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Examining the Northern Shrimp Fishery in a Changing Gulf of Maine

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EXAMINING THE NORTHERN SHRIMP FISHERY

IN A CHANGING GULF OF MAINE

By

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By Ashley Charleson

Thesis Advisor: Dr. Yong Chen and Dr. Keith Evans

An Abstract of the Thesis Presented
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Northern Shrimp (*Pandalus borealis)* once supported a key commercial fishery in the State of Maine. Since its closure in 2013, the stock has remained in a particularly vulnerable state following recruitment failure, overfishing, and rising water temperatures. Furthermore, without this source of supplemental income, local fishermen have also experienced financial stress following unstable fishing conditions in other fisheries. The collective goal of this research project was to assess factors impacting the feasibility of reopening and maintaining this vulnerable winter fishery. These goals are addressed over 4 chapters.

Chapter two offers insight regarding what is most often omitted from the regulatory process in fisheries management, including fisher acumen and cooperative opportunities to broaden the coalition for stewardship among resource users. By examining qualitative data collected through survey efforts, fishermen provide a first-hand account of fundamental and broadly applicable circumstances that impact fisher behavior, often resulting in inefficient outcomes in fisheries management. Collectively, qualitative data collected through industry-based surveys highlight relevant environmental, biological, socioeconomic, and fishery-specific factors hindering the development and implementation of more efficient management practices.

Assessment of the response of shrimp to changing environmental conditions and anthropogenic activity is critical to accurately determine appropriate fishing levels, especially given the lowered ability of the stock to build resilience. In Chapter three, I explore the relationship between size-at-transition and potential environmental and anthropogenic sources of influence impacting this biological process. Results showed that size-at-transition is more strongly influenced by environmental conditions experienced by northern shrimp as juveniles. Specifically, surface temperatures observed throughout the summer and fall seasons inshore were most significant, with decreases in size-at-transition observed at higher temperatures. Size at which shrimp transition from male to female is a critical stage in the life history strategy of northern shrimp. Given the vulnerable state of the fishery, managers will need to account more strongly for decreases in reproductive potential associated with smaller female body size. Such information is important to incorporate into future regulatory strategies in support of the stock's restoration. It is hypothesized that decreases in size-at-transition will continue to occur considering rising water temperatures; additional studies show that warm water accelerates metabolic growth rates in juvenile shrimp, facilitating increased molting frequency with lower overall growth observed.

Consistent with past trends, it is likely that shifting environmental conditions will continue to have adverse impacts on the northern shrimp fishery in the Gulf of Maine (GOM). If the fishery is to reopen, managers will likely be forced to make tough decisions regarding effort and participation if they intend to establish an ecologically and economically sustainable fishery. In the fourth and final chapter, I utilize a fishery-level production function to understand what suite of factors most strongly influence output (*i.e. landings*) within the fishery, highlighting key differences in strategy between both trap and trawl gear types. Furthermore, results of this analysis provide insight into the relationship between effort and shifts in harvestable biomass. A deeper understanding of sources of vulnerability and factors impacting a fisherman's adaptive capacity is crucial for the development of more effective management strategies. Used as a proxy for shifting environmental conditions, monthly remaining biomass exhibited a positive relationship with northern shrimp landings for both gear types, as did landings and certain input effort factors such as sea time, number of traps used (trappers), and number of tows (trawlers). Results suggest that certain gear types are likely to experience increased vulnerability than others, and increased control on effort will likely be necessary to better control landings within the fishery.

Shortcomings within each chapter are observed, namely due to inconsistent data collection efforts and a shortened times series regarding the data utilized within each study. Despite relatively short time series of data included, this study provides important information to help determine fleet size and effort levels should the fishery reopen in the future. Collectively, the information obtained through these studies provide valuable insight regarding 1) the impact shifting environmental conditions may continue to have on the fishery, and 2) ways in which fishers and managers may account for these shifts while facilitating cooperative efforts in the interest of biological and socioeconomic stability within the fishery.

ACKNOWLEDGEMENTS

I would like to thank all the volunteer fishermen who took time out of their busy schedules to meet with me in person, providing hours of insight into their experience and opinions surrounding the northern shrimp fishery. More graciously, I extend my deepest gratitude to those fishermen who welcomed my presence on their vessels during my first field season in 2016, during the northern shrimp RSA, and thereafter agreed to be interviewed while providing additional interview contacts; my interactions with these people and their livelihoods are some of my fondest memories here, and they are the reason for my work.

Margaret Hunter and Anne Richards, at the Maine DMR and the Northeast Fisheries Science Center, respectively, spent countless hours compiling fishery-independent survey data and answering numerous questions thereafter; without your support, this project would not be possible. I thank my advisors, Dr. Yong Chen and Dr Keith Evans, for their unwavering encouragement and guidance throughout this process, as well as my two additional committee members, Dr. Anne Richards and Dr. Joshua Stoll. Additional people who made this project possible were Rob Watts of the Maine DMR and Kelly McGrath of NOAA, who graciously took the time to collect and provide me with the state and federal harvester-dealer data needed in order to complete this work, Mackenzie Mazur, Cameron Hodgson, Dr. Kisei Tanaka, Dr. Jonathan Malacarne, and Antonio Jurliana at the University of Maine for their coding expertise and statistical insight.

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1. STATEMENT OF PURPOSE AND STUDY BACKGROUND

Northern shrimp, *Pandalus borealis*, once represented a critically important fishery to the State of Maine. Noted in previous years for its value, and more notably, its supplemental nature, the Gulf of Maine Northern Shrimp fishery has, over the past 80 years, experienced severe economic and biological booms and busts, due largely in part to changing thermal habitat, high recruitment variability, inconsistent market conditions, and intensive fishing. Following the most recent stock collapse in 2012 the fishery was placed under moratorium due to historically low recruitment and low biomass levels. While the fishery currently remains closed, my research explores sources of economic and biological vulnerability surrounding the fishery, provides guidance with which to increase the adaptive capacity of regulatory action, as well as evaluates the potential ecological and economic feasibility of maintaining this winter fishery in a changing Gulf of Maine.

Collectively, each study within this thesis seeks to answer questions surrounding sources of vulnerability within the fishery in addition to addressing gaps in information within the regulatory process. The three studies detailed here are as follows: (1) to examine and reflect upon the relationship between biological, environmental, regulatory, and socioeconomic trends over time (Chapter 2), (2) to access the potential impact of shifting environmental and anthropogenic conditions on the life history strategy of northern shrimp, specifically, size-at-transition (Chapter 3), and lastly (3) to quantify the relationship between shifts in fisher participation and effort, relevant socioeconomic, biological, and regulatory factors, and landings (Chapter 4).

Chapter 5 reviews the collective impact of each study in its review of past management strategies, examining strengths, and shortcomings in regulatory efforts, while highlighting impediments to more effective management tactics. The results of this analysis emphasize the

interrelated nature and combined implications of fishing pressure, fluctuating environmental stress, and mismanaged regulatory efforts within the northern shrimp fishery. Shortcomings of this study, as well as suggestions for continued areas of research, are also highlighted.

2. INDUSTRY MEMBER SURVEY ANALYSIS

2.1 Introduction

Utilizing responses from industry-member surveys, this research examines factors impacting behavior and effort amongst fishers, as well as market conditions, concerning the northern shrimp market; additional emphasis is placed on industry member perception of regulatory, socioeconomic, and environmental trends within the fishery. While the course of regulatory action taken is unique to each individual fishery, this chapter explores the deeper questions of *why* these actions produce undesired results, and *what* suite of factors are responsible. The outcomes of this research are intended to highlight sources of inefficiency and identify major trends within the fishery that elicit inefficient behavior and impact market conditions. With this knowledge, managers may make more well-informed choices when constructing future regulations.

2.1.1 Current Management

The regulation of fisheries nation-wide remains a source of variable discontent for both fishers and managers. While human and climate-induced impacts on marine capture fisheries is now better understood, this does not negate the fact that stabilizing fisheries means exuding more control on effort. Despite recent setbacks in productivity, the northern shrimp industry retains promising potential for economic growth if restructured efficiently. This growth, however, is dependent on a myriad of factors coming together with perfect cohesion, mainly, conditions surrounding the northern shrimp stock, and the amount of effort that may be allowed back into the fishery. Often, consideration for the socioeconomic implications of these decisions on public welfare remains largely unstudied. It is crucial that we take a proactive approach to understanding the ways in which various demographics are likely to be affected; a deeper understanding of the factors that impact behavior and effort among fishermen, as well as the inner workings of the market structure supporting this fishery are necessary to reach this goal. In anticipation of continued shifting environmental conditions, it is especially crucial to assess the circumstantial involvement and actions of all parties involved.

2.1.2 Background

2.1.2.1 Life History and Biology

Pandalus borealis are a cold-water, circumboreal species (Komai, 1999). Within the Northwest Atlantic, northern shrimp range as far north as Greenland, to their southernmost extent in the Gulf of Maine (Figure 2.1); the stock found in the Gulf of Maine is considered a genetically distinct stock (Jorde et al., 2015). As protandrous hermaphrodites, northern shrimp hatch and mature first as male before transitioning to female around year three. Stage, sex, and temperature play a major role regarding the distribution of northern shrimp, with seasonal movement an especially notable factor in the overall reproductive strategy of the species (Apollonio et al., 1986; Clark et al., 2000). The seasonal distribution of shrimp may be observed in Figure 2.2, taken from Clark et al (2000). For more information regarding northern shrimp biology, refer to Chapter 3.

Figure 2.1: Distribution and genetic distinction between northern shrimp stocks found within the Northwest Atlantic. Altered version. original taken from (Jorde et al.,2015)

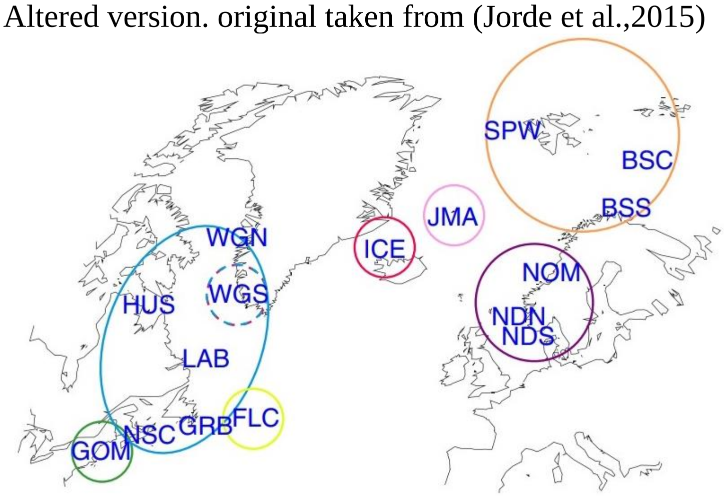
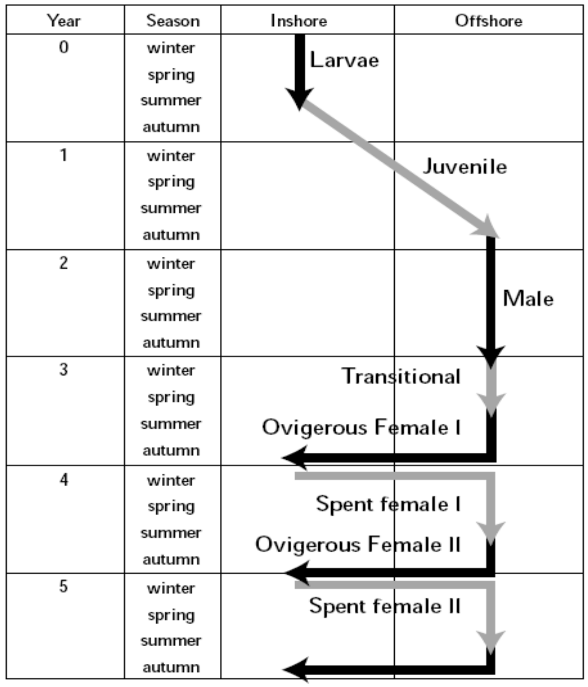


Figure 2.2: Spatio-temporal distribution based on the life cycle of Gulf of Maine northern shrimp



2.1.2.2 Description of the Fishery

Established in 1938, the northern shrimp fishery targets ovigerous (egg-bearing) females for the high quality of meat upon their inshore migration to spawn (Clark et al., 2000). As one of the last remaining open access fisheries in coastal New England, historically there were no measures in place controlling entry or managing participation levels. The fishery has served primarily to supplement fishermen's income, providing added resilience for both fishermen and coastal communities. Once a source of commercial importance, the northern shrimp fishery in the GOM was not only a valuable food source but was also a means for fishermen in the lobster and groundfish industries to diversify their income portfolio, especially during times of financial stress (Clark et al., 2000).

Heterogeneous in nature, the fishery is comprised of two different gear types (pots and trawls) with involvement that spans the entire coast of Maine. Groundfishermen utilizing trawl gear were the primary participants within the shrimp fishery until a trap fishery comprised of lobstermen began in the 1970s. Lobstermen and groundfishermen were typically the most active participants, as the shrimp fishery represented a safe alternative to following lobster and groundfish further offshore during the winter. Ground fishing boats typically traveled further offshore into deeper waters, employing the use of trawls equipped with smaller mesh nets to target female shrimp during their inshore and offshore migration. Alternatively, lobstermen fished mostly inshore using traps, as their boats are readily set up with pot haulers; in most instances, the variable topography of inshore habitat utilized by shrimp ultimately restricted trawl vessels from fishing closer to shore, allowing the trap fishery to maintain some degree of economic stability. Given the increased capacity of most trawl vessels to travel further offshore and carry more cargo, these fishers consistently accounted for a much higher percentage of landings than did vessels hauling traps.

2.1.2.3 Management History

Harvestable concentrations of shrimp were discovered in the 1800s, however, a commercial fishery was not established until 1938 (Bruce, 1971). Shrimp landings in New England grew exponentially beginning in the 1940s, following the advent of new refrigeration technology. Formal management was not employed until the 1950s. Once the fishery was established, the northern shrimp stock experienced exceptionally high removal rates of female biomass. Following the mid-1960s, the presence of management within the fishery evolved in response to continued growth in popularity and effort. Continuing with vast declines in economically important groundfish species, the increasing need for a regulatory presence within the fishery grew steadily as the northern shrimp fishery became a sinkhole for the redirection of effort orphaned by other declining fisheries. With the entry of New Hampshire and

Massachusetts draggers in the 1960s, the fishery experienced subsequent declines in abundance and decreasing product quality.

Following a growing need to combat increasing effort in a fast-declining fishery, the Fishery Management Plan (FMP) for northern shrimp was approved in 1986, establishing a three-way partnership between Maine, Massachusetts, and New Hampshire (Clark et al., 2000; McInnes, 1986). Designated representatives from participating states were tasked with the development of fishery management plans, through the solicitation of public participation and consideration of advice presented by the Northern Shrimp Technical Committee (NSTC), a team of scientists designated to provide recommendations within the regulatory process (ASMFC, 2011). Initial management efforts included the use of tools such as season length and gear restrictions. Such remedial constraints on effort were introduced to alleviate declining conditions within the fishery. Following complaints from the industry surrounding a general lack of representation, the Advisory Panel (AP) was established in 1993; composed of fishermen and other industry representatives, the AP was tasked with the job of providing additional advice towards management initiatives.

After the implementation of the original northern shrimp FMP in 1986, it has been subject to three major amendments. Amendment 1 made in 2004 incorporated improved biological reference points based on more accurate biological relationships and information, effectively expanding the tools made available to managers (ASMFC 2004). It incorporated new management tools such as quotas, possession and vessel limits, management areas, research needs and other monitoring requirements. It’s goals and objectives focused on increasing public involvement in the regulatory process, reducing the impact of regulations on coastal communities, and the continued maintenance and protection of the northern shrimp stock

(ASMFC 2004). Progress following the implementation of Amendment 1 was reflected in subsequent years through stock growth and increased fishing opportunities. However, this success was short-lived as landings rates in 2010 and 2011 were higher than anticipated, resulting in early season closures and an overharvest of the recommended total allowable catch (TAC) (ASMFC 2004). To ameliorate growing concern, Amendment 2, implemented in 2011 effectively replaced the original FMP, establishing regulatory measures designed to slow catch rates through the use of trap limits, trip limits, and mandatory days out of the fishery. Such measures were deemed necessary to provide management with greater jurisdiction and control over effort. Amendment 2 also implemented new *F* reference points, updated old biological reference points, introduced a more efficient and timely reporting system, as well as initiated the process to potentially introduce a limited entry program into the fishery (ASMFC, 2011). These measures were designed to prevent the overharvest of the soft TAC and further stock collapse, using sustainable biological reference points following the recognition that environmental conditions, in addition to fishing effort and stock abundance, play a large role in stock status. Following the implementation of Amendment 2, even though statutes were positive and well intentioned, the fishery continued to experience serious decline following 2011, as well as other significant changes (ASMFC, 2016). The combination of unfavorable environmental conditions, pressure surrounding other fisheries within the northeast (influencing swings in recruitment), and extremely low abundance indices, engulfed the northern shrimp fishery with uncertainly regarding its future health and status. In 2012, the Section (responsible for the management of the fishery) implemented Addendum I to Amendment 2 of the FMP. This adjustment provided clarification regarding the annual specification process, while establishing a set allocation of the annual hard TAC based on historic landings by gear type, splitting it up with 87% given to the trawl fishery, and 13% allocated to the trap fishery (ASMFC, 2016). This revision also provided more control to management by implementing a season closure provision designed to shut down the fishery once a predetermined percentage (80 – 95%) of the annual TAC was projected to be caught (ASMFC, 2011). The provision was precautionary in that it was implemented to anticipate untimely reporting and (ideally) prevent landings from exceeding the established TAC.

To stabilize declining conditions within the fishery, the Section implemented an indefinite moratorium for the 2014-2018 fishing seasons. During this closure, the Section implemented Amendment 3 in October 2017 detailing additional regulatory specifications in the event the fishery reopens in the future. The amendment effectively increases the flexibility of managers, allowing the use of "best available science" when defining stock status and TAC. Participating states also received more flexibility following new state-specific allocation specifications (ASMFC, 2017). Furthermore, the amendment provides additional specifications aimed to strengthen reporting requirements and accountability measures, formalize the inclusion of fishery-dependent monitoring tactics, minimize the bycatch of small shrimp through the use of size-sorting grates, and establish a maximum season length (ASMFC, 2017).

Despite best efforts to identify and ameliorate problems, improvement in this fishery remains to be seen. Amidst consecutive yearly reports of low abundance and recruitment failure (ASMFC, 2019), the northern shrimp fishery has remained closed since 2013 due to continued poor resource conditions. As of November 2018, the Section saw fit to implement a three-year moratorium, extending the moratorium on the northern shrimp fishery through 2021; this decision was made following continued reports of low recruitment, and based on the premise that, in the event recruitment improves, commercially harvestable shrimp would not be accessible for several years (ASMFC 2018).

2.1.3 Study Summary

Given the significant influence that market trends and regulatory measures impose on this fishery, it is important to understand how these fishing communities and fishermen have adapted their efforts in response to shifting opportunity and accessibility. Our primary research questions ask: how do market trends and the imposition of new regulations impact or alter trends in effort and participation within multiple fisheries (shrimp, lobster, groundfish, and scallop)? To what degree? What adaptive strategies do they employ? With these questions in mind, we aim to highlight relevant biological, socioeconomic, and regulatory factors hindering the development and implementation of more efficient management practices.

This chapter analyzes the behavioral response of industry members to shifting conditions within the Gulf of Maine northern shrimp fishery. Specific attention is paid to that which has transpired over the last two decades, namely the rate of increase in warming water temperatures within the GOM, and the moratorium that has remained in effect since 2013. This research explores the adaptive capacity of northern shrimp fishermen in the face of climate change, given its impact on resource availability and coastal vulnerability. The recurrence of themes such as regulatory distrust, economic inefficiency, and over expenditure of effort shed further light on the need for more cooperative efforts and regulatory restructuring, without which the northern shrimp fishery will remain unsuccessful.

2.2 Materials and Methods

2.2.1 Stakeholder Selection

To better understand the adaptive capacity of participants in the northern shrimp fishery, as well as the impact of market factors and regulatory influence on this decision, this survey followed a mixed method research design. Mixed method research design, as outlined by

Creswell (2009) incorporates both qualitative and quantitative data in the research and in our methodology includes conducting semi-structured interviews.

Participant selection was based on a stratified random sampling strategy, in combination with a snowball sampling method to obtain additional potential participant information from interviewees willing to provide the contact information of additional persons who met similar criteria. Participants were selected based on (i) location along the coast, (ii) gear type, (iii) participation, whether fisherman or processor, in the fishery prior to 2011, and (iv) licensing records from the Maine Department of Marine Resources (ME DMR). All participants were initially invited to participate in interviews via telephone cold-calls or email with key informants known to the participants from previous research, or their contact information provided via the ME DMR, and additional informants provided by key informants during the interview process. Participants recruited for the interviews were active stakeholders in the industry, including lobstermen, scallopers, and groundfisherman that participated in the northern shrimp fishery, as well as dealers and processors of northern shrimp, prior to the moratorium in 2013. Ethnicity, sex, or health status were not important factors in this study. Human subjects training was completed through the Collaborative Institutional Training Initiative (CITI).

2.2.2 Stakeholder Interviews

The interview questionnaire employed was designed in an effort to better understand how fishermen and fishing communities have adapted to the influence of market trends and management on participation in the northern shrimp fishery, the vulnerability and resilience of fishermen, and how to create a more sustainable northern shrimp fishery. Survey questions were developed in collaboration with University of Maine marine policy faculty, select fishers and dealers, as well as DMR staff. Questions were open-ended to elicit natural, unprompted responses. Participants were asked questions related to the impact of closures and regulations imposed within the shrimp fishery, as well as how these actions impacted their behavior in other fisheries. Questions directed towards fishermen (appendix A) addressed changes in effort and participation, socioeconomic influence (i.e. market price, variable costs, congestion, etc.) and impact on income. Additionally, interviewees were asked to provide their opinions regarding the state of management, prospects for the future, and identification of areas in need of general improvement within the northern shrimp fishery. Interview questions directed towards dealers and processors (appendix B) addressed the impact of closures and regulations within the fishery on the interviewee's business. Questions also addressed the costs associated with running said business, factors impacting shrimp product quality, and market trends. For a full summary of fishermen and dealer responses, refer to appendices C and D, respectively. Interviews were recorded with the use of a hand-held recording device, following consent from the fisher being interviewed.

Interview audio was manually transcribed Participants' names and identifying information were removed from the interview transcripts and replace with an alpha-numeric code to maintain confidentiality. Where applicable, answers were given numeric codes (-1 = no/negative, 0 = neutral, 1 = positive/yes) and were analyzed using the package igraph in RStudio. Survey responses were reviewed, coded thematically, and analyzed based on their alignment within constructed network diagrams for each interview question. Networks were constructed of nodes and edges; nodes were representative of the individual entities or responses to each question (labeled circles) while edges (directional arrows) were representative of the association or relationship between nodes (see figure 2.4 for example). The size of each node corresponds to its frequency of mention relative to the question asked. Similarly, the weight of each edge corresponds to the frequency of each relationship specified, with the direction of each arrow indicative of the directional impact of each relationship. Due to the low response rate, the data collected through these interviews serves as qualitative, ground-truthing research only, and is not intended for further statistical analysis.

2.3 Results

In total, 176 phone calls and 46 emails were made, with a return rate of 35 volunteers (16%). Each participant was given the choice of a phone or in-person interview, to which all participants opted to meet in-person. All interviews were conducted in person in the location of the participant's choosing, often occurring in the interviewee's home, on docked boats, coffee shops, and fish processing plant offices. Given interviews were conducted in person, the response rate per question was consistently high, with few blanks. Questions most often left blank were those that participants perceived as redundant. For example, fishers were asked to explain factors that influenced the decision to buy a license, to utilize said license, and to increase or decrease effort following the decision to utilize it. Percentages for each question were calculated based on the total number of respondents that answered the question, the number of which is indicated on all tables and plots.

2.3.1 Participant Summary Information

2.3.1.1 Fisher Participants

Of the fishermen that agreed to participate, 63% (17 fishers) of participants identified as trawlers, and 37% (10 fishers) identified as trappers. Table 2.1 summarizes the geo-location of each fisher's residency, homeport, and port most often landed, as well as the geo-location of each dealer. Grouped according to county lines, 26%, 44%, and 30% of fisher's maintain homeports in Downeast, Midcoast, and Southern locations, respectively (Figure 2.3). Table 2.2 provides a summary of the demographics and vessel characteristic of fisher survey respondents. Trap vessels ranged from 26 to 42 ft, while trawl vessels ranged from 31 to 71 ft. Those that reported use of a larger vessel were primarily those based out of Southern locations, while the medium to smaller sized vessels were based mostly out of Midcoast and Downeast locations. Regarding total years of experience, trappers ranged from 18 to 58 years, averaging 38 years of experience, while trawlers ranged from 26 to 60 years, with an average of 43 years of experience. Concerning shrimp, trapper experience ranged from 3 to 43 years, averaging 23 years of experience, and trawlers ranged from 6 to 48 years, averaging 27 years of experience. Fishermen reported a range in crew member employment from 0 – 3 members, zero indicating that the captain worked alone with either no deckhands or sternman. There was no discernible difference in the number of crew employed based on gear type. Regarding trip-level costs (i.e. daily costs incurred following the decision to fish), 62% of trawlers reported fuel (62%) to be the highest variable cost followed by crew salary (8%) and ice (4%); alternatively, trapper responses appear more evenly spread, with 27% reporting bait as the highest variable cost, followed by fuel (19%), crew salary (4%), and the start-up cost of gear (4%). Dependence on shrimp varied by gear type amongst fishers, and across locations amongst dealers. On average, trappers reported that income from shrimping represented a lower percentage of seasonal (i.e. winter months) and total annual income than that reported by trawlers; trappers reported income from shrimp averaged 45% for winter months and 13% annually, while trawlers averaged 75% for winter months to 28% annually (Table 2.3) . During the winter, 40% of trappers and 80% of trawlers reported that shrimp represented 75 to 100% of their seasonal income. Annually, 70% of trappers indicated that shrimp represented 0 to 14% of their annual income, while 35.5% of trawlers indicated shrimp represented 30 to 49%, as well as 15 to 29% of their annual income (Table 2.3).

Collectively, 100% of fishers indicated that fishing represented their main source of income. 90% of trappers reported fishing a full 12 months out of the year, while trawlers reported activity ranging 5 – 12 months, with over 75% reporting fishing a full 12 months.

Figure 2.3: Geo-locational map of survey participant homeports and dealer location

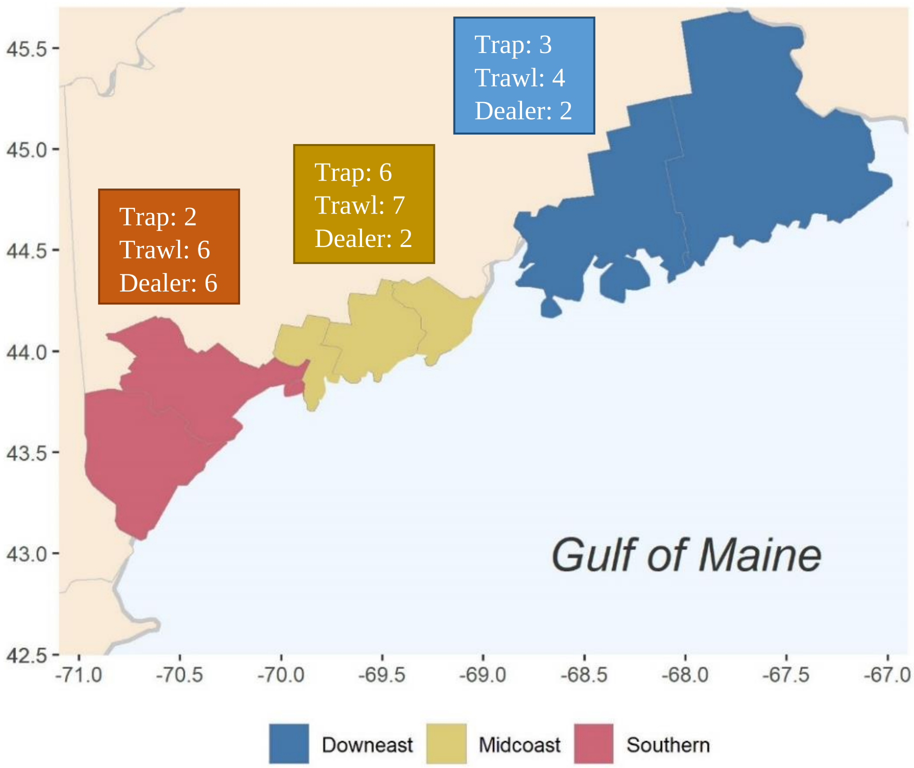


Table 2.1: Geographic location of fisher residence, homeport, and port landed most often, as well as geographic location of dealer facility. (n) represents the number of individuals.

	Fishermen									Dealer Location
	Residency			Homeport			Port Landed			
Location	Trawl	Trap	Total	Trawl	Trap	Total	Trawl	Trap	Total	
Downeast	29%	30%	30%	24%	30%	26%	29%	20%	26%	20%
Midcoast	47%	50%	48%	41%	50%	44%	41%	60%	48%	20%
Southern	24%	20%	22%	35%	20%	30%	65%	20%	48%	60%
(n)	17	10	27	17	10	27	17	10	27	10

*Totals that do not add up to 100% indicate multiple responses per individual

Table 2.2: Fisher participant statistics detailing years of fishing experience and boat length.

(n = 27)	# Years Fishing Experience						Boat length (ft)		
	In Total			Shrimp Only					
Gear Type	min	max	avg	min	max	avg	min	max	avg
Trap	18	58	38	3	43	23	26	42	34
Trawl	26	60	43	6	48	27	30	71	50.5

Table 2.3: Fisher participant statistics describing what percent of their respective winter (i.e. December – March) and Annual (entire year) income came from shrimping.

%	% Winter Income		% Annual Income	
	Trap	Trawl	Trap	Trawl
(0-14%)	40%	0.0%	70.0%	17.6%
(15-29%)	10%	20.0%	30.0%	35.3%
(30-49%)	0%	6.7%	0.0%	35.3%
(50-74%)	10%	6.7%	0.0%	11.8%
(75-100%)	40%	80.0%	0.0%	0.0%
(n)	10	15	10	17

2.3.1.2 Dealer Participants

Split by county, 20%, 20%, and 60% of dealers, were based out Downeast, Midcoast, and Southern locations, respectively (Figure 2.3). Regarding the size of their business, 40% of dealers reported their business as “small”, 30% reported as “medium”, and 30% reported as “large,” in comparison to other businesses. Businesses self-identified as either a cooperative (20%), a sole proprietorship (20%), or a corporation (60%). Years in operation ranged from 12 to 106 years, averaging 59 years of experience, while years participating in shrimp range from 6 to 53 years, averaging 30 years of experience.

Annual staff employed ranged from 6 to 150 people in total, while the seasonal number of employees varied relative to the size of the business; small, medium, and large dealers reported 6 to 15, 10 to 50, and 16 to 150 annual employees on average, respectively, outside of winter months. Both smaller and larger-sized facilities reported increasing the number of employees during the winter, especially when handling catch from seasons characterized by higher shrimp abundance. Prior to the moratorium, dealers reported staying in operation between

10 to 12 months out of the year, with 90% reporting operating a full 12 months. Following 2013, all dealers noted that business slowed down drastically during winter months; many stated that an unsustainable or slow flow of business was not enough to keep the business running properly.

100% of dealers reported obtaining their shrimp directly from fishermen, 50% of which reported fishermen as their main source of shrimp. Of those who reported buying from fishermen, 40% of respondents specified buying from both gear types, though they indicated that trawlers were their primary source due to volumetric needs. The latter 60% bought from other dealers/processors secondarily, on an as-needed basis, with only 1 dealer reporting that they bought primarily (90%) from other dealers. All facilities (100%) reported buying shrimp within their own jurisdiction, however, only large Southern-based businesses (30% of dealers) reported buying outside their own geographic location. Those that outsourced indicated buying shrimp in Downeast and Midcoast locations; two facilities reported purchasing shrimp outside of Maine in New Hampshire and Massachusetts. All dealers reported buying shrimp whole (i.e. untouched, prior to processing). Regarding the processing of shrimp, 40% of dealers identified solely as dealers, facilitating the sale of shrimp only, whereas 60% identified as both dealers and processors of northern shrimp, involved in both preparation and sale. For those that did not process shrimp, the product was sold whole (i.e. legs, head, antennae still attached). The remainder reported selling their product either headless (50%), peeled (30%), frozen (30%), cooked (10%) when selling internationally, as well as handpicked or hand-peeled (20%).

2.3.2 Effort in the Northern Shrimp Fishery

Survey respondents reported annual participation in multiple fisheries; results are summarized in Tables 2.4 and 2.5. In addition to shrimp, fishermen reported participating in groundfish (78%), lobster (70%), scallops (56%), other (26%), and shellfish (19%) fisheries.

Dealers reported involvement in groundfish (90%), lobster (80%), scallops (20%), shellfish (40%), and other (10%) fisheries (Table 2.4). Participants also reported their target species. For fishermen, 80% of trappers indicated their primary species was lobster, followed by scallops (20%); 47% of trawlers also identified lobster as their target species, followed by groundfish (41%), and shrimp (6%) (Table 2.4). Overall, the number of fisheries each fisher was involved in annually, including shrimp, ranged from 1-6 (Table 2.5). The majority of trappers (50%) indicated participation in 4 fisheries annually, while the majority of trawlers (59%) expressed involvement in 3 fisheries annually; 4% of all respondents indicated that shrimp was their only participating fishery. On average, trappers participated in a higher number of fisheries each year than trawlers.

Table 2.4: Survey participants indicated other fisheries they participated in throughout the year during their involvement in the northern shrimp fishery. Fishers were also asked to indicate their target species during participation in northern shrimp.

Species	Participating Species				Target Species		
	Trap	Trawl	All Fishers	Dealer	Trap	Trawl	All Fishers
Groundfish	60%	88%	78%	90%	0%	41%	26%
Lobster	100%	53%	70%	80%	80%	47%	94%
Shrimp	100%	100%	100%	100%	0%	6%	4%
Scallops	70%	47%	56%	20%	20%	0%	7%
Other	50%	18%	26%	10%	0%	0%	0%
Shellfish	10%	24%	19%	40%	0%	0%	0%
(n)	10	17	27	10	10	17	27

Table 2.5: Survey participants indicated the number of fisheries they were consistently involved in during the time of their participation in the northern shrimp fishery. “1” indicated participation only in northern shrimp.

# fisheries	# participating fishereis		
	Trap	Trawl	All Fishers
1	0%	6%	4%
2	10%	12%	11%
3	30%	59%	48%
4	50%	12%	26%
5	10%	6%	7%
6	0%	6%	4%

2.3.2.1 Entry and Participation

Fishers were asked to describe what reasons drove them to purchase a license; full results are summarized in Table 2.6. 100% of respondents indicated that conditions within the shrimp fishery was one of the primary drivers influencing their decision to buy a license. More specifically, fishers indicated that access to supplemental income (78%), fisher behavior concerning past success and tradition (52%), and stock conditions related to abundance and accessibility (41%) were among the most influential. Fishers also indicated that conditions in other fisheries (52%), including dissatisfactory regulations (30%) and declining stock conditions (19%), as well as environmental conditions, such as bad weather (26%), also contributed towards their decision to purchase a license.

When fishermen were asked, for every year they bought a license, whether they utilized that license, 63% of fishermen answered “yes,” 30% replied “no,” and 7% did not reply (Table 2.7). 100% of fishermen reported having fished during the shrimp season at times regardless of whether it was cost effective or not. Table 2.8 indicates which factors contributed towards an individual’s decision to utilize their license during the shrimp season. Factors discouraging utilization (Table 2.8a) included declining shrimp fishery conditions (15%), such as low abundance, low profit, and gear conflict, as well as poor market conditions (10%) and attractive conditions in other fisheries (10%). Factors encouraging involvement (Table 2.8b) included, most notably, conditions within the shrimp fishery (80%), namely dependence on supplemental income (70%) and positive return on effort (15%). Additional factors encouraging utilization included diminished conditions in other fisheries (15%), regulatory distrust (10%), and attractive price (5%).

