oysters.

In addition to the direct costs of harvesting ($B(t)$), we assume the cost of harvest is decreasing in the stock of market sized oysters, and increasing in the total annual harvest. These assumptions are valid in the case of the Maryland oyster fishery. The larger the number of oysters available for harvest, the less effort it will take to achieve any level of harvest. Similarly, to harvest more oysters, more time out on the water has to be expended to catch them. We specify a cost function which is equal to the direct harvesting costs plus an adjustment for the harvesting costs which decreases as the stock approaches the carrying capacity.

Let $C(h(t), x(t)) = B(t)\left(1 + \frac{k-x}{x^2}\right) = 25,000\,h(t)\left(1 + \frac{k-x}{x^2}\right)$

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[21] Given the small increases in production that our model predicts, we are confident in assuming that the increased production will not have a significant impact on the price of oysters. In 2003, U.S. production of oysters was 2,800 million bushels (Lipton, Kirkley, and Murray, 2006). In the no moratorium scenario (figure 2), oyster harvests in 70 years are predicted to be 160 million oysters or .533 million bushels of oysters. The largest single year harvest predicted in the optimization model is only 1.333 million bushels occurs in 5057, the first year after a 50 year moratorium. Additionally, regional MD and VA processed oyster production comes from oysters harvested in other states, with the majority coming from the Gulf of Mexico (Murray, 2002; Lipton, 2008). Given that the substantial production of oysters from the Gulf act as a near perfect substitute for oysters from the Chesapeake, it seems reasonable to ignore price effects from the model's predicted increase in production relative to total U.S. production of oysters.

[22] We implicitly assume in this estimate that managers and harvesters would prefer a more rational level of capacity in the fishery and that the number of boats would be reduced to meet such an allocation of available catch. The current average catch per day of single dredges operating in New Jersey's Delaware Bay oyster fishery is 53 (US) bushels. (Jason Hearon, undated)

Therefore, substituting in for $R(h(t),x(t))$, $C(h(t),x(t))$, $h(t)$ and $\varphi(r,k,q,x(t),\alpha(t),\gamma)$, we can write the problem of maximizing the discounted profits from the Maryland oyster fishery as follows[23]:

$$\underset{q}{\text{Max}} \sum_{t=0}^{T-1} \left(p(t)\, q\, x(t) - 25{,}000\, q\, x(t) \left(1 + \frac{k-x}{x^2} \right) \right) \left(\frac{1}{1+\delta} \right)^{t} + \lambda(T)$$

$$\begin{aligned} &\text{s.t.}\; x(t+1) = \big(x(t) \text{-} qx(t) \big) e^{\left\{ r\left(1 \text{-} \frac{(x(t)\text{-}qx(t))}{k} \right) \right\}} && \text{if } \alpha(t) \geq \gamma \\ &\quad x(t+1) = d\, x(t) - qx(t) && \text{if } \alpha(t) < \gamma \qquad \forall t = 1,\dots,T-1 \end{aligned}$$

This problem was solved using numerical optimization and Monte Carlo simulations using Excel and built in numerical optimization method Solver. For each simulation, a new random draw of $\alpha(\mathrm{t}),\dots,\alpha(\mathrm{T})$ parameters was generated, and Solver determined the optimal harvesting percentage (q) which maximizes the net present value of the oyster fishery[24].

3.2 Model Results

We ran 1,000 simulations of this model to determine the optimal harvest percentage over the period, and the net present value of the oyster fishery. The mean values are presented in the first column of **Table 4**. The optimal harvest percentage for this fishery averages about 7.29% of the market sized oysters. This implies that the optimal harvest percentage would actually correspond to a much lower percentage of total oyster abundance. This 7.29% harvest rate corresponds to an average net present value from the fishery of over $110 million dollars. Harvesting at such a low rate allows the stock to reestablish itself in the early years, generating an average stock at the end of one hundred years (2107) of 2,438 million market sized oysters, up from a starting population of 81 million market sized oysters. We denote this model as the Optimization model from this point onward.

Table 4: Net Present Value Under Different Management Regimes

Average from all simulations	Optimization Model	Current Policy
Net Present Value	$110,169,242	$2,761,237
Harvest %	7.29	28.4
Ending Stock (millions of oysters)	2,438.22	0.0000376

We then compare these numbers to running the model with a fixed harvest rate of 28.4%, which is equal to the average harvest rate over the period 1994-2007. We denote this model as the Current Policy model as it represents a continuation of our current policy in the Maryland portion of the bay. The results of the 1000 simulations using the same

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[23] The discount rate utilized in the base case is 4%, which is representative of a social rate of discount.

[24] This analysis was enabled through the use of an Excel add-in called MCSimSolver which was developed by Economics Professors at Wabash College Humberto Barreto and Frank Howland to go along with their text "Introductory Econometrics: Using Monte Carlo Simulation with Microsoft Excel."

growth parameters as before with a fixed 28.4% harvest rate are summarized in column 2 of **Table 4**. As the average harvest rate over the period is greater than the intrinsic growth rate of the market sized oyster population, the population of market sized oysters quickly declines toward zero.

As the stock continually declines toward zero, the net present value of harvests from the continuation of current policy is only around $2.76 million. Also, as the ending stock is near zero, there is no salvage value for the stock because there are no oysters to harvest. These effects are reflected in Figures 1 and 2, which compare the population of oysters and annual harvests under the two policies.

Figure 1

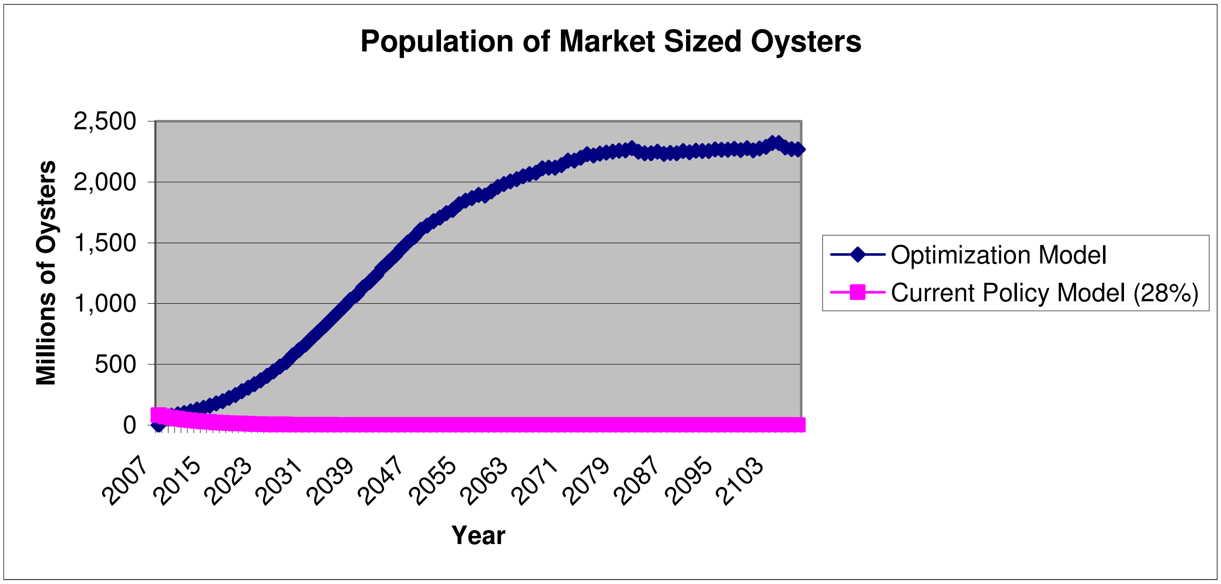
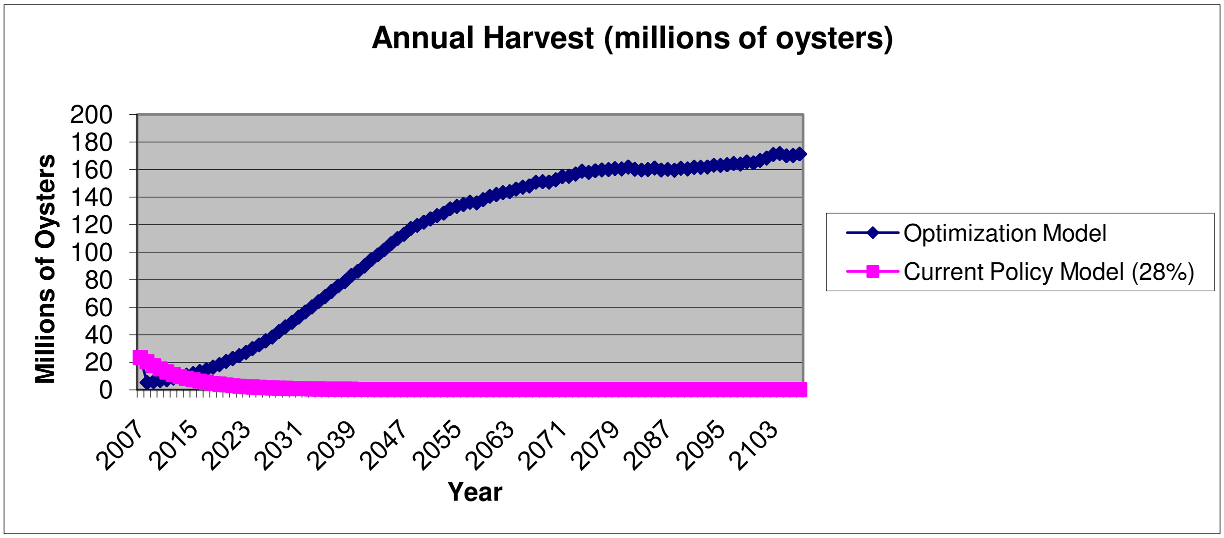


Figure 2



Thus a decrease in the harvest rate from 28.4% to 7.29% would increase the net present value of the oyster fishery in the Maryland section of the bay by over 108 million dollars. It seems clear from the comparison of these models that the current oyster population in Maryland can have a significant value, but a change in policy is required to achieve this result. The high net present value of the oyster fishery with such a low harvest rate implies that short term losses are made up for many times over if we allow the stock to recover to reasonable levels. It is on this basis likely that delaying any harvest until some future period will increase the net present value of the oyster fishery. We now use our model to determine the optimal length of delaying harvests whose aim is to maximize the net present value of the fishery.

3.3 Optimal Harvest Delay

The above analysis shows that the harvest rate which maximizes the net present value of the oyster fishery is much lower than the current exploitation rate. We now turn our attention to the question of the optimal length of a moratorium on harvest with the goal of maximizing the value of the fishery. Given low current stock levels, it may make economic sense to delay harvesting for a number of periods to allow the population to recover, if this makes it possible to later harvest a large enough number of oysters to generate sufficiently higher profits from the fishery.

