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Modeling shellfish harvest policies for food safety: Wild oyster harvest restrictions to prevent foodborne *Vibrio vulnificus*[☆]

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ABSTRACT

Vibrio vulnificus has been identified as one of the main causative agents of foodborne disease associated with shellfish consumption. Infections of *V. vulnificus* increase during the summer months due to higher densities of the bacteria in warmer water and inappropriate handling of shellfish. In Florida, the daily harvest period is regulated to control the length of time between shellfish harvest and processing, and this harvest period has been recently reduced during the summer months to decrease the risk of foodborne disease. Adoption of this public health policy can affect the profitability and economic sustainability of wild oyster harvesters, especially in resource-dependent coastal communities. This study develops a dynamic and stochastic bioeconomic model to assess the impact of this policy on fishers' harvest and revenues, and weighs that impact against the policy's potential public health benefits. Our results show that fishers will experience reduced harvests early in the season due to the shorter harvest hours, but this initial loss is partially recouped later in the season as harvests remain high for longer than they would have if the policy were not in place. This study highlights the relationship between food safety interventions and management of fishery resources, and provides a comprehensive framework for evaluating the costs and benefits associated with such interventions.

1. Introduction

Consumption of raw and undercooked shellfish is associated with outbreaks of foodborne diseases (FBD) resulting in hundreds of reported cases and multiple fatalities each year. Worldwide production of shellfish has risen dramatically since 1950, and it has been accompanied by an increase in the number of reported outbreaks of FBD associated with shellfish consumption (Fig. 1). However, it is unclear whether the rise in reported outbreaks can be attributed to increased consumption of shellfish or better reporting and attribution systems for FBD (Rippey, 1994; Potasman et al., 2002). Among causative agents of FBD associated with shellfish consumption, *Vibrio vulnificus* has been identified as a special concern due to the high mortality it can induce—particularly to individuals with poor health and immune disorders—and its estimated economic cost in the United States is approximately $319 million a year (USDA-ERS, 2014).

Seafood harvest is an important economic driver in the US, especially among resource-dependent coastal communities (Evans et al., 2016). The National Marine Fisheries Service (2015) shows that the ex-vessel value of oyster landings in the US totaled $240 million per year. Historically, Florida has been a major contributor to the supply of wild oysters in the US. The wild oyster fishery in Florida is an artisanal industry where oysters are harvested primarily by independent fishers using low-tech and low-cost harvesting practices, providing an important source of income for more than 2000 state-licensed shellfish harvesters.

Apalachicola Bay, located in Franklin County on the Florida Panhandle, has historically been one of the most productive oyster fisheries in the US, supplying close to 10% of all domestically produced oysters (Pine et al., 2015). The fishery in this area is almost entirely composed of small, owner-operated vessels lacking on-board cooling systems working with the same harvest technology in use since the late 1800 s. Franklin County is also one of the most economically depressed counties in the state of Florida, as evidenced by high poverty (25.3%) and child poverty rates (37.1%), as well as low median household income ($36,788) for 2014, which lag well behind indicators for the state of Florida as a whole (poverty 16.6%, child poverty 24.2% and median household income $47,439).

[☆] The views and opinions expressed or implied in this article are those of the authors and do not necessarily reflect the positions of their respective institutions.
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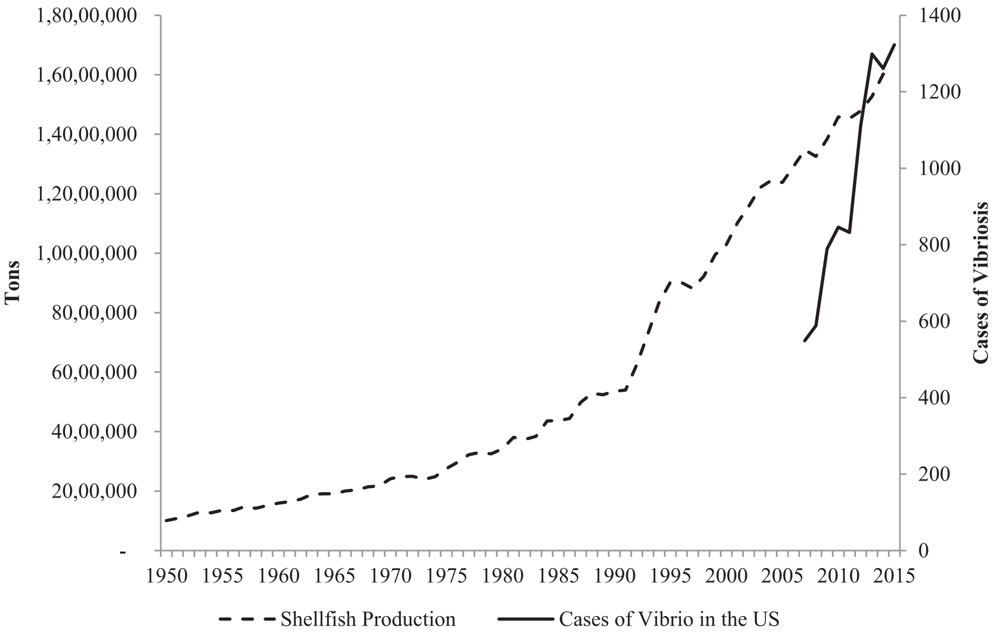

Fig. 1. Global production of bivalve shellfish, including clams, cockles, arkshells, mussels, oysters, and scallops (solid line), and number of reported vibriosis cases in the United States (dashed line). Vibriosis became a reportable disease in 2007, and consistent reporting data is available since then. Sources: FAO Fisheries and Aquaculture, Centers for Disease Control and Prevention.

In 2015, the legal daily harvest period for vessels without on-board cooling systems participating in the fishery during the summer season was reduced by 4 h. The intent of this restriction is to reduce the incidence of FBD, particularly infections of *V. vulnificus*, by curtailing the amount of time oysters are unrefrigerated prior to processing. The handful of vessels with on-board cooling systems participating in the fishery are not subject to this restriction and can harvest for a longer period. Furthermore, in recent years, the fishery has experienced an unprecedented collapse, endangering the sustainability of the fishery and the well-being of one of Florida's few remaining waterfront communities. In this context, a food safety policy that keeps oyster harvesters off the water for most the day raises concerns as it could potentially devastate this struggling waterfront community.

In this study, we focus on oysters, rather than on a wider group of shellfish, because more than 98% of food borne *Vibrio* infections are associated with oysters (Rippey, 1994), and the policy targets summer season oysters in Apalachicola Bay exclusively. Oysters are not harvested commercially anywhere else in Florida during the summer months.

In this study, we develop a non-linear, dynamic, and stochastic bioeconomic model using detailed trip ticket harvest data from Apalachicola Bay to analyze the impact of the harvest time policy restriction in terms of landings and revenues on a daily basis. Further, we use data from before and after the regulatory change to assess the accuracy of the forecasts developed with the bioeconomic model, which is implemented using *ex-ante* data.

The bioeconomic model developed in this study depicts changes in fishing behavior resulting from adjustments in the profitability of the industry due to harvest constraints imposed by the new policy. Hence, our approach highlights the inherent links between a policy designed to improve food safety outcomes, the economic impacts it imposes on the industry due to changes in production levels, and the resulting implications for marine resource management and fishing behavior. By providing a framework for estimating harvest losses resulting from implementation of the policy, our modeling approach also allows policy-makers and fishery managers to weigh the costs of the intervention—in terms of lost oyster harvests—with the expected benefits in terms of reduced numbers of foodborne *Vibrio* infections. Therefore, we contribute to the literature by developing a bioeconomic model that illustrates how a policy designed to improve food safety outcomes changes fishing behavior and affects the productivity and profitability of the industry. Our methodology and results also have global implications, as increases in global sea surface temperatures are already expanding the range of *V. vulnificus* into high latitude areas (Baker-Austin et al., 2013), and policy changes like those enacted in Florida may become necessary in other parts of the world. Our proposed methodology is also novel and different from previous studies on the economics of food safety, which have mainly focused on issues of product liability associated with FBD (Buzby and Frenzen, 1999), preferences for risky foods (Petrolia, 2016), multi-criteria evaluation of food safety interventions (Mazzocchi et al., 2013), interactions between food producers and food safety inspectors (Buckley, 2015), willingness to pay for prevention of FBD (Roberts, 2007; Hammitt and Haninger (2007); Sharma et al., 2012), and evaluation of food safety interventions at different points in the supply chain (Fraser and Souza-Monteiro 2009). Similarly, by incorporating and explicitly modeling changes in fishing behavior, our approach differs from previous studies that evaluate losses from shellfish harvest area closures (Evans et al., 2016).

The rest of this article is structured as follows. Section 2 provides an overview of shellfish and the pathogens associated with its consumption, the costs associated with foodborne *V. vulnificus* infections in the US, and the regulatory framework that exists to prevent shellfish-related FBD. Section 3 describes the Apalachicola Bay oyster fishery and the trip ticket data used in this study, as well as the food safety policy under study. Section 4 presents the dynamic non-linear bioeconomic model used to conduct the analysis of the food safety policy, along with a framework for estimating the costs of the policy intervention. Section 5 discusses the model's results and the ensuing benefit-cost analysis. Finally, Section 6 offers a discussion, policy implications, and concluding remarks.