Table 2.6: Fishers indicate what factors positively influenced their decision to purchase a license for the northern shrimp fishery.

	Variable	Trawl	Trap	Total
Conditions in Other Fisheries	Stock conditions	12%	30%	19%
	Declining access	18%	0%	11%
	Return on effort	12%	0%	7%
	Regulations	35%	20%	30%
	% unique fishers:	65%	30%	**52%**
Shrimp Fishery	Competition	0%	30%	11%
	Supplemental Income	76%	80%	78%
	Fisher behavior	47%	60%	52%
	Stock conditions	35%	50%	41%
	Vessel capacity	18%	0%	11%
	% unique fishers:	100%	100%	**100%**
Regulatory Conditions	Input Controls	6%	0%	4%
	Distrust	6%	10%	7%
	% unique fishers:	6%	20%	**11%**
Market Conditions	Price	6%	10%	7%
	% unique fishers:	6%	10%	**7%**
Environmental Conditions	Weather	18%	40%	26%
	% unique fishers:	18%	40%	**26%**
(n)		17	10	27

Table 2.7: Following the decision to purchase a license, fishermen were asked whether they participated in the fishery each year they bought a license.

Gear Type	Yes	No	No Reply
Trap (n = 10)	40%	40%	20%
Trawl (n = 17)	76%	24%	0%
Total (n = 27)	63%	30%	7%

Table 2.8: Fishers describe what factors (a) discouraged them from utilizing and (b) encouraged them to utilize their shrimp license post purchase. "% unique fishers" indicates the percentage of fishers, by gear type, who provided a response. Percent emboldened in red indicates the total percentage of all respondents.

(a) Do not utilize license (post purchase)			(n = 20)	
	Variable	Trawl	Trap	Total
Conditions in Other Fisheries	Market Conditions	5%	0%	
	Stock conditions	5%	0%	
	% unique fishers:	10%	0%	**10%**
Shrimp Fishery	Competition	5%	0%	
	Shrimp stock	5%	0%	
	Reurn on effort	5%	0%	
	% unique fishers:	15%	0%	**15%**
Market Conditions	Price	5%	0%	
	Market stability	5%	5%	
	% unique fishers:	5%	5%	**10%**
(b) Utilize license (post purchase)			(n = 20)	
	Variable	Trawl	Trap	Total
Conditions in Other Fisheries	Stock conditions	10%	0%	
	% unique fishers:	10%	0%	**10%**
Regulatory Conditions	Regulatory distrust	5%	5%	
	Output controls	5%	0%	
	% unique fishers:	5%	5%	**10%**
Shrimp Fishery	Access	55%	15%	
	Return on effort	5%	10%	
	% unique fishers:	60%	20%	**80%**
Market Conditions	Price	0%	5%	
	% unique fishers:	0%	5%	**5%**
(n)		20	20	20

2.3.2.2 Expenditure of Effort

Following the decision to fish, fishermen were also asked what factors influenced how much effort they put into fishing. Tables 2.9 and Table 2.10 provide a detailed summary regarding what factors elicit increases and decreases in effort within the northern shrimp fishery, respectively. Regarding positive sources of influence, 89% of fishers indicated attractive conditions within the shrimp fishery such as high abundance and spawning behavior (59%), proximity to homeport (52%), seasonality (48%), and positive return on effort (44%) were most influential (Table 2.9). Fishers also made frequent note of regulatory conditions surrounding the fishery as a source of encouragement (74%) including input controls such as season length and days at sea (63%), as well as regulatory distrust (19%). Additionally, 41% of fishermen reported market conditions, namely price (33%) and product quality (26%), as additional sources of influence. Factors leading to decreased effort levels (Table 2.10) most notably included declining conditions within the shrimp fishery (89%); fishers frequently cited decreasing return on effort like low landings and declining profit (47%), increased frequency of gear conflict (37%), and declining shrimp abundance and accessibility (26%). Adverse weather conditions (32%) were moderately influential, with mainly trawl fishermen (42%) making note of the fact that bad weather strongly impacted their ability to chase shrimp offshore. Visual representation of Tables 2.9 and 2.10 may be observed in Figures 2.4 and 2.5, respectively.

Differences in target months between gear types coincided with the timing of northern shrimp movement inshore and offshore, with only 38% trawlers responding positively to targeting northern shrimp in December (Figure 2.6). Fishermen agreed that April and May (96-100%) were the worst months to target northern shrimp. On average, January, February, and March, were identified as the most ideal months due to the accessibility of shrimp, given their proximity to shore, the heightened market demand, and high product quality during this time (Table 2.11, Figure 2.6); After March, respondents noted that the shrimp were often too far offshore to chase, and the product quality severely declines following the shrimp egg drop. Slight differences in opinion were observed between location and gear type.

Tables 2.9: Factors influencing a fisher's choice to increase effort within the northern shrimp fishery. "% unique fishers" indicates the percentage of fishers, by gear type, who provided a response. Percent emboldened in red indicates the total percentage of all respondents.

	Variable	Trawl	Trap	Total
Conditions in Other Fisheries	Competition (+)	12%	10%	11%
	Stock Conditions	6%	0%	4%
	% unique fishers:	12%	10%	**11%**
Shrimp Fishery	Shrimp Stock (+)	71%	40%	59%
	Proximity to port	59%	40%	52%
	Seasonality	47%	50%	48%
	Competition (-)	6%	20%	11%
	Gear Conflict (-)	29%	20%	26%
	Return on Effort (+)	53%	30%	44%
	% unique fishers:	94%	80%	**89%**
Market Conditions	Price (+)	12%	70%	33%
	Product Quality (+)	18%	40%	26%
	Supply (-)	0%	10%	4%
	Demand (+)	12%	10%	11%
	% unique fishers:	41%	40%	**41%**
Regulatory Conditions	Distrust	12%	30%	19%
	Input Controls	59%	70%	63%
	Quota	6%	0%	4%
	% unique fishers:	71%	80%	**74%**
(n)		17	10	27

Tables 2.10: Factors influencing a fisher's choice to decrease effort within the northern shrimp fishery. "% unique fishers" indicates the percentage of fishers, by gear type, who provided a response. Percent emboldened in red indicates the total percentage of all respondents.

	Variable	Trawl	Trap	Total
Environmental	Bad Weather	42%	14%	32%
	% unique fishers:	42%	14%	**32%**
Shrimp Fishery	Shrimp stock (-)	8%	57%	26%
	Input effort (+)	8%	43%	21%
	Competition (+)	0%	43%	16%
	Gear Conflict (+)	33%	43%	37%
	Return on effort (-)	50%	43%	47%
	% unique fishers:	83%	100%	**89%**
Conditions in Other Fisheries	Stock conditions (+	25%	0%	16%
	% unique fishers:	25%	0%	**16%**
Regulatory Conditions	Input Control	8%	14%	11%
	Distrust	0%	14%	5%
	% unique fishers:	8%	29%	**16%**
Market Conditions	Product Quality (-)	0%	14%	5%
	% unique fishers:	8%	14%	**5%**
(n)		12	7	19

Figure 2.4: Visual representation of fisher responses detailing factors that elicit **increased** effort within the northern shrimp fishery, split between trap and trawl gear types. The size of each node corresponds to frequency of mention, while the width of each edge indicates the frequency of each indicated relationship.

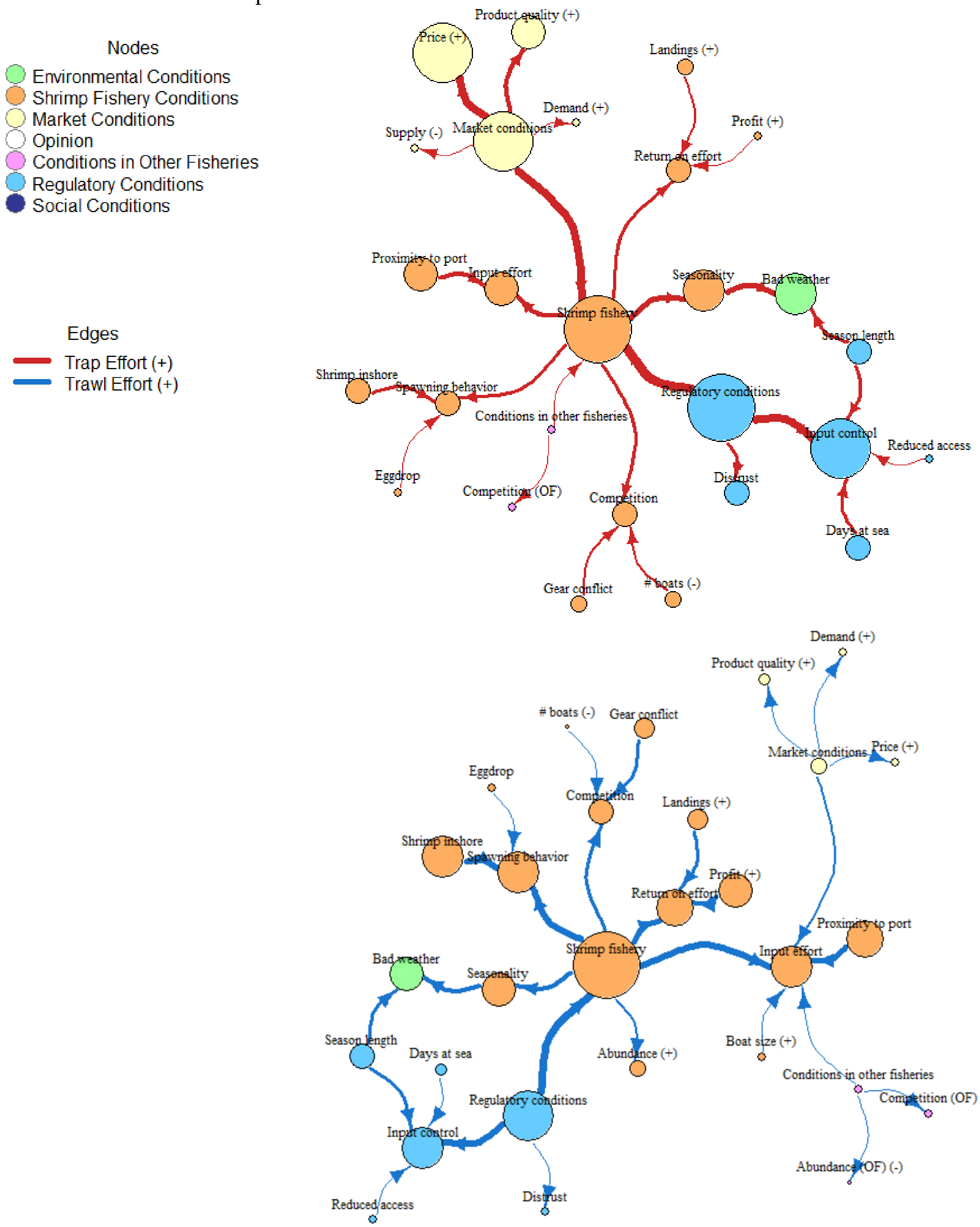


Figure 2.5: Visual representation of fisher responses detailing factors that elicit **decreased** effort within the northern shrimp fishery, split between trap and trawl gear types. The size of each node corresponds to frequency of mention, while the width of each edge indicates the frequency of each indicated relationship.

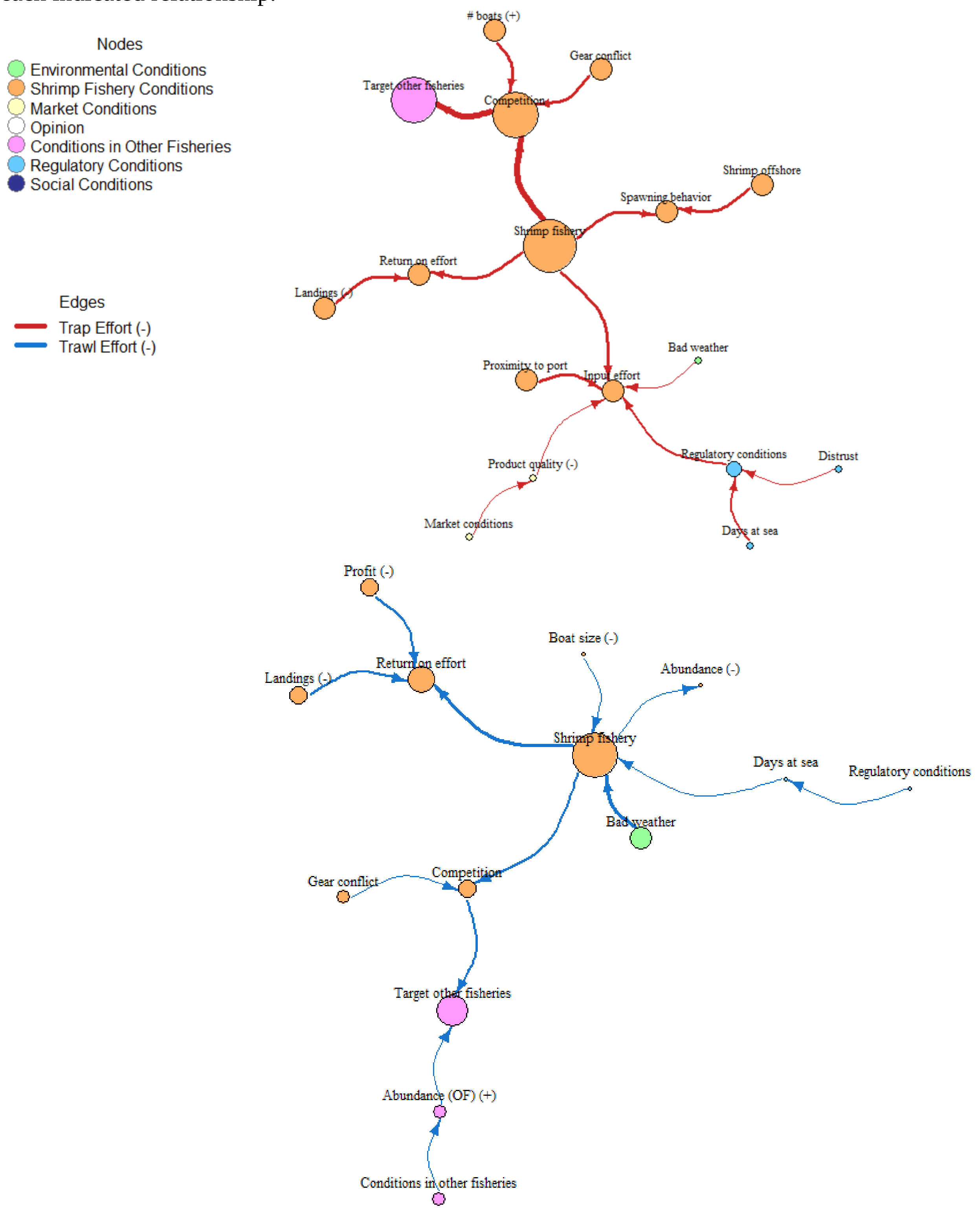


Figure 2.6: Fishers indicate which months they avoided targeting *versus* those they actively targeted northern shrimp during, split by gear type.

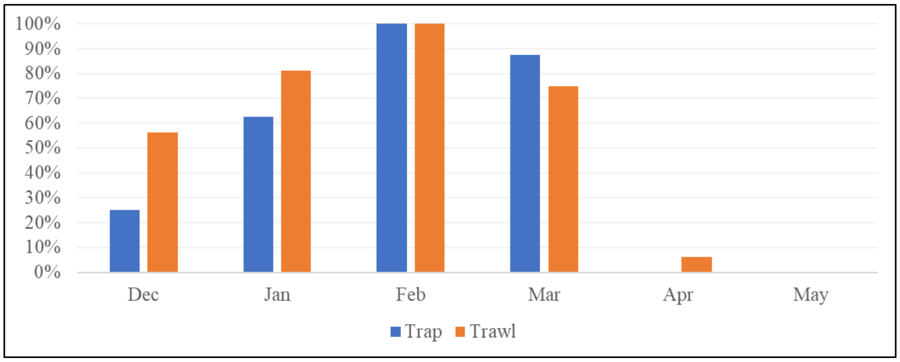


Table 2.11: Fishers indicate what factors influence their decision to (+) target certain months. Percent emboldened in red indicates the total percentage out of all participating fishermen.

Variable		Trap	Trawl	Total
Fishery	Inshore	63%	56%	56%
	Seasonality	38%	44%	40%
	% unique fishers:	100%	81%	**88%**
Market Conditions	Holiday demand	13%	13%	12%
	Market conditions	0%	19%	12%
	Product quality	0%	31%	20%
	% unique fishers:	13%	56%	**42%**
Competition	Gear conflict	0%	13%	8%
	% unique fishers:	0%	13%	**8%**
(n)		8	16	25

2.3.3 The Northern Shrimp Market

2.3.3.1 Method of Sale

Regarding location of sale, 48% of fishermen reported landing or selling both locally (i.e. around their homeport), and non-locally (outside their homeport), while the remaining 52% (80% of trappers and 35.5% of trawlers) of fishermen reported selling only within proximity to their homeport (Table 2.12). Of the 48% who chose to fish out of or sell outside their homeport, 85% indicated doing so out of Portland, ME, specifically, while the remaining 15% also indicated doing so in Midcoast locations; driving reasons for doing so included factors such as market capacity (83.3%), shrimp abundance (33%), and price (17%). In total, 70% of fishers sold to Southern, 52% to Midcoast, and 30% to Downeast locations (Table 2.12).

Table 2.13 provides a detailed summary on method of sale and associated reasoning. Fishers reported multiple methods of sale; most frequently, respondents reported bringing their catch to a dealer (93%), followed by sale to a peddler, or self-peddling (48%), and selling to a buyer or representative waiting on the dock (19%). Of those that reported selling to a peddler or self-peddling, the majority (44%) had homeports in Midcoast and Downeast locations. Fishermen who sold to multiple dealer reported doing so for reasons including increased market capacity (63%), price (37%), convenience (26%), and guaranteed business (15%).

2.3.3.2 Market Price

Collectively, respondents provided similar indication regarding factors believed to impact price (Table 2.14); respondents identified product quality (59%) as the most prominent factor controlling price, followed by demand (57%), market saturation (38%), and processing capacity of dealers (28%). Some fishers and dealers (24%) also made note of price differentials observed between gear types.

Table 2.12: Survey respondents indicate whether they landed and sold their catch within their designated homeport

(a) Landed in homeport; sold in homeport (52%)			
Location	Trap	Trawl	Total
Downeast	20%	18%	19%
Midcoast	40%	6%	19%
Southern	20%	12%	15%
Total	80%	35%	**52%**
(b) Landed or sold to locations outside of homeport (48%)			
Location	Trap	Trawl	Total
Downeast	10%	12%	11%
Midcoast	10%	41%	30%
Southern	0%	12%	7%
Total	20%	65%	**48%**
(c) Location sold to (upon landing)			
Location of Sale	Trap	Trawl	Total
Downeast	30%	29%	**30%**
Midcoast	60%	47%	**52%**
Southern	60%	76%	**70%**
	(n = 10)	(n = 17)	(n = 27)

Table 2.13: Survey respondents indicate their main method(s) of sale after landings shrimp.

(a) Method of Sale (upon landing)		Trap	Trawl	Total
	Response	Trap	Trawl	Total
	Buyer waiting on dock	10%	24%	**19%**
	Sold to Dealer	100%	88%	**93%**
	Sold to Peddler or Self-Peddled	50%	47%	**48%**
		(n = 10)	(n = 17)	(n = 27)
(b) Reason for selling to multiple vs. single dealer(s)				
	Response	Trap	Trawl	Total
Sold to Multiple Dealers	Dealer Loyalty	20%	18%	19%
	Peddled	40%	35%	37%
Sold to Single Dealer	Guaranteed Business	20%	12%	15%
	Convenience	40%	18%	26%
	Market Capacity	40%	76%	63%
	Price	30%	41%	37%
		(n = 10)	(n = 17)	(n = 27)

*Totals does not sum to 100% because fishers indicated multiple methods of sale

Table 2.14: Survey respondents indicate what factors they perceive to most strongly impact the price of shrimp. Respondents were not limited in the number of responses they provided.

Reason	Dealer	Trap	Trawl	Total
Dealer 's Choice	60%	100%	100%	**89%**
Fisher Influence	10%	0%	0%	**3%**
Demand	80%	70%	35%	**57%**
Market Capacity	30%	10%	35%	**27%**
Market Saturation	40%	20%	47%	**38%**
Price Elsewhere	10%	10%	6%	**8%**
Product quality	80%	50%	53%	**59%**
Count per lb	60%	10%	35%	35%
Level of Damage	30%	50%	18%	30%
Gear type (trap)	40%			24%
	(n = 10)	(n = 10)	(n = 27)	(n = 37)

2.3.4 Survey Participant Opinions and Perception

2.3.4.1 Observed Changes

When asked to identify some of the more notable changes in the fishery since the beginning of their involvement (Table 2.15), almost 90% of fishermen identified regulatory changes, such as increases in number and restrictiveness, as most apparent. Increases in fishing effort (39%) were also noted; many cited an unsustainable rise in the number of boats entering the fishery prior to its closure, as well as increased efficiency of gear.

Table 2.15: Survey respondents indicate greatest perceived changes during their involvement in the northern shrimp fishery.

Variable	Detail	% Detail
Fishing Effort	Increased # Boats	26%
	Increased Size of Boats	17%
	Increased # Traps	22%
	Increased Gear Efficiency	22%
	Total % unique:	**39%**
Gear Conflict	Increased gear conflict	9%
	Total % unique:	**9%**
Stock Condition	Declining stock condition	4%
	Total % unique:	**4%**
Regulatory	Increased Restrictiveness	48%
	Increased # Regs. Implimented	57%
	Increased Frequency of Closures	26%
	Total % unique:	**83%**

(n = 23)

2.3.4.2 Perceived Problems

Fisher and Dealer survey participants were both asked for their opinion regarding what they perceived to be threats currently facing the revitalization of the northern shrimp fishery. Detailed responses are available in Tables 2.16 and 2.17, recounting regulatory and non-regulatory opinions regarding perceived threats, impediments, and hindrances to efficiency within the northern shrimp fishery. Participants unanimously identified the state of shrimp regulations as the source of their primary concern, most notable of which was the credibility and effectiveness of management (78%). Respondents made note of a severely diminished level of trust in the effectiveness of regulations (41%) and complained further with regard to the biological inefficiency of targeting egg-bearing females (32%). Participants also made note of their extreme skepticism regarding the science used in the creation of regulations (70%). Specific concerns were expressed towards the fishery-independent survey data collected and used to produce stock assessments; most notably, respondents criticized survey methodology (49%), making note of their disapproval in choice of sampling crew, the lack of involvement of fishermen in the survey process, and the frequency, survey area coverage, and site selection of sampling. Respondents relayed further criticisms surrounding control on effort in the northern shrimp fishery (57%), namely unsustainable participation levels and the use of days at sea as a management tool. Concern for the structure of management was also heavily cited (51%) as respondents expressed their displeasure at the lack of industry representation (30%), federal involvement (27%), and disregard for industry input valuation (19%). Non-regulatory areas of concern were also identified. Following qualms against regulations, unease surrounding market conditions was also articulated; participants conveyed apprehension at reopening the fishery prior to evaluating the logistics of establishing a functional market (59%); operational needs of shrimp processors, limited market capacity, and weakened demand were noted.

Table 2.16: Survey respondents indicate their opinions regarding regulatory-based threats, impediments, and hindrances to the revitalization of the northern shrimp fishery (fisher and dealer responses combined). Percent emboldened in red indicates the total percentage of respondents within a general category.

General	Sub - Variable	Total
Credibility and Effectiveness	Adaptive capacity	3%
	Level of trust	41%
	Biological Consideration	32%
	Restrictiveness	19%
	Reduced access	5%
	Total % unique:	**78%**
Input Controls	Day length	3%
	Season length	14%
	Vessel capacity	11%
	Days at sea	19%
	Fishery closures	14%
	Participation	22%
	Total % unique:	**57%**
Output Controls	Landings	35%
	Total % unique:	**35%**
Management Structure	Federal involvement	14%
	Industry representation	30%
	MA-NH involvement	27%
	Total % unique:	**51%**
Science Going into Regulations	Survey Methods	49%
	Trust in Science (negative)	16%
	Trust in Science (positive)	8%
	Total % unique:	**78%**

(n = 37)

Table 2.17: Survey respondents indicate their opinions regarding non regulatory-based threats, impediments, and hindrances to the revitalization of the northern shrimp fishery. Percent emboldened in red indicates the total percentage of respondents within a general category.

General	Sub - Variable	Total
Conditions in Other Fisheries	Increased Predators	10%
	Total % unique:	**10%**
Environmental Conditions	Water Temperature	28%
	Total % unique:	**28%**
Fishery Conditions	Ghost Gear	17%
	Fisher Behavior	24%
	Total % unique:	**28%**
Market conditions	Consumer demand (low)	10%
	Limited market	38%
	Price (low - unstable)	10%
	Processing capcity (unstable)	3%
	SSC operational needs	41%
	Total % unique:	**59%**
Shrimp Stock	Recruitment	7%
	Abundance	3%
	Total % unique:	**10%**

(n = 29)

2.3.4.3 Suggestions for Improvement

When asked what changes were necessary in order to increase sustainability and profitability in the fishery, participants identified regulatory controls on effort (89%) as the area most strongly in need of attention; the most frequently suggested means of improvement included the implementation of a no harm, low impact fishery (44%), followed by improved methodology to control landings (42%), and the implementation of limited entry (22%). Respondents also suggested that increased biological consideration in regulatory efforts (56%) was necessary to maintain the viability of a future fishery. Specific mention included a reduction in the amount of spawning stock biomass removed from the fishery (39%) and the prioritization of spawning females (31%). 61% of participants reiterated the need to establish market stability and infrastructure prior to the reopening of the fishery while providing added suggestions related to the need for consistent landings and the prevention of market saturation through controlled landings. 44% of respondents specified a desire for revitalization surrounding the structure of management, including a strong preference for a state-run fishery (33%) and increased industry representation in the regulatory process (17%). A summary of related survey responses may be found in Table 2.18.

Table 2.18: Survey respondents indicate their opinions regarding what is needed to increase sustainability and profitability of the fishery in the future. "Total % unique" indicates the percentage of respondents who provided a response within the general category. Percent emboldened in red indicates the total percentage of respondents within a general category.

General	Sub - Variable	Total
Credibility and Effectiveness of Regulations	Level of trust	11%
	Biological Consideration	56%
	Total % unique:	**67%**
Control on Effort	Day length	3%
	Season length	17%
	Vessel capacity	11%
	Days at sea	17%
	Restrictions by gear type	17%
	Fishery closures by location	6%
	Low-impact fishery	44%
	Limit entry	22%
	Landings	42%
	Total % unique:	**83%**
Management Structure	Federal involvement	14%
	reference for state-run fishery	33%
	Industry representation	17%
	Total % unique:	**44%**
Science Going into Regulations	Survey Methods	39%
	Total % unique:	**39%**
Market Conditions	Establish market stability	39%
	Establish demand	6%
	SSC operational needs	33%
	Supply	14%
	Total % unique:	**61%**

(n = 36)

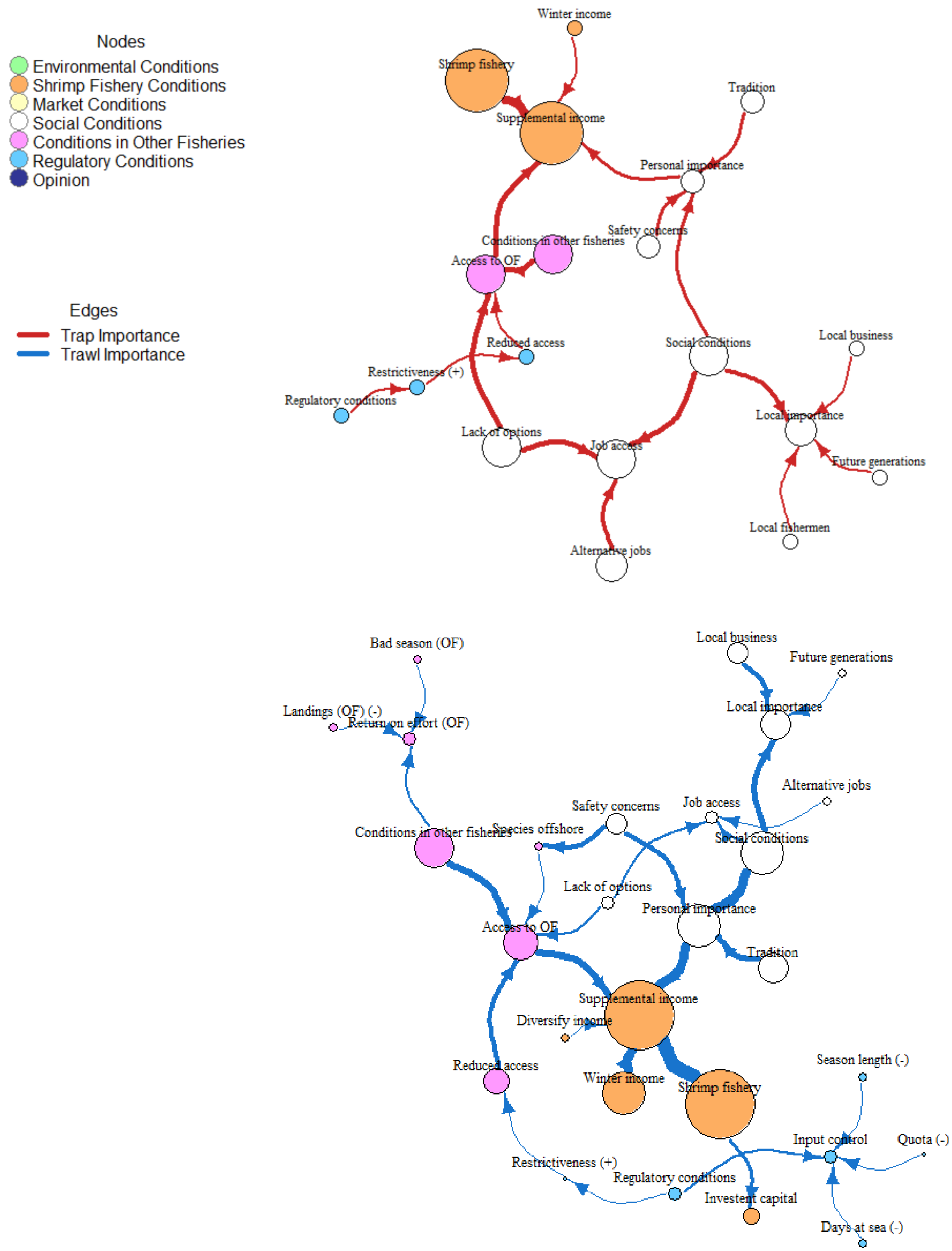
2.3.4.4 Level of Importance

Survey participants were asked to describe the importance they attributed to this fishery and for what purpose; 22% of fishers expressed it was of little to no importance, many of whom provided indication that they had found alternative ways to support their income; alternatively, 26% indicated the fishery remained moderately important, while the remaining 52% of fishermen ascribed a high sense of importance to the fishery. Those that ascribed remaining value to the fishery (78% of all fishers) stressed its importance as a stable source of winter income (96%), followed by declining conditions in other fisheries (52%), tradition (40%), local support (36%), and safety concerns (32%). Regarding the moratorium's impact on fisher livelihood, 90% of fishermen expressed that the closure forced them to rely far heavier on their target species than they normally would or would care to. Many indicated their distain at being forced to put added pressure on fisheries already under duress, or their concern at following the seasonal movement of fisheries offshore in inclement weather. Additionally, 33% of fishermen reported relying more heavily on land-based sources of income, while 22% reported targeting new fisheries to establish more reliable sources of income. Visual representation of fisher responses, separated by gear type, may be observed in Figure 2.7.

Table 2.19: Fishers indicate the level of importance the associate with the northern shrimp fishery, providing added indication regarding why it is or is not important.

(a) Level of Importance			
Variable	Trap	Trawl	Total
Little to None	40%	12%	22%
Moderate	30%	24%	26%
Very - Extremely	30%	65%	52%
(b) Reasoning for Unimportance			
Variable	Trap	Trawl	Total
More for Younger Generation	20%	6%	11%
Closed too Long	10%	6%	7%
Other Opportunities	30%	29%	30%
Expensive to Rejoin	10%	6%	7%
(c) Reasoning for Importance			
Variable	Trap	Trawl	Total
Tradition	30%	41%	37%
Personal Enjoyment	30%	12%	19%
Local Support	20%	41%	33%
Safety	30%	29%	30%
Supplemental Income	80%	94%	89%
Conditions in Other Fisheries	40%	53%	48%
(n)	(n = 10)	(n = 17)	(n = 27)

Figure 2.7: Visual representation of responses detailing what reasons fishers ascribe remaining importance to the northern shrimp fishery, split by gear type. The size of each node corresponds to frequency of mention, while the width of each edge indicates the frequency of each indicated relationship.



2.3.4.5 Outlook on Involvement

In closing, when asked about their outlook regarding their personal involvement in the fishery over the next five years, 58% of fishers indicated that they would participate in the even it reopened, but generally provided no indication of faith in the idea that it actually would; 37% of fishers indicated a generally negative attitude regarding their potential for participation, citing reasons including age, cost, access to alternative substitutes, and general discouragement and distrust in management. Regarding the future of the shrimp fishery, the majority (85%) of fishermen responded negatively, explaining that their desire to stay positive was often overwhelmed by the realistically negative state the fishery has declined to; 37% of respondents indicated current regulatory efforts and their lack of success to be the main contributing factor impacting their outlook, followed by diminished faith in the science to accurately reflect the status of the stock, the unpredictable and unreliable nature of the fishery, and lastly, the continued unfavorable environmental conditions that hinder the growth of the stock.

2.4 Discussion

2.4.1. Selection and Response Rate

Given the sample size, it is not wise to assume these results are representative of participation in the northern shrimp fishery. Participant selection was based on participation prior to the control date instituted in 2011, in the event that the fishery should decide to implement a limited entry system in the future; while basic selection criteria were adequately composed, the final selection was based on a randomized number generator. This becomes problematic in the case where one participant selected had joined the fishery in 2010, meaning they had < 3 years of experience in the northern shrimp fishery. While this did not appear to severely impact results overall, one could argue that this particular participant's responses might not fully encompass the experience of a more seasoned shrimp fisherman. Of additional concern was the lack of response stemming from faulty phone lines (18%), unreturned messages (69%), and admission by those who did answer but indicated they did not in fact participate in the fishery (12%). Based on this, we are unsure as to whether or not those invited to participate declined or did not respond because they were not involved in the fishery or because they did not receive the invitation to participate.

The category most participants left blank were questions regarding factors that influenced fishers' decisions to purchase and utilize a license. In this situation, those that failed to answer both questions often treated the two as the same question, and would, for example, preemptively answer what factors influenced whether or not they used their license when asked what drove them to purchase it in the first place. In other instances, fishers would answer only half of the question, for example, providing feedback as to what questions positively influenced their decision to utilize their license, while failing to provide examples of instances where they chose not to utilize it. In a more ideal situation, a larger sample size would increase the confidence surrounding the results of such topics.

Following the response rate of fisher survey participants, with 37% trap and 63% trawl, the results are slightly biased towards trawl fishermen in the Maine northern shrimp fishery. Looking at activity in the years prior to the fishery's shutdown, records indicate that quota allocation was split 87% trawl, 13% trap, with trappers having landed as low as 17% and as high as 35% of the quota from 2000 to 2013 (ASMFC, 2013). With this in mind, the return rate appears to be relatively well-reflective of the true gear division within the fishery when it was open.

2.4.2 Participant Summary Information

Differences regarding demographics, years of experience, and boat size of survey participants were observed between gear types. On average, shrimp trawlers maintained a higher number of years of experience than trappers did; this difference is likely due to the delayed emergence of a trap fishery until the 1970s, as well as the inclusion of one survey respondent whose delayed start date lowered the overall average. Trawl vessels were also often larger than trap vessels. This is likely due to the involvement of each gear type in their respective target fisheries; trawl vessels reported high instances of participation in other fisheries such as groundfish and scallop, which in many cases requires a larger vessel in order to travel further offshore, tow heavy gear, and hold higher catch volumes. Alternatively, trappers reported involvement mainly in the lobster industry, which generally takes place in closer proximity to shore. Trappers did report, to some degree, the use of a larger vessel for the purpose of chasing lobster further offshore.