Using the same 100-year timeframe and salvage value function, we forced harvests to start in later periods, and allowed our model to determine the optimal harvest rate to maximize net present value of the fishery. For each year that harvest is delayed, there is one less year to make up for lost harvests. Therefore, we would expect that the optimal harvest rate will increase with the length of the delay in harvest. Starting with the no delay scenario (same as the above model), and increasing the delay in harvest from one year to fifty years, our model determined the optimal harvest and net present value of the fishery in each scenario. Figure 3 presents the average net present value of delaying harvest through the year on the x axis under the optimal harvesting model and under the current policy of harvesting 28.4% of the oysters each period after the moratorium.

Figure 3 shows that to maximize the net present value of the oyster fishery, it is best to wait to harvest until after the 2024 season (begin harvest in the 2025 season) through 2107 at a rate of 9.57% which will provide a net present value of $145 million. Under this scenario, the net present value is over 2 times greater than the current policy with moratorium, and over 50 times greater than the current policy with no moratorium. The optimal harvest percentage for each length of harvest delay is presented in Figure 4.

As expected, as the length of moratorium increases, the optimal harvest percentage increases up to a point and then marginally declines. The concave nature of the optimal harvest rate is likely due to the perpetuity of harvests after the 100 year time frame. Initially, the early harvests are very valuable because they are not heavily discounted. However, after some point, the marginal increase in profit from units of harvest during the model are worth less than increasing the stock (and therefore harvest) during the steady state. The optimal harvest rates are still well below the current harvest rate. However, by its very nature, the optimal harvest percentage will always lead to a weakly higher net present value than the current policy.

Figure 3

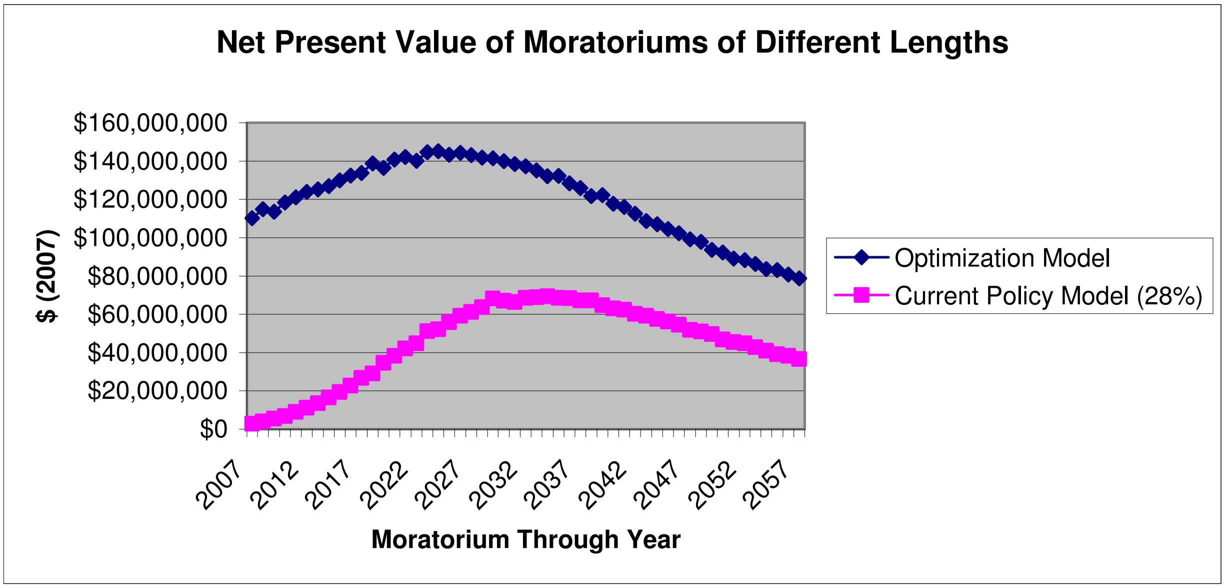
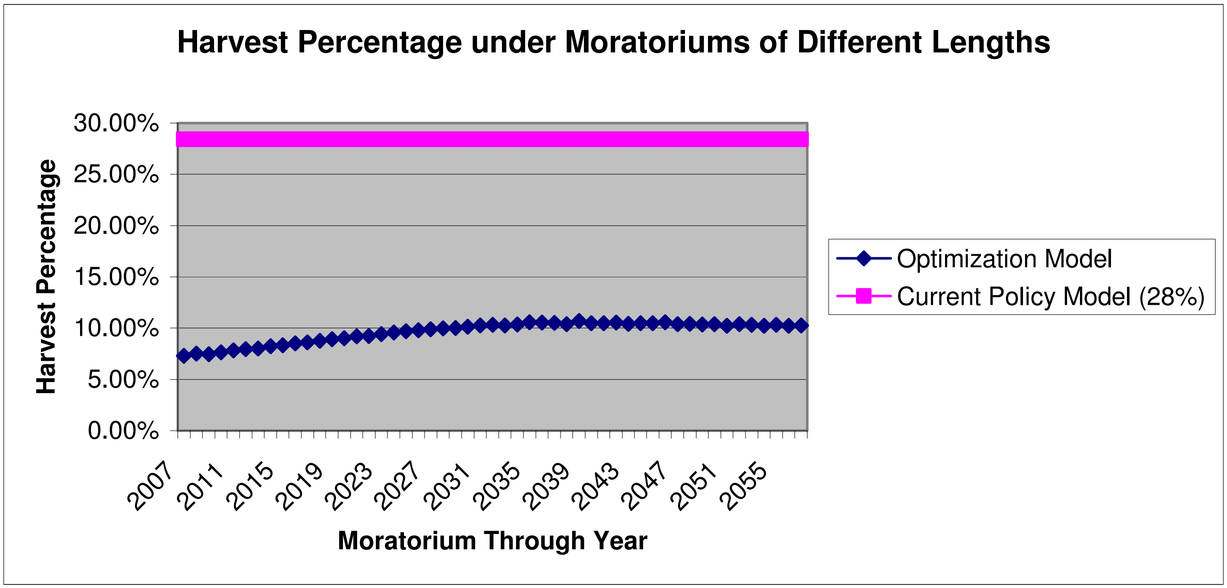


Figure 4



Another interesting prediction of the model is that the net present value of the fishery can be substantially increased through no changes in the property rights structure of the fishery, so long as the harvest is sufficiently delayed. We can achieve a net present value of the fishery almost $70 million harvesting the current 28.4% of the market population as long as we delay harvest until after 2034. However, limiting effort in the fishery to achieve the optimal harvesting rate will lead to a higher net present value regardless of the length of delay.

3.4 Model Caveats

We have excluded the value of ecological services provided by the oyster population which could be significant. The model can easily be extended to include the value of ecological services from the population of market sized oysters which would likely lead to increases in the optimal population size and lower the optimal harvest rate. However, for the initial analysis we wanted to focus more narrowly on the commercial benefits of oyster harvests, which generally accrue to the watermen. This model suggests that focusing solely on the rents earned in the fishery, watermen's income could greatly be increased if they delay harvesting for a number of years. We believe that the model's conclusions reflect the reality of the current situation in the Maryland oyster fishery; that, up to a point, a longer moratorium on the harvest of oysters will result in higher profits from the fishery and a larger population of oysters.

3.5 Ecological Value of Oyster Stocks

Oysters in the Chesapeake Bay are not only a source of revenue for watermen and food for consumers; they also provide important ecological services to the system of which they are a part. Oyster bars create valuable habitat for other fish species which in turn provides value to recreational fishermen (Hicks, Haab, and Lipton 2006). Oysters play an important water quality role, filtering out particles that block the movement of sunlight through the water column thus increasing the amount of light that reaches submerged aquatic vegetation and, consequently, improving benthic habitat for species that need places to hide. The habitat created by the submerged aquatic vegetation is thought to create a very large value through its role in recreational fisheries (Kahn and Kemp 1985). In their filtering, oysters also concentrate nutrients in pseudo-feces, which, with help from other benthic organisms are either buried in sediment or denitrified out of the water column (Newell et al. 2005).

Concerns about eutrophication of the Chesapeake Bay have led to efforts to reduce the amount of nitrogen and phosphorus flowing into it from water treatment facilities and agricultural lands in the watershed. Estimates of the cost of reducing a kilogram of nitrogen delivered to the Bay range from $4.6 for planting cover crops to $1,125 for erosion and sediment control measures, but has been estimated to average $23.8 per kilogram of nitrogen removed (Newell et al. 2005). In their research, Newell and others estimate that a million oysters can, through trophic interactions with other benthic organisms, reduce on average approximately 753 kg of nitrogen from the water column per year. Using the average value of nitrogen removal, this implies a value of $17,932.26

per million oysters[25] per year. We use this as a low estimate of the current ecological value of oysters in the Chesapeake Bay, since it ignores the value of oysters' benefits to recreational fisheries (Hicks and others, 2004), among others.

However, oysters' filtering capacity increases at a decreasing rate, so that each additional oyster will contribute slightly less to denitrification (Cerco and Noel 2007). In addition to the declining effectiveness of oysters filtering capacity, the value of nitrogen removals is likely decreasing with improvements in nitrogen concentrations in the bay. This is because as the bay becomes clearer, the majority of the value to improvements in recreational fishing and boating will already have been experienced and additional clarity is less valuable. Both of these factors imply that the ecological value of oysters is also decreasing in the cumulative amount of oysters in the bay. We therefore estimate that the ecological value ($EV(x(t))$) of the standing oyster stock to be equal to

$$EV\left(x(t)\right)=17{,}932.26 * x(t)\left(\frac{1}{1-\left(x(t)\Big/\sum_{t=0}^{t-1}x(t)\right)}-1\right).$$

The total value from this fishery can now be expressed as the profit from fishing activities (including the salvage of the stock) plus the value of the in situ stock of oysters. Similar to the salvage value of the harvestable oyster stock, the term $\lambda\left(EV\left(x(T)\right)\right)$ describes how the oyster stock continues to provide ecological benefits in the steady state. Amending the model to include ecological services from the oyster population, the same problem of maximizing the net present value of the oyster fishery can be expressed mathematically as:

$$\underset{q}{\text{Max}}\ \sum_{t=0}^{t=100}\left(p\,q\,x(t)-25{,}000\,q\,x(t)\left(1+\frac{k-x}{x^2}\right)+EV\left(x(t)\right)\right)\left(\frac{1}{1+\delta}\right)^{t}+\lambda(T)+\lambda\left(EV\left(x(T)\right)\right)$$

$$\begin{aligned}
&\text{s.t.}\ x(t+1)=\left(x(t)\text{-}qx(t)\right)\mathrm{e}^{\left\{r\left(1\text{-}\frac{(x(t)\text{-}qx(t))}{k}\right)\right\}} && \text{if } \alpha(t)\geq\gamma && \\
&\quad x(t+1)=d\,x(t)-qx(t) && \text{if } \alpha(t)<\gamma && \forall t=1,\dots,T-1
\end{aligned}$$

We denote the above ecological value function **Stock 1** to contrast it with a different ecological valuation function below, which we denote **Stock 2**. The second ecological valuation function holds the ecological value of oysters at a constant value per million oysters. The rationale for this is twofold. First, for the ecological value to be decreasing in the cumulative stock of oysters, the population of oysters needs to be large enough to not only reduce the additional nitrogen being introduced into the bay each year, but also decrease the concentration of nitrogen in the Bay. Secondly, the ecological value of oysters in the Chesapeake Bay results from things additional to removing nitrogen from the water. Therefore, the value of nitrogen reductions from the bay could be conceived as a lower bound estimate for the value of the ecological services provided by the oysters.

