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Measuring the impact of pollution closures on commercial shellfish harvest:

The case of soft-shell clams in Machias Bay, Maine

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Abstract

Temporary closures of polluted coastal waters to shellfish harvesting protect human health but also generate broad socioeconomic impacts on rural, fishing-dependent communities. Improved understanding of these impacts could help coastal managers prioritize investments to protect water quality and mitigate the effects of coastal pollution. Using a regression model of monthly landings, we explore the impact of temporary closures on the commercial harvest of soft-shell clams (*Mya arenaria*) in the Machias Bay region of Maine (USA). We find that economic losses are significant and depend heavily on tidal activity, and the size, frequency and timing of closures. Over the nine-year sample period (2001 e2009), temporary pollution closures contributed to the loss of \$3.6 million in forgone revenue (2014 dollars), approximately 27.4% of total revenue. Closures linked to combined sewer overflows from the Machias wastewater system produce the majority of these losses (\$2.0 million) with the largest occurring during the peak clamming season (May-August). Our results highlight the variability of the impacts of closures and the information burden for efficient management of shellfish areas and coastal waters. By strategically reducing pollution, managers could limit public health risks, avoid destabilizing harvesting and revenue, and bolster the resilience of fishing communities.

Keywords:

Soft-shell clams, Fisheries management, Pollution closures, Water pollution

1. Introduction

Pollution in coastal waters can make molluscan shellfish unsafe to eat. Pathogens found in the local environment become concentrated inside the meat of filter-feeding shellfish making them a potential vector for food-borne illness (U.S. DHHS, 2005; MDMR, 2008). Fishery managers prohibit or restrict access to harvesting shellfish from impaired waters to protect human health (NSSP, 2013). These closures represent a loss of access to productive intertidal and subtidal areas and thereby affect harvesting effort and revenue for the shellfish industry. In fishing-dependent communities, these temporary pollution closures can engender broad economic and social impacts (Murray et al., 2001; Stevens et al., 2004; Athearn, 2008b; Parsons et al., 2009). Often, these resource-dependent coastal communities lack alternate sources of income, leaving them vulnerable to water pollution and environmental change (Hall-Arber et al., 2001; Adger et al., 2005; Dolan and Walker, 2006; Safford and Hamilton, 2010). Better information about the socioeconomic impacts associated with temporary pollution closures can help resource managers prioritize water quality protection efforts and refine mitigation strategies to lessen the vulnerability of rural communities.

Managing water quality is particularly important to fisheries. Water pollution can affect the abundance, location, and/or size of fish. These impacts can affect fishing costs and effort, landings and revenue (McConnell and Strand, 1989; Ofiara and Seneca, 2001; Huang et al., 2012). Regulatory restrictions can have similar economic effects (Lipton and Strand, 1997; Ofiara and Seneca, 2001; Leung and Pooley, 2002). When water pollution affects the safety of consuming seafood, consumer well-being and market demand are impacted - potentially reducing the market demand for unrelated species (Hoagland et al., 2002; Granel and Turner, 2006; Morgan et al., 2009). Changes in fishing activity also impact seafood wholesalers, processors, restaurants, marine services firms, and communities that depend economically on fishing-related businesses (Thurman and Easley, 1992; Leung and Pooley, 2002; Mulkey et al., 2005; Athearn, 2008a, b; Richmond et al., 2015).

Measuring the socioeconomic impacts of changes in fishery conditions and management actions, such as access restrictions, is paramount to policy-makers. The National Marine Fisheries Service maintains an active economic and social analysis program related to fisheries in the U.S. (NMFS, 2015). Economic assessments focus on changes in social welfare (Kahn and Rockel, 1988; McConnell and Strand, 1989; Freeman III, 1991; Thurman and Easley, 1992; Barbier, 2000), regional and national economic impacts (Leung and Pooley, 2002; Mulkey et al., 2005; Athearn, 2008a, b), and other economic effects (Johnston et al., 2002; Morgan et al., 2009; Carrasquilla-Henao et al., 2013; Tuya et al., 2014). Social impact assessments consider the impacts on mental, physical, social, cultural, and economic well-being of fishermen and their communities (Pollnac et al., 2006; Jepson and Jacob, 2007; Richmond et al., 2015). Our work adds to this body of research, combining qualitative (i.e. semi-structured interviews) and quantitative (i.e. statistical analysis) research methods to explore the localized impacts of access restrictions on fishermen behavior and commercial harvest outcomes.

The availability and quality of fish habitat is important for successful fishing outcomes. This has been demonstrated in fisheries across the globe (Hartill et al., 2005; Tuya et al., 2014). Carrasquilla-Henao et al. (2013) find a strong correlation between the availability of fishing habitat (i.e. mangrove forest cover) and landings by artisanal fishers in the Gulf of California, Mexico. Regulatory restrictions on access of fishermen to fish habitat (harvest grounds) can further generate impacts on harvest activities and fishing communities.

Temporary access restrictions in fisheries can originate either from conservation efforts to protect or rebuild the fish stock, or as an effort to protect public health due to concerns over water quality. Past research on conservation closures suggests that while these closures may generate long-term gains for the ecologic system and the community, they can also create financial strain on resource-

dependent communities during the rebuilding period. For example, assessing the social impacts of an extended conservation closure on harvesting big eye tuna in Hawaii in 2010, Richmond et al. (2015) determined this closure created stress on individuals and businesses connected to the fishery, and in some cases reduced incomes. Stevens et al. (2004) found similar results in their economic analysis of re-opening prolonged conservation closure areas to recreational harvest of bay scallops in Florida.

