Estimating Ecological Benefits and Socio-Economic Impacts from Oyster Reef Restoration in the Choptank River Complex, Chesapeake Bay

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Table of Contents

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Executive Summary

The oyster reef system in the Chesapeake Bay was so extensive that 18th century European visitors often remarked on the threat these reefs posed to nautical navigation. Large-scale exploitation of the oyster began in the 19th century through the dredging of oysters, with Maryland harvest peaking in the late 19th century at an estimated 15 million bushels annually. In contrast, in the 2016-2017 wild oyster harvest season, 224,609 bushels were harvested – about 1.5% of the 19th century peak. Less than 1% of the historic oyster population remains in Maryland Chesapeake Bay waters due to a combination of overharvesting, habitat loss, and disease.

The profound decrease in oysters in the Chesapeake Bay led to a reduction in oyster-related ecosystem services. Water filtration by oysters can reduce excessive nutrient loads from waterways and increase water clarity, which can in turn potentially enhance growth of submerged aquatic vegetation. Oyster reefs also provide habitat and forage, increasing faunal production and potentially increasing seafood harvests.

The overarching purpose of this project was to explore potential changes in commercial fisheries harvest and regional economic impacts resulting from the oyster reef restoration efforts in the Choptank River System on the Eastern Shore of Maryland. These oyster restoration efforts were driven by the Executive Order 13508 for Chesapeake Bay Protection and Restoration (2009) and supported by the Chesapeake Bay Watershed Agreement (2014) that was signed by governors of the six states of the Chesapeake Bay Watershed, mayor of Washington D.C., and officials from the U.S. Environmental Protection Agency and Chesapeake Bay Commission. Specifically, these Chesapeake Bay Program partners have a stated goal to “Restore native oyster habitat and populations in 10 tributaries by 2025 and ensure their protection” in the Chesapeake Bay. This project focuses on the first three tributaries in Maryland chosen for restoration – Harris Creek, Little Choptank River, and Tred Avon River. The projected cost for achieving the total restoration acreage target was $72 million – actual costs incurred to this point have been $53 million.

To accomplish this, the project team developed an ecological trophic model of the Choptank River System, which also incorporated commercial fishers as top predators in the food web. The abundance of oysters and associated filter feeder bivalves in the model were manipulated across different scenarios to examine the effect of these organisms on ecological production, and ultimately, seafood harvested and regional economic impacts to Dorchester and Talbot counties – the two Maryland counties in the NOAA-defined Choptank Habitat Focus Area. Specifically, these scenarios are: **Scenario 1** – Young Reef in current sanctuaries, **Scenario 2** – Mature Oyster Reef with Oyster biomass increase in sanctuaries, **Scenario 3** – Mature Oyster Reef with biomass increases in Oysters and associated Filter Feeders, **Scenario 4** – Fished Down Oyster biomass, sanctuaries opened to harvest, and oyster density back to pre-restoration levels, and **Scenario 5** – Fished Down with decreased biomass of Oysters and associated Filter Feeders, sanctuaries opened to harvest.

Harvested biomass estimates from the scenarios described above were translated into dockside values by applying mean, species-specific prices by fishery to the biomass harvest estimates. An original cost-earnings data collection effort involving 12 commercial fishers active in the region – in conjunction with IMPLAN regional economic impact modeling software – enabled the calculation of direct, indirect, and induced economic effects for four key economic measures: output, labor income, value-added and employment.

Fisheries managers, seafood harvesters, and other commercial fishing stakeholders are increasingly seeking information regarding the regional economic impacts resulting from fisheries management decisions. This project contributes to addressing this need by generating estimates of key economic measures associated with the commercial fishing industry - and connected industries - of the Choptank River System. This project is a Regional Economic Impact Analysis, which accounts for changes in spending and the resulting changes in regional economic activity. The types of economic measures provided here are different from the measures needed for an economic Benefit-Cost Analysis – a different methodological approach that evaluates a project's contribution to aggregate economic welfare. Please see below for key findings associated with this project.

Key Findings

Finding 1: Increase in Commercial Harvest

The Mature Oyster Reef (Scenario 2) supports an increase in annual commercially harvested finfish and shellfish biomass of about 45%, relative to the current Young Reef (Scenario 1) in the Choptank River System. These Mature Oyster Reefs are predicted to increase total harvested biomass by about 80% relative to the scenario in which restored oyster reef sanctuaries have been fished down to a level that reflects the pre-restoration status of the area (Scenario 4).

Finding 2: Oyster-Associated Filter Feeders Matter

Model scenarios were constructed to explore the potential impact of all major filter feeding groups on fisheries harvest. To do so, the project team developed scenarios in which the changes in oyster abundance affect the abundance of filter feeders (Anemones, Barnacles, Hooked Mussel, and Tunicates) known to be associated with oyster reefs. Accounting for filter feeders on oyster reefs affects fisheries harvest by between 11% and 17% relative to the analogous scenarios that account for change in oyster biomass alone.

Finding 3: Large Predicted Increase in Blue Crab Harvest with Oyster Reef Restoration

The ecological model predicts large increases in Blue Crab commercial harvest due to the trophic effects of the restored oyster reefs. In the Mature Reef with Associated Filter Feeders scenario, the ecological model projects an 80% increase in Blue Crab harvest relative to the current Young Reef scenario, and a 160% increase in harvest relative to the "Fished-Down" scenario where both oyster structure and associated Filter Feeders are reduced. These large gains are specific to the Choptank River system analyzed in this project. The project team urges caution with respect to assumptions about the transferability of these predicted gains to other areas of the Chesapeake Bay, where many other factors not present in the Choptank could affect harvest.

Finding 4: Finfish: Large Predicted Change in White Perch Harvest; Negligible Change to Striped Bass

The ecological model predicts large increases in White Perch commercial harvest resulting from the restored oyster reefs. In the Mature Reef with Associated Filter Feeders scenario, the ecological model predicts that White Perch harvests will be about 110% greater than that of the Young Reef scenario, and more than 650% greater relative to the Fished Down with Associated Filter Feeders scenario. The ecological model predicts negligible effects on Striped Bass harvest across the scenarios.

Finding 5: Total Dockside Sales

The changes in commercially harvested biomass have the potential to contribute to millions of dollars in additional sales for commercial seafood harvesters. The Mature Reef with Associated Filter Feeders scenario is projected to increase dockside sales receipts by more than \$4.5 million relative to the Young Reef scenario, and by about \$11 million relative to the Fished Down with Associated Filter Feeders scenario. These changes in dockside sales are primarily driven by harvest changes for a single species – Blue Crab.

Finding 6: Multiplier Effects for Sales

Each dollar generated through the dockside sales revenues received by commercial fishers has an economic multiplier effect of 2.07. That is, for each dollar of dockside sales, an additional \$1.07 of economic activity is generated in Dorchester and Talbot Counties through inter-industry transactions and additional spending generated through the increases in employee wages and business owner income.

Finding 7: Regional Economic Impacts for Dorchester and Talbot Counties in Maryland

This modeling effort predicts sizable increases in total regional economic effects (direct effects + indirect effects + induced effects) in Dorchester and Talbot Counties, Maryland from oyster reef restoration for four key economic measures: Output, Labor Income, Value-Added, and Employment. Total economic effects reflect the initial change to the economy resulting from the dockside sale of harvested seafood in the region (direct effects), all the iterations of inter-industry regional spending generated by the initial dockside sale (indirect effects), and the spending - at regional businesses - of labor income that stem from both the direct and indirect effects (induced effects).

In summary, this project found that oyster reef restoration in the Choptank River System has the potential to generate biomass increases for certain fish and shellfish species, ultimately leading to increases in commercial seafood harvest and regional economic impacts. This project's findings suggest that there would be substantial increases in blue crab biomass and harvest that would benefit commercial seafood harvesters. This is an important finding, given the highly lucrative nature of the blue crab fishery and that most commercial fishers in this region target different finfish and shellfish species depending on the time of year. As many commercial fishers have voiced strong opposition to oyster sanctuaries and restoration efforts that have eliminated certain areas from commercial oyster harvest, increased harvest of other species due to oyster restoration would be a welcomed mitigating factor. As this is a predictive modeling exercise, a key next step is to track whether projected harvest increases in the Choptank River System are realized. The project team will be tracking future commercial seafood harvest and effort in this area, comparing with trends in other areas to assess whether projected increases of key species such as blue crab are being realized.

Differences in Total Regional Economic Effects, by Economic Measure and Across Scenarios

	Young Reef -> Mature Reef w/ FF	Fished Down Reef w/ FF -> Mature Reef w/ FF
Output (Sales) Total value of production	+ $9.9 million	+ $22.8 million
Labor Income All forms of employment income (employee and owner compensation)	+ $3.3 million	+ $7.8 million
Value-Added Difference between output and cost of intermediate inputs	+ $6.0 million	+ $13.3 million
Employment Full and part-time annual jobs	+ 142 jobs	+ 319 jobs

Introduction

The large (165,760 km^2) Chesapeake Bay watershed, encompassing six states and the District of Columbia, has a long history of anthropogenic impacts and change. As documented by an early 18th century Swiss visitor, the waters of the Chesapeake Bay were rich with dense oyster reefs (Michel 1702). Large-scale dredge harvesting of oysters in the Chesapeake Bay began in the 19th century and peaked in the late 19th century with estimates of 15 million bushels of oysters harvested annually in Maryland. Now, less than one percent of the original oyster population remains in Maryland (Wilberg et al. 2011) due to a combination of overharvesting, habitat loss, and disease.

The loss of oysters and oyster reefs has heavily impacted the commercial harvesting of oysters. Wild (non-aquaculture) oyster harvest in Maryland during the 2016-2017 harvest season totaled 224,609 bushels – a 42% drop from the previous year and about 1% of the peak late 19th century harvests. Beyond the harvest of oysters for seafood markets and consumers, oysters and oyster reef habitat contribute to the provision of other ecosystem services such as water filtration, carbon sequestration, habitat and shoreline stabilization, habitat for benthic aquatic organisms, and increased fisheries production (Grabowski and Peterson 2007), and more. The severe depletion of the oyster population in the Chesapeake Bay consequently has reduced the provision of these ecosystem services.

The filtering capacity of the historic oyster population was substantial. Newell (1988) estimated that prior to large-scale human exploitation the oyster population could filter the entire volume of the Chesapeake Bay in a few days. Now it would take the current oyster population about 55 times longer, or nearly a year for the remaining oyster population to filter the volume of the Chesapeake. Increased water filtration would result from additional oyster reef – supported filter feeders such as barnacles. Oysters produce new substrate for additional filter feeders to live and grow, and these additional filter feeders can more than double the filtering capacity of the oysters themselves (Gedan et al. 2014). As Newell solely accounted for oyster filtration in his estimate of biological filtering capacity, his estimate of the scale of filtration is a conservative estimate of the actual filtering power of oyster reefs.

The water filtration capacity of oysters reduces nutrient loads (primarily nitrogen and phosphorous) from the waterway through the sequestration of nutrients in the oyster shell and through denitrification stimulated through the deposition of feces and pseudofeces in the sediment (Newell and Mann 2012, Kellogg et al. 2013). Specific to the Choptank River system, researchers have estimated the removal of nitrogen from the water column (Kellogg et al. 2013). Using the FARM (Farm Aquaculture Resource Management) model, Bricker et al. (2018) estimate that 199 kg nitrogen per acre/year are removed by restored oyster reefs through sequestration of nitrogen into oyster tissue and shell. Denitrification rates associated with restored oyster reefs in the Choptank system were estimated to be 225 kg/acre/year (Kellogg et al. 2013). Combining estimates from these two studies yield an estimate of 424 kg nitrogen per acre/year removed from nitrogen sequestration and denitrification. Across the anticipated 964 acres of oyster reef restoration in the Choptank system, this projects to 408,736 kg removed per year in this area. Using the avoided cost approach and applying a nitrogen price per kg range from DePiper et al. (2016) of \$8.80 (low nutrient trading credit estimate) and \$44 (high nutrient trading credit estimate), the nitrogen removal value in the Choptank system would be between $3.6 million and $18.0 million annually.

Besides filtering the water, oysters provide other critical ecosystem services. Recent research suggests that restored oyster reefs enhance growth of submerged grasses (R. Lipcius, unpublished manuscript), likely because grasses require adequate light to grow, and oysters enhance water clarity by clearing the water column of small plankton and suspended particles (National Research Council 2004). Oyster reefs provide complex habitat for a wide variety of fauna many of which are forage for higher trophic groups (Kellogg et al. 2013). Peterson et al. (2003) directly link oyster reefs to increased fish production, and Grabowski and Peterson (2007) multiply this increase in fish production by species-specific dockside prices to estimate the increase in dockside landings values for different fish species.

Project Objective

The objective of this project is to quantify the changes in seafood production – both in terms of harvested biomass and regional economic impacts – that results from oyster reef restoration and alternative oyster management strategies in the Choptank and Little Choptank river complex (CLC). First, an ecological food web model is developed to estimate the ecological function and productivity of oyster reef restoration across multiple alternative management scenarios in the CLC. Annual estimates of harvested biomass are then converted to annual dockside values by multiplying historic, species-specific mean per-unit prices paid by seafood dealers by the total quantity of biomass harvested. These annual dockside values are then used in IMPLAN (regional input-output economic modeling software and data) to produce estimates of the direct, indirect, and induced effects for four key economic impact measures – output (sales), income, value-added, and employment. The overarching goal of this project is to provide Chesapeake Bay fishery managers with useful ecological and socioeconomic metrics to support decision-making for the oyster fishery.

Study Area

This project models the effect of oyster reef restoration on fisheries production in the 445 km^2 CLC (Figure 1, inset). Per the NOAA Habitat Blueprint, the CLC is a spawning area for finfish species such as striped bass and river herring and has historically abundant oyster reefs that have been severely depleted through a combination of overharvesting, habitat degradation and disease. The CLC is an important commercial fishing area. According to harvest and dealer report data (personal communication C. Lewis and B. Walters, Maryland DNR) 2015 blue crab harvest totaled 4.7 million lbs ($8.7 million in dockside value) and 2015 finfish harvest totaled 1.3 million lbs ($807,000 in dockside value).

The goal of the Chesapeake Bay Watershed Agreement of 2014 (signed by governors of the six states of the Chesapeake Bay Watershed, mayor of Washington, D.C., officials from the U.S. Environmental Protection Agency, and the Chesapeake Bay Commission) had been to *"Restore native oyster habitat and populations in 10 tributaries by 2025 and ensure their protection"* in the Chesapeake Bay by 2025. The ten tributaries were to be spread equally across Maryland and Virginia. The first three tributaries selected for Maryland were Harris Creek, Tred Avon River, and Little Choptank River. Restoration acreage targets and expected projected implementation and monitoring costs are detailed in the bullet points below.[1] These estimates were obtained from the Harris Creek (Allen et al. 2013), Tred Avon (Maryland Interagency Oyster Restoration Workgroup 2015b), and Little Choptank River (Maryland Interagency Oyster Restoration Workgroup 2015a), Oyster Restoration Tributary Plans.

- ✓ **Harris Creek –** 377 acres of restored reef at a projected total cost of $31.7 million
- ✓ **Tred Avon River –** 147 acres of restored reef at a projected total cost of $11.4 million
- ✓ **Little Choptank River** – 440 acres of restored reef at a projected total cost of $29 million
- ✓ **TOTAL –** 964 acres of restored reef at a projected total cost of $72.1 million

Methods

This section describes the development of an ecological model and the linking of these outputs in a regional economic impact input-output model to estimate the increase in seafood production and change in key economic measures associated with oyster reef restoration in the CLC. First, an ecological model (Ecopath with Ecosim) was used to estimate the biomass of the commercially important fish species supported by oyster reefs and primary productivity in the region through habitat and food web connections. The fitted model was then used to project future restoration scenarios and estimate terminal year catch associated with different restoration scenarios. Second, terminal year catch from these scenarios were used as inputs in an economic model (IMPLAN) to estimate regional economic impacts of the active commercial fisheries of the CLC.

Ecological Model

The Ecopath with Ecosim software (version 6.6.14980.0) was used to create an ecosystem model of CLC oyster reefs. This model was a modified version of an existing ecosystem model of a “typical” Chesapeake Bay oyster reef and the commercially and recreationally important fish species supported by such a reef (Madeo 2012). The model is used to quantify the habitat and trophic relationships between oyster reefs, lower trophic level invertebrates and forage fish, and commercially and recreationally important fish and shellfish.

Ecopath with Ecosim (EwE) is an ecological modeling suite of software that uses a mass-balance approach to estimate group productivity (in terms of biomass, in this case), considering predator-prey interactions and fishery removals. The model estimates all group biomasses at one point in time in the mass-balance module, Ecopath. These biomasses are projected forward in time, constrained by specified predator-prey interactions and fishery harvests, in the time-dynamic simulation module - Ecosim (Christensen and Walter 2004). Extensions to the approach (functional responses and forcing functions in the model) allow explicit consideration

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[1] Actual restoration costs incurred by May 2018 (obtained from Stephanie Westby at NOAA) total $52.9 million across the three tributaries.

of environmental constraints for dissolved oxygen, temperature, salinity, and Chlorophyll *a* (Chla) for specific groups modelled.

Ecopath: Model domain, ecological groups, fisheries

The region modelled (Figure 1, inset hashed area) includes the areas (445.0 km^2) where most natural oyster settlement has historically occurred in the CLC. The Ecopath model was used to estimate initial conditions for the Ecosim simulations. Subsequently, Ecopath was used to estimate a snapshot of the trophic flows in the CLC for 2006 (Figure 2).

