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Oyster Economics: Costs, Returns, and Ecosystem Benefits of Commercial Bottom Production, Commercial Off-Bottom Aquaculture, and Non-Harvested Reefs

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Abstract: We present an analysis of Eastern oyster (*Crassostreia virginica*) production systems dominant in the U.S. Atlantic and Gulf Coasts. We identify likely ranges of costs, returns, and ecosystem benefits associated with three production systems: commercial bottom production, commercial off-bottom aquaculture, and non-harvested reefs. We compile the limited and disparate literature on costs, yields, and returns associated with U.S. commercial oyster production. Benefits associated with commercial bottom production are expected to be less variable than off-bottom aquaculture and non-harvested reefs. Bottom production is expected to yield positive returns, whereas off-bottom aquaculture is equally likely to yield positive or negative returns. Off-bottom aquaculture has higher per-unit costs, but also higher per-unit revenues. Non-harvested reefs are expected to yield negative net benefits. Market benefits dwarf nonmarket benefits. Non-harvested reefs are generally expensive, but may provide benefits that commercial production systems do not, particularly shoreline protection and larvae for nearby harvested reefs.

Keywords: ecosystem services, harvest, off-bottom farm, shellfish, yield
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Introduction

This paper is an in-depth analysis of oyster (Eastern oyster, *Crassostreia virginica*) production systems dominant in the U.S. Atlantic and Gulf Coasts. It identifies likely ranges of costs, returns, and ecosystem benefits associated with three different production systems: commercial bottom production, commercial off-bottom aquaculture, and non-harvested reefs. The paper also compiles the limited and disparate literature on costs, yields, and returns associated with commercial oyster production in the United States.

Oyster reefs (public and private) have historically been managed for commercial harvest, but it has long been known, and recent scholarship confirms, that they provide a myriad of other environmental benefits, that is, ecosystem services (Piehler and Smyth 2011; Grabowski et al. 2012; Smyth, Geraldi, and Piehler 2013; Kellogg et al. 2014; Humphries and La Peyre 2015; Interis and Petrolia 2016; Fodrie et al. 2017). Off-bottom oyster farming is a relatively new intensive farming practice, and it, too, is focused on commercial harvest, but recent scholarship shows that it too can provide more than just a market harvest (Miller 2009; Alleway et al. 2019; Gentry et al. 2020). Non-harvested oyster reefs, including preserved or restored subtidal "sanctuary reefs" designed to expand oyster habitat and act as a source of larvae, as well as intertidal reef structures designed to provide shoreline protection, often called "living shorelines", yield no market benefits but they too provide a variety of other nonmarket ecosystem services (Meyer, Townsend, and Thayer 1997; Piazza, Banks, and La Peyre 2005; Scyphers et al. 2011; Parker and Bricker 2020).

Grabowski et al. (2012) conducted the most comprehensive economic analysis of the benefits provided by oysters to date, although it addressed only benefits, not costs. Other papers provide glimpses into the economic values of ecosystem services provided by oysters. For instance, some papers have estimated the economic value of enhanced fish and crustacean abundance due to oyster reefs (Kroeger and Guannel 2014; Lai, Irwin, and Zhang (2020; Knoche et al. 2020). Parker and Bricker (2020) estimated the value of harvest, water quality, and nutrient removal benefits associated with off-bottom farms. Other papers have provided various estimates of the value of nitrogen removal by oysters in nutrient trading programs (Miller 2009; DePiper, Lipton, and Lipcius 2017; Stephenson and Shabman

2017). Anderson and Plummer (2017) estimated the value of recreational oyster harvest by assessing household willingness to pay for avoiding beach closures. Analyses of how oyster management can be optimized for the provision of multiple ecosystem services have also been carried out (Kasperski and Weiland 2009; Mykoniatis and Ready 2016).

All this past work has been critical to building up our understanding of the variety of ecosystem services provided by oysters, but how these benefits differ among the different approaches to producing oysters is not clearly understood. In fact, in many of the cited cases, details regarding production specifics are unclear. Additionally, there is very limited work documenting costs, yields, and returns of commercial oyster production. We are aware of no work attempting to combine cost, market return, and ecosystem benefit information into one unified analysis including commercially harvested bottom oyster reefs, off-bottom oyster farms, and non-harvested oyster reefs. Better data about the relative costs, market returns, and ecosystem benefits should allow resource managers and industry members to make better informed, more holistic decisions.

Production Systems

We report both the local unit and a common unit, using a U.S. standard (level) bushel (2,150.4 cubic inches). We use the following conversions: 1 Louisiana sack (3225.6 cu. in.) = 1.5 U.S. bushels; 1 Maryland bushel (2800.9 cu. in.) = 1.3025 U.S. bushels; 1 Mississippi sack (3421.4 cu. in.) = 1.5911 U.S. bushels; and 1 Virginia bushel (3003.9 cu. in.) = 1.3969 U.S. bushels (GSMFC 2012; MDNR 2020; Melancon and Condrey 1992).

Commercial Bottom Production

Extensive bottom production varies by region. Production and harvest may take place on public harvest grounds, as in Apalachicola Bay, Florida, or private leases, as is typical in Louisiana and Maryland. In its simplest form, production involves landing naturally-occurring oysters and delivering them to market, which would involve a boat, harvest equipment (e.g., dredge or tongs), labor, and culling tools. It may also be necessary to "work" grounds in areas of high siltation to prevent smaller oysters and shell from getting buried (personal communication with Doug Lipton, August 24, 2020). Bottom production commonly also involves the planting of cultch (often shell) to harden the bottom and improve habitat for larval settlement and subsequent oyster growth and survival. Less commonly, seed (either set as spat-on-shell from hatchery-produced larvae or transplanted from public seed grounds as in Louisiana) may be directly planted onto the bottom grounds. In some cases, it may also involve relaying oysters from an area closed to harvest due to public health restrictions to a different location for depuration and eventual harvest.

Estimating yields for extensive bottom harvest is challenging. One key factor is whether production relies on natural recruitment or seed planting (often through the purchase of spat-on-shell), where the latter is likely associated with higher yields. Additionally, the estuarine environment is inherently unpredictable, which may affect oyster bed productivity over time. To hedge risk, oystermen may hold multiple private leases in different locations (GSMFC 2012) and public resource agencies may make investments in several different locations. Keithly and Kazmierczak (2006) write that "the gradual deterioration of Louisiana’s wetlands have forced lessees to hedge against failure by leasing acreage in different areas throughout South Louisiana" (p. 13). Additionally, the grow-out period can range from as short as 6-9 months in productive locations in the Gulf of Mexico (GSMFC 2012; Banks et al. 2016) to as long as 2-4 years in Maryland (Parker, Lipton, and Harrell 2020). Private oystermen and resource managers may follow an annual rotation, or they may harvest the same acreage annually, keeping market-size oysters and returning under-sized ones to the water for harvest later.