2. Foodborne illness in shellfish

Shellfish are commonly found and harvested in areas close to the shoreline, where the waters are sheltered, salinity is low, and nutrient levels tend to be higher than in open waters. In many cases, these areas are also more likely to be contaminated with human sewage and other man-made wastes. Oysters and other bivalve shellfish are filter feeders, that is, they feed by pumping large volumes of water across specialized gills and capturing phytoplankton and other microscopic food particles, including organic materials. When pathogenic microorganisms are present in the water, they are filtered by the gills and become highly

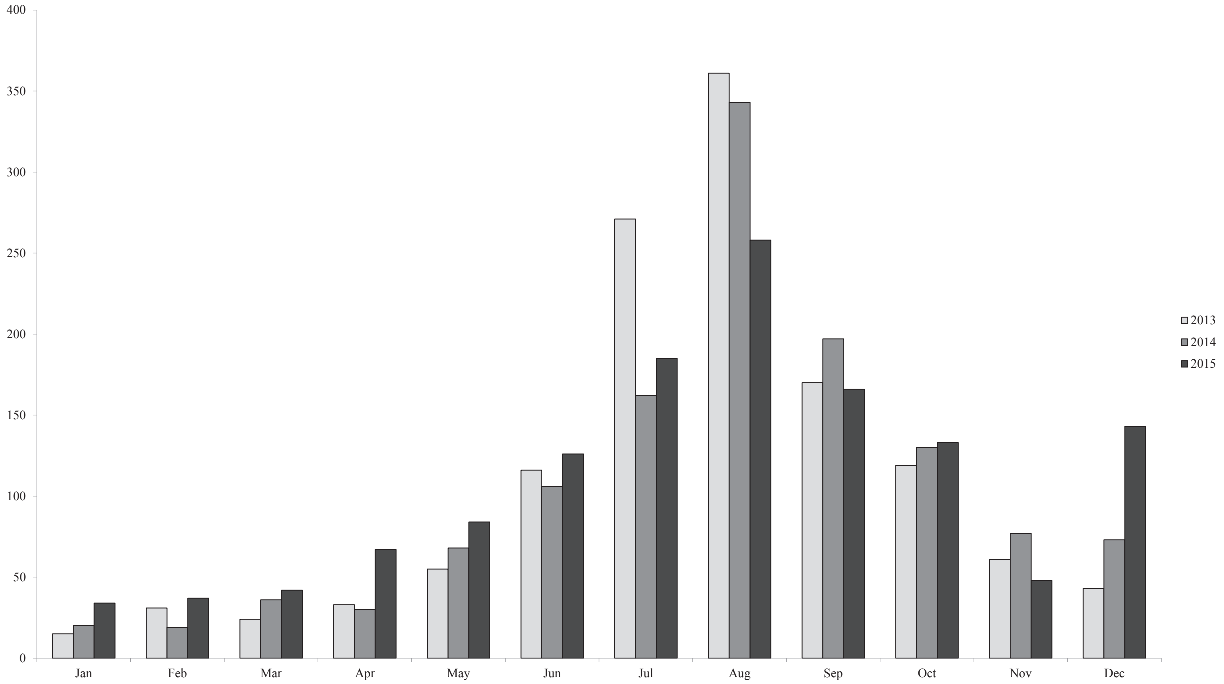

Fig. 2. Monthly reported cases of *Vibrio* related illnesses in the US (2013–2015), with the exception of cholera. Source: Centers for Disease Control and Prevention.

concentrated in the shellfish's digestive glands (Potasman et al., 2002).

There are two major types of foodborne pathogens associated with shellfish consumption. The first type are known as enteric or intestinal bacteria and viruses, and thrive in human sewage and other human wastes. Among the viruses in this group, the most common are the Norwalk family of viruses (norovirus) which cause gastroenteritis in humans. Other important viral agents of FBD associated with shellfish include hepatitis A, hepatitis E, small round-structured viruses, and poliovirus. The bacterial agents in this group include *Salmonella* spp., *Shigella* spp., *Campylobacter* spp., *Plesiomonas* spp., *Aeromonas* spp., and *Escherichia coli*, all of which cause human gastroenteritis or similar illnesses (Rippey, 1994; Potasman et al., 2002).

The second type of foodborne pathogens includes naturally occurring bacteria that are present in marine and estuarine environments, specifically members of the genus *Vibrio* such as *V. vulnificus*, and *V. cholerae*, among others. Densities of these pathogens are related to water temperatures and salinity (Rippey, 1994). Fig. 2 shows that most cases of *Vibrio* infection occur in conditions of warm weather and higher water temperatures (Weis et al., 2011; Baker-Austin et al., 2013). Illnesses associated with this type of bacteria are generally more serious than those associated with the first type, with conditions ranging from gastroenteritis to septicemia, and in some cases resulting in death (Rippey, 1994; Potasman et al., 2002; Weis et al., 2011).

Of all the pathogens associated with shellfish consumption, *V. vulnificus* leads to the most serious health outcomes. On average, less than 2000 cases a year are reported throughout the US, yet the mortality rate associated with *V. vulnificus* infections is much higher than for other shellfish related FBD. For example, the case fatality rate for *V. vulnificus* in Florida between 1998 and 2007 was 27.5%, which dwarfs those for other causative agents of FBD such as *Salmonella* (0.4%), *Campylobacter* (0.1%), *Shigella* (0.1%), and *E. Coli* (0.2%) (Weis et al. 2011). *V. vulnificus* is particularly dangerous for individuals suffering from conditions such as liver disease, diabetes and immune disorders (Rippey, 1994; Potasman et al., 2002). For individuals suffering from any of these conditions, the case fatality rate in Florida between 1998 and 2007 was 96.1% (Weis et al., 2011).

The serious nature of *Vibrio* infections is also reflected in the high costs associated with this illness. For example, Hoffmann et al. (2012) estimate the average cost of illness of each case of *V. vulnificus* at $3.03 million, by far the costliest FBD on a per case basis. Similarly, Scharff (2012) estimates this cost at $2.8 million, again the most expensive of all the foodborne pathogens on a per case basis. Besides *Listeria monocytogenes* (listeriosis) and *Clostridium botulinum* (botulism), whose costs per case are in the $1–2 million range, all other FBD have costs per case below $50,000. The estimated costs per case of *V. vulnificus* for different potential outcomes, as estimated by USDA-ERS (2014), are shown in Table 1.

To minimize the incidence of shellfish-related FBD in the US, the regulatory framework has relied on three major components. The first component involves water sampling and monitoring in areas where shellfish are harvested. Regulatory entities conduct water sampling throughout the year and test water samples for fecal coliform, which indicate the presence of untreated sewage or other human wastes in the water. If water testing indicates the presence of fecal coliform beyond

Table 1
Costs of Illness for cases of *Vibrio vulnificus*, and percentage of cases by outcome. Adapted from USDA-ERS (2014)

Outcome	Cost per Case	Percent of Cases		
		Base Scenario	Low Severity	High Severity
Physician Visit and Recovery	$641.14	3.1%	8.1%	0.1%
Hospitalized without Sepsis and Recovery	$34506.05	19.3%	24.3%	7.3%
Hospitalized with Sepsis and Recovery	$103230.04	40.1%	45.1%	40.1%
Hospitalized with Sepsis and Death	$8657357.03	37.5%	22.5%	52.5%

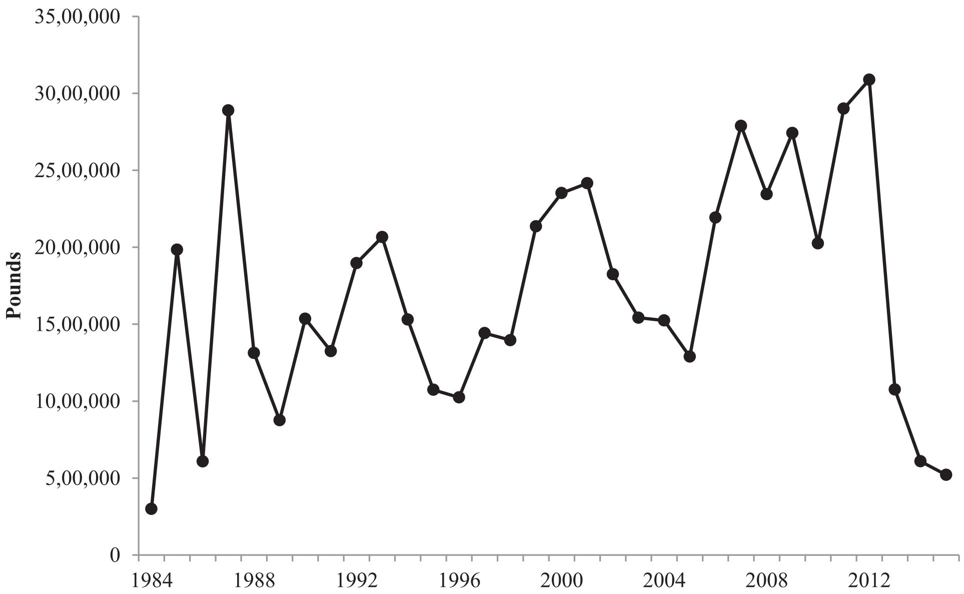

Fig. 3. Historic oyster landings in Apalachicola Bay. Source: Florida Fish and Wildlife Conservation Commission.

legal thresholds, the area is closed for harvest until further testing indicates that the concentration of fecal coliform has decreased. In combination with nationwide adoption of sewage treatment standards, this component has been very effective at reducing the risk from pathogens associated with raw sewage. Since shellfish harvest generally takes place close to shore, this component is generally carried out by state agencies that have jurisdiction in these waters.