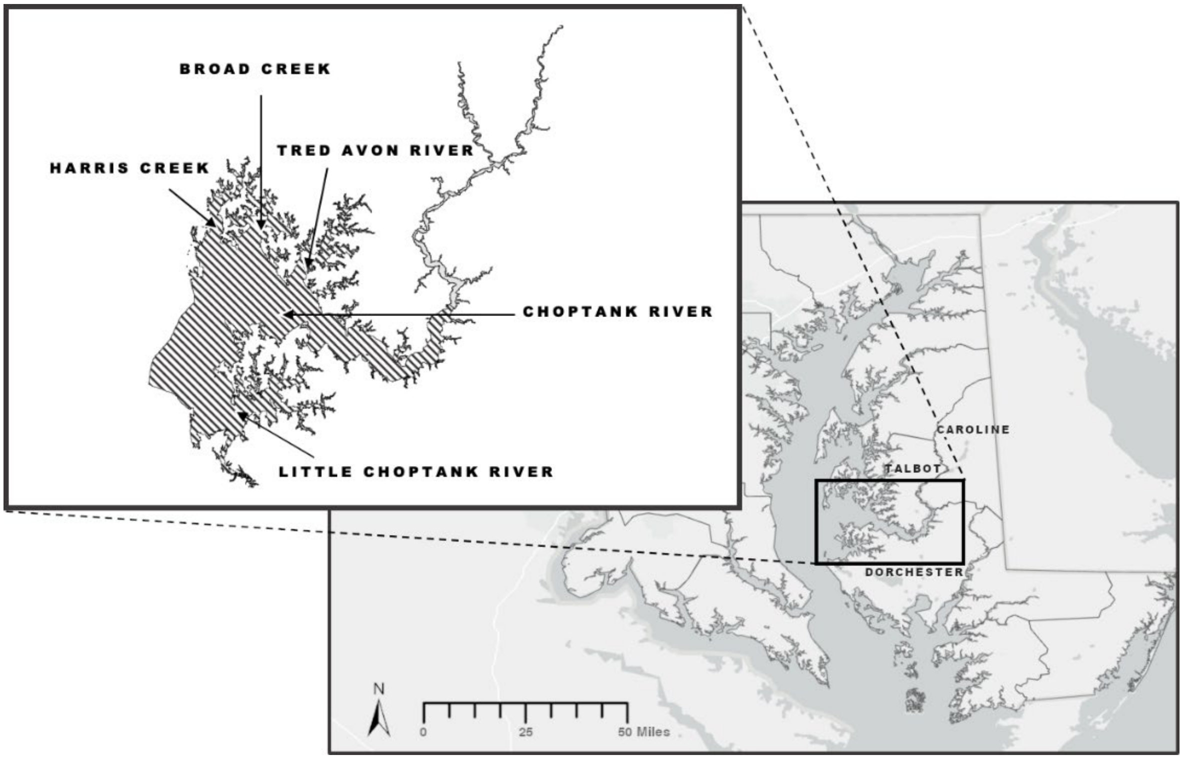

Figure 1. Study area. Hashed area (inset) is the area modeled with EwE (445 km^2).

Restored oyster reef has been established in Harris Creek, Tred Avon River, and the Little Choptank River (Figure 1). Oyster reef restoration projects in the Choptank and Little Choptank rivers (CLC) are the focus for this analysis (inset-hashed area, Figure 1). Oyster reefs have been constructed in Harris Creek, Tred Avon River, and Little Choptank River, part of Talbot and Dorchester counties, Maryland. The area modeled with EwE (445 km^2) corresponds to the natural oyster settlement area that has been most commonly observed. Economic impacts are estimated separately for three regions: a) Talbot and Dorchester counties, b) all coastal Chesapeake Bay counties in Maryland, and c) all Maryland counties combined. A rich variety of both invertebrate and vertebrate fauna exists on the restored oyster reef; however, ecological groups modeled were limited to valuable targeted species, and non-targeted species considered important for ecosystem function (Table 1).

Table 1. Ecological groups modeled. Commercially important species and groups necessary for important ecosystem functions were included in the ecosystem model. Juveniles (J) and (A) adults are designated for groups that are modeled by life stage (called multi-stanza groups).

Group name	**Scientific name(s)**
Weakfish	*Cynoscion regalis*
Peprilus spp.	–Butterfish (*Peprilus triacanthus*) –Harvestfish (*Peprilus alepidotus*)
Oyster Toadfish	*Opsanus tau*
Striped Bass (J, A)	*Morone saxatilis*
Catfish	–Black Bullhead (Ameiurus melas) –Blue Catfish *(Ictalurus furcatus*) –Channel Catfish (*Ictalurus punctatus*) –Flathead Catfish (*Pylodictis olivaris*) –White Catfish (*Ameiurus catus*)
White Perch	*Morone americana*
Reef Fishes	–Tautog (*Tautoga onitis*) –Black Seabass (*Centropristis striata*)
Blue Crab (J, A)	*Callinectes sapidus*
American Eel	*Anguilla rostrata*
Forage Reef Fishes	–Blennies (Suborder: Blennioidei) –Gobies (Family: Gobiidae) - primarily Naked Goby (*Gobiosoma bosc*) –Skilletfish (*Gobiesox strumosus*)
Atlantic Croaker	*Micropogon undulatus*
Diving Ducks	–Surf Scoter (*Melanitta perspicillata*) –Long-tailed duck (*Clangula hyemalis*)
Ghost Anemone	*Diadumene leucolena*
Cownose Ray	*Rhinoptera bonasus*
Sea Nettle	*Chrysaora quinquecirrha*
Mud Crabs	–*Eurypanopeus depressus* –*Panopeus herbstii*
Ctenophore	*Mnemiopsis leidyi*
Panfish	–*Leiostomus xanthurus* –*Lepomis gibbosus*
Atlantic Menhaden	*Brevoortia tyrannus*
Mysid	*Neomycis americana*
Tunicate	*Molgula manhattensis*
Barnacles	Subclass: Cirripedia
Isopods, copepods & amphipods	

Group name	Scientific name(s)
Bryozoans	Phylum: Bryozoa
Oyster (J,A)	Eastern Oyster (*Crassostrea virginica*)
Small Clams	–Macoma spp. –Dwarf Surf Clam (*Mulinia lateralis*) –Gem Clam (*Gemma gemma*)
Hooked Mussel	*Ischadium recurvum*
Large Clams	–Soft Shell Clam (*Mya arenaria*) –Stout Tagelus Clam (*Tagelus plebeius*)
Zooplankton	
Annelids	*Alitta succinea*
Gizzard Shad	*Dorosoma cepedianum*
Dinoflagellates	Class: Dinophycaea
Phytoplankton (Large)	2-200 µm
Phytoplankton (Small)	0.2-2 µm
Detritus	

Since EwE is not a spatial approach, the area (445 km^2) modeled includes all the major features of the aquatic CLC region, including hard bottom and soft bottom areas, all floral and faunal groups (Table 1), sanctuaries and fished areas. This area was chosen for modeling because it includes the CLC areas where natural oyster recruitment has been commonly observed, its circulation is thought to be somewhat independent from that of the larger Chesapeake Bay and can thus be assumed to be a (nearly) closed system, and it includes all the sanctuaries of interest to Maryland decision-makers.

Harvested species in the model are commercially important species, including: American Eel, Atlantic Croaker, Atlantic Menhaden, Blue Crab, Eastern Oyster, Striped Bass, catfish (Channel, Bullhead, and White combined), Gizzard Shad, and White Perch. Twelve commercial fisheries were modeled based on occurrence in MD DNR catch records (2006-2015). These included: trotline, hook and line, eel pots, fish pots, pound net, haul seine, gillnet (anchored), fyke net, oyster (power dredge, skipjack, hand tongs, dive; Table 2). However, the number of fisheries modeled in IMPLAN was reduced to nine, because the other fisheries were reported by the active community of watermen (details of fisher interviews below) to be fished infrequently enough to prevent identification of a fisher of these gears. The clam bait fishery was added to the analysis, due to the recommendation of multiple commercial fishers as a relatively important fishery for the CLC. Harvests for “Duck Hunt” and “Recreational Fishery” are included in Table 2, even though harvests specific to the study area were not available, because these harvests are thought to be important. The Diving Duck group was essential to include in the model, because the primary prey for sea ducks is Hooked Mussels – a major competitor with oysters, whose consumption can exceed that of the oysters themselves (Gedan et al. 2014) – and realistic control of the Hooked Mussel group is needed to avoid an unrealistic constraint on oyster growth. Duck harvests are, in turn, important to include to constrain the Diving Duck population; however, predation on Diving Ducks (hunting) is not well described in this analysis. Recreational fishery harvests were included for Striped Bass, White Perch, and Atlantic Croaker (percentage of total harvest by species: 9%, 9%, and 6%, respectively) because these species are commonly consumed by recreational fishers and it was considered unrealistic to exclude consumption by humans.

Ecosystem service benefits were estimated only for those groups targeted by fisheries. Non-targeted benthic species that were considered important were defined as those species or groups (Table 3) that occurred in a minimum of 25% of all field samples collected (unpublished data, L. Kellogg, VIMS).

Landed weight was based on 2006 MD DNR landings (C. Lewis, unpublished data), and were specific to the CLC, corresponding to the start of the modeled timeframe. Weight conversions from bushels to lb. were based on current practice of MD DNR: soft clams 12 lb/bushel, blue crab 40 lb/bushel, oyster 6.4 lb/bushel (shucked meat weight) as per C. Lewis, MD DNR. The 2015 value of oyster is based on NMFS landing statistics data.[2]

Landed value was based on 2015 data for all species. We calculated the aggregate price/lb. for each CLC fishery (called a “fleet” in EwE) by summing the average price by species weighted by the proportion of each species caught in that gear over a 10-year span (2006-2015). Values for blue crabs, clams, and most finfish were estimated by multiplying harvest by average price per pound from dealer reports (C. Lewis, personal communication). The “Reef Fish” group (see Table 2), unlike other finfish prices, and Oyster prices came from NOAA landings data by state.[3]

Table 2. Fisheries harvests for the study area, for year 2006. Numeric values (Metric Tons/km^2/year) used to initiate model runs are based on harvest data sources as specified, but note that harvests for “Duck Hunt” and “Recreational Fishery” sectors specific to the study area were not available (see text for details).

	Harvest Sectors											
Group name	**Trotline[1]**	**Hook & Line[2]**	**EelPots[2]**	**FishPots[2]**	**Poundnet[2]**	**Haulseine[2]**	**Gillnet[2]**	**Fykenet[2]**	**Oyster Harvest[3]**	**Clamming (bait)[2]**	**Duck Hunt**	**Recreational Fishery**
StripedBass		1.33E-02			1.92E-02		8.33E-02					1.16E-02
Diving Ducks											1.00E-05	
Catfish			3.06E-04	1.73E-01	6.10E-03	2.27E-02	2.10E-03	2.00E-02				
Reef Fish								2.75E-01				
American Eel			6.33E-02	9.14E-03								
White Perch		4.39E-05		2.79E-03	4.01E-03	1.53E-04	1.29E-01	1.99E-02				1.56E-02
Atl. Croaker		1.53E-05			1.48E-03							1.00E-04
Gizzard Shad				4.28E-02	4.78E-03	3.66E-02	1.97E-02	6.07E-04				
Atl. Menhaden				1.73E-03	7.50E-03		3.90E-04					
Blue Crab	2.23E+00											
Lg. Clam										7.29E-04		
Oysters									7.44E-01			

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[2] https://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual- landings/index , last accessed 14 November 2018).

[3] https://www.st.nmfs.noaa.gov, downloaded 15 November 2017

Table 3. Important non-targeted, benthic species. These groups were consistently observed to comprise at least 25% of the species observed in field samples (unpublished data, L. Kellogg, VIMS).

Group in Model	Animal	Representative Species
Forage Reef Fishes	Naked Goby	*Gobiosoma bosc*
Tunicates	Molgula	*Molgula manhattensis*
Annelids	Polychaete (worm)	*Alitta succinea*
Hooked Mussel	Hooked Mussel	*Ischadium recurvum*
Small Clams	Macoma spp.	*Macoma balthica*
Small Clams	Macoma spp.	*Macoma mitchelli*
Small Clams	Surf clam	*Mulinia lateralis*
Mud crab	Flatback Mud Crab	*Eurypanopeus depressus*
Barnacles	Subclass: Cirripedia	*Amphibalanus spp.*
Large Clam	Mya (Soft Shell Clam)	*Mya arenaria*

Predator-prey relationships (Table 4) and life history information (e.g., growth, age at maturity), of the balanced EwE base model were based on input from a range of sources including field data specific to the CLC (Kellogg et al. 2016; C. Bonzek, unpublished ChesMMAP data), an existing EwE model of the Chesapeake (Christensen et al. 2009), an existing Atlantis ecosystem model of the Chesapeake (Ihde et al. 2016), and literature review (Appendix A), in order of preference. Very small, arbitrary proportions (<0.01) were added to include additional suspected dietary connections between predators and prey that were not reflected in the sources specified above; without such connections, the model would not allow a predator to consume the specified prey, even if it the prey became very abundant.

Table 4a. Predator-prey relationships. Estimates are output of the balanced EwE base model. Entries that appear in grey boxes indicate either aggregate groups where one member preys on another, or a single species that exhibits cannibalism (table continues next page).

No.	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	**StripedBassJuv**	0	0	0.006	0	0	0.004	0	0.009	0	0	0	0	0	0	0	0
2	**StripedBassAdult**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	**Weakfish**	0	0.008	0.001	0	0	0	0	0.000	0	0	0	0	0	0	0	0
4	**DivingDucks**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	**CownoseRay**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	**Catfish**	0	0	0.038	0	0	0.001	0.006	0.016	0	0	0	0	0	0	0	0
7	**ReefFish**	0	0.003	0.038	0	0	0.006	0.000	0.016	0	0	0	0	0	0	0	0
8	**OysterToadfish**	0	0	0.038	0	0	0.006	0.006	0	0.006	0.001	0	0	0	0	0	0
9	**AmericanEel**	0	0.001	0.038	0	0	0.006	0	0	0	0	0	0	0	0	0	0
10	**Panfish**	0	0.324	0.341	0	0	0.100	0.029	0.045	0	0	0.012	0	0	0	0	0
11	**WhitePerch**	0	0.007	0.038	0	0	0.054	0.006	0	0	0	0	0	0	0	0	0
12	**AtlCroaker**	0	0.007	0.001	0	0	0.006	0.006	0.002	0	0	0.004	0	0	8.38E-05	0	0
13	**GizzardShad**	0	0.041	0.038	0	0	0.006	0.006	0	0.006	0	0	0	0	0	0	0
14	**Peprilus spp.**	0	0.027	0.038	0	0	0.006	0.032	0	0	0	0	0	0	0	0	0
15	**AtlMenhaden**	0	0.127	0.015	0	0	0.030	0	0	0.006	0	0.003	0	0	0	0	0
16	**ForageReefFish**	0.273	0.136	0.038	0	0	0.008	0.006	0.033	0.006	0.011	0.072	0	0	0	0	0.002
17	**BlueCrabJuv**	0.088	0.005	0	0	0	0.015	0.074	0.026	0.085	0.009	0.080	0.040	0	0	0	0
18	**BlueCrabAdult**	0	0.005	0	0	0	0.015	0.074	0.026	0.085	0	0	0	0	0	0	0
19	**MudCrabs**	0.025	0.018	0.199	0	0	0.209	0.113	0.359	0.068	0.009	0.080	0.030	0	0	0	0
20	**Iso_cope_amph**	0.100	0.055	0	0.061	0	0.155	0.119	0.051	0.089	0.044	0.080	0.028	0	0	0	0.337
21	**Mysids**	0.102	0.106	0.121	0	0	0.046	0.061	0.175	0.018	0	0.037	0.082	0	0.102	0.036	0.197
22	**Ctenophores**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.407	0	0
23	**SeaNettles**	0	0	0	0	0	0	0	0	0	0	0	0	0	0.279	0	0
24	**SeaAnemone**	0	0	0	0	0	0.009	0.010	0.022	0	0.030	0.034	0.062	0	0	0	0
25	**HookedMussel**	0	0	0	0.231	0.002	0.056	0.034	0.016	0.157	0.018	0.023	0.038	0	0	0	0
26	**LgClam**	0	0.010	0	0.065	0.578	0.056	0.034	0.016	0.157	0.009	0.023	0.038	0	0	0	0.014
27	**SmBivalves**	0.076	0.010	0	0.538	0.419	0.056	0.034	0.016	0.157	0.064	0.023	0.038	0	0	0	0.050
28	**Barnacles**	0	0	0.002	0.019	0	0.001	0.007	0.022	0	0.000	0.000	0.001	0.001	0.001	2.12E-04	0.016
29	**OysterJuv**	0	0	0	0	0	0.056	0.034	0.016	0	0.018	0.023	0.038	0	0	0	0.077
30	**OysterAdult**	0	0	0	0	0.001	0	0.034	0	0	0	0	0	0	0	0	0
31	**Bryozoans**	0.025	0	0	0	0	0.031	0.091	0.022	0	0.030	0.034	0.062	0	0	0	0
32	**Tunicates**	0	0	0	0	0	0.031	0.080	0.022	0	0.030	0.373	0.062	0	0	0	0
33	**Annelids**	0.265	0.108	0.008	0.085	0	0.003	0.010	0.069	0.160	0.108	0.064	0.420	0	0.210	0	0.231
34	**Zooplankton**	0.045	0	0	0	0	0	0	0	0	0.030	0	0	0.010	0	0.376	0.077
35	**Dinoflagellates**	0	0	0	0	0	0	0	0	0	0	0	0	0.005	0	0.138	0
36	**Phytoplankton(Lg)**	0	0	0	0	0	0	0	0	0	0	0	0	0.884	0	0.276	0
37	**Phytoplankton(Sm)**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.172	0
38	**Detritus**	0	0	0	0	0	0.031	0.091	0.022	0	0.588	0.034	0.062	0.100	0.000	0.001	0
	Import	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*

Table 4b. Predator-prey relationships. Estimates are output of the balanced EwE base model. Entries that appear in grey boxes indicate either aggregate groups where one member preys on another, or a single species that exhibits cannibalism.

No.	Prey \ predator	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	StripedBassJuv	0	0	0	0	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0
2	StripedBassAdult	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Weakfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	DivingDucks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	CownoseRay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Catfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	ReefFish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	OysterToadfish	0	0.047	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	AmericanEel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Panfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	WhitePerch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	AtlCroaker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	GizzardShad	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Peprilus spp.	0	0	0	0	0	0	0.051	0	0	0	0	0	0	0	0	0	0	0	0
15	AtlMenhaden	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0	0	0	0	0	0
16	ForageReefFish	0.036	0.047	0	0	0	0	0	0.014	0	0	0	0	0	0	0	0	0	0	0
17	BlueCrabJuv	0	0	0	0	0	0	0	0.013	0	0	0	0	0	0	0	0	0	0	0
18	BlueCrabAdult	0	0.002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	MudCrabs	0.195	0.198	0.000	0	0	0	0	0.028	0	0	0	0	0	0	0	0	0	0	0
20	Iso_cope_amph	0.221	0.012	0.089	0	0.006	0	0	0.087	0	0	0	0	0	0	0	0	0	0	0
21	Mysids	0.222	0.012	0.069	0	0	0	0.088	0.110	0	0	0	0	0	0	0	0	0	0	0
22	Ctenophores	0	0	0	0	0	0	0.179	0.012	0	0	0	0	0	0	0	0	0	0	0
23	SeaNettles	0	0	0	0	0	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0
24	SeaAnemone	0.001	0.001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	HookedMussel	0	0.091	0.089	0	0	0	0	0.089	0	0	0	0	0	0	0	0	0	0	0
26	LgClam	0	0.091	0.089	0	0	0	0	0.028	0	0	0	0	0	0	0	0	0	0	0
27	SmBivalves	0.119	0.182	0.064	0	0	0.048	0.034	0.089	0	0	0	0	0	0	0	0	0	0	0
28	Barnacles	0	0.072	0.064	0	0.001	0	0	0.027	0	0	0	9.09E-05	0	0	0	0	0.005	0	0
29	OysterJuv	0	0.091	0.097	0	0	0.014	0	0.083	0	0	0	0.091	0	9.90E-05	0	0	0.012	0	0
30	OysterAdult	0	0.091	0.064	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Bryozoans	0	0.014	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Tunicates	0	0.014	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	Annelids	0.097	0.014	0.089	0	0.012	0	0	0.146	0	0	0	0	0	0	0	0	0.001	0	0
34	Zooplankton	0.055	0	0	0.200	0.365	0.767	0.370	0.135	0.050	0.045	0.012	0.182	0.012	0.050	0.010	0.300	0.002	0.001	0.250
35	Dinoflagellates	0	0	0.089	0.200	0.142	0.057	0.092	0.135	0.150	0.045	0.309	0.182	0.309	0.347	0.470	0.200	0	0.082	0.001
36	Phytoplankton(Lg)	0	0	0.089	0.200	0.158	0.057	0.092	0	0.250	0.364	0.309	0.182	0.309	0.545	0.470	0	0	0.467	0.250
37	Phytoplankton(Sm)	0	0	0	0.200	0.071	0.057	0.092	0	0.500	0.091	0.309	0.182	0.309	0.010	0	0.450	0	0.450	0.250
38	Detritus	0.055	0.023	0.107	0.200	0.245	0.000	0.000	0	0.050	0.455	0.062	0.182	0.062	0.050	0.050	0.050	0.980	0.001	0.250
	Import	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*

Diets (DC_{ij}) are shown in Table 4, and denote the average fraction of prey *i* in the diet of predator *j* (note that when DC is 0 *j* does not eat *i*). At a minimum, Ecopath requires input of DC_{ji} (Table 4), catch (Table 2), and three of the following four parameters for each species or biomass pool in the model:

- Biomass (B_i) as wet weight (MT/km^2) during the period in question
- The ratio of group production/biomass $(P/B)_i$ -- roughly equivalent to the instantaneous rate of total mortality but pertains only to the study area
- The ratio of consumption/Biomass $(Q/B)_i$ is the food consumption per unit biomass for the consumer, and
- Ecotrophic efficiency (EE_i), defined as the fraction of production consumed in the study area.