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[25] This ecological value corresponds to \$5.38 per bushel of oysters which is 20% of the average value of a bushel of harvested oysters (\$25.72) over the period 1994-2007.

While it is likely that the value of nitrogen reductions will decrease with cumulative oyster stocks, it is possible that the benefits to recreational fishing, boating, and swimming may increase over time. Therefore, we estimated the stock 2 model with ecological values where the ecological value of the stock was constant at $17,932.26 per million oysters. Expressed mathematically: $EV_2\left(x(t)\right)=17,932.26*x(t)$.

Similar to the above analysis, we use these models to analyze the net present value of the oyster fishery under harvest moratoriums of different lengths. When we account for the ecological value of the oyster stock, the optimal harvest rate is lower, and the optimal moratorium is longer. This is not surprising as when we place a value on the resource in situ, it makes sense that we would want a larger population of oysters and for harvests to start at a later date.

Figure 5

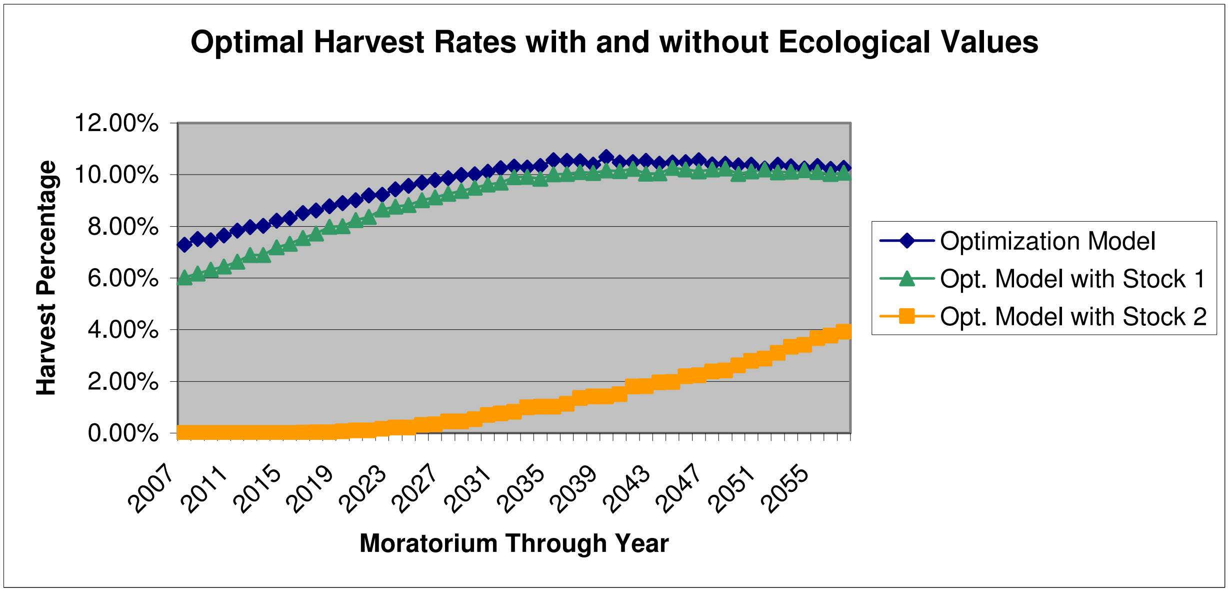


Figure 5 shows that the optimal harvest rate accounting ecological value is below the previous optimization model harvest rate for all moratorium lengths. Figure 5 implies that the harvest rate which maximizes the fishing returns to the oyster fishery (which is very low relative to today's harvest rates) would be higher than the harvest rate which maximizes the total return to the oyster fishery and its environs. Using these parameters, the maximum net present value of the oyster fishery including its ecological value is $194 million which occurs after a moratorium through 2030. This implies waiting an additional six years before harvesting compared to the optimization model without ecological values.

Using the constant ecological value for the oyster stock results in a much lower optimal harvest rate. With such a large value for ecological services relative to the profits from harvesting, it now does not make economic sense to begin harvesting at all until after 2016. However, the optimal harvest rate never increases beyond 4%, which means that the majority of the value of the oyster fishery does not come from the fishery itself, but rather from the ecological role that oysters play in the Chesapeake Bay on other valuable resources.

The results of the models which include ecological services values consistently show that the optimal harvest rates are lower and the optimal moratorium is longer than models which ignore these values. As we know oysters do provide some ecological services value, relatively less intense harvest and a longer moratorium period will likely lead to increases in the net present value of the oyster fishery and its environs.

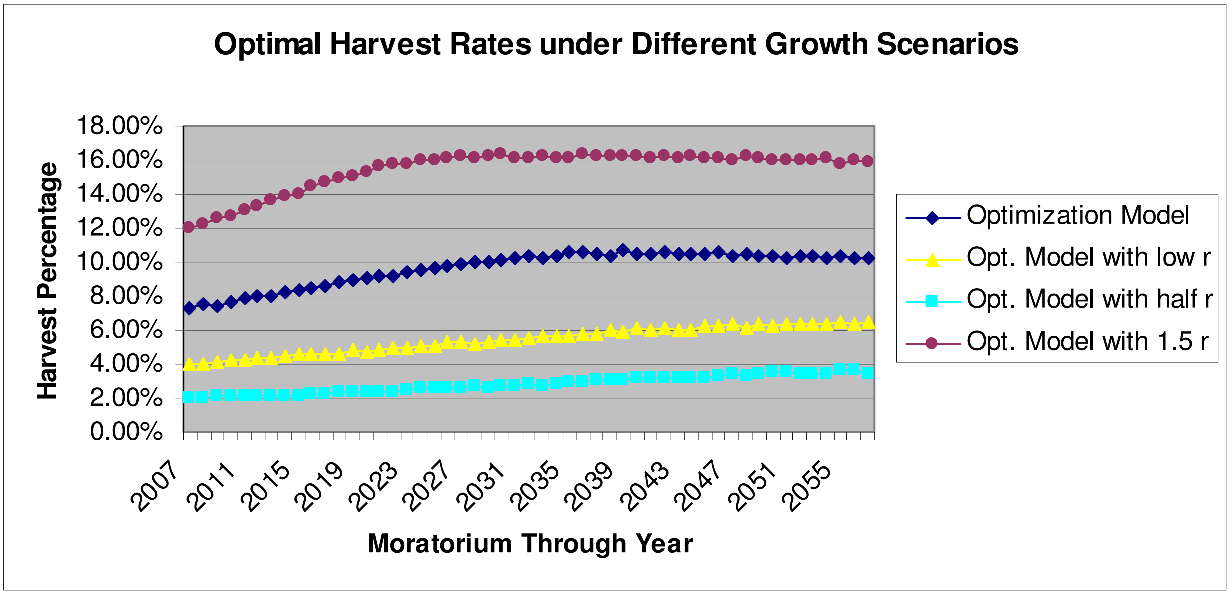
3.6 Sensitivity to the Intrinsic Growth Rate (r)

Given the current state of the oyster population in the Chesapeake Bay and the increasing prevalence of parasitic diseases, it is possible that the current oyster population cannot grow as fast as it has in the past. It is also possible that we have underestimated the oyster's growth potential in our calculation of the growth rate. As a sensitivity analysis, we estimate our model using an intrinsic growth rate that is one half of the previous model (i.e., $r = .137$), a low growth estimate using the average growth of all years (including the high mortality years) between 1994-2007 from Table 3 ($r = .184$), and a high estimate of 1.5 times the growth rate (i.e. $r = .412$).

As in the model described above, we continue to include random high mortality events with these varied growth rates. This has the effect of reducing the expected value of the intrinsic growth rate for all scenarios, which can be expressed as: $\mathrm{E}(r \mid d, \gamma) = (1-\gamma) * (r) + \gamma(1-d)$. Therefore, in the original optimization where $r = .2744$, the expected value of the growth rate conditional on the high mortality negative recruitment factor (d) and probability of a high mortality event (γ) is: $\mathrm{E}(r \mid d, \gamma) = 0.19$. The expected value of the other intrinsic growth rates are 0.072, 0.113, and 0.308 for the half growth ($r = .137$), low growth ($r = .184$), and the high growth ($r = .412$) rate scenarios respectively.