All fishermen reported shrimp as a contributing source to their annual income, though the degree of contribution varied by gear type. In general, dependence on shrimp was higher during the winter. On average, trawlers indicated heavier reliance on shrimp as a source of seasonal (i.e. winter months) income and as a percentage of their annual income. This may be due to multiple reasons. Historically, trawlers were responsible for higher volumes of shrimp in comparison to trappers, and as such, likely more dependent on that income. Trawlers also reported being involved in fewer fisheries annually, while trappers, reported increased instances of diversification and involvement in a higher number of fisheries each year. Regardless of what percentage of income fishers attributed to the shrimp fishery, almost 100% of fishermen indicated the importance of shrimp as a supplemental winter fishery, especially in light of declining conditions in other fisheries. While most dealers no longer ascribed a sense of importance to the fishery in connection to their own business, they were generally in agreement regarding the importance of the fishery to local fishermen and the economies of coastal communities; in particular, small to medium sized dealers made note of the winter jobs the shrimp fishery creates during a time in which many people are otherwise unemployed. Collectively, this information sheds light on the heightened vulnerability of small-scale coastal communities and suggests that coastal demographics should be given more consideration in the regulatory process.

2.4.3 Effort in the Northern Shrimp Fishery

2.4.3.1 Purchase and Utilization of a License

Survey results regarding the purchase and utilization of a shrimp license, and the subsequent expenditure of effort within the fishery, provide insight on the adaptive capacity of fishermen by identifying the most influential factors driving fishing behavior. Fishermen identified conditions in the shrimp fishery as a key factor in their decision to purchase a license, indicating the desire for positive return on effort, and ultimately, financial stability in their actions to be of utmost importance. Fishermen also noted that conditions in other fisheries were highly influential regarding their fishing strategy. Most notably, this included diminished access to alternative fisheries, whether due to the movement of species offshore, or as a results of imposed regulatory restrictions on effort or quota. A number of fishers also made note of the importance of tradition in their decision to purchase a license, often recounting their participation as a child in the shadow of their elders. This furthers the idea that heritage runs deep in the blood of many fishing families that characterize the state of Maine.

Survey results showed similarities in the response rate between the decision to purchase vs. the decision to utilize a license, though slight variations amount to discernible differences in behavior. Almost 70% of fishermen who bought a license confirmed participating in the subsequent season, whereas 30% of fishermen admit to inconsistent participation despite purchasing a license; low shrimp abundance and poor market conditions strongly discouraged participation, especially in the presence of more attractive conditions in other fisheries. Alternatively, an increased sense of dependency on access to supplemental income, as well as anticipated positive return on effort related to profit, price, or landings, encouraged fishermen to use their license. Worthy of note was one fisher’s response concerning regulatory distrust and fear of losing access that drove their participation; in the event the fishery were ever to institute a limited entry system, this fisher expressed concern that, if they did not have landings to show, it would preclude their eligibility to remain in the fishery. This notion was paralleled by many fishers who recounted their experience in other fisheries that experienced conditions of similar nature, most notably, the collapse of the New England groundfish fishery. This remark was deeply concerning, as it suggests the existence of more deeply rooted problems in fisheries management, beyond controlling effort, that remain unaddressed. Concurrent with findings thus far, survey results confirm the use and importance of northern shrimp as a supplemental fishery and, overall, the importance of diversification as a fishing strategy.

2.4.3.2 Expenditure of Effort

Survey results exploring effort expenditure centered primarily around factors that either hindered or promoted positive economic returns. Unsurprisingly, fishermen overwhelmingly identified positive conditions within the northern shrimp fishery to be the strongest source of influence regarding continued expenditure of effort. Increased abundance and proximity of shrimp to shore were often noted, followed closely by the fishery's seasonal nature.

Given the short amount of time shrimp are inshore, in conjunction with an equally shortened season length, fishermen are often subject to a very small window of opportunity regarding participation. For these reasons, fishermen almost unanimously identified January, February, and March as the most ideal months to target northern shrimp. These months were also highly regarded for their product quality, a strong factor influencing price and profit. Come April, shrimp begin to move offshore; during this time, they become harder to catch and are often of lesser value, following a sharp decline in product quality post-hatch.

Almost 90% fishermen noted that the most influential factors hampering effort were linked to declining conditions within the shrimp fishery. Increased competition (i.e. number of boats) and high frequency of gear conflict resulted in decreased expenditure of effort, as did declining shrimp abundance and lowered accessibility regarding proximity of shrimp to shore. Fishermen generally indicated they were less likely to devote added time and effort towards shrimping if they experienced decreasing returns on effort (i.e. profit or landings). Congestion proved to be more influential than anticipated regarding its impact on fisher behavior. Under normal conditions, most fishers noted poor weather often discouraged them from chasing shrimp offshore. Alternatively, some fishers noted, in the presence of high congestion, it was more economically viable to go shrimping in bad weather or to chase shrimp further offshore on the basis of "high risk, high reward" principles. This situation applies equally to the use of days-at-sea as a management tool. Despite its intended purpose as an effort control measure, many fishermen lament its use in fisheries management and often criticize it for its inefficiency and its unintended side effects. 100% of fishermen reported having fished in dangerous weather or when it was not economically advantageous to do so, many of whom also noted that days-at-sea often force fishermen into unfavorable situations they would otherwise avoid, such as highly congested fisheries and inclement weather. Added sources of influence discouraging effort included increased abundance in more attractive fisheries, and declining product quality in northern shrimp following their movement offshore. Overall, trends in effort expenditure were generally consistent and reflective of economically conscious behavior. Fishermen were most likely to expend additional effort if they deemed it self-promoting and monetarily advantageous. Conversely, fishermen were most likely to withdraw effort if they anticipated incurred loss beyond reparation.

2.4.4 The Northern Shrimp Market

Similar to factors controlling effort, behavior and concerns related to the northern shrimp market were consistent with profit maximization; in most cases, the method of sale and the location to which fishermen either landed or sold to varied based on prospective returns.

2.4.4.1 Method of Sale

Fishermen often reported multiple methods of sale; while almost 100% of participants reported having sold to a dealer, 50% of respondents also reported having peddled or sold to a peddler. Most responses of this nature came from fishermen based out of Midcoast and Downeast locations. Typically, trappers were more likely to utilize this method of sale than trawlers, given volumetric differences in landings, although a high number of trawlers also indicated utilizing this method of sale when volumes were low, or the market was poor.

Where fishers landed and sold their catch followed spatial trends along the coast related primarily to market capacity. Almost all fishers reported landing shrimp in their homeports, though almost 50% of fishers also reported landing outside their homeports, most notably for promising conditions related to market capacity and price. Similar principles applied when fishermen were asked what conditions impacted where they sold their shrimp. Fishers based in Southern Maine were least likely to land and sell outside their homeport or geographic location, followed by Downeast fishers; Midcoast fishers were most likely to land and sell outside their port of origin or geographic location. Trawlers (64.7%) reportedly landed and sold outside their homeports more often than trappers (20%). Collectively, 85% of all fishers who reported fishing, landing, or selling outside of their homeport reported doing so in Southern locations, particularly Portland. This is most likely explained by the high volume that is typical of trawlers; during years characterized by high landings or poor market conditions, Midcoast and Downeast locations often do not maintain the processing capacity or the level of demand fishermen require in order to sell their catch or turn a profit. Portland was noted by almost all participants as the hub of the shrimping industry, given its access to both national and international markets, as well as the processing capacity it maintains.

2.4.4.2 Market Price

Fishers maintained they had very little control over price, especially during years characterized by high landings; price was often lower and less flexible when the market was highly saturated with shrimp and, thus, subject to lower demand. Conditions of this nature often severely limited options as to where fishermen, particularly trawlers, could bring their catch. “Take it or leave it” was a phrased used regularly to describe the level of control fishermen felt in that instance. Typically, participants received a higher price when market saturation was lower, or if the market capacity (i.e. processing equipment and work force) was in place to handle larger volumes of shrimp; alternatively, the market would become flooded, causing a large drop in price. Interestingly, one Southern processor made note of the importance of

Canada's processing capacity to market dynamics. It was suggested that, during times in which an overabundance of shrimp flooded southern markets, dealers in Portland picked out the larger shrimp before sending the smaller shrimp to Canada. This is consistent with higher instances of increased landings surrounding the Portland area.

Product quality also strongly influenced the price fishermen received for their product; a lower count per pound typically received a higher price, as it indicated the shrimp were larger. Larger shrimp were often in high demand by retail consumers like sushi and other high value markets. The state in which the shrimp were sold also impacted quality and price; live shrimp were in high demand, with fresh, moving, and whole shrimp garnering a higher price. Some fishers and dealers (~25%) made note of the fact that they observed price differentials between gear types, suggesting that trapped shrimp were of higher quality. Alternatively, a few respondents argued that, if tows were kept short, trawl shrimp maintained just as high a quality as trapped shrimp. Differences in product quality are potentially important factors for managers to consider when planning the reopening of the fishery. Given that it has been closed for an extended amount of time, careful consideration for the needs and demands of target markets will be required for the fishery to be successful.

2.4.5 Survey Participant Opinions and Perception

Overall, our findings suggest that participants are overwhelmingly displeased with the state of the fishery, how it has been managed, and the direction in which it is headed.

2.4.5.1 Regulatory Distrust

Survey participants noted extremely diminished levels of trust in the ability of regulators to exert proper control over the fishery, providing added suggestion that regulatory awareness surrounding the impact and impetus of regulations was underwhelming at best; generally, respondents made note of the fact that they perceived many regulations to be either ineffective, misguided, or biased towards specific gear types. An additional few commented on “the politics” of management, suggesting the overly bureaucratic process contributed to further inefficiency within the fishery. Regarding the structure of management, many felt very strongly that the fishery would be more effectively run as a state fishery. Of added concern was the fact that more than half of respondents were highly skeptical of “the science going into regulations”, most often referencing the ASMFC Annual Summer Survey conducted in the Gulf of Maine. While a small number of participants conveyed their support and belief in the science reported, most fishermen were highly critical of its survey methodology, specifically, the experience of its crew and coverage of sampling efforts. These beliefs appear based on the idea that survey results are not fully representative of stock conditions in the Gulf of Maine.

Respondents felt very strongly that numerous problems could be ameliorated through the propagation of more cooperative efforts between scientists, managers, and fishermen. Generally, most felt that their opinions were undervalued, and their inclusion to date felt more like an appeasement or formality. Many relayed their desire to be better represented in regulatory proceedings and more frequently included in data collection efforts, arguing that their expertise, something that could be of great value and service to fisheries management, remains severely underutilized. Overall, the inclusion of fishermen in the regulatory process could be extremely advantageous, as they are able to provide added perspective and support. As one participant phrased it, “fishermen want to be part of the solution, not part of the problem.”

2.4.5.2 Perceived Regulatory Success and Effectiveness

Respondents opinions regarding the effectiveness of regulations implemented were also quite negative. Generally, survey participants felt that, despite increased regulatory involvement over the years, the amount of effort within the fishery was either inefficient or ill-contained, and the regulations failed to rectify this. Participants felt that regulations often encouraged inefficient and dangerous fishing behavior, citing examples such as days at sea, inconsistent season length, and the allocation criteria related to quota and landings. Fishers also noted that a lack of control over the number and size of boats in the fishery allowed effort levels within the fishery to grow to unsustainably. Despite the implementation of a control date in 2011, which effectively capped entry to the fishery, many fishermen argued that the number of boats that would be eligible to participate is still much higher than the northern shrimp fishery could support, especially in its current weakened state.

In light of declining environmental conditions (i.e. rising water temperatures), most fishers appear cognizant of the fact that recruitment and abundance of northern shrimp are in a severely weakened, depressed state; more than half of respondents indicated the need to prioritize spawning females and, for the time being, severely reduce the amount of spawning stock biomass removed from the fishery. A number of fishermen seemed highly supportive of the idea of a low-harm fishery, or some form of limited entry system, with improved methods to monitor and control landings. Many suggested that smaller coastal communities, like those characteristic of Midcoast and Downeast Maine, would benefit greatly from a small-scale fishery with lower overall landings and fewer participants. Those opposed to this notion appeared to base their perception of viable effort on a time during which landings were much higher, often encouraging unrealistic expectations regarding anticipated participation levels. Due to the diversity in opinion surrounding controls on participation, varied support for a limited entry system could prove to be yet another hurdle to successfully reopening the fishery.

2.4.5.3 Future Involvement

Regarding the future of the industry as a whole, fishermen did not respond positively; few expressed hopefulness in the ability of the resource to recover and the climate to shift toward more favorable conditions. Most fishermen responded negatively, explaining that their desire to stay positive was often overwhelmed by the realistically negative state the fishery has declined to. Dealers expressed similar worries, with added emphasis on market-related factors. Concern centered around the viability of reestablishing the market and whether it would remain open long enough to reestablish business. Many of the larger dealers also made note of logistical issues facilities would face regarding attaining enough volume to keep production operational. Overall, the attitude of both fishermen and dealers remained largely distrustful, with many participants expressing deep concern regarding the fishery's history of shutdowns with little warning. Managers will need to take added precautions to reassure the valid concerns of industry members who will ultimately bear most of the risk surrounding the revitalization of this fishery.

2.5 Conclusion

In closing, the results of this study showed that, while the fishery's composition is diverse, it serves primarily as a supplemental fishery. The nature of its importance often varies based on conditions in other fisheries, market-related factors, location, and gear type. Consequently, the effort of its participants and the degree to which they depend on this fishery is hard to pinpoint. These results provide insight into factors impacting effort and participation. Additionally, respondents provided valuable information regarding perceived sources of inefficiency surrounding regulatory efforts, improvements to reduce wasteful behavior, and ways in which the market can be made more sustainable. Fishermen were generally in agreement on most issues; however, due to divergent opinions regarding controlling effort within the fishery, additional research is necessary in order to assess the viability of controlled entry within the northern shrimp fishery.

3. EVALUATING SIZE-AT-TRANSITION IN NORTHERN SHRIMP

3.1 Introduction

The objectives of this research are twofold, firstly, to evaluate spatio temporal trends in size-at-transition in northern shrimp (*Pandalus* borealis) and secondly, to identify the underlying mechanisms causing variation in this life history process. The outcomes of this research are intended to inform scientists and managers of the vulnerability of northern shrimp stock to shifting environmental and fishery-related conditions.

3.1.1 Current Science and Management

Effective fisheries management requires a thorough understanding of a species' population structure, growth patterns, and relationship with the environment in which it resides. Improved understanding regarding the impact of environmental fluctuations on the species' biology is crucial to maintain adaptive capacity in fisheries management. Changes regarding the impact of thermal dynamics on northern shrimp recruitment have already been observed in the Gulf of Maine (Richards 2012) as recent years' recruitment failure are suspected to be related to unfavorable conditions surrounding water temperature and spawning stock biomass (ASMFC 2013). The relationship between size of breeding females and its impact on fecundity has been studied at length (Shumway et al., 1985; Hanes and Wigley, 1969), providing evidence that the size structure of spawning stock biomass has a strong impact on recruitment. These factors are incorporated into management of the northern shrimp stock when projecting anticipated recruitment and abundance. However, management efforts fail to incorporate a deeper understand regarding what factors influence the size structure of the northern shrimp stock, most importantly, factors influencing the size at which northern shrimp transition from male to female. It is well documented that the size structure of female shrimp is an important determinant of individual fecundity, with larger body size positively correlated with the number of eggs per clutch (Shumway *et al.,* 1985), yet, factors influencing size-at-transition for northern shrimp are not fully understood in light of shifting climatic conditions. This knowledge may have direct implications for the reproductive capacity of the northern shrimp stock in the Gulf of Maine, and as such should be taken into careful consideration regarding its management.

3.1.2 Species Overview

Northern shrimp, *Pandalus borealis,* are a genetically distinct, cold-water species of shrimp, historically ranging from Artic boreal waters to the Southernmost extent of their range in the Gulf of Maine (GOM) (Jorde et al., 2015). Warm waters limit their extension further south, as GOM northern shrimp are considered a temperature-sensitive species (Richards et al., 2012). Genetic diversity in Northern Shrimp is directly attributed to geographically distinct variation in depth, shifting water temperatures, recruitment, and fecundity, as well as currents and vertical mixing systems specific to the GOM (Johnson *et al.,* 2011).

3.1.2.1 Life History and Biology

Between late spring and early fall, the stock is found congregating (male and female) offshore in deep, cold-water basins to escape the vertical mixing of warmer surface layers (Hanes and Wigley, 1969; Apollonio et al., 1986). Mature females mate with males between late August and early September, after which they bear the developing eggs on their abdomen for up to six months. The size structure of female shrimp directly impacts fecundity, following a positive linear relationship between the number of eggs per clutch relative to female carapace length (Shumway et al., 1985; Hanes and Wigley, 1969). A similar relationship exists between female carapace length and the viability of the eggs, as smaller females were discovered to produce fewer, weaker eggs more susceptible to disease (Shumway et al., 1985; Hanes and

Wigley, 1969). During egg development, shrimp embryos rely on the egg yolk as their main source of sustenance, the quality of which is temperature dependent (Subramonium, 1999). Come winter, egg-bearing females migrate shoreward along the ocean floor, resulting in high inshore concentrations of female shrimp from mid-December to late February (Hanes and Wigley, 1969). Once eggs have hatched, females return offshore by mid to late spring. Following the hatch, juveniles will remain inshore for up to a year and a half before they in turn migrate offshore (Apollonio and Dunton, 1969). Historically, shrimp mature first as males at 2-year-olds and mate at 2 ½ years-of-age before entering a transitional period, during which male characteristics disappear and female maturation beings. Shrimp enter their female life stage between the ages of 3 and 4, mating at 3 ½ to 4 ½ years-of-age, respectively (Richards *et al.*, 2012). It is possible for females to reproduce a second time as stage two females, though female mortality increases following the first reproductive cycle (Shumway et al., 1985).

3.1.2.2 Growth and Maturation

Seasonal and stage-specific growth patterns have been observed and extensively documented. Rapid growth is consistently observed to occur between spring and fall, followed by a slower growth rate during the winter (Berkeley, 1930; Shumway et al, 1985; Apollonio, 1986). Stagewise, growth occurs most rapidly in larvae and juveniles, as well as during transitional life stages (Hanes and Wigley, 1969; Shumway et al., 1985). Historically, size of *Pandalus* populations within the North Atlantic is attributed to age and differs across location.

From larvae to adult female, each stage northern shrimp pass through is separated by a certain number of molts. Molting is often a time of high stress for the individual (Stickney and Perkins, 1977), regardless of age or stage. High stores of energy are required, not only to survive, but to maintain the energetic functional capacity necessary to resume stage-associated life processes. Larval and juvenile shrimp expend considerable amounts of energy on metabolic processes during this time and are subject to strong influence by outside forces such as water temperature and nutritional availability (Stickney and Perkins, 1977). Male characteristics (i.e. male copulatory structures) typically become apparent in juveniles once they have reached 6-7mm carapace length (CL) (Stickney and Perkins, 1977). Historically, incremental growth and maturation was a factor of size associated with a particular age and size; early studies supported the pattern that the time at which shrimp transitioned from male to female was inversely related to size at age, with earlier transitions a common occurrence for larger shrimp (Rasmussen 1953; Fox 1972; Clark MS 1982; Koeller et al., 2006). Problematically, shrimp fail to maintain hard structures following their molts, making it almost impossible to determine age. Instead, age estimates and growth rates must be inferred from length frequency distributions despite considerable overlap between associated age and length estimates. While size-at-transition was thought to occur consistently at 22 mm carapace length, multiple studies (Hanes and Wigley, 1969; Apollonio 1986; Hansen and Aschan, 2000; Koeller 2006; Charnov, 1982) provide reasonable doubt in support of alternative theories; across time and space, multiple populations of *P. borealis* were discovered to exhibit variation in size-at-age (Apollonio 1986; Hansen and Aschan, 2000) and size-at-transition within the North Atlantic (Koeller 2006). Following proof of transition at smaller CL, it is strongly believed that additional factors, primarily temperature and sex ratio, influence the timing and size at which transition occurs, though the mechanisms controlling this process are still widely contested.

3.1.3 Study Summary

Many studies on various pandalid species outside the GOM show the combined influence of multiple factors, such as temperature and stock composition, on the biology of the stock.

Regarding northern shrimp, factors that influence size-at-transition are strongly debated. In this research, we propose tests aimed towards discovering what suite of environmental and/or commercial elements most strongly influence size-at-transition in GOM northern shrimp. As such, we will use fishery-independent data from multiple sources in order to examine the effect of (1) climatic parameters such as temperature and salinity, (2) anthropogenic influence via distortion of sex ratio, and (3) the combined influence of both sex ratio and environmental factors. For the first component, we examine the influence of shifting ocean temperature and salinity over multi-year time lags. The second component includes examining the impact of altered sex ratio, and whether the timing and size-at-transition is altered to match breeding opportunities. The final test aims to determine whether the combined influence of the aforementioned factors provides added significance to model results. These tests are conducted only on northern shrimp in the GOM and are not representative of other genetically distinct northern shrimp stocks found in the North Atlantic. For the purpose of this research, we consider the impact of these factors on one stage class, comprised of transitional and female 1 shrimp (females having just transitioned but not yet born eggs); these individuals are grouped as such because it is assumed they are representative of the same year class, and thus, subject to similar conditions. It is the goal of this research to capture the potential effect of annual fluctuations in climate and sex ratio on this important life history strategy. With these results, we may infer the strength of one source over the other, if not potentially the combined influence of both, on the GOM northern shrimp stock. This research may be used to inform theoretical discussion concerning the potential impact of continued climatic shifts and fishing pressure on the ability of the stock to maintain strength and resiliency. Finally, we discuss the importance of the proposed research regarding its impact on the size structure of northern shrimp spawning stock biomass.

Collectively, this research may be used to anticipate potential shifts in the size structure of northern shrimp and, subsequently, changes in reproductive potential. This may have implications for management given its potential impact on recruitment and abundance of northern shrimp.

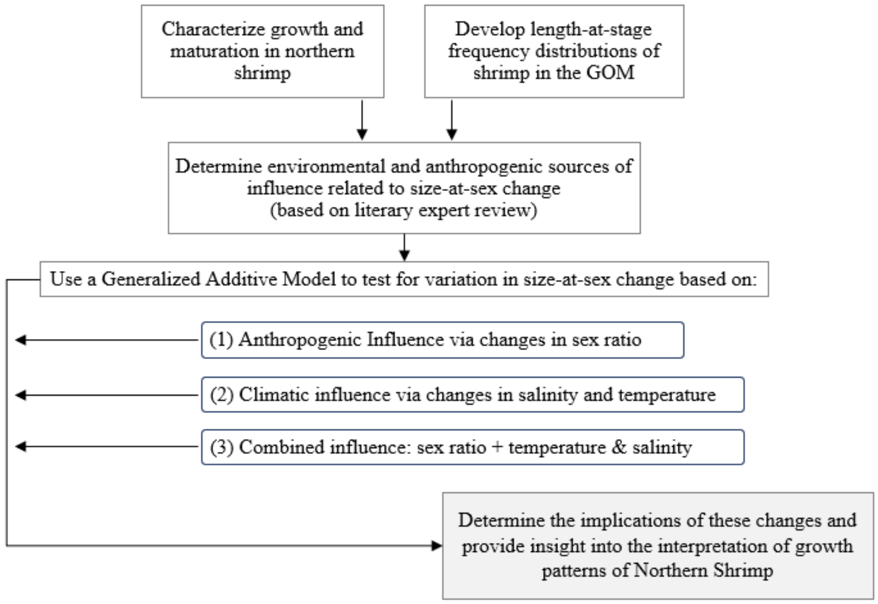
3.2 Methods

3.2.1 Study Design

3.2.1.1 Generalized Additive Models

The purpose of this study was to test potentially significant sources of influence on size-at-transition in GOM northern shrimp, with the goal of providing managers a more well-informed idea regarding the potential impact of fishing pressure and climate change on the northern shrimp stock (Figure 3.1). This research employs the use of a generalized additive model with a Gaussian error distribution, applied to fishery-independent survey data, to examine the impact of six type of non-parametric covariates (x), sex ratio, sea surface temperature, bottom temperature, sea surface salinity, and bottom salinity, as well as longitude, on the response variable (y) length-at-transition. Year is also included in some models to capture potential year effects. GAMs are a non-parametric regression technique that allows for flexibility regarding the statistical distribution of the data, as it is not restricted by linear relationships (Swartzman *et al.*, 1995). We employ the use of non-parametric smoothing functions on our predictor variables; this gives our models flexibility as it relaxes the assumptions on the actual relationship between response and predictor to create a better fit. There are limitations to this methodology, as it obscures the interpretive power of the results. Predictor variables were selected based on a review of relevant literature and expert analysis regarding the influence of environmental factors and sex ratio-dependent, compensatory effects on northern shrimp biology. This GAM-based analysis was conducted using the "mgcv" package of the R program.

Figure 3.1: Flowchart diagram summarizing the process and outcomes of our research approach.



3.2.1.2 Model Configuration

Patterns in northern shrimp growth within the Gulf of Maine and vary widely by stage. As such, separate regression tests were conducted for four separate time lags within each survey to determine any stage- or location specific patterns in size-at-transition. Changes in the dependent variable are measured in millimeters (Δmm).

Preliminary models were constructed following the results of Variance Inflation Factor (VIF) tests used to create the most effective combination of environmental covariates. Two separate VIF tests were conducted for each lag to determine reliable combinations of 1) temperature covariates (bottom and surface) and, 2) combined temperature and salinity covariates (bottom and surface). Environmental covariates were removed from the models if they exhibited a VIF value of 3 or higher. Following VIF tests, environmental covariates were removed from the model if i) the p. value was greater than 0.05 and ii) the AIC value decreased when the term was dropped (Wood 2001). GAMSs examining the impact of density-dependent influence (i.e. sex ratio) on length-at-transition did not require a VIF test, as each model incorporated only one lagged sex-ratio variable at a time, in conjunction with longitude and (for some) year. Models with the lowest AIC values were selected. If the use of the selected model resulted in convergence errors, covariates were removed until the approximate of all terms was < 0.001 (Wood 2001). Wood (2001) conveys that the removal of covariates is often subjective; as such, covariates are subject to removal if doing so results in a small change to the model's AIC. Smoothing functions were applied to continuous environmental parameters, as GAM models have a difficult time processing continuous variables.

The first set of models incorporates a suite of environmental parameters, including surface temperature, bottom temperature, surface salinity, and bottom salinity with added smoothing factors. The second set of models incorporates sex ratio as the main predictor variable. The final set of models incorporates a combination of both environmental and sex ratio-based factors in order to 1) determine if their combined impact exhibits any additional explanatory power, and, if not, 2) which effect displays a stronger impact on size-at-transition. Each model included in this analysis incorporates longitude. Year was included in the first two sets of preliminary models to assess unexplained variability in the presence of a year effect. The first two sets of preliminary models display two versions of each model, one with year, and one without year (denoted by the presence of a "Y" preceding each model number) to account for any potential, unexplained variability in the data due to a year effect.

Transitional length (L_T) is the dependent variable; for the purpose of this research, sexes "transitional" and "female 1" are assumed as part of the same year class and are henceforth referred to simply as "transitionals." In total, 42 preliminary GAMs were run examining the relationship between length-at-transition and potentially influential factors, including 36 environmentally focused models and 6 density-dependent models. Following this, one final model was created, utilizing a combination of variables from preliminary models exhibiting the strongest explanatory power.

Deviance explained, Akaike Information Criterion (AIC), and adjusted r(sq) were calculated to assess the results of each model. "Deviance explained" provides a first glimpse at the explanatory power of a model by examining its goodness-of-fit. AIC is derived from serial non-linear, non-parametric, regression techniques used fit to length-at-transition to the combined series of covariates included in each model; the model with the lowest AIC corresponds to the best fit and the most explanatory power. Models containing multiple predictor variables were done so based on the compilation of variables with the lowest AICs. Observed vs. predicted plots were utilized to further assess the explanatory power of each model.

3.2.2 Survey Data

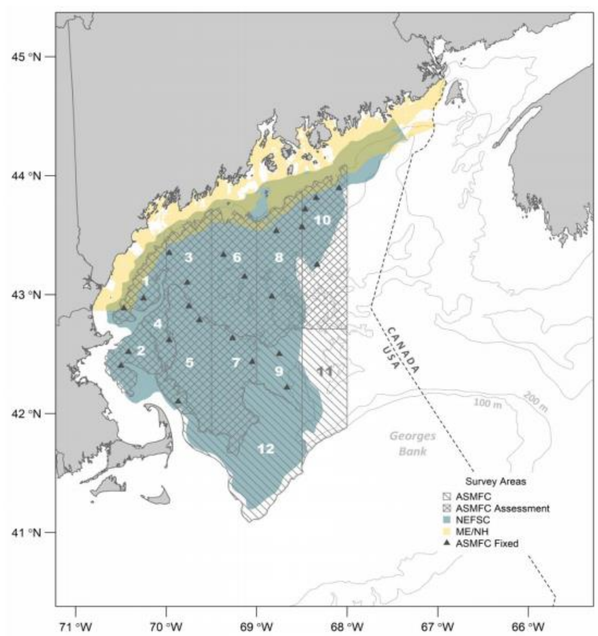
3.2.2.1 NEFSC Summer Shrimp Survey

This survey is conducted by the Atlantic States Marine Fisheries Commission (ASMFC), targeting northern shrimp in GOM waters from July to August. The survey incorporates a depth stratified random design with a fixed component. Tows are standardized by 15-minute intervals and use a four-seam modified commercial shrimp trawl net; the net body utilizes a mesh size of 1 3/8th inch stretch mesh, while 1-inch stretch mesh is employed in the codend and extension (ASMFC, 2019). The Summer Shrimp Survey began in 1984, making it one of the longest running, single-species, cooperative state-federal research surveys on the eastern seaboard. Data collected includes data regarding size, weight, and abundance of northern shrimp thus providing an idea of year class strength, sex-stage composition, and maturity of the GOM northern shrimp stock. ASMFC Summer Survey data is the primary data set utilized in this analysis and will be hence forth referred to as “the Summer Survey.”

3.2.2.2 ME-NH Spring Bottom Trawl Survey

Data taken from the Maine/New Hampshire (ME-NH) Bottom Trawl Survey (2000-2013) was also used in this research. The ME-NH Survey is a fishery-independent assessment of the aquatic resources in the coastal waters of Maine and New Hampshire. It incorporate a depth stratified random design with a fixed component and has occurred biannually since 2000, taking place in the spring (May-June) and fall (October-November) (Figure 3.2). Data is collected using a demersal otter trawl and 1-inch stretch mesh liner in the cod end. Tows are standardized by 20-minute intervals over a 0.8 nautical mile tow area at a rate of 2.2-2.3 knots (Sherman et. al., 2005). The net used is a modified version of the shrimp net design typically used in Maine waters. In total, 115 stations are selected for sampling each year (Sherman et. al., 2005). The survey collects length, weight, age, and abundance data on commercially important species in the Gulf of Maine; shrimp are separated from subsampled tows, enumerated, weighed, sexed, and measured. A CTD device is used to collect surface and bottom water temperature for each tow. Although the survey begins in 2000, data prior to 2005 was purposefully not incorporated in the current study, as survey data collection methods were not officially standardized until then. Data utilized from the ME-NH survey primarily included shrimp abundance indices by year and stage, which were used to calculate sex ratio, as well as latitudinal and longitudinal coordinate pairs, which were used to collectively average inshore temperatures over the survey area. For the remainder of this research, the ME-NH Spring Bottom Trawl Survey will be referred to as "the Spring Survey."

Figure 3.2: ASMFC Summer Shrimp Survey Area and Strata (ASMFC, 2019)



3.2.2.3 FVCOM

Temperature and salinity data incorporated into this study were obtained from University of Massachusetts (UMass) Dartmouth School for Marine Science and Technology (SMAST)'s Finite Volume Community Ocean Model (FVCOM). This system takes data collected from stationed buoys in the Gulf of Maine, in conjunction with a surface wave model, to compute monthly mean data on variables including temperature, salinity, and currents (FVCOM, 2016). FVCOM data incorporated into the analysis was considered reliable only until 2013; alternatively, Spring Survey data was collected from 2005 to 2017; in order to effectively compare the combined impact of sex ratio and environmental factors across each applied time lag, we drastically reduce our effective sample size by shortening the timeseries of data from 2008 to 2014, following the removal of NA's across datasets.

For each set of coordinate-based survey tow locations, a monthly average of bottom and surface temperature, as well as bottom and surface salinity, were obtained for each observed shrimp length. The closest station within ½ km radius of each tow was used to describe the abiotic conditions specific to that location. If a tow was beyond this range, an average of all FVCOM stations within a 1 km by 1 km grid centered around the tow location was used.

3.2.3 Data Treatment

With regards to both surveys, observations for which sex and/or length were "NA" or missing, were removed, as were observations missing latitude and longitude. This did not constitute a significant portion of the data. From the Summer Survey, removals of this nature constituted ~ 1.7% of the data, leaving 103,445 observations (Table 3.1), while removals from the Spring Survey constituted ~2.5% of total observations, leaving 74,906 observations (Table 3.2). Initially, data obtained from both surveys did not distinguish between juvenile and mature males; all were grouped collectively as “male.” Given that juvenile males and mature males exhibit spatial variability depending on their life stage, it follows they are also exposed to different environmental and stock-related conditions. For our research, it was important to make this distinction in the data to evaluate the impact of covariates on specific life stages. Male shrimp were divided into two groups, mature (“male”) and immature (“juvenile”) based on recruit length mode cutoffs provided by the NEFSC and Maine DMR and applied to the Summer and Spring Surveys, respectively (Table 3.3). Size frequency distributions of each sex are found in Figures 3.3 and 3.4.

Table 3.1: ASMFC Summer Shrimp Survey observation removal information by stage

Summer Survey	Male	Transitional	Female 1	Female 2	**Total**
Before removal	48,983	428	29,891	25,956	105,258
After removal	48,365	427	29,307	25,346	103,445

Table 3.2: ME-NH Inshore Bottom Trawl Survey observation removal information by stage

Spring Survey	Male	Transitional	Female 1	Female 2	**Total**
Before removal	46,959	685	11,025	18,087	76,756
After removal	45,622	651	10,896	17,737	74,906

Table 3.3: Recruit Length-Mode Cutoffs for ME-NH Spring and ASMFC Summer Shrimp Survey observations.