  Mass balance principles are used to estimate the fourth parameter.

The approach assumes that the ecosystem under study is described completely by an *n*-dimensional system of linear equations, the solutions of which can be easily calculated (Mackay 1981, as cited by Christensen et al. 2000). The resulting estimates of biomass, production, and consumption can be used to construct a quantitative network diagram (Figure 2) of energy flow for the system (Ulanowicz 1986, as cited by Christensen et al. 2000).

Using the input parameters described above, the model was mass-balanced using the Ecopath module (Table 5). Typically, Ecopath estimates ecotrophic efficiency to achieve mass balance. Ecotrophic efficiency should be estimated between 0 and 1 for mass balance. Minor changes to biomass and production/biomass inputs were made such that ecotrophic efficiency for each group was estimated in this range.

Table 5. Balanced Ecopath model parameterization. Estimated trophic level (TL), group biomass (B) MT/km^2 in 2006, the ratio of production/biomass (P/B), ecotrophic efficiency (EE) defined as the fraction of production consumed in the study area, and the ratio of consumption/biomass (Q/B). Model estimates are in bold. Juveniles (J) and adults (A) are designated for groups that are modeled by life stage (called multi-stanza groups).

Group No.	**Group name**	**TL**	**B**	**P/B**	**Q/B**	**EE**	**P/Q**
1	**StripedBass(J)**	**3.61**	0.643	1.5	8	**0.581**	**0.188**
2	**StripedBass(A)**	**3.61**	1.75	0.45	2.512	**0.162**	**0.179**
3	**Weakfish**	**3.87**	0.8	0.35	2	**0.172**	**0.175**
4	**DivingDucks**	**3.18**	0.043	0.511	120	**0**	**0.004**
5	**CownoseRay**	**3.13**	0.2	0.16	0.938	**0**	**0.171**
6	**Catfish**	**3.57**	**4.934**	0.228	1	0.8	**0.228**
7	**ReefFish**	**3.52**	**2.037**	0.51	4.05	0.9	**0.126**
8	**OysterToadfish**	**3.69**	6.8	1	5	**0.697**	**0.2**
9	**AmericanEel**	**3.44**	2.55	0.4	2.5	**0.164**	**0.16**
10	**Panfish**	**2.55**	5	1.75	6.5	**0.507**	**0.269**
11	**WhitePerch**	**3.53**	4.531	0.5	3.8	**0.258**	**0.132**
12	**AtlCroaker**	**3.23**	1	1	8	**0.252**	**0.125**
13	**GizzardShad**	**2.01**	**0.884**	0.7	3	0.75	**0.233**
14	**Peprilus spp.**	**3.74**	3.9	4.1	14	**0.989**	**0.293**
15	**AtlMenhaden**	**2.54**	**0.574**	2	11	0.8	**0.182**
16	**ForageReefFish**	**3.26**	15	1.5	5	**0.508**	**0.3**
17	**BlueCrab(J)**	**3.39**	4	2	11.007	**0.612**	**0.182**
18	**BlueCrab(A)**	**3.46**	18.732	1.5	5.182	**0.161**	**0.289**
19	**MudCrabs**	**2.94**	15	3.5	13	**0.868**	**0.269**
20	**Iso_cope_amph**	**2.34**	40	3.8	19	**0.44**	**0.2**
21	**Mysids**	**2.5**	40	3.5	12	**0.596**	**0.292**
22	**Ctenophores**	**2.92**	17	8.8	35	**0.51**	**0.251**
23	**SeaNettles**	**3.11**	15	5	20	**0.203**	**0.25**
24	**SeaAnemone**	**3.18**	4	2	6	**0.385**	**0.333**
25	**HookedMussel**	**2.15**	60	2.25	10	**0.244**	**0.225**
26	**LgClam**	**2.08**	25	2	10	**0.629**	**0.2**
27	**SmBivalves**	**2.21**	30	3.5	14.5	**0.839**	**0.241**
28	**Barnacles**	**2.42**	8	4.7	13	**0.754**	**0.362**
29	**Oyster(J)**	**2.21**	18.707	5	15	**0.737**	**0.333**
30	**Oyster(A)**	**2.27**	42	1	3.962	**0.533**	**0.252**
31	**Bryozoans**	**2.31**	2.5	3.75	10	**0.553**	**0.375**
32	**Tunicates**	**2.44**	40	1	4	**0.27**	**0.25**
33	**Annelids**	**2.02**	50	4.5	22	**0.337**	**0.205**
34	**Zooplankton**	**2.05**	40	90	216	**0.789**	**0.417**
35	**Dinoflagellates**	**1.63**	20	140	360	**0.52**	**0.389**
36	**Phytoplankton(Lg)**	**1**	180	101		**0.37**	
37	**Phytoplankton(Sm)**	**1**	72	125		**0.73**	
38	**Detritus**	**1**	100			**0.169**	

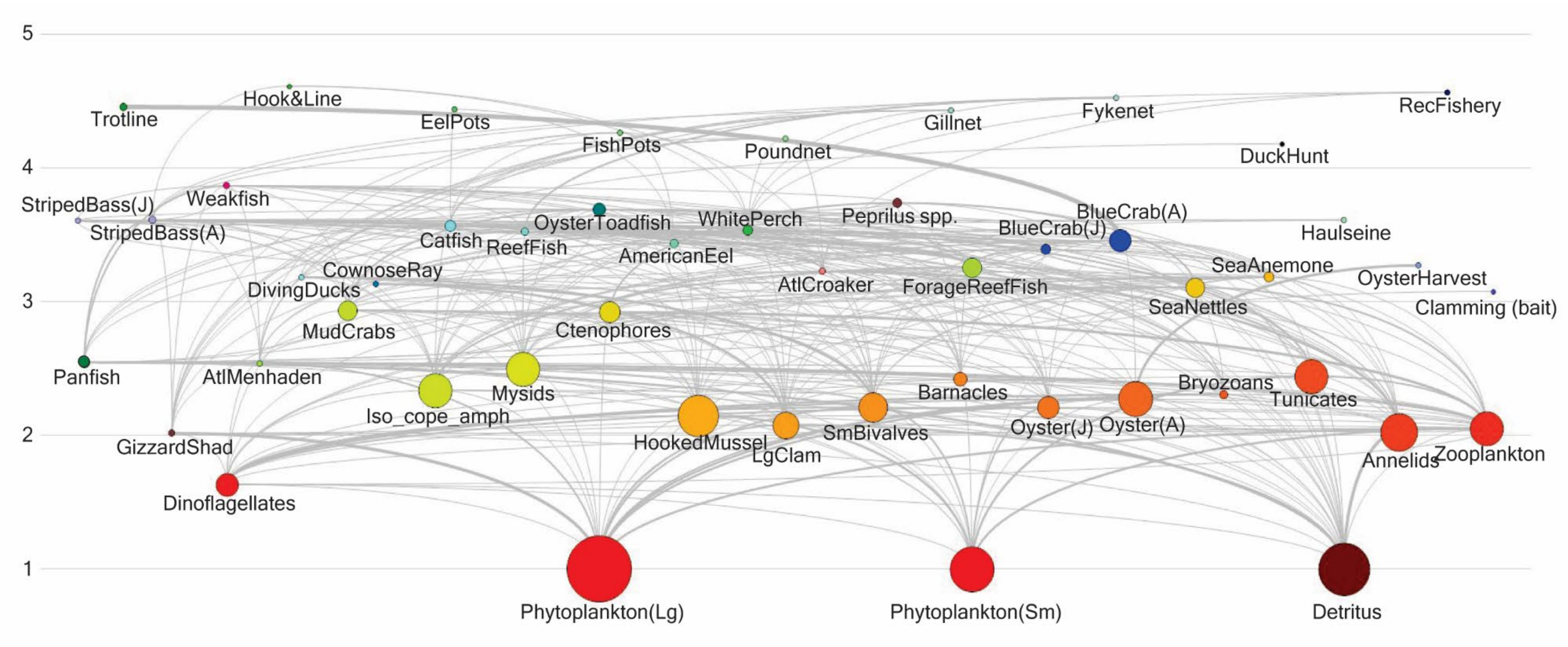

Figure 2. Energy flow diagram of the balanced Ecopath model, including all ecological groups and commercial fisheries. Relative group node size and line width between nodes, are quantitative indicators of energy flow through that group and the trophic pathway, respectively. Numbers on horizontal lines indicate model-estimated trophic level. Juveniles (J) and adults (A) are designated for groups that are modeled by life stage (called multi-stanza groups).

Ecosim: Model Calibration

Before using an EwE model for future predictions and policy analysis, the model should be able to reproduce historical patterns of abundance (Shannon et al. 2004). To this end, calibration is an important step in model development as it allows for adjustments to input parameters within a plausible range of solutions and demonstrates the model's ability to capture historical system dynamics. Adjustments provide the 'best fit' of model predictions to field survey data.

The Ecosim model was calibrated to fit model predicted biomass to observed relative biomass indices from scientific survey data. Variability in the simulation was driven by fisheries harvest, environmental forcing functions, and trophic interactions. The model was tuned once, for the Base scenario conditions (i.e., biomass, harvest, environmental, and trophic conditions observed 2006-2015). All projection scenarios build on the calibrated Base scenario. The groups used for the fitting process included only those groups for which we have survey observations for during the model years 2006-2015, and that are commonly captured in fishing gear. These groups include: Atlantic Croaker, Atlantic Menhaden, Blue Crab (adult and juvenile), Catfish, Cownose Ray, Eastern Oyster (adult and juvenile), Gizzard Shad, Striped Bass (adult and juvenile), Weakfish, and White Perch. Calibration to survey data was a two-step process. In Step 1, environmental forcing functions were used to drive variability in ecological groups (based on the group's functional response to the driver). In Step 2, a trophic interaction parameter is adjusted to modify predator group responses to prey biomass.

Fisheries harvest

Estimates of historical fishing effort were created to simulate historical harvest patterns for the calibration period. Time series of harvest data for each fleet were scaled to their catches in the initial year of the model (Table 2) to create annual relative effort estimates for each fleet. In the simulation module, Ecosim, annual catch rate is used to drive changes in biomass attributable to fishing, following the relationship:

$$H/B = qE$$

where catch rate is the harvest, H, divided by the population biomass B of a given group. Catch rate is equal to the fishing effort, E, multiplied by the constant of proportionality, q, also known as the catchability coefficient. Harvest and effort are roughly proportional, assuming constant catchability. Thus, time series data of harvest scaled to the first year would produce a suitable effort time series to drive fisheries catch rate in the model. Ecosim catch rates can also be driven directly with harvest data; however, in practice, effort serves as a better catch rate driver. Overestimates in harvest, where harvest is higher than modeled biomass, can cause populations to crash in the model, but scaled effort data limits the model from estimating a higher harvest than is physically possible in the modeled system.

Environmental response

The first step of model calibration was to incorporate group functional responses to environmental drivers. The model presented here made use of both the Functional Response and Forcing Function capabilities of the EwE model to calibrate the model to fit to survey data.

First, we developed the Functional Responses in the model for each of the ecological groups for temperature, salinity, and dissolved oxygen (DO), as these are some of the most important physical conditions (Funderburk et al. 1991) that drive production in the Chesapeake, and that are fairly well documented for all of the ecological groups. Curves for functional responses to environmental conditions (Figure 3) were derived from Funderburk et al. (1991), and other published literature (Appendix A) following the methodology of de Mutsert et al. (2017).

Time series of environmental variables (temperature, salinity, DO, and Chla) were derived from CBP data (Figure 4). These data are well-documented[4] and readily available on the scale of the CLC over the years modeled (personal communication, D. Dorfman)[5]. The time series of environmental drivers were used as forcing functions to drive variability in group biomass. The forcing functions were applied to ecological groups based on *a priori* hypotheses about the importance of the environmental driver to the ecological group. Functional response curves (Figure 3) applied to the ecological groups influenced how the group responded to the forcing function time series. Specifically, individuals of a group cannot survive if model conditions fall outside the distribution of the functional response curve, while forcing functions influenced production and trophic interactions.

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[4] www.chesapeakebay.net/what/data, last accessed 14 November 2018

[5] NOAA/NCCOS mapping tool, available at: https://coastalscience.noaa.gov/project/ecological-assessment-choptank-complex- habitat-focus-area/, last accessed 14 November 2018

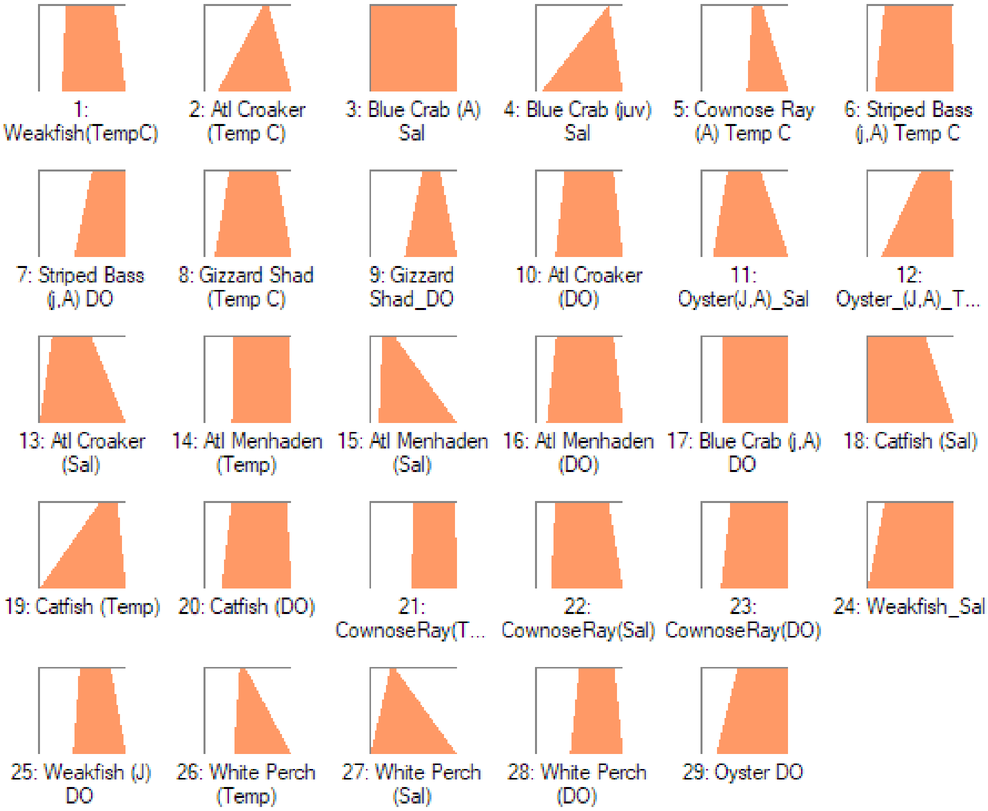


Figure 3. Environmental functional response curves (temperature [Temp C], salinity [Sal], and dissolved oxygen [DO]) developed for groups used in the fitting process.
Values on vertical axes are 0 – 1, where 1 indicates optimal conditions for growth and survival. Individuals of a group cannot survive if model conditions fall outside the distribution of the forcing function. Juveniles (j) and (A) adults are designated for groups that are modeled by life stage (called multi-stanza groups).

Following the approach of de Mutsert et al. (2017), forcing function curves were applied on a group by group basis if the forcing function improved the model fit (i.e., minimized the model sums of squares (SS)) - then the forcing function was retained and used for scenario analysis. Functional responses and forcing functions used for scenario analysis are shown in Table 6 and Figure 5, respectively.

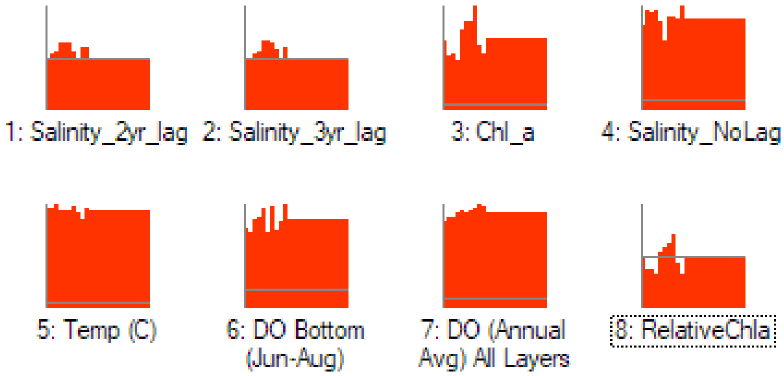


Figure 4. All forcing function time series developed for the Ecosim model. The salinity (no lag), Temperature, DO Bottom, DO (Annual average), and RelativeChla time series improved model fit for select groups (see Table 6), and were applied to the final Ecosim model.