Although regulatory agencies generally track total acreage of oyster harvesting grounds (leased and public), the above makes clear how challenging it can be to associate a given harvest quantity with a particular quantity of reef acreage to calculate yield per acre directly. To complicate matters further, a leased acre is not necessarily a productive one. Keithly and Kazmierczak (2006), for example, argue that more than half of all Louisiana oyster leases were non-productive, held "for no other purposes than the expectation that income from oil and gas activities will be forthcoming" (p. 27). In Virginia, Beckensteiner, Kaplan, and Scheld (2020) report that although rates of lease use increased from 2006 to

2016, only 33% of leases were ever used for oyster production and about 63% of leaseholders reported no commercial harvests. Non-productive leases may be less of an issue in some states such as Maryland that have a "use it or lose it" provision.

Given all of the above, it is not surprising that the yields per acre reported in the literature span a wide range. It should also be noted that estimates in the literature are scarce, and we summarize these yields in Table 1. Keithly and Kazmierczak (2006) report yields on leased acreage in Louisiana at 15.5 sacks (23.25 US bushels) per acre in the 1960s and 3-4 sacks (5-13 U.S. bu.) per acre circa 2000. Using survey data for Chesapeake Bay, Meritt and Webster (2019) estimate a bay-wide average potential harvest of 186 bushels (242 U.S. bu.) per acre relying on natural set of oyster spat. With hatchery spat-on-shell plantings, however, they estimate potential harvest yields between 884 and 1767 bushels (1,151 and 2,302 U.S. bu.) per acre. Melancon (1990), who tracked individual bedding operations in Lower Barataria Bay, Louisiana, reports yields between 694 and 1092 sacks (1,041 and 1,638 U.S. bu.) per acre. These yields are likely at the upper end of the range, as this appears to be short-term bedding ranging between 17 and 40 weeks from bedding to harvest. Other authors (Burrage, Posadas, and Veal 1991; Posadas, Burrage, and Homziak 1990) report yields ranging between 125 and 284 sacks (199 and 452 U.S. bu.) per acre from individual relaying operations in Mississippi and Alabama . In addition, yield estimates based on statewide data and total acreage tend to be much lower than those based on individual-level observations, adding credence to the argument that many oyster leases are unproductive.

Beckensteiner, Kaplan, and Scheld (2020) provide the most thorough analysis of oyster yields to date. These authors report two sets of estimates. First, they compile statewide landings and leased acreage data from twelve states and calculate yields, which range from less than 1 U.S. bu. per acre in New Jersey to over 90 U.S. bu. per acre in Massachusetts. However, data were not differentiated by production method, and yields are generally higher for states whose production is dominated by intensive off-bottom container culture and lower for states dominated by extensive bottom production. As a direct comparison, their estimate of Louisiana's yield is roughly the same as that of Keithly and Kazmierczak (2006). The second set of estimates in Beckensteiner, Kaplan, and Scheld's (2020) focuses on leased acreage in Virginia. In this detailed analysis, they remove what they perceive to be unproductive acreage and estimate Virginia's leased acreage yield to be just under 30 bushels (42 U.S. bu.) per acre, compared to less than 1 U.S. bu. per acre based on statewide data.

Other sources of yield information come from papers that assume certain production levels rather than observing them. For instance, Parker, Lipton, and Harrell (2020) assume a yield of 1,091 bushels (1,421 U.S. bu.) per acre for leased bottom culture in Maryland, but also conduct a sensitivity analysis to obtain yields ranging between 273 and 1,309 bushels (356 and 1,705 U.S. bu.) per acre. Lappin (2018) analyzes costs and returns of spat-on-shell stocking of public beds by expressing yields as a function of spat survival, and on this basis estimates a range from 578 U.S. bu. per acre (5% survival) to a theoretical high of 15,289 U.S. bu. per acre (100% survival).

An alternative source of productivity and yield information for commercially harvested bottom oyster reefs are annual stock assessments conducted by state agencies. The assessments are generally based on square-meter samples, and oysters are categorized into three class sizes: spat (< 1"), seed (1-3"), and market (> 3"). Louisiana's 2018 stock assessment (LDWF 2020), for example, implies potential yields of market-sized oysters between zero and 193 sacks (290 U.S. bu.) per acre, with a mean of 7.7 (11.6 U.S. bu.). The Virginia Oyster Stock Assessment and Replenishment Archive (VIMS 2020) reports market-size oysters ranging from zero to 152 bushels (212 U.S. bu.) per acre across 8 reefs between 1998 and 2019. As harvest methods (dredging, tonging, and hand-harvest) are not generally 100% efficient, these estimates should represent an upper bound on harvested yield. Because stocks assessments are conducted on public seed grounds, these numbers offer an informative comparison with harvest estimates from private leases. Considering all the factors listed above, the mean yield may be in the single digits, for instance, when all non-productive acreage is included, but average yields on more productive acres may be more likely in the neighborhood of 200 sacks (300 U.S. bu.), with considerable spatio-temporal variation.

Production and harvest cost can vary greatly depending on the specific production method used in bottom production, as discussed earlier. Table 1 reports harvest cost estimates obtained from the literature. All dollar values are adjusted to 2019 dollars using the Implicit Price Deflator for GDP (2012 = 100, Bureau of Economic Analysis 2020). Again, the literature is thin, and estimating harvest cost appears to be as challenging as estimating yields. The literature varies in terms of units used to report costs (per acre, per bushel/sack harvested, etc.). We have attempted to convert all cost estimates to a per-acre basis, using either individual author assumptions or our own assumptions as indicated in the table footnotes. Parker, Lipton, and Harrell (2020) and Parker (2019) report the results of multiple enterprise budgets that vary by lease size and financial arrangements (based on the same production assumptions cited for these papers in the previous section). Total costs over 10 years range from $900,000 for a five-acre lease to $8.6 million for a 100-acre lease. We calculated the implied annualized cost estimates using Parker's (2020a) online cost analysis spreadsheet, and found cost to range from about $12,767 to $26,553 per acre. Other estimates found in the literature generally report or imply costs per acre between $1,017 and $19,750 (Burrage, Posadas, and Veal 1991; DePiper, Lipton, and Lipcius 2017; Kazmierczak and Keithly 2005; Keithly and Kazmierczak 2006; Melancon 1990; Melancon and Condrey 1992; Mykoniatis and Ready 2017; Posadas, Burrage, and Homziak 1990). Lappin (2018) reports an annual cost of $92,456 for production of remote spat-on-shell required to cover 1 acre of ground in 1 inch of shell cultch. This estimate is likely an outlier, but does point to a potential key difference in cost due to the purchase of spat. It appears that in Louisiana oystermen harvest seed from public grounds at no cost and/or rely on natural recruitment, whereas many private oystermen along the Atlantic coast purchase spat-on-shell.