The second regulatory component includes handling requirements to ensure food safety once the shellfish are removed from the water. Handling requirements include: (a) rapid cooling capabilities for primary processors of shellfish; (b) the establishment of Hazard Analysis and Critical Control Points (HACCP) plans by seafood dealers, processors, distributors, and retailers; (c) tagging programs that differentiate between shellfish that can be eaten raw and shellfish that must be cooked before eating; and (d) the use of labels that will allow traceability if FBD or other issues are identified. In addition, shellfish harvesters must follow refrigeration requirements, and harvesters who are unable to meet refrigeration requirements must deliver shellfish to a processing facility within a specified timeframe following harvest. Refrigeration requirements are particularly important to prevent FBD, including *Vibrio* infections, as bacterial densities increase rapidly if shellfish are held at temperatures above 45 °C (113°F; Rippey, 1994). This component is enforced by state agencies in collaboration with the US Food and Drug Administration.

The third regulatory component consists of epidemiological studies for all outbreaks that implicate shellfish so that the sources of these outbreaks can be identified, and measures to prevent further cases can be taken. This component relies heavily on the appropriate use of tags and labels that are part of the seafood handling requirements, but can easily break down when tags are lost during transportation, processing, and distribution, or when shellfish are accidentally or purposefully mislabeled or improperly tagged. Proper traceability is particularly difficult to achieve when shellfish are transported across state borders, or are intermingled in large processing and distribution facilities, as labels and tags may be lost or tampered with. Since labels and tags are issued under the authority of individual states, the issuing state has limited jurisdictional authority to prosecute the tampering of tags or labels when it occurs in different states. Epidemiological studies of FBD outbreaks associated with shellfish consumption are completed in close collaboration between state and Federal authorities.

To prevent the incidence of *Vibrio* infections, the US Food and Drug Administration requires shellfish producing states to develop a *Vibrio* control plan and conduct an annual risk evaluation. In Florida, the result of this process has been the enactment of a policy that reduces the legal daily harvest period to minimize the length of time between shellfish harvest and processing. Given the relationship between cases of vibriosis and temperature (Fig. 2), the amount of time allowed between harvest and delivery to a processing facility varies by season with more restrictions in effect during warm-weather months, and the specific requirement that each harvester must follow depends on whether the individual vessel contains on-board cooling capabilities.

3. Fishery and data description

3.1. Apalachicola Bay's oyster fishery

Apalachicola Bay, located in the Florida Panhandle along the Gulf Coast, has traditionally supported a vibrant oyster industry whose product is marketed by name for its distinctive size and flavor. The harvesting technology used in Apalachicola Bay today is not very different from that used 100 years ago, and single owner-operator small vessels using hand tongs dominate the fishery (Pine et al., 2015). In addition, Franklin County's coastline is dotted with small seafood dealers and processors where vessels deliver oysters and other fish products daily. Apalachicola Bay has been a highly productive oyster fishery since at least the 1890s (Pine et al., 2015), but in recent years it has experienced a drastic resource collapse (Camp et al., 2015). Between 1992 and 2012, oyster harvests in Apalachicola Bay ranged between 1 million and 3 million pounds, with an average of 1.98 million pounds (Fig. 3). During this time period, Apalachicola Bay was the source of 85% of all Florida oysters, and 8% of all US oysters, on average (Fig. 4). The fishery's collapse began in the summer of 2012, and by 2015 landings had decreased to 520,910 lb, representing 58% of Florida's oyster production and 2% of all oysters landed in the US. At its height in 2012, the annual dockside value of the fishery was just over $9 million.

In the summer of 2012, commercial harvesters and regulators first identified a possible resource collapse through observations of very low oyster densities in locations that are repeatedly sampled. By September of 2012 the resource collapse had become evident, and Florida's governor wrote a letter to the US secretary of commerce requesting a fishery disaster declaration pursuant to Section 312(a) of the Magnuson-Stevens Fishery Management and Conservation Act[1]. In his letter, the governor cited two potential causes of the collapse: low water

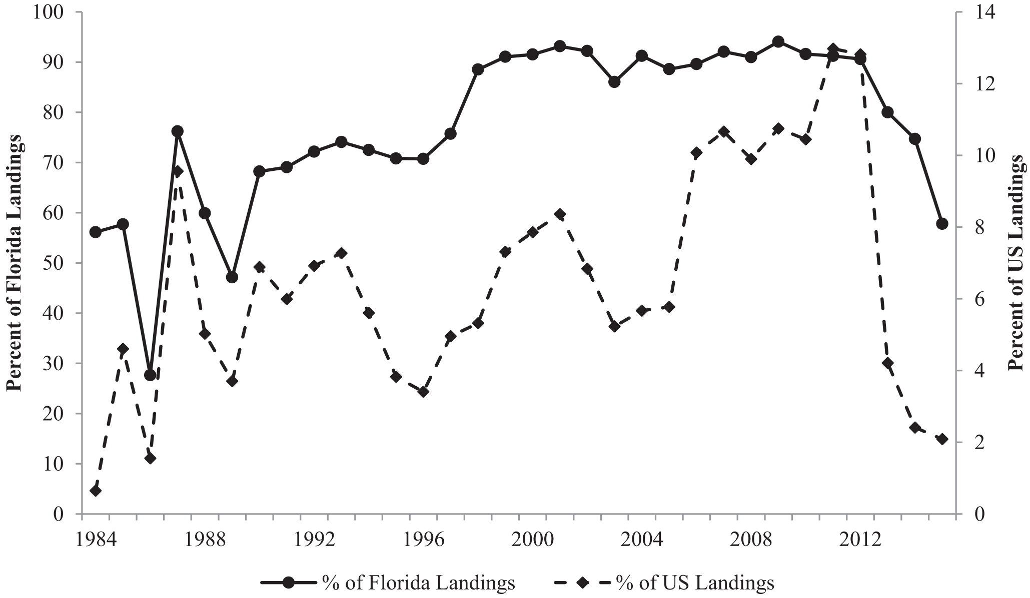

Fig. 4. Apalachicola oyster production as a percentage of Florida and US oyster production. Sources: Florida Fish and Wildlife Conservation Commission and National Marine Fisheries Service.

flows from the Apalachicola River which led to increased salinity in the Bay and thus higher oyster mortality, and overexploitation during the BP/Deepwater Horizon oil spill of 2010, when a total of 110 days were added to the summer and winter Apalachicola Bay harvest seasons (FWC, 2013). This resource collapse gave rise to a lawsuit filed by the state of Florida against the state of Georgia in the US Supreme Court over water rights in the Apalachicola-Chattahoochee-Flint river basin[2], which includes one of the main drinking water sources for metropolitan Atlanta and is the main source of freshwater in the Apalachicola Bay estuary.

Camp et al. (2015) and Pine et al. (2015) provide a thorough description of the fishery collapse and its contributing factors. For example, sampling at different locations in the Bay supports the hypothesis that decreased freshwater flows and the resulting increased salinity results in higher predation of oyster by conchs. Similarly, these studies suggest that removal of oyster shells from existing reefs has contributed to the decline of the fishery by removing potential settling locations for oyster larvae.

Individuals harvesting oysters in Apalachicola Bay must possess a general commercial saltwater products license for the state of Florida in addition to an Apalachicola Bay oyster harvesting license. Other than an annual fee, there are no major requirements for the commercial saltwater products license. However, to obtain an Apalachicola Bay oyster harvesting license, all applicants must complete a shellfish harvest education training every year. The training requirement is designed to educate fishers on sanitary shellfish harvesting, handling, and transportation practices, and can be completed in person or online. When the licenses are purchased in conjunction, the fee for the saltwater products license is waived.

The total number of licensed oyster fishermen varies between years. Historically, the number of annual harvest licenses issued has varied between more than 1,000 in the early 1990s, to close to 400 in the mid-2000s, and increasing again to nearly 1000 after 2010 (Pine et al., 2015). However, only a portion of all license holders actively participate in the fishery. For example, the summer oyster season in Apalachicola Bay brought 596 active participants in 2014, and 477 active participants in 2015.