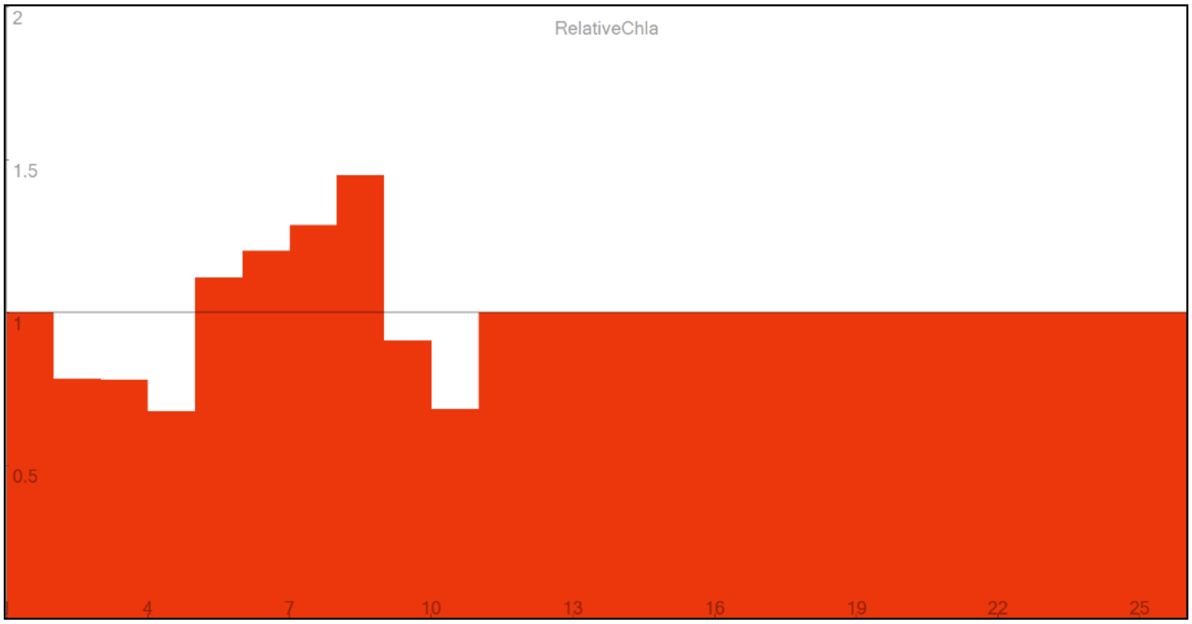


Figure 5. Time series detail (from Figure 4). Example is for relative chlorophyll a (Chla), the primary production forcing function applied to the Ecosim model. Numbers on the vertical axis are standardized measures of concentration relative to 2006. Modeled time (years) is on the horizontal axis. The standardized average of observed years (1) is applied to the model for model years 16-25.

A primary production forcing function based on monthly changes in chlorophyll a (Chla) was applied to primary producer groups in the model. This forcing function drives variability in primary productivity in the model, which in turn drives variability in the food web based on trophic interactions. We applied a standardized Chla time series (all years relative to 2006 concentrations) to the Forcing Functions capabilities of the model (Figure 5).

Table 6. Forcing functions applied (X) to final model, by ecological group applied. Juveniles (J) and (A) adults are designated for groups that are modeled by life stage (called multi-stanza groups).

	Temp. (°C)	Salinity (no lag)	DO (bottom)	DO (yearly average)	Chla
Atlantic Croaker	X			X	
Atlantic Menhaden				X	
Oyster (J)			X		
Oyster (A)			X		
Weakfish (J)			X		
White Perch		X			
Dinoflagellates					X
Phytoplankton (Lg)					X
Phypoplankton (Sm)					X

Trophic interactions

The second calibration step was the fitting to time series of survey data by adjusting trophic interaction parameters. Ecosim has an automated routine for adjusting trophic interactions to improve model fit. During this routine, model runs are fitted to observed biomass and landings data, while the model is forced or driven with fishing mortality or effort data and/or environmental variables (e.g. salinity). The routine searches for the lowest SS by adjusting the vulnerabilities of groups to predation.

In Ecosim, the rates of consumption can be limited at very small temporal scales, allowing for the flow of prey from varying states of vulnerability to limit the rates of predation to levels that the traditional Lotka-Volterra mass-action models of predator-prey interaction would not predict. That is, behavior and location of prey limit the ability of predators to consume them. The vulnerability parameter in Ecosim summarizes this prey limitation for predators. The concept of the foraging arena theory, which regulates consumption rates by assuming predator-prey interactions occur in restricted arenas where prey vulnerability in terms of predation depends on a prey's need for a particular resource (Ma et al. 2010; Walters et al. 1997). Ultimately, adjustments to the vulnerability parameter influence the variability of predators' response to prey biomass in the Ecosim simulations.

We used the Ecosim automated routine to adjust vulnerability parameters for key species thereby improving model fit. Table 7 shows the vulnerability estimates that were adjusted. Other predator-prey interactions were not adjusted and we assumed the Ecosim default vulnerability of 2. Judicious use of the vulnerability is necessary to prevent overfitting.

Table 7a. Group vulnerabilities applied for all modeled scenarios. Entries that appear in grey boxes indicate either aggregate groups where one member predates on another, or a single species that exhibits cannibalism (table continues next page).

Group No.	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	StripedBassJuv			1.5			2.0		10.0								
2	StripedBassAdult																
3	Weakfish		1.5	1.5					10.0								
4	DivingDucks																
5	CownoseRay																
6	Catfish			1.5			2.0	1.5	10.0								
7	ReefFish		1.5	1.5			2.0	1.5	10.0								
8	OysterToadfish			1.5			2.0	1.5		2.0	1.5						
9	AmericanEel		1.5	1.5			2.0										
10	Panfish		1.5	1.5			2.0	1.5	10.0			1.5					
11	WhitePerch		1.5	1.5			2.0	1.5									
12	AtlCroaker		1.5	1.5			2.0	1.5	10.0			1.5			1.5		
13	GizzardShad		1.5	1.5			2.0	1.5		2.0							
14	Peprilus spp.		1.5	1.5			2.0	1.5									
15	AtlMenhaden		1.5	1.5			2.0			2.0		1.5					
16	ForageReefFish	2.0	1.5	1.5			2.0	1.5	10.0	2.0	1.5	1.5					2.0
17	BlueCrabJuv	2.0	1.5				2.0	1.5	10.0	2.0	1.5	1.5	1.6				
18	BlueCrabAdult		1.5				2.0	1.5	10.0	2.0							
19	MudCrabs	2.0	1.5	1.5			2.0	1.5	10.0	2.0	1.5	1.5	1.6				
20	Iso_cope_amph	2.0	1.5		2.0		2.0	1.5	10.0	2.0	1.5	1.5	1.6				2.0
21	Mysids	2.0	1.5	1.5			2.0	1.5	10.0	2.0		1.5	1.6		1.5	1.5	2.0
22	Ctenophores														1.5		
23	SeaNettles														1.5		
24	SeaAnemone						2.0	1.5	10.0		1.5	1.5	1.6				
25	HookedMussel				2.0	1.5	2.0	1.5	10.0	2.0	1.5	1.5	1.6				
26	LgClam		1.5		2.0	1.5	2.0	1.5	10.0	2.0	1.5	1.5	1.6				2.0
27	SmBivalves	2.0	1.5		2.0	1.5	2.0	1.5	10.0	2.0	1.5	1.5	1.6				2.0
28	Barnacles			1.5	2.0		2.0	1.5	10.0		1.5	1.5	1.6	2.0	1.5	1.5	2.0
29	OysterJuv						2.0	1.5	10.0		1.5	1.5	1.6				2.0
30	OysterAdult					1.5		1.5									
31	Bryozoans	2.0					2.0	1.5	10.0		1.5	1.5	1.6				
32	Tunicates						2.0	1.5	10.0		1.5	1.5	1.6				
33	Annelids	2.0	1.5	1.5	2.0		2.0	1.5	10.0	2.0	1.5	1.5	1.6		1.5		2.0
34	Zooplankton	2.0									1.5			2.0		1.5	2.0
35	Dinoflagellates													2.0		1.5	
36	Phytoplankton(Lg)													2		1.5	
37	Phytoplankton(Sm)															1.5	
38	Detritus						2	1.5	10		1.5	1.5	1.6	2	1.5	1.5	

Table 7b. Group vulnerabilities applied for all modeled scenarios. Entries that appear in grey boxes indicate either aggregate groups where one member predates on another, or a single species that exhibits cannibalism.

Group No.	Prey \ predator	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	StripedBassJuv							2.0												
2	StripedBassAdult																			
3	Weakfish																			
4	DivingDucks																			
5	CownoseRay																			
6	Catfish																			
7	ReefFish																			
8	OysterToadfish		2.0																	
9	AmericanEel																			
10	Panfish																			
11	WhitePerch																			
12	AtlCroaker																			
13	GizzardShad																			
14	Peprilus spp.							2.0												
15	AtlMenhaden							2.0												
16	ForageReefFish	2.0	2.0						2.0											
17	BlueCrabJuv								2.0											
18	BlueCrabAdult		2.0																	
19	MudCrabs	2.0	2.0	2.0					2.0											
20	Iso_cope_amph	2.0	2.0	2.0		2.0			2.0											
21	Mysids	2.0	2.0	2.0				2.0	2.0											
22	Ctenophores							2.0	2.0											
23	SeaNettles								2.0											
24	SeaAnemone	2.0	2.0																	
25	HookedMussel		2.0	2.0					2.0											
26	LgClam		2.0	2.0					2.0											
27	SmBivalves	2.0	2.0	2.0			2.0	2.0	2.0											
28	Barnacles		2.0	2.0		2.0			2.0				2.0					2.0		
29	OysterJuv		2.0	2.0			2.0		2.0				2.0		1.5			2.0		
30	OysterAdult		2.0	2.0																
31	Bryozoans		2.0																	
32	Tunicates		2.0																	
33	Annelids	2.0	2.0	2.0		2.0			2.0									2.0		
34	Zooplankton	2.0			2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	2.0	2.0	2.0	2.0	2.0
35	Dinoflagellates			2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	2.0	2.0		2.0	2.0
36	Phytoplankton(Lg)			2	2	2	2	2		2	2	2	2	1.5	1.5	2			2	2
37	Phytoplankton(Sm)				2	2	2	2		2	2	2	2	1.5	1.5		2		2	2
38	Detritus	2	2	2	2	2	2	2		2	2	2	2	1.5	1.5	2	2	2	2	2

Five Scenarios Modeling Differing Management Options

Five scenarios were developed in this study to account for the potential impacts of various management options (Table 8). The scenarios are projections based on the calibrated years (2006-2015) where drivers of the outcomes were based on observations (see Model Calibration, above), into future years, where all drivers are held constant (e.g., fishing effort, primary production) other than the drivers of interest (i.e., oyster and filter feeder biomass change). The scenarios simulate 15 years (2016-2030) of system changes that the model predicts would result under a range of management options for the current oyster sanctuaries of the CLC. We modeled a range of management options: from the most conservative - allowing the restored oyster reef sanctuary to persist and develop into a Mature Oyster Reef, to the elimination of sanctuaries, allowing commercial harvests in all areas. The Current Young Reef scenario simulates the mix of sanctuaries and commercial harvests in the CLC as of 2015. Two scenarios simulate the change (from Young Reef) in oyster biomass alone (both an increase and a decrease), and two additional scenarios explored oyster change along with a corresponding change in associated filter feeder biomass for groups that depend on the structure of the oyster reef to prosper. The associated filter feeding groups (FF) include: Hooked Mussel, Ghost Anemone, Tunicate (Mogula spp.), and Barnacles.

Table 8. Scenarios modeled. Filter Feeders (FF) groups include: Barnacles, Ghost Anemone, Hooked Mussels, and Tunicates.

Scenario Number	Name	Description
1	Current Young Reef	Newly restored reef - oyster harvest held constant (average of harvests 2006-2015)
2	Mature Oyster Reef	Mature reef - oyster harvest held constant (average of harvests 2006-2015) - increased oyster biomass (15.4%/yr)
3	Mature Oyster Reef & Associated FF	Mature reef - oyster harvest held constant (average of harvests 2006-2015) - increased oyster biomass (15.4%/yr) - increased hard-bottom community (FF) biomass (rate of increase varies by group modeled, see text for details)
4	Fished Down Oysters	Declining reef structure - no oyster sanctuaries - decreased oyster biomass (-14.2%/yr)
5	Fished Down Oysters & Associated FF	Declining reef structure - no oyster sanctuaries - decreased oyster biomass (-14.2%/yr) - decreased hard-bottom community (FF) biomass (-10%/yr)

Scenario 1: Current Young Reef: This scenario simulates ecological production of 2015 conditions in the study area, including the recently restored oyster reef. The restored reef includes oysters as well as the filter feeding organisms largely dependent on the hard substrate

of the reef structure produced by the oysters. FF groups include: Barnacles, Ghost Anemone, Hooked Mussels, and Tunicates. Oysters, together with associated FF groups provide both biological filtering (plankton consumption) and water-clearing (particulate removal). Our scenarios, however, account only for plankton consumption. Oyster harvests in this scenario are based on 2015 harvest data (unpublished data, MD DNR).

Scenario 2: Mature Oyster Reef: The sanctuary scenario assumes that with no harvest in the sanctuary, oysters will continue to increase in biomass after 2015 at a rate of 15.4 percent per year, over the course of the 15-year scenario (see below for additional details). The increase assumes that the goal of the restoration - an average abundance of 15 oysters per square meter (Oyster Metrics Workgroup 2011, Allen et al. 2013) - will be achieved after 15 years of protection in the current oyster sanctuaries. Oyster harvests are assumed to be similar to the Young Reef simulation in this scenario, because most of the increased oyster biomass will occur within the sanctuaries where harvest is not permitted. As this model is temporal, but not spatial-temporal, we do not account for any expected increase in oyster biomass outside the sanctuary due to increased oyster recruitment that could result from the oyster biomass within the sanctuary. Consequently, our estimates of oyster harvests are conservative estimates.

Scenario 3: Mature Oyster Reef with Associated FF: A second sanctuary scenario simulates allowing the newly restored oyster reef sanctuaries to mature and grow. This scenario accounts for a more complete realization of the oyster reef community benefits for plankton consumption and food production. This scenario is similar to the Mature Oyster Reef in all respects, except that we steadily increase biomass of other major filter feeding groups that benefit from the increased available surface area provided by new oyster growth. The rate of increase of these additional reef community groups varies by group (Hooked Mussel: 5.5%, Ghost Anemone 9.5%, Tunicates 5.5%, and Barnacles 8.8%), and is described in Appendix B.

Scenario 4: Fished Down with Decreased Oyster Biomass: The fourth scenario simulates no sanctuaries, where oyster harvest is allowed throughout the study area. The dredging process breaks up oyster clumps as larger oysters are harvested. Thus, in this scenario, we assume oysters persist, but that the original reef structure (Current Young Reef) is eroded over time and oyster biomass per area decreases. We assume that 10% of the reef structure (and oyster biomass) remains after the 15 years simulated in the fourth scenario. The density of oysters that results from this approach falls within the range observed on Harris Creek bottom prior to restoration activities (Versar 2012). This level of harvest corresponds to an annual rate of loss of 14.2 percent of oyster biomass available in the sanctuaries in 2015.

Scenario 5: Fished Down with Oyster & FF Biomass Decrease: A fifth scenario accounts for both the loss of oyster reef biomass and oyster reef fouling organisms over time, which are dependent on the hard substrate made available by oyster reefs. This scenario assumes that associated filter feeder biomass is reduced annually at a similar rate to that assumed for oysters, 14.2% per year. All other aspects of this scenario are similar to Scenario 4.

IMPLAN: Economic Impact Analysis for Planning

IMPLAN is a widely used economic input-output model that measures the regional economic impacts generated by an initial change in spending in a defined area (e.g., state, county). For this project, we focus on four key economic measures that are accounted for in IMPLAN - Output (Sales), Labor Income, Value-Added, and Employment. Each of these four economic measures have a *direct effect* (initial change in the industry in question), *indirect effect* (changes in inter-industry transactions when supplying industries respond to increasing demands from other industries) and *induced effect* (changes in local spending resulting from income changes in the directly and indirectly affected industry sectors). Total effects for an economic measure are the summation of direct, indirect, and induced effects for that measure. These economic measures are defined below.

- **Output (Sales) –** Output is the value of production and is equal to value-added plus intermediate expenditures.
- **Labor Income –** Labor Income is comprised of two components – Employee Compensation and Proprietor Income. Employee Compensation are the wages and benefits paid to wage and salaried employees. Proprietor Income are the profits earned by self-employed individuals.
- **Value-Added –** Value-Added is defined as gross regional product - the regional version of gross domestic product. Value-Added accounts for all non-commodity spending associated with an industry's production.
- **Employment –** Employment is defined to include full and part-time annual jobs for employees and self-employed workers.

IMPLAN is regularly used by state and federal resource management agencies to estimate the economic impacts associated with commercial fishing. NOAA uses IMPLAN to estimate commercial fishing economic impacts in its annual report "Fisheries Economics of the United States" (see National Marine Fisheries Service 2017) and state agencies routinely use IMPLAN to estimate commercial fishing related economic impacts (see, e.g., Murray 2015, Hadley 2015, Hodges et al. 2015). Increasingly, researchers are deploying IMPLAN in conjunction with ecological-economic modeling efforts to provide economic metrics relevant to natural resource managers and decision makers (Byron et al. 2015).

Developing Fishing Fleet-Specific Custom Production Functions

IMPLAN is equipped with production functions describing how each of the 528 pre-loaded industry sectors proportionally allocates expenditures to generate a dollar of output. However, as Steinback and Thunberg (2006) point out, the level of aggregation in the generic, pre-loaded "fishing" sector is too gross for conducting impact assessments of fishery management actions on specific fisheries or gear types. The small-scale commercial fishers of the CLC use small vessels and minimal crew and thus have production functions that likely differ substantially from the generic pre-loaded fishing sector. The flexibility of IMPLAN enables the construction of a custom commercial fishing industry fleet that accounts for multiple gear and location-specific expenditure relationships (Steinback and Thunberg 2006). This allows for a more accurate accounting of economic impacts than would be the case if using the generic pre-loaded fishing sector in IMPLAN. To ensure that IMPLAN accounts for the specific nature of CLC fisheries, the project team developed a single custom CLC fishing sector for use in IMPLAN that aggregates the production functions associated with the nine types of gear used in the CLC commercial fisheries, linking this custom sector to the pre-loaded IMPLAN industry sectors.

To accomplish this, the project team modified template fishing production functions developed for use in the Northeast Region Commercial Fishing Input-Output Model (Steinback and Thunberg 2006) and obtained expenditure information through interviews with CLC commercial fishers. Information obtained from the commercial fishers was based on the information specified in the Northeast Fisheries Science Center Observer Data Entry Manual (NEFSC-ODEM; 2016) (Table 9). Interviews were conducted with commercial fishers working in nine fishing fleet sectors: Bait Clam, Trotline (target: Blue Crab), Pound net (target mixed finfish), Gillnet (target mixed finfish), Eel Pots, and four oyster gears (Power Dredge, Skipjack, Hand Tongs, Divers). The initial goal was to interview two-to-three fishermen in each active fishery. Following the approach of the Northeast Fisheries Science Center (2016), capital expenses for vessel improvements are excluded from this analysis.