Off-Bottom Aquaculture

Intensive off-bottom aquaculture generally involves growing out of oysters on leased acreage in containers (cages or mesh bags) where oysters are kept off the bottom, and is often referred to as off-bottom culture or container culture. Growers generally rely on triploid oysters, a sterile, hatchery-produced oyster that grows faster, but is more expensive. The production process generally involves the purchase of seed from a hatchery that is stocked in mesh bags, cages, or trays. As they grow, oysters are sorted and moved into larger containers. Oysters may need to be dried or cleaned periodically to prevent/control fouling by elevating them out of the water. Oysters may also be put through a tumbler periodically to improve shape.

Yield per acre for off-bottom aquaculture is a function of several variables, including mortality from seed to harvest, stocking density per container, and number of containers per acre. Published information on off-bottom aquaculture yields appears to be extremely limited. Parker, Lipton, and Harrell (2020) and Parker (2019) calculate a yield of 100,000 oysters per acre assuming 200,000 spat per acre with 50% mortality. Grice and Walton (2019) report Alabama's 2018 off-bottom harvest at 1,921,586 oysters. They further note that Alabama had at least 64 acres permitted, with at least 37 acres in production, implying a yield range between 30,025 and 51,935 oysters per acre. Other state situation and outlook reports (e.g., New Jersey, Virginia) do not report acreage, making calculation of yields infeasible. The off-bottom budgeting tool published by the Alabama Seafood Marketing Commission assumes as default values a yield of 100,000 oysters per acre for a representative 2-acre operation (2020), assuming 10% mortality. Williamson, Tilley, and Campbell (2015) report yields of 618,672 and 784,410 oysters per acre in an on-bottom cage operation in Tar Bay and a floating raft operation in the Choptank River in Maryland, respectively. Terry et al. (2018) write that they "have seen examples of farmers with a 4-acre lease growing around 5 million oysters, while others with leases well over 10 acres are growing fewer than a million animals" (p. 6). Under the liberal assumption that all are harvest-size, these numbers imply a range from less than 100,000 to as many as 1.25 million oysters per acre. They also write that a "million oysters will fit on a single acre if you can get 23 oysters per square foot of surface area" (p. 7).

Information on off-bottom aquaculture production cost is also limited. Parker, Lipton, and Harrell (2020) and Parker (2019) provide the most detailed coverage of off-bottom production costs to date. They report the results of multiple enterprise budgets that vary by lease size and financial arrangements (with the same underlying production assumptions as discussed in the previous section). Total costs over 10 years range from $2.2 million for a 5-acre farm producing 500,000 oysters annually to $6.7 million to produce 2.5 million oysters annually. We calculate the implied annualized cost estimates using Parker's (2020b) online cost analysis spreadsheet, and find annual cost per acre to range from about

$59,580 to $195,663. Wieland (2007) reports costs for bottom cages between $64,085 and $76,851, and for floating cages between $72,469 and $83,510 to produce 1 million market-size oysters, implying per-oyster costs between $0.06 and $0.08. Wieland notes that "estimates do not include capital carrying costs or maintenance costs (except in replacement) and, perhaps most importantly, they do not capture the cost of either a boat or a facility at which to dock a boat and maintain equipment and gear" (p. 6). Lipton (2007) reports costs from the 2003-2005 Virginia Seafood Council trials between $0.28 and $0.30 per oyster, and his own simulations yield cost estimates as low as $0.15 per oyster, but as high as $0.30 if management costs are included.

Non-Harvested Reefs

This category covers two broad uses of oysters. The first is intertidal living shorelines, which generally consist of rock or concrete structures on which oysters are expected to recruit. These structures are generally built linearly, the main purpose of which is shoreline protection, but with other ecosystem services expected. Harvest is not generally feasible nor typically allowed by regulation. The second type is preserved or restored subtidal oyster reefs, called "sanctuary reefs", on which harvest might be feasible, but is typically prohibited. The main purposes of these reefs are to serve as a larval source for nearby harvested reefs and to provide other ecosystem services. Although these represent two very different uses of oysters, likely with different levels of ecosystem services, both are non-harvested, and because of this, for our purposes, stand more in contrast to commercial bottom and off-bottom production than they do to each other. The most likely difference between the two non-harvested reefs with regard to ecosystem services is shoreline protection; living shorelines are designed specifically for this purpose, whereas subtidal restored reefs may or may not provide any such benefit. Thus, the shoreline protection benefits attributed to this category may be overestimated if attributed to all non-harvested reefs.

We collected cost information for 25 oyster-based living shorelines projects completed across the U.S. Gulf Coast between 2005 and 2018. The length of the restored reefs ranged from 125 feet to 17,210 feet among projects, with total cost ranging from $6,600 to $15 million. The cost per constructed foot ranged from $9 to $3,220 (2019$), with a mean of $699 and a median of $312. Maintenance cost information was not available.

Additional sources of cost information include costs of constructing other types of living shorelines. Allen (2019) reports cost estimates ranging from a low of $75 per constructed foot for living shorelines using bags of oyster shells (although other sources indicate the difficulty of sourcing shell; see GSMFC 2012; Stokes et al. 2012; LDWF 2004), to $350 using granite rock. SAGE (2015) provides estimates for a variety of living shoreline types, including $1,000-2,000 per constructed foot when featuring vegetation only, edging, and/or sills, plus $100 per foot of annual maintenance. For breakwaters, which in some cases, may be more similar to a restored oyster reef when its design includes rock or concrete structure, they report costs between $5,000 and $10,000 per constructed foot, with annual maintenance of over $500 per foot.

Knoche et al. (2020) reports the project cost of three reef restoration projects in Chesapeake Bay. Cost per acre ranges from a low of $65,909 per acre to $84,085 per acre. Converting the aforementioned range of $9-$3,220 per constructed foot for living shorelines to a per-acre basis, assuming a 3.28 foot (1 meter) width, we obtain a range between $119,494 and $42.76 million per acre, with a mean of $9.28 million. These estimates suggest that oyster reef restoration costs fall at or below the lower end of the range of living shoreline costs.

Ecosystem Service Values

Nutrient Reductions

There are at least three approaches to monetizing nutrient reductions. The first derives from prices observed in a nutrient credit trading program. To the extent that these payments reflect the preferences of resource users, such payments represent reliable value estimates. The nutrient offset program in North Carolina, for example, has made payments ranging between $8 and $138 / lb N (NC-DEQ 2020). The second approach is the stated preference valuation method, by which one asks resource users directly about their willingness to pay for nutrient reductions (e.g., Interis and Petrolia 2016). This valuation method is challenged by the possible disconnect between the metric used to elicit household preferences, which may often be expressed in qualitative terms to facilitate understanding by a lay audience (e.g., "better water quality"), and the objective measure of the change in water quality (e.g., lbs. N reduced). Papers such as Johnston et al. (2012) have attempted to move the valuation literature toward using metrics that are both preference-relevant and ecologically meaningful. The third and what appears to be the most commonly-used method among the ecosystem services literature is the replacement/avoided cost method, whereby the per-unit value of nutrient reduction is based on the per-unit cost of such reduction using the next best alternative technology. For example, if the next best alternative to removing nutrients via oysters is a wastewater treatment facility (WWTF), then the per-unit cost of operating the facility would be used to estimate the benefit of nutrient removal by oysters as it represents the benefit of not having to operate the WWTF. Yet, there are at least two caveats with the replacement/avoided cost approach. On the one hand, it will underestimate the true value if resource users value nutrient reduction more highly than the cost of the next-best alternative. On the other hand, it will overestimate the true value if the next-best alternative provides benefits other than reduction of the nutrient in question. For example, if a WWTF also removes phosphorus, sediment, and potentially harmful bacteria and chemicals, then its operating cost probably does not reflect the benefit of nitrogen removal only.