Quantifying the impacts of access restrictions to harvest areas from pollution is complicated by data gaps, uncertainty about changing coastal environments, and complex interactions among human and natural systems (Carter and Woodroffe, 1997; Hoagland et al., 2002). In theory, fishery landings are directly related to the abundance of fish, fishing effort and environmental conditions (Clark, 2005). In practice, lack of available data on these factors and our general inability to observe fishing outcomes under alternate conditions (the counterfactual) create challenges for empirical estimation of the economic effects of changes in access or environmental conditions. Some authors have used simulation models and harvester interviews to fill in data gaps in fisheries models, however, data challenges remain (Hartill et al., 2005; Dinesen et al., 2011; Moreno-Beaez et al., 2012). These data challenges extend to estimating the relationship between shellfish closures and annual harvest values (Hoagland et al., 2002). Accordingly, much of the literature has focused on measuring the impact of the presence of pollution closures from a single source of water pollution (e.g., harmful algal blooms) on the trend in landings of shellfish at broad spatial scales (Hoagland et al., 2002; Athearn, 2008b; Jin et al., 2008; Jin and Hoagland, 2008). The insights of these studies provide the foundation for our research.

This past work highlights the importance of protecting both public health and fishing activities in resource-dependent coastal communities. Achieving these goals and bolstering the resiliency of rural coastal communities to environmental change requires an understanding of the conditions under

which water quality management is most productive. To this end, quantifying the impacts of closures that are linked to human activity in the water system is essential to prioritizing water management alternatives. In this paper, we estimate the impact of pollution closures on the commercial harvest of soft-shell clams (*Mya arenaria*); we use two fishing-dependent towns in northeastern Maine (USA) as our study setting. We examine the effect on landings and revenue under counterfactual scenarios, isolating the role of various sources of water pollution (e.g., untreated wastewater, urban and agricultural runoff and coastal flooding). Our results highlight the variability of the impacts of closures on commercial harvest activity. This variability illustrates the potential gains from incorporating finer-resolution spatial and temporal information into management decisions. We find that losses from reduced harvest access can be significant and depend heavily on the level of harvest and tidal activity, and the size, frequency and timing of closures. Our results suggest that efforts directed at abatement of water pollution from wastewater during the peak clamming season will generate the largest benefits for this fishery.

2. Study setting

Clams are commercially valuable marine species. According to the National Marine Fisheries Service, the ex-vessel value of clam landings in the U.S. totaled \$208.6 million in 2013 with soft-shell clams representing 11.5% (\$24.1 million) of this total (NMFS, 2014). The state of Maine is a major contributor to soft-shell clam production in the U.S., providing 62.2% of the landings and 75.2% of the total value (NMFS, 2014; MDMR, 2015). The soft-shell clam is the highest valued molluscan shellfish species in Maine with an ex-vessel value of \$19.2 million in 2014 (MDMR, 2015). Soft-shell clams are harvested primarily by independent harvesters who dig clams from intertidal mudflats by hand or with a handheld tool (clam hoe). This low-cost fishing opportunity provides an important source of income for more than 1500 state-licensed shellfish harvesters in Maine (MDMR, personal communication). Additional value for coastal communities accrues as the

shellfish pass through market channels and generate indirect and induced multiplier effects.

Our study focuses on the harvest of soft-shell clams in the towns of Machias and Machiasport located in Washington County, Maine (Fig. 1). Machias is located along the Machias River, upstream of Machiasport, and manages its wastewater using a combined sewer system. The Maine Department of Environmental Protection (DEP) allows the Machias wastewater treatment system to discharge untreated wastewater, called combined sewer overflows (CSOs), into the Machias River when the volume of wastewater is too great for the system; these discharges may contain untreated human waste and toxic material (DEP, 2012; EPA, 2015). Machiasport employs septic tanks to handle its wastewater. Both towns have access to the intertidal flats in the Machias Bay region, which includes the Machias River and Little Kennebec Bay. Tides in this region typically fluctuate 10-16 feet (3.0-4.9 m) in vertical distance between low tide and high tide (USC, 2011). At low tide, approximately 2838 acres of intertidal mudflats are exposed. Machiasport, which accounts for most of the intertidal acreage, is one of the most productive soft-shell clam towns in Maine. Machiasport has a shellfish conservation ordinance that requires clam harvesters to hold a town license and prohibits night-time harvesting. The town of Machias, which contains very little harvestable mudflats, does not have a shellfish ordinance. Soft-shell clams are the most valuable commercial marine species landed in these two small towns with an average annual ex-vessel value of \$1 million (2014 dollars) between 2001 and 2009.

As part of the National Shellfish Sanitation Program (NSSP) the Maine Department of Marine Resources (DMR) closes coastal waters and intertidal mudflats to shellfish harvesting when concentrations of pollutants (e.g., fecal coliform and vibrio) rise to harmful levels (NSSP, 2013). Two hundred forty eight of the 2838 acres in this region have been permanently closed to harvesting because of impaired water quality. The harvesting status of the remaining acreage (2591 acres)

varied over the nine-year period (2001-2009) of our study (Table 1). While the long term growing area classification changed on some of the acreage, the most frequent changes in status were due to four sources of water pollution: (1) temporary (conditional) closures linked to CSOs from the Machias wastewater treatment system, (2) temporary closures linked to other localized sources of bacterial pollution (such as septic tanks, animal waste and runoff), (3) temporary closures linked to coastal flooding and (4) temporary closures linked to red tide. Red tide is the common name for a type of toxic marine algae (*Alexandrium fundyense*) found in the Gulf of Maine. These harmful algal blooms occur naturally and may be stimulated by high levels of freshwater runoff and nutrient loads (Anderson, 1995). Finally, although closures linked to CSOs are spatially isolated to the intertidal mudflats along the Machias River and its opening into Machias Bay (including Randall Point Flats and Sanborn Cove), pollution closures from the remaining sources of water pollution were spread throughout the bay.