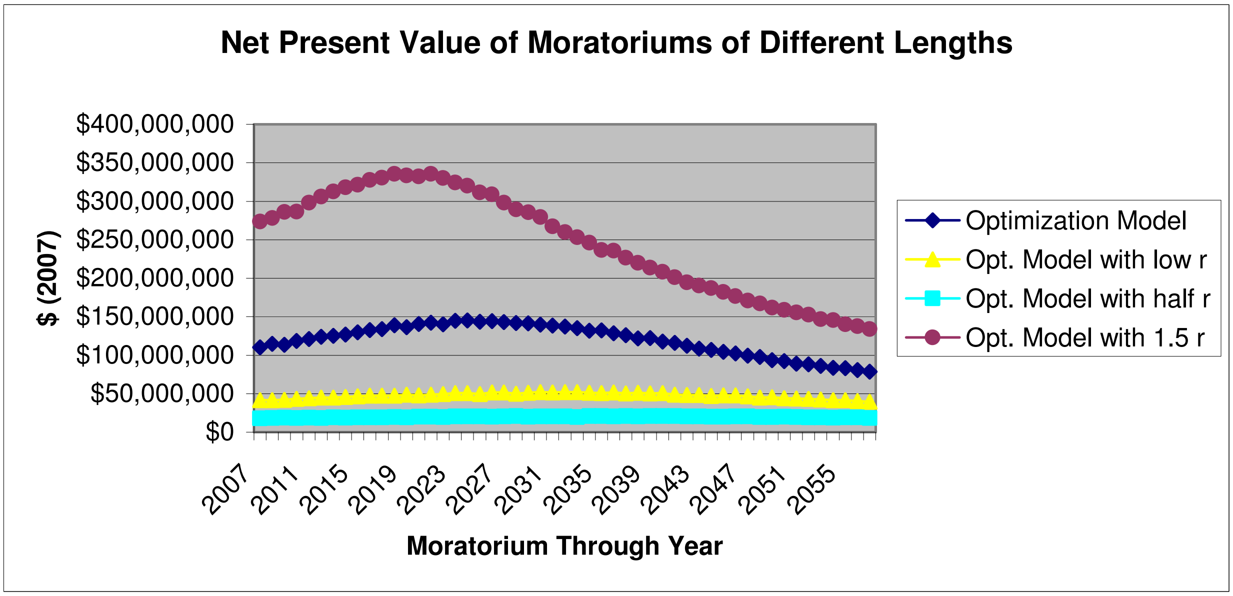
Under the half r scenario, with an intrinsic growth rate of only .137, and high mortality events, the oyster population does not grow nearly as fast as in the original ($r = .2744$) model. Correspondingly, the optimal harvest rates are on average over three times lower than with the original growth rate. The low growth rate scenario ($r = .184$) results in harvest rates that are slightly above half of the harvest rates from original growth rate scenario. Not surprisingly, the optimal harvest rates in the high growth rate scenario ($r = .412$) are about 1.5 times the harvest rates of the normal ($r = .2744$) growth rate model. The optimal harvest rates for the models are shown in Figure 6. Similar to the high intrinsic growth optimization model, the optimal harvest rates are increasing with longer moratoriums.

Figure 6



The net present value estimates for the optimization model, the current policy model, and the optimization model with a lower intrinsic growth rates are presented in Figure 7. The lower growth rate causes both the harvest rates to be lower, which causes the net present value of the fishery to be lower for two reasons. The first is that lower harvests mean lower profits. The second, and more subtle reason, is that a lower intrinsic growth rate lowers the steady state growth of the oyster population and therefore lowers the steady state harvest as well. The opposite is true of the high growth rate model.

Figure 7

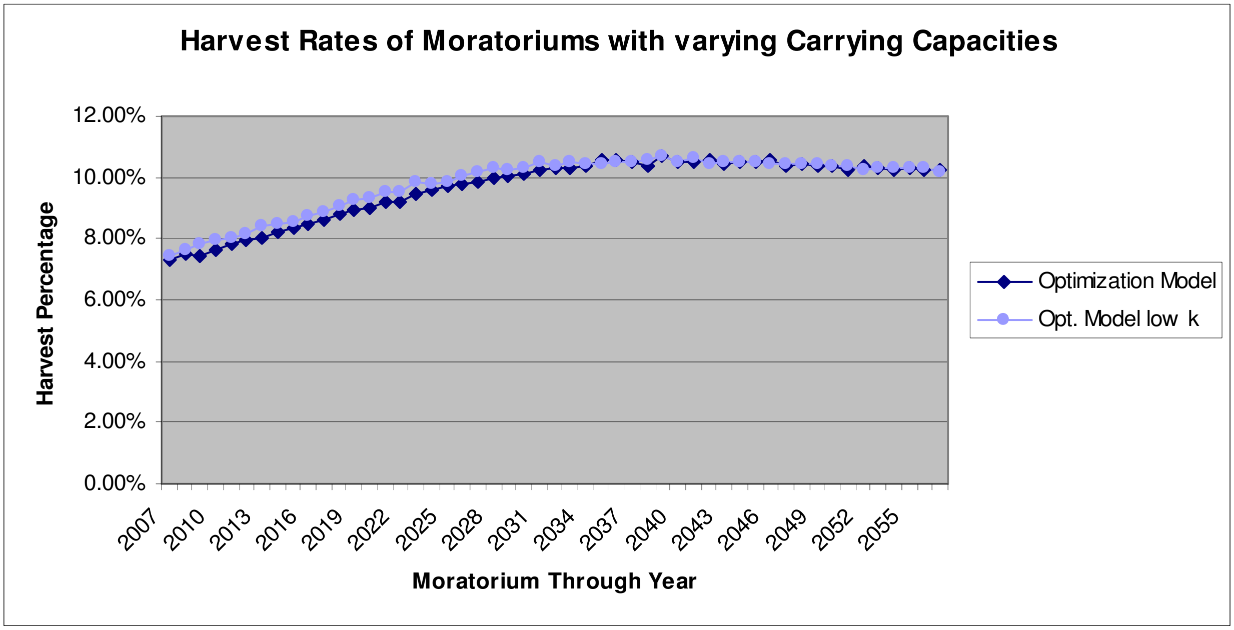


All three growth rate scenarios, half *r* (*r*=.137), low *r* (*r*=.184), and the 1.5 *r* (*r*=.412) scenarios result in net present value estimates which have an inverted U shape with regards to increasing moratorium length. With a moratorium through 2042, a harvest rate of 3.20% maximizes the net present value of the half (*r* = .137) growth rate oyster fishery with a net present value of $21 million. The low (*r*=.184) growth rate scenario has an optimal moratorium through 2033, with a net present value of $52 million and optimal harvest rate of 5.60%. The high (*r* = .412) growth rate oyster fishery's net present value is maximized at a rate of 15% starting in the year 2018 with a net present value of $336 million. Put in the context of the current policy, if the oysters only grow at half the rate we estimate in the original model, a 35 year moratorium and a 3.20% harvest rate will produce 10 times the benefit of a continuation of the current policy.

3.7 Sensitivity to the Carrying Capacity (k)

As a result of current and potential future habitat degradation, it is possible that we have overestimated the carrying capacity of market sized oysters in the northern Chesapeake. To test the sensitivity of our results to this parameter, we reduce our estimate of the carrying capacity by over 25% (*k*=3,678.9 million oysters) and rerun the model. This estimate is the sum of the carrying capacity of the low, medium, and high salinity zones in the Maryland portion of the Chesapeake Bay from Jordan and Coakley (2004). This estimate is lower than the total Maryland carrying capacity because they lacked salinity data for all areas with oyster habitat.

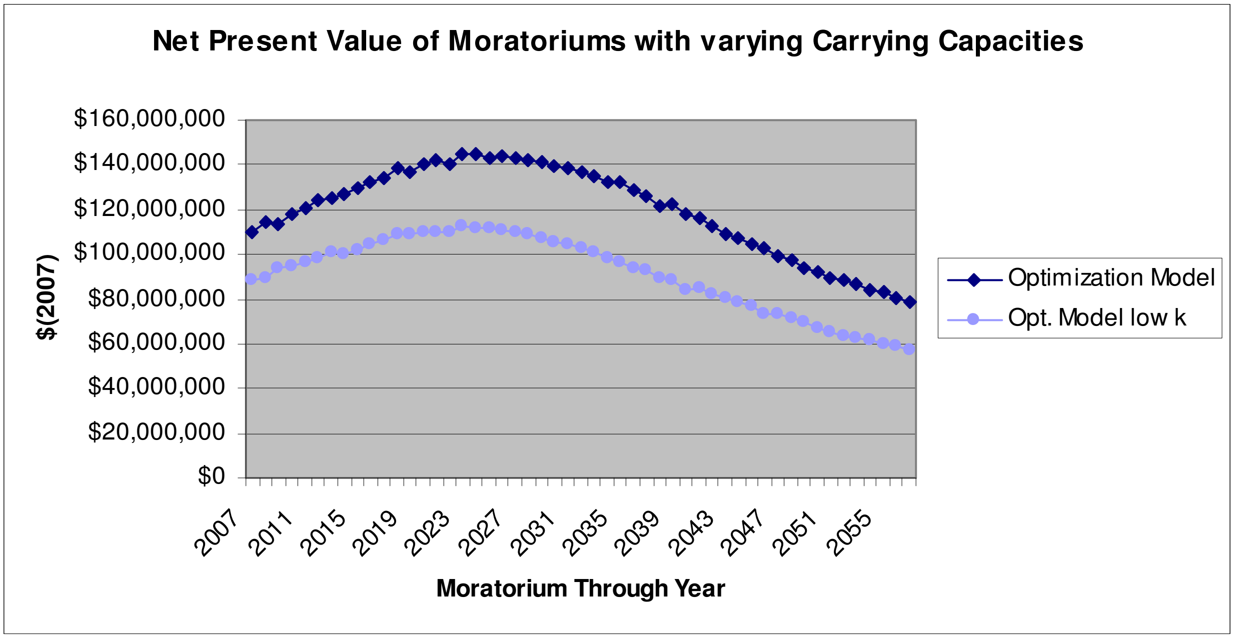
Figure 8



Despite the lower carrying capacity, the optimal harvest rate with a lower carrying capacity is nearly identical to the optimal harvest rate under the original optimization model for the moratorium lengths shown in Figure 8. Despite being slightly higher in the short moratorium years, the difference in harvest rates is never greater than half of one percentage point. This suggests that the carrying capacity estimate does not have a large impact on the choice of optimal harvest rate in the model.

The lower carrying capacity estimate also does not materially change the predictions of the optimization model in terms of which moratorium length maximizes the net present value of the oyster fishery. The optimal moratorium decreases from 2024 in the original optimization model (k = 5,089.2) to 2023 in the model with a lower carrying capacity (k = 3,678.9). The net present value estimates are presented in Figure 9. The net present value of the oyster fishery with the smaller carrying capacity is lower for all moratorium lengths for two reasons. The first reason is that the population can not grow as large, and therefore leads to smaller harvests at the same harvest rate. Secondly, density dependence in the stock begins with a lower stock, which means that the net growth of the stock, and therefore harvest, is lower. Therefore, while the value of the resource changes, changes in the carrying capacity estimate does not cause large changes in other predictions of the model.

