Oyster Economics: Simulated Costs, Market Returns, and Nonmarket Ecosystem Benefits of Harvested and Non-Harvested Reefs, Off-Bottom Aquaculture, and Living Shorelines

Short Title: Oyster Economics

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Abstract: We simulate expected costs, market returns, and nonmarket ecosystem benefits associated with four oyster resources: harvested bottom reefs, off-bottom aquaculture, non-harvested (restored) reefs, and living shorelines. Benefit categories include market returns from harvest, improved water quality (reduced nitrogen), habitat for other species (blue crab and red drum), and shoreline protection. Bottom reefs and off-bottom aquaculture yield both market returns and nonmarket ecosystem benefits, whereas non-harvested reefs and living shorelines yield only nonmarket ecosystem benefits. Overall gross benefits are expected to be greater and much more variable for off-bottom aquaculture and living shorelines relative to harvested and non-harvested reefs. We find that harvested bottom reefs, off-bottom aquaculture, and living shorelines are expected to yield positive net benefits more often than not, but that non-harvested restored reefs are expected to yield positive net benefits only 36% of the time. We discuss the uncertainty and limitations surrounding these estimates.

Keywords: blue crab, ecosystem services, erosion, harvest, nitrogen, red drum, shoreline protection, shellfish

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Introduction

Oyster reefs provide a variety of ecosystem services beyond commercial harvest, including nitrogen removal and habitat for other fish species (Fodrie et al. 2017; Grabowski et al. 2012; Humphries and La Peyre 2015; Kellogg et al. 2014; Piehler and Smyth 2011; Smyth, Geraldi, and Piehler 2013). Off-bottom oyster aquaculture, which is a relatively new practice, can do likewise (Alleway et al. 2019; Barrett, Swearer, and Dempster 2019; Callier et al. 2018; DeAlteris, Kilpatrick, and Rheault 2004; Gentry et al. 2020; Miller 2009; Petrolia et al. 2020; Sardenne, Forget, and McKindsey 2019; van der Schatte Olivier et al. 2020). Non-harvested reefs, including preserved or restored subtidal "sanctuary reefs" and intertidal "living shorelines", expand oyster habitat, act as a source of larvae, and provide shoreline protection, all in addition to providing the aforementioned ecosystem services (Meyer, Townsend, and Thayer 1997; Piazza, Banks, and La Peyre 2005; Scyphers et al. 2011; Parker and Bricker 2020).

Several papers have monetized the benefits provided by oysters (Anderson and Plummer (2017); Barrett et al. 2022; DePiper, Lipton, and Lipcius 2017; Interis and Petrolia 2016; Kasperski and Weiland 2009; Knoche et al. 2020; Kroeger and Guannel 2014; Lai, Irwin, and Zhang 2020; Miller 2009; Mykoniatis and Ready 2016; Parker and Bricker 2020; Stephenson and Shabman 2017), with Grabowski et al. (2012) being the most comprehensive analysis to date. All of this work has been critical to building up our understanding of the variety of ecosystem services provided by oysters, but there is no clear understanding of how these benefits differ among production methods. In fact, in many of the cited cases, details regarding production specifics are unclear. We are aware of no work attempting to combine cost, market return, and nonmarket ecosystem benefit information into one unified analysis, including commercially harvested bottom reefs, off-bottom aquaculture, living shorelines, and restored reefs.

This paper presents the results of a simulation of diverse oyster (Eastern oyster, *Crassostrea virginica*) production systems dominant in the U.S. Atlantic and Gulf Coasts to identify and compare their likely ranges of costs, returns, nonmarket ecosystem benefits, and net benefits. Better data about the relative costs, market returns, and ecosystem benefits positions resource managers and industry members to make better informed, more holistic decisions for oyster resource management.

Oyster Resource Types

Bottom Reefs

"Bottom reefs" refers to commercial harvest of wild or seeded oysters from the sea floor. Commercial harvest varies by region; it may take place on public harvest grounds, as in Apalachicola Bay, Florida, or on private leases, as is typical in Maryland. Louisiana has both public and leased grounds. 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. 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) may be planted directly onto the bottom grounds. For the purposes of this analysis, we assume a production system typical of a commercial bottom lease in Louisiana, which is likely to involve cultch planting.

Off-bottom aquaculture

Intensive off-bottom aquaculture generally involves growing out of oysters on leased acreage in containers where oysters are kept off the bottom, and is also referred to as off-bottom culture or container culture. Although it has existed for a long time, oyster aquaculture has experienced rapid growth recently (Botta et al. 2020). 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.

Living shorelines

Living shorelines are intertidal constructed reefs, which generally consist of rock or concrete structures on which oysters are expected to recruit. Living shorelines are generally constructed in terms of length, but their reef habitat is often described in terms of length or area. The main purpose of living shorelines is shoreline protection, but with other ecosystem services expected. Harvest is not generally feasible nor typically allowed by regulation.

Non-Harvested Restored reefs

These are preserved or restored subtidal oyster reefs, sometimes 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. These reefs are typically described in terms of area, i.e., acres restored or enhanced. We refer to these simply as "restored reefs" throughout the manuscript.

Methods

We model potential present-value costs, market returns, nonmarket ecosystem benefits, and net returns on a per-acre-equivalent basis over a 20-year period for the four aforementioned oyster resource types using Monte Carlo simulation. The following sections describe the key data inputs and assumptions. All dollar values are adjusted to 2019 dollars using the Implicit Price Deflator for GDP (2012 = 100, BEA 2020). Yields are reported in native units (e.g., sacks or local bushels), with the U.S. bushel equivalent reported in parentheses.

Costs

Table 1 reports the fixed input values for the simulation, and Tables 2 and 3 report the variable input values; see Table A1 of the Appendix for the formulas. For bottom production, we rely primarily on Kazmierczak and Keithly (2005), who surveyed harvesters of private oyster leases in Louisiana. They provide mean, standard error, median, and range for all data. We rely on their values for lugger (boat) and other equipment purchase prices, diesel usage, and crew hours. We assume triangular distributions for these variables, applying their range for minimum and maximum, and the median as the peak value of the distribution. We use the wage rates, insurance cost, marketing costs, retail container cost for oysters bound for the half-shell market, and overhead rate from Parker, Lipton, and Harrell (2020). We take 2010-2021 observed diesel prices from EIA (2021), and find that a unform distribution provides a very good fit for these data (Figure 1, top-left panel; for all variables where data series are available, distributions are overlaid on histograms). We assume annual repair costs are 3% of the total capital purchase amount. Capital costs for bottom reefs, which includes the purchase of a lugger (20-year life) and other harvest equipment (10-year life) are incurred in Years 0 and 11 (other equipment only). Operating costs are incurred in Years 1-20.[1]

Parker, Lipton, and Harrell (2020) provide the most detailed coverage of off-bottom production costs to date, on which we rely heavily. We allow number of cages per acre to vary between 10 and 250, with 100 the most likely number (triangular distribution). We assume a final stocking density of 333 oysters per bag, and 6 bags per cage, which, for 100 cages, implies an initial purchase of 199,800 seed per acre. We calculate repair cost as noted above. Capital costs for off-bottom aquaculture, which includes the purchase of a boat, truck, and other harvest equipment (all 10-year life) are incurred in Years 0 and 11, and new mesh bags are purchased every five years. Operating costs are incurred in Years 1-20.[2] We follow Parker, Lipton, and Harrell (2020) for remaining parameters.

We base living shoreline and restored reef costs on data collected on 89 completed and planned oyster-based living shoreline and 129 restored reef projects along the U.S. Atlantic and Gulf Coasts between 1998 and 2020. Most project information comes from the NOAA Restoration Atlas (NOAA 2021). A few additional projects were identified through The Nature Conservancy project fact sheets (TNC 2021), and contacts at the Alabama Department of Conservation and Natural Resources, NOAA, and Swann (2008). To obtain the relevant projects from the NOAA database, we filtered on those with "shellfish" as the restoration strategy, those with "oyster reef/shell bottom" habitat, and/or those with "oysters" as one of the benefitting species. Constructions costs can vary widely depending on several factors, including site accessibility (barging if access from shoreline is infeasible), engineering fees, permitting costs, substrate (e.g., shell versus concrete structures), whether fill sediment is needed, and whether the project has a marsh building component (personal communication with Eric Sparks, Mississippi State University, 6/23/2021). Project reports included volunteers hours spent, which we added to project cost at $15 per hour.

Projects that had the word "shoreline" in the title as well as any project whose description highlighted shoreline protection benefits were included as a living shoreline project (Figure 1, bottom-left panel). Living shoreline project reef acreage ranged from < 1 to 24 acres, with project cost ranging from $1,715 to $3 million. Cost per acre of oyster habitat constructed ranged from $16,841 to $9.47 million, with a mean of $965,912 and median of $421,503.[3] We find that a lognormal distribution with parameters best fits these data (Figure 1, bottom-left panel). Construction costs are incurred in Year 0 only; no maintenance costs are included.

Projects that did not qualify as a living shoreline project were categorized as a restored reef project (Figure 1, bottom-right panel). Project reef acreage ranged from < 1 to 303 acres, with total project cost ranging from $11,227 to $5.91 million. The cost per constructed acre ranged from $295 to $21.6 million, with a mean of $799,536 and a median of $164,662.[4] We find that a lognormal distribution best fits these data (Figure 1, bottom-right panel). Restored reef construction costs are incurred in Year 0 only; no maintenance costs are included.