3. Methods

In theory, calculating the landings lost from pollution closures is straightforward. It involves comparing the landings of soft-shell clams under the presence of pollution closures Y^0 against the landings that would have occurred otherwise Y^1 :

$$\Delta Y = Y^1 - Y^0.$$

In practice, this approach is complicated by the fact only one outcome is realized. Since we cannot observe landings under both states of the world, we must rely on statistical models to predict outcomes under the unobserved states to estimate these forgone opportunities.

3.1. Statistical model

In our model we use information regarding environmental, economic, and regulatory conditions in Machias and Machiasport to predict landings of soft-shell clams under alternate conditions. We employ a Box-Cox transformation on landings to incorporate flexibility in our selection of functional form (Box and Cox, 1964). Standard functional forms, such as linear ($\lambda = 1$), log-linear ($\lambda = 0$), and reciprocal ($\lambda = -1$), are special cases of the Box-Cox specification and are tested during the estimation process. The Box-Cox specification allows for heterogeneity of marginal impacts across the sample, providing a rich description of variation in landings. Let $Y^{(\lambda)}$ denote the Box-Cox transformed landings of soft-shell clams where,

$$Y_t^{(\lambda)} = \begin{cases} \frac{Y_t^\lambda - 1}{\lambda} & \text{if } \lambda \neq 0 \\ \ln Y_t & \text{if } \lambda = 0. \end{cases}$$

We model the transformed landings of soft-shell clams in date t as a linear function of local conditions X_t and an error term u_t ,

$$Y_t^{(\lambda)} = \beta X_t + u_t.$$

where β captures the marginal influence of local conditions on landings. We estimate two models, a single region and a two region model, to test whether spatial patterns of closures linked to CSOs are important in how the fishery responds to closures, e.g., whether there are differences between the region that experiences mudflat closures from CSOs and the one that does not (Fig. 1). In the two region model, *Region 1* contains the intertidal zones along the Machias River from the town of Machias to the river's opening into the bay. These areas have experienced closures connected with CSOs. *Region 2* contains all other harvest areas in Machias Bay and Little Kennebec Bay. Alternate spatial definitions of regions are possible. These are beyond the scope of this paper and are hence reserved for future work.

Following Spitzer (1982), we estimate the model parameters using a two-stage process (see Spitzer's paper for complete details on the estimation algorithm). In the first stage, we recover an estimate of the transformation parameter $\hat{\lambda}$ by maximum likelihood estimation of the concentrated log-likelihood function (i.e. the log-likelihood function is partially optimized to remove its dependence on β). In the second stage, we use transformed landings calculated from the first stage estimate of $\hat{\lambda}$ to recover estimates of $\hat{\beta}$ using ordinary least squares.

3.2. Interviews

To generate hypotheses about factors affecting soft-shell clam landings and better understand harvester responses to closures, we conducted semi-structured interviews with local fishery participants. Using a random sample of 20 harvesters holding a Machiasport clam license we conducted phone interviews with 11 harvesters that could be reached and agreed to participate (55% response rate). Interview questions asked the harvesters about factors affecting their clam harvesting effort and clam landings, and how closures affect them. We supplemented harvester responses with interviews from a convenience sample of two local shellfish dealers. The insights from these interviews and economic theory guide the selection of control variables for the statistical model.

3.3. Data

We generate our data set using monthly information on the commercial landings of soft-shell clams in Machias and Machiasport between 2001 and 2009 (Table 2). Since both harvesting effort and biomass of clams are not directly observable we control for conditions in the fishery that are related with these outcomes. Control variables are separated into three categories: environmental, economic, and regulatory.

Environmental variables control for seasonal variation and accessibility to the mudflats. These variables include the average temperature (measured in heating degree days), the number of daylight tides (night-time harvesting is not allowed in Machiasport), and the average height of the low tide. Low tide height is an important variable for modeling harvesting effort as the size of the tide affects how much clammers can harvest. That is, during very low (“big”) tides more of the mudflat is accessible. In addition, these regions of the mudflat may be more productive for clamming as they are harvested less frequently. We include an interaction term between acres closed and low tide height (measured as the average interaction per daylight tide) to allow for differential impacts of pollution closures depending on localized conditions.

Economic variables control for unobserved fishing effort, capturing factors that influence the application of harvest effort. These variables include the real ex-vessel price of clams, the real value of landings of other species (landed in Washington County, Maine), and the local unemployment rate. Since the market price for soft-shell clams is determined by landings throughout New England, we treated the price of clams as exogenous for clammers in Machias and Machiasport. The remaining economic variables control for changes in opportunities in local labor markets. Clam harvesters participate in several fisheries, especially the local lobster, scallop and urchin fisheries. As conditions improve or worsen in these other fisheries harvesting effort directed at soft-shell clams changes as well. We use local unemployment rates to represent the influence of opportunities outside the fishery. All monetary values are expressed in real dollars based on the New England CPI and a base year of 2014.