Figure 9

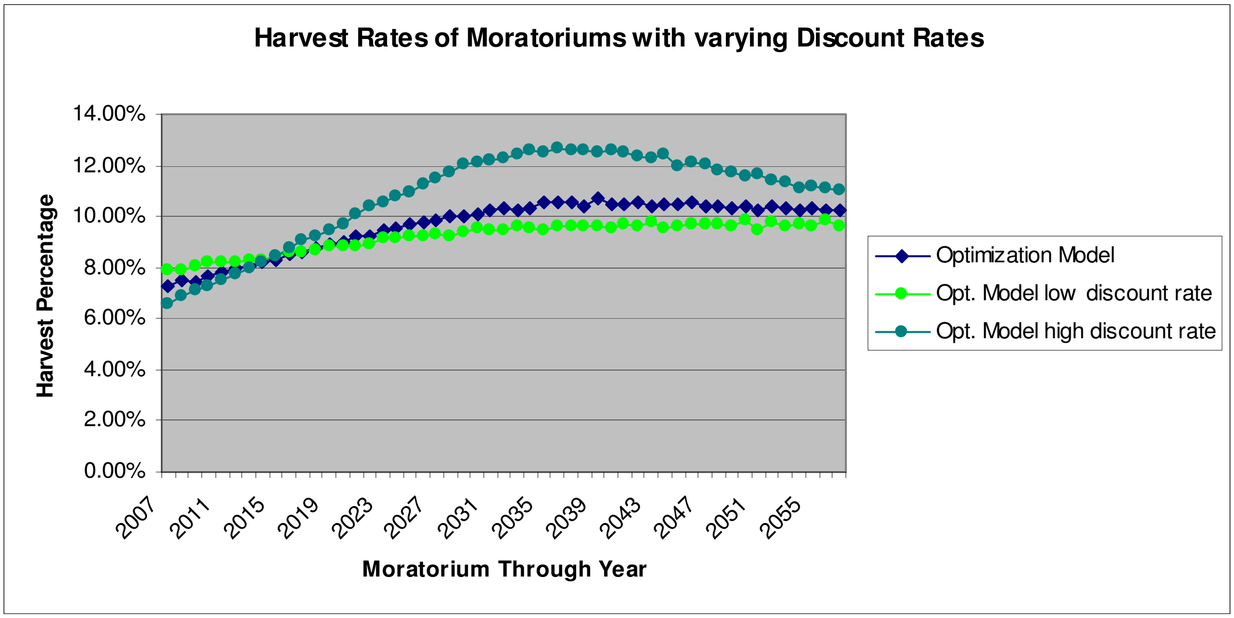


3.8 Sensitivity to the discount rate (δ)

Due to the long time frame of this study, the discount rate (δ) plays an important role in determining the optimal harvest rates in the future. In the initial analysis, we chose a relatively modest discount rate of $\delta = .04$. We chose two additional discount rates to test the sensitivity of our model results to the discount rate; a low discount rate scenario ($\delta = .02$), and a high discount rate scenario ($\delta = .07$).

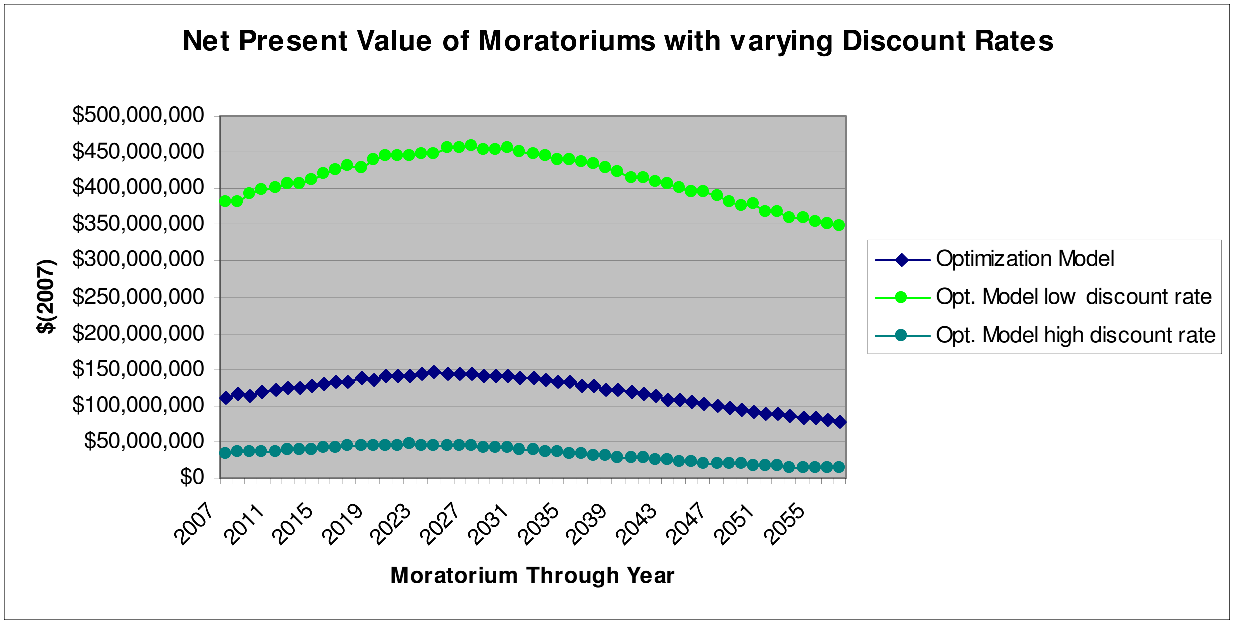
The optimal harvest rates are somewhat sensitive to changes in the discount rate, but the general concavity of the optimal harvest rates over different moratorium lengths remains the same. The optimal harvest rates for each discount rate are presented in Figure 10, and do not vary by more than three percentage points for any moratorium length. The high discount rate scenario begins below the original model and ends above it. This may seem counterintuitive as one would expect that the higher discount rate would force harvests to be higher earlier. However, with the high discount rate, harvests far out in the future are worth very little, so we prefer harvests earlier. The best way to increase harvests in the middle early years is to let the stock grow and harvest a smaller portion of stocks each year. At some length of moratorium, the stock has already increased in size so that a larger percentage harvest is now optimal because they are more valuable in the near term. The opposite argument holds for the case with the low discount rate.

Figure 10



The net present value estimates are shown in Figure 11. Not surprisingly, the discount rate has a dramatic effect on the net present value estimates for each scenario. However, each scenario still shows an inverted U shape as moratorium length increases, which suggests that for any reasonable discount rate, the net present value of this oyster resource could be improved by a moratorium. The optimal moratorium changes from year 2024 in the normal model to 2022 in the high discount rate scenario and to 2027 in the low discount rate scenario. This suggests that while the net present value estimates are quite different, the optimal moratorium length may not vary substantially.

Figure 11



3.9 Pessimistic Scenario

Recently, it has been suggested that the Eastern oyster can no longer grow sufficiently well in the Chesapeake Bay to support a thriving oyster industry as a result of degradation in water quality, reduction in available habitat and increased disease mortality as well as many other potential reasons. This is evidenced by the proposal to introduce a non-native oyster. The last sensitivity test of our model uses the low growth rate ($r = .184$), the low carrying capacity estimate ($k = 3678.9$), the high discount rate ($\delta = .07$), and no ecological services value in what we will call the pessimistic scenario.

This scenario is included to test two questions: “Under these pessimistic circumstances, can it be optimal to harvest the Eastern oyster to economic extinction as the current policy would suggest?” and “What are the optimal harvests if the oysters cannot grow sufficiently well in the Chesapeake Bay?” The first question asks whether our parameters were misspecified and the current policy really is an optimal economic outcome, or if the optimization model can do better under these pessimistic circumstances. The second question relates to an alternative to the introduction of a non-native oyster into the Chesapeake Bay. If the Eastern oyster can no longer grow sufficiently well to support an oyster industry as large as it has in the past (which appears to be the goal of management), what are the optimal harvest rates (and therefore industry size) under this scenario?

The optimal harvest rates under the pessimistic scenario are shown in Figure 12. Not surprisingly, they are lower than the original model and higher than the optimization model with only a low growth rate. With shorter moratoriums, the optimal harvest rates are close to those of the low growth rate scenario, but as the length of moratorium increases, the high discount rate leads to higher harvest rates to make up for the additional harvests occurring later in time. However, in all scenarios, the harvest rates are still substantially below the current policy of allowing watermen to harvest on average 28% of the population of market sized oysters annually.

Figure 12

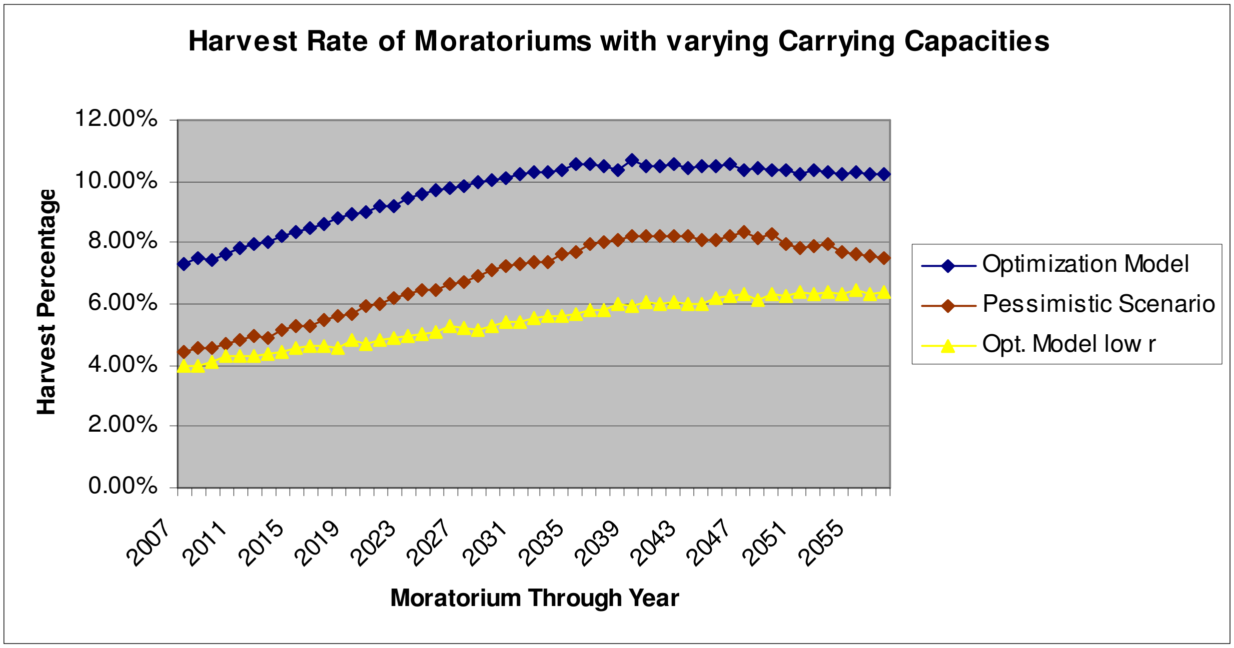
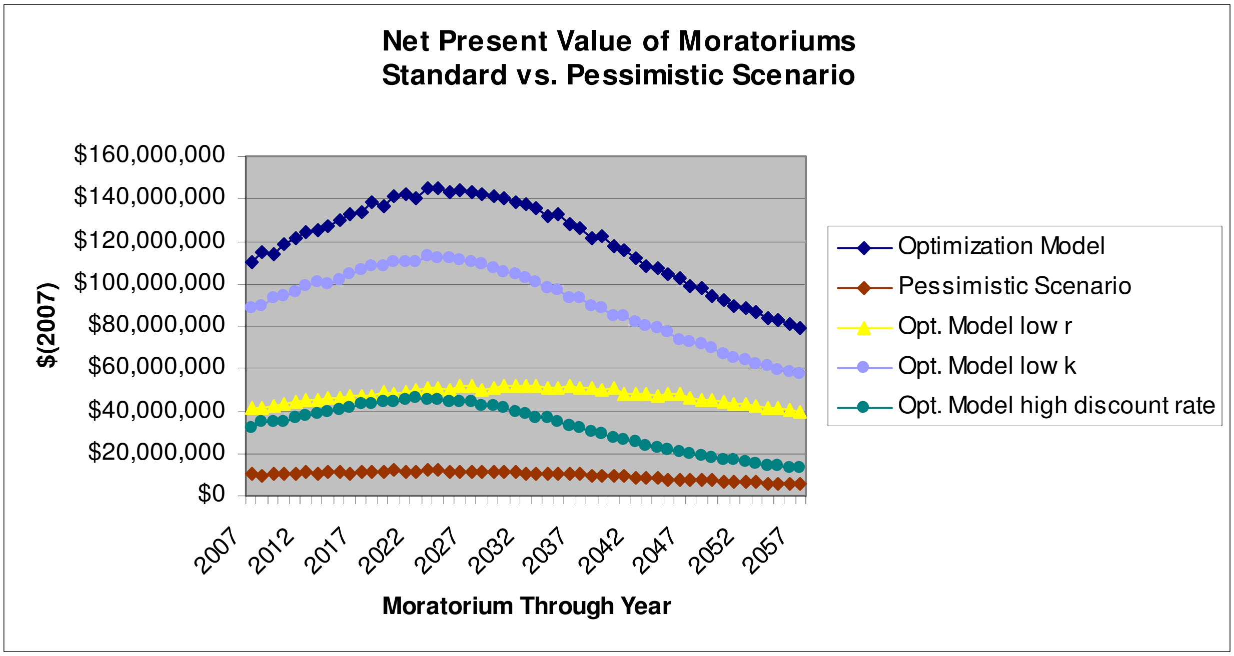