Since the fishery collapse in 2013, licensed oyster fishers have been employed by the state of Florida in re-shelling programs, where fishers are paid to deposit oyster shell or limestone rock in specific locations across the Bay to provide areas for oyster spat or larvae settlement and thereby aid the restoration of oyster reefs. By possessing a commercial salt water fishing license, oystermen in this area are also licensed to participate in other fisheries, such as crab and shrimp, and may regularly work in seafood processing facilities and seafood markets. Some oyster fishers have started small oyster aquaculture operations, but there are significant concerns in the community about embracing oyster aquaculture as it is perceived to be the harbinger of the end of the wild oyster harvest and the lifestyle that has characterized this community for generations. The south end of Apalachicola Bay, St. George Island, is a well-known tourist destination with a healthy vacation home rental market, where many part-time oyster fishers also work as part-time cleaning crews. While there are opportunities for alternative work for people who would traditionally fish for wild oysters, the resource collapse has brought significant hardship to this community, prompting a fishery disaster declaration by the US Government.

Oyster harvesting in Apalachicola Bay is managed through seasonal harvest areas. The winter oyster reefs are open for harvest between October 1 and May 30, while the summer oyster reefs are open between June 1 and September 30 (Fig. 5). In addition, the Florida Department of Agriculture and Consumer Services monitors water quality in shellfish harvest areas throughout the year and may close individual harvest areas on a temporary basis if the fecal coliform counts are found to be higher than a pre-specified threshold. To maintain the integrity of the resource, the Florida Fish and Wildlife Conservation Commission (FWC) has also enacted a daily bag limit that can change depending on stock assessments, and a minimum size limit of three inches or more.

After the 2014 summer harvesting season, significant changes to the legal daily harvest period were enacted. Prior to this change, summer oyster harvesters in Apalachicola Bay could fish from sunup until 3 PM, at which time all shellfish harvested that day had to be delivered to a certified seafood dealer for rapid cooling, a process that reduces the internal temperature of oysters to 12 °C (53.6°F) within two hours. Vessels equipped with an on-board cooling option, in which oysters are

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[1] Public documents surrounding this and other fishery disaster declarations are available at: https://www.fisheries.noaa.gov/national/funding-and-financial-services/fishery-disaster-determinations.

[2] More information on this case is available at the US Supreme Court's blog (http://www.scotusblog.com/case-files/cases/florida-v-georgia-2/) and the Special Master's online docket for this case (https://www.pierceatwood.com/florida-v-georgia-no-142-original).

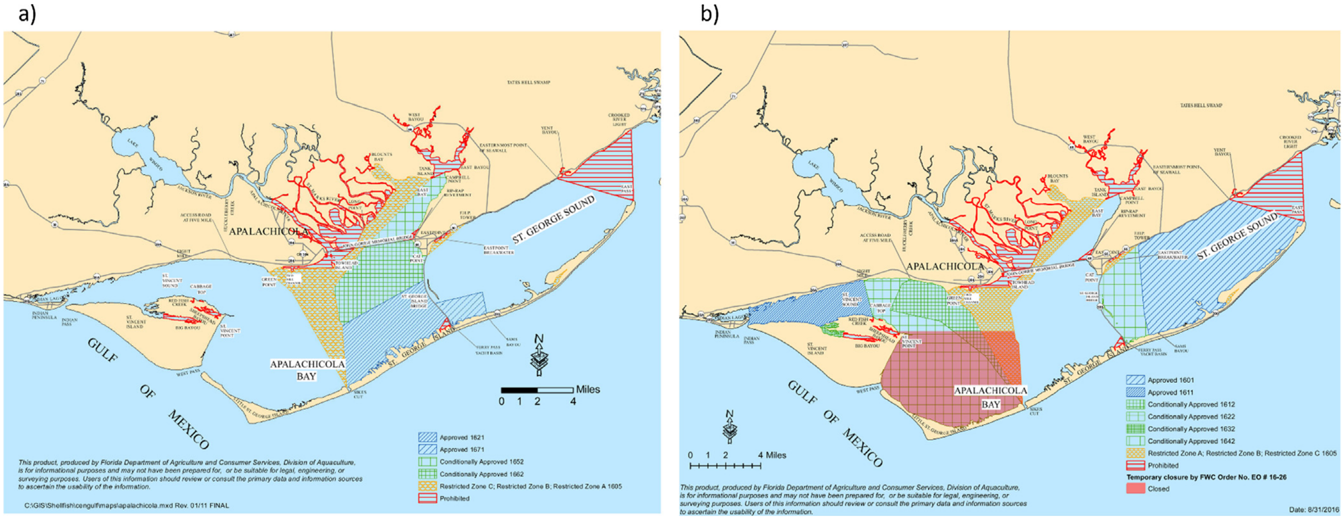

Fig. 5. Summer (a) and Winter (b) oyster reefs in Apalachicola Bay. Source: Florida Department of Agriculture and Consumer Services.

cooled immediately using an ice and saltwater slurry mix, could harvest from sunup until 4 PM. The regulatory change that took effect in 2015 reduced allowed fishing time from 3 PM to 11 AM for traditional vessels, and from 4 PM to 3 PM for vessels equipped with an on-board cooling option. It is important to note that traditional oyster vessels in Apalachicola Bay are not equipped to maintain ice or any other temperature control device. The FWC, through its law enforcement branch, enforces the time restrictions, along with other rules and regulations governing the management of the fishery such as minimum sizes and bag limits.

3.2. Data

The state of Florida has been collecting landings and fishing effort data since 1984, and state law requires the reporting of all sales of seafood products harvested in state waters using a marine fisheries trip ticket at the time of first sale. Trip tickets include information about the harvester, the dealer who purchases the product, the date of the transaction, the county in which the product was landed, and the weight of the product (Solís et al., 2013). In the past, trip tickets were completed and mailed to the FWC, but recently the system has also become available as an online platform where seafood dealers can input the necessary information[3].

This study uses all Apalachicola Bay oyster trip ticket records from June 1 to September 30 for years 2014 and 2015. The harvest areas open during this period of the year are different from those open throughout the rest of the year (Fig. 5). While shellfish all throughout the bay can be expected to interact through recruitment, as oysters from one reef can produce oyster larvae that could be moved to another reef by water flows, the oyster reefs are fixed in space and oysters do not move throughout the year as part of their life cycle or to avoid areas that are being fished heavily. Thus, there is only a minimal loss of realism by solely modeling the summer reefs, as opposed to modeling both summer and winter reefs connected through biological dispersal (Sanchirico and Wilen, 2005).

At a glance, the summer fishery appears to have adjusted dramatically between 2014 and 2015 when the new time restrictions were put in place. Fig. 6a and d show the daily participation level between the first and last days of the summer harvest in 2014 and 2015, respectively. Prior to the policy change, participation in the fishery was highest during the first day of the fishery, then remained somewhat stable between 100 and 150 vessels per day, and finally plummeted during the last 20 to 25 days in which the summer reefs were open. These dynamics contrast drastically with those seen in 2015, when an overall lower participation was observed but stayed relatively stable throughout the summer season.

The contrasting effort dynamics seen in 2014 and 2015 translate into equally contrasting dynamics for oyster landings and dockside value of the harvest. As seen in Fig. 6b and c, oyster landings and their associated dockside value in 2014 were very high on the first day of the summer season, but then decrease steadily throughout the rest of the summer harvest season. Fig. 6a–c suggest a typical open access scenario where virtually all the oysters above the minimum size requirement are harvested by the end of the season, and where fishing effort decreases as the available resource dwindles. In contrast, the daily landings and associated dockside value shown in Fig. 6d and e remained relatively high throughout the season, even though there were two multi-day periods towards the end of the season with relatively high fishing effort but very low levels of landings. Aside from these anomalous periods, Fig. 6d–f suggest a scenario where the resource is not being depleted by the end of the harvest season.

4. Methods

4.1. Bioeconomic model

In this study, we use a bioeconomic model to examine the impact of changes in oyster harvest policies for food safety on fishing effort, oyster harvests, oyster dockside prices, and fishing revenues. First, we aggregate Apalachicola Bay oyster summer harvest trip tickets into daily observations of fishing effort, landings, prices, and the associated value of landings, which allows us to run the bioeconomic model on a daily time-step. While shellfish grow and reproduce throughout the year, most growth and recruitment[4] of oysters in Apalachicola Bay takes place in late spring (March-May) and in the month of October (Pine et al., 2015), all of which are outside of the summer harvest period of interest in this analysis. Hence, it is reasonable to assume that daily growth and recruitment are negligible during the period of interest. Furthermore, since our bioeconomic model runs on a daily time step and only encompasses a single 89-day season, ignoring growth and recruitment is unlikely to affect the practicality of the model.

With this consideration in mind, our model starts by calculating the

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[3] For more information visit: http://myfwc.com/research/saltwater/fishstats/commercial-fisheries/wholesale-retail-dealers/.