Harvest Yields

Estimating yields for extensive bottom harvest is challenging. Several factors, including whether production relies on natural recruitment or hatchery seed planting; the estuarine environment, which is inherently unpredictable; and the grow-out period, which 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). Estimates in the literature are scarce. 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 recruitment, and 884-1,767 bushels (1,151-2,302 U.S. bu.) per acre with hatchery spat-on-shell plantings. Melancon (1990), who tracked individual bedding operations in Lower Barataria Bay, Louisiana, reports 694-1,092 sacks (1,041-1,638 U.S. bu.) per acre. Other authors (Burrage, Posadas, and Veal 1991; Posadas, Burrage, and Homziak 1990) report 125-284 sacks (199-452 U.S. bu.) per acre from relaying operations in Mississippi and Alabama. Parker, Lipton, and Harrell (2020) assume yields ranging from 273-1,309 bushels (356-1,705 U.S. bu.) per acre. Reef assessments conducted by LDWF (2020) and VIMS (2020) imply potential yields of 0-193 sacks (290 U.S. bu.) and 0-152 bushels (212 U.S. bu.) per acre, respectively. Yield estimates based on statewide data and total acreage tend to be much lower than those based on firm-level observations, due to the inclusion of unproductive acres (Keithly and Kazmierczak 2006; Beckensteiner, Kaplan, and Scheld 2020). Yields on more productive acres are more likely in the neighborhood of 200 sacks (300 U.S. bu.), with considerable spatio-temporal variation. Given the limited data on bottom reef yields, we adopt a triangular distribution with parameters 200 (most likely), 0 (minimum), and 750 (maximum) sacks per acre.

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 is limited. Parker, Lipton, and Harrell (2020) 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, with 64 acres permitted and 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. ASMC (2020) assumes a yield of 100,000 oysters per acre for a representative 2-acre operation, assuming 10% mortality. Williamson, Tilley, and

Campbell (2015) report yields of 618,672 and 784,410 oysters per acre in on-bottom cage and floating raft operations 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. Given the limited data on off-bottom yields, we adopt a fixed final stocking density of 333 oysters per bag, a triangular distribution for seed survival-to-harvest rate with parameters 0.75 (most likely), 0 (minimum, in case of mortality event), and 1 (maximum); a fixed number of 6 bags per cage; and a triangular distribution for cages per acre with parameters 100 (most likely), 10 (minimum), and 250 (maximum). Under the 100-cage scenario, these assumptions imply an initial seed rate of 199,800 per acre. Combined, these imply harvest yields of 150,000 (most likely), 0 (minimum), and 499,500 (maximum) oysters per acre.

Market Prices and Ecosystem Service Values

Figure 2 contains mean implied dockside prices for Louisiana-landed oysters and landings-weighted mean prices for all landings of blue crab 2000-2019, based on NOAA Fisheries (2021) commercial landings data. NOAA Fisheries oyster landings data contain both wild bottom-harvested oysters bound for the shucked market and off-bottom farmed oysters bound for the half-shell market. Prices in these two markets are very different, where in the former one pays by the sack and in the latter one pays by the oyster. Given that Louisiana landings are most likely bound for the shucked market and that Louisiana has, historically, accounted for half of all U.S. landings of Eastern oysters, we argue that Louisiana provides the purest shucked market price signal. Given the nearly-monotonic increases in oyster prices over the past 20 years, we argue that the most recent prices are the most likely to be observed whereas the oldest prices are the least likely. Accordingly, we construct a triangular distribution that has the 2019 (maximum observed) value as both the peak and the maximum, and has the oldest (and generally the minimum observed) price as the minimum. We assume that 10% of bottom harvest goes to the half-shell market, whereas 100% of off-bottom harvest goes to the half-shell market (see Table 1). Although enhanced blue crab and red drum abundance is beneficial for both commercial and recreational fishing, we choose to monetize blue crab benefits using commercial market prices only. Red drum is primarily a recreational species, with commercial catch limited to small amounts in only a handful of states. We rely on Rhodes et al. (2018) for the estimated range of values for red drum.[5] Similar to the case of oysters, red drum prices have increased nearly monotonically over the past 20 years, so we construct a triangular distribution in the same manner as that of oysters. Because blue crab prices have fluctuated over this same period, we fit a triangular distribution to the observed prices. For nutrient removal benefits, we rely on observed payments made in the North Carolina nutrient offset program, 2010-2021 (Figure 1, top-right panel; NC-DEQ 2021).[6] Payments range between $8.28 and $149.82 per lb. N, but less than 5% of payments exceed $35. We find that a triangular distribution fits the data well when the outliers are excluded, with parameters $18 (most likely), $7 (minimum), and $35 (maximum).

For shoreline protection, a service we attribute to living shorelines only, we use avoided cost of bulkhead construction as a reasonable proxy to monetize this benefit. Cost estimates for bulkheads range $125-$360 per constructed foot for wooden bulkheads, $125-$389 for vinyl bulkheads, and $616-$916 for sheet pile bulkheads (Webb et al. 2019; personal communication with Eric Sparks, Mississippi State University, 7/29/2020).[7] We rely on Webb et al.'s reported median values for the various bulkhead types to define a triangular distribution with parameters $163 (lower value, median cost of vinyl bulkhead), $332 (most likely value, median cost of a wooden bulkhead with toe protection), and $766 (upper value, median cost of a sheet pile bulkhead). We convert these per-foot values to a per-acre basis as follows: we assume a reef width of 15 feet, implying a length of 2,904 feet, for a total area of 43,560 square feet (1 acre). Thus, an acre of living shoreline reef will protect 2,904 feet of shoreline, though the level of performance is uncertain. Webb et al. (2019) rates the wave attenuation and erosion-reducing performance of living shorelines and reefs as "medium / some benefit" (as compared to "none", "low / minimal benefit", and "high / significant benefit"). We interpret this rating to mean that perhaps 25-50% of the cost of bulkheads can be avoided with the use of living shorelines. However, some living shorelines could also be described a breakwaters, which Webb et al. rate as "high / significant benefit", which we interpret to mean that upwards of 75% of bulkhead cost can be avoided. We adopt a triangular distribution with parameters 25% (lower bound), 50% (most likely), and 75% (upper bound) to capture the uncertainty in shoreline protection performance. Thus, the shoreline protection value assigned to an acre of living shoreline is the avoided per-foot bulkhead cost multiplied by 2,904, multiplied by the performance rate.

Ecosystem Services

Ecosystem service levels used for nitrogen reduction, blue crab abundance, and red drum abundance levels come from Petrolia et al. (2020), which reports the distributions of estimates given by a panel of 38 oyster experts from the Atlantic and Gulf Coast regions regarding ecosystem service provision by various oyster resource types (see further details, including conversions, in Appendix Table A2).

Ecosystem service levels must be scaled to reflect the proportion of resource area actually containing oysters and providing services. We adopt Parker, Lipton, and Harrell's assumption that 80% of a bottom lease's area is productive (the remaining area serves as a buffer). We estimate that 6% of an off-bottom aquaculture acre is productive for ecosystem benefits, assuming a representative farm has 100 containers per acre, with each container having 6 3 ft x 1.5 ft mesh bags within, implying 100 x 6 x 3 ft x 1.5 ft = 2,700 ft^2 containing oysters per acre (2,700 ft / 43,560 ft = 0.06). We assume that 100% of the areas of a living shoreline and a restored reef are capable of producing ecosystem services.

Of particular importance to analyzing the ecosystem services provided by bottom reefs are the questions of whether a natural reef existed prior to entering commercial production and whether harvest has a deleterious impact on other ecosystem services. If a reef existed prior to production, then any services provided by it should not be credited as a new benefit. If, however, the reef was constructed where no prior reef existed (at least in recent decades), then the associated ecosystem services should be credited as new benefits. Regarding harvest impacts, it is reasonable to expect that oyster harvest would result in some reduction of other ecosystem services, given that the reef is being disturbed and oysters are being removed. Evidence to date about such potential associations is mixed, however, with some work indicating that ecosystem service provision may vary widely across similar levels of oyster productivity (Geraldi et al. 2009, Kellogg et al. 2014, Sharma et al. 2016), and other work indicating that harvest has at least some deleterious impacts on reefs (Beck et al. 2011; Breitburg et al. 2000; Lenihan and Micheli 2000; Lenihan and Peterson 1998, 2004; Lenihan et al. 1999). To address these possibilities, we consider four alternative scenarios. For our baseline analysis, we assume that a natural reef existed prior to production and that harvest reduces the level of nonmarket ecosystem services that would have otherwise been provided by 25%, based on Lenihan and Peterson's (1998, 2004) findings that tonging and dredge harvesting reduced reef height by 23-34%. We compare baseline results to those of three alternative scenarios: 1) an existing reef, with a larger, 50% reduction; 2) a new reef, with a 25% reduction due to harvest, such that only 75% of the nonmarket ecosystem services that would have been provided otherwise, are credited; 3) a new reef, with a 50% reduction due to harvest, such that only 50% of ecosystem services are credited.

Correlations and other details

We find that NOAA Fisheries oyster, blue crab, and red drum prices (we rely on commercial red drum prices for this exercise only) and landings are negatively correlated, respectively, and we adopt these estimated correlations directly (see Appendix Table A3). Although we have no data, we assume that a similar relationship must hold, to some extent, for the half-shell market, so we assume a correlation between half-shell prices and off-bottom yields (via seed survival-to-harvest rate) of -0.1. Finally, we impose a correlation of 1 between number of trips taken and diesel use on bottom reefs. All other correlations are set at zero.

We assume a 20-year timeframe for all resource types, based on the typical expected lifespan of a living shoreline (personal communications with Dan Van Nostrand, NOAA (3/5/21) and Judy Haner, TNC (3/8/21)). For each set of simulated values, cost, returns, and benefits over the 20-year period are calculated and discounted to present values using an 8% discount rate. Simulations are conducted 10,000 times.

Results

For discussion of results, we focus on the 99% confidence intervals of the 10,000 simulated observations (i.e., we drop the 50 extreme observations from each tail); see Table A4 for summary statistics for the full set of simulated observations. Figure 3 contains simulation results for present value costs, which merely reiterate the cost distributions assumed. The key take-away is the relative magnitudes and ranges of costs across the four resource types: bottom reef costs over the 20-year period range between $11,674 and $51,145 per acre, with a mean cost of $28,684; off-bottom aquaculture costs range between $251,381 and $408,092 per acre, with a mean of $321,037; living shoreline costs range between $13,966 and $12.250 million per acre, with a mean cost of $883,355; and restored reef costs range between $1,996 and $14,445,580 per acre, with a mean of $633,868.