Figure 13



Not surprisingly, the net present value estimates for the pessimistic scenario, which are presented in Figure 13, are much lower than any of the previous models. Combining all of the negative influences of a low growth rate, low carrying capacity, and a high discount rate on the net present value of the fishery results in a fishery which is valued at 10% of the original optimization model.

However, the net present value of the optimization model and the current policy model with the pessimistic scenario is presented in Figure 14 and suggests that even this scenario results in an inverted U shaped net present value curve. The optimal harvest moratorium for the pessimistic scenario is through the year 2023, which is just one year before the original optimization model's optimal harvest moratorium. While the moratorium does not appear to increase the value of the oyster fishery by as much as the optimization model, the additional two million dollars in net present value terms for waiting until after 2023 to begin harvesting results in a 20% increase in the value of the fishery. The current policy model also results in an inverted U shaped net present value curve, but result in a lower value for the fishery in all moratorium lengths.

Figure 14

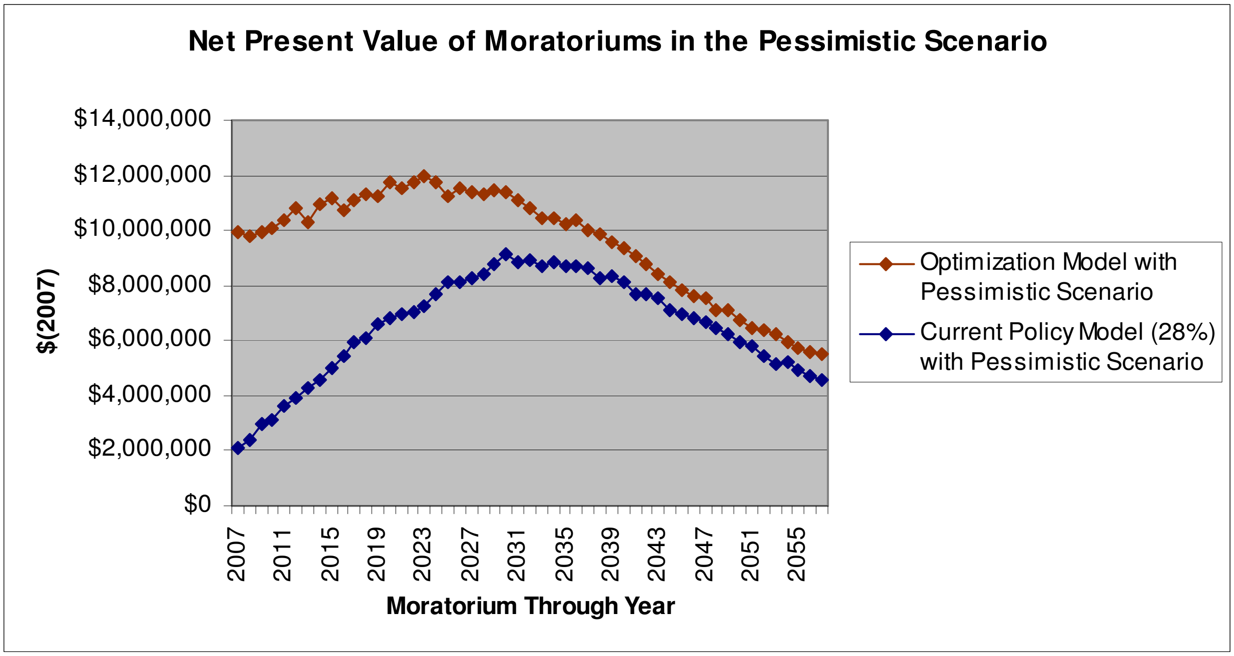


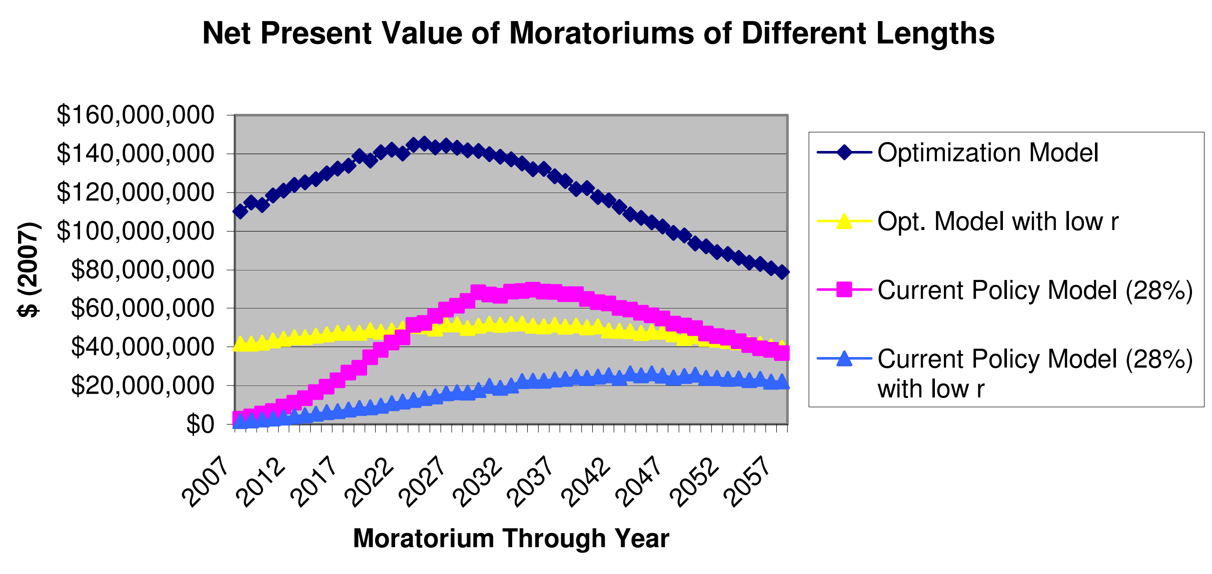
Figure 14 shows that, for some lengths, a moratorium can increase the net present value of the oyster fishery at harvest rates that are lower than the original optimization model. These lower harvest rates never lead to the depletion of the Eastern oyster population in the Maryland portion of the Chesapeake Bay in any of the 1000 simulations for each potential moratorium year. In contrast, the current policy model leads to depletion of the oyster population in nearly all of the simulations for each potential moratorium year. Therefore, under these pessimistic circumstances, the model suggests that the current policy is not optimal, and also suggests that we should be harvesting at a lower harvest rate, not a higher one. Even with these pessimistic circumstances, the Eastern oyster in the Chesapeake Bay can have substantial value if the stock is allowed to rebound and then is harvested at a modest rate.

3.10 Model Conclusions

The results of the model suggest that the current policy of harvesting 28% of the market sized oysters is not sustainable, and leads to a much lower net present value of the fishery than the optimization model. The model also suggests that a long moratorium from harvesting could dramatically increase the net present value of the fishery. Even the current policy model of a 28% harvest rate leads to substantial increases in the net present value of the fishery with longer moratoriums. Lower growth rates tend to cause the optimal harvest rate to be lower, and the optimal moratorium length to be longer, while a higher growth rate causes the optimal harvest rate to be higher and the optimal moratorium length to be shorter, but still positive.

The net present value of the optimization model and the current policy model with the normal (r=.2744) and low (r=.184) growth rates are presented in Figure 15. Figure 15 shows that the net present value of the oyster fishery under the optimization model is always greater than a continuation of the current policy regardless of the underlying growth rate. This is true by the nature of the optimization model. The moratorium which maximizes the net present value of the oyster fishery for the original optimization model runs through 2024 (begin harvesting in the 2025 season) at a value of over $110 million.