	ASMFC Summer		MENH Spring	
Year	Lmin (mm)	Lmax (mm)	Lmin (mm)	Lmax (mm)
1984	12	16.5		
1985	12	18		
1986	12	18.5		
1987	12	18.5		
1988	12	18.5		
1989	12	18		
1990	12	18		
1991	12	19		
1992	12	19		
1993	12	19		
1994	12	19		
1995	12	18		
1996	12	18		
1997	12	18		
1998	12	18		
1999	12	18		
2000	12	19		
2001	12	17		
2002	12	20		
2003	12	16.5		
2004	12	18.5		
2005	12	18.5	*NA*	16.25
2006	12	16.5	*NA*	14.75
2007	12	16.5	*NA*	14.25
2008	12	18.5	*NA*	16.25
2009	12	18	*NA*	16.25
2010	12	18	*NA*	16.25
2011	12	17	*NA*	14.25
2012	12	17	*NA*	14.75
2013	12	17	*NA*	16.25
2014	12	20.5	*NA*	18.75
2015	11.5	18	*NA*	16.25
2016	11	21.5	*NA*	18.25
2017	12	18	*NA*	16.25

Figure 3.3: Annual ASMFC Summer Survey length frequency distributions (1984-2017) for juvenile, male, transitional (i.e. transitional + female 1), and female 2 shrimp. Error bars are displayed about the mean

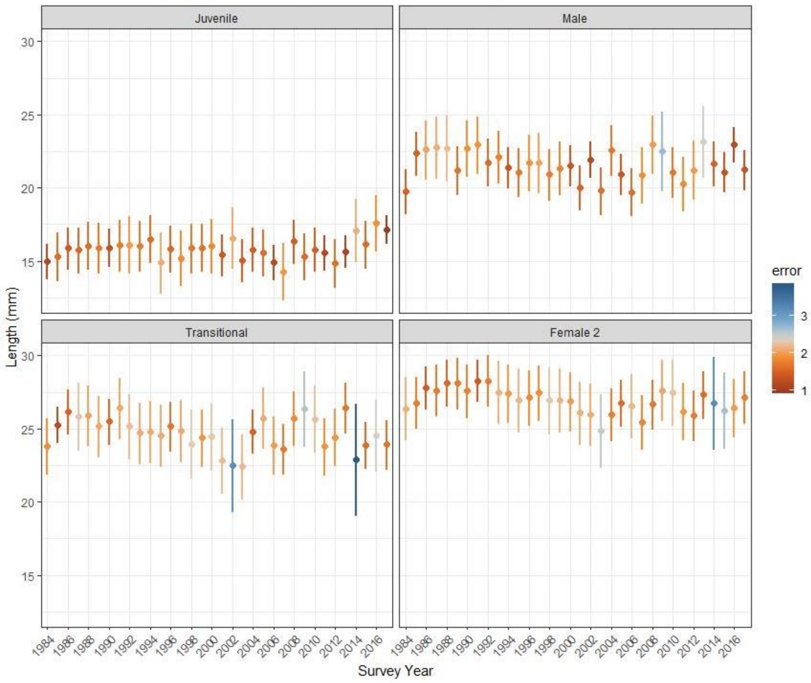
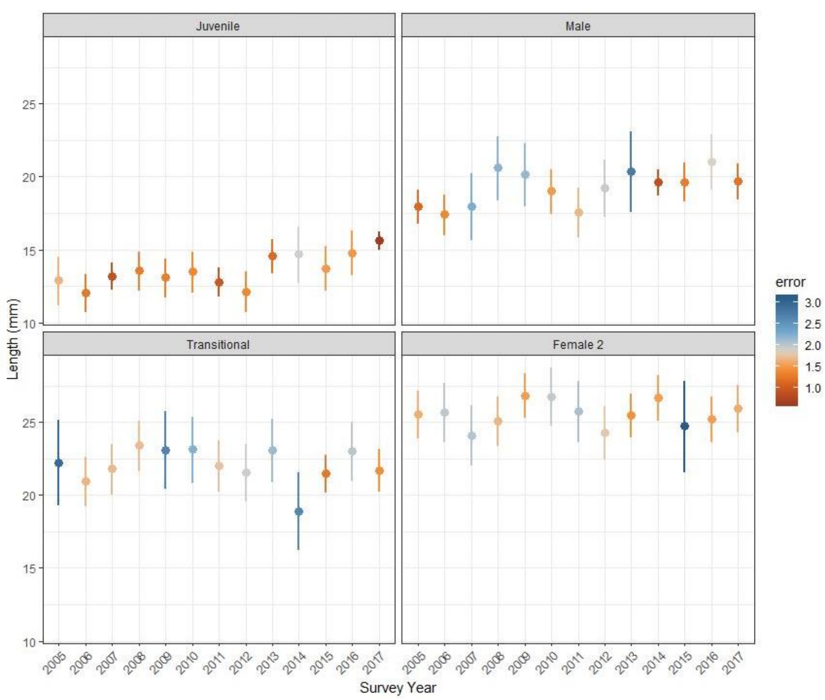


Figure 3.4: Annual ME-NH Spring Survey length frequency distributions (2005-2017) for juvenile, male, transitional (i.e. transitional + female 1), and female 2 shrimp. Error bars are displayed about the mean.



Abiotic FVCOM variables were averaged monthly over the area covered by each individual survey. Given that each survey tow is associated with a specific set of latitudinal and longitudinal coordinates, monthly averages of each variable were calculated by averaging all location-based values over the area covered by each survey each year. These methods were utilized due to the nature of shrimp behavior; shrimp are not a sedentary species, nor are there any studies confirming site fidelity in shrimp. As such, we cannot say with confidence that shrimp return to the same locations they were caught in previous survey years. This methodology allows us to evaluate the impact of inshore environmental conditions against offshore survey data. Looking at Summer Survey data, it is impossible to anticipate the exact location of earlier life stages found inshore, and, thus, impossible to know exactly what environmental conditions it was subject to. Alternatively, we may still evaluate the impact of previous years' average inshore temperature values taken from the Spring Survey. While this may lower the explanatory power of the model, this method allows some examination of the impacts of conditions experienced at earlier life stages, found inshore. It is anticipated that this methodology will detect anomalies in size-at-transition, despite decreased spatial variability in the data. Inshore and offshore averaged bottom and surface temperature may be observed in Figures 3.5 and 3.6, respectively.

Figure 3.5: Mean annual bottom temperature for the inshore (top) and offshore (bottom) portions of the Gulf of Maine from 1980 to 2013. Inshore averages were calculated by averaging FVCOM inshore temperature values over ME-NH Spring Survey Area. Offshore values were calculated in similar fashion, using ASMFC Summery Survey area.

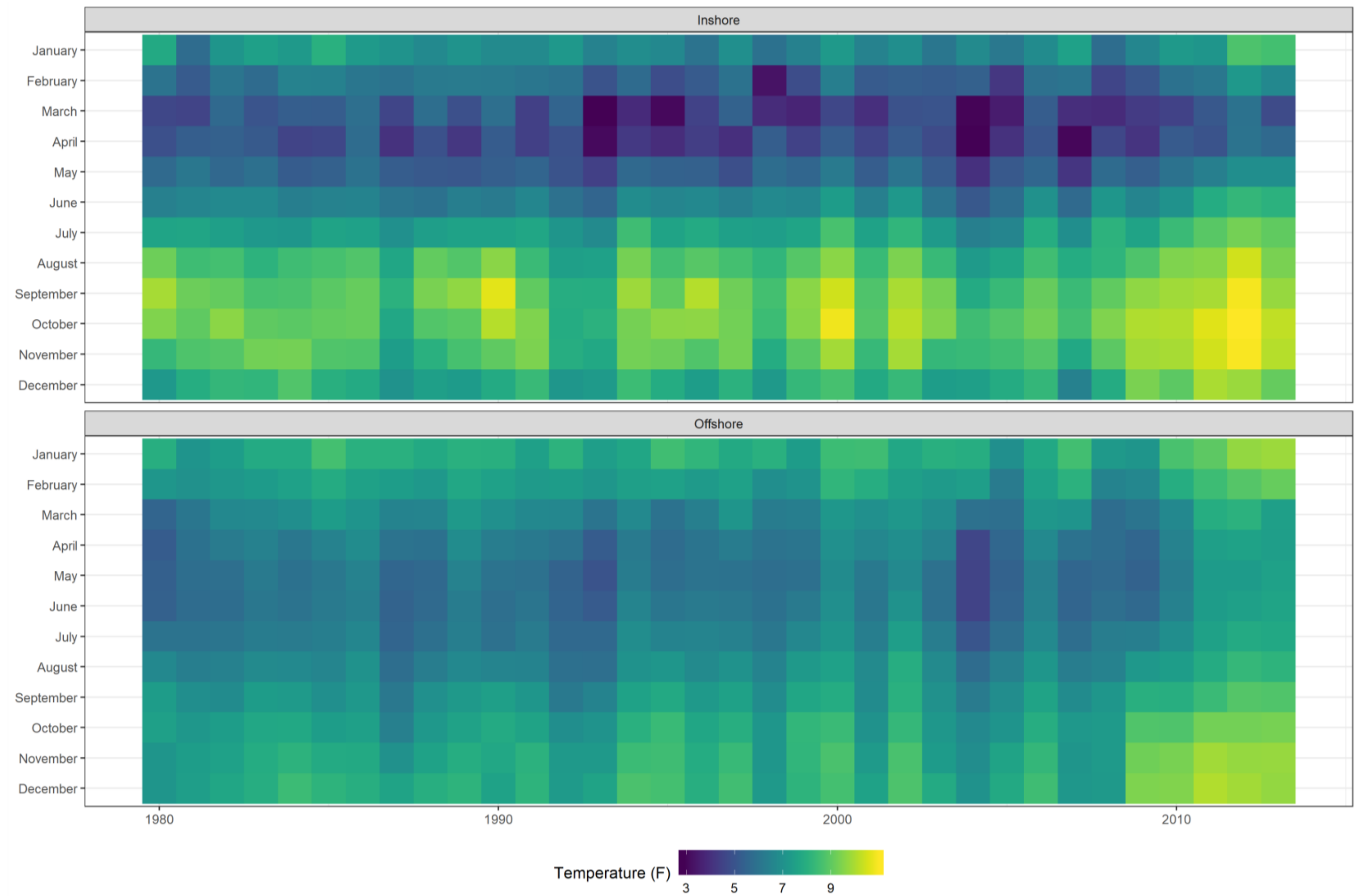
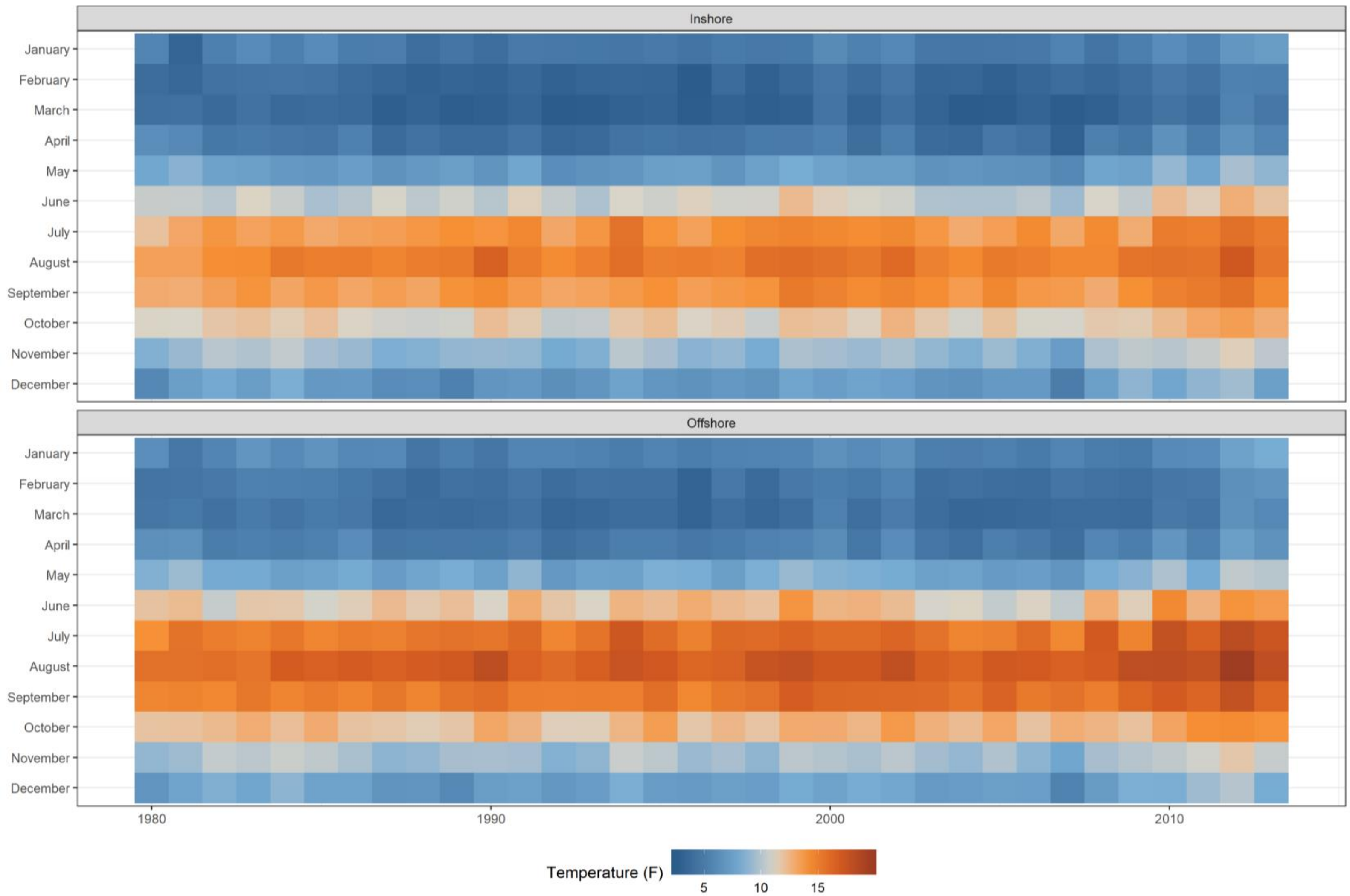


Figure 3.6: Mean annual surface temperature for the inshore (top) and offshore (bottom) portions of the Gulf of Maine from 1980 to 2013. Inshore averages were calculated by averaging FVCOM inshore temperature values over ME-NH Spring Survey Area. Offshore values were calculated in similar fashion, using ASMFC Summery Survey area.



Sex ratio for GOM northern shrimp was determined based on the abundance of females that bred as females in the previous season (female 2 shrimp), the abundance of transitionals and newly transitioned females (i.e. female 1 shrimp), and the abundance of mature males from Summer Survey data. Annual sex ratio was calculated by dividing the number of mature males by the collective abundance of mature female and transitional shrimp and then lagged one year.

3.2.4 Variable Selection and Justification

Potential variables influencing size-at-transition in northern shrimp were selected based on data availability and expert literary review following its applicability to stage-specific distribution, abundance, and ecology of the northern shrimp stock. As such, initial variables considered for testing were latitude (°), longitude (°), bottom and surface temperature (°F), bottom and surface salinity (ppt), sex ratio, and year. Depth (m) was not considered for testing, as depth was not applicable beyond lag 0 (where shrimp were initially caught). Year was incorporated as a factor to evaluate potential year effects, while latitude and longitude were included to determine whether localized affects existed within the data (Winton et al., 2014, Rooper et al., 2014). Models constructed to evaluate the impact of outside factors on size-at-transition were based on length data taken from the Summer Survey. Survey collection efforts were not consistent or detailed in their collection of environmental data regarding water temperature and salinity. To maintain consistency, none of the environmental data from either survey was used in the assessment. Rather, we obtained all salinity and temperature data from FVCOM buoys.

3.2.4.1 Environmental Effects

Based on a review of literature by authors who extensively review the impact of environmental parameters on northern shrimp size-at-stage, selected variables include bottom temperature (Hanes and Wigley, 1969; Stickney and Perkins, 1977; Apollonio et al., 1986; Richards et al., 2012), surface temperature (Shumway et al., 1985; Hansen and Aschan, 2000), latitude, and longitude (Winton et al., 2014; Rooper et al., 2014). Additional models incorporating the use of year, bottom, and surface salinity were also created to examine other potential sources of influence impacting size-at-transition in northern shrimp.

Bottom temperature is regarded by many as a significant source of influence concerning northern shrimp growth and maturation. First noted by Hanes and Wigley (1969), northern shrimp larvae subject to cooler, sub-artic water temperatures were discovered to exhibit slower developmental growth rates and longer life spans. Alternatively, same-age juveniles subject to warmer temperatures were observed to grow faster and molt more frequently, with larger individuals shown to exhibit external male characteristics earlier in warmer temperatures (Stickney and Perkins, 1977). Continuous observation regarding the timing and development of male characteristics provide added support to the notion that size, not age, determined sexual differentiation (Stickney and Perkins, 1977). Originally thought to be an entirely size-dependent process, Apollonio (1986) observed differences in length at age across time and location, suggesting that differences in growth by location (i.e. variation in geographic location) could be ascribed to variation in temperature.

Warming sea surface temperature was found to reduce average larval development time (Rasmussen & Tande 1995, Storm & Pedersen 2003; Kai and Siegstad, 2012) with variation in growth and maturation rates in northern shrimp larvae observed following exposure to variable sea surface temperatures (Shumway et al., 1985). It is inferred that warm water accelerates natural metabolic growth processes, acting as a catalyst for faster growth and increased frequency of molting, resulting in overall decreased carapace length (CL) growth per molt (Shumway et al., 1985). Furthermore, Hansen and Aschan (2000) argue that inter-annual variation in environmental conditions were found to further influence age- and size-at-maturity in females, with areas characterized by colder water (due to variable mixing of Artic and Atlantic currents) found to exhibit increased age at female maturity due to slower growth rates.

Regarding any one specific stage, it was observed that the majority of growth occurs within the first two years of life, followed by a strong decline in growth the third year (Apollonio, 1986); given a heightened degree of susceptibility during this critical life stage, as well as the species' overall dependence on water temperature, we anticipate that environmental conditions experienced during the first two years of life are highly influential regarding growth trajectory and size-at-transition. It may be inferred that decreased length at sex transition is largely a result of warming conditions; differences in age and growth at maturity may vary according to location and temperature (Hansen and Aschan, 2000; Skuladottir, 1999; Apollonio and Dunton., 1969; Rasmussen, 1953). Alternatively, Koeller (2006) claims that environmental influence does not specifically target certain life stages, rather it effects all size categories equally, regardless of stage or age. Thus length- and age-at-transition vary flexibly, dependent on collective environmental influence and occur as a result of growth rate and metabolic opportunism, not at any set length or age.

Longitude and latitude were included in initial models to test for sources of spatial significance in the data (Winton et al., 2014). Results displaying strong significance regarding latitude or longitude could denote the importance of, and need for, spatially explicit data in continued monitoring efforts. Though there is a relatively low abundance of literature suggesting that salinity impacts the transitional process, preliminary model runs were evaluated with and without salinity to rule out whether this effect has any influence on size-at-transition.

3.2.4.2 Sex Ratio-Dependent Effects

It is typical for other pandalid populations to show variation in age composition based on size. Another explanation for this phenomenon suggests that individuals may alter the age at which they change sex to account for a lack of breeding females (Charnov *et al.*, 1978). Sexual expression varies in males and females depending on their given environment; within the GOM, there is particular interest as to whether or not timing and size-at-transition is altered in order to match current breeding opportunities in response to stock composition and sex-selective fishing pressure (Hansen and Aschan, 2000; Charnov, 1982). Studies conducted on *Pandalus jordani* (pink shrimp), the shorter-lived, West Coast cousin of *borealis*, conclude that individuals alter their size structure and/or age class in order to compensate for yearly fluctuations within the stock's structure (Hansen and Aschan, 2000; Charnov *et al.*, 1978). Prior to transition, it follows that sex ratio lagged by one year would be potentially most impactful, as it is representative of the time during which mature males first encounter the available breeding population. Following a review of literature by authors who argue, alternatively, that density-dependent effects directly influence size-at-transition, sex ratio was also determined to be an important covariate worth testing given that increased competition between mature males may directly impact the size and timing of transition.

3.2.5 Generalized Additive Models

To examine the relationship between size-at-transition and factors potentially influencing this life history process, we employed the use of a generalized additive model (GAM). GAMs are a non-parametric regression technique that allow flexibility in the data as they do not require linearity in the distribution of the data. Rather, error distributions commonly associated with GAMs allow for a wider fit, thus enabling a non-linear relationship to be established between dependent and independent variables (Swartzman *et al*., 1995). Data in this study was subject to a low proportion of zero observations (instances of no presence observed). GAMs were fitted using a Gaussian error distribution given the normal distribution of continuous data being utilized.

Covariates were selected based on Akaike Information Criteria (AIC) following model results for each variable grouping within each lag and survey. Generally, the addition of variables to a model increases the uncertainty surrounding its predictive capacity; while bias declines with each new variable's addition to the model, this simultaneously increases the variance of each model, broadening its confidence limits and contributing further uncertainty in the model's predictive capacity (Burnham and Anderson, 2002). AIC measures the overall quality of a given model, balancing the trade-offs between model complexity (number of variables) and its goodness-of-fit to mitigate the risk of over-fitting. Within a collection of models, the best model is that with the lowest AIC value, as it identifies the ability of a model to simultaneously minimize bias and variance (Burnham and Anderson, 2002). It is also noted for its ability to compare goodness-of-fit across models that utilize the same data and dependent variable (Johnson & Omland, 2004).

Within each survey, time lag, and variable grouping, a model was fit with all remaining candidate environmental variables (initial model), following initial removal based on first round VIF results. Following the first run, each subsequent model removed one variable until each variable's p value was < 0.05. If the model's AIC remained unchanged following each successive variable-removal, the less complicated model was selected. Following the methods of Hastie and Tibshirani (1990), GAMs were chosen based on final AIC scores. Models were determined statistically different from each other if they displayed a difference in AIC value of 2 or more (Arnold, 2010).

3.3 Results

3.3.1 Environmental Effects (Preliminary Models)

During the configuration process, statistically insignificant variables were subsequently removed from base models following a stepwise selection techniques. For each survey dataset, the model exhibiting the lowest AIC was determined as representative of the best fit (i.e. the most explanatory power).

3.3.1.1 Model Configuration

Environmental variables with a lag of zero (i.e. y-0, concurrent with that year) were excluded from testing, as the literature suggests the stages most strongly impacted by environmental conditions are the larval, juvenile, and male stages. Comparatively, models that included year performed poorly in comparison to those that did not. Models including temperature only, *versus* those that included temperature and salinity, were preferred. Due to a lower number of observations on transitionals, preliminary results examining the impact of inshore environmental effects on Spring Survey data are used solely as a robustness test against the lag and variable selection of inshore effects on Summer Survey data. As such, the remainder of this research explores the significance of those models exhibiting the highest overall explanatory power based solely on the impact of temperature and longitude on Summer Survey size-at-transition. A list of all preliminary environmental models and their components may be found in Table 3.4. The two-preliminary environmental-based models with the highest overall explanatory power are as follows:

[Model 11 (inshore)] $L_T = \beta_0\,(longitude) + f(Jan\ ST_{y-2}) + f(Jul\ ST_{y-2}) + f(Sep\ ST_{y-2}) + f(Oct\ ST_{y-2}) + f(Dec\ ST_{y-2})$

[Model 16 (offshore)] $L_T = \beta_0\,(longitude) + f(Mar\ BT_{y-2}) + f(Jan\ ST_{y-2}) + f(Jul\ ST_{y-2}) + f(Aug\ ST_{y-2}) + f(Oct\ ST_{y-2}) + f(Dec\ ST_{y-2})$

3.3.1.2 Model Diagnostics and Analysis of Fit

A full description of model output for all tested models may be found in Appendix E1. Of the models listed above, model 16 displayed the lowest AIC value and the highest deviance explained (Table 4.4). Overall, environmentally based preliminary models experienced few convergence problems. Following the first run of each model, output describing the significance of smoothed terms indicated that the specified k' value within both models was not high enough and, therefore, did not accurately reflect the complexity of the smoothed term. Shifting the value of k' from 5 to 6 resulted in full convergence of both models (Appendix E2). Despite full convergence, both models indicated that the specified k' value on longitude was not high enough, and therefore likely not able to capture the full complexity of the data based on model composition as is.

3.3.1.3 Generalized Additive Model Output

Models that included year exhibited lower explanatory power than their counterparts that did not. Of the models that excluded year, those including a combination of averaged temperature and salinity values, versus those that only included temperature, exhibited little to no change in significance and results often varied inconsistently with literature regarding their identification of significant sources of influence. As such, models incorporating salinity were discarded. Decreasing model significance, based on variation in each model's components, is depicted in Tables 3.4 and reflected by higher AIC values.

Both models exhibiting the highest significance, each identified Lag 2 as the most influential time timeframe regarding size-at-transition (L_T). Model 11 examined the potential relationship of offshore environmental conditions on Summer Survey L_T (Appendix E1a). Model 16 examined the influence of inshore environmental effects on Summer Survey L_T. Overall, Model 16 was preferred, as it the impact of inshore conditions exhibited stronger significance than conditions offshore. Components of the model include March bottom temperature, January, July, August, October, and December surface temperature, and longitude (Appendix E1b). Model 16 indicated the strongest overall performance regarding explanatory power and was selected for further analysis from amongst all environmental models. Diagnostic plots for Model 11 and Model 16 may be observed in Figures 3.7-3.8 and Figures 3.9-3.10, respectively.

Table 3.4: List of environmental-based models, including their composition, deviance explained, AIC, R2, RMSE, and MAE values for each model, with and without year, for each time lag specified. Those models bolded indicate the best fit version within their respective grouping; those in red denote AIC values associated with models included in future analysis.

(a) The relationship between inshore environmental effects and Spring Survey L_T
(b) The relationship between offshore environmental effects and Summer Survey L_T
(c) The relationship between inshore environmental effects and Summer Survey L_T

(a) Inshore Effects on Spring Survey L50 (n = 9,148)										Monthly Averaged Variables			
Year	ENV effect	Model	Survey	Lag	Dev. Expl.	AIC	R2	RMSE	MAE	BSAL	SSAL	BT	ST
Without year	Salinity & Temp	1	Spring	(y-2)	29.53	**41523.90**	0.26	1.94	1.54			1,3	9
		2	Spring	(y-3)	29.53	41526.61	0.26	1.94	1.54	6		3	12
		3	Spring	(y-4)	29.53	41526.00	0.26	1.94	1.55	1,12		3	1
	Temp	4	Spring	(y-2)	29.53	**41526.00**	0.26	1.94	1.54			1,3	4,12
		5	Spring	(y-3)	29.53	41526.69	0.26	1.94	1.54			1,3	7,12
		6	Spring	(y-4)	29.53	41526.57	0.26	1.94	1.54			1,3,12	8
With year	Salinity & Temp	Y1	Spring	(y-2)	29.53	41526.700	0.26	1.94	1.54			1,3	9
		Y2	Spring	(y-3)	29.53	41526.690	0.26	1.94	1.54	6		3	1,12
		Y3	Spring	(y-4)	All variables removed due to non-significance					1,12		3	1
	Temp	Y4	Spring	(y-2)	29.53	41526.690	0.26	1.94	1.54			1,3	12
		Y5	Spring	(y-3)	29.53	41526.690	0.26	1.94	1.54			1,3	7,12
		Y6	Spring	(y-4)	29.53	41526.690	0.26	1.94	1.54			1,12	8
(b) Offshore Effects on Summer Survey L50 (n = 27,411)										Monthly Averaged Variables			
Year	ENV effect	Model	Survey	Lag	Dev. Expl.	AIC	R2	RMSE	MAE	BSAL	SSAL	BT	ST
Without year	Salinity & Temp	7	Summer	(y-1)	36.07	131144.60	0.26	2.10	1.64	1	6,12	3	2,7,9,12
		8	Summer	(y-2)	36.07	**131144.50**	0.26	2.10	1.64	1,6	12	3	1,7,9,10,12
		9	Summer	(y-4)	30.90	133252.80	0.20	2.19	1.68	12	7		6,9,12
	Temp	10	Summer	(y-1)	30.70	133316.90	0.23	2.15	1.67				2,7,9
		11	Summer	(y-2)	36.06	**131144.00**	0.26	2.10	1.64			3	1,7,9,10,12
		12	Summer	(y-4)	30.27	133501.40	0.19	2.21	1.70			12	6,9,10,12
With year	Salinity & Temp	Y7	Summer	(y-1)	All variables removed due to non-significance					1,12	7	3	6,9,12
		Y8	Summer	(y-2)	All variables removed due to non-significance					1,6	12	3	1,7,9,10,12
		Y9	Summer	(y-4)	36.07	131145.100	0.26	2.10	1.64	1,12	7	3	6,9,12
	Temp	Y10	Summer	(y-1)	All variables removed due to non-significance								2,7,9
		Y11	Summer	(y-2)	All variables removed due to non-significance							3	1,7,9,10,12
		Y12	Summer	(y-4)	36.07	131,145.10	0.26	2.10	1.64			3,12	1,6,9,10,12
(c) Inshore Effects on Summer Survey L50 (n = 27,411)										Monthly Averaged Variables			
Year	ENV effect	Model	Survey	Lag	Dev. Expl.	AIC	R2	RMSE	MAE	BSAL	SSAL	BT	ST
Without year	Salinity & Temp	13	Summer	(y-2)	36.07	131144.30	0.26	2.10	1.64	12	1,8	3	1,7,8,12
		14	Summer	(y-3)	36.07	**131142.40**	0.26	2.10	1.64	12	6,8	3	1,7,8,12
		15	Summer	(y-4)	24.95	135502.20	0.15	2.25	1.74	12			9,12
	Temp	16	Summer	(y-2)	36.07	**131143.60**	0.26	2.10	1.64			3	1,7,8,10,12
		17	Summer	(y-3)	29.56	133773.50	0.20	2.18	1.71			3,10	8,12
		18	Summer	(y-4)	29.89	133651.50	0.19	2.20	1.70			4,10	7,9,12
With year	Salinity & Temp	Y13	Summer	(y-2)	All variables removed due to non-significance					12	1,8	3	1,7,8,12
		Y14	Summer	(y-3)	All variables removed due to non-significance					12	6,8	3	1,7,8,12
		Y15	Summer	(y-4)	36.07	131,145.10	0.26	2.10	1.64	12	1,4,8		1,4,7,9,12
	Temp	Y16	Summer	(y-2)	All variables removed due to non-significance							3	1,7,8,10,12
		Y17	Summer	(y-3)	All variables removed due to non-significance							3,10	8,12
		Y18	Summer	(y-4)	36.07	131,145.10	0.26	2.10	1.64			1,10	7,9,12

Figure 3.7: Partial residual plots for model 11, following final selection amongst preliminary models, analyzing the relationship between offshore environmental effects and Summer Survey L_T. Each plot examines the relationship between individual independent variables (averaged environmental effects) and the dependent variable (size-at-transition).

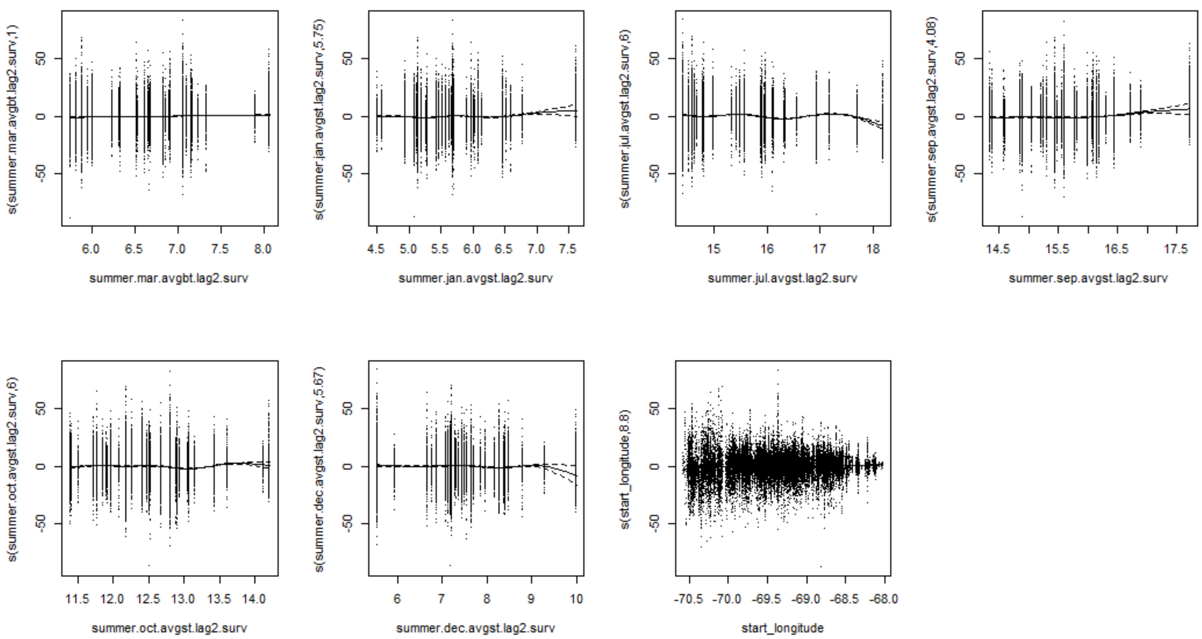


Figure 3.8: Diagnostic plots for model 11 residuals, including a QQplot (top left), a plot of residual values *versus* the linear predictor (top right), a histogram of residuals (bottom left) and a plot of the response *versus* fitted values.

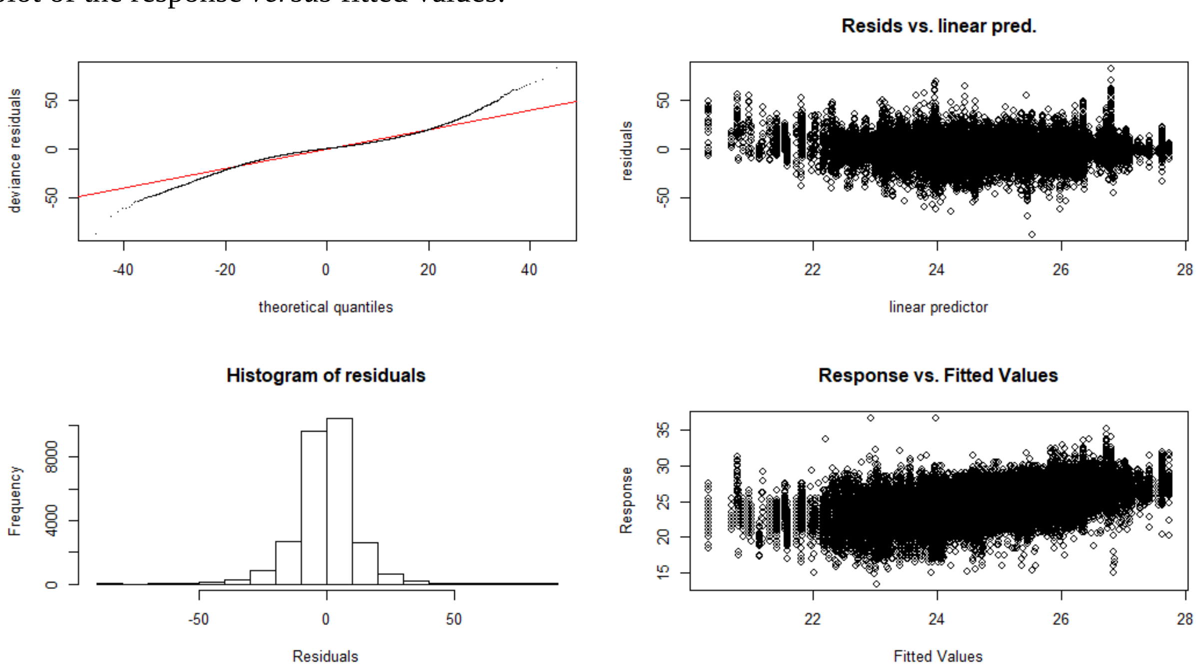


Figure 3.9: Partial residual plots for model 16, following final selection amongst preliminary models, analyzing the relationship between inshore environmental effects and Summer Survey L_T. Each plot examines the relationship between individual independent variables (averaged environmental effects) and the dependent variable (size-at-transition).