Potential commercial fisher participants were identified through a networking approach, either by interacting with regional watermen’s associations or by interacting with researchers who had worked with regional commercial fishers on other projects. Individuals contacted were asked to provide contact information for several of their commercial fishing contacts using the fishing gears of interest. Once those individuals were contacted, they were asked about other commercial fishers working fishing gears that still lacked cost-earnings data. The majority of commercial fishers contacted were willing to be interviewed (67%), while the other 33% either did not reply to phone messages (22%) or had no interest in participating (11%).

All interviews were conducted by a single investigator to minimize potential bias from inconsistent presentation of project goals, definitions of cost categories, and other aspects of the interview and cost-earnings data collection process. Interviews were conducted via phone, with a typical length of 20 – 40 minutes per gear type. The single investigator worked with each commercial fisher to proportionally allocate their costs across the different expenditure categories to create the production functions and custom fishing fleet sector required for IMPLAN (Table 10). Production functions are displayed in Table 10 as proportions of total costs by expenditure category for each fishery. The NEFSC-ODEM expenses for “Water” and “Catch Handling” were not encountered for any fisheries in the CLC. Income-related expenses “Crew share costs“ and “Proprietor Income” were high for most fisheries, but the non-income related “Repair and Maintenance”, “Vehicle”, and “Fuel” costs were also consistently relatively high in all commercial fisheries. Though there are exceptions, most other expense categories seldom exceed 5% of total costs for CLC fisheries.

Table 9. Potential cost categories for commercial fishers active in the CLC for each gear type. Used to customize IMPLAN commercial fishing sectors for the CLC. Definitions and examples were used consistently with fishers for every interview performed.

Cost Category	As defined for Fishers	Examples
Repair/maint	Any repair or maintenance cost associated with your vessel or the fishing operation itself	Engine or hull repair; gear repair or maintenance costs
Mooring	Docking or mooring fees	
Shop expenses	Onshore business expenses	GearShed rental, or workshop expenses
Office expenses	Onshore business expenses	Office supplies, rental, utilities
Permit fees	Vessel permits or license expenses	
Vehicle costs	Onshore vehicle expenses	Costs related to any business vehicle
Travel costs	Expenditures for professional travel	Lodging or travel costs for professional meetings, fishing organizations, etc.
Association fees	Membership fees	Co-op fees, fishing orgs., sector fees, union dues
Professional fees	Fees associated with running your business (not accounted for in other categories)	Settlement, accounting, or legal fees
Insurance	Vessel insurance	
Fishery monitoring costs	Costs for agency observers, or dockside monitoring	
Non-crewshare labor costs	Any personel expenses for non-crew employees	Secretary, security guard, etc.
Fuel	Fuel	
Food	Food while on the water	Includes drinking water
Ice	Specifically to preserve the catch	
Bait	Bait	
Water	Purchased freshwater access for gear or vessel washdown	This would include crew showers, etc.
Communications costs	Any communication cost	Radio or a cell phone specifically for vessel, including a Vessel Monitoring System
Fishing supplies	Any expendable supplies needed for the fishing operation	Includes knives, picks, hooks, boxes, bags, ties, rags, etc.
Crew supplies	Any gear you need for the crew	Includes gloves, foul-weather gear, etc.
Catch handling costs	Any costs to pay others to handle your catch	Auction, lumping, grading, shipping, etc.
Other costs	Other costs not covered in the other categories	
Crew share costs (may include Captain)	Costs to pay personnel, including the Captain if the fishing business is incorporated	
Proprietary Income	The salary the operator or owner pays him/herself	

Table 10: Production functions.

						Oyster Harvests			
Cost Categories	Clamming (Bait)	Trotline	Poundnet	Gillnet	Eel pots	Power dredge	Skipjack	Hand tongs	Dive
Repair/maint	23.2	6.2	29.2	9.9	14.8	7.7	11.3	3.6	11.7
Mooring	2.7	3.0	0.0	2.9	2.6	2.9	4.7	2.0	4.9
Shop expenses	5.9	2.1	0.0	6.5	1.9	3.6	2.9	2.7	3.8
Office expenses	1.6	1.9	0.0	2.2	0.3	1.7	2.5	3.5	0.9
Permit fees	4.6	4.1	0.9	6.4	1.1	4.4	8.4	3.7	9.6
Vehicle costs	7.2	7.9	14.6	8.7	4.0	8.7	11.3	9.3	10.8
Travel costs	2.5	1.8	0.0	2.3	1.6	2.0	2.5	2.7	0.9
Association fees	1.2	1.8	2.7	1.0	0.7	1.6	2.5	2.7	2.9
Professional fees	2.8	1.3	3.7	2.8	1.1	1.5	5.8	0.7	1.9
Insurance	3.1	2.8	0.0	1.0	0.3	2.0	4.3	1.3	0.0
Fishery monitoring costs	0.5	0.0	0.0	1.7	0.0	0.4	0.0	0.0	2.8
Non-crewshare labor costs	0.9	1.7	0.0	1.5	1.1	0.3	1.5	0.0	0.0
Fuel	13.5	9.9	7.3	14.8	9.0	12.7	5.5	8.2	9.8
Food	0.9	2.8	0.0	4.7	0.9	2.2	2.5	2.1	4.0
Ice	0.0	3.0	0.0	0.0	0.2	0.3	3.3	0.0	0.0
Bait	0.0	9.6	0.0	0.0	11.8	0.0	0.0	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Communications costs	2.8	2.5	3.7	3.2	0.3	2.2	3.3	2.9	3.4
Fishing supplies	3.9	5.9	3.7	5.2	3.7	3.9	4.4	3.1	1.9
Crew supplies	3.6	1.8	3.7	3.8	1.9	2.7	5.1	1.8	5.3
Catch handling costs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other costs	0.0	2.3	0.0	3.1	0.0	2.4	0.0	0.0	0.0
Crew share costs	7.6	0.9	30.7	11.8	15.4	5.3	9.1	0.0	16.2
Proprietary Income	11.8	26.6	0.0	6.5	27.4	31.4	9.1	49.7	9.1

Several approaches were taken to simplify this process. First, commercial fishers were asked to think of each gear as an independent activity, regardless of the proportion of a typical year they work a specific fishery. Second, commercial fishers were asked to initially "ballpark" their costs as a percent (based off their total cost for that gear) *without* attempting to add up to 100 percent. Commercial fishers were asked to base their cost estimates on those incurred during the most recent tax year. Rounding numbers was suggested for this stage. To simplify the estimation process and avoid potential anchoring effects (Tversky and Kahneman 1974), the interviewer did not provide suggestions for values or provide examples. Initial ranked cost values were normalized to sum to 100%. Third, commercial fishers were asked to review and refine the percentages allocated to each expenditure category - it generally required completion of the first three or four categories before commercial fishers reported confidence in their estimates. In some instances, the commercial fishers pointed out that the most recent year was atypical due to individual circumstance. In those cases, it was suggested that they base their ranking on a typical year instead. The commercial fishers generally made small adjustments to the estimated percentages. Plots of the distributions were provided to fishers within a day of the interview as a final verification of their chosen cost allocation. Each interview received equal weighting in the calculation of average costs by gear category (Figure 6).

Each of the 12 commercial fishers interviewed (Table 11) worked more than one gear type. Six (50%) of the commercial fishers interviewed worked either three or four different gears, and six of the commercial fishers used trotlines during a typical year. Trotlines target Blue Crab, the most valuable fishery in this region with $8.7 million in estimated dockside value in the CLC in 2015. In contrast, all finfish harvested in the CLC is about 10% of this figure ($807,000 in 2015).

Table 11. Interviews conducted by commercial fisher and by gear.

Target Species:	*Mixed*	*Mixed*	*Blue Crab*	*Amer. Eel*	*Bait*	*Oysters*				
Fisher No.	**Gillnet**	**Poundnet**	**Trotline**	**Eel Pots**	**Clammers**	**(Shaft) Hand tongs**	**Power Dredge**	**Skipjack**	**Dive**	**Number of interviews by Fisher**
1			X					X		*2*
2			X			X	X			*3*
3			X						X	*2*
4			X			X	X			*3*
5	X		X				X			*3*
6					X					*1*
7	X		X			X	X			*4*
8		X								*1*
9				X						*1*
10					X			X		*2*
11	X				X				X	*3*
12	X			X			X			*3*
Number of interviews by gear	*4*	*1*	*6*	*2*	*3*	*3*	*5*	*2*	*2*	***28***

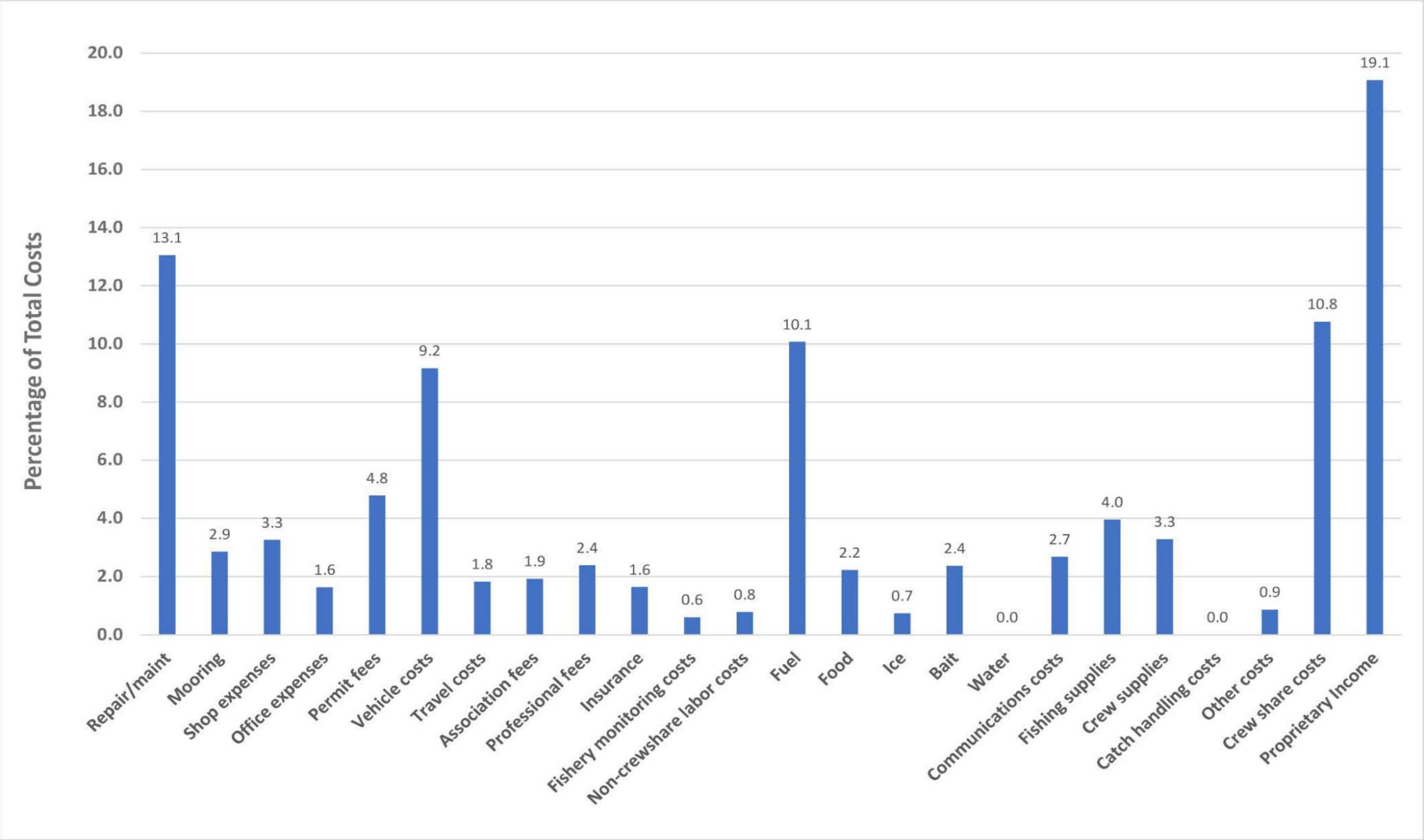


Figure 6. Average costs across gear types. Repair and maintenance was consistently the highest cost that was not income-related. Fuel and on-shore vehicle expenses were also consistently about 10% of total costs for all fishers.

Defining Regions for Analysis

Regional economic impact analysis tracks the backward-linked supply chain effects and resulting income to business owners and employees within a defined study area. At each stage of spending there is leakage when inter-industry expenditures occur *outside* of the study area. As such, it is important to define the study area to provide information that is relevant to regional managers and policy makers. The prime focus of this project is the CLC; thus, we focus our economic impact analysis on the two-county region of the Dorchester and Talbot counties that comprise the Maryland portion of the CLC (Figure 7, dark blue). However, we also examined the regional economic impacts of two other regions, for a total of three study areas analyzed. These two additional regions are: a) all Maryland counties bordering the Chesapeake Bay (13 counties; Figure 7, medium- and dark-blue; Table 12), and b) all counties in the state of Maryland (23 counties).

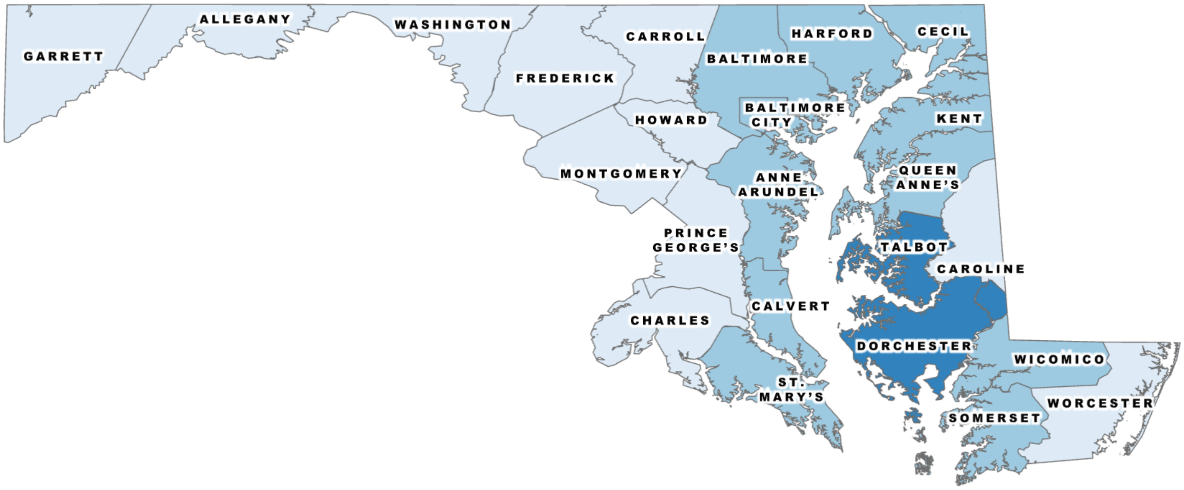


Figure 7. Maryland counties included for three IMPLAN analyses. (1) Talbot and Dorchester counties (dark blue) are the two counties that comprise the primary study region, (2) Talbot, Dorchester, and all other Chesapeake Bay counties combined (medium blue) comprise a second study region, and (3) all Maryland counties combined (light blue) form the region for the third analysis.

Table 12. Counties in each of the three study areas in Maryland.

Study Area	Maryland Counties
Choptank and Little Choptank river system	Dorchester, Talbot
Bay counties	Anne Arundel, Baltimore, Calvert, Cecil, Dorchester, Harford, Kent, Queen Anne, Somerset, St. Mary, Talbot, Wicomico, Baltimore City
Maryland	Allegany, Anne Arundel, Baltimore, Calvert, Caroline, Cecil, Charles, Dorchester, Frederick, Garrett, Harford, Howard, Kent, Montgomery, Prince George, Queen Anne, Somerset, St. Mary, Talbot, Washington, Wicomico, Worcester, and Baltimore City

Estimating Direct Effects

Calculation of direct effects for commercial fishing does not involve the use of IMPLAN. Described below are the descriptors for **direct effects** for the four economic measures reported on in this project.

- **Output –** The direct output effect for each commercial fishing gear is the total annual dockside value (i.e., sales) for that gear. Total dockside value is equal to biomass harvested multiplied by a mean estimate of the species-specific per-unit price. Note that applying this method across different biomass harvest scenarios implies that there are no price effects as the biomass harvested increases or decreases across different reef restoration scenarios. The project team believes that large price effects are unlikely to result from increases in regional harvest. The justification for this is that the CLC is a small component of a larger Chesapeake Bay fishery and larger global marketplace for seafood products. The most valuable species in our analysis – the Blue Crab – is harvested throughout the Chesapeake Bay, throughout the southeast U.S. and the Gulf of Mexico, with substantial volume of imported Blue Crab meat from Indonesia and Venezuela.
- **Labor Income –** The direct labor income effect is the total annual dockside value for that gear minus non-labor income. That is, total annual dockside value minus all expenditure categories that are not Employee Compensation or Proprietor Income. Commercial fisher data collection and the resulting gear-specific productions functions are used to identify the proportion of labor income.
- **Value-Added –** To compute the value-added direct effects, we used the study area data in IMPLAN to obtain the total output (value of production) to total value-added ratio for the commercial fishing sector. This ratio was applied to the direct fish harvest revenue to estimate direct value-added.

- **Employment –** Figures from the NOAA Fisheries Economics of the U.S. report (NMFS 2017) were used to estimate direct employment. The ratio of commercial harvester direct output to direct employment obtained from NOAA FEUS was applied to the direct output calculation described above to estimate commercial harvester direct employment.

Estimating Indirect and Induced Effects

Indirect and Induced effects are obtained by using IMPLAN. The key input for calculating these effects are the nine fishing gear-specific custom production functions that contain proportional allocations of commercial fisher revenues across different expenditure categories. The expenditures incurred were summed across the nine fishing gears to create one custom fish harvesting sector for use in IMPLAN.

IMPLAN models require all values to be in producer prices (manufacturer prices) so each type of commercial fisher expense was associated with its corresponding IMPLAN producing sector. Appendix C delineates how commercial fisher expenses were allocated to IMPLAN sectors. Commercial fisher expense categories that included more than one IMPLAN sector were assigned to individual IMPLAN sectors as shown in Appendix C. In IMPLAN, margins are used to convert retail-level purchases into appropriate producer values. Margins ensure that correct values are assigned to products as they move from producers, to wholesalers, through transportation sectors, and finally on to retail establishments. IMPLAN's default margins were used for all retail-level commercial fisher purchases except for boat fuel and bait expenses. Adjustments were made to the retail margins associated with fuel and bait to properly account for purchases by commercial fishermen.

IMPLAN's default local purchase proportions (LPPs) were applied to all of the retail-level commercial fisher expenses to ensure that imported goods and services were excluded from the analysis. IMPLAN's LPPs reflect the proportion of retail-level sales that are derived from manufacturers within a particular region. The one exception was for commercial fisher bait purchases. Bait supplies are generally derived from local harvesters, so region-level LPP values for bait purchases were set to 100%.