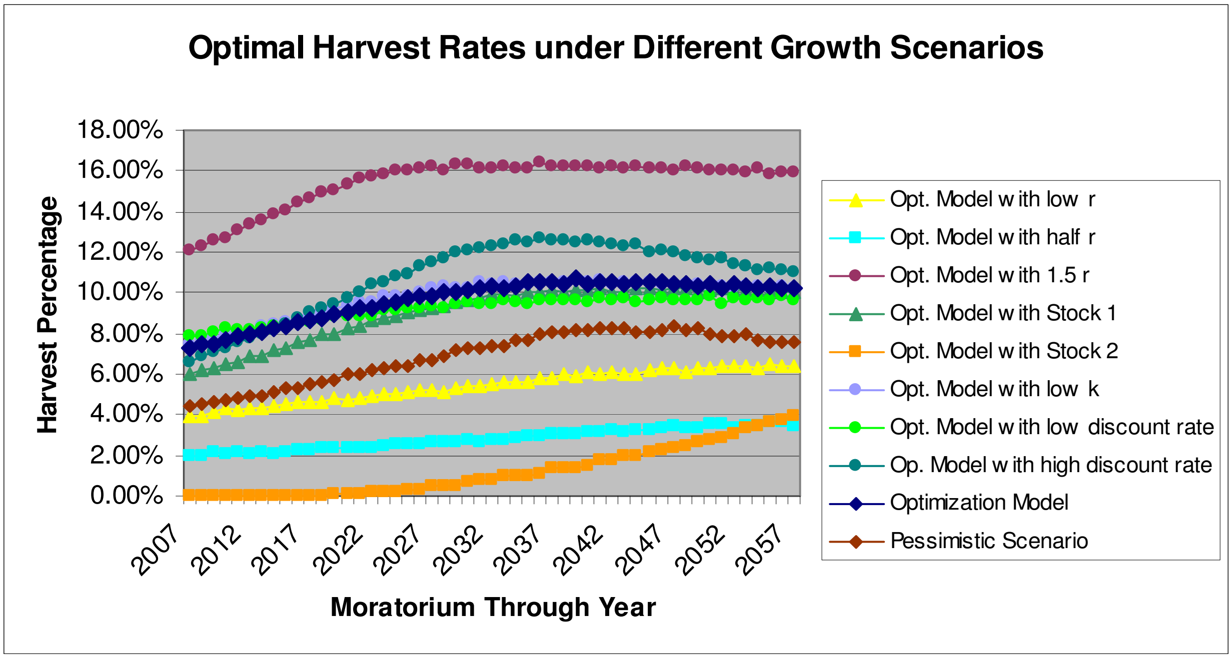
Figure 15



The y-axis in Figure 15 is especially interesting. This suggests that with no moratorium, but by limiting the harvest, the net present value of the oyster resource can increase from less then $3 million to over $110 million, an increase of almost 40 times. The vertical distance between the optimization model net present value (dark blue) line and the current policy model (pink) line is the wasted profit from a continuation of the current policy rather than a policy which maximizes the net present value of the oyster fishery by limiting harvest. It bears stressing that this net present value represents profits to the fishery over and above providing the watermen their income (at a market rate of return on their capital and effort).

The harvest rates which maximize the net present value of the oyster fishery under the different optimization scenarios are much lower than the current policy of harvesting 28% of the market sized oysters. Figure 16 presents the optimal harvest rates for all of the different management scenarios and sensitivity tests. The optimal harvest rates are all concave with respect to the length of moratorium (with the exception of the stock 2 scenario), and they all remain lower than 13%, with the exception of the 1.5 times the growth rate (*r*=.412). Reducing the carrying capacity estimate by over 25% does not greatly change the optimal harvest rates. Changes in the discount rate result in changes in the optimal harvest rates, but do not lead to very large changes in the optimal moratorium length. The optimal harvest rate for the model with half the intrinsic growth rate is on average over three times lower than the optimization model which suggests that the optimal harvest rate are sensitive to changes in the growth rate. Therefore, in the face of significant uncertainty about the intrinsic growth rate of the oyster population, it may make economic sense to set the harvest rates lower than the optimization model would suggest.

Figure 16



The ecological services provided by oysters in the Chesapeake Bay have substantial value through providing habitat for other species, improving water clarity, and removing excess nutrients. When a proxy for these values is included in the model, the optimal harvest rates are lower, and the optimal moratorium length is longer.

Various scenarios were run as sensitivity tests to the original optimization model. While Figure 16 shows that optimal harvest rates vary, they generally suggest reducing harvest rates to a level below 8% for moratoriums which are short or non-existent. These scenarios also result in different net present value estimates, but the general conclusions of the original optimization model are confirmed. All sensitivity tests consistently predict that a moratorium is required to allow stocks to rebound so that harvesting can resume with the goal of maximizing the net present value of the oyster fishery.

The model arrives at two general policy recommendations. The first is that the current open access policy is unsustainable and a lower harvest rate will increase the net present value of the fishery. Over the longer term, this will increase the income of watermen currently in the fishery and provide additional jobs for watermen who have left the fishery. The lower harvest rate will also allow for the oyster stock to recover and provide substantial ecological benefits. The second recommendation is that shutting down the fishery for a number of years to allow the stock to recover can significantly increase the value of the fishery both to the watermen and other users of the Chesapeake Bay at any harvest rate.

4. Practical Issues for Pursuing Greater Value for the Oyster Resource.

The discussion thus far has considered the pursuit of higher net present value for the oyster fishery and changes in the harvest rate in the abstract; as if these were possible. Since a capacity for limiting harvest effort below the open-access equilibrium[26] has not been revealed over the past 100 years of oyster management in Maryland's portion of the Chesapeake Bay's public oyster fishery, it is reasonable to question whether or not restricting harvest effort at a level which still provides resource rents is possible.

Feasibility for a value-maximizing policy can be addressed at several different levels. Is there any practical means for restricting oyster harvests? Could binding and enforceable regulations be instituted? Could a mandate for a value maximizing policy be brought forward through the legislative process? What are the equity considerations? Before addressing these feasibility questions, it is useful to review what is implied by the value maximization model for the oyster resource.

Our model tests the effect of several different policies that are predicted to allow stocks and, thereby, resource value to grow. These policies entail a reduction in harvest effort. Under the existing open-access policy and consequent rent-diminishing harvest effort,

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[26] While gear restrictions do provide some brake on harvest effort, resulting in larger equilibrium stock sizes than expected for the disallowed technology, they still leave harvesters at the open-access equilibrium – just one for a less efficient harvest technology.

stocks are falling and the resource appears to be headed toward economic extinction. If so, then there will be an effective moratorium on harvests when stocks fall so low there is no profit in their harvest. Under the open access harvest regime, that condition, once attained, is assumed to obtain in perpetuity.

With respect to what harvesters are able to take from the fishery, a natural moratorium is the same as one that is established by legislative or agency order. However, in terms of public perceptions and attitudes in the harvest industry, a moratorium established by legislative or agency order would be very different from one resulting from the combined effects of disease and harvests. This public/industry view may be based in the uncertainty of future events and the purposefully optimistic viewpoint of fishermen. Because the uncertainty inherent in measuring oyster stocks and stock change has not been mitigated with improved population monitoring practices and demographic research, these perceptions are widespread.

A publicly-decided moratorium on oyster harvests is also limited with respect to ownership of the oyster resource. Although oysters are generally perceived to have value in their natural habitat, the oyster resource on the bottom is not owned by anyone.[27] In Maryland's portion of the Chesapeake Bay, DNR is charged with managing and regulating the taking of oysters. And in various other mandates it is charged with restoring the oyster resource. But in none of its legislative mandates is it claimed that the State explicitly owns the oyster resource. While the State and Counties assert legal ownership of various parts of the Bay's bottom, neither claims to own the oysters that sit on that bottom. This clearly begs the question, who is seeking to maximize the net present value of the resource, if no one owns it.

One condition that may surmount these barriers to adopting a more economically rational policy toward the oyster resource is the fact that the decline in the resource has already happened. While the difference in future oyster stocks under open harvest versus limited harvest scenarios has been somewhat predictable at least since Jordan and Coakley (2004), the continuing decline in both harvests and fisheries independent monitoring of abundance now provides even more compelling evidence that the current trajectory is not what we desire. As the "natural moratorium" outcome becomes more apparent, the objective used in our model (maximizing net present value) may take on greater relevance in the policy debate.

4.1 Policies for Limiting Harvest Effort

There are fisheries that have formerly operated as open-access resources but, due to declines in abundance, are now managed with more efficient, catch-limiting policies[28]. Therefore, in the general case, there are policies by which it is possible to limit harvest effort in fisheries. With specific regard to oysters, more efficient management of the resource has generally entailed assigning property rights (or, more accurately, lease-

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[27] See Wieland (2007)

[28] See Iudecello and others (1999)

rights) for either oysters or the bottom on which they grow (NRC 2004). However, these private producers often rely on wild brood stock to populate their leased beds, and to keep this source functioning at a productive level requires some management.

A nearby example of a more considered approach to managing a public oyster resource can be found in New Jersey's management of its Delaware Bay oyster fishery. This resource was so seriously impacted by Dermo disease in the late 1980s that the fishery was closed from 1990 to 1994. The public oyster fishery had formerly operated largely as a source for seed stock, for planting on leased beds. However, because the leased beds were principally in the lower bay, where salinities and disease virulence were higher, as disease mortality increased this ceased to be profitable.

After New Jersey's Delaware Bay oyster fishery was re-opened, large oyster bars that had formerly been used as seed beds – providing stock to be grown out on down-bay leases – were shifted to an alternative use. From 1996 onward, these bars have been opened for direct harvest. Because the resource is small relative to the capacity of the harvest industry and, because of the consequent danger of over-fishing, harvests have been limited to a level that does not reduce stock abundance over time (Klinck and others, 2001). This restricted harvest has been implemented by distributing a total harvest allotment among the boats in the fishery and instituting an allotment accounting system that ensures that what gets harvested is reported.

A tri-partite system of governance has developed around oyster harvest allocations. This is composed of the New Jersey Department of Environmental Protection (NJDEP) and, especially, its Shellfish Division; Rutgers University's Haskin Shellfish Research Laboratory; and the Delaware Bay section of the Shell Fisheries Council. The last of these three entities is a group established by legislative statute and appointed by the Governor, who promote the interests and voice the concerns of the harvest industry in policy decision-making. While the New Jersey Department of Environmental Protection holds ultimate authority in the management of the oyster resource, this system of independent groups working cooperatively to decide harvest policy appears to be working so far.

In the fall of the year, monitoring surveys are undertaken on New Jersey's Delaware Bay oyster bars and stock abundances are estimated. These monitoring data are evaluated by NJDEP staff biologists and scientists at Haskins Shellfish Research laboratory and, in the winter, a Stock Assessment Workshop is held where all three groups come together and agree on an harvest allocation for the coming year. Invitations are then sent to license holders to participate in the coming year's harvest. When it is determined how many boats will work the fishery, per boat allocations are decided. These per boat allocations are then bought ($2.00/tag) as numbered tags that each represent a bushel of oysters. The harvester exchanges the tags with the buyer when he sells his oysters.

Each of the 76 vessels that participated in the 2007 season was granted an initial quota of 1,040 bushels. Catch per boat day averaged 66.5 bushels, but the industry is made up of double dredge and single dredge boats. The former averaged 101 bushels per day and the latter, 53 bushels per day[29]. Fishery exploitation rates have been very low since the start of this controlled harvest policy; less than 2 percent of abundance and around 4 percent of total biomass (Kraeuter and others 2006).