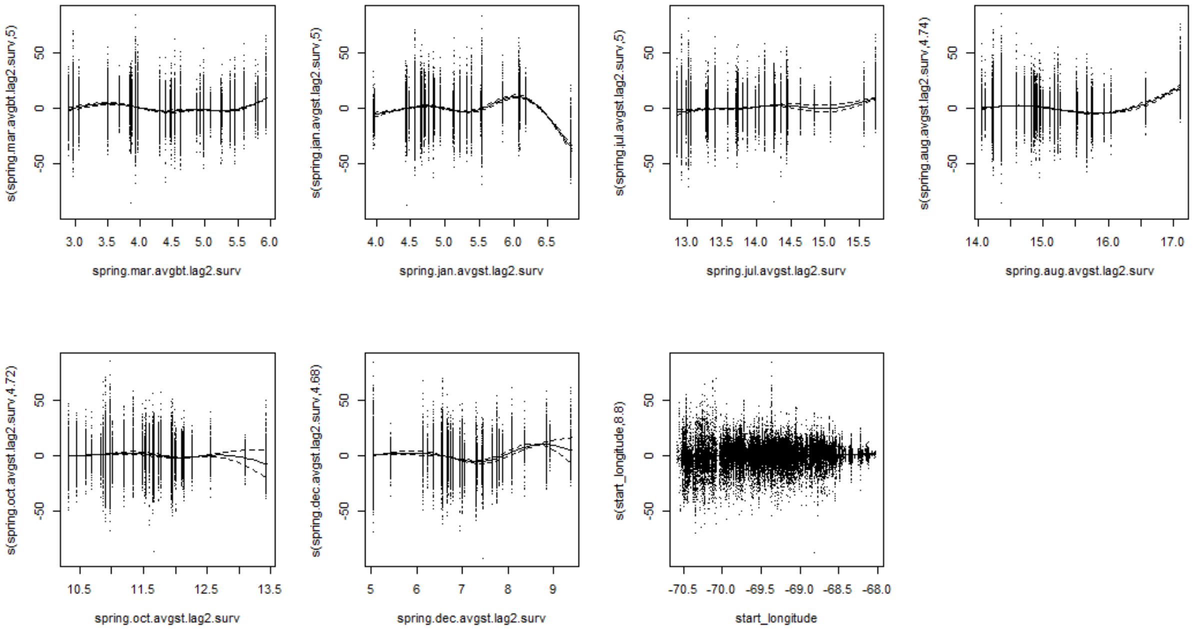
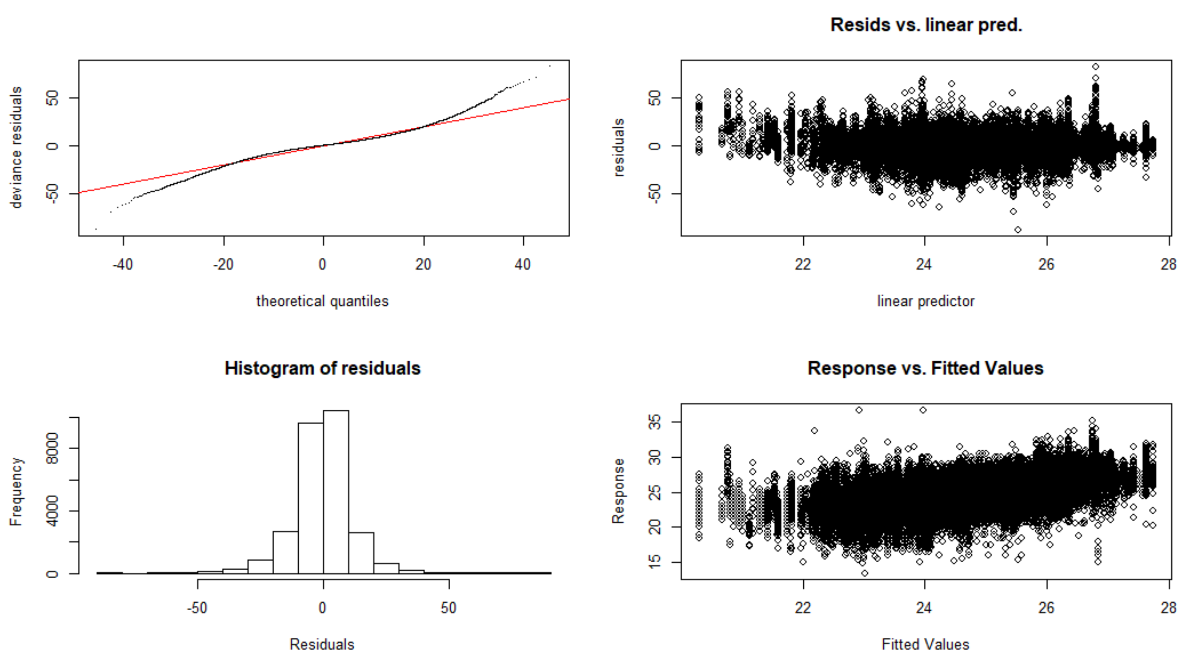


Figure 3.10: Diagnostic plots for model 16 residuals, including a QQplot (top left), a plot of residual values *versus* the linear predictor (top right), a histogram of residuals (bottom left) and a plot of the response *versus* fitted values.



3.3.2 Sex Ratio-Dependent Effects (Preliminary Models)

3.3.2.1 Model Configuration

All models examining the impact of sex ratio on size-at-transition incorporated longitude. Model's incorporating year and/or latitude lost significant explanatory power. As such, models including year were discarded. Sex ratio was calculated using Summer Survey data and was lagged one and two years. Lags of two and three years were tested to confirm whether conditions experienced as mature males proved most impactful.

3.3.2.2 Model Diagnostics and Analysis of Fit

A detailed summary of model output, as well as a list of each model and their components, may be found in Appendix E3 and Table 3.5, respectively. Summer Survey sex $\text{ratio}_{(y-1)}$ (model 19) exhibited the highest deviance explained and the lowest AIC of other summer-based models (Table 3.5). Overall, model 19 exhibited the highest deviance explained and R^2, as well as the lowest AIC value, of all other lags and sex ratios (Table 3.5). As such, it was selected for further analysis.

Diagnostic reports on model 19 indicate low k-index specification on longitude, combined with a significantly low p-value (Appendix E4). This suggests there are patterns in the residuals not fully explained by the composition of the model. Model 19 was selected for further analysis regarding final model composition to determine whether its significance as a predictor would improve in the presence of environmental variables. Diagnostic plots for model 19 may be observed in Figures 3.11 and 3.12.

3.3.2.3 Generalized Additive Model Output

Following preliminary model runs examining the relationship between Summer Survey sex ratio on Summer Survey L_T , results collectively identified sex ratio lagged one year as the most significant of all calculated ratios (Table 3.5). Sex ratio lagged two and three years exhibited a less significant relationship with size-at-transition.

Table 3.5: List of sex ratio-based models, including their composition, deviance explained, AIC, R2, RMSE, and MAE values for each model, with and without year, for each time lag specified. Those models bolded in red indicate the best fit version within their respective grouping (i.e. lowest AIC value) and those used in continual analysis. Preliminary results depicted are reflective of results measuring the impact of summer sex ratio on Summer Survey L_T

Summer Sex Ratio on Summer Survey L50								Sex Ratio
Model	Year	(n)	dev_expl	AIC	R2	RMSE	MAE	Lag
19	Without Year	28,709	18.19	**145,854.60**	0.08	2.34	1.83	(y-1)
20		28,709	14.24	147,208.80	0.08	2.34	1.85	(y-2)
21		28,709	16.64	146,395.10	0.09	2.35	1.84	(y-3)
22	With Year	28,709	35.41	139,123.40	0.25	2.11	1.64	(y-1)
23		28,709	35.41	139,123.40	0.25	2.11	1.64	(y-2)
24		28,709	35.41	139,123.40	0.25	2.11	1.64	(y-3)

Figure 3.11: Partial residual plots for model 19, following final selection amongst preliminary models, analyzing the relationship between Summer Survey sex ratio$_{(y-1)}$ and Summer Survey L_T. Each plot examines the relationship between individual independent variables (sex ratio) and the dependent variable (size-at-transition).

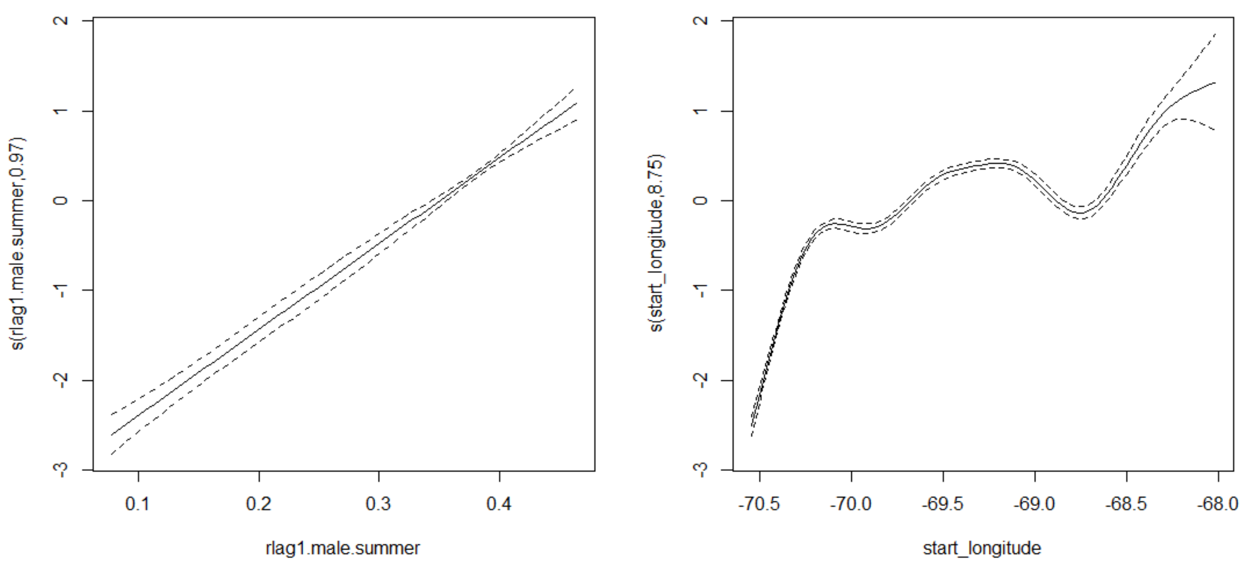
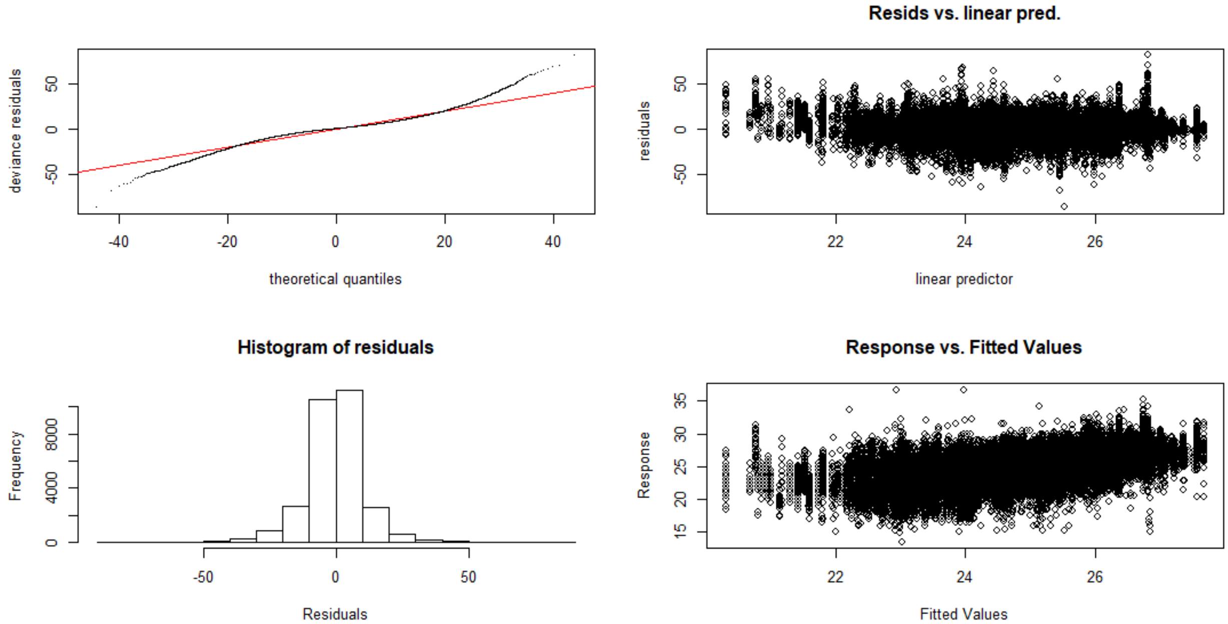


Figure 3.12: Diagnostic plots for model 19 residuals, including a QQplot (top left), a plot of residual values *versus* the linear predictor (top right), a histogram of residuals (bottom left) and a plot of the response *versus* fitted values.



3.3.3 Combined Variable Effects (Final Model)

3.3.3.1 Model Configuration

For the final combination model, measuring the potential combined impact of environmental effects and sex ratio on size-at-transition, models in each test-variable category were chosen based on the overall lowest comparative AIC values and highest explanatory power. Model 16, which measures the impact of inshore environmental effects on Summer Survey L_T , exhibited stronger influence on Summer Survey L_T in comparison to offshore select variable. As such, it was incorporated into the base of the final model. Model 19, representative of the sex ratio exhibiting the strongest explanatory power, was incorporated as the sex-ratio component. The composition of the final model reflects the combination of the two most explanatory preliminary models:

[Model 25] $Summer\ L_T = \beta_0\,(longitude) + f(Mar\ BT_{y-2}) + f(Jan\ ST_{y-2}) + f(Jul\ ST_{y-2}) + f(Aug\ ST_{y-2}) + f(Oct\ ST_{y-2}) + f(Dec\ ST_{y-2}) + f(sex\ ratio_{\ y-1})$

The final model was evaluated using data from Summer Survey L_T data (n = 27,670). Non-significant covariates were removed if 1) its associated p-value was > 0.5, or 2) the AIC value of the model decreased or remained the same following the removal of said covariate, in which case the less complicated model was selected. Additionally, following the final removal of all non-significant covariates, robustness checks on the model’s variable groupings was performed; the model’s previously combined components were separated once again and evaluated individually using the same survey data as the original. This measure was performed to determine 1) if their combined influence provided additional explanatory power, and if not 2) which effect, environmental or density-dependence, displayed stronger influence over size-at-transition. A list of the final model components may be found in Table 3.6.

Table 3.6: Model configuration for final model testing, analyzing the combined influence of environmental and sex-ratio-dependent sources of influence.

Final Model Components (Model 25)										Envio. Variables		Sex Ratio
Model Type	Effect	Model #	Lag	(n)	dev_expl	AIC	R2	RMSE	MAE	BT	ST	Summer
Environmental	Inshore	16	(y-2)	27,411	36.07	131,143.60	0.26	2.10	1.64	3	1,7,8,10,12	
Sex Ratio	Summer	19	(y-1)	28,709	18.19	145,854.60	0.08	2.34	1.83			(y-1)

ENV: Environmental Averaged Effects
SR: Sex Ratio
SP: Spring
SM: Summer

3.3.3.2 Model Diagnostics and Analysis of Fit

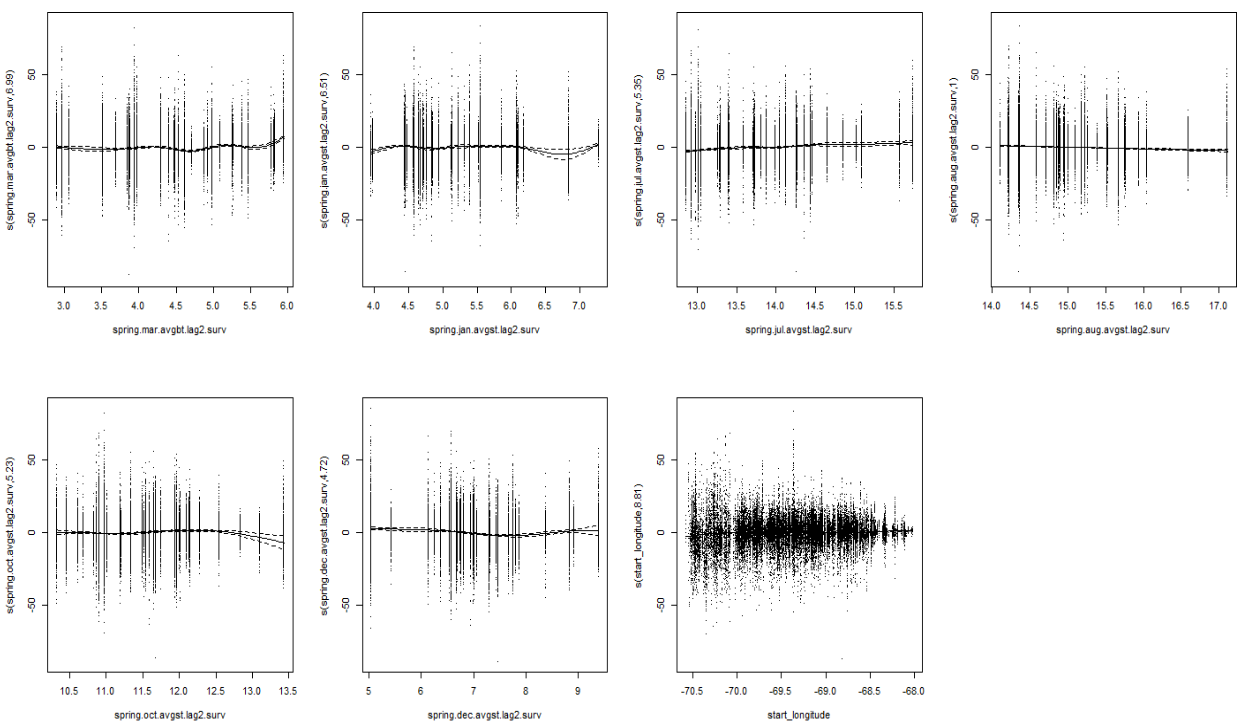
Results detailing the output of combo model 25 and robustness checks on environmental and density-dependent components, may be found in Appendices E5 and E6, respectively. AIC values for each model may be found in Table 3.7. Complementary printouts detailing the approximate significance of smooth terms provide added explanation as to the complexity of the smooth function, also specified by 'effective degrees of freedom' (EDF), associated with each covariate; this relationship is visualized by the complexity of the line displayed in each residual plot. A value of 1 indicates a linear relationship, while higher values indicate increasing complexity. Following the removal of non-significant variables, the robustness check on environmental components within the final model exhibited the lowest AIC value, while its density-dependent component exhibited the highest when assessed alone. There was little to no change in deviance explained or R^2 in any of the subsequent model runs.

Table 3.7: Deviance explained, Aikaike Informaiton Criterion (AIC), r-squared, RMSE, and MAE values for final model configuration. Sub models listed document the changes in explanatory power following the removal of non-significant variables, as well as robustness checks measuring the combined explanatory power of each model against the significance of their effective component groupings. AIC in red represents the lowest AIC value of all models.

Effect	Model	(n)	dev_expl	AIC	R2	RMSE	MAE	Removal
Combo (envio + sex ratio)	25	27,670.00	36.32	132676.40	0.27	2.06	1.60	none
Environmental (only)	25.1	27,670.00	36.33	**132675.40**	0.28	2.05	1.59	none
Sex Ratio (only)	25.2	27,670.00	19.15	139229.00	0.11	2.28	1.79	none

Final output for model 25, prior to robust analysis, longitude appears most significant, followed by sex ratio (Appendix E5). Examining the robustness check on environmental aspects of the model, all variables appear to be nonlinear and significant except for August, which appears entirely linear (Appendix E5). Next to longitude, March bottom temperature appears most influential to the model. Regarding density-dependent components of the model, sex ratio$_{(y-1)}$ exhibited moderate complexity and nonlinearity, while longitude exhibited high nonlinearity, complexity, and significance (Appendix E5).

Figure 3.13: Partial residual plots for the environmental robustness check on model 25.1, examining the relationship between Summer Survey L_T and the environmental components of the model

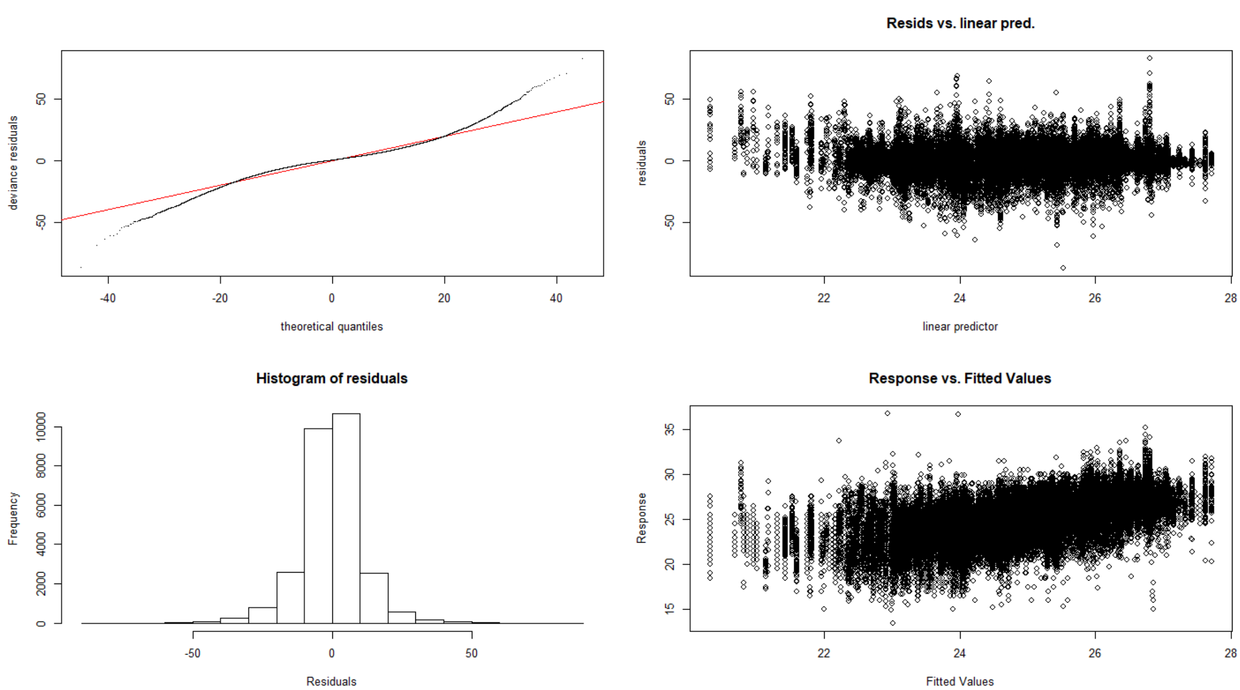


Additionally, diagnostics assessing each model's goodness-of-fit were conducted by assessing 1) the basis dimensions used for smooth terms in each model and 2) whether distributional assumptions were violated. A full diagnostic summary of model 25 and robustness checks on its individual components is available in Appendix E6. K-index values reported by gam.check indicate whether the transformation and composition of the model components accurately capture the complexity in model residuals. Effectively, model residuals should display no patterns about the mean (i.e. they should be randomly distributed); small p-values provide indication that residuals exhibit patterns and are not randomly distributed, while non-significant p-values suggest non-significant patterns and accurately capture patterns within the data.

Statistical diagnostics performed on the fit of base model 25 display k-index values close to 1 for all model components except longitude, which exhibits a lesser value of 0.80 and significance in its associated p-value (Appendix E6a). This trend is similar in the diagnostic reports for environmental (model 25.1, Appendix E6b) and density-dependent (model 25.2, Appendix E6c) robustness checks as well; all model components display k-index values close to 1, while longitude consistently reports values of 0.70 or lower that are highly significant. Of additional concern how close k' and edf are for sex ratio in the base as well as the robust model for sex ratio components (Appendix E6), potentially an indication that specified k in the model is set too low for this variable. Concerns surrounding the specification of spring sex ratio and longitude indicate that there are missed patterns in the residuals that are not fully explained by the model in relation to longitude; a low p-value suggests that the basis dimension k' has been set too low, i.e. there are not enough basis function to capture the true relationship within the data. Of the three final models, the model examining environmental components alone appears to be the most well received.

Plots examining fit provide additional interpretive power to our analysis of the most significant model. Observable in Figure 3.14, the QQplot (top right) compares model residuals to a normal distribution, represented by the red line. Most quantile points appear to fall along the middle of the theoretical normal line, however, noticeable tails on both ends suggest abnormality within the data, suggesting that there may be more extreme values in our data than would be expected of a normal distribution and, otherwise, calls into question the goodness of fit captured by this mode. This implies that the model is more likely to underestimate smaller lengths and overestimate larger lengths. The histogram of residuals exhibits a symmetrical distribution around zero, however, the longer left-sided tail indicates that data utilized are slightly skewed; this suggests that the model may not fully meet model assumptions and, therefore, the normal approximation confidence intervals surrounding our predictions could be inaccurate. When plotting residuals *versus* the linear predictor (Figure 3.14, top right), residuals appear relatively normally distributed; slight upended inflection towards the left-hand portion of the plot could indicate the existence of patterns within the residuals, though these appear to be extremely minimal.

Figure 3.14: Diagnostic plots for final combination model 25.1 residuals, including a QQplot (top left), a plot of residual values *versus* the linear predictor (top right), a histogram of residuals (bottom left) and a plot of the response *versus* fitted values.



3.3.3.3 Generalized Additive Model Output

Collectively, results suggest that model 25.1, evaluating the robustness of the environmental components, outperforms all other final models. Components of this model include March bottom temperature, as well as January, July, August, October, and December surface temperature, and longitude. All environmental variables are lagged two years.
Model 25.2, comprised solely of the density-dependent component sex ratio$_{(y-1)}$, exhibited the lowest overall significance, indicating that sex ratio alone does not account for variability observed in size-at-transition in northern shrimp. The original model, composed of previously specified environmental and density-dependent components, exhibited slightly less significance than did the model comprised solely of environmental components. This potentially suggests that the influence of sex ratio is negligible on transitional growth, rather, the significance ascribed to density-dependent components may capture alternative trends in the data.

3.4 Discussion

The objectives of this study were to examine the relationship between environmental and density-dependent variables, and their potential impact on size-at-transition in northern shrimp. Methods incorporated utilized a generalized additive modeling approach. The results appear consistent with literature regarding the impact of environmental variables on this important life history process. Preliminary models identified inshore environmental conditions as the most significant factor influencing size-at-transition more so than density-dependent effects; in particular, March bottom temperature experienced as juveniles displayed the strongest significance. The inclusion of salinity in preliminary models did not contribute significant explanatory power to models, nor did it adhere to patterns consistent across outside literary sources. Though trends reported are consistent with literature beyond this research, given the nature of the data treatment included in this research, it is important to make note of the shortcomings that coincide with an overall loss in interpretability following the averaging of environmental variables across entire survey areas,

3.4.1 Model Configuration

Base variables removed from all models were year and latitude. Latitude and longitude displayed strong multicollinearity when simultaneously included in the model, while longitude displayed stronger explanatory power in each model when isolated. As such, latitude was removed. Preliminary model runs including year as a variable were highly inconsistent across survey data and peer-reviewed literature; this is potentially due to the nature of the explanatory variables included in the model. Given that averaged environmental effects are already lagged yearly for each model, introducing an additional variable for year creates redundancy in the data and produces distorted results. Model fit improved following the subsequent removal of year from each GAM.

3.4.1.1 Environmental Effects

Stages identified by literature as critically influential, regarding growth patterns, were consistent across Summer Survey data; documented seasonal and stage-specific variation in variable significance were observed. Temperature exhibited significant influence concerning size-at-transition in northern shrimp, with specific year-lags (i.e. stages) exhibiting a stronger relationship between explanatory variables and length at transition. Results generally agreed with literature in that certain stages of growth were observed to be more strongly influenced than others. The two strongest preliminary models exhibit patterns in variable significance and selection, following seasonal- and stage-specific growth patterns for juveniles. Trends in variables included in both Model 11 and Model 16 are consistent with each other and with similar trends found in peer-reviewed literature, within which the strongest trends appear to be environmentally driven at earlier life stages. Variation in the inclusion of environmental variables across models is potentially a representation of stage-specific tolerance and exposure to different habitat variables and their spatio-temporal relationship with the northern shrimp's life history cycle.

Inconsistent results surrounding the inclusion of bottom and surface salinity in preliminary models may be potentially attributed to numerous factors. Exploratory model runs evaluating the significance of averaged values against size-at-transition resulted in the removal of salinity from the analysis due to inconsistency across preliminary model output. Given that differences between salinity values vary within a much smaller range than temperature, it is extremely likely that the averaging of surface and bottom salinity across survey area inhibited any potential explanatory power; as such, results of this nature are anticipated to be unrepresentative of true conditions influencing growth in shrimp. Overall, few literary sources reference the importance of salinity to size at transition; it is likely that any indication of significance in preliminary models is of spurious relation or a proxy for other conditions not captured within the data. Models excluding bottom and surface salinity exhibited overall stronger significance consistent with peer-reviewed research. As such, those including salinity were removed from the analysis; this suggests that salinity does not explain a substantial amount of variation in length-at-transition, nor does it contribute to the overall explanatory power of the model.

3.4.1.2 Sex Ratio-Dependent Effects

The identification of sex ratio lagged one year as the primary sex ratio-dependent source of influence in the transitional process agrees with the literature. This coincides with a time during which all adult stages collectively coexist offshore prior to spawning, suggesting that discrepancies in abundance and availability of suitable breeding partners impacts the size at which mature male shrimp begin to transition. Less significance is attributed to sex ratios ascribed lags of two and three years, as juveniles experience a reduced amount of contact with breeding populations, and larvae inshore experience none.

3.4.2 Generalized Additive Model Output

3.4.2.1 Environmental Effects

As larvae, shrimp float freely in the water column until they are able begin settling as juveniles. The impact of environmental conditions on early shrimp life stages is captured by Preliminary Model 16, as well as the final model selected (Model 25.1), which highlights the significance of March bottom temperature inshore when lagged two years. This highlights the importance of bottom temperature on growth early in a juvenile's second year, during which time they reside inshore. The remaining components of Model 25.1, also shared by Model 16, including July, August, October, and December surface temperature, attribute strong significance to the impact of environmental conditions as juveniles mature to adult males. Furthermore, the inclusion and heightened significance of summer and fall surface temperature signifies the continued importance of environmental conditions inshore prior to departure from the coastal shallows of Maine. Results suggest that conditions experienced during the juvenile phase strongly influence size-at-transition; this directly coincides with the phase during which northern shrimp experience an otherwise significant portion of their growth. These results provide added confirmation that conditions surrounding this sensitive period of growth strongly impact the size at which northern shrimp begin their transition from male to female.

3.4.2.2 Sex Ratio-Dependent Effects

Initial results suggest the ratio of mature male shrimp to the available breeding population (transitionals and mature females) when lagged one year exhibited strong significance in relation to size-at-transition. However, further statistical analysis uncovered cause for question regarding its suggested significance.

3.2.3 Patterns in Carapace Length of Transitionals

There is a visible shift in the average length at transition in northern shrimp across the 1984-2017 timeseries of Summer Survey data visible in Figure 3.18**.** Results from this research generally agree with the research put forth by multiple studies; Daoud et al., 2010 suggests that variation in size-at-transition is more dependent on environmental conditions experienced as juveniles, following increased sensitivity to temperature, and is likely to drive the growth trajectory of the entire population. Trends visible in Figure 3.20 provide added support for the idea that shifting environmental conditions impact more than just length-at-transition.

Figure 3.15: ASMFC Summer Survey length frequencies (% length composition) of transitionals (i.e. transitional + female 1)for years 1985, 1998, 2009, and 2015 of the 1984-2017 timeseries.

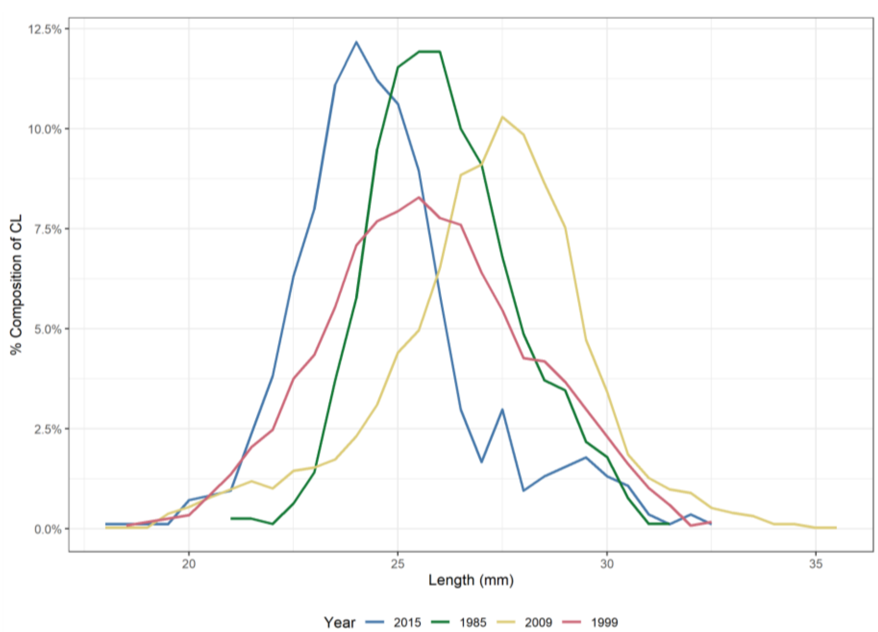
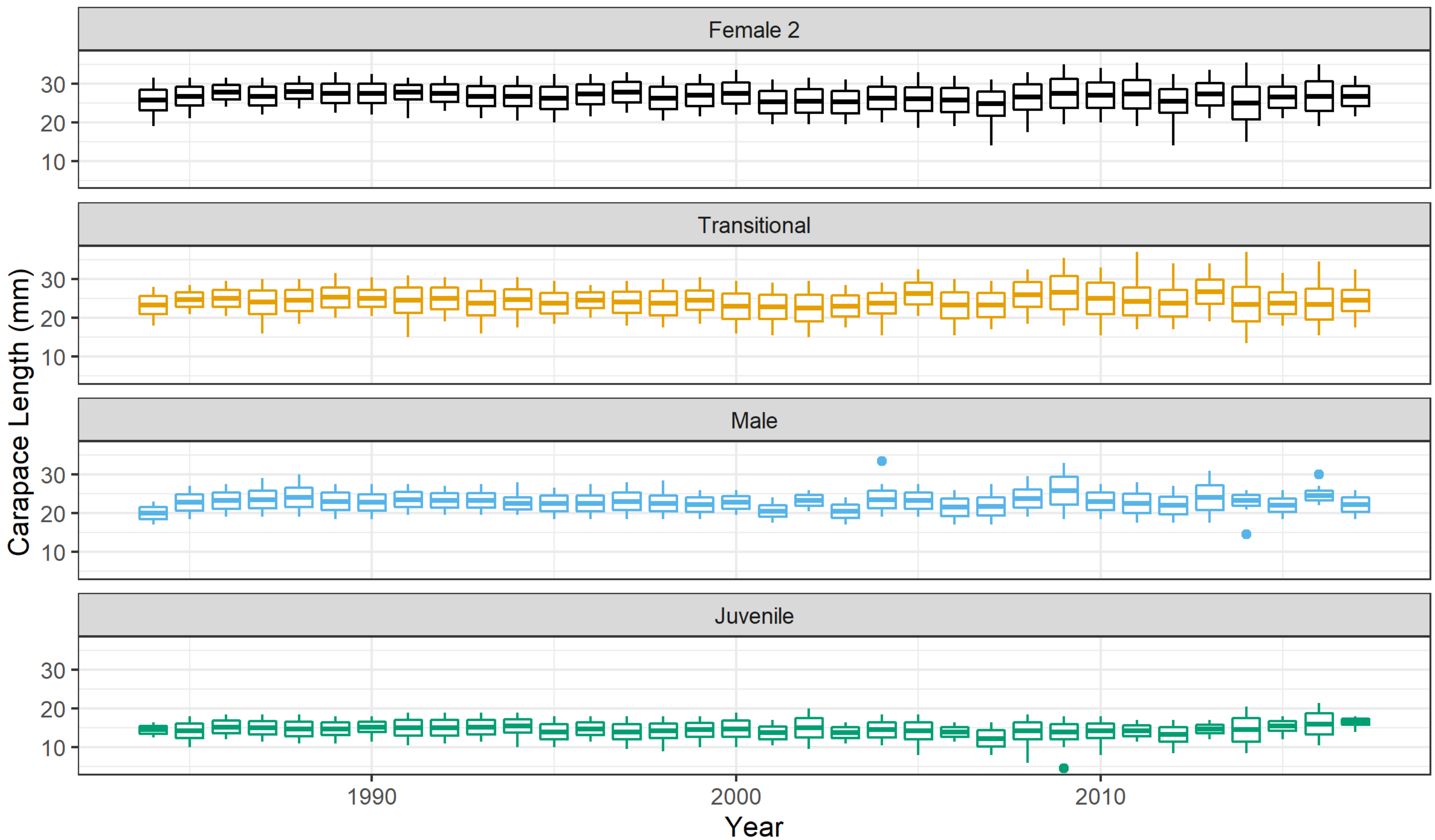


Figure 3.16: ASMFC Summer Survey length distribution by stage and year for the 1984-2017 timeseries. Error bars are displayed about the mean



3.4.4 Shortcomings of this Research

GAM was chosen given its flexibility via related assumptions on the actual relationship between the response and predictor. This provides increased potential for a better fit to the data than purely parametric models. However, this comes with loss in interpretability, following the use of smoothing parameters on the explanatory variables in each model. Explanatory power within the models utilized was further diminished by the decision to average inshore and offshore values across Spring and Summer Survey area, respectively. This decision was made based on the nature of shrimp biology as it is not well-understood whether northern shrimp exhibit site fidelity regarding onshore-offshore migration; as such, it is nearly impossible to incorporate a lagged spatial aspect to this analysis other than through the inclusion of survey tow coordinates. While the inclusion of longitude aims to capture any semblance of spatial significance, averaging environmental variables across survey location area aims to capture outlying trends and major shifts in temperature on size-at-transition. Though negligible, this likely contributed to small patterns observed in the residuals of model output for final combination Model 25. One potential solution to this problem would be through the addition of added variables to the model such as squared terms or interactions between variables. Specifically, an interaction placed between longitude and latitude might relieve some of the abnormality observed in model residuals.