Table A1 of the Appendix contains a summary of nitrogen reduction values from the literature, all converted to $/lb N reduced, removed, or assimilated, in 2019 dollars. The values come from a variety of sources, including nutrient credit trading programs and replacement/avoided costs for other methods of nitrogen removal. Values range between $3 and $3,273 / lb N, and interestingly, both ends of the range are associated with the cost of planting agricultural cover crops. Generally, however, values associated with agricultural practices tend to be in the lower end of the range, whereas urban practices and those addressing erosion and sediment issues tend to be in the upper end. Values associated with WWTFs lie under $50 / lb N. Importantly, there does not appear to be consensus in terms of which part of the range is most applicable to shellfish; the correct value is likely site-specific, depending on the magnitude of nutrient concentration at the site and the next-best alternative available for reduction.

Of the papers specifically focused on an economic analysis of oysters, Mykoniatis and Ready (2016) assume a value of \$5.31 / lb N removed; Grabowski et al. (2012) use \$14.39 / lb N removed, based on the average nitrogen trading price for estuarine sites in the North Carolina Nutrient Offset Credit Program at the time they did their study. Kasperski and Weiland (2009) rely on the mean value reported by Newell et al. (2005) of \$12.91 / lb N removed. Parker and Bricker (2020) consider a range of values from \$3.19 to \$2,210.36 / lb N removed, but note that in a market-based trading program the value will be at the lower end of this range. Knoche et al. (2020) rely on a range of values from \$8.80 to \$44.00 / lb. N removed. Weber et al. (2016) examine the potential for nutrient credit trading programs to expand oyster aquaculture in Maryland under a range of values from \$10.62 / lb N to \$201.75 / lb N removed.

Shoreline Protection

Similar to nutrient reduction, there appears to be two types of metrics on which to base shoreline protection values. The first approach is to base it on user / landowner willingness to pay (WTP) to curtail erosion. The literature is thin on estimates of WTP for reduced erosion. Existing estimates apply hedonic pricing methods to real estate transaction data to estimate the contribution of beach width to sales price. Landry and Hindsley (2011) estimate an effect of beach/dune width on coastal property sales between \$16 and \$60 per foot of shoreline width. Gopalakrishnan et al. (2011) report a much larger estimate, with the sales price of an average ocean-front property increasing by \$8,800 per foot of beach width.

The second approach is to base values on the replacement/avoided cost method. The latter is the approach followed by Grabowski et al. (2012), where the replacement alternative is the cost of building bulkheads. Bulkheads are generally built for the sole purpose of erosion control, and landowners may perceive them to be more reliable as well as providing better water access than living shorelines. Recent research has shown that restored oyster reefs have the potential to be equally or even more efficient than bulkheads at reducing shoreline erosion over the long term (Morris et al. 2018, 2019). However, to the extent that landowners may perceive bulkheads to be more effective at reducing shoreline erosion and to provide better water access in comparison with oyster reefs, bulkhead construction costs will overestimate the true value of shoreline protection benefits. Cost estimates for bulkheads range between \$125 and \$250 per constructed foot for wooden bulkheads, $150-$275 for vinyl bulkheads, and $500-$1000 for concrete bulkheads or seawalls (personal communication with Eric Sparks, Mississippi State University, 7/29/2020). SAGE (2015) reports cost estimates for groins and bulkheads between $2,100 and $5,400 per constructed foot with $100-$500 per foot for annual maintenance; for breakwaters, revetments, and seawalls, they report costs between $5,400 and $10,700 per constructed foot, with annual maintenance ranging from $100 to over $500 per foot. Kroeger and Guannel (2014) combine their mean shoreline hardening cost with their estimated magnitude of shoreline protection from reefs to arrive at a mean avoided shoreline armoring cost of $253 / ft, which falls within the range of the estimates compiled.

Fish Habitat

Grabowski and Peterson (2007) rely on National Marine Fisheries Service (NMFS) dockside landings values to estimate benefits associated with 13 fish species whose production was augmented by oyster reefs. Grabowski et al. (2012) rely on these same estimates, adjusted to current dollars. Lai, Irwin, and Zhang (2020) model impacts of restored oyster reefs on commercial and recreational fisheries separately. For commercial fisheries they rely on NMFS landings values to monetize harvest potential, and for recreational fisheries they rely on a single central per-unit value of recreational angler WTP obtained from Johnston et al. (2006) to monetize harvest potential of 14 reef-dependent fish species in Alabama.

Kroeger and Guannel (2014) monetize commercial and recreational fisheries enhancement attributable to oyster reefs for 15 fish species using NMFS dockside landings values and recreational angler WTP estimates from McConnell et al. (1994), EPA (2004), Haab et al. (2009), and Gentner (2009). Their estimates show recreational WTP ranging between $9 and $23 per fish. Knoche et al. (2020) model the impact of reef restoration on fish abundance and harvest potential for 12 commercial species (including oysters) and 3 recreational species. They rely on market prices reported by local dealers for all species except oysters, for which they rely on NMFS landings values.

Monte Carlo Simulation of Costs, Returns, and Ecosystem Benefits

With these ranges and means for each production method in hand, we estimate likely distributions of costs, returns, and ecosystem benefits using Monte Carlo simulation. To do that, we focus on the inputs that appear to have the most uncertainty as shown by the range of values found in the literature. These include bottom and off-bottom production and harvest cost, bottom and off-bottom harvest yield, and levels of the ecosystem services of nitrogen removal, blue crab abundance, and red drum abundance. Although we acknowledge that all inputs have some degree of variability and/or uncertainty, these inputs do appear to bear higher uncertainty in relation to other inputs (e.g. market prices, construction and maintenance cost for non-harvested restored reefs, ecosystem service values, and other underlying assumptions), which we leave at fixed values. Past research has shown that, in cases where variables are calculated from several inputs, the derivation of Monte Carlo simulations for such variables based on the inputs with the most uncertainty is adequate to capture overall uncertainty (Lehrter and Cebrian 2010, Cebrian et al. 2020). Given our thorough compilation of ranges for the inputs as reported in the literature, the distributions depicted by the Monte Carlo simulations should represent a realistic characterization of the magnitude and variability of costs, returns, and ecosystem benefits for each of the three oyster production methods, at least as allowed by the current state of knowledge.