Finally, regulatory conditions influence the ability of clammers to access intertidal zones. These variables include the number of annual municipal shellfish licenses issued by Machiasport (licenses run May-April) and the average number of acres of intertidal zones closed to harvest (excluding

areas that are closed during the entire sample period). We use geographic information system (GIS) mapping tools to estimate intertidal mudflat acreage and the number of acres open and closed on every daylight low tide between 2001 and 2009. Legal notices and closure history, including the cause of the pollution closure, are from DMR. Using ArcGIS we mark the intersection of closure boundaries with intertidal areas falling within Machiasport and Machias town boundaries. Mudflats are divided into 20 polygons that delineate the areas open and closed on any given low tide. Three of the polygons were never open to harvesting during the study period, but the remaining 17 polygons experienced changes in harvesting status. With the acreage of each polygon calculated by ArcGIS, we code all daylight tides according to the harvesting status of each polygon, reason for closure of each polygon, and the corresponding acreage. We divided these polygons into two regions for estimation of the statistical model (see Fig. 1).

3.4. Analysis

Parameter estimates from the statistical model inform predictions of landings under the unobserved or counterfactual states of interest. Calculation of these conditional expectations is complicated by the Box-Cox transformation of the landings data (see Appendix A for a detailed discussion). Due to concerns over autocorrelation and heteroskedasticity we approximate these expectations as

$$\hat{E}[Y_t | X_t^1] = \left(1 + \hat{\lambda} \left[\hat{\beta} X_t^1 + \hat{u}_t \right] \right)^{1/\hat{\lambda}},$$

where X_t^1 denotes the local fishery conditions (environmental, economic, and regulatory) under the counterfactual at date t . As we are interested in isolating the impact of pollution closures, we fix environmental and economic conditions in X_t^1 at the values observed in the data. We also fix the

number of municipal shellfish licenses at the observed sample values. The remaining portion of X_t^1 contains information on the acres closed under the counterfactual scenario.

To estimate the losses from the pollution closures observed in the sample we set closures to zero in X_t^1 . Predicted landings are used to calculate estimates of forgone landings and revenue under the following scenario:

$$\widehat{\Delta} Y_t = \widehat{E} \left[Y_t \mid X_t^1 \right] - Y_t^0,$$

where Y_t^0 denotes the observed landings at date t and $\widehat{E} \left[Y_t \mid X_t^1 \right]$ denotes our prediction of landings under the counterfactual (no pollution closures). Using real ex-vessel clam prices for each date t , we convert these forgone landings into forgone revenue. We decompose these impacts by source of water pollution using the proportion of acres closed each month from each source.

4. Results

The statistical models fit the data very well (Table 3). The adjusted R^2 values for both models are fairly high: 0.78 and 0.81 for the single region and two region models, respectively. This, coupled with large model F-statistics (21.82 and 34.36), suggests that the variables included in the statistical models are jointly relevant and capture most of the variation in landings. These results support our choice of model variables and validate the use of interviews to guide their selection. In addition, both models reject the linear, log-linear and reciprocal specifications in favor of the Box-Cox transformed models (all p-value less than 0.01). Finally, we find no statistical evidence that the two regions respond differently to closures; the p-value on the joint F-test ($H_0: \beta_{Clsd1} = \beta_{Clsd2}$ and $\beta_{Clsd1, Tidehgt} = \beta_{Clsd2, Tidehgt}$) equals 0.228. As such, the discussion that follows focuses on the results from the single

region model.

The results from the statistical model are consistent with the information learned from interviews. All parameter estimates, except for the variable *unemployment rate*, are statistically significant and have the expected sign. Lagged landings were considered as a model variable but were not included due to stationarity in the landings data. Marginal effects of control variables are nonlinear and depend on a combination of parameter estimates, the Box-Cox transformation parameter, and the level of harvest generating heterogeneity across the sample. For example, in the single region model the marginal effect of an additional acre of mudflat closed over a month will generate an average loss of 32 pounds of soft-shell clams (\$51 in revenue). The marginal impact of closures varies widely across the year, ranging from a minimum loss of 3 pounds (\$4 in revenue) per acre closed in January 2008 to a maximum of 132 pounds (\$273 in revenue) in August 2001.

The parameter estimates reveal seasonal variation in the responsiveness of the commercial harvest to changes in both the real price of clams and the real value of other species landed in Washington County. On average, a 1% increase in the real price of clams corresponded with a 1.19% increase in landings. During the peak clamming season (May-August) we observed an increasing own-price elasticity, peaking in August. The range of responsiveness varied over the peak season, from as low as a 0.85% increase in May to a 1.44% increase in August. Elasticities are calculated at the sample values.

We also observed this pattern of seasonal sensitivity when assessing the responsiveness of harvest to the value of other species. As the peak clamming season progressed commercial landings became more sensitive to the value of outside opportunities, though not as sensitive as to the real price of clams. On average, a 1% increase in the real value of other species landed in the area corresponded

with a 0.32% reduction in the commercial landings of soft-shell clams. Again, we see varying responsiveness, ranging from almost non-responsive (an average of 0.09% in April) to very responsive (as large as 0.78% in October).

4.1. Impact of pollution closures from combined sewer overflows

Pollution closures from CSOs are the most common reason for lost access to harvest areas and represent the only point source pollutant in our sample. Over the sample period of 108 months, 89 of them experienced at least some acreage closure due to overflows from the Machias wastewater system with closures lasting on average 91% of the month. These closures led to an average loss of access to 535 harvest acres per daylight tide, with the most productive mudflats being closed during 37 months.

Using the model parameters we estimated the expected change in landings and revenue associated with the pollution closures linked to the CSOs observed in the sample (Table 4). Over the nine-year sample period, these closures generated a loss of 1.3 million pounds of clams, equivalent to \$2.0 million in revenue. This is an average loss of 14,492 pounds of soft-shell clams, or \$22,516 in forgone revenue per month that experienced a closure from CSOs. This loss of revenue for the shellfish industry represents a loss of income for shellfishermen. The observed pollution closures linked to CSOs generated a total loss of \$16,916 of income per licensed clammer in Machiasport (an average of \$1880 per year). Sewage overflows created an annual loss of income for shellfishermen equivalent to 5.0% of the annual median household income in the county (United States Census Bureau, 2015).