Figure 4 (top panel) contains the 99% confidence intervals of simulated distributions of present-value gross market returns over the 20-year period for bottom reefs and off-bottom aquaculture. Like costs, gross market returns for bottom reefs fall within a relatively narrow range, between $17,188 and $399,960 per acre, with a mean of $167,136, whereas off-bottom aquaculture gross market returns ranges from $55,166 and $2.387 million, with a mean of $733,921.

Figure 4 (middle panel) contains the 99% confidence intervals of simulated distributions of present-value gross nonmarket ecosystem benefits. Recall that in the baseline simulation that assumes a pre-existing bottom reef, nonmarket benefits are debited against bottom reefs. Nonmarket losses on bottom reefs range between $2,644 and $25,111 per acre, with a mean loss of $10,582. Gross nonmarket benefits are relatively small for off-bottom aquaculture, ranging between $484 and $12,136 per acre, with a mean of $3,790. Gross nonmarket benefits are somewhat greater for restored reefs, ranging between $32,350 and $189,650 per acre, with a mean of $92,104. Gross nonmarket benefits on living shorelines range between $342,422 and $1,159,232 per acre, with a mean of $701,598. Figure 5 breaks down the distribution of gross nonmarket benefits by benefit type. Most of the variation in gross nonmarket benefits for bottom reefs, off-bottom aquaculture, and restored reefs is due to variation in nitrogen removal benefits; blue crab and red drum benefits make relatively smaller contributions. For living shorelines, however, all other benefits are swamped by the variation in shoreline protection benefits.

Figure 4 (bottom panel) contains the 99% confidence intervals of simulated distributions of present-value overall gross benefits, i.e., the sum of market returns and nonmarket benefits. Restored reefs have the lowest mean and least-variable gross benefits, ranging between $32,350 and $189,650, with a mean of $92,104 per acre. Bottom reef gross benefits are next, ranging between $4,502 and $390,885 million, with a mean of $156,520. Off-bottom aquaculture and living shorelines yields much higher mean gross benefits. Living shoreline gross benefits range between $342,421 and $1,159,232, with a mean of $701,598 per acre. Off-bottom aquaculture has the largest range and magnitude, ranging between $56,542 and $2.392 million, with mean gross benefits of $737,739 per acre.

Figure 6 combines all of the above: costs, market returns, and nonmarket benefits, to provide an estimate of present-value overall net benefits. The general picture is that all four resources are capable of yielding positive and negative net benefits, but not with the same likelihood. Off-bottom aquaculture yields the largest mean net benefits ($416,823 per acre) and the largest upper bound ($2.003 million). Off-bottom aquaculture yields positive net benefits 85% of the time, that is, of the 9,900 simulated values, 8,436 are greater than zero. Bottom reefs also yield positive mean net benefits ($127,820 per acre) and have the greatest lower bound (-

$24,841 per acre). Bottom reefs yield positive net benefits 98% of the time. Living shorelines net returns are highly skewed to the left, with negative mean net benefits (-$182,876) but positive median net benefits ($256,595). Living shorelines still yield positive net benefits 66% of the time. Restored reefs net returns are also highly skewed to the left, though both mean and median net benefits are negative (-$541,908 and -$82,857, respectively). Restored reefs yield the lowest lower bound (-$14.359 million), and yield positive net benefits 36% of the time.

Alternative Bottom Reef Scenarios

As discussed earlier, the baseline scenario assumes that a natural reef existed prior to production and that harvest reduces the level of nonmarket ecosystem services that would have otherwise been provided by 25%. Here we compare the baseline to the three alternative scenarios: 1) an existing reef, with a larger, 50% reduction; 2) a new reef, with a 25% reduction due to harvest, such that only 75% of the nonmarket ecosystem services that would have been provided otherwise, are credited; 3) a new reef, with a 50% reduction due to harvest, such that only 50% of ecosystem services are credited.

Figure 7 displays a comparison of baseline and alternative scenario simulations for those bottom reef distributions affected by these assumptions. The top panel compares present-value gross nonmarket benefits. Given the construction of the alternatives, the impacts are straightforward: under the existing reef and larger 50% reduction scenario, gross nonmarket losses would double, from a mean loss of $10,582 to $21,165 per acre. Under the new reef scenarios, gross nonmarket benefits would be positive, with a mean gain of $31,747 per acre under the 75% gain scenario, and $21,165 under the 50% gain scenario.

The middle panel shows the comparison for overall gross benefits: a 50% reduction in services on an existing reef results in a 7% reduction in mean gross benefits relative to the baseline. Mean gross benefits would increase by 27% and 20%, respectively, under the new reef (+75%) and new reef (+50%) scenarios. The bottom panel displays the comparison with regard to overall net benefits. Mean net benefits would decrease by 8% under the existing reef (-50%) scenario, and would increase by 33% and 25%, respectively, under the new reef (+75%) and new reef (+50%) scenarios. Although these are sizable differences, they do not alter substantially the relative comparisons to the other three oyster resource types discussed earlier. More importantly, the differences between the existing reef and new reef scenarios highlight the differences in how ecosystem services should be accounted for depending on the type of bottom production being considered.

Discussion and Conclusion

To the extent that the assumptions capture the true range of costs, returns, and benefits, the results point to a few key takeaways. First, all of the oyster resources considered are expected to deliver benefits, either market returns, nonmarket ecosystem services, or both. Restored reefs and living shorelines yield only nonmarket benefits because harvest is generally not allowed, and although bottom reefs and off-bottom aquaculture yield both market and nonmarket benefits, the lion's share of the benefits accruing from these latter two resources are market benefits. Market returns accruing from off-bottom aquaculture are expected to be greater but also more variable than those of commercial bottom reefs. Nonmarket benefits from living shorelines are expected to be much larger but also much more variable than any other resource.

Taken together, overall gross benefits are expected to be greater and much more variable for both off-bottom aquaculture and living shorelines.

Three of the four resources – harvested bottom reefs, off-bottom aquaculture, and living shorelines -- are expected to yield positive net benefits more often than not, i.e., that their benefits are generally expected to exceed costs. Restored reefs are expected to deliver positive net benefits only 36% of the time. Living shorelines and restored reef costs are highly skewed to the right; of the actual observed projects, the mean living shoreline cost per-acre is more than double the median, and the mean restored reef cost per-acre is almost five times the median. In other words, there is a relatively small number of extremely expensive living shoreline and restored reef projects that are influencing our cost estimates.

In the case of living shorelines, the high costs are often compensated by the benefits, primarily shoreline protection, such that they still yield positive net benefits more than half of the time. We wish to speak to this point now. Our cost estimates are based on 89 NOAA, TNC, or state-funded projects in nine Atlantic and Gulf Coast states. Although we are confident in the cost estimates, the benefits estimates are more tenuous. First, we rely on avoided bulkhead construction costs as a proxy for the value of shoreline protection. Though we are confident in our bulkhead cost estimates, we acknowledge that avoided cost can be a poor substitute for willingness to pay; but better estimates of the value of shoreline protection are hard to come by and are likely very site specific.[8] Further uncertainty exists in how we apply these estimates. We are confident in our assumption, based on Webb et al. (2019), that living shorelines do not eliminate all wave action and erosion, but exactly how much is unknown. It may be that our assumption that living shorelines reduce the need for bulkheads by 25-75% may be too high or too low; but the end result is that in our simulation, living shorelines derive 87% of the value of benefits from shoreline protection. In its absence, our living shoreline results would look much worse, with benefits more similar to that of restored reefs.

Restored reefs generate neither market benefits nor shoreline protection benefits, and combined with high costs, result in negative net benefits three-quarters of the time. Here we note that we exclude cultch planting projects from our restored reef category. Cultch plantings are generally much cheaper, but are usually used to enhance harvested reefs, whereas our restored reef category is intended to be non-harvested. We also note that our analysis does not account for all possible benefit categories that non-harvested reefs can provide, such as acting as a source of larvae for nearby harvested reefs. Including cultch plantings and other benefits would indeed improve the performance of restored reefs.

We also recognize that our resource categories could be broken down further into subcategories. Within commercial bottom production, for example, some producers invest in 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 or enhanced at relatively low cost, while full-scale 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.

In conclusion, these four types of oyster resources, operating together likely yield a diversity of benefits while vulnerable to different risks and obstacles. The present work has taken the preliminary step in estimating what the relative differences are in terms of benefits and costs, so that communities can make more informed decisions regarding the resource tradeoffs involved in oyster production and management. Even with the likelihood that at least some of the quantified values for benefits and costs can be improved, the qualitative results suggest that management strategies that rely too heavily on a single oyster resource are less resilient than those that support multiple oyster resources.