It is reasonable to expect that more productive reefs with higher yields may also tend to have higher levels of other ecosystem services (i.e. larger nutrient reduction, shoreline protection and habitat provision). However, evidence to date about such potential association is scant, and it seems ecosystem service provision may vary widely across similar levels of oyster productivity (Geraldi et al. 2009, Kellogg et al. 2014, Sharma et al. 2016). Consequently, we do not assume any correlations between input values for yield and other ecosystem services. Similarly, we assume no correlations between yields, services, and production and harvest cost inputs.

We assume a triangular distribution for each variable input, which consists of the minimum, maximum, and most likely values. Such values are based on the preceding discussion and summarized in Table 2. We simulate costs, gross market returns, nonmarket benefits, and overall net benefits by drawing a value for each variable input independently each time, and calculating the resulting outcomes. This process is repeated 10,000 times, from which summary statistics and distributions are constructed. We rely on Petrolia et al.'s (2020) expert-derived estimates of the distribution of nitrogen reduction, blue crab abundance, and red drum abundance levels (reported in Table A2 of the Appendix).

Table 3 reports the values of fixed assumptions. Regarding bottom leases, we assume that 10% of bottom harvest goes to the half-shell market at 275 oysters per bushel. The shucked market price is set at $45.33 per bushel, which corresponds to the 2014-2018 landings-weighted implied per-unit price for the Gulf region based on NMFS landings data, in 2019 dollars (see Table A3 of the Appendix). The half-shell price is set at $0.50 per oyster based on data collected from various state situation and outlook reports, summarized in Table A4 of the Appendix.

Ecosystem service levels must be scaled to reflect oyster growth and harvest effects. We arrive at a 67% share of leased bottom that is productive for ecosystem benefits as follows. We assume a 3-year cycle for any given acre such that in the first year there is 1/3 productivity to reflect productivity post-harvest and/or predominantly small oysters; in the second year, there is 2/3 productivity to reflect partial recovery post-harvest and/or predominantly intermediate-size oysters; and in the third year there is full productivity to reflect predominantly full-size oysters prior to harvest. The cycle then repeats itself and, thus, the average productivity is $(1/3 + 2/3 + 1) / 3 = 2/3 \approx 0.67$. We assume no shoreline protection benefits for bottom culture, although we acknowledge that reefs located in close proximity to the shoreline, under the right conditions, could indeed provide such benefits.

For off-bottom aquaculture, we assume the same half-shell price as for bottom leases, although there is evidence that off-bottom culture can fetch higher half-shell prices than bottom culture. We arrive at a 6% share of off-bottom aquaculture that is productive for ecosystem benefits as follows. We assume a representative farm has 100 containers per acre, with each container having 6 3' x 1.5' mesh bags within, implying 100 x 6 x 3' x 1.5' = 2,700 square feet containing oysters per acre. Thus, 6% of a farmed acre (2,700' / 43,560' = 0.06) contains oysters capable of delivering other ecosystem services. Because oyster size is more consistent and growers can restock after harvest more rapidly, we do not make further adjustments for size differences. We assume no shoreline protection benefits for off-bottom aquaculture, although it is possible that some such benefits could accrue.

For non-harvested reefs, we assume a living shorelines reef. Such reefs are generally constructed in terms of length, not area (i.e. linear feet, not acres). Hence, we converted those units into acres for comparison with bottom and off-bottom production. We assume a reef width of 3.28 ft (1 m). Thus, an acre-equivalent of reef has a length of 43,560' / 3.28' = 13,277'. However, a non-harvested reef of this size is still not readily comparable to commercial production; both cost and ecosystem service levels are orders of magnitude higher. Thus, to facilitate comparison, we scale down to one-fourth of an acre, that is, 3,320' x 3.28', as the unit of analysis for non-harvested reefs. Note that this does not bias the comparison, but simply puts input and output values within similar, readily-comparable ranges. To annualize reef construction cost, we assume a 15-year project life. Although annual maintenance costs are possible, we assume none. Because there is no harvest, we assume that, after establishment, there is full productivity potential for other ecosystem services. The percent share of the reef that is productive for ecosystem benefits (67% for bottom cultures; 6% for off-bottom aquaculture; and 100% for non-harvested restored reefs) reflects the percent area in the reef that can produce ecosystem benefits, which by definition are dependent on the occurrence and growth of oysters. Thus, these percent values are used to weight input values.

Some additional assumptions are necessary to reconcile blue crab and red drum abundance levels with harvest potential and market value. We assume that 25% of total abundance is harvest size, and include only this percent toward the derivation of benefits. We assume an average size per individual of 0.33 lbs and 5 lbs for blue crab and red drum, respectively.

We consider enhancement of blue crab and red drum abundance by the three types of reefs as beneficial for both recreational and commercial fishing. However, we choose to use commercial market prices to monetize these benefits. Table 6 reports landings-weighted mean implied per-unit prices of eastern oysters, blue crab, and red drum for each NMFS region based on the agency’s landings data (NOAA 2020). We use the 2014-2018 Gulf region mean. For nitrogen removal, we use the median of all values reported in Table A1 of the Appendix. For shoreline protection benefits, we apply the replacement cost method by using the mean value of the cost of wooden and vinyl bulkheads ($200 per foot constructed).

Simulation Results

Figure 1 displays simulated costs (top left), gross market returns (top right), gross nonmarket benefits (bottom left), and net benefits (bottom right). See table A5 of the Appendix for summary statistics in tabular format. Simulation of costs as shown in the top-left panel of Figure 1 merely restates the cost distributions assumed. The key take-away is that the distribution of bottom production per-acre cost is the narrowest (between $2,000 and $26,500) and lowest among the three resources. The maximum simulated cost for bottom production is $34,000 lower than the minimum simulated off-bottom cost, and is below the 25th percentile of non-harvested reef cost.

The top-right panel of Figure 1 contains the distribution of gross market returns for commercial bottom production and off-bottom aquaculture. Non-harvested reefs are not included. Like costs, gross market returns for bottom production fall within a relatively narrow range compared to off-bottom aquaculture. Bottom production gross market returns range from a low of nearly zero to a high of $52,000 per-acre, with a mean of $20,920, whereas the range for off-bottom aquaculture is from $1,900 to $246,700, with a mean of $106,900.

Gross nonmarket benefits, shown in the bottom-left panel of Figure 1, however, follow the opposite pattern: they are highly variable for bottom production whereas they fall within a relatively narrow range for off-bottom aquaculture and non-harvest reefs. This result reflects the relatively large variability in the magnitudes of the services for bottom production. Nonmarket benefits from bottom production range from a low of $1,000 to a high of $26,330 per acre. Conversely, nonmarket benefits from off-bottom aquaculture is likely to fall within the narrow range between nearly zero and $2,230 per-acre, and those from non-harvested reefs are likely to fall between $11,350 and $13,430 per-acre.