While these summary statistics are helpful for understanding the scale of impacts from these pollution closures, our results also suggest the impacts vary greatly across time and depend heavily

on landings, the number of acres closed and tidal activity. Closures from CSOs can lead to significant reductions in revenue (as large as \$95,956 during a single month in our sample), however, more than two thirds of these pollution closures generated less than \$23,000 in forgone revenue for the month (or \$184 in forgone income per licensed clammer).

Grouping these estimates by month and reason for closure allows us to explore the distribution of impacts across the year (Fig. 2). The greatest losses from CSO closures occurred during the productive spring and summer months (an average of \$35,471-\$52,176) while closures in fall and winter generated relatively modest losses (an average of \$5,552-\$12,037). Interestingly, it is during the winter months that we see an increase in the average number of acres closed from CSOs, yet observe smaller losses. The reduced size and frequency of closures during late-spring and summer is offset by the increased value of clam landings from summer demand, generating larger losses from forgone harvest opportunities.

4.2. Impact of pollution closures from additional sources of water pollution

While pollution from overflows of the Machias wastewater treatment system generated the largest losses in the region, other sources of pollution, both natural and human, contributed additional losses. Animal waste, septic tanks and runoff (labeled 'Other') represent the second largest source of losses. During 87 months of the sample period at least some loss of harvest area occurred from these sources, lasting on average 95% of the month. While these closures were similar in characteristics to those from CSOs, they were generally smaller in size (only 133 acres per daylight tide on average) and primarily located around Machiasport (as the town relies on septic tanks to handle sewage). The pattern of losses over the year is similar to those from CSOs, with the largest losses experienced during the summer months; they are generally smaller in magnitude than those from CSOs (Fig. 2). Over the nine-year sample period, these other closures led to the loss of 487,286 pounds of clams,

equivalent to \$799,102 in revenue (Table 4). This represents an average loss of 5601 pounds of soft-shell clams, equivalent to \$9185 in forgone revenue per observed closure. For the licensed clammer, these closures corresponded to an annual loss of \$661 in income (1.8% of annual median household income).

Coastal flooding from heavy rainfall, the next largest source of losses in the bay, leads to large area closures (an average of 1714 acres per daylight tide) but only for brief periods during the month (on average 25%). Flood closures occur throughout the region over 21 months and led to an average loss of 10,783 pounds of soft-shell clams, equivalent to \$16,924 in forgone revenue per sample closure (Table 4). In aggregate this was a total loss of 226,438 pounds of clams, or \$355,414 in revenue. Red tide events are much less common in the Machias Bay region (only 9 months in the sample), have a shorter duration (on average 24% of the month), are mostly isolated south of Machiasport, and generated the smallest aggregate losses (Table 4). Closures from red tide, corresponding to the loss of access to an average of 849 harvest acres per daylight tide, generated 78,871 pounds (\$166,004) in losses over these 9 months. While these closures generated the smallest total loss across reasons for closures, the average impact of a red tide closure was the second largest: a loss of 8763 pounds of soft-shell clams, or \$18,445 in forgone revenue per observed closure. These large losses are due to the size and timing of the red tide outbreaks, which coincided with summer demand for soft-shell clams, July and August (Fig. 2). Combined, coastal flooding and red tide generated an annual loss of \$515 in income per licensed clammer.

The remaining pollution closures in the sample cannot be attributed to any single cause. Instead, multiple factors simultaneously led to the closure of access to these impaired waters. Since we cannot separate the influence of the various sources of pollution we have grouped these closures into a single category labeled 'overlapping' closures. These overlapping closures contributed an

additional loss of 139,537 pounds of soft-shell clams, equivalent to \$232,279 in revenue.

4.3. Combined impact of pollution closures

Combining losses across sources of water pollution provides a broad picture of the combined impact of pollution closures for this region. Over the nine-year sample period these harvest access restrictions generated a total of \$3.6 million in forgone revenue (2.2 million pounds of soft-shell clams; see Table 4). Per licensed clammer this represents an annual loss of \$3294 in income (8.8% of the median household income in Washington County). \$2.8 million of the total impact was closely linked to anthropogenic sources (e.g., bacterial pollution from CSOs and septic tanks), accounting for an annual loss of \$2541 in income per licensed clammer. The remaining losses originated from natural events (e.g., coastal flooding and red tide) exacerbated by pollutants from human activity, and overlapping causes that cannot be separated into a single source of pollution. Finally, the strong seasonal pattern of losses suggested from the decomposed impacts (Fig. 2) remains. The late-spring and summer months experienced the largest losses in revenue, coinciding with the peak clamming season, followed by a sharp drop-off during fall and winter. This seasonal pattern and dependence on local conditions highlight the variability of benefits to the commercial fishery from improved water quality (fewer closures).

5. Discussion

Water pollution can engender restrictions on activities in coastal waters to protect public health. For fishing-dependent communities, these restrictions represent the loss of access to productive harvesting areas and important sources of income. Improved water quality may generate large benefits to fishery participants from improved access, lessen the vulnerability of these communities to environmental changes and protect public health. However, improving water quality is costly.

Understanding the likely benefits of public investments in water quality projects is important for evaluating the efficacy of those investments and for the efficient use of public funds. To this end, quantifying the impacts of closures that are linked to human activity in the water system is essential to prioritizing water management alternatives.