Several of the IMPLAN commercial fishery expense assignments warrant further clarification. Food expenses were assigned to IMPLAN sectors according to the Bureau of Economic Analysis' 2014 national average expenditure pattern for food purchased for off-premise consumption (i.e., groceries). This expenditure pattern consists of approximately 50 food processing and agricultural producing sectors that represent the average grocery list. Spending by commercial fishers on permit fees represent payments to state and federal governments. It was assumed that 50% of the permit fees flowed to the state government non-education sector in IMPLAN and 50% to the federal government non-education in IMPLAN. Lastly, crew share expenses (includes captain and benefits) and non-crew share expenses (i.e., office secretary, night watchman) represent employee compensation, and this was assigned to employee compensation labor income in IMPLAN. Owner net revenue was assigned to proprietor labor income in IMPLAN.

Results

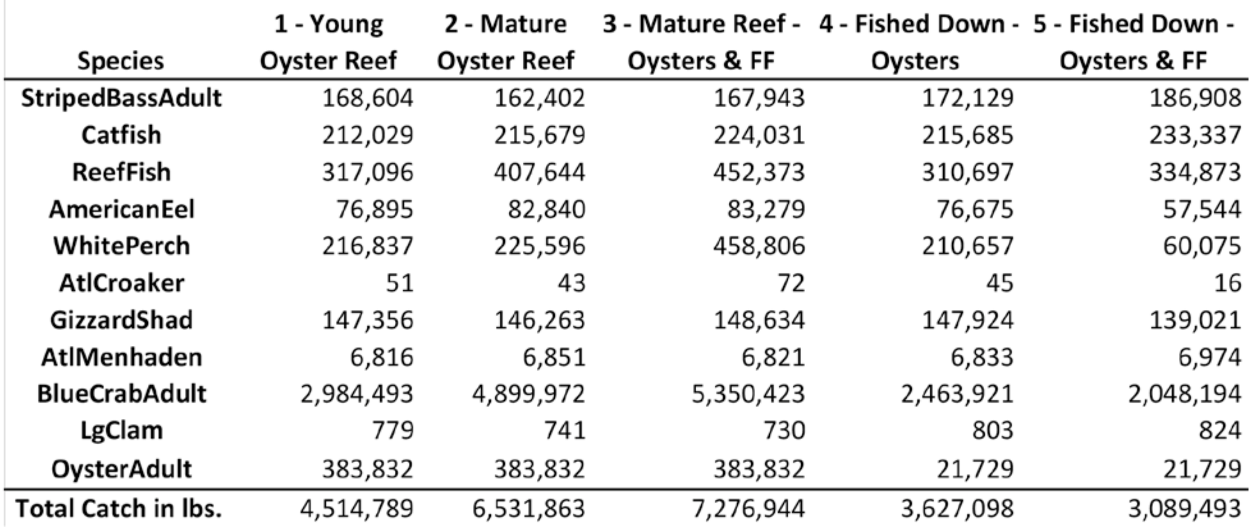
We linked ecological model outputs to an economic model to estimate the impacts of a range of possible oyster management scenarios on the regional economy of the CLC. First, we provide biomass estimates in terms of per-area unit values for all species in the ecological model (Table 13). Estimates of total biomass harvested annually by each scenario, both by gear type and by key finfish and shellfish species are shown in Tables 14-15. Filter Feeders (FF) are those groups whose growth depends on the increased surface area provided by oyster shell (Hooked Mussels, Barnacles, Tunicates, and Anemones). Note also that oyster harvest was held constant for the sanctuary scenarios (1,2, and 3), since oyster growth was assumed to occur in the sanctuaries where commercial fishers cannot harvest oysters. Oyster harvest also remains constant between scenarios 4 and 5, because the forced decrease in the Filter Feeders in scenario 5 did not affect oyster harvests. Total annual dockside values were estimated for each scenario (Table 16). Summaries of the most extreme differences between the modeled scenarios (i.e., Scenarios 1 and 5 are compared to the Current Young Reef), and are shown in Tables 17 (landed value) and 18 (total output effects). Contrasts show substantial differences between the economic impacts of oyster management policy that allows the oyster sanctuaries to persist and mature (Scenario 3), and the most extreme alternative where sanctuaries are eliminated (Scenario 5). Scenario 5 assumes oyster sanctuaries are eliminated, and oyster biomass (and encrusting FF groups) is reduced to levels similar to those observed before sanctuaries were established. Figures 8-11 show estimates of all direct, indirect, and induced regional economic impacts from the different scenarios.

This project focuses on economic impacts for Talbot and Dorchester counties, but we also estimated these impacts for two other regions of interest: all Maryland coastal counties bordering on the Chesapeake Bay and its major tributaries, and Maryland-wide (i.e., all Maryland counties), shown in Figure 12. Patterns seen in the two- county model are representative for all three regions, and in all scenarios (horizontal axis). Only slight additional increases were evident in the analyses that included the larger regions.

Table 13. Biomass estimates for all groups in model by scenario. Units are MT/km^2 wet weight. Juveniles (J) and (A) adults are designated for groups that are modeled by life stage (multi-stanza groups). All estimates shown are for the final year of the simulation only.

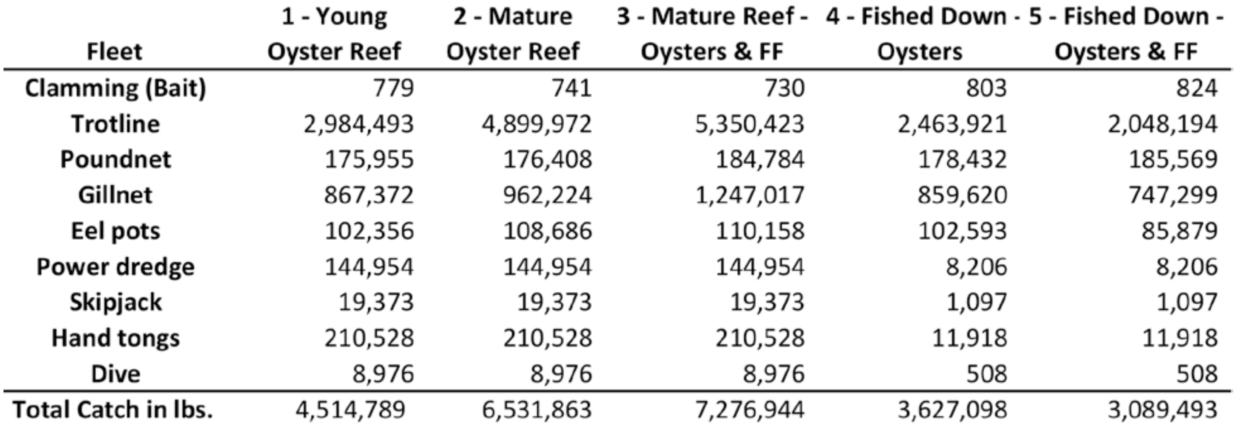
Group	1 - Young Reef	2 - Mature Oyster Reef	3 - Mature Reef Oysters & FF	4 - Fished Down Oyster Reef	5 - Fished Down Oysters &FF
StripedBass (J)	6.72E-01	6.45E-01	6.14E-01	6.91E-01	8.44E-01
StripedBass (A)	1.67E+00	1.61E+00	1.67E+00	1.70E+00	1.84E+00
Weakfish	7.83E-01	8.29E-01	8.97E-01	7.83E-01	7.81E-01
DivingDucks	4.34E-02	4.07E-02	4.37E-02	4.74E-02	3.29E-02
CownoseRay	2.01E-01	1.88E-01	1.83E-01	2.16E-01	2.38E-01
Catfish	3.87E+00	3.92E+00	4.11E+00	3.93E+00	4.23E+00
ReefFish	2.15E+00	2.76E+00	3.10E+00	2.11E+00	2.20E+00
OysterToadfish	6.02E+00	7.51E+00	1.01E+01	5.24E+00	2.52E+00
AmericanEel	2.63E+00	2.86E+00	2.88E+00	2.62E+00	1.96E+00
Panfish	5.28E+00	5.15E+00	6.08E+00	5.30E+00	4.97E+00
WhitePerch	2.68E+00	2.79E+00	4.82E+00	2.57E+00	3.46E-01
Atl.Croaker	6.80E-11	5.53E-11	1.13E-10	5.86E-11	1.66E-11
GizzardShad	7.35E-01	7.29E-01	7.37E-01	7.38E-01	6.95E-01
Peprilus spp.	3.91E+00	3.85E+00	3.79E+00	3.90E+00	4.15E+00
Atl.Menhaden	3.42E-01	3.44E-01	3.43E-01	3.41E-01	3.46E-01
ForageReefFish	1.52E+01	1.29E+01	1.28E+01	1.50E+01	1.73E+01
BlueCrab (J)	4.31E+00	5.46E+00	5.43E+00	3.98E+00	4.04E+00
BlueCrab (A)	1.86E+01	3.11E+01	3.43E+01	1.56E+01	1.30E+01
MudCrabs	1.47E+01	2.25E+01	2.54E+01	1.32E+01	1.20E+01
Iso_cope_amph	4.02E+01	3.99E+01	3.87E+01	4.15E+01	4.50E+01
Mysids	4.03E+01	3.96E+01	3.83E+01	4.15E+01	4.51E+01
Ctenophores	1.69E+01	1.67E+01	1.64E+01	1.66E+01	1.77E+01
SeaNettles	1.50E+01	1.49E+01	1.44E+01	1.51E+01	1.67E+01
SeaAnemone	4.42E+00	4.01E+00	9.25E+00	4.26E+00	2.36E-01
HookedMussel	6.03E+01	5.97E+01	7.14E+01	6.17E+01	3.21E+00
Lg.Clam	2.51E+01	2.38E+01	2.34E+01	2.58E+01	2.65E+01
Sm.Bivalves	3.01E+01	2.93E+01	2.84E+01	3.17E+01	3.51E+01
Barnacles	7.68E+00	6.56E+00	1.33E+01	7.22E+00	3.76E-01
Oyster (J)	1.51E+01	8.51E+00	8.51E+00	8.51E+00	8.51E+00
Oyster (A)	3.47E+01	1.88E+02	1.88E+02	2.18E+00	2.18E+00
Bryozoans	2.79E+00	2.79E+00	2.69E+00	2.96E+00	3.34E+00
Tunicates	4.39E+01	4.44E+01	6.88E+01	4.47E+01	3.07E+00
Annelids	5.06E+01	5.00E+01	5.04E+01	5.05E+01	5.11E+01
Zooplankton	3.99E+01	4.00E+01	3.96E+01	3.95E+01	4.09E+01
Dinoflagellates	2.04E+01	2.07E+01	2.01E+01	2.14E+01	2.40E+01
Phytoplankton (Lg)	1.81E+02	1.80E+02	1.81E+02	1.82E+02	1.81E+02
Phytoplankton (Sm)	7.20E+01	7.25E+01	7.19E+01	7.19E+01	7.51E+01
Detritus	1.00E+02	1.01E+02	1.01E+02	1.00E+02	1.01E+02
total	*884*	*1,047*	*1,102*	*847*	*752*

Table 14. Total landed weight (lbs) by species for each scenario. FF = Filter Feeders dependent on oyster shell (Hooked Mussels, Barnacles, Tunicates, and Anemones). All estimates shown are for the final year of the simulation only.



Species	1 - Young Oyster Reef	2 - Mature Oyster Reef	3 - Mature Reef - Oysters & FF	4 - Fished Down - Oysters	5 - Fished Down - Oysters & FF
StripedBassAdult	168,604	162,402	167,943	172,129	186,908
Catfish	212,029	215,679	224,031	215,685	233,337
ReefFish	317,096	407,644	452,373	310,697	334,873
AmericanEel	76,895	82,840	83,279	76,675	57,544
WhitePerch	216,837	225,596	458,806	210,657	60,075
AtlCroaker	51	43	72	45	16
GizzardShad	147,356	146,263	148,634	147,924	139,021
AtlMenhaden	6,816	6,851	6,821	6,833	6,974
BlueCrabAdult	2,984,493	4,899,972	5,350,423	2,463,921	2,048,194
LgClam	779	741	730	803	824
OysterAdult	383,832	383,832	383,832	21,729	21,729
Total Catch in lbs.	4,514,789	6,531,863	7,276,944	3,627,098	3,089,493

Table 15. Total landed weight (lbs) by fishing fleet for each scenario. FF = Filter Feeders dependent on oyster shell (Hooked Mussels, Barnacles, Tunicates, and Anemones). All estimates shown are for the final year of the simulation only.



Fleet	1 - Young Oyster Reef	2 - Mature Oyster Reef	3 - Mature Reef - Oysters & FF	4 - Fished Down - Oysters	5 - Fished Down - Oysters & FF
Clamming (Bait)	779	741	730	803	824
Trotline	2,984,493	4,899,972	5,350,423	2,463,921	2,048,194
Poundnet	175,955	176,408	184,784	178,432	185,569
Gillnet	867,372	962,224	1,247,017	859,620	747,299
Eel pots	102,356	108,686	110,158	102,593	85,879
Power dredge	144,954	144,954	144,954	8,206	8,206
Skipjack	19,373	19,373	19,373	1,097	1,097
Hand tongs	210,528	210,528	210,528	11,918	11,918
Dive	8,976	8,976	8,976	508	508
Total Catch in lbs.	4,514,789	6,531,863	7,276,944	3,627,098	3,089,493

Table 16. Dockside values (revenues in $'s) by fleet for each scenario. FF = Filter Feeders dependent on oyster shell (Hooked Mussels, Barnacles, Tunicates, and Anemones). All estimates shown are for the final year of the simulation only.

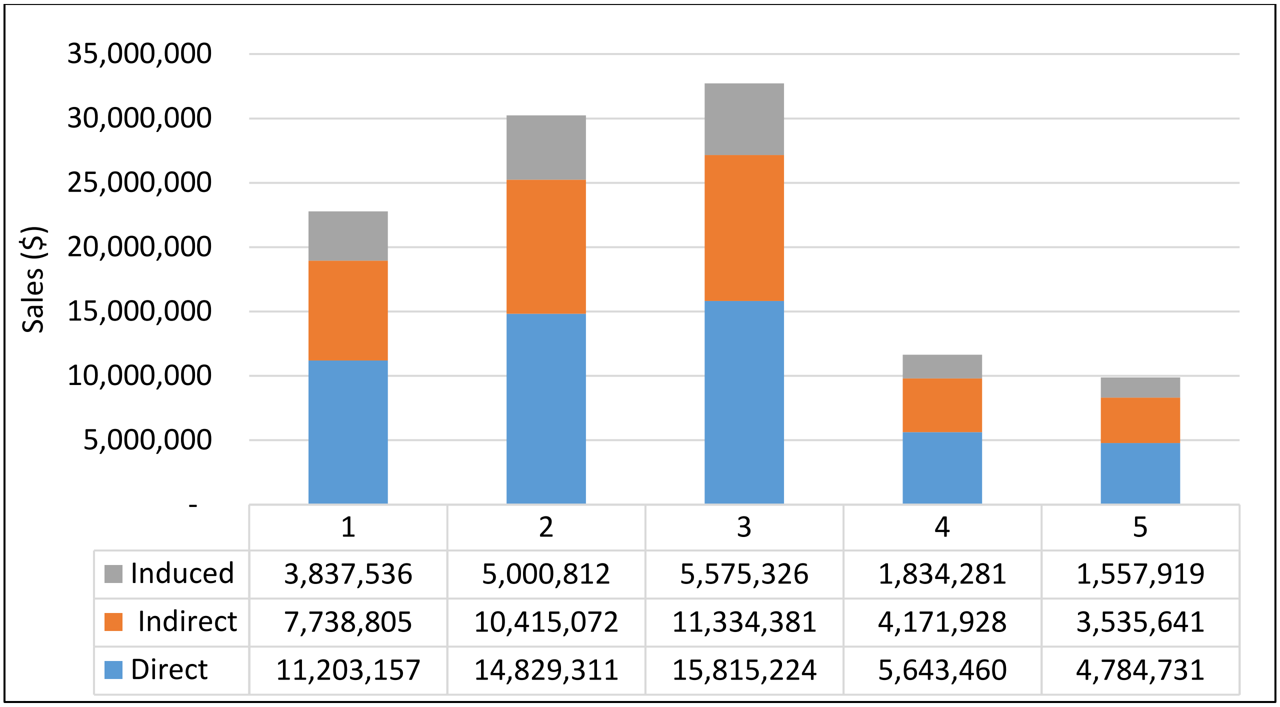
Fishery	1 - Young Oyster Reef	2 - Mature Oyster Reef	3 - Mature Reef - Oysters & FF	4 - Fished Down - Oysters	5 - Fished Down - Oysters & FF	*Price $/lb.*
Clam Bait	6,001	5,703	5,618	6,181	6,346	*$7.70*
Trotline	5,557,125	9,123,748	9,962,487	4,587,821	3,813,736	*$1.86*
Poundnet	135,589	135,938	142,392	137,498	142,997	*$0.77*
Gillnet	419,167	465,005	602,635	415,421	361,140	*$0.48*
Eel pots	220,637	234,280	237,454	221,147	185,118	*$2.16*
Power dredge	1,837,132	1,837,132	1,837,132	104,002	104,002	*$12.67*
Skipjack	245,533	245,533	245,533	13,900	13,900	*$12.67*
Hand tongs	2,668,206	2,668,206	2,668,206	151,050	151,050	*$12.67*
Dive	113,766	113,766	113,766	6,440	6,440	*$12.67*
Scenario Total	11,203,157	14,829,311	15,815,224	5,643,460	4,784,731	

Table 17. Differences in landed values ($'s) compared to Current Young Reef for the most extreme scenarios. All values are annual.