The bottom-right panel of Figure 1 combines all of the above: costs, market returns, and nonmarket benefits, to provide an estimate of overall net benefits. The general picture is that net returns from bottom production are less variable, at least compared to the other resource types, and are likely to yield smaller, but positive, benefits. Non-harvested reefs, however, are likely to yield negative net benefits and off-bottom aquaculture is as likely to yield positive net benefits as it is to yield negative net benefits. Net benefits for bottom culture range between -$15,640 and $65,900 per acre, with a mean net benefit of $19,590. Net benefits from non-harvested reefs range between -$163,460 and $11,300, with a mean of -$60,110; and net benefits from off-bottom aquaculture range between -$182,960 and $169,740, with a mean of -$4,990.

Discussion and Conclusion

To the extent that the assumptions capture the true range of yields, costs, and benefits, the results point to a few key takeaways. First, results imply that the range of benefits accruing from commercial bottom production may be less variable, at least in dollar terms, than either intensive off-bottom aquaculture or constructed non-harvested reefs. This is not at all to say that oysterman involved in bottom production face less risk, but simply that the likely range of dollars returned per unit of operation falls into a narrower range. Additionally, the results indicate that, on average, we expect bottom production to have a positive return, whereas off-bottom aquaculture is just as likely to have a negative as it is to have a positive return. Off-bottom aquaculture has higher per-unit costs, but also higher per-unit revenues; the extent to which a given farm will have positive net returns depends on whether they are able to keep costs and mortality down, and find buyers willing to pay premium prices for their oysters.

Regarding non-harvested reefs, the results indicate that they are most likely going to yield negative net benefits. Market benefits drive the results here, dwarfing nonmarket benefits (compare the range of values in the bottom-left panel of Figure 1 to that of the top-right panel). So, given that there is no harvest of such reefs, they must rely on nonmarket benefits to justify their use, at least economically. First, it is likely that they provide benefits not accounted for here, but likely so do bottom and off-bottom production. It is possible that they provide them at levels greater than that of the other resource types that could swing the results in the other direction. See Alleway et al. (2018) for a discussion along these lines. Acknowledging these limitations, the more obvious point here is that non-harvested reefs are expensive. Comparing the three types on a per-acre basis (recall that non-harvested reefs were scaled down in the main analysis to 1/16 of an acre for ease of comparison), estimated construction of non-harvested reefs is an order of magnitude higher than off-bottom aquaculture, with a mean cost of over $1 million per acre compared to $113,000 per acre, and two orders of magnitude higher than that of bottom production ($13,689). Previous work has been right to tout the many benefits of non-harvested reefs, but it generally does not account for cost; thus, it does not make clear the fact that these benefits come with a big price tag. To the extent that construction costs can be reduced for such endeavors, such projects will look more favorably relative to other harvest-based systems.

That said, non-harvested reefs have been demonstrated to provide benefits that bottom harvest and off-bottom aquaculture have not, particularly shoreline protection benefits, in the case of living shorelines. They can also serve as an undisturbed source of larvae for harvested reefs, if they are situated in close enough proximity for larvae to reach those reefs. Most bottom production relies on some sort of seed plantings, either purchased or provided by public seed grounds, so these reefs have the potential to offset some of the costs associated with such efforts.

We recognize that there are sub-categories within each of our three production categories, where costs may be correlated with returns. Within commercial bottom production, some producers invest in cultch and/or spat on shell with the expectation of greater returns. Within off-bottom aquaculture, some farmers lower stocking densities and increase labor inputs, again with the expectation of greater farmgate value. Within non-harvested reefs, some currently productive reefs may be conserved at relatively low cost, while restoration projects require greater investment to acquire the desired benefits. The paucity of data on costs and returns, however, precludes us from analyzing these subcategories explicitly with confidence. At the same time, our combining of these subcategories does not alter most of the overall message. For example, the distribution of bottom production costs lies well to the left of that of off-bottom production; assuming one sub-category or the other would not change that. Similarly, the distributions of gross market returns and overall gross benefits for bottom production and restored reefs lie at the lower end of those of off-bottom production; again, assuming one sub-category or the other would not change the overall comparison much. In short, a better understanding of these correlations as well as the frequency distribution of each sub-category would certainly improve simulated annual net benefits. The limitations of current data do not allow this more detailed analysis, but that there are still valuable lessons to learn from the broader analysis.

At the end of the day, these three types of oyster resources, operating in harmony likely yield a diversity of benefits while vulnerable to different risks and obstacles. The present work has taken the very preliminary step in estimating what the relative differences are in terms of benefits and costs, so that we can make more informed decisions regarding the resource tradeoffs involved in oyster production and management.

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Table 1. Yield, Cost, and Return estimates for commercial bottom production.

Source	Location	Harvest Yield (units / ac)	Harvest Yield (US bu / ac)	Cost per unit (nominal)	Unit	Cost / ac (nominal)	Cost / ac (2019$)
Parker, Lipton, Harrell (2020) / Parker (2019)	MD	745 bu / ac[1]	970[8]	$928,053[13]	5-ac lease, 10 yrs	$26,553	$26,553
				$1,331,050[13]	10-ac lease, 10 yrs	$19,301	$19,301
				$2,138,272[13]	20-ac lease, 10 yrs	$15,685	$15,685
				$8,579,570[13]	100-ac lease, 10 yrs	$12,767	$12,767
Meritt and Webster (2019)	MD	186 bu[2]	242[8]				
		884-1767 bu[3]	1,151-2,302[8]				
Lappin (2018)	AL	578-15,289 bu[4]	548-14,483[9]	$90,872[14]	acre	$90,872	$92,456
DePiper, Lipton, Lipcius (2017)	MD			$150.22	cubic m	$2,253[18]	$2,348
Mykoniatis and Ready (2016)	MD/VA			$18,600	acre	$18,600	$19,750
Grabowski and Peterson (2007)	NC	243-647 bu[5]	317-843[10]				
Lipton (2007)	MD			$37.58-81.00[15]	bu		
Keithly and Kazmierczak (2006)	LA			$7.84[16]	sack	$1,568[19]	$1,956
Weiland (2006)	MD/VA			$16.60-29.76/bu[17]	bu		
Kazmierczak and Keithly (2005)	LA			$5.32-$6.38	sack	$1,064-$1,276[19]	$1,367-$1,640
Melancon and Condrey (1992) / Melancon (1990)	LA	74-815 sacks[6]	111-1,223[11]	$3,745	acre	$3,745	$6,608
Burrage, Posadas, and Veal (1991)	MS	284 sacks[7]	451[12]	$13.03	sack	$3,694	$6,305
Posadas, Burrage, and Homziak (1990)	MS	125 sacks[7]	199[12]	$4.61-$16.76	sack	$576-$2,095	$1,017-$3,697
		264 sacks[7]	420[12]	$7.38-$19.84	sack	$1,950-$5,244	$3,441-$9,253

[1] Personal communication with Matt Parker, August 27, 2020

[2] With natural spat production

[3] With planted seed

[4] Harvest potential under theoretical seed survival rates

[5] Harvest potential of subtidal reefs using data from oyster reef restoration projects in North Carolina

[6] Bedding operation, from public seed ground to private leases.

[7] Relaying operation; costs include dredging, planting, monitoring, and harvesting.