This paper provides an important addition to the literature: combining qualitative (i.e. semi-structured interviews) and quantitative (i.e. statistical analysis) research methods to explore the effect of access restrictions from pollution on fishermen behavior and commercial shellfish harvest. The design of our statistical model allows us to address questions that were previously inaccessible in the literature. Specifically, we quantify changes in harvest and revenue based on the number of acres closed, distinguish losses of closures from multiple pollution sources, predict fishing outcomes under alternate conditions and incorporate the ability of shellfishermen to substitute their fishing effort toward alternate opportunities in response to closures and changes in fishery conditions.

Previous econometric work on pollution closures (e.g., Jin et al. (2008); Jin and Hoagland (2008)) focused on estimating the impact of the presence of a closure from a single source of water pollution (e.g., red tide) at broad spatial and temporal scales capturing general trends in shellfish landings rather than behavior. Athearn (2008b) extended these trend models to allow for two sources of pollution closures, red tide and coastal flooding, in Maine. In other settings, authors have turned to simulation methods to explore the impacts of closures from pollution. Dinesen et al. (2011) simulated the impact on mussel harvesters in Denmark from fishery closures due to excess nutrient loads. Collectively, these studies demonstrated that losses from the presence of access restrictions can be significant, highlighting the importance of continued research.

Our results are consistent with this past work, finding significant losses in the Machias Bay region.

Over the nine-year sample period, 2001-2009, pollution closures linked to anthropogenic and natural

sources contributed to the loss of \$3.6 million in forgone revenue, approximately 27.4% of total revenue from the fishery. This represents a sizable strain on the income of shellfishermen. Per licensed clammer, this is equivalent to an annual loss of \$3294 in income (8.8% of the median household income in Washington County).

Given the finer spatial and temporal resolution of our data we also explored in-sample variation. We found considerable heterogeneity in the impact of closures. Our results suggest that the size of these impacts depends heavily on the level of harvest and tidal activity, and the size, frequency and timing of pollution closures. Forgone revenue and landings from the closures observed in the sample were largest during the peak clamming season (May-August) and negligible during the winter months. This seasonal pattern and dependence on local conditions highlight the variability of benefits to the commercial fishery from improved water quality (fewer closures) and illustrate the information burden for efficient management of shellfish areas in coastal waters.

The largest losses from closures in Machias Bay are closely linked to anthropogenic sources of pollution (CSOs and other sources of bacterial pollution such as septic tanks). \$2.8 million of the total losses are connected to these sources. Combined sewer overflows (CSOs) from the Machias wastewater treatment system are the largest single source of pollution closures for the region and accounted for an estimated \$2.0 million in forgone revenue (17.5% of the total revenue from the fishery and over half of the total losses). Non-point source pollutants (e.g., urban and agricultural runoff and coastal flooding), which are historically difficult to manage, generated another \$1.3 million in forgone revenue for this fishery. We encourage future research to explore how these patterns (the relative impacts of point and non-point source pollutants) relate to management structures in other coastal settings, providing broader management recommendations that connect water quality management and fishery outcomes.

CSOs provide an interesting example of upstream/downstream externalities associated with coastal waters; this type of externality has been associated with dams and their removal (Whitelaw and MacMullan, 2002), water pollution and wastewater management (Cho et al., 2011; Fernandez, 2008) and the provision of public goods (Delaney and Jacobson, 2014), among others. The state environmental protection agency (DEP) allows the direct discharge of untreated wastewater into the Machias River when the volume of wastewater in the Machias combined sewer system is too large (DEP, 2012). To protect public health from bacterial pathogens contained in this wastewater, the state fishery agency (DMR) issues temporary prohibitions on harvesting filter-feeding shellfish in these impaired waters (MDMR, 2008). As such, these direct discharges of untreated wastewater into the Machias River (CSOs) generate negative spillovers downstream on the town of Machiasport in the form of reduced harvest access to intertidal and sub-tidal waters. In this situation, we see external costs spilling across municipalities (from Machias to Machiasport) and shifts in the regulatory burden (from regulation of pollutants entering coastal waters to access restrictions on human activity in impaired waters). This suggests that abatement efforts targeted at the management of wastewater from Machias have the potential to generate large benefits for the fishery and internalize the externality on Machiasport.

A full cost-benefit analysis would provide additional information about the merits of wastewater treatment upgrade options. Besides economic benefits for the shellfish industry, wastewater system upgrades could reduce risk to public health, increase recreation and tourism values, and enhance resilience to climate change effects. Cost estimates require an engineering analysis and depend partly on financing method, economic life of upgrades, and annual operating costs. Estimation of those costs and other potential benefits is outside the scope of this paper, but reserved for future work.

While pollution closures are necessary to protect public health, and in the long-run the shellfish industry, they represent a real cost for the rural coastal communities that are financially dependent on these resources. Improved water management could reduce the frequency and extent of water quality impairment and avoid some of the losses to shellfish harvesters and coastal communities. The results of our study highlight the complexity of coastal and marine resource management and the importance of incorporating finer-resolution spatiotemporal data into its design. Connections between human activity on land and in coastal waters link management units with potentially different aims and objectives (e.g., public health, land use planning, water quality management and fishery management). Decisions made in isolation in those distinct units are likely to generate unintended conflicts between resource users in the marine system.