[4] In population biology, recruitment is when juvenile individuals survive to be added to the population, usually through birth or immigration.

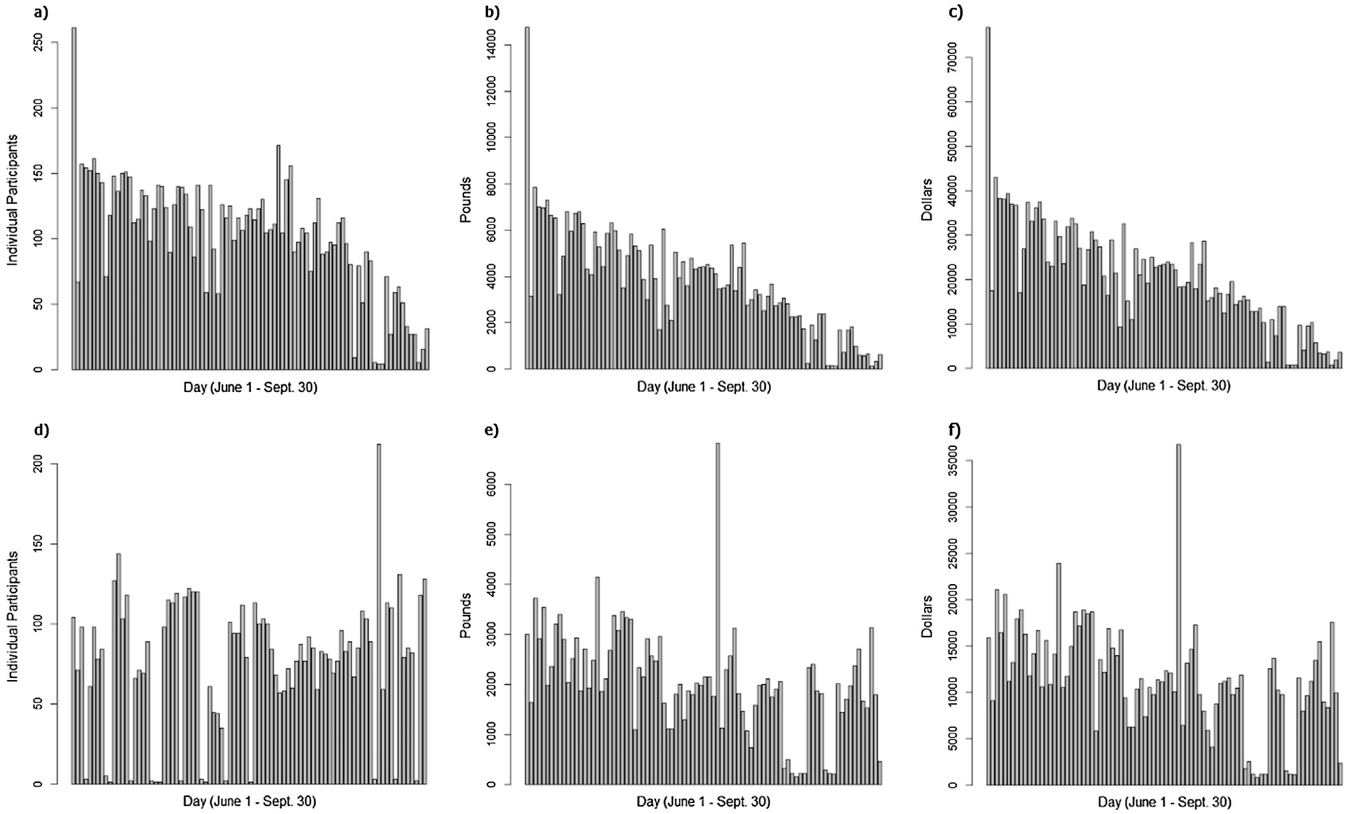

Fig. 6. Participation, landings, and dockside value of harvest for the Apalachicola Bay oyster Fishery in 2014 (top row) and 2015 (bottom row). (a) Participation in 2014; (b) Landings in 2014; (c) Dockside value in 2014; (d) Participation in 2015; (e) Landings in 2015; and (f) Dockside value in 2015.

pounds of oysters available for harvest at the opening of the summer season (X_0), as the sum of all summer landings by the end of the season. More precisely, we assume that X_0 is known retroactively after the oyster reefs are fished to exhaustion throughout the harvest season. Natural mortality through the season is assumed to be negligible, and the daily change in the biomass stock is therefore given by:

$$X_{t+1} = X_t - H_t$$
$$X_0 = \sum_{t=1}^{T} H_t, \tag{1}$$

where X_t represents the standing biomass at day t, and H_t represents the harvest in day t. In turn, the daily harvest is modeled using a Schaeffer catch equation (Conrad, 1999; Clark, 2006) given by:

$$H_t = E_t q X_t \tag{2}$$

where E_t is fishing effort, measured as the aggregate number of hours that all individual harvesters participated in the fishery on day t, and q is the catchability coefficient, a parameter that captures the efficiency of the harvest technology[5]. We arrive at an hour-based measure for E_t by multiplying the number of participating fishers by an assumed eight hours on the water per fishing day (7 AM – 3 PM) for the 2014 actual season, and four hours per fishing day (7 AM – 11 AM) for the 2014 counterfactual season, which simulates the 2014 season if the daily harvest period restrictions had been in place. Given the homogeneity of the fishing fleet and considering that all oyster harvesters use hand tongs, it is reasonable to assume that q is constant throughout each season.

Using the daily biomass and harvest model (Eqs. (1) and (2)) as a basis for calculating daily biomass stock and landings, and using the aggregated trip tickets to obtain the daily effort levels, we obtain enough information to estimate the catchability coefficient, q, using non-linear least squares regression (Amemiya, 1983). The non-linear least squares estimator, $\hat{q}$, is the value of q that minimizes the sum of squared residuals. That is:

$$\text{Min. } S_T(q) = \sum_{t=1}^{T} [H_t - (E_t q X_t)]^2 \tag{3}$$

Given the harvest policies and the fact that the fishery is completely located inshore and within the confines of Apalachicola Bay, individual licensed harvesters make a daily decision regarding whether to go fishing or not that day. Following Conrad (1999) and Clark (2006), we model this decision as a linear response function:

$$F_t = \alpha_0 + \alpha_1 (p_{t-1} H_{t-1}) + u_t \tag{4}$$

where F_t is the number of harvesters that choose to fish on day t, p_{t-1} is the average price paid for oysters on day $t-1$, and u_t is the residual error. Eq. (4) implies that F_t is a function of the fishing revenues achieved in the previous day. In other words, our model assumes that at the end of each fishing day licensed harvesters receive word-of-mouth information on the day's overall harvest, and they in turn use this information to decide whether to go fishing the next day. Also, note that fishing effort measured in hours, E_t, is simply F_t multiplied by the length of the fishing day.

We add to the traditional framework used in bioeconomic modeling by accounting for fluctuations in dockside price caused by changes in oyster harvest levels. To do so, we estimate an inverse demand function

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[5] Most modern fisheries are composed by vessels whose capacity can be differentiated by factors such as vessel size, engine power, and fuel and labor costs. However, the case of Apalachicola Bay is different from other fisheries because the entire fishery takes places within the Bay and very close to land, and since the location of the oyster reefs is well known to all participants, there are no search costs to find fish. Hence, fuel costs are not important. Similarly, all vessels are essentially the same—small two-person vessels, and are not differentiated by vessel size or engine power. Instead of vessel owners hiring deckhands, the two people on each boat typically split the day's revenues in half, after paying for the small fuel costs.

for Apalachicola Bay oysters. After testing several functional forms, the best fit was found to be the semi-log function:

$$p_t = \beta_0 + \beta_1 Ln(H_t) + \varepsilon_t \tag{5}$$

where ε_t is the residual error term.

To estimate the impacts of the legal daily harvest period changes enacted in 2015, we develop a counterfactual scenario, and compare it to a factual scenario. The difference between these two scenarios is the legal daily harvest period used to calculate E_t, which is eight hours in the factual scenario and four hours in the counterfactual scenario. In both scenarios, the endogenous effort function (Eq. (4)), the estimated catchability coefficient (Eq. (2)), and the stock differential equation (Eq. (1)) are used to predict daily landings. The impact of the policy becomes evident when the factual and counterfactual scenarios are compared in terms of landings and dockside value.

To develop a confidence interval around the bioeconomic model's results, we set up a Monte Carlo simulation with 1000 trials in which the unknown parameters (α_0, α_1, β_0, β_1 and q) are randomly drawn from their distributions using the estimated parameter means and standard errors. This procedure allows us to report the distribution of the estimated cost of the daily harvest period restriction enacted in 2015.