Scenario	Clamming (Bait)	Trotline	Poundnet	Gillnet	Eel pots
1 - Current Young Reef	--	--	--	--	--
3 - Mature Oyster Reef with Associated FF	-6% < $400	+79% $4M	+5% ~$7,000	+44% $0.1M	+8% $0.02M
5 - Fished Down Oysters & Associated FF	+6% < $400	-31% -$2M	+5% ~$7,000	-14% -$0.1M	-16% -$0.04M

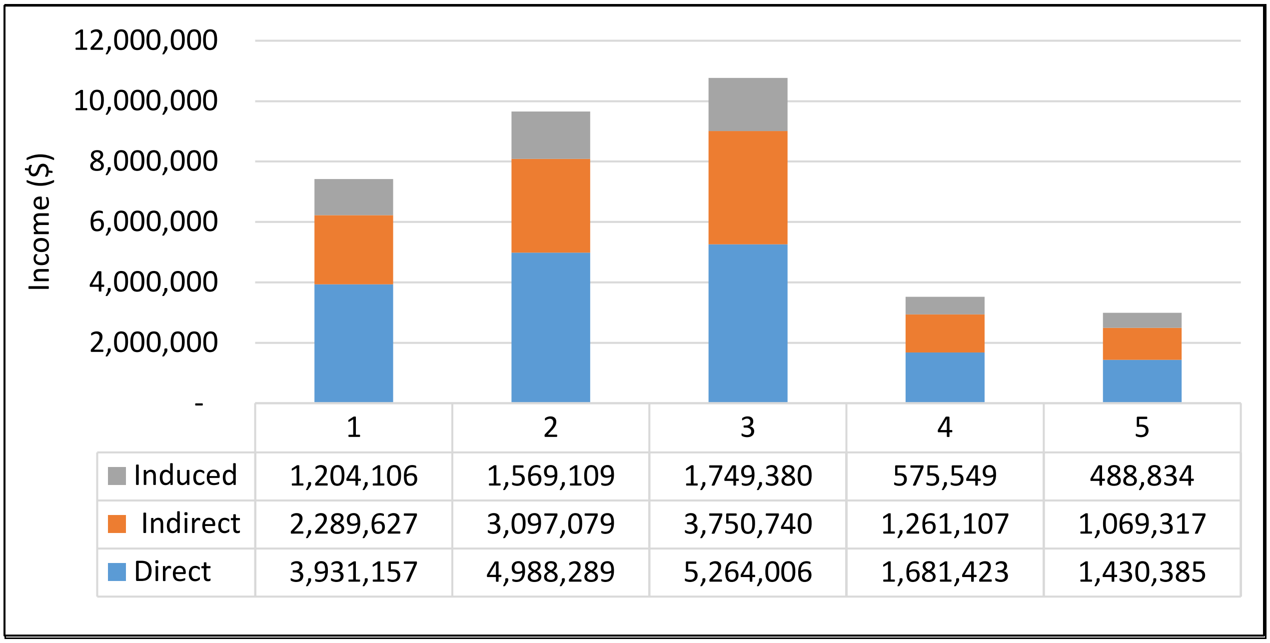
Table 18. Total Output ($'s) Effects (rounded) for scenarios with the most extreme differences, compared to those of the Young Reef scenario. All effects are annual.

Scenario	Total Effect	Difference
1 - Status Quo	$23M	--
3 - Oyster & FF Increase	$33M	$10M
5 - Oysters & FF Decrease	$10M	-$13M



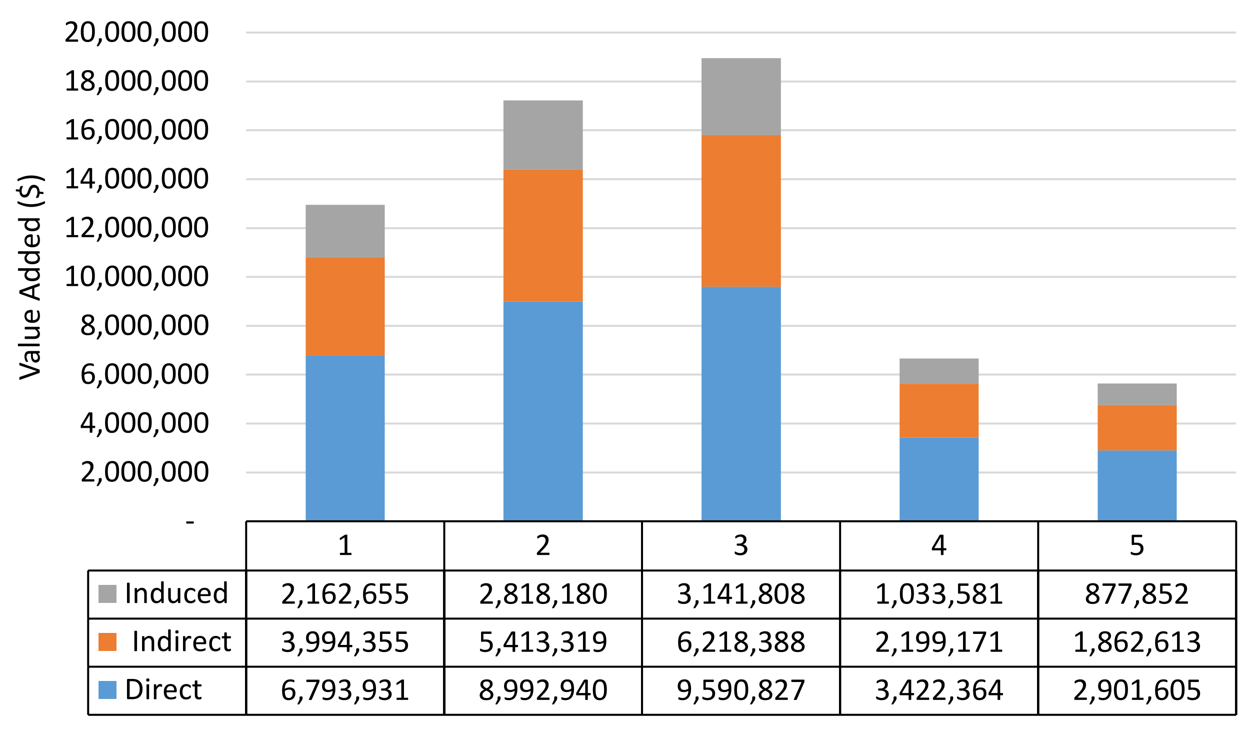
	1	2	3	4	5
Induced	3,837,536	5,000,812	5,575,326	1,834,281	1,557,919
Indirect	7,738,805	10,415,072	11,334,381	4,171,928	3,535,641
Direct	11,203,157	14,829,311	15,815,224	5,643,460	4,784,731

Figure 8. Output (Sales in $'s) Effects. The restored reefs generate $32.7 million in total Output effects (scenario 3, Mature Oyster Reef & FF), compared to the lowest output effects of $9.8 million (scenario 5, Fished Down Oyster & FF).



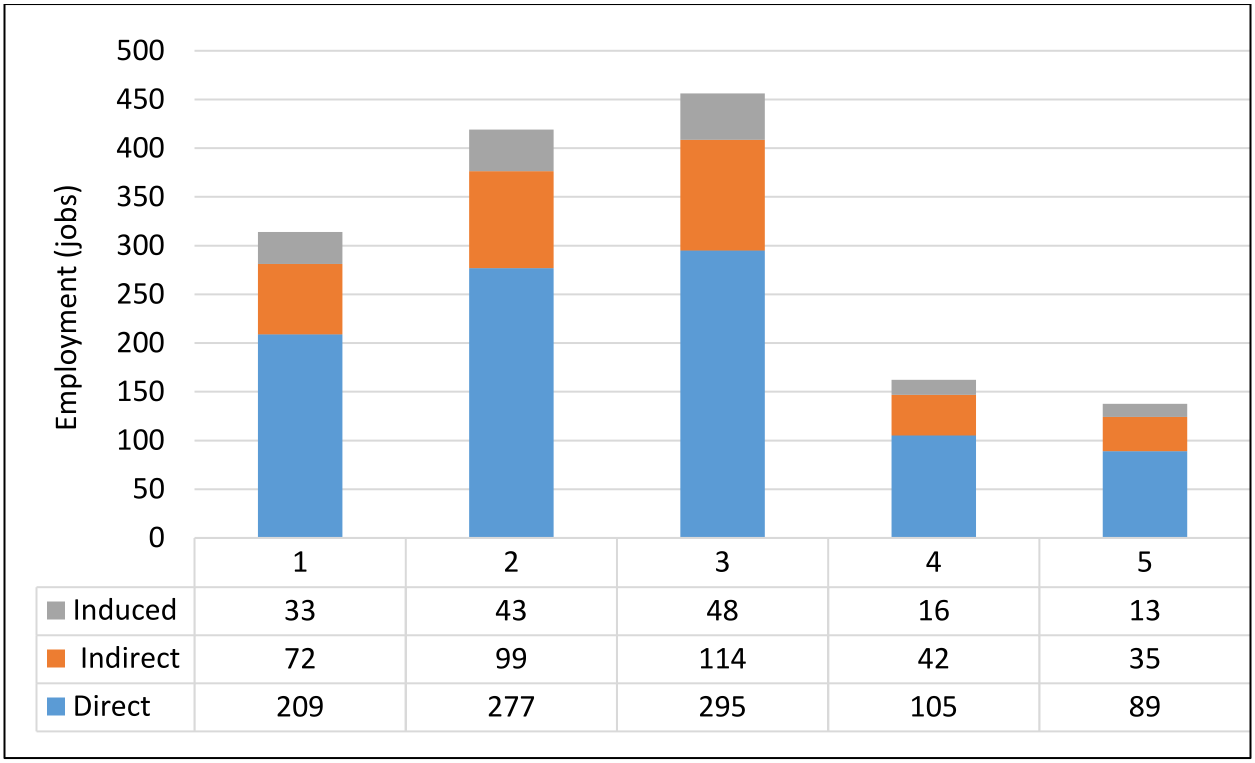
	1	2	3	4	5
Induced	1,204,106	1,569,109	1,749,380	575,549	488,834
Indirect	2,289,627	3,097,079	3,750,740	1,261,107	1,069,317
Direct	3,931,157	4,988,289	5,264,006	1,681,423	1,430,385

Figure 9. Labor Income ($'s) Effects. A measure of employment income that includes wages, benefits, and proprietor income. The fish harvesting sector generates between $2.9 million in total Labor Income effects (scenario 5, Fished Down Oyster & FF) to $10.8 million (scenario 3, Mature Oyster Reef & FF).



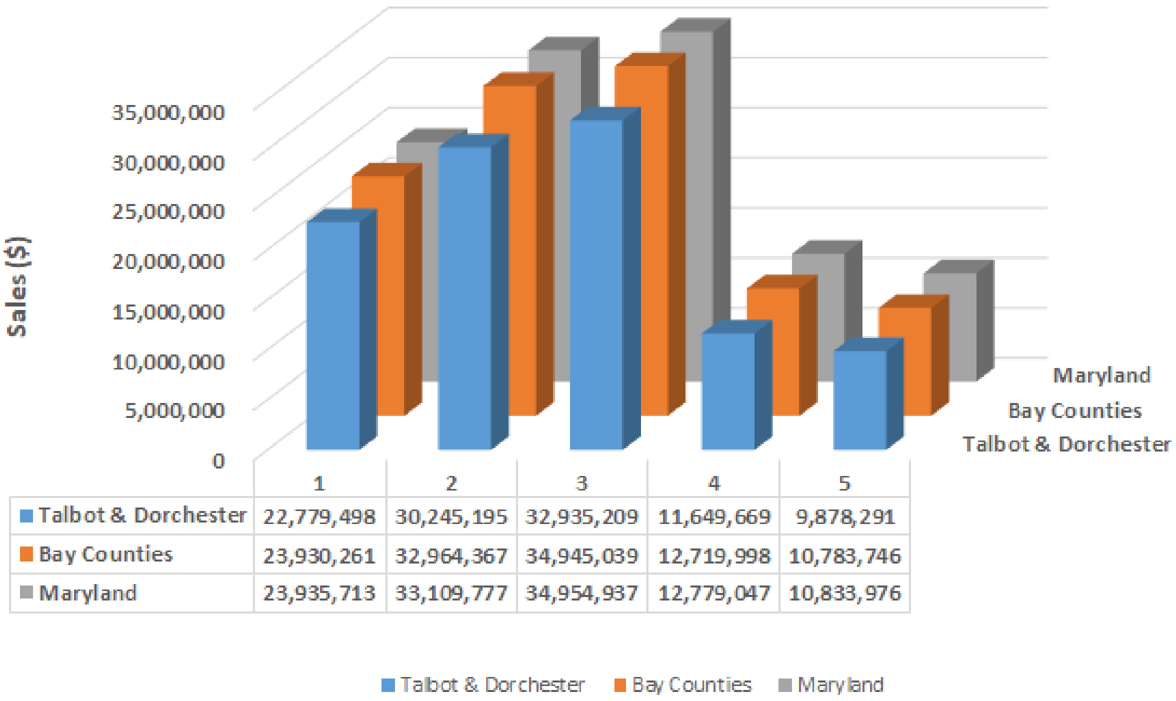
	1	2	3	4	5
■ Induced	2,162,655	2,818,180	3,141,808	1,033,581	877,852
🟧 Indirect	3,994,355	5,413,319	6,218,388	2,199,171	1,862,613
🟦 Direct	6,793,931	8,992,940	9,590,827	3,422,364	2,901,605

Figure 10. Value-added ($'s) Effects. Value-added, representing the difference between an industry's total output and the cost of its intermediate inputs, ranges from $5.6 million in total value added effects (scenario 5, Fished Down Oyster & FF) to $19.0 million (scenario 3, Mature Oyster Reef & FF).



	1	2	3	4	5
Induced	33	43	48	16	13
Indirect	72	99	114	42	35
Direct	209	277	295	105	89

Figure 11. Employment (full and part-time jobs) Effects. Under the various oyster management scenarios modeled, the total (direct + indirect + induced) number of jobs supported ranges from a low of 137 (scenario 5, Fished Down Oyster & FF) to a high of 456 (scenario 3, Mature Oyster Reef & FF) jobs supported in Talbot and Dorchester counties.



	1	2	3	4	5
🟦 Talbot & Dorchester	22,779,498	30,245,195	32,935,209	11,649,669	9,878,291
🟧 Bay Counties	23,930,261	32,964,367	34,945,039	12,719,998	10,783,746
⬜ Maryland	23,935,713	33,109,777	34,954,937	12,779,047	10,833,976

Figure 12. Total Output Impact ($'s) effects for three regions.

Summary and Discussion

Oyster reef restoration efforts in the Chesapeake Bay are both expensive and controversial. Incurred oyster restoration costs in the three restored tributaries in the CLC totaled approximately $53 million (see Knoche et al. 2018). Further, some commercial fishing stakeholders are aggrieved with the restriction on harvesting oysters in reef sanctuary areas. As such, there is a clear need to understand the potential of oyster reef restoration to contribute to the increased provision of a key ecosystem service – seafood production. To this end, the project team developed an ecological model of an oyster reef under multiple management scenarios and linked the commercial fisheries harvest outputs from this ecological model to a regional economic impact model to estimate the changes in key economic measures across these scenarios.

The ecological model predicted substantial increases in Blue Crab production and harvest when oyster reefs are restored, relative to scenarios where reef structure is fractured and dispersed to pre-restoration conditions. A Mature Oyster Reef with Associated FF is projected to increase harvest of blue crab by 2.4 million pounds, and dockside values by about $4.5 million, relative to the Current Young Reef (intended to be reflective of the current bottom habitat composition in the CLC). These increased revenues generate additional economic impacts through the backward-linked supply chain effects. Total output effects, driven primarily by Blue Crab, increase by about $10 million when comparing the Young Reef and Mature Reef (both with Oyster & FF) scenarios (Table 18). Perhaps the most interesting and relevant comparison is to contrast a Mature Oyster Reef (with Oyster & FF) with the most extreme alternative state modeled, where sanctuaries no longer exist and the reef structure is fractured and scattered. In effect, this comparison is intended to capture the changes from a pre-restoration CLC to a CLC with mature restored reefs. In this comparison, the mature oyster reef (with Oyster & FF) produces an estimated increase in Blue Crab harvest of 160% and an increase in total output effects of $23 million (Figure 8).

The large increases in Blue Crab harvest for the sanctuary scenarios are driven mainly by an increase in the availability of food when the oyster restoration goals are realized (Oyster Metrics Workgroup 2011). Adult Blue Crabs eat a wide range of prey (Table 4), including juvenile and adult oysters and all the FF that increase in the Mature Oyster Reef with FF scenario. Consequently, Blue Crabs would be expected to benefit to some extent given the increased availability of their food. Even so, Mud Crabs benefit even more than Blue Crabs from the increases in these same groups. Because Mud Crab are a large component of both the juvenile and adult Blue Crab diet (approximately 20% in both life stages), it is primarily the increase in Mud Crab that drives the increases in Blue Crab reported here. It should be noted that these estimates are specific to the CLC region, and may not apply to oyster restoration sites elsewhere in the Chesapeake Bay.

The ecological model also predicted sizable increases for finfish harvest. For the gillnet fleet, which harvests a mixed-species catch, harvested biomass in the mature reef scenario with filter feeders is estimated to be about 30% greater than the Young Reef scenario, and the Mature Reef with FF scenario is about 70% greater than the scenario in which oysters and filter feeders have been fished down. These harvest biomass increases are largely due to an increase in White Perch harvest (see Table 2). White Perch harvest in the Mature Reef with FF scenario is over 100% greater than that in the Young Reef scenario, and over 600% greater in the Mature Reef with FF scenario relative to the Fished down Oyster & FF scenario. Despite these large increases in White Perch harvest, dockside values for finfish are relatively small when compared to Blue Crab, as the commercial finfish fishery is only about a tenth of the size (in terms of dockside value) of the Blue Crab fishery. Maximum dockside value, the direct output effect, is about $600,000 annually for gillnet fleet in the Mature Reef with FF scenario. Differences in Striped Bass harvests are negligible across scenarios.

Unlike many ecosystem service estimates for oyster restoration, we explicitly accounted for expected changes in the associated hard bottom community that result when available oyster shell is increased or decreased. The inclusion of the additional filter feeders ("FF" includes Anemones, Barnacles, Hooked Mussel, and Tunicates) that grow on oyster shell amplifies results of scenarios that included changes in oyster biomass alone. An additional $2.5 million annual impact is predicted when the commensal FF groups increase in biomass along with oysters (Scenario 3 compared with Scenario 2). Conversely, an additional annual loss of $1.8 million is predicted when FF group biomasses decrease along with the corresponding decrease in oyster biomass (Scenario 5 compared to Scenario 4).

The ecological and regional economic impact modeling effort undertaken here has limitations. The ecological model implicitly assumes catchability (Equation 1) is constant. This is a simplifying assumption that is common in the fisheries literature, but this assumption is also known to be commonly violated (Ihde et al., 2008). Such violations in real-world fisheries can result in biased estimates of biomass. However, any biases in harvest estimations that were unknowingly incorporated into the base scenario (2006-2015) are extended through all the scenarios equally, and cancel when quantifying the change between scenarios. It is these relative differences between the scenarios that are the focus of our study.

The specific ecosystem service that this work is focused on is seafood harvests and impacts of those harvests on the connected industries. Oyster reefs, however, provide a wide range of other important ecosystem services as well (Peterson and Lipcius 2003) that are not accounted for in this work. Oyster reefs clear the water column of both over productive plankton and sediments. Oysters remove nitrogen by sequestering the nutrient in their meat, shell, and through biogeochemical cycling (Kellogg et al. 2013, Bricker et al. 2018). The hard surface of their live shell growth benefits other organisms as both shelter from predation (i.e., refuge habitat), and as an aggregator of prey, attracting more predators relative to unstructured areas (Karp et al. 2018, Stunz et al. 2010).