While there are many other details helping to ensure success in New Jersey's Delaware Bay oyster management, the point being made in this brief description is simply that it is feasible in some instances to control public oyster harvests for biological (and economic) objectives. This cause was aided in New Jersey by the fact that there were relatively few boats in the fishery by 1996 and that these boats had formerly taken seed oysters and not market product from the bars in question. There thus was no historical claim to open access rates of harvest.

In both its market structure and its biophysical characteristics, the Delaware Bay oyster fishery is different from that of the northern Chesapeake Bay. To the extent that the model reported in the previous section was based on a supposition that positive growth rates are feasible for Chesapeake Bay oyster stocks even in the presence of disease, this is just as well, since New Jersey's harvest management has not generated stock increases there. However, under new shell replenishment projects managers hope to increase the resource in coming years. And, clearly, their management efforts have led to more stable stocks over time than those of the northern Chesapeake Bay.

4.2 Enabling a Value-Maximizing Objective

Kennedy and Breisch (1981) describe the history of the management of the oyster resource in Maryland's portion of the Bay and of legislative attempts to change that management. In the years since Kennedy and Breisch's study, management has changed little, with the exception of some attempts to set productive oyster bottom aside as longer term sanctuaries and the relaxation of gear restrictions on power dredging. The resource is still managed largely as an open access fishery (Wieland 2007).

It is widely maintained[30] that any important change in policy for oyster management requires acceptance by the harvest/processing industries. Indeed, stakeholder interests are an essential consideration in most of what the State undertakes with respect to the oyster fishery. This central role of the harvest and processing industries is integral to understanding why it proves so difficult to implement a change in oyster management.

The history of efforts to change the way the oyster resource is managed tracks closely with the political economy expectations described in the Public Choice literature[31]. The interests of a small group (harvesters and processors) who derive benefits from a particular policy (larger current harvests) are able prevail over larger interests of the wider public because their benefits are more concentrated and they are more motivated to protect them. The larger benefit of alternative policies (limited harvests and larger

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[29] Jason Hearon, undated.
[30] Wolman (1990).
[31] For an overview, see Buchanan and Tullock (1962).

stocks) is not pursued as effectively by the broader public because that benefit is more widely dispersed.

The Public Choice literature posits models to explain how these sub-optimal outcomes can unfold in the legislative arena. But, if the policy preferred by the interest group results ultimately in a degraded resource, it is reasonable to ask how can this be rationally preferred? First, as noted above, uncertainty about future benefits would undermine support for a value maximizing policy that entails present sacrifice for future benefit. Clearly one is not likely to support what one does not believe. Secondly, the harvest industry and processors may just have a very high discount rate, so that whatever benefits might accrue in the future are less valuable than benefits that can be gained from harvests in the current period. Either of these factors could be reinforcing to the other.

If the difference in the perceived benefit of better oyster stock management derives from a lack of confidence in predictions about future outcomes, then an obvious approach to gaining acceptance for policy change is to undertake and extend credible oyster demographic research. Twenty years after the collapse of oyster stocks in Maryland's portion of the Chesapeake Bay, there is surprisingly little demographic research addressing the stock effects of oyster harvests in the presence of dermo and MSX. But, the accumulating evidence of oscillations around a diminishing mean stock abundance now provides part of that demographic research evidence.

If, on the other hand, the main factor distinguishing apparent current harvester preference from the value maximizing preference is a high discount rate, then gaining harvester acceptance for management change would require paying some material compensation to them. Specific ways to think of this compensation are discussed in the following sub-section. Here we will just assert that with some payment marginally greater than harvesters' expected benefit from current harvests, they should be willing to accept foregoing those harvests, allowing a population rebuilding policy to be put into effect.

If stakeholders accepted a policy targeting maximum net present value in the fishery, it is likely that such a policy would be legislated.

4.3 Equity Considerations in Moving from Current to Value Maximizing Policies

Under Maryland's current oyster management policies, the value of the oyster resource is trending toward zero. This ignores public investments made in restoring oyster stocks which, if factored into the calculation, would very likely push the value of the resource negative. Under alternative policies that sought to maximize its value, the oyster resource would gain value as long as the rate of growth of the stock's value sufficiently exceeded the time value of money (the interest rate).

Whether or not the value of oyster stocks in Maryland's portion of the Bay or the whole of the Bay will increase in the absence of harvests at a rate higher than the interest rate is not known with certainty. However, stock abundance estimates and harvest data from the past 14 years provide some indication that oyster stocks could grow faster than any appropriate interest rate, if harvest mortality was removed from the equation. Moreover, given that oyster stocks appear to be declining in the face of current policy, it is difficult to discern any economic justification for continuing to restore stocks in the presence of such harvests. While the results of our estimation of the net present value are uncertain, they provide a basis for considering how one might advance the objective of maximizing the net present value of the oyster resource with regard to "winners" and "losers".

Pareto conditions are a widely used standard in economic literature which addresses different economic outcomes with particular regard to "winners" and "losers". A Pareto improvement is a reallocation of resources that makes at least one person better off without making anyone else worse off. It is a way of extending the common-sense idea that, a trade that makes both parties better off will happen, while a trade that leaves either party worse off will not be entered into voluntarily.

The cost of an oyster harvest moratorium would be born primarily by current harvesters, who would forego current period harvest income. Processors would also be affected by a closure, but the impact on them is assumed to be mitigated by alternative sources for oysters and we restrict our focus to the harvesters. Benefits from an oyster harvest moratorium will accrue to the owners of the resource and, depending on the growth of stocks and the effects of their filtering, to those who benefit from a better functioning Chesapeake Bay ecosystem. For the sake of simplicity, we exclude ecological value of increased oyster stocks in this calculation of winners and losers and welfare gain.

In order to go forward with this analysis, it is necessary to assume that someone has the ability and the desire to maximize the net present value of the oyster resource. As noted above, this is not currently the case. Such a scenario could be envisaged as a state agency charged with achieving the highest possible commercial return to the resource over time, or as the community of harvesters, who might be vested with some corporate ownership of the resource. Either way, it is assumed that there is some owner or steward of the resource who wants to maximize its net present value with respect to commercial harvests. We further assume that the value stored in the fishery can be traded in financial markets and thereby accessed independently of harvests.

The easiest part of the Pareto-improvement problem is the estimate of what is available to compensate current harvesters so that they are not made worse off by a harvest moratorium or binding harvest quotas. If the net present value of a profit maximizing harvest policy (with no moratorium) over the next 100 years is, as predicted by our model, $110 million, then this is what the owner of the resource might be able to borrow to compensate current harvesters for giving up their harvests[32]. Borrowing this amount to compensate current harvesters implies removing all of the resource rents from future harvests and transferring them back to current harvesters.

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[32] To the extent that it may be difficult to find a willing lender at a 4% interest rate, the potential loan amount would be lower than this.

The more difficult part of the problem is identifying who among current harvesters needs to be compensated to keep anyone from being made worse off. There are, in Maryland's public oyster fishery, approximately 2,600 licenses. While the majority of those licenses are not used to harvest oysters, paying to own the license implies that a harvester derives some value from it. Moreover, since the set of current harvesters includes some who might never expect to benefit from future harvests (under the 17 year moratorium) as well as others who can, there may be different perceptions of the fairness of transferring all the profits from future harvests back to current harvesters.

A resolution for establishing who the "losers" are and what is the value of their loss can be found in the current trajectory of oyster stocks under existing harvest policy. If harvesters were just the victims of poor stock management by some third party, it could be argued that their true valuation of the resource might be higher than what is revealed by harvest behavior over time. But, as harvesters have been active participants in this management regime, those arguments are not tenable. In this respect, harvesters value the resource at its net present value under current harvest policy; estimated by the model at $2.76 million.

Somewhere between the net present value of the oyster resource under current policies and conditions ($2.76 million) and its maximized commercial value of $110 million there is likely some price at which losers could be compensated for a change in policy.

5. Summary and Conclusions

From the foregoing analysis it is apparent that the management of the Eastern Oyster resource in the Chesapeake Bay has pursued a goal other than the maximization of value from the resource. Management practice, along with environmental and disease factors, has resulted in a much diminished resource. The Eastern Oyster Biological Review Team (2007) provides a concise description of this result in the Chesapeake Bay. In this report we have developed a more detailed description of the present state of the resource with respect to disease and harvest effects on stocks and stock change, with particular regard to the northern part of the Bay.

The report has developed an argument for a positive population growth rate for oysters in the northern Chesapeake Bay in the absence of harvests. This is used in turn to develop a model based on an underlying stock growth rate of 27 percent (in the absence of harvests) that predicts that harvest moratoria will boost stocks over time, if restoration practices employed over the past 14 years are continued and if environmental conditions are similar to those over the past 14 years. According to this model, a harvest moratorium of 17 years will generate sufficient standing stocks that limited harvests after that 17 year hiatus would generate greater value (in net present value terms) than simply continuing to allow harvesters to overwhelm the reproductive capacity of existing stocks with open access levels of harvest effort.

The model does not directly consider the costs to harvesters of not being able to harvest oysters, but this is addressed in a general discussion of equity issues and winners and losers. If there were an entity that could claim the benefit of a restored oyster stock and if the value of that restored oyster stock was tradable in financial markets, it should be possible to compensate current harvesters for their loss relative to current trends. That is, harvesters could be compensated for not being able to drive stocks to economic extinction from current levels, not for harvests on the scale that were possible before stocks fell to their current levels.

With respect to valuations of some ecological services rendered by oyster stocks, the model shows higher returns and lower optimal harvest levels when these are considered. If the value of oysters in the water is captured in the model, it is to be expected that this would reduce the relative returns from removing oysters for consumption.

We tested the model's sensitivity to lower growth rates by cutting the modeled growth rate in half and found that optimal harvest rates were far lower than those for the higher growth rate. However, the net present value for that scenario was still about six times greater than the net present value estimated for current (open-access) policy.

While current policy compares poorly with effort-limiting policies in terms of net present value of the oyster resource, it remains current policy. From this it can be adjudged that some objective other than maximum commercial or environmental resource value dominates policy decision-making and oyster management in the Chesapeake Bay. Current policy diminishes the value of the resource and, thereby, the number of harvesters who can make a living from a shrinking pie. It extends the time required to restore oyster stocks by moving oyster abundance in the wrong direction.

We are not clear what objective is served by these outcomes, but either there is such an objective or current policy is simply misdirected. In either event, we would argue for a value maximizing mandate for managers of the oyster resource. Such a mandate would place the net present value of the resource front and center, where it could be pursued with greater purpose. It might also reduce opposition to policy-change from harvesters, to the extent that they may be able to support a more valuable resource over a less valuable one.

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