Additional sources of error potentially stem from the combination of transitionals and female 1 shrimp referred to collectively as "transitionals" for the purpose of this analysis. A strong assumption was made when attributing these two stages to the same year class. Following the transitional phase, female 1 shrimp remain at said stage for only a few months before spawning in the summer and beginning their first shoreward migration as egg-bearing females that upcoming winter. Their identification as female 1 shrimp is based on the presence of sternal spines located along their abdomen; these indicator spines disappear following their first season bearing eggs. It is entirely possible that unforeseen circumstances, whether due to late transition or low abundance of suitable males, led female 1 shrimp to remain as such for an additional year; this could potentially introduce bias to our data by allowing the presence of outliers to impact the results of the analysis.

Regarding additional analysis, additional measures could be taken to supplement results. In place of a detailed, monthly analysis of environmental factors, additional models examining the aggregate impact of annual and seasonal mean temperature could provide a baseline with which to determine major underlying trends. It is possible that a detailed monthly analysis including all potential bottom and surface temperature values could obscure results. Presuming the main effect of environmental variables is on growth, and size-at-stage may influence the probability of transition, this aggregate analysis would look at inshore lagged variables corresponding to the first two years of life (i.e 'y-2' and 'y-3'), and offshore lagged variables corresponding to the third year of life spent offshore as mature males (i.e. 'y-1'). The dependent variable, size-at-transition (L_T) would be calculated based on the stratified annual mean size of transitionals (i.e. transitional and female 1 shrimp).

3.4.5 Implications for Management

Understanding the effects of overfishing and shifting environmental conditions on the size structure of the stock is critical to effectively manage it. Decreased size of female biomass has direct, measurable implications for the reproductive capacity of spawning stock biomass. Multiple studies have ascertained that decreased female body size results in decreased egg production and quality; smaller females were found to produce fewer, genetically weaker eggs less likely to be recruited into the fishery, thus directly contributing to decreased abundance. Regarding commercial viability, the conditions resulting in decreased size-at-transition have direct implications for the northern shrimp fishery, which typically targets 4- and 5- year-old females. Not only does decreased size-at-transition impact recruitment and abundance, but it decreases the product quality of northern shrimp given market preference for and increased value of larger shrimp (see Chapter 2). Despite the fishery's economic and ecological significance, there is an evident lack of knowledge and data to fully determine how great of an impact temperature has on population reproduction and recruitment. Information obtained through this research may contribute to a deeper understanding of the impact of outside factors on the size structure of the northern shrimp stock. The incorporation of this knowledge into future stock assessments may be used to account for shifts in the reproductive potential of the stock, following anticipated phenological shifts in female body size. A more robust understanding of this relationship may provide a more accurate depiction of the pressure that the northern shrimp fishery may or may not be able to withstand. In anticipation of continued climatic shifts in the Gulf of Maine ecosystem, managers may account for the implications of this relationship in consideration of more viable regulatory options by adjusting future levels of fishing effort and quota in anticipation of shifts in abundance. Assessment of the response of shrimp to changing environmental conditions and anthropogenic activity is critical to accurately determine appropriate fishing levels, especially given the reduced ability of a vulnerable stock to build resilience (Gregg *et al.*, 2016). Further analysis regarding the magnitude of the effects that climate change and fishing pressure will continue to impose on *P. borealis* is key to predicting trends in growth, as well as future management and conservation efforts.

3.5 Conclusion

The dynamic ecosystem that characterizes the GOM is currently one of the most severely affected by climate change. The northern shrimp stock appears highly susceptible to shifting environmental conditions, more so than fishing pressure, following its noticeable impact on growth rate. Surface temperature exhibits the strongest influence, with decreased size-at-stage attributed to more rapid growth at higher temperatures during the juvenile phase. The influence of warming waters on size-at-transition is likely to have a sizeable impact on the breeding structure of the stock, namely through fecundity and recruitment, which exhibit a positive relationship with female body size (Shumway et al., 1985). Large repeat spawners are important given the success of associated large egg size and quality, as is found largely to be true for many other decapod crustaceans (Wieland and Siegstad, 2012). The cumulative impact of the effects of rising temperatures on the reproductive biology of northern shrimp is remarkably visible, yet the precise mechanisms remain hard to quantify; this provides added complication for managers who will need to account for changes in reproductive potential, and subsequent abundance, in their regulation of the commercial fishery.

It is highly likely that extreme weather events, will continue and grow to become more common as climate shifts continue and the environmental impacts become more pronounced (Hansen et al., 2012; Mills et al., 2013). As such, the Gulf of Maine will continue to become an increasingly inhospitable environment for the northern shrimp stock due to the sensitive nature of patterns in growth and recruitment to rising water temperatures. Continued annual studies regarding the relationship between size-at-transition, shrimp abundance, and the reproductive capacity of the stock are crucial to monitor the health and commercial viability of the Gulf of Maine northern shrimp stock.

4. EFFORT AND VULNERABILITY IN THE NORTHERN SHRIMP FISHERY

4.1 Introduction

In this study, we explore the sensitivity of fisher behavior to changes in abundance of harvestable biomass, as well as examine fishers' vulnerability through variation in landings. Furthermore, we examine the relationship between input effort and variation in landings across both gear types. Using projections of harvestable biomass from the University of Maine Size Structured Stock Assessment Model as a proxy for shifting environmental conditions, we aim to provide insight regarding gear-specific sources of influence impacting effort and vulnerability within the GOM northern shrimp fishery. Using two models designed to incorporate the unique characteristics of both gear types, our goal is to develop a deeper understanding of fishers' actions to better inform managers of factors influencing human behavior within the northern shrimp fishery. Ultimately, this information may be utilized by managers to increase the adaptive capacity and efficiency of regulatory efforts, provide insight regarding the biological and economic implications of climate change, and examine the feasibility of reestablishing an economically and ecologically viable northern shrimp fishery in a changing Gulf of Maine

Northern shrimp, *Pandalus borealis,* support one of the few remaining open access commercial fisheries in the U.S. Supplemental in nature, the fishery is composed mainly of lobstermen and groundfishermen who target shrimp in the winter to diversify their income; swings in participation were exceedingly common, dependent on conditions in other fisheries. Within the past 70 years, the fishery has been subject to a myriad of stressors such as variable recruitment success, intense overfishing, and subsequent crashes in the population. This may be directly attributed to unstable stock dynamics, high recruitment failure, rising water temperatures, and inconsistent management efforts, all of which have resulted in massive declines in biomass and abundance of northern shrimp. Fluctuation in historic landings were largely associated with adverse environmental and anthropogenic impacts on the shrimp fishery, directly accounting for the extreme fluctuations in landings and value, as well as introduced management, restriction, and occasional closure of the seasonal fishery (Clark *et al*, 2000). Most notably, these factors have resulted in the most recent population crash in 2013, since which the fishery has remained closed.

4.2 Background

4.2.1 Biology

Established in 1938, northern shrimp represent an open access commercial species of great value in the Gulf of Maine. The species' range spans from the Arctic Boreal to the southernmost extent of the Gulf of Maine where warm water temperatures limit further extension southward. Temperature is regarded as a primary environmentally distinguishable determinant in Northern Shrimp, regarding range, growth, abundance, recruitment, and survival (Richards, 2012). As protandrous hermaphrodites, northern shrimp mature and spawn first as males before transitioning to female between 2 – 3 years of age Spawning takes place between July and August, with most females bearing eggs by late September. From September to November, egg-bearing females will migrate inshore to hatch their eggs in the cooler coastal shallows. Commercial fishing efforts target egg-bearing (ovigerous) females following their inshore migration (Clark *et al.,* 2000), due primarily to a preferred higher quality of meat observed at this time. For a more comprehensive explanation of shrimp biology, please refer to Chapter 3.

4.2.2 Environmental Influence within the Northern Shrimp Fishery

The effects of climate change are well documented in the Northwest Atlantic (Pershing et al., 2015; Mills et al., 2013), and the intensity of which has occurred most notably within the

Gulf of Maine (Mills et al., 2013). Sea surface temperature (SST) on the northern American continental shelf displays one of the strongest ocean warming trends globally (Burrows et al., 2011; Pershing et al., 2015; Pershing et al. (2017); summers are found to be warming faster and beginning earlier and ending later (Thomas et al., 2017). Kavanaugh et al. (2017) summarizes that bottom temperatures have increased for much of the Northwest Atlantic between 1982-2014, with the fastest rates observed nearshore and on Georges Bank (Kavanaugh et al., 2017).

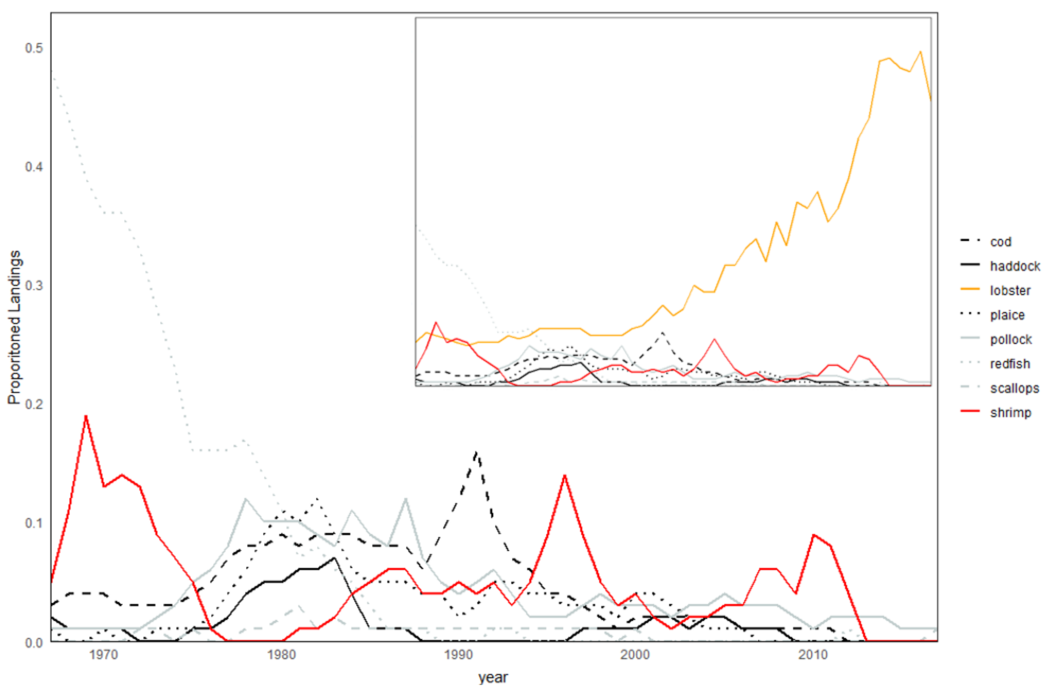
As a climate sensitive and temperature dependent species (Richards et al., 2012), ecological shifts in temperature are predicted to have a large effect on northern shrimp abundance, reproductive capacity, and recruitment. SST has been identified on multiple occasions to be a significant contributing factor to the success of recruitment for northern shrimp in the Northwest Atlantic (Dow 1977a; Richards, MS 1996; Oullet et al,, 2007, 2011; Kai and Siegstad, 2012); observed decreases in recruitment are strongly attributed to increasing sea-surface temperatures experienced by juveniles (Dow, 1977a; Richards et al., 1996). Apollonio and Dunton (1969) made note of a negative correlation between trends in bottom temperature and its effect on recruitment via egg development, arguing that warmer bottom temperatures resulted in larger amounts of nonviable eggs and increased recruitment failure.

Over time, observed trends show that the species composition of *P. borealis* fluctuates with corresponding environmental factors, specifically fluctuating water temperatures.

4.2.3 Fishery Description

Once a source of commercial importance, the northern shrimp fishery in the GOM was not only a valued food source, but also a means for fishermen to diversify their income portfolio or supplement their income during times of financial stress (Clark et al., 2000). As an open access fishery, participation levels remained uncheck and often varied inconsistently. The supplemental nature of the fishery quickly became its most appealing quality; conditions in other fisheries related to species abundance and regulatory efforts often dictated how heavily fishermen relied on shrimp as an alternative source of income. This is directly correlated with increases and decreases in participation and may also be inferred through variation in landings (Clark et al., 2000). Consequently, this fishery has served primarily as a supplemental one, providing added income and resilience for fishermen and local coastal communities often in times of financial hardship or following poor stock conditions in other fisheries. Collectively, fishers maintain a highly adaptive response capacity regarding economic opportunity; effort existed in a flux and centered on the balance of market conditions, profitability, and availability of target species (Figure 4.1).

Figure 4.1: Recorded landings for multiple GOM commercial fisheries for the 1967-2017 timeseries. Landings are proportionate to highest observed lobster landings of the timeseries. Inset plot includes lobster landings, while the outer plot observes detail in landings without lobster included.



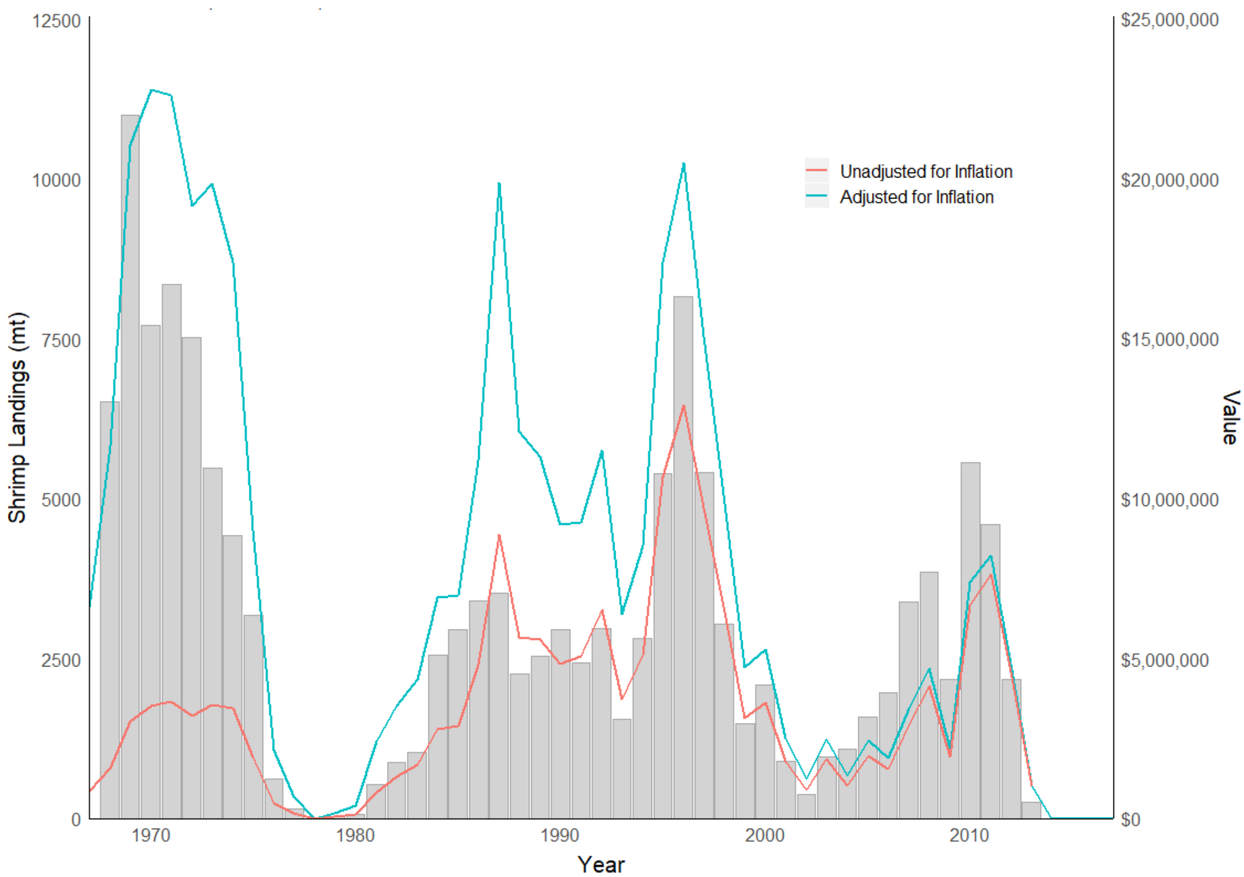
4.2.4 Management History

Interest in the exploitation of northern shrimp arose in the early 1920s following the discovery of sizeable stock concentrations in the Gulf of Maine deemed large enough to harvest (Clark et al., 2000). Following its establishment in 1938, the fishery began as a fleet of 13 draggers based out of Portland, ME; formal management was not introduced until the 1950s. Entering the 1960s, New England groundfishermen saw severe declines in the abundance of silver hake (whiting) (Kallio, MS 1973); effects of this stock collapse were observed secondarily in the northern shrimp fishery, as the number of participating boats within rose from 102 in 1964 to over 300 in 1970 (Kallio, MS 1973). Record landings were observed in 1969 at 13,000 tons (Figure 4.2), much of which may be attributed to the efforts and influx of larger draggers with a more extensive ranges of both distance from shore and depth. Around this time, the fishery also saw increased efforts from lobster boats (Bruce 1971; Clark *et al.*, 2000), as well as pressure from the development of an offshore summer fishery in the early 1970s.

Distress surrounding recruitment failure and declining abundance in the early 1970s ultimately catalyzed the movement towards more cooperative management between NMFS and the participating states (Clark *et al.*, 2000) and the introduction of more restrictive management efforts to better regulate the commercial fishery. Following the fishery's first stock assessment in 1975, results confirmed the impacts of over exploitation, rising water temperatures, and recruitment failure on the weakened state of the northern shrimp stock. Unfortunately, a great deal of damage had already severely undermined the resiliency of the fishery prompting its first major collapse and closure in 1977. The severity of the situation catalyzed the movement to introduce more restrictive management through the establishment of the fishery's first Fisheries Management Plan (FMP) in 1986. Regulatory efforts under the new FMP sought to aid in the recovery of the shrimp stock through purposeful reductions in landings, effort, and participation. While trends in landings from the 1980s to the 1990s appear low, collectively, these conditions allowed the stock to regain moderate stability under lower levels of exploitation. The fishery's revival was short lived as the mid-90s saw a resurgence in landings and fishing mortality followed by subsequent declines in abundance and increased recruitment failure (Clark *et al.*, 2000). Despite continued regulation of effort, habits and trends that characterized the latter half of the 20th century continued into the new millennium. Regulatory efforts yielding positive growth in abundance often instilled an inadvertently false sense of optimism in managers and fishermen; in retrospect, this, in conjunction with pressure from the industry, often encouraged managers to set quotas higher than the stock could withstand as growth was typically much lower than anticipated. Simultaneously, the role of shifting water temperatures began to exert a much greater impact on the stock than previously observed, thus contributing additional pressure on the stock, and reducing its capacity to replenish itself. Similar trends continued into the 21st century, further exacerbated by continually declining environmental conditions.

At the height of its commercial significance in 1969, 10,992.98 mt of shrimp were landed between the trap and trawl fishery, worth $3,044,948 nominal, or about $22,074,000 real value after accounting for inflation (Figure 5.1). However, landings and revenue have remained inconsistent since the opening of the fishery in 1953 with fluctuations due in part to suboptimal water temperature conditions and its impact on recruitment. That, in combination with inconsistent fluctuations in fishing effort, has cumulatively resulted in the third and most recent stock collapse in 2013, since which the fishery has remained under a moratorium. Final landings in 2013 were recorded at 255.51 mt, worth $1,008,766 (nominal) or $1,051,000 as of this year.

Figure 4.2: Total value of commercial shrimp landings (mt) in the Gulf of Maine northern shrimp fishery (1967-2017), both adjusted and unadjusted for inflation. Adjusted inflation rates are based on 2017 real value.



4.3 Objectives

Currently, the management of the northern shrimp fishery is at a critical transition point. Looking ahead, it is strongly predicted that large biogeographic shifts in seasonal reproductive timing, species abundance, and distribution will occur due to climatic shifts and years of overexploitation (Johnson et al., 2011). Trends observed in multiple studies specifically ascertain the influence that varying environmental factors have on the reproductive success and stock dynamics of northern shrimp. Currently, the health of the stock remains heavily dependent on the strength of incoming year classes indicating that shifting environmental conditions beyond our control will likely continue to have adverse effects on the northern shrimp stock. The degree to which these changes will occur and how long they may continue is not fully understood, contributing further uncertainty as to whether the GOM can support a sustainable northern shrimp fishery. As such, regulatory efforts must be reevaluated to reflect the diminished reproductive capacity of the stock. While there are already efforts underway aimed towards examining the implications of fishing pressure and environmental vulnerability of the stock, a significant gap in research hinders the adaptive capacity and efficiency of regulations controlling the fishery; studies examining shifts in reproductive potential are often done under the guise of measuring a stock's capacity to withstand fishing pressure, yet research highlighting the other half of the equation, more specifically the human dimensions of the northern shrimp fishery, is currently lacking.

As managers, regulating a commercial species largely means regulating human behavior within that fishery; following environmentally driven alterations in abundance and recruitment, managers will likely be forced to make tough decisions regarding appropriate levels of effort and participation if they intend to promote simultaneous economic and ecological sustainability within the fishery. To facilitate a more long-term planning strategy, reductions in recruitment and harvestable biomass will need to be incorporated into decisions surrounding fleet size and effort levels within the fishery. A deeper understanding of the relationship between fishing effort, shifts in harvestable biomass, and gear-specific vulnerability is critical to the development of more sustainable regulations. To do this, I will construct two empirically estimated fisher-level production functions to garner a better idea of gear-specific shifts in effort as it relates to landings. Socioeconomic data utilized in this research includes harvester and dealer reports collected through the Maine DMR from 2007 to 2013. Estimates of harvestable biomass, taken from the University of Maine's Size Structured Stock Assessment Model for Northern Shrimp, are incorporated into both models to serve as a proxy of environmental influence on changes in recruitment and abundance within the northern shrimp fishery.

Like the methods employed by Daniel Holland (2011) in his evaluation of changing productivity and catchability in the Maine lobster fishery, the fisher-level model is meant to capture seasonal shifts in landings associated with variation in fisher effort as well as estimates of harvestable biomass. Using the socioeconomic data provided through harvester and dealer reports from the DMR, as well as estimates of harvestable biomass from the University of Maine Size Structured Model, these models will be used to examine the response of fishermen to shifts in abundance, reflective of climate change within the Gulf of Maine. Furthermore, we will use shifts in landings as a proxy with which to measure vulnerability associated with each gear type. With this information, we can indirectly explore the potential impact of alternative management scenarios in the likely event that climatic shifts will require a downsizing of effort within the fishery; observed shifts in associated landings will provide similar indication of effective effort levels that may elicit positive economic returns to maintain the socioeconomic needs of vulnerable fishing communities. Collectively, these changes will ideally be applied in conjunction with consideration for the biological susceptibility of the northern shrimp stock to changing environmental conditions.

Our research goals are two-fold:

1) To examine the effect that shifting environmental conditions may have on landings and fisher vulnerability in the Gulf of Maine northern shrimp fishery
2) To examine the relationship between individual-level fisher effort and associated landings as output.

4.4 Methods and Materials

4.4.1 Methods

For this research, I analyze the impact of shifting environmental conditions and other fisher-level input factors on landings in the northern shrimp fishery in the Gulf of Maine. Trip-level fishery data (i.e. landing data and other input uses) was gathered through harvester reports obtained from the Maine Department of Marine Resources (DMR). To evaluate the relationship between changing environmental conditions, input effort, and landings, I created two gear-specific production functions. Both models incorporate estimates of harvestable biomass provided by the University of Maine Size Structured Stock Assessment Model as a proxy for shifting environmental impact on the northern shrimp stock,

4.4.1.1 Fishery Production Function

The Cobb-Douglas production function (Cobb and Douglas, 1928) is often used in econometrics to represent the relationship between specific output as a function of two or more inputs. Empirically estimated models are based on the original Cobb Douglas production function:

$$y^i = AX_i^{\beta}e^{\alpha Zi}$$

Where y_i denotes live mt landed per trip in season *i*, *A* denotes total factor productivity, *X* and Z represent inputs of productions (i.e. crew, days at sea, available biomass, etc.), and α and β represents output elasticities and semi elasticities on input effort variables, respectively. In modeling northern shrimp landings as a function of specified inputs, one of the strict assumptions of this methodology is its assumed constant elasticity of substitution; the basis of this assumption provides that a production function with *n* inputs implies that any change in input factors results in a constant returns to scale regarding output (Arrow, Chenery, Minhas and

Solow, 1961). By log-transforming input effort components within each model, we can relax this otherwise rigid assumption to capture a loose relationship between effort and landings.

To examine this relationship, we utilize Ordinary Least Squares regression techniques. OLS is applied to linear regression models in order to estimate the unknown parameters of a set of explanatory variables This methodology assumes that inputs are exogenous to the model, meaning the any sources of influence impacting the variables used within the model must come from outside the model. OLS also relies heavily on the assumption that the data used is representative of the larger population; this is addressed through residual analysis in the results section.

Two base gear-specific production functions were estimated initially to examine the relationship between landings, effort, and changes in shrimp abundance. Variables included were done so following industry member interviews (see chapter 2), personal communications with DMR staff, and supplemental literary review. Base models included shared variables like trip month, latitude, longitude, fishing season, crew, depth, sea time, and gear-specific estimates of monthly remaining biomass; trawl-specific variables included number of tows, while trap-specific variables included soak time and traps used. Both based models utilize mt landed as dependent variables.

Following initial test runs, variables were removed from base equations if their removal resulted in a decrease in AIC value (indicative of higher explanatory power); latitude was the only variable decidedly removed from the trawl model, while both latitude and crew were removed from the trap model; longitude maintained a higher degree of explanatory power than latitude, while crew provided little additional explanatory power to the trap model; both sea time and traps used were too significant for either to be removed from the trap model.

Furthermore, due to the underlying structure of our data, it was necessary to correct for standard error clustering when running each model; given that fishermen are often habitual in practice or consistent regarding their actions within a given fishery, error terms within the model, though independent across groups, are correlated within groups. By clustering our standards errors, we subsequently allow correlation within clusters, but not across clusters; failing to account for clustering could lead to deceptively small standard errors. Clustered errors were obtained through model residuals and computed in R using the vcovHC() function from the plm package. The following two models represent the final version used and discussed for the remainder of this analysis. Within each model β represents the coefficient on each explanatory variable, representative of the strength each explanatory variable has with the dependent variable; β_0 is the regression intercept, indicative of the expected value for the dependent variable, landings, if all independent variables are zero; ε represents random error with each model, otherwise, that which is unexplained regarding the dependent variable; *i* is representative of fishing season. The models are as follows:

Equation 1 - Trap Model

$$\log(landings_i)_{Trap} = \beta_0 + \beta_1(trip\ month_i) + \beta_2(longitude_i) + \beta_3(fishing\ season_i) + \beta_4\log(soak\ time_i) + \beta_5\log(depth_i) + \beta_6\log(sea\ time_i) + \beta_7\log(traps\ used_i) + \beta_8\log(monthly\ remaining\ biomass_i) + \varepsilon_i$$

Equation 2 - Trawl Model

$$\log(landings_i)_{Trawl} = \beta_0 + \beta_1(trip\ month_i) + \beta_2(longitude_i) + \beta_3(fishing\ season_i) + \beta_4\log(crew_i) + \beta_5\log(number\ of\ tows_i) + \beta_6\log(set\ time_i) + \beta_7\log(sea\ time_i) + \beta_8\log(monthly\ remaining\ biomass_i) + \varepsilon_i$$

4.4.2 Data

Data provided by the DMR covers a timeseries that reflects eight seasons worth of fishing activity, spanning from 2005 to the fishery's closure in 2013. However, data incorporated into the subsequent models only includes the last six years of harvester data, as reporting efforts and data collection were not mandatory or consistently recorded until the 2007-2008 fishing season. As such, the timeseries of data utilized examines activity between the
2007-2008 and 2012-2013 fishing seasons (6 seasons).

4.4.3 Data Treatment

Northern shrimp data from DMR harvester reports totaled 16,809 individual observations on reported landings total, with 14,290 observations (7,105 trap, 7,185 trawl) remaining following cleaning, processing, and removal of the first two seasons. A description of the nature of each variable is provided in Table 5.1. Prior to building and running the models, it was necessary to address any zeros or NA's found in the dataset. Given that each observation is based on recorded landings, missing data representative of input effort could not be included, as zeros would skew the relationship between landings and effort. Missing data was addressed one of two ways: missing variables were either dropped from the dataset or filled manually using unconditional means or by following consistent hull number- and party ID-specific patterns in the data, representative of individual fisher patterns in behavior.

Missing values (either NA or 0) for "crew" totaled 60 observations; often in situations where zeroes are concerned; the captain has failed to include him/herself as crew (personal communication). Where applicable, missing crew data was filled in following patterns in other observations matching hull number and party ID; the remainder of missing crew were filled in with the conditional mean for each gear type.

Prior to cleaning, there were 1,909 and 1,881 missing values for latitude and longitude, respectively. Much of this was able to be filled in based on comparisons made between matching hull numbers and an additional column titled “fishing location,” in which fishermen often made note of the name of the bay, rock, island, or general location where they were fishing. For those that only had fishing location and no additional location-based information, a quick Google Maps search often proved highly productive in producing a coordinate pairing. In total, only 227 latitude and longitude pairings were unable to be filled in. These observations were subsequently removed from the data set.

Depth totaled 263 missing observations; these were filled in using a conditional mean of other observations by hull number, party ID, location, latitude, and longitude. Similar methodology was used to fill in the 47 missing values for sea time.

Regarding soak time, observations of less than 12 hours, and more than 337 hours (i.e. 2 weeks) were subsequently removed from the data set. In placing an upper and lower cap on this variable, it is possible to have introduced a small degree of bias to the model results, however, it was determined that, beyond these cut offs, the data was not truly representative of the relationship between input effort and landings being examined and could potentially skew the results.

Two observations in the data reported 0’s in place of mt landed, despite showing input effort in other columns. Both observations were removed from the dataset.

Regarding trawl data, number of tows, regarding trawl data, had 41 zero’s in total, despite showing landings for that day. When compared to other observations bearing the same hull number and party ID, these zeroes were subsequently turned to 1’s following consistently reported “1”s in all other matching rows of data. Three observations were observed with 30 tows, though when investigated this was determined to be a mistake; these observations were changed to 3's, following consistency across data bearing the same hull number and party ID.

Regarding trap data, the relationship between number of tows, total gear in the water, and gear quantity caused some initial confusion and minor issues when cleaning data; Trap data was observed to have 111 missing observations for gear quantity, 4,628 for number of tows, and 3,945 for total gear in water; problems arose when trying to determine which variable was the most representative of the number of pots being hauled. Through a personal email communication with a DMR representative, it was determined that "gear quantity," in relation to trap data, was representative of the number of units of gear used, meaning, the count of traps the harvester hauled that day. "Total gear in water" was explained to be a relatively new data requirement as of 2008, and includes all the traps or other gear a harvester has in the water at the time; not all gear types required this field to be filled in, such as trawls, dredges and dive gear for instance, however, all trap data required this field to be filled in from 2008 onward. The main source of confusion concerning data cleaning was regarding why trapper data would have the field "number of tows" filled out, although this was explained as another indication of the number of pots hauled that day. There appeared to be inconsistencies throughout the data, as gear quantity and number of tows, though assumed to be representative of similar information, often displayed high instances of mis-matched numbers. Given that there was too much discrepancy between the two variables, it was not possible to fill in missing information for "gear quantity" with information from the "number of tows" column. As such, we opted for the variable with the smallest number of missing variables, "gear quantity", and excluded "number of tows" from the analysis. Total gear in water was also excluded from the analysis based on inconsistent reporting until the beginning of 2008.

Where necessary, new variables were added to the final data set. “Fishing season” was created since the commercial season for northern shrimp spans two different years; the creation of this variable was necessary in order to simplify the summation of daily and monthly landings within a given commercial year. It was also necessary to calculate remaining biomass available to the fishery using one of the outputs from the University of Maine Size Structured Northern Shrimp Model, estimates of harvestable biomass available to the fishery at the beginning of each season. To do this, we first needed to sum daily and monthly landings within the fishery. Monthly summed landings were calculated by summing total landings by month and fishing season; daily summed landings were summed by day, month, and fishing season. Output estimates of available harvestable biomass, taken from the UMaine Size Structured Model, were then included in our calculations to determine remaining available biomass within the fishery as it proceeded on a daily and monthly basis (Table 4.2). Estimates of harvestable biomass provided by the Size Structured Model differ between gear types based on catchability and accessibility, given that the two gear types employ vastly different techniques in targeting northern shrimp. Prior to applying estimates of harvestable biomass to the data, the main dataset was split by gear type into two separate datasets, trap and trawl. “Month sum remaining,” was calculate by subtracting monthly compounded landings from gear-specific estimates of initial biomass.

Following cleaning, all variables to be included in model runs were log-transformed, save latitude and longitude. Metric tons landed, crew, depth, sea time, and month sum remaining, representing shared variables between both datasets, as well as trap-specific variables like soak time, and traps used, and trawl-specific variables including number of tows and set time.

Table 4.1: Definition of variables used in the analysis of factors impacting landings and fishing effort in the Gulf of Maine northern shrimp fishery

Variable	Definition
Party ID	Permit unique to individual fisher
Season	Trip year (often spans two physical years)
Homeport	Harvester's homeport
Trip year	Year trip occurs
Trip month	Month of trip
Trip day	Date of trip
Lbs landed	Live pounds of shrimp landed (per trip)
Total gear in water	Total number of gear in the water (for trappers this does not necessarily indicate use)
Traps used	Number of traps pulled (trap only)
Set time	Duration time of tow (trawl only)
Soak time	Amount of time in water since traps last pulled (trap only)
Number of tows	Number of tows made over the course of one fishing trip (trawl only)
Depth	Depth at which fishing actiivty occurs (ft)
Fishing location	Location of fishing activity, indicated by the fisher
Latitude & Longitude	Fishing location - coordinates of tow or traps pulled
Crew	Reported number of crew aboard vessel, per fishing trip
Time at sea	The amount of time spent traveling to and from fishing locations (does not include time spent fishing)
Harvestable biomass	Biomass estiamtes obtained from the University of Maine Size-Structured Stock Assessment Model, which factors the impact of shifting environmental conditions on northern shrimp abundance.
Month sum remaining	Estimates of harvestable biomass (taken from UMaine Model), subtract monthly compounded landings

Table 4.2: Estimates of gear-specific available exploitable shrimp biomass (mt) relative to the start of each fishing season. Source: University of Maine size structured northern shrimp stock assessment model

Fishing Season	Trawl (mt)	Trap (mt)
2005-2006	30,151.82	21,693.55
2005-2007	37,356.63	28,045.59
2007-2008	44,730.84	32,281.42
2008-2009	45,428.02	32,742.89
2009-2010	17,173.62	15,025.53
2010-2011	7,069.35	7,998.53
2011-2012	10,448.74	8,049.10
2012-2013	7,220.11	5,396.35

4.5 Results

4.5.1 Regression Results

A full table of the results is available in Table 4.3. When interpreting the coefficients on variables, readers should be wary of the limited explanatory power of both models due to the nature of the data utilized within this study.