Reefs structure may enhance larval fish recruitment by providing protection from the frequently alternating currents in the estuary (Breitburg et al. 1995). Further, restored oyster reef has recently been shown to enhance the growth of neighboring submerged grasses (Lipcius, unpublished manuscript), which is likely to result in synergistic habitat effects with those observed for the grasses (Orth 1984). Shell deposits by growing oysters and associated filter feeders (e.g., barnacles and mussels) sequester carbon, reducing greenhouse gases. Their aggregate structure also functions as a breakwater, protecting shorelines from erosion.

The work presented here fully accounts for only the importance of the restored oyster reef as a consumer of plankton, as food for predators, as a producer of substrate (habitat) for other filter feeders to grow on, and ultimately, the regional economic impacts generated by the commercial seafood harvesting sector and connected industries.

Further study could expand this work substantively to include a spatial approach (EwE using Ecospace) that would distinguish between fished and non-fished areas and allow for specific accounting of each oyster harvest subsector. The current work cannot identify impacts to specific subsectors of the oyster fishery because the oyster increase scenarios allow only for increased oyster production *inside* the sanctuary where oyster harvesters do not have access, and thus, these fishers cannot benefit from potential increases in oyster abundance *outside* these sanctuary areas. With a spatial Ecospace approach, it would be possible to estimate the effects of varying oyster management strategies on harvests specific to power dredgers, skipjack operators, hand tongers, and dive harvesters who face different spatial restrictions on harvest. Moreover, in the non-spatial approach taken here, these diverse oyster fisheries were lumped into one aggregate fishery where harvests are forced by the presence or absence of the sanctuary.

Our results suggest that Blue Crab harvesters would benefit from allowing the restored oyster reef to mature, but effects of such a policy on specific oyster harvesters remains beyond the scope of this project. Many of the commercial oyster fishers, who worked closely with the project team to develop custom production functions for each fishery (Table 10), expressed frustration at the loss of harvestable oyster grounds that were used for the new sanctuaries in the CLC. Projecting landing effects specific to each oyster gear would show the economic impacts of improved oyster harvests in areas adjacent to sanctuaries where they have access (estimations of a "spillover" effects). Predictions of settlement, recruitment and growth of oyster larvae and spat by sub tributary and by bottom type could be added to a spatial approach, thereby more fully accounting for enhanced oyster production of the established reefs. The improved spatial and sectoral resolution of such an approach would help these fishers understand how each of their businesses are likely to be affected by the new sanctuaries, compared to a policy with no sanctuaries. Additionally, such an approach would allow for movement of ecological groups and use of the oyster habitat as refuge by prey species, further adding to the realism of the model.

Additional future work on the economics portion of this model could also enhance the realism and usability of this effort moving forward. The regional economic impact measures produced here are ***not*** *net economic benefits,* and as such are not suitable for use within an economic benefit-cost analysis. A future effort might involve the estimation of economic surplus (i.e., consumer surplus, producer surplus), which could contribute to a benefit-cost analysis.

The assumption of constant per-unit prices applied across different harvest scenarios may not be tenable in the face of large increases in harvest of a perishable seafood good such as Blue Crab. That is, the large increases in Blue Crab harvest predicted to occur with oyster reef restoration may result in decreases in the per-unit price paid by seafood dealers at the dock. The application of existing inverse demand modeling efforts (e.g., Huang 2015) could provide information on price responsiveness to changes in quantity harvested.

Behavioral responses from commercial fishers could also be modeled, such as the movement into the area by commercial fishers due to the increase in blue crab harvest, and the potential for fishers currently in the area to increase fishing effort and expand their operations.

Finally, the treatment of time in linking ecological and economic models is not straightforward. The ecosystem model assumes the gradual forcing of oyster biomass over a reasonable timeframe for the system to transition to the target status, while IMPLAN is based on current economic data and industry relationships. Moreover, industries and industry linkages will likely be different in future alternative state scenarios, relative to the Current Young Reef scenario. To keep things straightforward and avoid further complicating this modeling effort, we abstract from the temporal issue when calculating economic impacts.

In summary, this project contributes to a growing literature linking ecological models to regional economic impact models to provide resource managers, policy makers, and other stakeholders with estimates of seafood production and the resulting economic impacts generated by alternative management scenarios. Specific to the CLC, this report complements recent and ongoing work examining the use of restored oyster reefs by finfish and macro faunal invertebrate species (Kellogg, 2016; D. Bruce, NMFS, unpublished data), and similar work on fish utilization of restored reef elsewhere in the Chesapeake Bay (Karp et al. 2018). With the estimation of economic impacts, we provide a new dimension that is useful to stakeholders in the region. Finally, we recommend that resource managers and decision-makers consider the *a priori* application of similar ecological – economic impact modeling efforts to identify the management strategies most likely to yield the greatest combination of biomass harvest and regional economic impacts *prior* to the management action. This could facilitate the achievement of desired ecological and socio-economic outcomes that provide the greatest benefits to the resource and society.

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Appendix A

Literature Review – Life History

Ecology and Life History References used for estimating EwE (Z, P/B, Q/B, EE, P/Q)

Striped Bass
Christensen et al. 2009
David Bruce, NOAA Chesapeake Bay Office, unpublished data

Weakfish
Christensen et al. 2009 Ihde et al. 2016

Diving Ducks
Christensen et al. 2009
D. Forsell, USF&W, unpublished data, 2004
Paige and Luckenbach 2008

Cownose Ray
Christensen et al. 2009 Heymans et al. 2016

Catfish
Randall and Minns 2000

Reef Fish
Madeo 2012
Christensen et al. 2009
Froese and Pauly 2013, FishBase (web resource, last accessed 3/15/17)

Oyster Toadfish
Kellogg et al. 2016
L. Kellogg, VIMS, unpublished data
Madeo 2012

American Eel
Morrison and Secor 2003
Christensen et al. 2009
David Bruce, NOAA Chesapeake Bay Office, unpublished data

Panfish
David Bruce, NOAA Chesapeake Bay Office, unpublished data
Christensen et al. 2009
Christensen and Walters 2004
Homer & Mihursky 1991
Froese and Pauly 2013, FishBase (web resource, last accessed 3/15/17)

White Perch
David Bruce, NOAA Chesapeake Bay Office, unpublished data
Klauda et al. 1988
Froese and Pauly 2013, FishBase (web resource, last accessed 3/15/17)

Atlantic Croaker
David Bruce, NOAA Chesapeake Bay Office, unpublished data
Christensen et al. 2009
Desfosse et al. 2002

Gizzard Shad
Brad Walters, MD DNR, unpublished data
Maryland Department of Natural Resources (web resource, http://www.dnr.state.md.us/fisheries/fishfacts/americangizzardshad.asp, last accessed 3/1/17)
Christensen et al. 2009
Randall and Minns 2000
Froese and Pauly 2013, FishBase (web resource, last accessed 3/15/17)

Butterfish & Harvestfish
Christensen et al. 2009
Ihde et al. 2016

Atlantic Menhaden
Christensen et al. 2009
Froese and Pauly 2013, FishBase (web resource, last accessed 3/15/17)
Atlantic States Marine Fisheries Commission 1999
Palomares and Pauly 1998
Vaughan and Smith 1988

Blennies/Gobies/Skilletfish aggregate group "Forage Fish"
Kellogg et al. 2016
L. Kellogg, VIMS, unpublished data
Delos Rayes, 1993
Christensen and Pauly 1993

Blue Crab (j)
Christensen et al. 2009

Blue Crab (a)
David Bruce, NOAA Chesapeake Bay Office, unpublished data
Kellogg et al. 2016
Ihde et al. 2016

Mud Crab
Kellogg et al. 2016
L. Kellogg, VIMS, unpublished data

Isopods, Amphipods, and Benthic Copepods
Madeo 2012
Schwinghamer et al. 1986
Vasslides et al. 2017

Mysids
Madeo 2012
Sudo et al. 2011
Christensen et al. 2009
Heymans et al. 2016

Ctenophores
Christensen et al. 2009
Chesapeake Bay Program (web resource, https://www.chesapeakebay.net/S=0/fieldguide/critter/comb_jellies, last accessed 11-1-18)
Shushkina et al. 2000

Sea Nettles
Christensen et al. 2009
Baird and Ulanowicz 1989
Shushkina et al. 2000
Hansson 1997

Sea Anemone
Steinberg and Kennedy 1979
Christensen and Pauly 1993

Hooked Mussel
Kellogg et al. 2016
Schwinghamer et al. 1986
Christensen et al. 2009
L. Kellogg, VIMS, unpublished data

Soft Shell Clam (Mya)
Kellogg et al. 2016
L. Kellogg, VIMS, unpublished data
Christensen et al. 2009

Small Bivalves
Kellogg et al. 2016
L. Kellogg, VIMS, unpublished data
Schwinghamer et al. 1986
Sealifebase (web resource, http://sealifebase.org/summary/Macoma-balthica.html, last accessed 11/1/18)
Christensen et al. 2009

Barnacles
McDonald 1982
Heymans et al. 2016
Jenkins et al. 2008
Madeo 2012
Bahr 1976

Oyster Juveniles (larval and spat stages)
Heymans et al. 2016
Madeo 2012
Steinberg and Kennedy 1979
Kellogg et al. 2016
Hidu and Haskin 1971
Nelson 1924

Oyster Adults
Madeo 2012
L. Kellogg, VIMS, unpublished data

Bryozoans
Madeo 2012
L. Kellogg, VIMS, unpublished data
David Bruce, NOAA Chesapeake Bay Office, unpublished data Keough 1986

Tunicates
L. Kellogg, VIMS, unpublished data
Madeo 2012
Christensen et al. 2009
University of Connecticut (web resource, http://www.eeb.uconn.edu/people/fried/LTREB%20WEB/Species/Ascidians.html, last accessed 3/1/17)
Gosselin and Qian 1997

Annelids
L. Kellogg, VIMS, unpublished data
Schwinghamer et al. 1986
Gillet et al. 2011
Seitz and Schaffner 1995
Madeo 2012
Ihde et al. 2016

Zooplankton
Polovina 1984
Christensen et al. 2009

Phytoplankton (Large)
Christensen et al. 2009
C. Buchanan and D. Jasinsky, survey data analysis, Chesapeake Bay Program
L. W. Harding and Perry 1997

Phytoplankton (Small)
Heymans et al. 2016
Schwinghamer et al. 1986

Literature Review – Diets

Striped Bass - Juveniles
Kellogg et al. 2016
David Bruce, NOAA Chesapeake Bay Office, unpublished data
Hartman and Brandt 1995
Madeo 2012
Ihde et al. 2016

Striped Bass - Adult
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis
Christensen et al. 2009
Ihde et al. 2016
Walter and Austin 2003
Buchheister and Houde 2016
Hartman and Brandt 1995

Weakfish
Lippson and Lippson 1997
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

Diving Ducks
Ross and Luckenbach 2008
Ihde et al. 2016

Cownose Ray
Smith and Merriner 1985
Lippson and Lippson, 1997
Franke, et al., 2015

Catfish
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis
Lippson and Lippson, 1997

Reef Fish
ChesMMap, VIMS, unpublished data (web resource, last accessed 2/23/17)

Oyster Toadfish
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

American Eel
Wenner and Musick 1975

Panfish
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

White Perch
Buchheister and Houde 2016
Kellogg et al. 2016
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

Atlantic Croaker
Buchheister a Houde 2016
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

Gizzard Shad
Miller 1960

Butterfish & Harvestfish
ChesMMap, C.Bonzek, VIMS, unpublished Choptank data analysis

Atlantic Menhaden
Ihde et al. 2016
Lynch et al. 2010

Blennies/Gobies/Skilletfish aggregate group "Forage Fish"
Harding 1999
Lippson and Lippson, 1997

Blue Crab (juvenile)
Seitz et al. 2011
Laughlin 1982

Blue Crab (adult)
Laughlin 1982
Hines et al. 1990

Mud Crab
L. Kellogg, VIMS, unpublished data McDonald 1982
Williams 1984
Lippson and Lippson, 1997
Smithsonian Indian River Lagoon species profiles, *Eurypanopeus depressus* (web resource, last accessed 3/5/17)
Henninger et al. 2009
Bowman et al. 1963

Isopods, Amphipods, and Benthic Copepods
Henninger et al 2009
Bowman et al. 1963
Lippson and Lippson, 1997

Mysids
Lehtiniemi and Nordström 2008
Zagursky and Feller 1985

Ctenophores
Ihde et al. 2016

Sea Nettles
Ihde et al. 2016

Sea Anemone
Steinberg and Kennedy 1979
World Register of Marine Species (web resource,
http://www.marinespecies.org/aphia.php?p=taxdetails&id=158230, last accessed 12-12-18)

Hooked Mussel
Gedan et al. 2014

Soft Shell Clam (Mya)
Abraham and Dillon 1986

Small Bivalves
Kellogg et al. 2016
Shumway and Newell 1984
Hummel 1985
Chalermwat et al. 1991
Sellmer 1967

Barnacles
Barnes 1959
Chesapeake Bay Program field guide (web resource, http://www.chesapeakebay.net/fieldguide/critter/barnacles, last accessed 12-12-18)

Oyster Juveniles (larval and spat stages)
Davis 1953
Baldwin and Newell 1995
Mackie 1969

Oyster Adults
Langdon and Newell 1990

Bryozoans
Riisgard and Manriquez 1997
Winston 1978

Tunicates
Hernández-Zanuy et al. 2007

Annelids
Fong 1987
Kellogg et al. 2016

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Appendix B: Calculation of Space for Filter Feeder Biomass

Calculating new space for colonization provided by oyster growth by 2030:

The increase for each group is based on the growth of the oysters, and the new substrate the oyster shell provides. The wet weight of the restoration goal (Oyster Metrics Workgroup 2011) of 15 oysters/m^2 is 187.5 g/m^2, based on the average wet weight of an oyster (12.5 g) by Mo and Neilson (1994). The estimated wet weight of oysters per square meter in the Ecosim model is 21.8 g in 2015. Thus, the growth to be attained 2016 – 2030 in order to achieve restoration biomass goals would be 165.7 g/m^2. The Solver add-on in Microsoft Excel was used to estimate yearly growth of oysters required to achieve the oyster goal (15.4%).

Since oysters grow in volume as well as area, the cubed root of 165.7 m^3 is an estimate of the linear measure of additional space now available for additional organisms to grow on the new substrate provided by the oyster shell (5.5 m), and $(5.5)^2$ is the new area available (30.2 m^2) to colonize *if* both sides of the oyster shell are free for colonization. We know that this would be an overestimate because oysters are attached to substrate and often grow in dense clumps. We conservatively estimate that ½ of the new oyster surface area is available for growth, thus, 15.1 m^2 is estimated as the area available for colonization. The linear measure (√15.1 m^2) of new oyster substrate available in 2030 is thus 3.9 m (per m^2).

Calculation of biomass of encrusting filter feeders on new oyster substrate by 2030:

The calculation of biomass in 2030 is the same for each encrusting filter feeder group. 2015 biomasses (g/m^2) for Ghost Anemone, Tunicates, and Barnacles are 2.4, 30.7, and 3.8, respectively. Hooked Mussels are presented as an example.

2015 biomass = 32.12 g/m^2 = 32.12 g/m^3 volume of Hooked Mussel present

$\sqrt[3]{32.12} = 3.18$ linear m

+ 3.9 m of colonizable oyster shell by 2030 = 7.06 m of linear space for Hooked Mussels by 2030

Assuming biomass is proportional to available space, set up proportion:

$\frac{32.12\, gg/mm^2{}_{2015}}{3.18\ \mathrm{m}_{2015}} = \frac{XX\, gg/mm^2{}_{2030}}{7.06\ \mathrm{m}_{2030}}$; Solving for X = 71.31 g/m^2 biomass of

Hooked Mussel by 2030.

Using Excel Solver as described above, yearly biomasses of Hooked Mussel were calculated. A 5.5% annual increase of Hooked Mussel is required to achieve a biomass of
71.31 g/m^2 by 2030.

Appendix C: Breakdown of Commercial Fishing Expenses Across IMPLAN Sectors

Fishing Expense	Percent allocated	Relevant IMPLAN Sector	NAICS Code
Repair and maintenance (haul out, engine, deck equipment, hull, fishing gear, electronics, refrigeration, safety equipment)	50% 50%	• Other Amusement and Recreation Industries • Personal and Households Goods Repair and Maintenance	713930 811490
Mooring (Includes docking)	100%	Other Amusement and Recreation Industries	713930
Shop expenses (gear shed rental and workshop expense)	80% 20%)	Real Estate Electric Power Transmission and Distribution	531110 221122
Office expenses (office rental, home office, office utilities - electric, heat, postage, photocopying, computer and office phone use, excluding communication costs)	50% 20% 10% 20%	• Real Estate • Electric Power Transmission and Distribution • Stationary Product Manufacturing • Postal Service	531110 221123 322230 491110
Vehicle costs (for fishing business related purposes only)	20%	• Automotive Repair and Maintenance	8111
Travel costs (business costs such as lodging and transportation)	80%	• Hotels and Motels	721110
Association fees (co-operative, fishing organization, sector fees and union dues)	100%	Labor and Civic Associations	813410
Professional fees (settlement, accounting, and legal fees)	80% 20%	• Accounting, Tax Preparation, Bookkeeping, and Payroll Services • Legal Services	54021 5413
Insurance (vessel)	100%	Insurance Carriers	524126
Fishery monitoring (observer or dockside monitoring cost)	100%	Scientific Research and Development Services	541715

Fishing Expense	**Percent allocated**	**Relevant IMPLAN Sector**	**NAICS Code**
Communication (for vessel, cell phones, radio, VMS, etc.)	100%	Wired Telecommunications Carriers	517110
Vehicle costs (for fishing business related purposes only)	80%	Petroleum Refineries	324110
Travel costs (business costs such as lodging and transportation)	20%	Petroleum Refineries	324110
Boat fuel (includes oil)	100%	Petroleum Refineries	324110
Ice	100%	Manufactured Ice	312113
Bait	100%	Commercial Fishing	114111
Fishing supplies[3] (knives, picks, hooks, boxes, bags, ties, lobster bands, rags, tape, links/rings, lines/twine, etc.)	Equal allocation, 12.5%	• Knives (Cutlery) • Fishing Line (Other Textile Product Mills) • Fishing Hooks (Sporting and Athletic Goods Manufacturing) • Boxes (Paperboard Container Manufacturing) • Bags (Plastics, packaging materials) • Steel Fishing Rings/Links (Spring and Wire Product Manufacturing) • Other Fabricated Wire Product Manufacturing • Tape (Paper Bag and Coated Treated Paper Manufacturing)	332215 314999 339920 322211 326111 314994 332618 322220
Crew supplies (gloves, boot liners and foul-weather gear)	Equal allocation, 33.33%	• Plastic Gloves (Other Plastic Product Manufacturing) • Foul-weather Gear (Men's and Boys' Cut and Sew Apparel Manufacturing)	326199 315220 316210

Fishing Expense	Percent allocated	Relevant IMPLAN Sector	NAICS Code
		• Rubber Boots (Footwear Manufacturing)	