[8] Converted using 1 MD bu = 1.3025 US bu

[9] 200 oysters/bu reported; converted using MD bu-equivalent: (200/275)*1.3025

[10] Maryland bushel conversion applied to North Carolina.

[11] Converted using 1 LA sack = 1.5 US bu

[12] Converted using 1 MS sack = 1.5911 US bu

[13] Author's calculation based on information reported for scenario "conventional funds without nutrient payments".

[14] Yearly costs for production of remote set spat on shell required to cover 1 acre of ground in 1 inch of shell cultch.

[15] Low estimate for hatchery diploid seed, high estimate for wild diploid seed.

[16] Authors state "Cost represents variable costs associated with harvesting only, hence, significantly underestimates total costs associated with growing and producing oysters" (p. 24).

[17] Estimates reported in Lipton (2008); low estimate is for shaft tonging and high estimate is for dredging.

[18] Calculated using $/m3 x 0.05 m3/bu x 300 bu/ac.

[19] Calculated using 200 sacks/ac.

Table 2. Triangular distribution parameters for variable inputs used during simulation.

		Most Likely	**Min**	**Max**	**Units**
Bottom Production	Cost	$12,500	$2,000	$26,500	$ / ac
	Yield	200	0	1000	bu/ac
	Nitrogen	104.09	5.95	297.39	lbs N / ac (scaled)
	Blue Crab	123.65	0.00	562.06	lbs / ac (scaled)
	Red Drum	12.37	0.00	224.83	lbs / ac (scaled)
Off-bottom Aquaculture	Cost	$80,000	$60,000	$200,000	$ / ac
	Yield	150,000	0	500,000	#/ac
	Nitrogen	8.57	2.93	24.89	lbs N / ac (scaled)
	Blue Crab	31.35	0.00	62.71	lbs / ac (scaled)
	Red Drum	1.57	0.21	2.09	lbs / ac (scaled)
Non-Harvested Reef	Cost	$699	$9	$3,220	($/linear ft constructed)
	Nitrogen	141.19	44.61	423.79	lbs N / ac (scaled)
	Blue Crab	337.24	0.00	1180.33	lbs / ac (scaled)
	Red Drum	38.78	0.00	168.62	lbs / ac (scaled)

Table 3. Fixed assumptions used in simulation.

Bottom Production	10%	share to half-shell market
	275	oysters / bu
	$45.33	market price, shucked
	$0.50	market price, half-shell
	67%	share of lease productive for ecosystem benefits
Off-bottom Aquaculture	$0.50	market price, half-shell
	6%	share of lease productive for ecosystem benefits
Non-harvested Reef	3.28	reef width (ft)
	13,277.09	reef length (ft)
	15	project life (years)
	100%	share of lease productive for ecosystem benefits
Blue Crab	25%	share of total abundance that is harvest size
	0.33	harvest size weight (lbs)
	$1.47	market price, $/lb
Red Drum	25%	share of total abundance that is harvest size
	5.00	harvest size weight (lbs)
	$2.56	market price, $/lb
Nitrogen	$87.52	$ / lb
Shoreline Protection	$200.00	$ / ft bulkhead constructed (replacement cost)

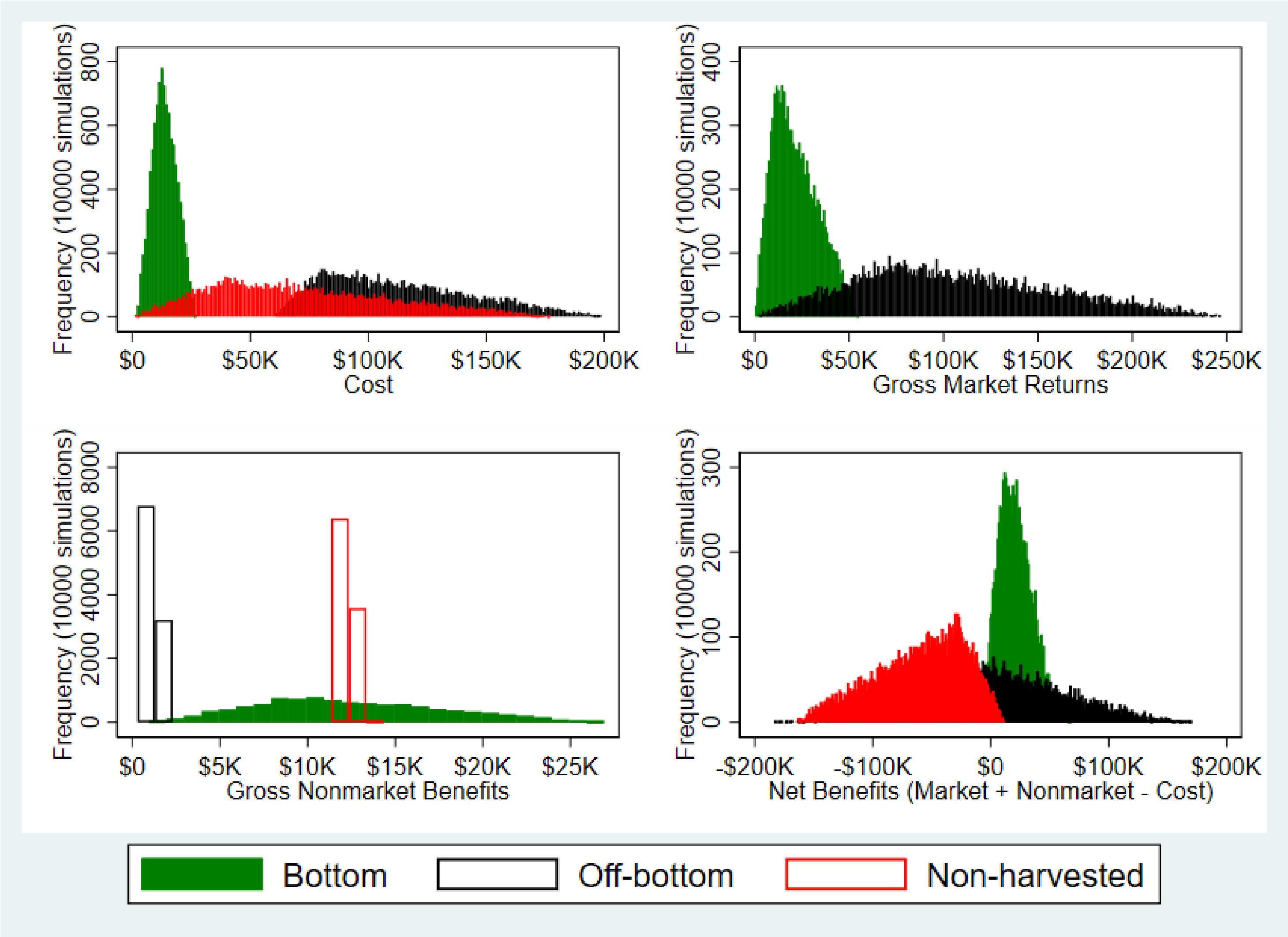

Figure 1. Histograms of simulated annual resource cost (top left), gross market returns (top right), gross nonmarket benefits (bottom left), and net benefits (bottom right) ($1,000 per acre for bottom and off-bottom; $1,000 per 16th of an acre for restored). Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000.