4.2. Cost estimation

Generally, the costs of food safety policy include the industry's cost of compliance, borne by the industry and consumers, and the administrative costs of enforcing the policy, which are borne by taxpayers. Similarly, the benefits of food safety policy are reductions in risks of morbidity and mortality associated with consuming foods that could be laced with causative agents of FBD (Antle, 1999), as well as improved consumer confidence reflected in higher demand and more secure markets for firms in the sector. In other words, effective food safety policies can be expected to reduce risks of 'collateral damage' from outbreaks of FBD involving the consumption of oysters[6]. As noted by Arrow et al. (1996) and Antle (1999), while costs of food safety policy can generally be ascertained, benefits are subject to considerable uncertainty.

In this study, the costs of the food safety policy (C) are the losses in oyster landings, estimated by comparing total landings over the season between the factual scenario (H_t^0) and the counter-factual scenario ($H_t^{'}$), or more explicitly:

$$C = \sum_{t=1}^{T} (\widehat{H}_t^{\,0}\widehat{p}_t^{\,0}) - \sum_{t=1}^{T} (\widehat{H}_t^{'}\widehat{p}_t^{'}) \tag{6}$$

5. Results

5.1. Model performance

The non-linear least squares model (Eqs. (2) and (3)) that estimates the catchability coefficient (q) yields a statistically significant parameter coefficient and fits the data well (Table 2). An exogenous effort model that uses this estimate, along with the observed effort levels, simulates landings during 2014 and fits the observed data as expected.

The ordinary least squares endogenous effort model shows a good fit of the data (Table 3; Fig. 7), with an adjusted-R^2 of 0.473. The parameter estimate on the previous day's revenue indicates that every \$10 increase in a day's average revenue will draw about seven additional fishers the following day. Similarly, the inverse demand model that relates dockside price to oyster landings also fits the data well (Table 4; Fig. 8), yielding, as expected, a downward sloping demand curve for oysters landed at dockside. These parameter estimates are used to build the policy model, where factual and counterfactual scenarios can be examined (Fig. 9).

Table 2
Non-linear least squares model of catchability coefficient (q).

$\hat{q}$	St. Error	t value	p value
2.342 e−05*	9.068 e−07	25.83	< 2 e−16
Residual St. Err.	1524		
DF	88		

Table 3
Ordinary Least Squares model of endogenous effort (F_t) as a function of average revenues in the previous day.

	Estimate	St. Error	t value	p value
Intercept	−25.71043	16.46608	−1.561	0.122
Revenue$_{t-1}$	0.68242*	0.08529	8.001	4.93E-12
Adj. R^2	0.4173			

The factual scenario, which simulates harvests if the policy is not implemented (8-hour harvest days), follows a path that mimics the one observed in the 2014 season, with very high levels of landings early in the season and a continual decline in landings as the season progresses. In contrast, the counter-factual scenario, which simulates harvests when the policy is implemented and the fishing day is reduced by four hours (4-hour harvest days), suggests that while harvests will be relatively high in the first days of the season, landings will level off after a few days and will remain stable for the duration of the season. In addition, the overall level of harvests in the counter-factual scenario is lower than that of the factual scenario.

To account for uncertainty and statistical error around the results of the policy model, we run a Monte Carlo simulation with 1000 trials. These simulations predict a mean difference in harvests between the factual and counterfactual scenarios of 110,218 lb during the entire season, or a loss in dockside value of \$593,442 (Eq. (6); Fig. 10). The box-and-whisker plot in Fig. 10 shows the boxes representing the interquartile range, or half of simulated losses, to be between 105,063 and 115,483 lb, or between \$561,798 and \$622,995 per year. All simulations range from a minimum estimated loss of 86,217 lb to a maximum of 134,035 lb, or a minimum of \$433,785 to a maximum of \$728,138 per year. The predicted change in the fishery resulting from the reduction in the legal daily harvest period is an adjustment in the timing of landings across time and a significant reduction in the overall level of landings or dockside value of the fishery.

5.2. Cost-benefit analysis

Benefit-cost analysis is widely advocated as an economic tool for comparing the desirable and undesirable impacts of proposed policies, thereby illuminating the trade-offs involved in public policy decisions (Arrow et al. 1996). While our model allows estimation of the costs of the food safety policy, estimation of the policy's benefits—which can be measured as reductions in cases of foodborne *V. vulnificus* infections—would require several years of post-policy observational data, which is not available now and will not be for several years. For example, Vugia et al. (2013) provide an assessment of the reduced caseloads of foodborne vibriosis resulting from a food safety policy enacted in 2003 in California by analyzing reported caseloads between 1991 and 2010.

Given the uncertainty surrounding cases of foodborne vibriosis and the potential impact of the policy, it is very difficult to develop a credible estimate of these benefits. To deal with this uncertainty, we create a series of scenarios of case reductions using the USDA-ERS (2014) estimates of costs per case along with the observed proportional distribution of cases into different health outcomes. To monetize these

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[6] We thank an anonymous reviewer for pointing out benefits of food safety policies beyond reductions in morbidity and mortality.

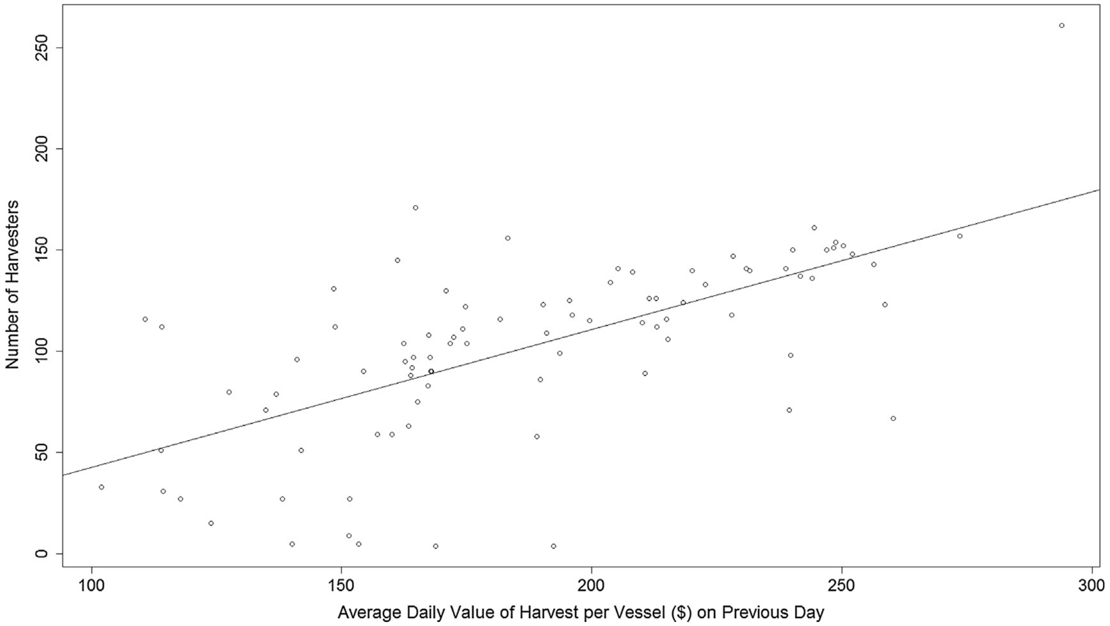

Fig. 7. Observed fishing effort (number of harvesters) as a function of average revenue in the previous fishing day (endogenous effort). The circles represent the observed data and the solid line represents predicted fishing effort using the ordinary least squares model.

Table 4
Ordinary Least Squares inverse demand model of daily oyster dockside price (P_t) as a function of the natural logarithm of oyster harvests in the same day.

	Estimate	St. Error	t value	p value
Intercept	6.15859	0.13357	46.11	$< 2e-16$
Ln(Harvest$_t$)	−0.08161	0.01669	−4.89	4.58E−06
Adj. R^2	0.2065			

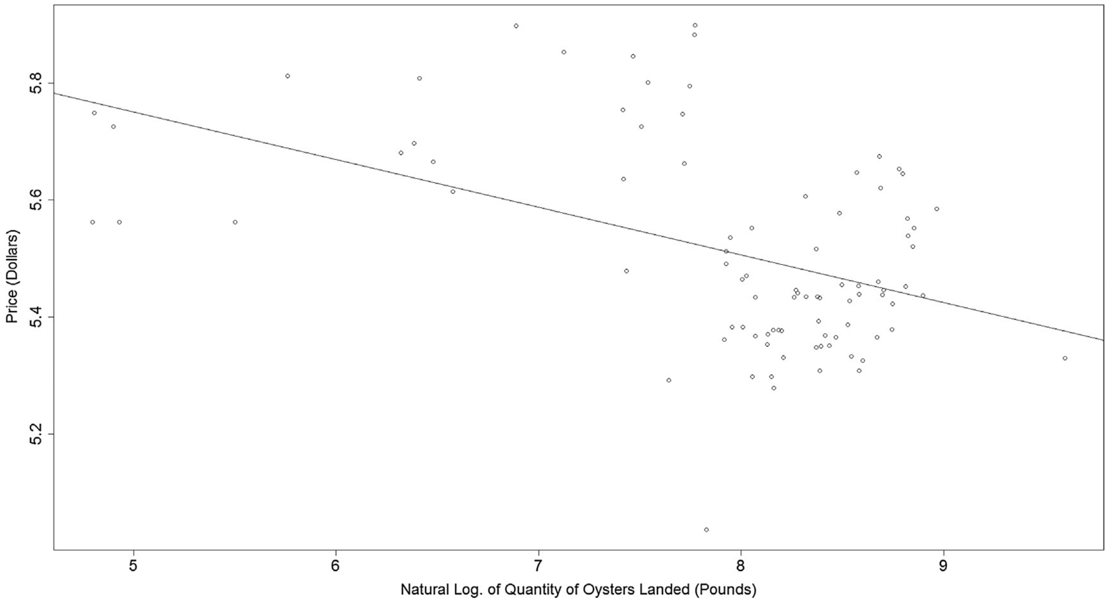

Fig. 8. Daily dockside price of oysters as a function of the natural logarithm of daily oyster landings in pounds (inverse demand function). The circles represent the observed data and the solid line represents predicted dockside prices using the ordinary least squares model.