To assess the explanatory power of each variable, we first examined the coefficient on each variable included in the models. Estimates of coefficients on each explanatory variable reflect the strength (or weight) and nature of each variable's relationship with the dependent variable. Negative signs on coefficients indicate a negative relationship between the explanatory variable and mt landed, whereas a positive sign indicate a positive relationship and increasing returns with regards to landings. Collectively, these coefficients represent proportional changes in the dependent variable, following a one-unit change in the explanatory variable. Reported t-statistics provide an indication of the significance of each variable from the average; the higher the number, the higher the likelihood that the results are statistically significant from the average. From here, we evaluate the associated p-value of each explanatory variable to determine its statistical significance from zero (the null hypothesis). Smaller p-values indicate a heightened degree of importance regarding that variable’s inclusion in the model as well as its statistical significance from zero; the smaller the p-value, the more effective a predictor the explanatory variable.

Table 4.3: Summary of trap (Eq 1) and trawl (Eq 2) production function model results. Trip month "January" and fishing season "(07-08)" are used as bases for each production function.

	Coefficient		Standard Error		P-value	
Explanatory Variable	**Trap**	**Trawl**	**Trap**	**Trawl**	**Trap**	**Trawl**
Monthly remaining biomass	4.27	2.00	0.50	0.39	< 0.01 ***	< 0.01 ***
Traps used	1.00		0.03		< 0.01 ***	
Number of tows		0.64		0.09		< 0.01 ***
Sea time	0.20	0.49	0.07	0.10	< 0.01 ***	< 0.01 ***
Set time		0.19		0.06		< 0.01 ***
Crew		0.18		0.11		0.09 *
Depth	-0.03	0.29	0.11	0.12	0.76	0.02 **
Soak time	-0.05		0.04		0.15	
Longitude	-0.07	-0.33	0.06	0.06	0.24	< 0.01 ***
(Intercept)	-80.48	-56.57	9.54	7.71	< 0.01 ***	< 0.01 ***
Trip month (February)	0.68	0.26	0.07	0.04	< 0.01 ***	< 0.01 ***
Trip month (March)	0.81	0.21	0.10	0.07	< 0.01 ***	< 0.01 ***
Trip month (April)	0.01	0.12	0.18	0.16	0.94	0.45
Trip month (May)		-0.30		0.27		0.28
Trip month (December)	-1.55	-0.12	0.24	0.08	< 0.01 ***	0.12
Fishing season ('08-09)	0.01	0.14	0.08	0.10	0.88	0.16
Fishing season ('09-10)	3.81	2.24	0.42	0.38	< 0.01 ***	< 0.01 ***
Fishing season ('10-11)	6.52	3.95	0.77	0.72	< 0.01 ***	< 0.01 ***
Fishing season ('11-12)	5.44	2.98	0.72	0.57	< 0.01 ***	< 0.01 ***
Fishing season ('12-13)	5.85	2.67	0.90	0.70	< 0.01 ***	< 0.01 ***

* = 90% significance, ** = 95% significance, *** = 99% significance

Regarding trip month, both gear types displayed negative coefficients on the month of December (-12 trawl, -1.55 trap) , as well as May for Trawlers (-30), indicating a decline in landings during this time; conversely, both gear types displayed a positive relationship between landings and the months of February (0.68 trap, 0.26 trawl) and March (0.81 trap, 0.21) trawl. Neither May nor December was statistically significant for trawlers, however, December for trappers, as well as February and March for both gear types, was observed to be statistically significant at the 99% confidence interval. Coefficients on fishing season varied between gear types, though all displayed a positive relationship; both gear types indicated that the 2010-2011 fishing season produced the highest landings in the timeseries (Figure 4.1). Of the five seasons included in the analysis, all seasons except '08-09, which displayed no statistical significance whatsoever, appeared to be statistically significant at the 99% confidence level; for both gear types, the 09’10 fishing season was the most significant. Both gear types displayed a negative relationship between longitude and landings, expressing coefficients of -0.07 and -0.33 for trappers and trawlers, respectively; longitude was statistically significant for trawlers, with a t-statistic of -5.83, indicating strong, negative spatial relationship. Regarding depth, trappers displayed a negative relationship between landings and depth (-0.07) while trawlers displayed a positive relationship (0.29); though statistically insignificant for trappers, trawlers maintained a moderate significant relationship with depth at the 95% confidence interval. Regarding the remaining shared explanatory variables, sea time displayed a positive relationship with landings, with both p-values displaying high statistical significance at the 99% confidence level, as did monthly remaining biomass, though this significance appeared higher for trappers than trawlers. Specific to the trapper model, traps used displayed a positive relationship (1.00) to landings, while soak time exhibited a negative relationship (-0.05); soak time displayed no statistical significance (0.15), while the number of traps used exhibited strong statistical significance at the 99% confidence level, and the highest t-statistic value of all trap variables at 30.49. The remaining trawl-specific variables crew, number of tows, and set time displayed a positive relationship with landings, with coefficients of 0.18, 0.64 and 0.19; both number of tows and set time exhibited high statistical significance at the 99% confidence level, while crew exhibit less significance (0.09) at the 90% confidence level.

4.5.2 Model Fit

Multiple models were tested prior to final model selection. Table 4.4 displays the results of model strength tests for both “full” and “final” models; “full” models represent those which contain all vairables initially selected for inclusion in the analysis while “final” models represent each gear-specific model following the careful removal of non-significant variables. Akaike Information Criterion (AIC) for both models (Table 4.4), help justify the use of one model over the other; smaller AIC values indicate the increased capacity of said model to account for model complexity while exhibiting an overall better fit regarding the osberved data. The removal of longitude from both models, as well as the additional removal of crew from the trap model, result in lower AIC values for both “final” models when compared to the “full” version.

Table 4.4: ANOVA, AIC, R2, RMSE, and MAE test results on production function models for both gear types, including a comparison between full and final models

Model	ANOVA						Additional Strength Tests				
	Res.Df	RSS	Df	Sum of Sq	F	Pr(>F)	n_obs	AIC	R2	RMSE	MAE
Trap (full model)	7087	4989.77	NA	NA	NA	NA	7105	17690.14	0.68	0.83	0.61
Trap (final model)	7089	4990.60	-2	-0.83	0.59	0.55	7105	17687.32	0.68	0.83	0.61
Model	Res.Df	RSS	Df	Sum of Sq	F	Pr(>F)	n_obs	AIC	R2	RMSE	MAE
Trawl (full model)	7166	3680.60	NA	NA	NA	NA	7185	15623.96	0.42	0.72	0.52
Trawl (final model)	7167	3680.65	-1	-0.05	0.10	0.76	7185	15622.06	0.42	0.72	0.52

An analysis of the F-statistic for both models reveals 334.8 on 17 and 7167 degrees of freedom for the final trawl model and 878.3 on 15 and 7809 degrees of freedom for the final trap model. Results of the F-test indicate that at least one variable’s weight in both models is significantly different from zero, providing initial confirmation of their basic functional capacity.

To measure the performance of a model, residual standard error, multiple and adjusted r-square, and F-statsitics are taken into consideration. Multiple R-squared and adjusted R-squared are measures of overall model fit. The multiple- and adjusted R-squared values for the final trawl model were 0.4426 and 0.4413, and 0.6502 and 0.6494 for the final trap model, respectively; adjusted appears lowers than multiple, as it considers the model's overall complexity based on the number of variables and is observed to be a more accurate measure of model fit. The final trap model displays higher explanatory power, accounting for 65% of the variation in landing, in comparison to the final trawl model, which accounted for only 44% of variation in landings.

In a regression, residuals reflect the difference between fitted and observed values (i.e. the deviation between predicted vs. actual model results) (Cordeiro and Simas, 2009). To further investigate the relationship between observed and fitted values, additional tests were run using marginal model plots (Figure 4.3 and 4.4). Marginal plots are scatter plots that show the relationship between response and individual predictor variables in the model, with the dependent variable, landings, on the y-axis, and each independent variable on the x-axis (Cook and Weisburg, 1997). Furthermore, on top of each scatterplot, smoothness of fit functions, labeled “Data” and noted by the solid blue line, are compared against a function that shows predicted model values as a function of the x-axis, labeled “Model” and exhibited by the red dashed line (Cook and Weisburg, 1997); the closer both functions align, the more evidence that the model fits the data well. Visibly, both models fit the data well.

Figure 4.3: Marginal model plots for trap production function explanatory variables

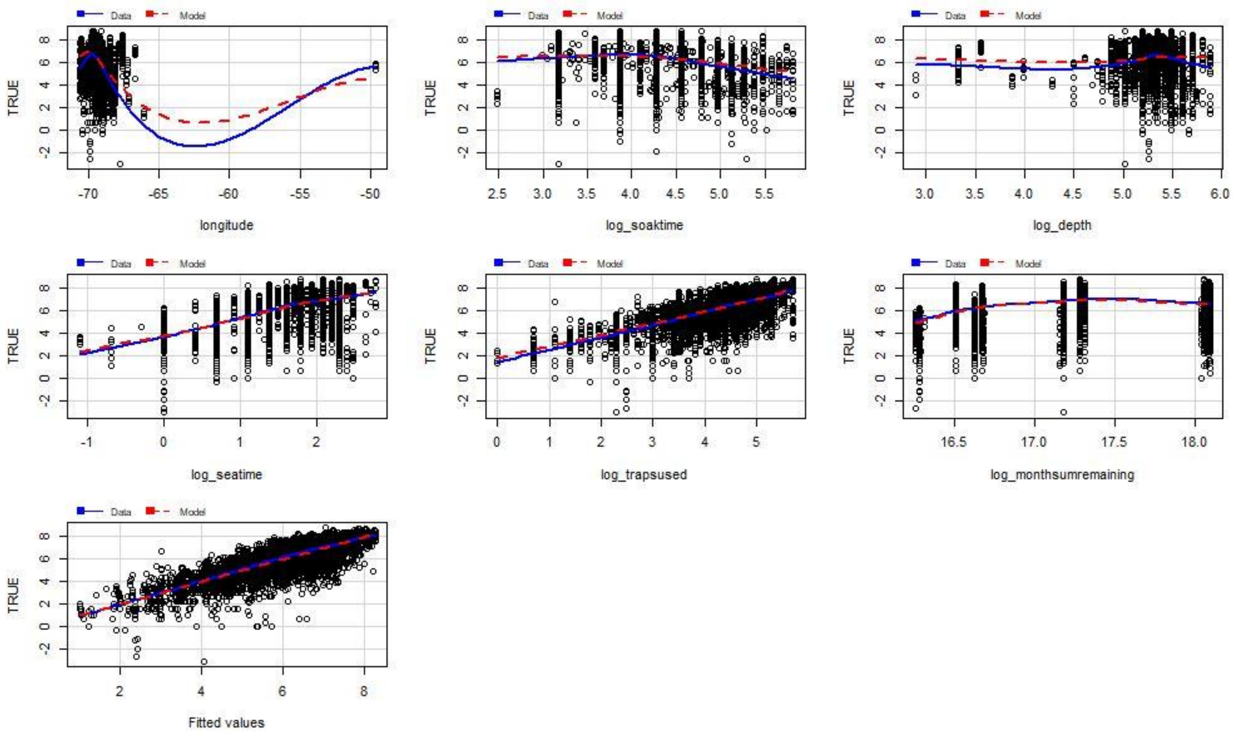
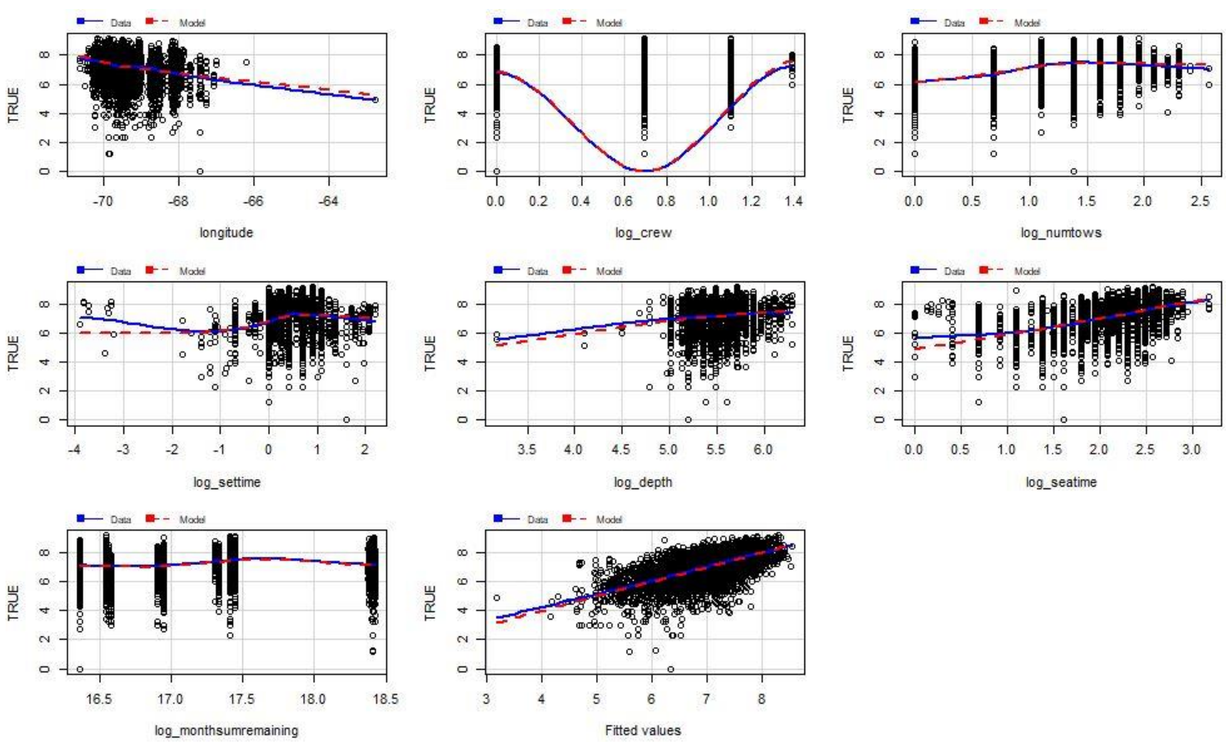


Figure 4.4: Marginal model plots for trawl production function explanatory variables



4.6 Discussion

4.6.1 Available Shrimp Biomass

Within each model, coefficients on estimates of available shrimp biomass appeared positive and significant for both ear types (Table 4.3), indicating that increases in shrimp abundance have a positive effect on landings. It was observed that trap landings appeared more responsive to changes in biomass than trawlers, which can be interpreted multiple ways.

From industry member interviews (see chapter 3) we may infer that the difference in coefficients between the two gear types may indicate varying gear-specific dependence on the resource. Compared to trawlers, trappers reported less overall dependence on the resource, and appeared generally less impacted by its closure, often expressing that, in absence of northern shrimp, trappers more easily switched back to their target species. Alternatively, trawlers expressed being more negatively impacted by the closure than trawlers given a reduced availability of alternative fisheries in its absence. Furthermore, trawlers admittedly reported fewer factors that would preclude them from fishing or reducing their effort when targeting northern shrimp. It is possible that differences between coefficients for each gear type is reflective of this level of dependence; trappers appear more selective in their decision making, while trawlers are less particular regarding conditions that discourage them from fishing. Figure 4.5 provides support for this theory; trawlers consistently exhibit higher landings on average than do trappers.

Given that estimates of available shrimp biomass are used in this analysis as a proxy for shifting environmental conditions, while declining shrimp abundance may preclude trappers from investing added effort into the fishery, results suggest that trawlers appear more vulnerable to declining environmental conditions and are generally more likely to suffer from environmentally-driven decreases in abundance. This is based on the relationship between trawl landings and the reported coefficient on available biomass for trawlers, in which landings appear less dependent on available biomass. Alternatively, it is also possible that high landings are characteristic of the trawl fishery given its high-volume nature and are not entirely representative of the level of dependence expressed by either gear type. The remaining explanatory variables included in the analysis provide further insight as to how fisher behavior and effort further impact respective landings within each fishery.

4.6.2 Input Effort Variables

Seasonal differences between landings were visible between both gear types (Figure 4.5). Trappers landings appear most strongly correlated to the months of February and March, coinciding with the closest proximity of shrimp to shore (Table 4.3); alternatively, December appeared negatively correlated with landings (more so for trappers than trawlers) given that it is harder for trappers to target shrimp on their incoming migration due to limited vessel capacity (Figure 4.5). Like trappers, trawlers also expressed higher, positive correlation with the months of February and March, although this relationship does not appear as strong given that trawl effort from December to April is more widely distributed across these months than it is for trappers (Figure 4.5, Table 4.3). This is consistent with prior knowledge of fishery characteristics by gear type; trawlers have access to a much larger window of opportunity than trappers following differences in vessel capacity between the two gear types. This is observable in Figure 4.6, in which the number of participants (boats) is found to vary by month and gear type. Trappers appear constrained by the two months where shrimp are closest to shore, while trawlers can follow shrimp further offshore during their incoming and outgoing migration. When further divided based on geographic location, trawl-specific (Figure 4.7) and trap-specific (Figure 4.8) plotted landings exhibited spatial patterns in output, indicating that Midcoast trawlers were responsible for the largest portion of landings across all gear types and locations. This is observed in Figure 4.3 and 4.4 for trap and trawl marginal model output, respectively. Collectively, this provides further support for the trends observed in remaining regression output.

Trawl landings expressed a strong, positive relationship with sea time more so than trap model output (Figure 4.4); trawlers consistently displayed higher overall time spent at sea, compared to trappers, for each season. This provides added indication that, on average, trawlers expend more effort following shrimp on- and offshore in relation to landings. Overall, the two explanatory variables exhibiting the strongest significance was traps used and number of tows for trap and trawl gear types, respectively. Trends in number of traps used exhibit the highest frequency in February (Figure 4.9), while number of tows appears highest for the months of January, February, and March (Figure 4.10) The relationship between both variables and respective landings were positive and significant at the 99% confidence level; this relationship was particularly strong for trappers. Results suggest that increased input effort, in relation to these two variables, exhibits the strongest relationship with landings. Trends in marginal model plots for both gear types indicated that the relationship between traps used and landings was positive and linear (Figure 4.3), while the relationship between landings and number of tows exhibits mostly positive returns before steadily declining. This suggests that trawlers are likely to experience diminishing returns on effort following a higher cost per unit of effort; alternatively, trappers expend comparatively less effort and resources when setting more traps.

Levels of remaining monthly biomass exhibit a positive, significant relationship with landings for both gear types. The nature of this relationship appears to vary by gear type, likely due to differences in dependence on the resource. Landings also exhibit a strong relationship with two significant explanatory variables representative of fisher input effort; trappers exhibit the strongest relationship with landings through the number of traps employed, while trawlers display a similarly significant relationship with landings and the number of tows made over the course of one fishing trip. Results are further corroborated by fisher interviews in Chapter 3.

Figure 4.5: Northern shrimp landings (mt) grouped by gear type, month, and fishing season. Each circle represents individual monthly summed landings for each participating fisherman. “X” denotes the monthly average for each gear type.

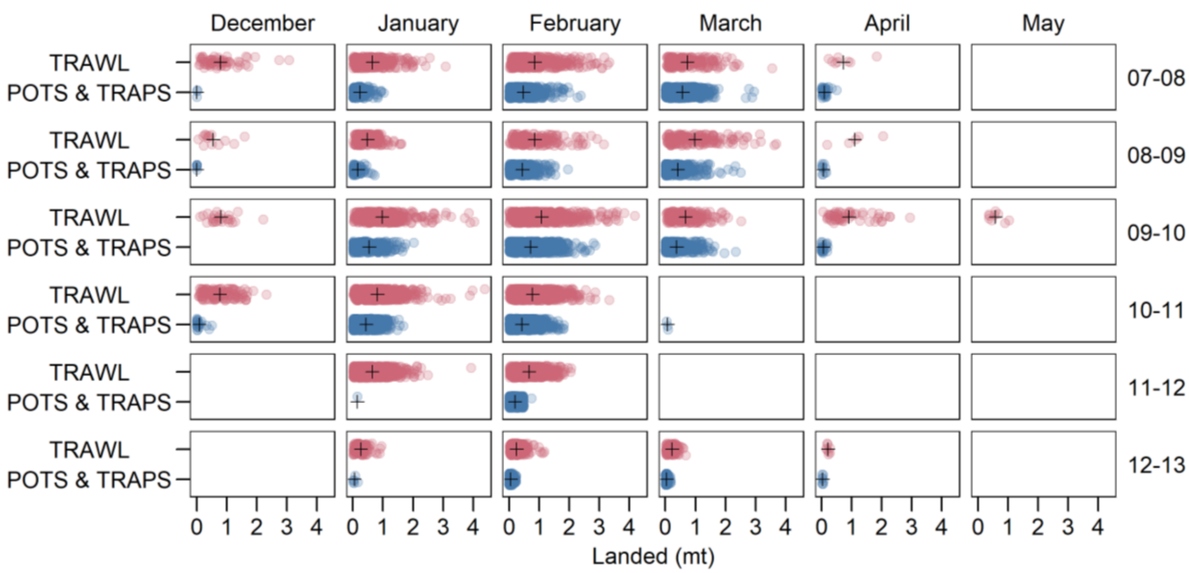


Figure 4.6: Number of participating boats, by landing day and gear type, chronologically ordered over the course of an entire fishing season, for each fishing season included in the analysis. The size of each circle corresponds to a specified number of boats.

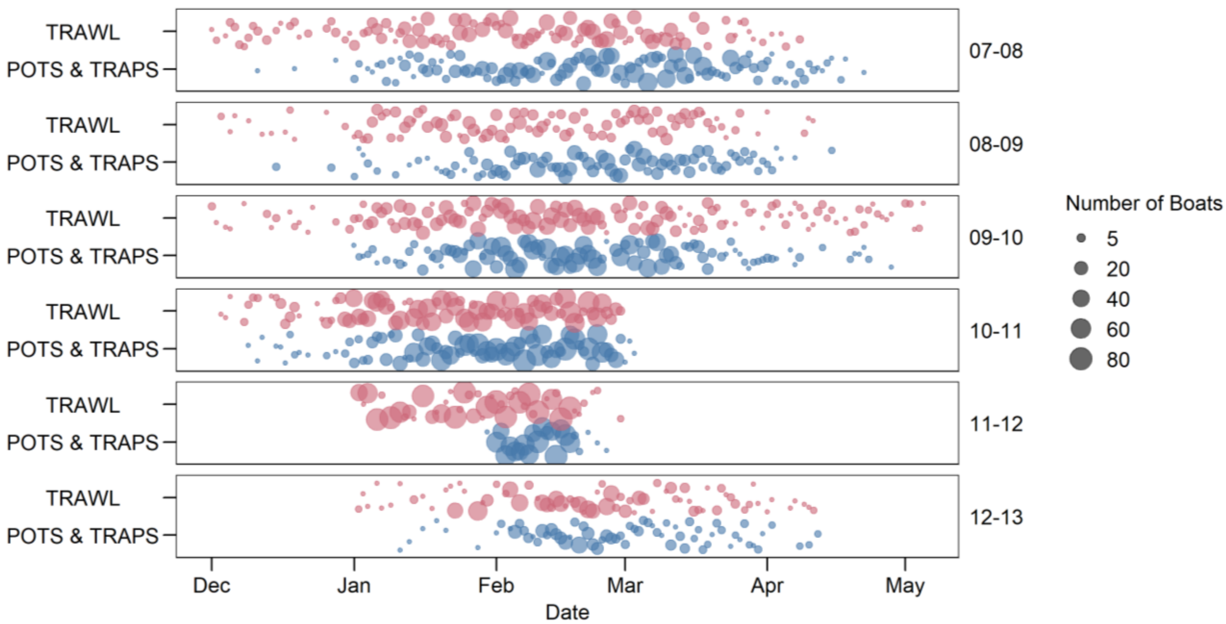


Figure 4.7: Northern shrimp landings (mt) for trawlers, grouped by geographic location, month, and fishing season. Each circle represents individual monthly summed landings for each participating fisherman. "X" denotes the monthly average for each gear type.

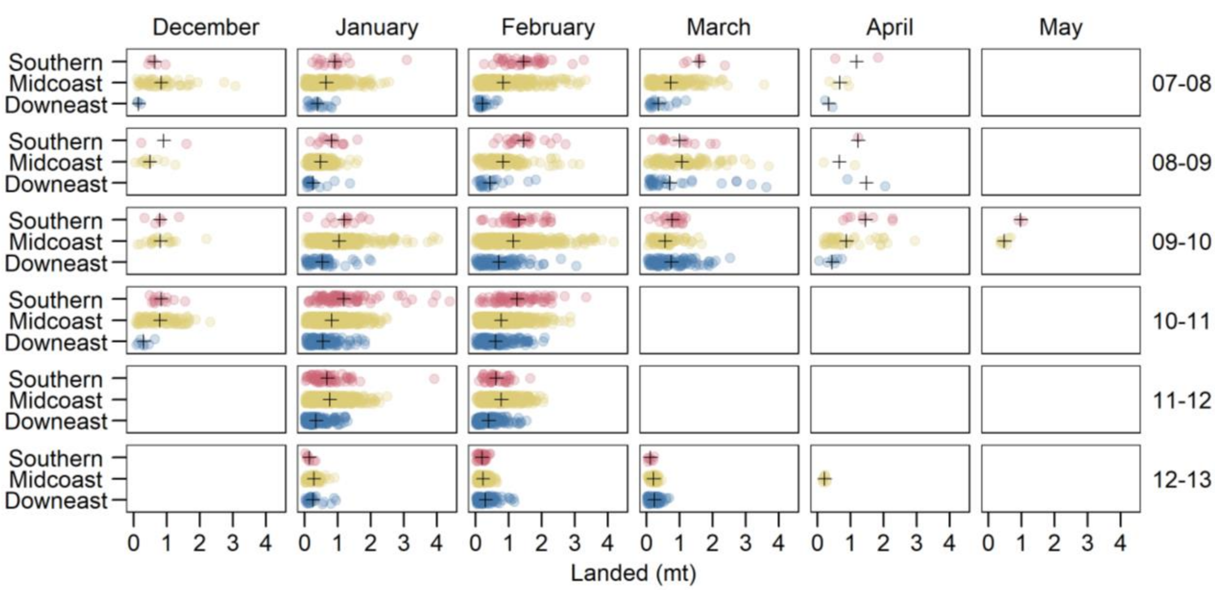


Figure 4.8: Northern shrimp landings (mt) for trappers, grouped by geographic location, month, and fishing season. Each circle represents individual monthly summed landings for each participating fisherman. “X” denotes the monthly average for each gear type.

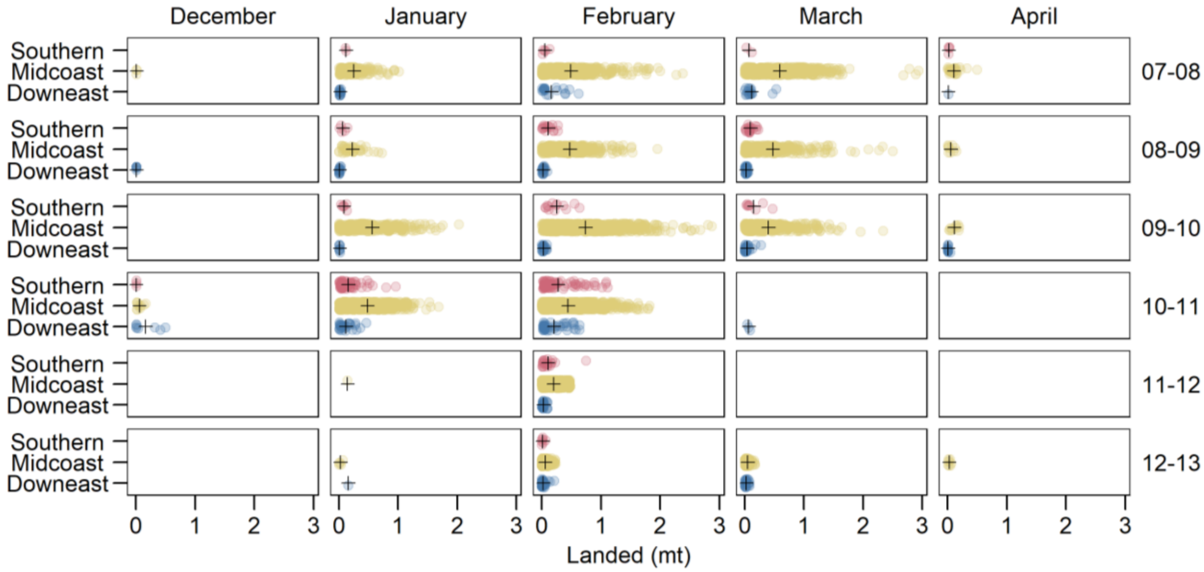


Figure 4.9: Average number of traps employed by trap fishermen per month, per fishing season, grouped by geographic location. Individual points represent each individual fisherman’s average for that month. “X” denotes the monthly average for each location.

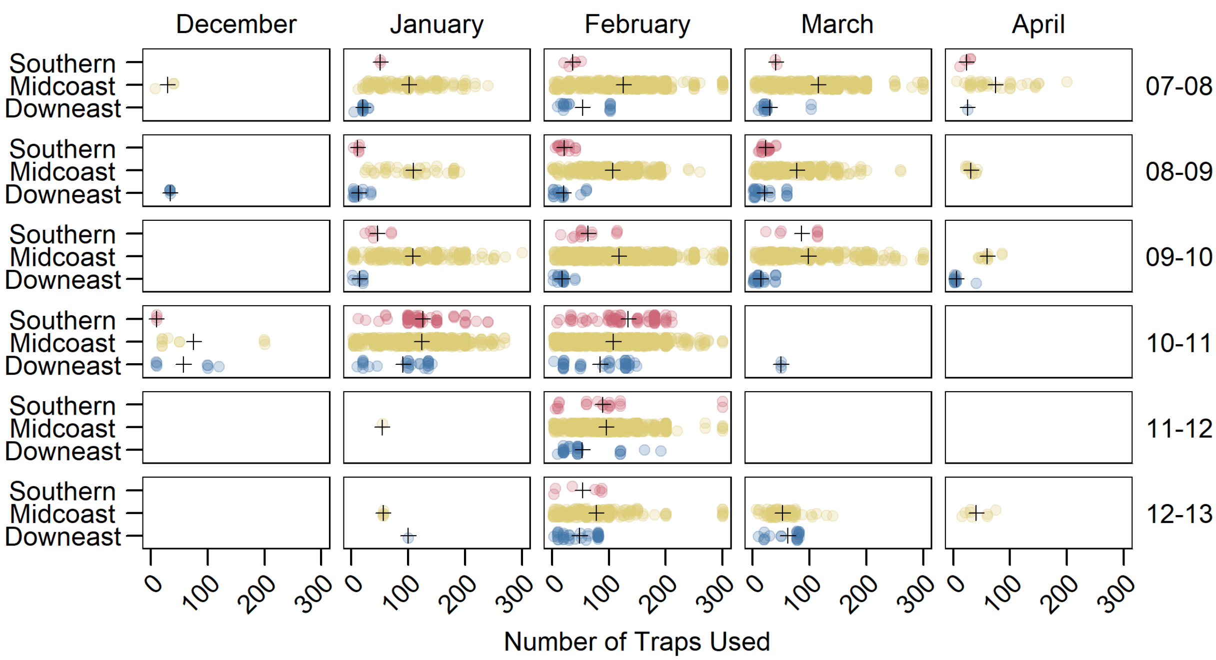
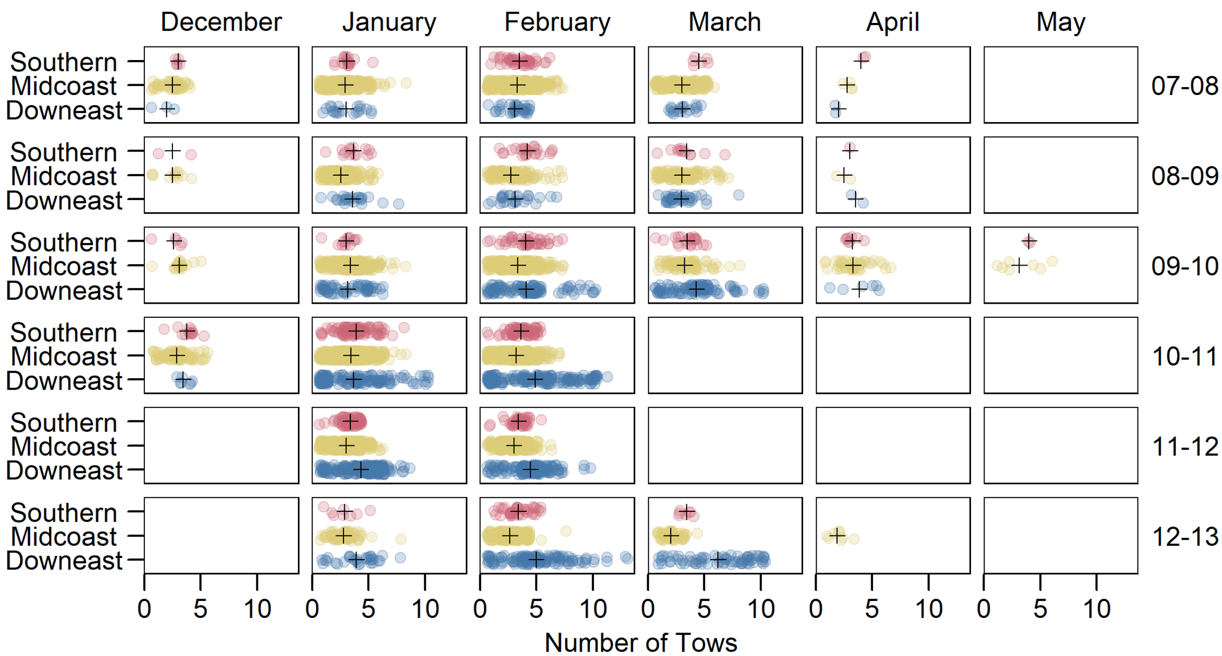


Figure 4.10: Average number of tows conducted by trawl fishermen per month, per fishing season, grouped by geographic location. Individual points represent each individual fisherman's average for that month. "X" denotes the monthly average for each location.



4.6.3 Limitations of this Study

In selectively choosing which variables to include in the regression, I am actively contributing to the potential introduction of omitted variable bias, in which case, I may be failing to include variables that are directly correlated with additional variables not included. This increases the potential likelihood of overestimating the impact that variables not included in either model have on effort and landings. Regarding the harvester data, the narrow timeseries of data, lack of pertinent socioeconomic information, and consistency in collection efforts presented numerous problems for our analysis, as it further limits the explanatory capacity of the models constructed. Due to the nature of the data employed in this research, it is difficult to determine which outliers deserved to be removed, as the data is manually self-reported by fishermen. More data would help to fill in these knowledge gaps. Furthermore, by using OLS regression techniques, the model makes the assumption there is no relationship between individual inputs in the model; this is likely a generous assumption regarding the composition of our model and may contribute some bias with regard to our results. This research acknowledges that there are likely more relationships that are present in the data that are not considered by this model. Despite these shortcomings, we may still find use for the results of this regression analysis through suggestive inference, and identify gaps in research knowledge and data collection to improve future research efforts with regard to the northern shrimp fishery in the Gulf of Maine, as well as other data poor fisheries. The methodology utilized in this analysis simple and aimed towards capturing major underlying trends, rather than for predictive purposes characteristic of projection models. In this regard, our results provide indication of general trends influencing effort and fisher behavior, as well as identify gaps in data and knowledge that could be of use for future regulatory efforts.

4.7 Implications for Management

It is understood that fisheries maintain an underlying degree of complexity that further complicate the task of management. Regarding northern shrimp, multiple political, biological, and technical aspects of this fishery create additional layers of complexity.

Given that Gulf of Maine northern shrimp exist at the southernmost extent of the species' range, it is subject to increased rates of warming more so than populations farther north. Furthermore, this climate-sensitive species has become inherently more vulnerable to impending threats, following shifts in their biological and reproductive potential. While no notable shifts in the GOM stock's spatial distribution have to occur due to the GOM's shifting climate, it is the overall impact that these rising temperatures have on the growth, maturation, and reproductive capacity of the species that attack its resiliency. As such, the Gulf of Maine will continue to become an increasingly inhospitable environment for the northern shrimp stock due to the sensitive nature of patterns in growth and recruitment to rising water temperatures. In the presence of remarkably high vulnerability, it is extremely likely that managers will be forced to exert more control over participation and effort levels within the fishery.