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Appendix A. Retransformation of the conditional expectation

Calculation of expected clam landings conditional on the model covariates $E[Y|X]$, necessary for estimating the impact of closures, is complicated by the nonlinear fashion in which the error enters the retransformed harvest equation:

$$E[Y|X] = \int (1 + \lambda[\beta X + u])^{\frac{1}{\lambda}} f(u) du.$$

If the probability density function $f(\hat{u})$ was known then this could easily be recovered through simulation. Unfortunately, we neither observe u nor know its probability density $f(\cdot)$. In addition, due to the nonlinearity of the expectation we cannot appeal to the standard assumption that $E[u] = 0$ to overcome this problem. This is easy to demonstrate. Suppose that $Y = h(\beta X + u)$ then $E[Y|X] \neq h(\beta X)$ unless the error is additively separable in $h(\cdot)$.

Duan (1983) suggests using the empirical distribution of residuals $g(\hat{u})$ approximate $f(u)$. With a sufficiently large sample of independent and identically distributed \hat{u}_t , the conditional expectation can be estimated as,

$$\tilde{E}[Y_t|X_t] = \frac{1}{T} \sum_{s=1}^T \left(1 + \hat{\lambda} \left[\hat{\beta} X_t + \hat{u}_s \right] \right)^{\frac{1}{\lambda}}.$$

However, in the presence of autocorrelation or heteroskedasticity this method will generate a biased prediction.

Instead, we employ an approach that utilizes our best available information about the unobserved error term u_t , namely the residual \hat{u}_t . We approximate the conditional expectation $\hat{E}[Y_t|X_t]$ using the parameter estimates and the current period residuals,

$$\hat{E}[Y_t|X_t] = \left(1 + \hat{\lambda} \left[\hat{\beta} X_t + \hat{u}_t \right] \right)^{\frac{1}{\lambda}}.$$

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Figures and Tables

Fig. 1. Machias Bay and Little Kennebec Bay. Panel (a): Location of Machias Bay along the Maine coastline. Panel (b): Location of pollution closures in Machias Bay. The dark shaded areas denote the polygons used in the estimation of the model. The “diamond” shaded areas were portions of the intertidal zone (along the Machias River) where clamming was prohibited during the entire sample period (2001-2009). The asterisk denotes the location of the Machias wastewater treatment plant. Region 1 contains the intertidal zones along the Machias River from the town of Machias to the river’s opening into the bay (including Randall Point Flats and Sanborn Cove). These areas have experienced closures connected with combined sewer overflows. Region 2 contains all other harvest areas in Machias Bay and Little Kennebec Bay.

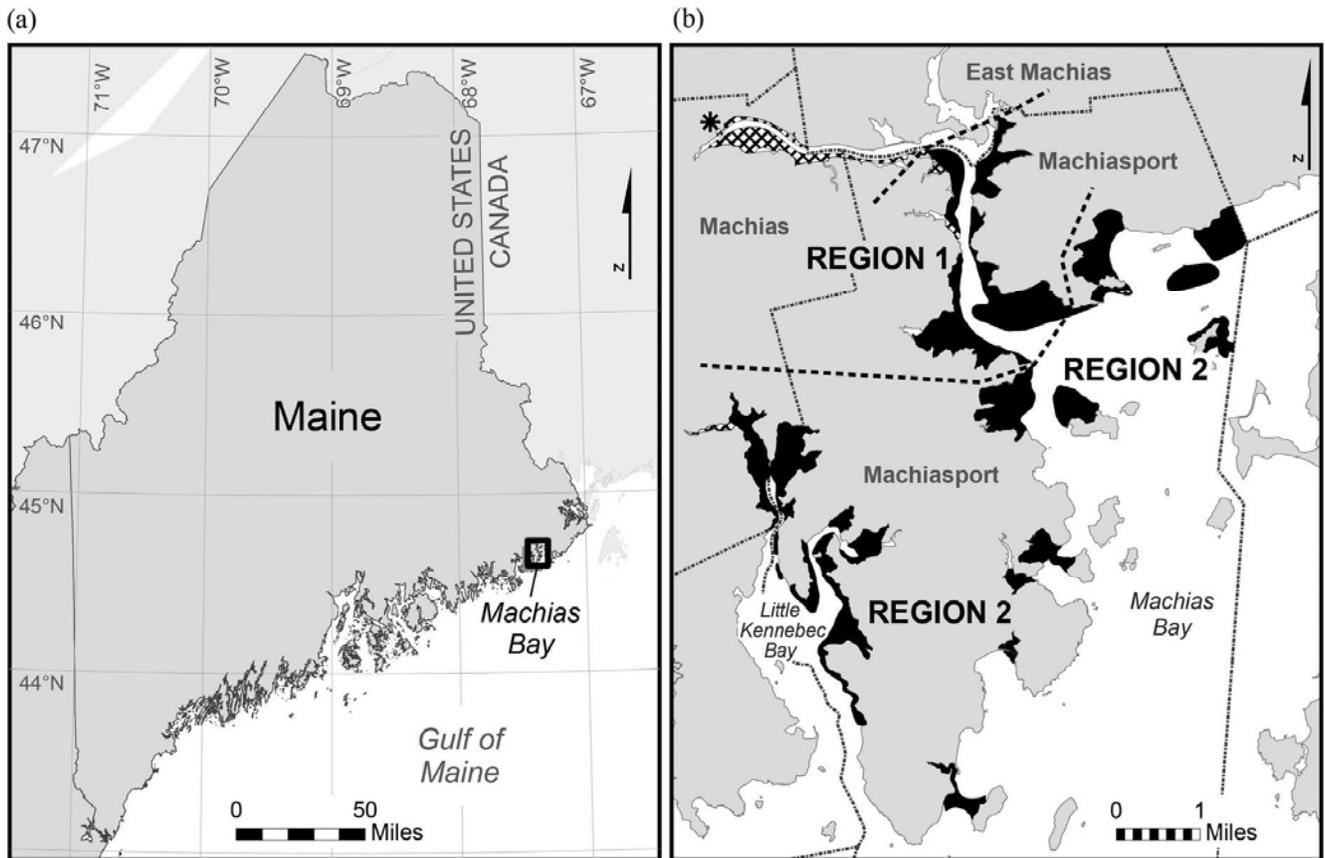


Table 1. Descriptive statistics of pollution closures (2001-2009); Machias and Machiasport, Maine, USA. The column labeled ‘Other’ shows closures due to other sources of bacterial pollution such as animal waste, septic tanks and runoff.