expected benefits, we use costs of illness avoided due to the policy. Our scenarios are constructed by considering a range of total reduction in *Vibrio* caseloads and assigning cases to potential outcomes in proportion to those reported by USDA-ERS (2014). We assign cases to outcomes according to the observed proportions of cases falling within each outcome category. Explicitly, for each total caseload reduction level (R) explored, we calculate the number of cases falling in each health outcome category, m_j, as:

$$m_j = \theta_j R \tag{7}$$

where θ_j is the proportion of cases falling in each health outcome category as reported in Table 1, and j denotes the health outcome. The benefits of the policy at each total caseload reduction level explored is then calculated by multiplying the number of cases in each health outcome category (m_j) by the costs of illness for the relevant health outcome category (k_j). Hence the overall benefits of the policy for each caseload reduction level (B_R) are simulated as:

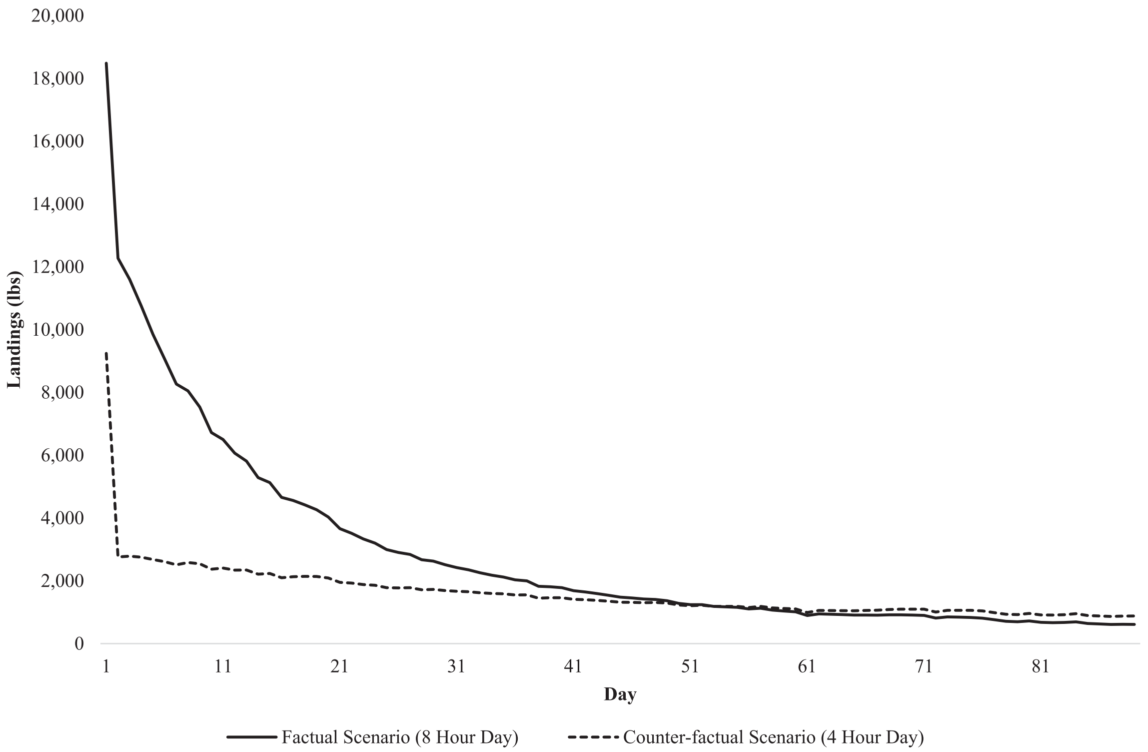

Fig. 9. Predicted daily landings in 2014 under two policy scenarios. The solid black line shows the daily landings in 2014, if fishers are allowed 8 trip hours per day. The dashed grey line shows the predicted daily landings in 2014, if fishers are allowed 4 trip hours per day.

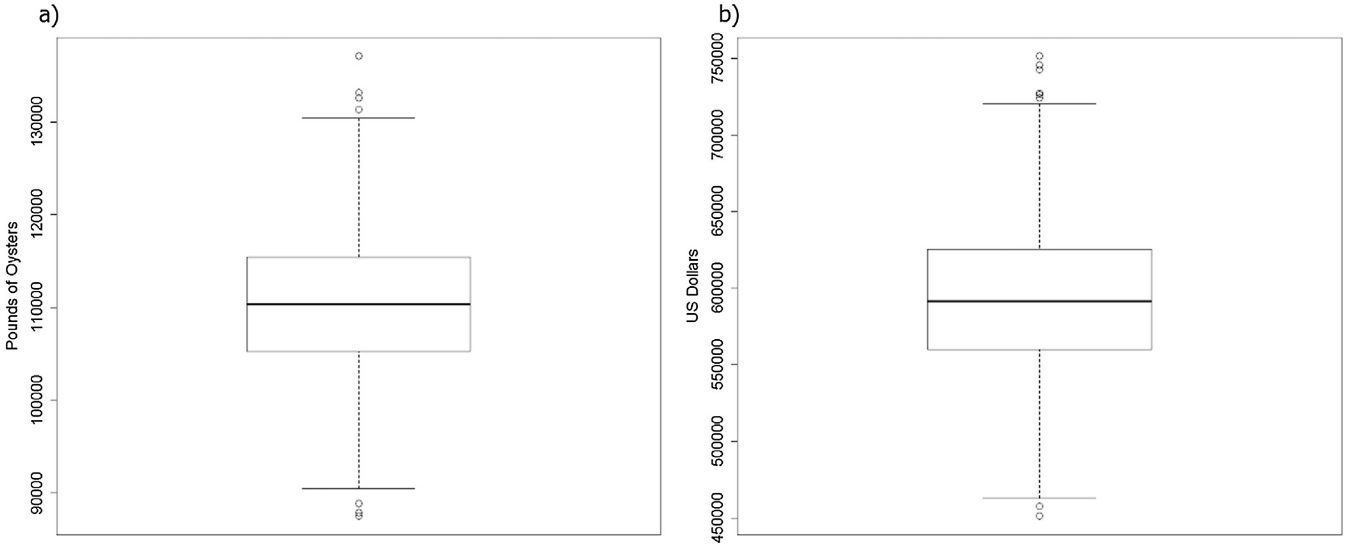

Fig. 10. Expected losses in Apalachicola Bay's summer oyster fishery as a result of reducing the length of the fishing day by four hours; (a) Expected losses in oyster landings; (b) Expected losses in oyster fishing revenues.

$$B_R = \sum_{j=1}^{J} m_j k_j \tag{8}$$

To illustrate the potential benefits of the policy, we consider a range of potential reductions in caseloads between 0 and 20. Given that annual foodborne cases of *V. vulnificus* infections in the US range in the hundreds every year, and that 196 cases were reported in Florida alone in 2015 (Adams et al., 2017), a reduction of 20 cases is reasonably attainable.

The potential net benefits of the policy under different scenarios of caseload reduction are shown as the black solid line in Fig. 11. Our results suggest that if at least two cases are prevented, the policy's benefits will outweigh the costs, as it is likely that human lives will be saved. Hence, the policy can be expected to pass the benefit-cost criteria. Prevention of 20 cases of foodborne *V. vulnificus* would yield net benefits to society exceeding $60 million, for a benefit to cost ratio of 102 to 1.