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Table 1. Fixed model parameter definitions and values. Source is Parker, Lipton, and Harrell (2020) unless noted otherwise. (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

Parameter	Description	Value
p_{cage}^{OB}	cage price ($/unit)	$101.40
p_{bag}^{OB}	bag price ($/unit)	$6
p_{seed}^{OB}	hatchery seed price ($/1000)	$17.50
p_{man}^{j}	wage, managerial ($/hr)	$20, j = B, OB
p_{lab}^{j}	wage, general ($/hr)	$12.50, j = B, OB
p_{box}^{j}	retail container price ($/unit)	$1, j = B, OB
c_{truck}^{OB}	truck cost (10–year life) ($/unit)	$15,000
c_{boat}^{OB}	boat cost (10–year life) ($/unit)	$25,000
c_{mark}^{j}	marketing cost ($/year)	$1,000, j = B; $5,500, j = OB
c_{ins}^{j}	insurance cost ($/year)	$3,000, j = B, OB
x_{sack}^{B}	oysters per sack	180 (source: GSMFC 2012)
x_{bag}^{OB}	bags per cage	6
x_{seed}^{OB}	final stocking density per bag	333
x_{hour}^{OB}	hours per week	40
x_{week}^{OB}	weeks per year	52
x_{acre}^{j}	lease acres	20, $j = B$; 5, $j = OB$
l^{LS}	LS length (ft) per acre	2,904 (source: this study)
r_{disc}	discount rate	8% (source: this study)
r_{half}^{B}	share of bottom harvest destined to half-shell market	10%
r_{rep}^{j}	repair cost per year as percentage of capital cost	3%, j = B, OB (source: this study)
r_{over}^{j}	overhead cost per year as percentage of operating cost	5%, j = B, OB
r_{s}^{j}	percent reduction in nonmarket services due to harvest	$j = OB, LS, R$: 0%, $j = B$: 0% (baseline), 50% (source: this study)

Table 2. Simulated prices and costs. (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

Variable	Description	Distribution	Most Likely	Min	Max	Source
p_{shuck}	dockside oyster price, shucked ($/sack)	triangular	$65.20	$21.21	$65.20	1
p_{half}	dockside oyster price, half-shell ($/each)	triangular	$0.51	$0.20	$0.91	2-6
p_{nit}	nitrogen removal value ($/lb)	triangular	$18	$7	$35	7
p_{crab}	dockside blue crab price ($/lb)	triangular	$1.25	$0.94	$1.66	1
p_{red}	red drum value, recreational ($/lb)	triangular	$1.96	$0.64	$3.86	8
p_{shore}	avoided bulkhead construction cost ($/ft)	triangular	$332	$163	$766	9
p_{dsl}	diesel price ($/gal)	uniform		$2.10	$4.67	10
c_{fuel}^{OB}	fuel cost ($/year)	triangular	$3,000	$1,000	$6,000	11
c_{lug}^{B}	oyster lugger cost (20–year life) ($/unit)	triangular	$86,306	$1,028	$385,531	12
c_{eq}^{B}	bottom harvest and other equipment cost ($/unit)	triangular	$20,504	$643	$192,765	12
c_{eq}^{OB}	off-bottom harvest and other equipment cost ($/unit)	triangular	$30,000	$15,000	$40,000	12
C^{LS}	living shoreline construction cost (20–year life) ($/ac)	lognormal	$986,986 (mean)	$2,217,266 (std. dev.)	$0 (location)	13-17
C^{R}	restored reef construction cost (20–year life) ($/ac)	lognormal	$778,338 (mean)	$3,370,192 (std. dev.)	$0 (location)	13

Sources: 1. NOAA Fisheries (2021); 2. Calvo (2017); 3. Calvo (2018); 4. Calvo and Flimlin (2016); 5. Grice and Walton (2019); 6. Hudson (2018); 7. NC-DEQ (2021); 8. Rhodes et al. (2018); 9. Webb et al. (2019); 10. EIA (2021); 11. Parker, Lipton, and Harrell (2021); 12. Kazmierczak and Keithly (2005), 13. NOAA (2021); 14. TNC (2021); 15. personal communication with Judy Haner, TNC (12/18/18, 1/21/21); 16. personal communication with Dan Van Nostrand, NOAA (12/19/18, 3/19/21); 17. personal communication with Ray Eaton, MS-DEQ (12/19/18, 1/30/19)

Table 3. Simulated harvest and ecosystem service levels, and other quantities, all triangular distributions. (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

Variable	Description	Most Likely	Minimum	Maximum	Source
h^B	oyster harvest yield (sacks/ac)	200	0	750	1
s_{nit}^{B}	nitrogen removed (lbs/ac)	125	7	357	1,2*
s_{nit}^{OB}	nitrogen removed (lbs/ac)	9	3	25	1,2*
s_{nit}^{LS}	nitrogen removed (lbs/ac)	7	2	21	1,2*
s_{nit}^{R}	nitrogen removed (lbs/ac)	141	45	424	1,2*
s_{crab}^{B}	blue crab habitat (lbs/ac)	148	0	674	1,2*
s_{crab}^{OB}	blue crab habitat (lbs/ac)	31	0	63	1,2*
s_{crab}^{LS}	blue crab habitat (lbs/ac)	17	0	59	1,2*
s_{crab}^{R}	blue crab habitat (lbs/ac)	337	0	1,180	1,2*
s_{red}^{B}	red drum habitat (lbs/ac)	15	0	270	1,2*
s_{red}^{OB}	red drum habitat (lbs/ac)	2	0	2	1,2*
s_{red}^{LS}	red drum habitat (lbs/ac)	2	0	8	1,2*
s_{red}^{R}	red drum habitat (lbs/ac)	39	0	169	1,2*
s_{shore}^{LS}	shoreline protection performance rate	0.5	0.25	0.75	3
x_{dsl}^{B}	diesel per trip (gal)	30	5	120	4
x_{hour}^{B}	hours per trip	9.5	2	30	4
x_{trip}^{B}	trips per year	30	15	45	1
x_{surv}^{OB}	seed survival–to–harvest rate	0.75	0	1	1
x_{cage}^{OB}	cages per acre	100	10	250	1

Source: 1. This study; 2. Petrolia et al. (2020); 3. Webb et al. (2019); 4. Kazmierczak and Keithly (2005)

* See Table A2 in the Appendix for more details.

Figure 1. Scatterplots and histograms of diesel price, N payments, and cost time series; fitted distributions used during simulation are overlaid on histograms.

Figure 2. Scatterplots and histograms of commercial seafood price time series; fitted distributions used during simulation are overlaid on histograms.

Figure 3. Histograms of simulated present value costs for oyster resource types. Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000.

Figure 4. Histograms of simulated present value gross market returns (top), gross nonmarket benefits (middle), and overall gross benefits (bottom). Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000.

Figure 5. Histograms of simulated present value gross nonmarket benefits, by specific benefit category. Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000. Y-axis indicates frequency out of 10,000 simulations.

Figure 6. Histograms of simulated net present value for oyster resource types. Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000.

Figure 7. Comparisons of baseline bottom reef histograms to alternative scenario histograms for gross nonmarket benefits (top), gross benefits (middle), and net benefits (bottom) Y-axis indicates frequency out of 10,000 simulations. Bin width = $1,000.

Table A1. Cost, return, and nonmarket benefit formulas. (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

Bottom reef: capital costs	$C^B_{Kt} = \begin{cases} \dfrac{c^B_{lug} + c^B_{eq}}{x^B_{acre}\left(1+r_{disc}\right)^t}, t = 0 \\ \dfrac{c^B_{eq}}{x^B_{acre}\left(1+r_{disc}\right)^t}, t = 11 \end{cases}$
Bottom reef: operating costs	$C^B_t = \left\{ \begin{array}{l} \left[\begin{array}{l} p_{fuel}x^B_{fuel}x^B_{trip} + r^B_{rep}\left(c^B_{lug} + c^B_{eq}\right) \\ +\left(p^B_{man} + p^B_{lab}\right)x^B_{hour}x^B_{trip} + c^B_{mark} + c^B_{ins} \end{array} \right] \Big/ x^B_{acre} \\ +\left(p^B_{box}r^B_{half}h^Bx^B_{sack}\right)/100 \end{array} \right\} \dfrac{1+r^B_{over}}{\left(1+r_{disc}\right)^t}, t = 1$
Off–bottom aquaculture: capital costs	$C^{OB}_{Kt} = \begin{cases} \dfrac{\dfrac{c^{OB}_{truck} + c^{OB}_{boat} + c^{OB}_{eq}}{x^{OB}_{acre}} + \left(p^{OB}_{cage} + p^{OB}_{bag}x^{OB}_{bag}\right)x^{OB}_{cage}}{\left(1+r_{disc}\right)^t}, t = 0,11 \\ \dfrac{p^{OB}_{bag}x^{OB}_{bag}x^{OB}_{cage}}{\left(1+r_{disc}\right)^t}, t = 6,16 \end{cases}$
Off–bottom aquaculture: operating costs	$C^{OB}_t = \left[\begin{array}{l} \left[\begin{array}{l} c^{OB}_{fuel} + r^{OB}_{rep}\left(c^{OB}_{truck} + c^{OB}_{boat} + c^{OB}_{eq}\right) \\ +\left(p^{OB}_{man} + 2p^{OB}_{lab}\right)x^{OB}_{hour}x^{OB}_{week} + c^{OB}_{mark} + c^{OB}_{ins} \end{array} \right] \Big/ x^{O}_{acre} \\ +p^{OB}_{box}h^{OB} + p^{OB}_{seed}x^{OB}_{seed}x^{OB}_{bag}x^{OB}_{cage}/1000 \end{array} \right] \dfrac{1+r^{OB}_{over}}{\left(1+r_{disc}\right)^t}, t = 1-20$
Bottom reef: market returns	$R^B_t = \dfrac{p_{shuck}\left(1-r^B_{half}\right)h^B + p_{half}r^B_{half}h^Bx^B_{sack}}{\left(1+r_{disc}\right)^t}, t = 1-20$
Off-bottom aquaculture: market returns	$R^{OB}_t = \dfrac{p_{half}x^{OB}_{seed}x^{OB}_{bag}x^{OB}_{cage}x^{OB}_{surv}}{\left(1+r_{disc}\right)^t}, t = 1-20$
Non–market benefits	$B^j_t = \dfrac{\left(1-r^j_s\right)\left(p_{nit}s^j_{nit} + p_{crab}s^j_{crab} + p_{red}s^j_{red}\right)}{\left(1+r_{disc}\right)^t}, \begin{array}{c} j = B, OB, LS, R \\ t = 1-20 \end{array}$
Living shoreline: nonmarket benefits	$B^{LS}_0 = p_{shore}s^{LS}_{shore}l^{LS}$
PV cost	$C^j = \sum_{t=0}^{20}\left(C^j_{Kt} + C^j_t\right), j = B, OB$
PV gross market returns	$R^j = \sum_{t=1}^{20} R^j_t, j = B, OB$
PV gross non–market benefits	$B^j = \sum_{t=0}^{20} B^j_t, j = B, OB, LS, R$
PV net benefits	$NB^j = R^j + B^j - C^j, j = B, OB, LS, R$

Table A2. Median, minimum, and maximum ecosystem service quantities reported in Appendix B of Petrolia et al. (2020). (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