Appendix

Table A1. Reported nitrogen reduction values associated with oysters.

Source	Method	$/lb N (2019$)
Flood (2019)	Manure removal	$5.84
	Cover crops	$7.10
	Conversion to riparian forest	$9.74
	Wetland restoration	$13.70
	Grassland buffers	$14.10
	Connect to sewer systems	$161.30
	Bioretention gardens	$526.32
Merrill et al. (2020)	Sewer cost	$108.86-$234.96
NC DMS Nutrient Offset Program (2019)	range, 2014-2018 payments	$8.28-$138.31
Newell et al. (2005)	EPA Chesapeake Bay Program	$14.03
	cover crops	$2.68
	erosion and sediment control	$728.64
Parker (2019)	nutrient payment for oysters	$3-$100
Piehler and Smyth (2011)	NC trading program	$6.75
Pollack et al. (2013)	WWTP in Back River, MD	$4.17
Rose et al. (2014)	WWTP in Connecticut River Basin	$13.01-$40.11
	Agricultural BMPs	$24.93-$3035.24
	Urban BMPs	$396.75-$2401.09
Stephenson et al. (2010)	ag, early cover crops	$30.39-$3272.94
	ag, crop to forest conversion	$30.39-$549.39
	ag, reduced fertilizer application	$9.35-$63.12
	urban, wet pond	$447.69-$763.3
	urban, Stormwater wetland	$100.53-$496.79
	urban, Bioretention area	$63.12-$427.82
	urban, Sand filter	$2428.99-$2589.13
	urban, Septic retirement	$38.57-$654.59
Van der Schatte Olivier (2018)	WWTF	$2.86-$8.83
Weber et al. (2018)	nutrient payment for oysters	$10.17-$193.31
Mean		**$387.05**
Median		**$87.52**
Min		**$2.68**
Max		**$3,272.94**

Table A2. Median, minimum, and maximum ecosystem service quantities reported in Appendix B of Petrolia et al. (2020).

		Median	**Min**	**Max**
Net N Assimilated	**Bottom**	17.50	1.00	50.00
g N / m2	**Off-bottom**	15.50	5.30	45.00
	Non-Harvested	15.82	5.00	47.50
Blue Crab Abundance	**Bottom**	0.55	0.00	2.50
# / m2	**Off-bottom**	1.50	0.00	3.00
	Non-Harvested	1.00	0.00	3.50
Red Drum Abundance	**Bottom**	0.06	0.00	1.00
# / m2	**Off-bottom**	0.08	0.01	0.10
	Non-Harvested	0.12	0.00	0.50

Table A3. Implied landings-weighted mean dockside prices by region.

		Landings-weighted Mean Implied Prices (2019$)				
		Gulf	**South Atlantic**	**Middle Atlantic**	**New England**	**Pacific Coast**
Eastern oyster	**2018**	$50.22	$92.58	$82.85	$292.57	
$ / bu*	**2014-2018**	$45.33	$78.78	$78.87	$303.39	
	2009-2018	$36.50	$60.44	$73.63	$304.96	
Blue crab	**2018**	$1.46	$1.30	$1.46	$2.66	$1.46
$ / lb	**2014-2018**	$1.47	$1.29	$1.59	$2.67	$1.47
	2009-2018	$1.28	$1.10	$1.41	$2.13	$1.28
Red drum	**2018**	$2.46	$2.72	$2.59		
$ / lb	**2014-2018**	$2.56	$2.70	$2.11		
	2009-2018	$2.40	$2.32	$1.97		

* Based on NOAA's 10:1 shell:meat ratio and 80-lb bushel weight.

Table A4. Reported off-bottom farmgate prices, acreage, and yields.

							Market Price, $/each (2019$)				
State	**Year**	**# Responses**	**Harvest (#)**	**Acres**	**Type**	**Market Share**	**Mean**	**Mode**	**Min**	**Max**	**Source**
AL	2018	13/22	1,921,586	37-64	Wholesale		$0.47	$0.51	$0.31	$0.71	Grice and Walton (2019)
VA	2017	47	38,900,000		All	>90% wholesale	$0.43				Hudson (2018)
NJ	2016	19	2,029,500		Wholesale	81%	$0.66		$0.37	$0.74	Calvo (2018)
					Direct	19%	$0.97		$0.70	$1.06	
NJ	2015	10	1,782,000		Wholesale	79%	$0.67		$0.20	$0.91	Calvo (2017)
					Direct	21%	$0.86		$0.43	$0.93	
NJ	2014	10	1,627,669		Wholesale	98%	$0.65		$0.33	$0.81	Calvo and Flimlin (2016)
					Direct	2%			$0.92	$1.08	
VA	2011	44	23,300,000		All		$0.34		$0.19	$0.57	Murray and Hudson (2012)

Table A5. Summary statistics of simulated costs, returns, and nonmarket benefits per-acre for bottom culture and off-bottom aquaculture and per 1/16-acre for non-harvested reefs, in $1,000.

	Resource Type	**Mean**	**S.D.**	**Min**	**25th**	**Median**	**75th**	**Max**
Cost	Bottom Production	$13,689	$5,048	$2,023	$9,960	$13,378	$17,366	$26,114
	Off-bottom Aquaculture	$113,000	$30,851	$60,730	$87,472	$108,224	$134,612	$198,630
	Non-harvested Reef	$72,341	$38,287	$984	$41,657	$66,713	$99,153	$176,393
Gross Market Returns	Bottom Production	$21,755	$11,734	$43	$12,296	$19,934	$30,061	$54,085
	Off-bottom Aquaculture	$106,901	$51,951	$1,900	$67,424	$100,652	$143,148	$246,706
Gross Nonmarket Benefits	Bottom Production	$12,414	$5,299	$931	$8,442	$11,806	$16,155	$26,496
	Off-bottom Aquaculture	$1,115	$410	$294	$796	$1,058	$1,409	$2,242
	Non-harvested Reef	$12,231	$437	$11,353	$11,888	$12,168	$12,531	$13,445
Gross Benefits	Bottom Production	$34,169	$12,927	$4,928	$24,263	$32,750	$43,230	$79,051
	Off-bottom Aquaculture	$108,016	$51,949	$2,349	$68,671	$101,927	$144,113	$247,703
	Non-harvested Reef	$12,231	$437	$11,353	$11,888	$12,168	$12,531	$13,445
Net Benefits	Bottom Production	$20,480	$13,944	-$15,505	$10,208	$19,306	$30,005	$67,986
	Off-bottom Aquaculture	-$4,984	$60,535	-$182,956	-$48,742	-$8,261	$36,982	$169,755
	Non-harvested Reef	-$60,111	$38,293	-$163,442	-$86,886	-$54,419	-$29,491	$11,311