	Closure type			
	Combined sewer overflows	Other	Coastal flooding	Red tide
Frequency (months)	89.0	87.0	21.0	9.0
Duration (% of month)				
Mean	90.9	95.4	24.7	34.0
St. Dev.	17.4	13.7	14.9	37.6
Size (acres in month)				
Mean	535.0	133.4	1714.0	849.2
St. Dev.	211.2	53.1	352.2	927.0

Table 2. Descriptive statistics of sample used in transformed clam landings model (n = 108). All data is monthly. Monetary values are in real dollars using the New England CPI and 2014 as the base year. The low tide height is measured relative to the mean low water mark.

Variables	Mean	Median	St. Dev
Landings of soft-shell clams (1000 lbs)	71.77	49.40	65.12
Temperature (heating degree days)	44.44	44.50	15.69
Number of daylight tides	32.74	33.00	6.76
Low tide height (feet)	0.44	0.40	0.26
Clam Price (per pound)	1.55	1.50	0.38
Value of other landings (\$1,000,000's)	4.75	3.24	3.55
Unemployment rate (Machias labor market)	7.33	6.70	1.78
Machiasport municipal shellfish licenses	121.81	120.00	23.10
Closed (hundreds of acres per daylight tide)	6.32	5.67	3.82

Table 3 Parameter estimates from the transformed clam landings model. Soft-shell clam landings are transformed using the Box-Cox transformation parameter λ . Newey-West standard errors reported in parentheses. *, **, *** indicate significance at the 90, 95, and 99% confidence levels, respectively. *Region 1* contains the intertidal zones that experience closures linked to combined sewer overflows. *Region 2* contains the remaining intertidal zones in Machias Bay and Little Kennebec Bay.

Parameter	Description	Single region Model	Two region Model
β_{temp}	Temperature	0.178** (0.070)	0.214*** (0.073)
β_{ntides}	Number of daylight tides	0.545*** (0.187)	0.545*** (0.200)
$\beta_{tidehgt}$	Low tide height	-6.167* (3.671)	-10.323** (3.969)
β_{price}	Clam price	6.583*** (1.233)	7.114*** (1.190)
β_{other}	Value of other landings	-0.564*** (0.173)	-0.593*** (0.168)
β_{ue}	Unemployment rate	0.362 (0.388)	0.337 (0.450)
$\beta_{license}$	Municipal clam license	0.064** (0.028)	0.071** (0.029)
β_{clsd}	Closed	-0.594*** (0.160)	-
β_{clsd1}	Closed (Region 1)	-	-0.615** (0.296)
β_{clsd2}	Closed (Region 2)	-	-0.859*** (0.299)
$\beta_{clsd \cdot tidehgt}$	Closed \times Low tide height	0.448*** (0.163)	-
$\beta_{clsd1 \cdot tidehgt}$	Closed \times low tide height (Region 1)	-	0.981** (0.471)
$\beta_{clsd2 \cdot tidehgt}$	Closed \times Low tide height (Region 2)	-	0.260 (0.264)
$\beta_{intercept}$	Intercept	0.142 (10.532)	0.828 (11.308)
λ	Transformation parameter	0.199*** (0.065)	0.207*** (0.064)
	Number of obs.	108	108
	Adjusted R ²	0.787	0.811
	F-statistic	21.820	34.360
	LR-statistic $H_0: \lambda = -1$ (Reciprocal)	239.920	244.602
	LR-statistic $H_0: \lambda = 0$ (Log-linear)	9.251	10.320
	LR-statistic $H_0: \lambda = 1$ (Linear)	119.182	120.531

Table 4. Estimates of forgone landings and revenue from pollution closures by reason for closure. Monetary values are in real dollars using the New England CPI with 2014 as the base year. The column labeled ‘Other’ includes closures due to other source of bacterial pollution such as animal waste, septic tanks and runoff. Finally, the column labeled ‘Overlapping’ includes all closures that are due to multiple causes.

	Combined sewer overflows	Other	Coastal flooding	Red tide	Overlapping	Total
Δ Landings (1,000 lbs)						
Total	1,289.81	487.29	226.44	78.87	139.54	2,221.95
Mean	14.49	5.60	10.78	8.76	5.81	20.57
Median	9.75	2.90	4.16	3.99	2.54	13.39
St. Dev	13.19	5.68	12.55	11.65	7.61	22.08
Δ Revenue (\$1,000's)						
Total	2,003.97	799.10	355.41	166.00	232.28	3,556.77
Mean	22.52	9.19	16.92	18.44	9.68	32.93
Median	15.78	5.38	5.13	7.08	3.52	18.74
St. Dev	22.08	10.04	22.17	27.74	14.86	39.87

Fig. 2. Box plot distribution of forgone revenue grouped by month and reason for closure. Monetary values are in real dollars using the New England CPI with 2014 as the base year. The circle and bar within the box denote the average and median values of the conditional distribution.