		Median	Min	Max
x_{nit}^{B}	Bottom net N Assimilated (g N / m2)	17.50	1.00	50.00
x_{nit}^{OB}	Off–bottom net N Assimilated (g N / m2)	15.50	5.30	45.00
$x_{nit}^{LS,R}$	Living shoreline / restored reef net N Assimilated (g N / m2)	15.82	5.00	47.50
x_{crab}^{B}	Bottom blue crab abundance (# / m2)	0.55	0.00	2.50
x_{crab}^{OB}	Off–bottom blue crab abundance (# / m2)	1.50	0.00	3.00
$x_{crab}^{LS,R}$	Living shoreline / restored reef blue crab abundance (# / m2)	1.00	0.00	3.50
x_{red}^{B}	Bottom red drum abundance (# / m2)	0.06	0.00	1.00
x_{red}^{OB}	Off–bottom red drum abundance (# / m2)	0.08	0.01	0.10
$x_{red}^{LS,R}$	Living shoreline / restored reef red drum abundance (# / m2)	0.12	0.00	0.50
		Value		
r_{crab}	harvestable % of crab abundance	25%		
w_{crab}	harvest weight (lbs)	0.33		
r_{red}	harvestable % of red drum abundance	25%		
w_{red}	harvest weight (lbs)	5.00		
r^{B}	% area productive for nonmarket services	80%		
r^{OB}	% area productive for nonmarket services	6%		
$r^{LS,R}$	% area productive for nonmarket services	100%		
s_i^j	$\left.\begin{array}{l} x_i^j w_i r_i r^j \left(4046.86\, m^2/ac\right), i = crab, red \\ x_i^j r^j \left(4046.86\, m^2/ac\right)/\left(453.59\, g/lb\right), i = nit \end{array}\right\} j = B, OB, LS, R$			

Table A3. Correlations used in simulation. (B=bottom reef, OB=off-bottom aquaculture, LS=living shoreline, R=restored reef)

Variable Pair		Corr. Coef.
p_{shuck}	h^{B}	-0.29
p_{half}	x_{surv}^{OB}	-0.10
p_{crab}	s_{crab}^{j}	-0.24 $\forall j = B, OB, LS, R$
p_{red}	s_{red}^{j}	-0.19 $\forall j = B, OB, LS, R$
x_{trip}	x_{dsl}^{B}	1.00

Table A4. Summary statistics of simulated results (N = 10,000).

	Mean	S.D.	Min	Max	99% CI	
				PV Cost ($/ac)		
Bottom reef	$28,718	$8,030	$8,038	$59,307	$11,674	$51,145
Off-bottom aquaculture	$321,140	$35,269	$239,872	$422,177	$251,381	$408,092
Living shoreline	$968,031	$1,933,840	$2,121	$56,562,820	$13,966	$12,249,700
Restored reef	$779,872	$2,951,957	$123	$135,127,400	$1,996	$14,445,580
				PV Gross Market Returns ($/ac)		
Bottom reef	$167,641	$82,984	$2,936	$482,693	$17,188	$399,960
Off-bottom aquaculture	$740,422	$474,305	$3,246	$3,801,759	$55,166	$2,387,453
				PV Gross Nonmarket Benefits ($/ac)		
Bottom reef (baseline, -25%)	-$10,621	$4,501	-$30,606	-$1,187	-$25,111	-$2,644
Bottom reef (-50%)	-$21,243	$9,003	-$61,213	-$2,373	-$50,222	-$5,287
Bottom reef (+75%)	$31,864	$13,504	$3,560	$91,819	$7,931	$75,333
Bottom reef (+50%)	$21,243	$9,003	$2,373	$61,213	$5,287	$50,222
Off-bottom aquaculture	$3,822	$2,252	$198	$15,901	$484	$12,136
Living shoreline	$702,145	$184,917	$290,090	$1,233,815	$342,422	$1,159,232
Restored reef	$92,338	$31,392	$22,585	$238,087	$32,350	$189,650
				PV Gross Benefits (Market + Nonmarket) ($/ac)		
Bottom reef (baseline, -25%)	$157,020	$83,049	-$9,663	$465,329	$4,502	$390,885
Bottom reef (-50%)	$146,399	$83,358	-$29,541	$456,731	-$8,322	$383,569
Bottom reef (+75%)	$199,506	$84,243	$23,892	$534,784	$43,453	$437,984
Bottom reef (+50%)	$188,884	$83,584	$17,771	$517,420	$35,921	$423,743
Off-bottom aquaculture	$744,244	$475,331	$3,540	$3,808,359	$56,542	$2,391,720
Living shoreline	$702,145	$184,917	$290,090	$1,233,815	$342,422	$1,159,232
Restored reef	$92,338	$31,392	$22,585	$238,087	$32,350	$189,650
				PV Net Benefits (Market + Nonmarket - Cost) ($/ac)		
Bottom reef (baseline, -25%)	$128,302	$83,216	-$55,683	$438,555	-$24,841	$359,866
Bottom reef (-50%)	$117,680	$83,525	-$75,260	$430,232	-$38,300	$351,692
Bottom reef (+75%)	$170,787	$84,401	-$23,735	$506,391	$11,549	$409,183
Bottom reef (+50%)	$160,166	$83,744	-$30,277	$489,027	$3,676	$395,032
Off-bottom aquaculture	$423,104	$450,318	-$325,940	$3,389,349	-$228,637	$2,003,178
Living shoreline	-$265,887	$1,943,600	-$56,087,040	$1,165,411	-$11,537,240	$1,009,119
Restored reef	-$687,534	$2,951,783	-$134,973,900	$210,836	-$14,359,330	$149,517

Endnotes

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[1] 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).

[2] 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, noting 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).

[3] Webb et al. (2019) reports a sample of living shoreline (construction material unspecified) costs ranging between $355 and $627, with a median of $491 per linear foot; and for oyster reefs specifically, between $203 and $386, with a median of $294 per linear foot.

[4] See Banks et al. (2016), Callihan et al. (2016), and Knoche et al. (2020) for alternative cost estimates.

[5] Lai, Irwin, and Zhang (2020) and Kroeger and Guannel (2014), and Knoche et al. (2020) account for commercial and recreational impacts separately. Our preferred range of values for red drum are consistent with those reported in the EPA (2006) meta-analysis; they are also similar to commercial landings values (NOAA 2021).

[6] Other estimates used in the literature include Mykoniatis and Ready (2016): $5.31 / lb N; Grabowski et al. (2012): $14.39 / lb N; Kasperski and Weiland (2009): $12.91 / lb N; Parker and

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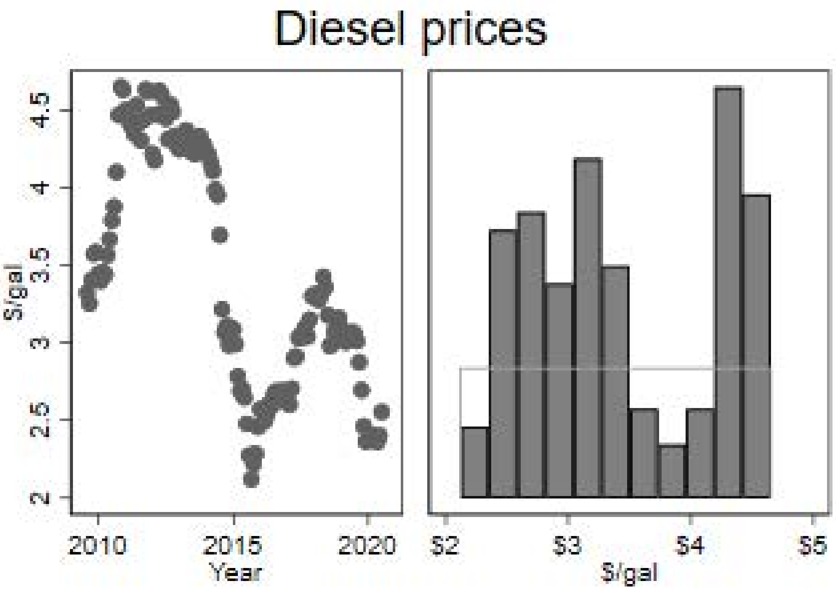
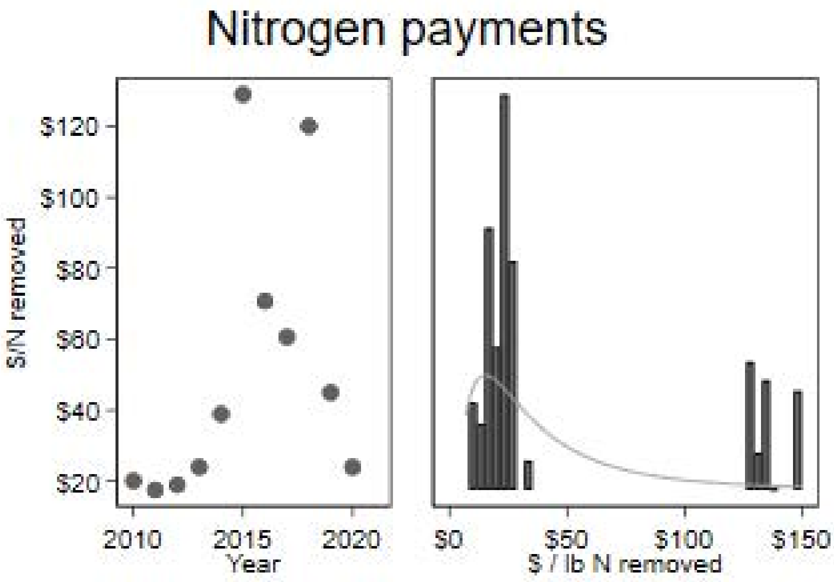
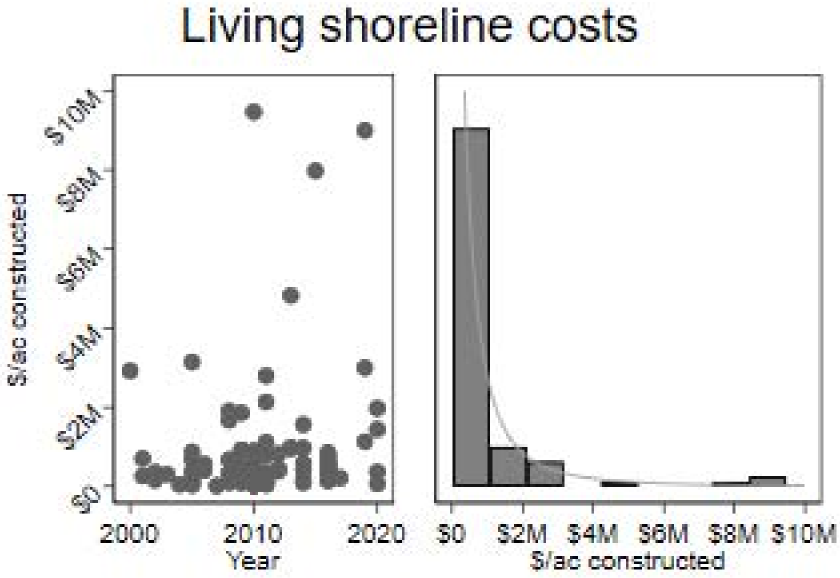
Bricker (2020): \$3.19-\$2,210.36 / lb N; Knoche et al. (2020): \$8.80-\$44.00 / lb. N; Weber et al. (2016): \$10.62-\$201.75 / lb N.