To examine the impact of our assumptions on the structure of the benefits, we conduct a sensitivity analysis that considers two alternate scenarios. In a low severity scenario, we manipulate the health outcome proportions reported by USDA-ERS (2014) to simulate a state of the world where *V. vulnificus* infections are less deadly and a higher proportion of cases result in recovery (dashed line on Fig. 11). On the other hand, we also consider a high severity scenario, where *V. vulnificus*

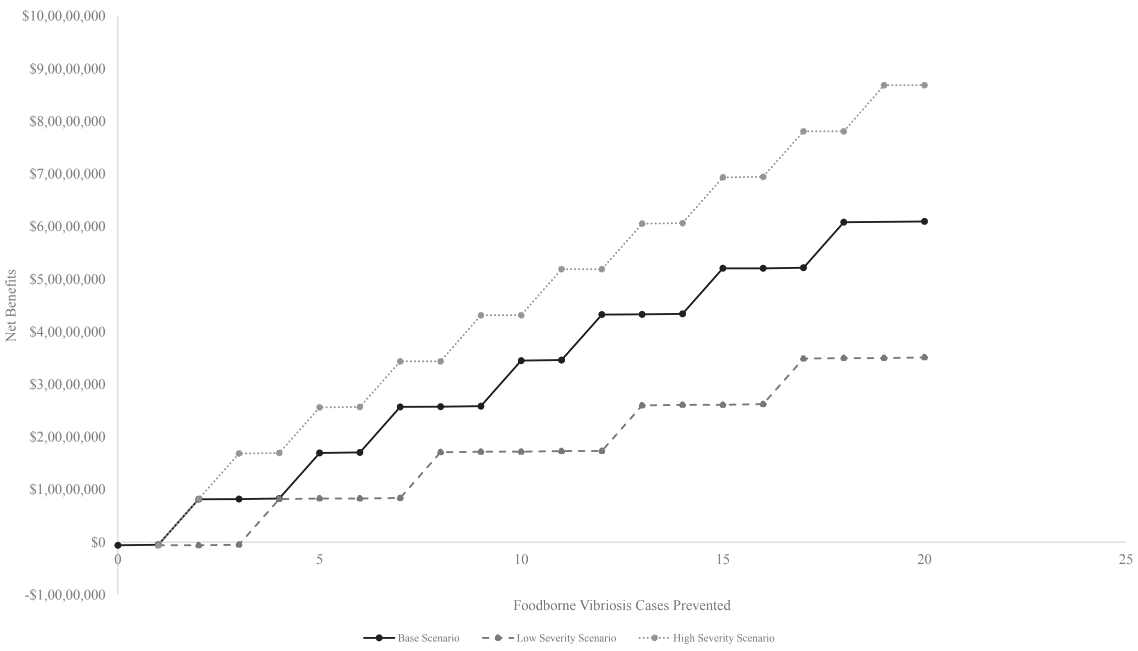

Fig. 11. The potential net benefits of the policy.

infections are deadlier than reported (dotted line on Fig. 11). Caseload proportions for all scenarios are reported in Table 1. As can be seen in Fig. 11, these changes in model assumptions do not change the qualitative results of the analysis, and benefits of the policy can be expected to outweigh its costs. However, it is important to note that these results are estimated using limited secondary information and need to be viewed with caution. This is clearly an area that merits further research.

The resource collapse in Apalachicola Bay has had deep implications for oyster fishing in this community, and as such it impacts the results of our analysis. Specifically, the size of the oyster stock at the beginning of the season (X_0) is a key parameter in determining the magnitude of the costs of the policy. A sensitivity analysis of our model shows that if the stock were larger than it was at the time of our study, the total loss in harvest value would have been greater, but the difference in value is relatively small[7]. Similarly, the benefits of the policy are a function of the cases of *V. vulnificus* prevented, which in turn are a function of the amount of raw and undercooked oysters consumed, and the level of risk inherent in the harvest and processing of these oysters. The number of oysters consumed are directly proportional to the level of harvest, which can be expected to increase if the oyster stock was larger. However, the policy would still be reducing the time of exposure of harvested oysters, and hence would be reducing the risk. Since the analysis of model sensitivity to harvestable stock levels shows that the costs of the policy are likely to be low even if the stock recovered, we expect the qualitative results of our analysis would be the same if the resource experiences a recovery.

6. Discussion

Through inclusion of several endogenous factors such as oyster stock levels, participation decisions, and dockside prices, the bioeconomic model presented in this study accurately depicts fisher behavior and predicts landings before and after implementation of the harvest time restrictions reasonably well. The factual model shown in Fig. 9 provides an accurate representation of the overall trajectory of the fishery in 2014, before the implementation of the policy. The two main features observed in the pre-policy landings data (Fig. 6b), namely a large peak in landings during the first day of the fishery, and a gradual reduction in landings as the season progresses, are well captured by the model. Similarly, the counter-factual model shown in Fig. 9 provides a good representation of the fishery in 2015, after the policy was implemented (Fig. 6e). Notably, the model accurately predicts that the gradual reduction in landings observed before the implementation of the policy will be replaced by more stable landings levels throughout the season. However, the policy model predicts a strong peak in landings on the first day of the season, and this peak was not observed in 2015. Similarly, the observed reduction in landings between 2014 and 2015, at 160,657 lb, is larger than the 110,218 lb predicted by the model.

It is important to note, however, that the Apalachicola Bay oyster fishery is a system in flux, and that in addition to the policy change evaluated here, the collapse of the stock is likely responsible for deeper adjustments that our model is not considering. For instance, there is an ongoing re-shelling program in which oyster fishers are paid by state authorities to place oyster cultch in the reefs to provide a larger area for oyster larvae to settle in and grow. In practice, this oyster restoration effort is paying oyster harvesters to exit the fishery, and may be responsible for the significantly larger reduction in fishing effort and oyster harvests, as compared to what our bioeconomic model had predicted. Hence, it is likely that individuals are leaving the fishery—but perhaps only temporarily. The underlying reason for this shift, however, is probably more due to the stock's collapse than to the new legal daily harvest period policy. Nonetheless, a determination as to which factor is most at fault requires research on rebuilding fisheries (Larkin et al. 2011), which is outside the scope of this study. Yet, this is an area that merits further research.

Recent research on consumer preferences for oysters in the US has shown that consumers associate Gulf oysters with higher risks of FBD, and prefer oysters harvested in other areas (Petrolia, 2016). This association between FBD risk and Gulf oysters can be expected to depress demand and prices of Gulf oysters, including oysters harvested in Apalachicola Bay. Therefore, if the harvest time restrictions are

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[7] The sensitivity analysis shows that at lower biomass levels, the costs of the policy would be slightly lower (11% lower for an oyster stock that was 15% smaller), and at higher biomass levels, the costs of the policy would be somewhat higher (78% higher for an oyster stock that was 5 times larger). However, the costs of the policy would be lower for oyster stocks that were 6 or more times higher than the current level. In summary, the annual costs of the policy are below $1.1 million for all stock levels examined.

effective and their effectiveness is adequately advertised, the policy may have a positive impact on demand and prices of Apalachicola Bay oysters. While this potential impact is not captured in our bioeconomic model, such an impact on prices would result in higher fishing effort, higher landings, and lower losses to the fishery. Conversely, demand for oysters can be expected to decrease when cases of vibriosis and other FBD are publicized and attributed to oyster consumption, especially if they can be traced to a given location. A publicized outbreak can be expected to reduce prices and thereby cause a reduction in fishing effort and lower landings. Due to lack of available data on timing and location of FBD outbreaks, our inverse demand function does not include any of these features. This is also an area that deserves further research.

The policy analyzed in this study does not apply to vessels with on-board cooling or refrigeration, but there are few if any such vessels in the fishery now. Oyster fishers have expressed that such a requirement would be prohibitively expensive and would drive most if not all oystermen out of the fishery. A future study could investigate a scenario where oyster vessels are forced to install on-board refrigeration equipment. Agar et al. (2017) indicate that such a type of economic analyses could be used to estimate a payment or subsidy that the state or the Federal government could use to modernize and improve the welfare of small-scale the fishery. However, that type of analysis lies beyond the scope of this study.

As discussed in the section describing the regulatory framework for shellfish in the US, water quality monitoring is already a feature of the US shellfish regulatory framework. However, the current system monitors water for presence of fecal coliform, and not for naturally occurring bacteria such as *V. vulnificus*. A program that monitors for these types of threats could be a good addition to the shellfish regulatory framework.

The increasing trend in global shellfish production (Fig. 1) is likely to be maintained in the future, bringing with it an increased risk of FBD vectored by shellfish. Along the US Gulf Coast, for example, aquaculture operations producing oysters and clams have grown rapidly as states continue to move towards provision of inexpensive submerged land leases and the technology for growing shellfish in floating cages continues to evolve. Ensuring that food safety policies such as the one examined in this paper are in place to protect the public will ensure that society can reap the rewards of a growing shellfish food supply without the inherent costs and of FBD outbreaks.

The policy we examine may also become relevant in other geographic areas and fisheries as the world's climate changes and sea surface temperatures rise. For instance, Baker-Austin et al. (2013) argue that an increased incidence of *V. vulnificus* infections in northern Europe's Baltic Sea is driven by higher sea surface temperatures, and infections that were rare or non-existent in the 1980′s are now commonplace. Changes in climate and rising sea surface temperatures can be expected to expand the range of *V. vulnificus* and other food and water-borne pathogens towards the poles, drastically increasing risks of infections. Hence, policies to protect the public from vibriosis and similar illnesses may need to be transferred from low latitude regions such as the Gulf of Mexico to high latitude areas.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2019.01.006.

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