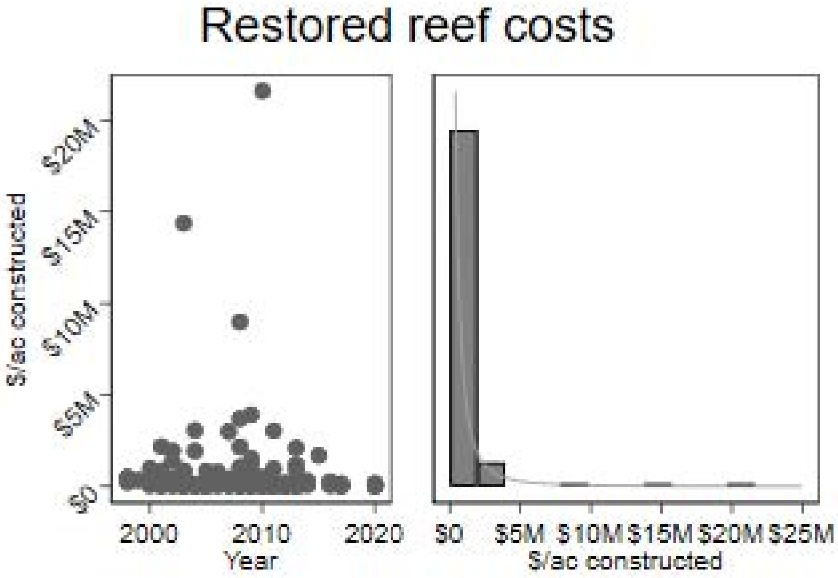
[7] SAGE (2015) reports cost estimates for groins and bulkheads (\$2,100-\$5,400/ft, \$100-\$500/ft annual maintenance); breakwaters, revetments, and seawalls (\$5,400-\$10,700/ft, \$100-\$500/ft annual maintenance). Kroeger and Guannel (2014) report avoided shoreline armoring cost of \$253/ft.

[8] Landry and Hindsley (2011) estimate an effect of beach width on coastal property sales of \$16-\$60/ft of shoreline width; Gopalakrishnan et al. (2011) estimate \$8,800/ft.


Diesel prices


Nitrogen payments


Living shoreline costs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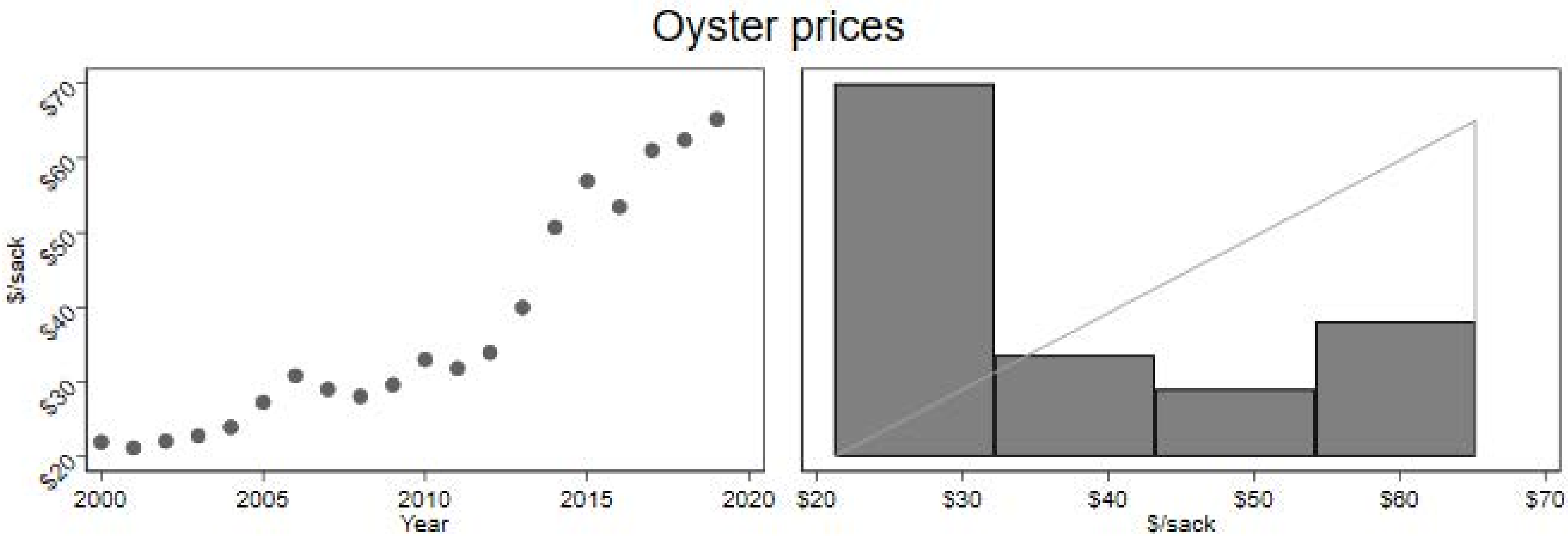
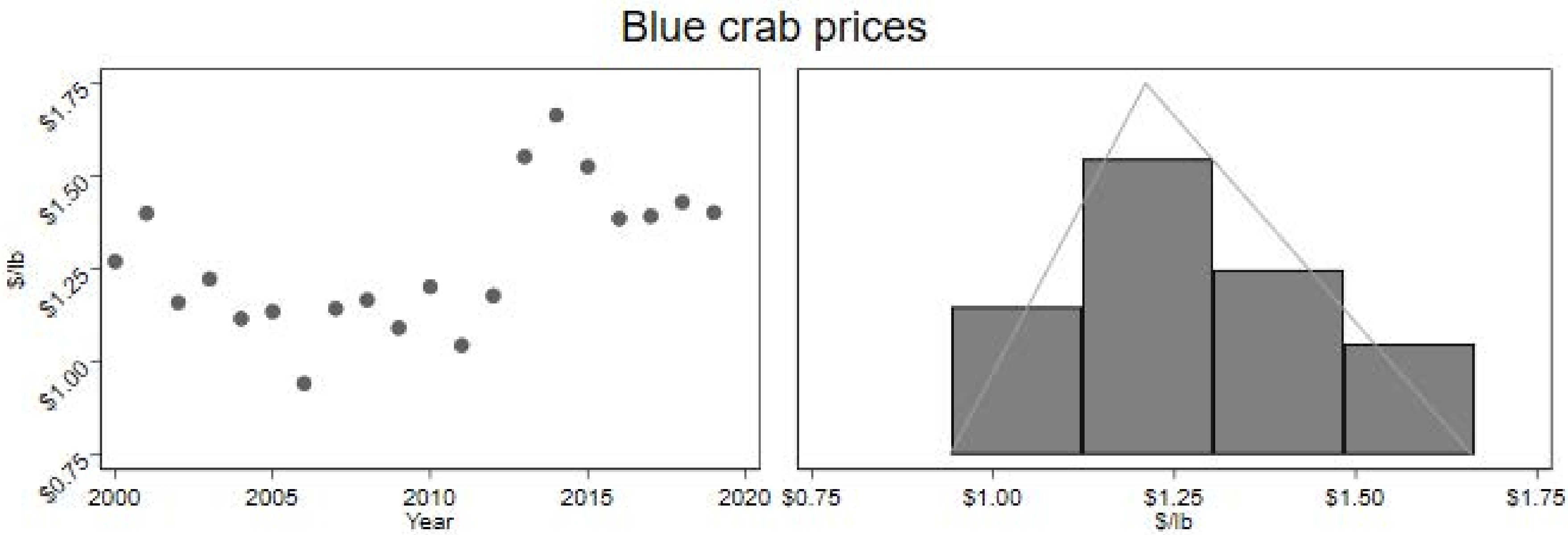
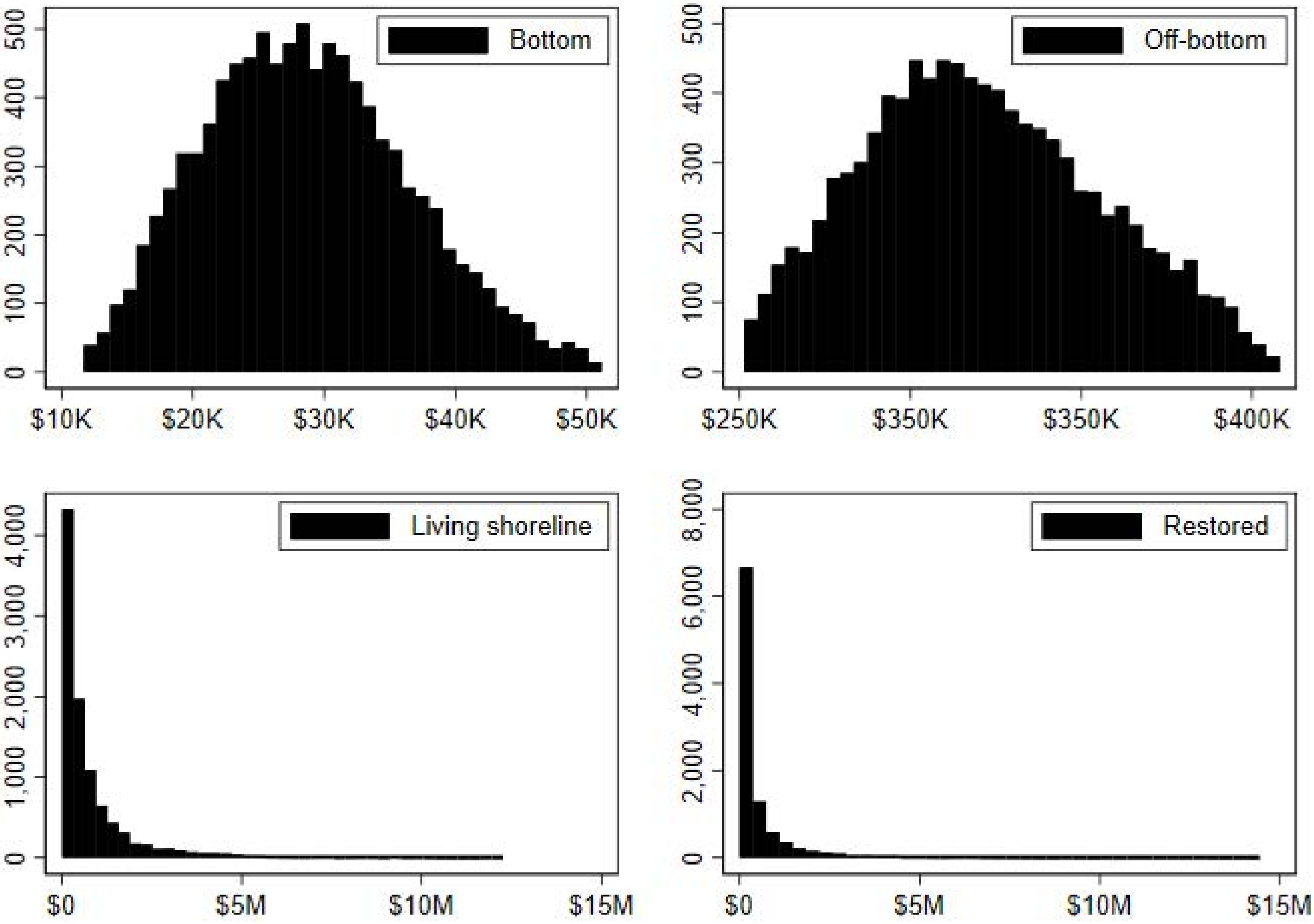
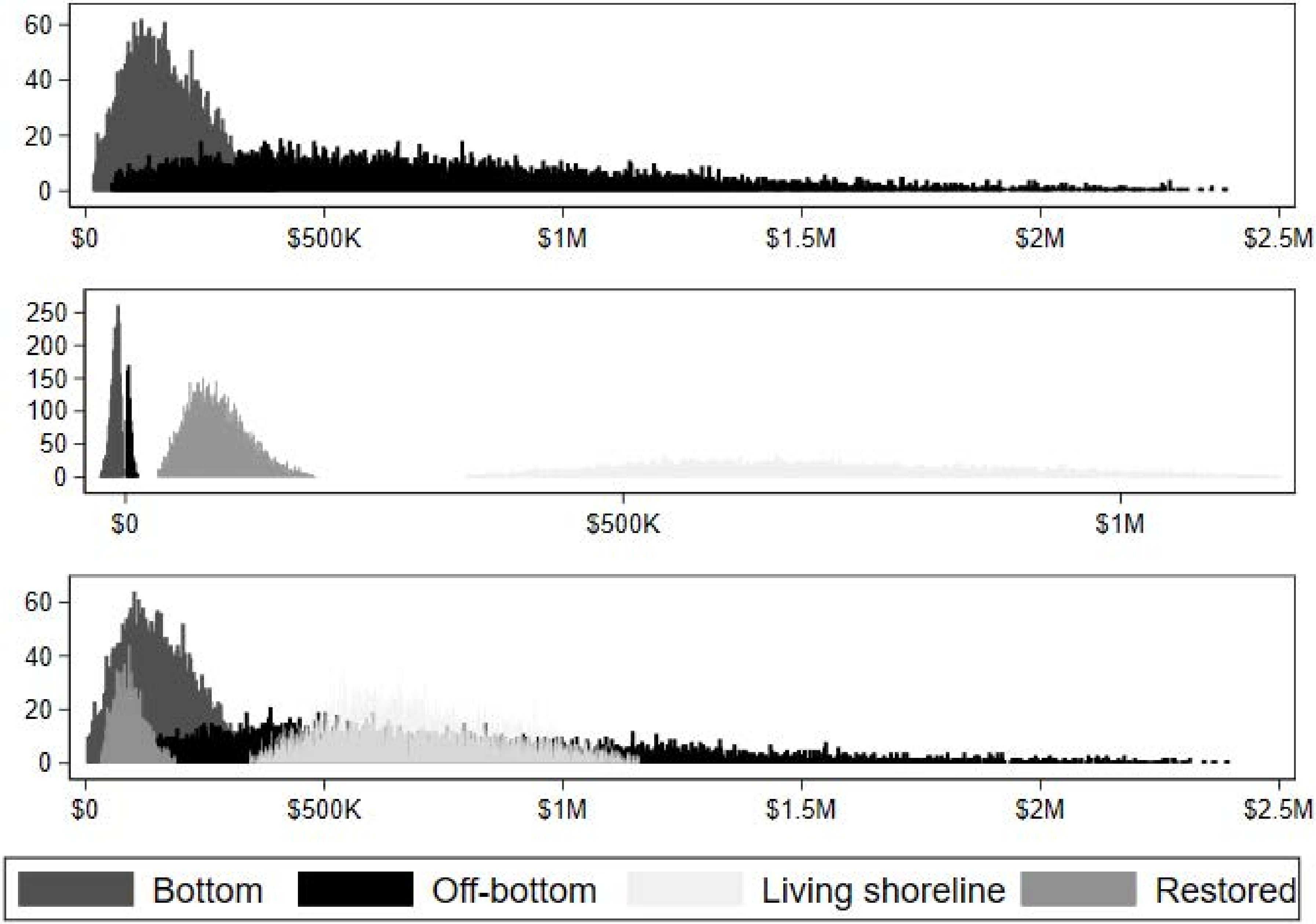


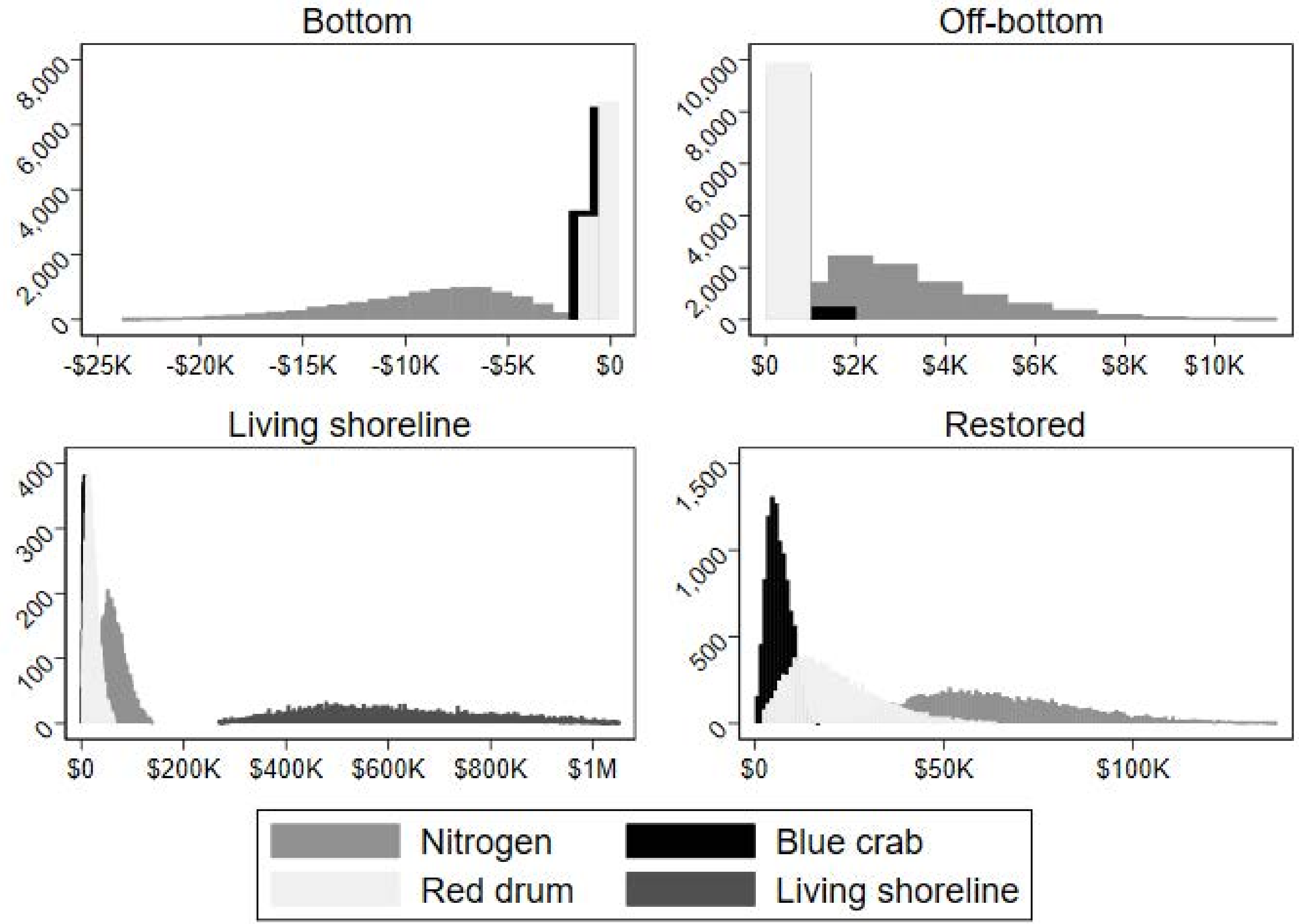
Oyster prices

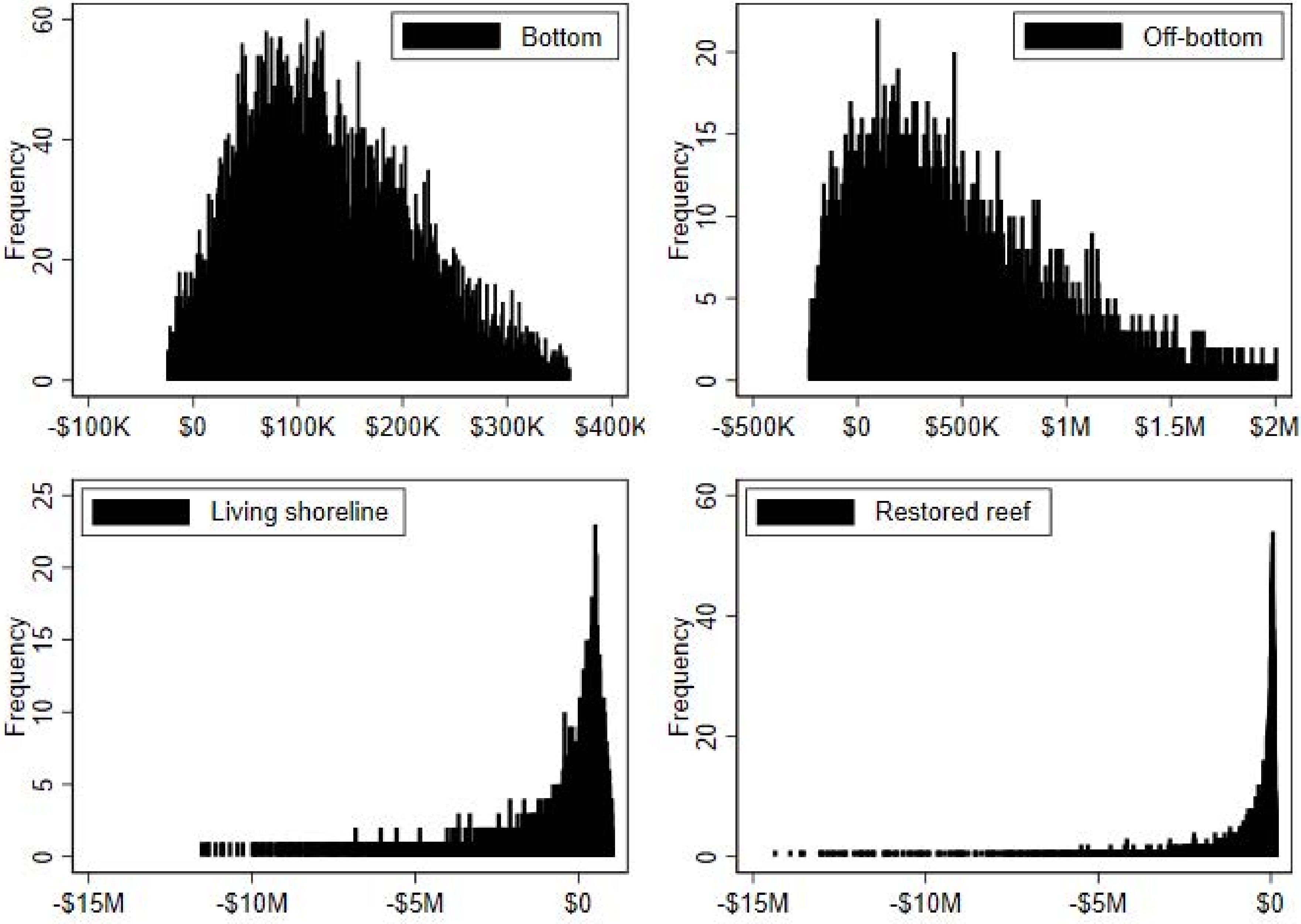


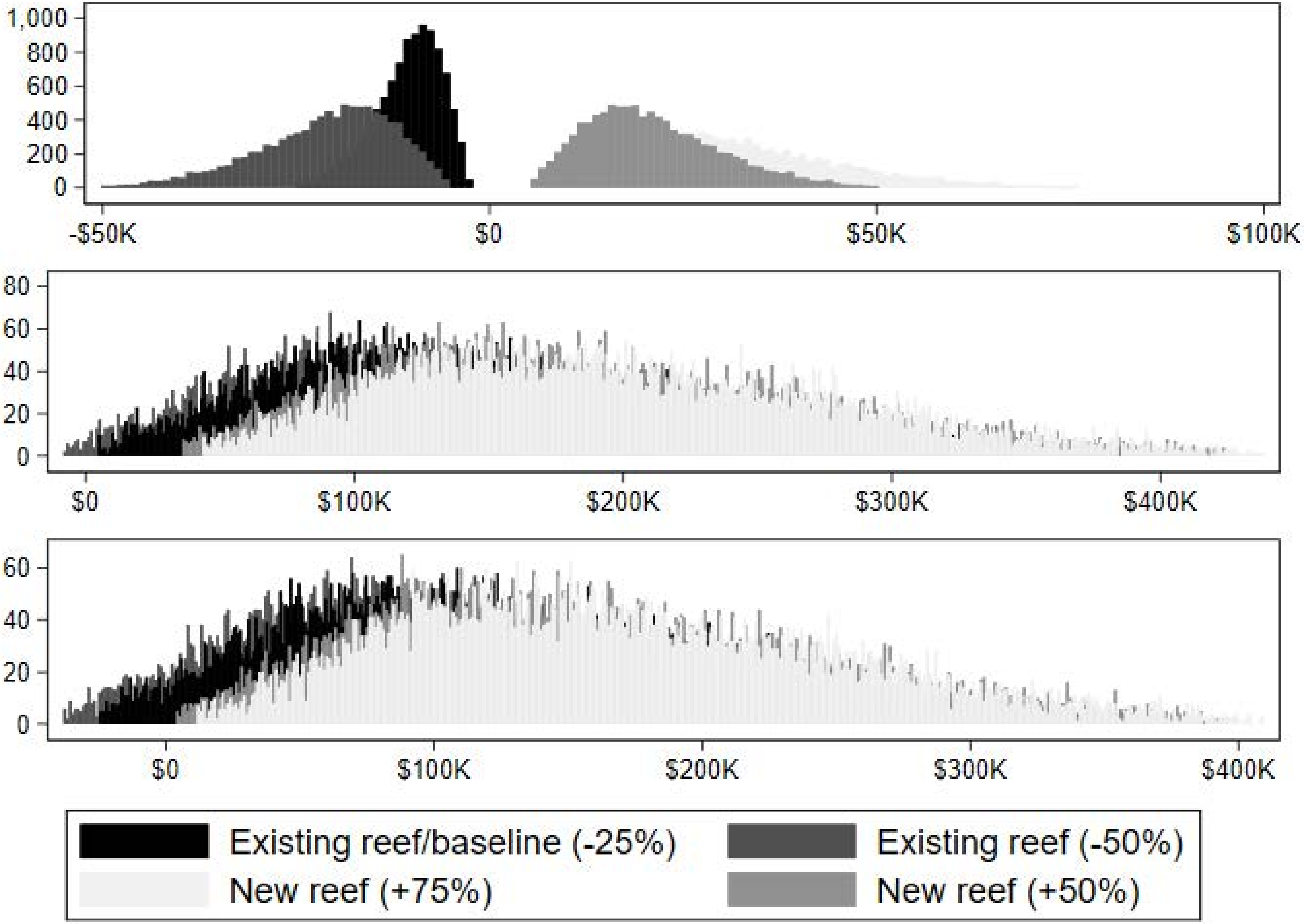
Blue crab prices


Bottom
0
100
200
300
400
500
$10K
$20K
$30K
$40K
$50K
Off-bottom
0
100
200
300
400
500
$250K
$350K
$350K
$400K
Living shoreline
0
1,000
2,000
3,000
4,000
$0
$5M
$10M
$15M
Restored
0
2,000
4,000
6,000
8,000
$0
$5M
$10M
$15M


60
40
20
0
$0
$500K
$1M
$1.5M
$2M
$2.5M
250
200
150
100
50
0
$0
$500K
$1M
60
40
20
0
$0
$500K
$1M
$1.5M
$2M
$2.5M
Bottom
Off-bottom
Living shoreline
Restored


Bottom
8,000
6,000
4,000
2,000
0
-$25K
-$20K
-$15K
-$10K
-$5K
$0
Off-bottom
10,000
8,000
6,000
4,000
2,000
0
$0
$2K
$4K
$6K
$8K
$10K
Living shoreline
400
300
200
100
0
$0
$200K
$400K
$600K
$800K
$1M
Restored
1,500
1,000
500
0
$0
$50K
$100K
Nitrogen
Red drum
Blue crab
Living shoreline


Bottom
Frequency
0
20
40
60
-$100K
$0
$100K
$200K
$300K
$400K
Off-bottom
Frequency
0
5
10
15
20
-$500K
$0
$500K
$1M
$1.5M
$2M
Living shoreline
Frequency
0
5
10
15
20
25
-$15M
-$10M
-$5M
$0
Restored reef
Frequency
0
20
40
60
-$15M
-$10M
-$5M
$0


1,000
800
600
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-$50K
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$50K
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80
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$200K
$300K
$400K
60
40
20
0
$0
$100K
$200K
$300K
$400K
Existing reef/baseline (-25%)
Existing reef (-50%)
New reef (+75%)
New reef (+50%)