Examining model results, coefficients on explanatory variables are loosely interpreted as measures of elasticity regarding the relationship between predictor variables (input effort and biomass) and their impact on landings. Regarding shrimp abundance, trap landings exhibit a stronger, positive relationship between trap landings and estimates of available biomass. This suggests that trappers are potentially more selective in their participation and increases in landings coincide with increased opportunity via availability of shrimp biomass. Alternatively, trawl landings exhibit a weaker relationship between landings and available biomass, indicating that their effort is less influenced by shrimp abundance and their dependence on the resource is higher than that of trappers. Regarding input effort, landings appear most strongly influenced by the number of traps pulled and the number of tows made by trap and trawl vessels, respectively. Trappers generally expend less effort than trawlers in this regard, given that they often spend less time at sea and devote

With the northern shrimp fishery dependent on shrimp migratory patterns, trends in abundance, and the timing of closed and open seasons, this fishery is increasingly vulnerable to changes in the northern shrimp stock following shifting environmental conditions. This research provides insight regarding changes gear-specific vulnerability, effort, and landings that coincide with shifting conditions in the northern shrimp fishery; collectively, it provides added emphasis on the interconnectedness of exogenous changes and trends within the fishery in order to facilitate a deeper understanding of the relationships between fisher and stock response to a changing Gulf of Maine . With this basic knowledge, managers will be better equipped to anticipate the broader effects of climate change by anticipating fisher response to shifting environmental conditions and stock abundance.

5. CONCLUSION

Collectively, this work was composed of several individual projects that aim to analyze the feasibility of maintaining an ecologically and economically sustainable fishery in a changing Gulf of Maine. In Chapter 2 we provide a through overview of biological, environmental, historical, and regulatory trends regarding the evolution of the fishery to present day. This summary highlights the conditions surrounding the northern shrimp fishery that have contributed to its most recent stock collapse. These findings form the basis of each subsequent chapter included in this document. Chapter 3 utilizes northern shrimp industry-member surveys to develop a more comprehensive understanding of factors that influence participation and effort within the fishery. Results suggest that fishermen act in favor of positive socioeconomic returns; entry into the fishery was reportedly most dependent on conditions within the northern shrimp fishery regarding proximity to shore and level of abundance. These concepts were later corroborated by results presented in Chapter 4. Responses detailing sources of influence surrounding fisher behavior, as well as questions aimed towards soliciting industry opinion of management provide insight as to ways in which management may be improved in the future. Consideration of this nature is often omitted from fisheries management; as such, it often contributes to further inefficiency within the fishery. This suggests the need for more cooperative opportunities in the management of the northern shrimp fishery. Chapter 4 examined factors influencing size-at-transition in northern shrimp. Results showed that this life history process for northern shrimp is most affected by conditions experienced as juveniles. Sea surface temperature experienced during the summer and fall was the most significant. Size-at-transition was observed to decrease with increasing temperature experienced during this critical life stage. Results from this study suggest that management will need to account for diminished reproductive potential, as fecundity is positively correlated with female body size (Shumway et al., 1985; Hanes and Wigley, 1969). In Chapter 4, we first explored the sensitivity of fisher behavior to changes in abundance of harvestable biomass, as well as examine fishers' vulnerability through variation in abundance of harvestable biomass. Results proved that both gear types are impacted by the availability of harvestable biomass; monthly remaining biomass appeared more significant to trappers than trawlers, a potential indication that trappers are more selective in their participation in the fishery, while trawlers appear less selective. This suggests that trawlers have fewer alternative options than trappers and are likely to be more vulnerable to shifting fishery conditions. We also examined the relationship between landings and different input effort components by gear type. On average, trawlers exude the most effort via the number of tows conducted, followed by sea time; landings initially increase with the number of tows conducted, though this begins to steadily decline with increasing tows, indicating diminishing returns on effort. This shows that trawlers must expend more resources following shrimp offshore and in their active targeting of shrimp. Alternatively, trappers exhibit a positive, linear increasing relationship with number of traps used, indicating that they experience increasing returns with the number of traps hauled. Overall, the cost of effort appears higher for trawl fishermen than trap; this further supports the notion that trawlers are more vulnerable to changes in fishery conditions.

Though largely independent of each other, each of these chapters collectively identify biological, environmental, socioeconomic, and regulatory hurdles to the reestablishment of an ecologically and economically sustainable northern shrimp fishery. To develop a stable northern shrimp fishery, we must continually assess the impact of climate change on the GOM stock in conjunction with the local communities that depend on them; this includes identifying ways in which fishers may need to adapt their fishing strategy and effort levels, building stock assessment models that consider potential changes in fishery performance and management effectiveness in light of climate change, and improving our general understanding of the socioeconomic aspects of fisheries in order to mitigate the effects of future management decisions on vulnerable communities. A proactive approach to fisheries management that emphasizes and strengthens the adaptive capacity of both fishers and fishery managers is crucial to the development of a viable northern shrimp fishery in a changing Gulf of Maine.

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APPENDICES

Appendix A: Industry Member In-Person Survey - Fishermen

Name:________________________________
Interview ID #:________________________
Stakeholder Group:_____________________

1. What type of gear did you use to fish for shrimp during the time of your involvement in the northern shrimp fishery?

2. What was the length of the boat you used?

3. What is your town of residence? What is its geographic location?

4. What town is your homeport located in?

5. In what port do you most often land your catch?
    a. Did you ever land shrimp outside your homeport?
    b. If yes, what reasons did you have for doing so?

6. Are you a full-time fisherman?

7. How many crew did you employ when shrimping?

8. What was your largest cost when shrimping?

9. Around what year did you begin fishing commercially?

10. What year did you first start fishing for shrimp commercially?

11. In a typical year, how many months out of the year do you fish?
    a. Did this change at all when the shrimp fishery closed? How did if affect you?

12. What fisheries, in addition to shrimp, do you primarily participate in?
    a. What was your primary target species?

13. When the shrimp fishery was open, what reasons drove you to purchase a shrimp license?

14. For every year that you bought a license, did you participate in the fishery?
    a. What were some of the reason that influenced your decision to <u>not participate</u>?
    b. What were some of the reason that influenced your decision to <u>participate</u>?

15. When is the best time to fish for and sell shrimp? The worst? Why?

16. What factor(s) most strongly influence the way you fished for shrimp (i.e. effort)
    a. What influences you to apply more effort?
    b. What influences you to apply less effort?

17. Were there seasons during which you fished regardless of whether it was cost-effective or safe?

18. How did you go about selling your catch, and where would you sell to?
    a. If you sold to multiple dealers/locations, could you explain why?
    b. Did you ever contract with dealers and processors during your involvement?

19. When selling your shrimp, do you recall what the product looked like?

20. How do you believe the sale price was determined for the shrimp you sold?

21. Overall, how important is this fishery to you? Why?

22. As a fisherman that lost access to the shrimp fishery when it shut down in 2014, how did this impact your livelihood and what have you done to make up for this lost income?

23. What would you save have been the biggest changes in the fishery since you started fishing it?

24. What do you believe to be threats currently facing the shrimp fishery?

25. Do you have any opinions on what is needed to ensure the future of the shrimp fishery, and increase sustainability and profitability?

26. What is your outlook regarding the following?
    a. Your potential future involvement in the shrimp fishery over the next five years
    b. Your outlook on the direction in which this fishery is heading?

Appendix B: Industry Member In-Person Survey - Dealers

Name:_________________________________
Interview ID #:__________________________
Stakeholder Group:______________________

1. Where is your business located?

2. Compared to other dealers/processors, would you consider this business to be a small, medium, or large?

3. What type of business does your organization identify as?
    a) Sole proprietorship
    b) Partnership
    c) Corporation
    d) Cooperative

4. How many years has your business been in operation?

5. When did your business start dealing in shrimp?

6. In an average year, how many people does your facility employ?
    a) Would this change during the shrimp season?

7. In a regular season, what months is your business in operation?
    a) Has this changed at all since the shrimp fishery closed?

8. What type of species would you typically deal in?

9. What number of fisheries did was your business consistently involved in during this time?

10. What was the target species of your establishment?
    If you had multiple, please include them in your response.

11. What was the nature of your involvement within the northern shrimp fishery?

12. IF YOU BOUGHT SHRIMP:
    a) Who did you buy shrimp from?
    b) What town/location did you purchase shrimp from? If multiple, please list.
    c) What state did purchased shrimp come in? (i.e. whole, headless, peeled, etc.)

13. Did you process and/or handle shrimp?
    a) If yes, how did your facility typically process shrimp?

14. When is the best time to fish for and sell shrimp? Why?

15. How do you believe the price was determined for shrimp?

16. Did you notice price differentials? If so, for what reason?

17. Overall, how important is this fishery to your business, and could you explain why?

18. When the shrimp fishery closed, how did your business make up for the loss in income?

19. What is your opinion on the threats currently facing the shrimp fishery?

20. Do you have any opinion as to what is needed to ensure the future of the shrimp fishery in order to increase sustainability and profitability?

21. Fishery Outlook: What is your outlook on perspective growth for your individual business over the next 5 years (concerning shrimp)?

Appendix C: Summary Transcripts of Fishermen Survey

Name:______________________________
Interview ID #:________________________
Stakeholder Group:____________________

1. What type of gear did you use to fish for shrimp during the time of your involvement in the northern shrimp fishery?
   Trawl (17) 63% - Downeast (18.5%), Midcoast (29.6 %), Southern (22.2%)
   Trap (10) 37% - Downeast (11.1%), Midcoast (18.5%), Southern (7.4%)

2. What was the length of the boat you used?
   29ft or less (1) 3.7 %, 30 – 39ft (8) 29.6%, 40 – 49ft (14) 51.9%, 50 ft or larger (6) 22.2%

   What is your town of residence? What is its geographic location?
   The physical residency (town) of interview volunteers was kept confidential.
   Geographic location: Downeast - Trawl (5) 19%, Trap (3) 11% Trap
   Midcoast – Trawl (8) 30%, Trap (5) 19% Trap
   Southern – Trawl (4) 15%, Trap (2) 7%

3. What town is your homeport located in?
   Downeast: Bar Harbor (1), Northeast Harbor (1), Sorrento (1), Stonington (1), Winter Harbor (1). **Midcoast:** Five Islands (2), Boothbay Harbor (1), Bristol (1), Cundy's Harbor (1), Friendship (1), New Harbor (1), Port Clyde (3), South Bristol (1), Tenants Harbor (1). **Southern** Biddeford Pool (1), Cape Porpoise (1), Kennebunk Port (1), Portland (4), Saco (1)

4. In what port do you most often land your catch?
   Downeast locations: Bar Harbor - Trawl (1) 4%, Northeast Harbor - Trawl (1) 4%, Sorrento – Trawl (1) 4%, Stonington (3) - (2) 7% Trawl, (1) 4% Trap, Winter Harbor – Trap (1) 4%.
   Midcoast locations: Five Islands – Trap (2) 7%, Boothbay Harbor – Trap (1) 4%, Bristol – Trawl (1) 4%, Cundy's Harbor (1) 4% - Trawl, Friendship – Trawl (1) 4%, New Harbor – Trawl (1) 4%, Port Clyde – Trawl (3) 11%, South Bristol (2) - (1) 4% Trawl, (1) 4% Trap, Tenants Harbor – Trap (1) 4%.
   Southern locations: Biddeford Pool – Trawl (1) 4%, Cape Porpoise - Trawl (1) 4%, Kennebunk Port – Trawl (1) 4%, Portland (13) 33% - (11) 41% Trawl, (2) 7% Trap

   a. Did you ever land shrimp outside your homeport?
      Yes (10) 37%, No (17) 63%

   b. If yes, what reasons did you have for doing so?
      Price (2) 16.7%, Market Capacity (10) 83.3%, Weather (1) 8.3%, Boat Size (1) 8.3%, Shrimp Abundance (4) 33.3%

5. Are you a full-time fisherman? 100% - yes

6. How many crew did you employ when shrimping?
   Trawl range**:** 1 – 3 crew, Trap range: 0* – 3 crew
   (*0 indicating that the captain worked alone)

7. What was your largest cost when shrimping?
   Trap Trip Level Costs: Ice – (0), Fuel – (5) 19%, Crew Salary – (1) 4% Bait – (7) 27%
   Start-Up Costs: Gear (traps, rope, etc.) – (1) 4%
   Trawl Trip Level Costs: Ice – (1) 4%, Fuel – (16) 62%, Crew Salary – (2) 8%

8. Around what year did you begin fishing commercially?
   Trap: Range: 1960 – 2000, Range # years of experience: 18 – 58 years
   Trawl: Range: 1958 – 1992, Range # years of experience: 26 – 60 years

9. What year did you first start fishing for shrimp commercially?
   Trap: Range: 1970 – 2010, Range # years of experience: 3 – 48 years
   Trawl: Range: 1965 – 2000, Range # years of experience: 13 – 60 years

10. In a typical year, how many months out of the year do you fish?
    Trap: ranged 10-12 months; Trawl: ranged 5-12 months

    a. Did this change at all when the shrimp fishery closed? How did if affect you?
       Highly Impactful (6): (5) Trawl, (1) Trap
       Location: Midcoast and Southern regions
       Reported changes in activity: Decreased fishing activity
       Loss of significant winter income
       Fall back to land-based income source
       Follow other fisheries offshore (dangerous)
       Less Impactful (7): (2) Trawl, (5) Trap
       Location: Primarily Midcoast and Downeast regions
       Reported changes in activity: Switched fisheries/redirected effort

11. What fisheries, in addition to shrimp, do you primarily participate in?
    Groundfish (21) 78% →Trap (6) 22%, Trawl (15) 56%
    Lobster (19) 70% → Trap (10) 37%, Trawl (9) 33%
    Scallops (15) 56% → Trap (7) 26%, Trawl (8) 30%
    Other (7) 26% → Trap (5) 19%, Trawl (2) 7%
    Tuna (1) 4% - Trawl
    Shellfish (5) 19% → Trap (1) 4%, Trawl (4) 15%

    a. What was your primary target species?
       Trap: lobster (8) 80%, scallops (2) 20%
       Trawl: lobster (8) 47%, groundfish (7) 41%, shrimp (2) 11%

12. When the shrimp fishery was open, what reasons drove you to purchase a shrimp license?
    Conditions in other fisheries (14) 52% – Trap (3) 11%, Trawl (11) 41%
    Conditions in the shrimp fishery (27) 100% - Trap (10) 37%, Trawl (17) 63%
    Regulatory conditions (3) 11% - Trap (2) 7%, Trawl (1) 4%
    Market conditions (2) 7% - Trap (1) 4%, Trawl (1) 4%
    environmental conditions (7) – Trap (4) 15%, Trawl (3) 11%

13. For every year that you bought a license, did you participate in the fishery?
    Yes (17) 63% - Trap (4) 15%, Trawl (13) 48%
    No (8) 30% - Trap (4) 15%, Trawl (4) 15%

    a. What were some of the reason that influenced your decision to not participate?
       Conditions in other fisheries 2 (10%), Shrimp fishery conditions 3 (15%), Market conditions (2) 10%

    b. What were some of the reason that influenced your decision to participate?
       Conditions in other fisheries (3) 15%, Regulatory conditions within the shrimp fishery (2) 10%,, Shrimp fishery conditions (16) 80%, Market conditions (1) 5%

14. When is the best time to fish for and sell shrimp? The worst? Why?
    Do not target: Dec (15) 54%, Jan (6) 26%, Feb (0) 0% Mar (5) 21%, Apr (23) 96%, May (26) 100% ,
    Target: Dec (9) 38%, Jan (18) 75%, Feb (26) 100%, Mar (19) 79%, Apr (1) 4%,, May (0) 0%

15. What factor(s) most strongly influence the way you fished for shrimp (i.e. effort)
    Environmental factors (6) 22% - Trap (1) 4%, Trawl (5) 19%
    Shrimp fishery conditions (26) 96%) – Trap (9) 33%, Trawl (17) 63%
    Conditions in other fisheries (9) 33% - Trap (2) 7%, Trawl (7) 26%
    Regulatory condition in the shrimp fishery (21) 78% - Trap (8) 30%, Trawl (12) 44%
    Market conditions (12) 44% - Trap (8) 30%, Trawl (4) 15%

    a. What influences you to apply more effort?
       Conditions in other fisheries (3) 11%, Shrimp fishery conditions (24) 89%, Market conditions (11) 41%, Regulatory conditions (20) 74%

    b. What influences you to apply less effort?
       Environmental conditions (6) 32%, Shrimp fishery conditions (17) 89%, Conditions in other fisheries (3) 16%, Regulatory conditions (3) 16%, Market conditions (1) 5%

16. Were there seasons during which you fished regardless of whether it was cost-effective or safe? Yes (25) 93% - Trap (10) 37%, Trawl (15) 56%, No (0) 0%, No reply (2) 7%

17. How did you go about selling your catch, and where would you sell to? (Tables 25-26)

    Method of sale:

    Buyer waiting on dock (5) 19% - Trap (1) 4%, Trawl (4) 15%
    Sold to dealer (25) 93% - Trap (10) 37%, Trawl (15) 55%
    Sold to peddler or self-peddled (13) 48% – Trap (5) 19.5%, Trawl (8) 29.5%

    Location sold to:

    Southern (19) 70% - Trap (6) 22%, Trawl (13) 48%
    Midcoast (14) 52% - Trap (6) 22%, Trawl (8) 30%
    Downeast (8) 30% - Trap (3) 11%, Trawl (5) 19%

    Local vs. Non-Local

    Sold Locally and Non-locally (14) 52% - Trap (5) 19%, Trawl (9) 33%
    Sold to Locally (13) 44% - Trap (5) 18%, Trawl (7) 26%
    Sold Non-locally (1) 4% - Trawl

    a. If you sold to multiple dealers/locations, could you explain why?
       Did: guaranteed business (15%), convenience (26%), market capacity (63%), price (37%). **Did not**: Loyalty to dealer (18.5%) peddled (37%)

18. Did you ever contract with dealers and processors during your involvement?
    Official contract (0) 0%
    No form of contracting (19) 70% - Trap (8) 30%, Trawl (11) 42%
    Unofficial contracting; dealer loyalty (8) 30% - Trap (2) 7%, Trawl (6) 22%

19. When selling your shrimp, do you recall what the product looked like?
    Unprocessed (24) 89%
    Self-Processed (4) 15% - handpicked (3) 11%, hand-peeled (1) 4%

20. How do you believe the sale price was determined for the shrimp you sold?
    Dealer's choice: Trap (10) 27%, Trawl (17) 63%
    Demand: Trap (7) 26%, Trawl (6) 24%
    Market Capacity: Trap (1) 4, Trawl (6) 22%
    Market saturation: Trap (2) 7%, Trawl 30%
    Prices elsewhere: Trap (1) 4%, Trawl (1) 4%
    Product quality: Trap (5) 19%, Trawl (9) 33%

21. Overall, how important is this fishery to you? Why?
    Level of importance (n = 27)
        Little to no importance (6) 22% - Trap (4) 15%, Trawl (2) 7%
        Moderate (7) 26% - Trap (3) 11%, Trawl (4) 15%
        Very to Extremely (14) 52% - Trap (3) 11%, Trawl (11) 41%
    Reason for unimportance (n = 11)
        More for younger generations (3)
        Closed too long (2)
        Found other opportunities (8)
    Reason for importance (n = 25)
        Tradition (10) 40% - Trap (3) 12%, Trawl (7) 28%
        Personal enjoyment (5) 20% - Trap (3) 12%, Trawl (2) %
        Local support (9) 36% - Trap (2) 8%, Trawl (7) 28%
        Safety (8) 32% - Trap (3) 8%, Trawl (5) 20%
        Supplemental income (24) 96% - Trap (8) 32%, Trawl (16) 64%
        Conditions in other fisheries (13) 52% - Trap (4) 16%, Trawl (9) 36%

22. As a fisherman that lost access to the shrimp fishery when it shut down in 2014, how did this impact your livelihood and what have you done to make up for this lost income?
    Went in debt (2) 7% - Trap
    Lost income (8) 30% - Trawl
    Relied on land-based sources of income (9) 33% - Trap (2) 7%, Trawl (7) 26%
    Targeted new fisheries (6) 22% - Trap (4) 15%, Trawl (2) 7%
    Fished target fisheries harder (24) 89% - Trap (8) 30%, Trawl (16) 59%

23. What would you save have been the biggest changes in the fishery since you started fishing it?
    Increased levels of fishing effort (39%)
    Increased occurrences of gear conflict (9%)
    Diminished stock conditions (4%)
    The nature of regulations in the shrimp fishery (83%)

24. What do you believe to be threats currently facing the shrimp fishery?
    Regulatory (37) 100%
        Credibility and effectiveness of management (29) 78%
        Input controls (21) 57%
        Output controls (13) 35%
        Management structure (19) 51%
        Science going into the regulations (78%)
    Non-regulatory
        Conditions in other fisheries (3) 10%
        Environmental conditions (8) 28%
        Conditions within the northern shrimp fishery (8) 28%
        Market conditions (17) 59%
        Diminished shrimp stock conditions (3) 10%

25. Do you have any opinions on what is needed to ensure the future of the shrimp fishery, and increase sustainability and profitability? (Table 35)

26. What is your outlook regarding the following?
    a. Your potential future involvement in the shrimp fishery over the next five years
    Positive (58%): Indicated they would participate in the event if it reopened but provide no indication of faith in the idea that it actually WILL reopen.
    Unsure (1) 4% : Unsure about the future of their involvement
    Poor (37%): (1) too old, (3) too costly, (6) distrustful of management, (2) moved on, (4) generally discouraged

    b. Your outlook on the direction in which this fishery is heading?

Positive (7) 27%	Hopeful that the resource will recover and the climate will change, but no definitive answers in this regard
Negative (22) 85%	"Realistically negative" (5) generally distrustful of its future (10) currently regulatory efforts not working (3) no faith in the science (1) unfavorable environmental conditions (2) fishery unpredictable and unreliable

APPENDIX D: Summary Transcripts of Dealer-Processor Survey

Name:___________________________
Interview ID #:_____________________
Stakeholder Group:__________________

1. Where is your business located?
   Downeast (2): Stonington (1), Jonesport
   Midcoast (2): Bristol (1), Port Clyde (1)
   Southern: Scarborough (2), Portland (4)

2. Compared to other dealers/processors, would you consider this business to be a small, medium, or large?
   Small (4) 40%, Medium (3) 30%, Large (3) 30%

3. What type of business does your organization identify as?
   a) Sole proprietorship (2) 20%
   b) Partnership (0) 0%
   c) Corporation (6) 60%
   d) Cooperative (2) 20%

4. How many years has your business been in operation?
   Range: 1910 – 2007, years in business: 13 – 107 years

5. When did your business start dealing in shrimp?
   Range: 1960 – 2007, years in business: 53 – 6 years

6. In an average year, how many people does your facility employ?
   a) Would this change during the shrimp season?
      Range during the regular season:
         Smaller businesses: 6 – 15 (regular season), 6 – 25 (winter months)
         Medium size businesses: 10 – 50 (regular season), 10 – 20 (winter months)
         Large size businesses: 16 – 150 (regular season), 65 – 150 (winter months)

7. In a regular season, what months is your business in operation?
   a) Has this changed at all since the shrimp fishery closed?
      Pre shutdown: (1) Part time operational months (~10 months)
      (9) Full time, 12 months/year
      Post shutdown: (4) Part time months (ranging 5-10 months)
      (4) Full time, 12 months/year
      (2) Shut down for the winter months

8. What type of species would you typically deal in? (Table 13)
   Groundfish (9) 90% - Downeast (1) 10%, Midcoast (3) 30%, Southern (5) 50%
   Lobster (8) 80% - Downeast (2) 20%, Midcoast (2) 20%, Southern (4) 40%
   Scallops (2) 20% - Downeast (1) 10%, Midcoast (0) 0%, Southern (1) 10%
   Other (1) 10% - Downeast
   Shellfish (4) 40% - Downeast (2) 20%, Midcoast (1) 10%, Southern (1) 10%

9. What number of fisheries did was your business consistently involved in during this time?
   Number of species involved in: Downeast: 4 – 5, Medium: 2 – 5, Large: 2 – 5

10. What was the target species of your establishment?
    If you had multiple, please include them in your response.
    Downeast (2): (2) lobster
    Midcoast (2): (1) groundfish, (1) groundfish and shrimp
    Southern (6): (3) groundfish, (1) lobster, (1) groundfish, lobster, and shrimp, (1) no target

11. What was the nature of your involvement within the northern shrimp fishery?
    Buyer (9) 90%, seller (8) 80%, auctioneer service (1) 10%, broker (1) 10%.

12. IF YOU BOUGHT SHRIMP:
    a) Who did you buy shrimp from?
       Fishermen (10) 100%, 40% of which fishermen only
       Other dealers and processors (5) 50%

    b) What town/location did you purchase shrimp from? If multiple, please list.
       Downeast businesses (2) - Locally (i.e. Downeast area only)
       Midcoast businesses (6) - Locally (i.e. Midcoast area only)
       Southern businesses (6) - (3) Southern locations only
       (3) Locally (Southern) and non-locally, including
       - (3) Midcoast
       - (3) Downeast
       - (2) Outside the state of Maine (MA and NH)

    c) What state did purchased shrimp come in? 100% whole

13. Did you process and/or handle shrimp?
    Did not process shrimp (4) 40%, did process shrimp (6) 60%

14. When is the best time to fish for and sell shrimp? Why?
    Months: Dec - yes (4), no (2), Jan - (6) yes, (0) no, Feb: (7) yes, (0) no, Mar: (5) yes, (2) no, Apr: (0) yes, (7) no, May: (0) yes, (7) no
    Reasons: (3) Accessibility – near shore, (1) Seasonality – short window of opportunity, (3) Holiday demand, (3) Market demand, (4) Product quality

15. How do you believe the price was determined for shrimp?

16. Did you notice price differentials? If so, for what reason?
    Higher price: Market saturation (low), market capacity (high – i.e. the processing capacity exists to handle larger volumes), product quality (count per pound (lower), physical state sold in (live, moving, fresh, whole, not frozen), gear type (higher for trapped shrimp) (9) 24%).
    Lower price: Market capacity (low), market saturation (high), product quality (count per pound (high), physical state sold in (multi-day old/not fresh, blackened heads)).

17. Overall, how important is this fishery to your business, and could you explain why?
    No answer (2), No importance to business (5) 50%, Somewhat important (1) 10%
    Very important: (2) 20%
    Reasoning for unimportance:
        Duty to the fishermen, not actually beneficial to their business (2) 20%
        Found other opportunities (3) 30%
    Reasoning for importance:
        Support for the local community (6) 60%
        Supplemental (winter) income (3) 30%

18. When the shrimp fishery closed, how did your business make up for the loss in income?
    Moved on to new species (4 - 40%), had enough business to keep busy (3 - 30%), invested in new and non-fishery related business ventures (1 - 10%), unconcerned (2 - 20%), no response (2 – 20%)

19. What is your opinion on the threats currently facing the shrimp fishery?
    Results are collectively summarized with fishermen's responses.

20. Do you have any opinion as to what is needed to ensure the future of the shrimp fishery in order to increase sustainability and profitability?
    Results are collectively summarized with fishermen's responses on page.

21. Fishery Outlook: What is your outlook on perspective growth for your individual business over the next 5 years (concerning shrimp)?
    Positive outlook (2) 20%, poor / negative outlook (7) 70%

APPENDIX E – Chapter 3 Model Diagnostics

Table E1: Preliminary model output for the top two environmental-based models, examining the relationship between:
(a) Select offshore environmental variables interaction with Summer Survey L_T (model 11)
(b) Select inshore environmental variables interaction with Summer Survey L_T (model 16)

(a) Offshore environmental effects on Summer Survey L50 *(Model 11)*						
Model	Lag	Term	edf	ref.df	statistic	p.value
11	(y-2)	Mar (bt)	1.00	1.00	168.91	0.00
		Jan (st)	5.75	5.88	96.64	0.00
		Jul (st)	6.00	6.00	93.48	0.00
		Sep (st)	4.08	4.43	23.48	0.00
		Oct (st)	6.00	6.00	101.42	0.00
		Dec (st)	5.67	5.79	61.12	0.00
		Longitude	8.80	8.99	436.66	0.00
n = 27,411						
(b) Inshore environmental effects on Summer Survey L50 *(Model 16)*						
Model	Lag	Term	edf	ref.df	statistic	p.value
16	(y-2)	Mar (bt)	5.00	5.00	460.92	0.00
		Jan (st)	5.00	5.00	244.06	0.00
		Jul (st)	5.00	5.00	445.93	0.00
		Aug (st)	4.74	4.81	704.53	0.00
		Oct (st)	4.72	4.78	217.97	0.00
		Dec (st)	4.68	4.75	572.32	0.00
		Longitude	8.80	8.99	436.59	0.00
n = 27,411						

Table E2: Preliminary model diagnostics for the top two environmental-based models, examining model fit, convergence of the smoothness selection optimization, and analysis of basis dimension choices for

(a) Select offshore environmental variables interaction with Summer Survey L_T (model 11)
(b) Select inshore environmental variables interaction with Summer Survey L_T (model 16)

(a) Offshore environmental effects on Summer Survey L50 *(Model 11)*					
Smoothing parameter selection converged after 20 iterations.					
The RMS GCV score gradient at convergence was 9.42729e-06 .					
The Hessian was positive definite.					
Model rank = 46 / 46					
Lag	Term	k'	edf	k-index	p-value
(y-2)	Mar (bt)	6	1	1.01	0.82
	Jan (st)	6	5.75	1.01	0.72
	Jul (st)	6	6	1.01	0.78
	Sep (st)	6	4.08	1.01	0.8
	Oct (st)	6	6	1.01	0.74
	Dec (st)	6	5.67	1.01	0.82
	Longitude	9	8.8	0.82	<2e-16***
(n = 27,411)					
(b) Inshore enironmental effects on Summer Survey L50 *(model 16)*					
Smoothing parameter selection converged after 20 iterations.					
The RMS GCV score gradient at convergence was 6.447269e-06 .					
The Hessian was positive definite.					
Model rank = 40 / 40					
Lag	Term	k'	edf	k-index	p-value
(y-2)	Mar (bt)	5	5.00	1.01	0.81
	Jan (st)	5	5.00	1.01	0.74
	Jul (st)	5	5.00	1.01	0.78
	Aug (st)	5	4.74	1.01	0.81
	Oct (st)	5	4.72	1.01	0.79
	Dec (st)	5	4.68	1.01	0.85
	Longitude	9	8.80	0.82	<2e-16 ***
(n = 27,411)					

Table E3: Sex ratio-dependent model output, prior to final model selection, examining the impact of Summer Survey sex ratio on Summer Survey L_T for time lags (y-1) and (y-2).

Summer sex ratio *on* Summer Survey L_T (n = 29,017)						
Model		Term(s)	edf	ref.df	statistic	p.value
19	(y-1)	Male	4.00	4.00	574.35	0.00
	(y-0)	Longitude	8.85	8.99	410.45	0.00
20	(y-2)	Male	4.00	4.00	216.32	0.00
	(y-0)	Longitude	8.91	9.00	422.71	0.00

Table E4: Preliminary model diagnostics for the most explanatory sex-ratio-based model, examining the fit of the model, convergence of the smoothness selection optimization, and analysis of basis dimension choices.

Summer Survey Sex Ratio on Summer Survey LT (Model 19)

Smoothing parameter selection converged after 8 iterations.
The RMS GCV score gradient at convergence was 5.299804e-05
The Hessian was not positive definite.
Model rank = 45 / 46

Lag	Term	k'	edf	k-index	p-value
(y-1)	sex ratio	5	0.97	1.01	0.87
(y-0)	longitude	9	8.76	0.87	<2e-16***

Table E5: Combined environmental and density-dependence model output for Model 25, examining the impact of combined components from Model 16 (inshore environmental variables) and model 19 (sex ratio) on Summer Survey L_T. Results displaying robustness checks for individual environmental and density-dependence model components are also included.

MODEL 25 - Combination (envio + sex ratio)					
Lag (*on variable*)	Variable	edf	ref.df	t-stat	p.value
(y-2)	Mar BT	5.95	5.95	3.74	0.00
(y-2)	Jan ST	5.00	5.04	2.26	0.03
(y-2)	Jul ST	1.00	1.00	6.23	0.01
(y-2)	Aug ST	5.48	5.51	3.20	0.00
(y-2)	Oct ST	4.55	4.57	1.91	0.05
(y-2)	Dec ST	3.23	3.26	7.67	0.00
(y-1)	Sex ratio	4.64	4.65	28.64	0.00
(y-0)	Longitude	8.77	8.98	442.62	0.00
MODEL 25.1 - Environmental Robustness Check (envio only)					
Lag (*on variable*)	Variable	edf	ref.df	t-stat	p.value
(y-2)	Mar BT	6.99	7.00	252.38	0.00
(y-2)	Jan ST	6.51	6.54	32.07	0.00
(y-2)	Jul ST	5.35	5.41	86.31	0.00
(y-2)	Aug ST	1.00	1.00	33.63	0.00
(y-2)	Oct ST	5.23	5.27	17.46	0.00
(y-2)	Dec ST	4.72	4.78	36.01	0.00
(y-0)	Longitude	8.81	8.99	442.50	0.00
MODEL 25.2 - Sex Ratio Robustness Check (sex ratio only)					
Lag (*on variable*)	Variable	edf	ref.df	t-stat	p.value
(y-1)	Sex ratio	6.98	7.00	388.02	0.00
(y-0)	Longitude	8.82	8.99	404.15	0.00

Table E6: Final model diagnostics for final combination Model 25, including inshore environmental variables and spring sex ratio. Results describe the fit of the model, convergence of the smoothness selection optimization, and analysis of basis dimension choices of the original model, as well robustness checks on the individual components, on Summer Survey L_T.

(a) Combo - Model 25 (Environmental + Sex Ratio)

```
Smoothing parameter selection converged after 11 iterations.
The RMS GCV score gradient at convergence was 5.450668e-05 .
The Hessian was not positive definite.
Model rank =  57 / 57

                                k'  edf k-index p-value
s(spring.mar.avgbt.lag2.surv) 7.00 5.95    0.99    0.23
s(spring.jan.avgst.lag2.surv) 7.00 5.00    0.99    0.20
s(spring.jul.avgst.lag2.surv) 7.00 1.00    0.99    0.23
s(spring.aug.avgst.lag2.surv) 7.00 5.48    0.99    0.22
s(spring.oct.avgst.lag2.surv) 7.00 4.55    0.99    0.25
s(spring.dec.avgst.lag2.surv) 7.00 3.23    0.99    0.20
s(rlag1.male.summer)          5.00 4.64    0.99    0.21
s(start_longitude)            9.00 8.77    0.80  <2e-16 ***
```

(b) Robustness Check - Model 25.1 (Environmental Components Only)

```
Smoothing parameter selection converged after 13 iterations.
The RMS GCV score gradient at convergence was 1.839972e-05 .
The Hessian was positive definite.
Model rank =  52 / 52

                                k'  edf k-index p-value
s(spring.mar.avgbt.lag2.surv) 7.00 6.99    1.00    0.58
s(spring.jan.avgst.lag2.surv) 7.00 6.51    1.00    0.58
s(spring.jul.avgst.lag2.surv) 7.00 5.35    1.00    0.58
s(spring.aug.avgst.lag2.surv) 7.00 1.00    1.00    0.60
s(spring.oct.avgst.lag2.surv) 7.00 5.23    1.00    0.56
s(spring.dec.avgst.lag2.surv) 7.00 4.72    1.00    0.63
s(start_longitude)            9.00 8.81    0.88  <2e-16 ***
```

(c) Robustness Check - Model 25.2 (Sex Ratio Components Only)

```
Smoothing parameter selection converged after 9 iterations.
The RMS GCV score gradient at convergence was 3.331118e-05 .
The Hessian was positive definite.
Model rank =  17 / 17

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                     k'  edf k-index p-value
s(sexratio.lag1)     7.00 6.98    0.85  <2e-16 ***
s(start_longitude)   9.00 8.82    0.71  <2e-16 ***
```

BIOGRAPHY OF AUTHOR

Ashley Charleson was born in Providence, Rhode Island on October 17th, 1991 and grew up in rural Coventry, Rhode Island. Ashley graduated from South Kingstown High School in South Kingstown, Rhode Island in 2009 before obtaining a Bachelor of Science degree in Marine Affairs as well as a minor in Natural and Environmental Resource Economics from the University of Rhode Island in 2013. Ashley took three years off prior to beginning her graduate studies, working as an environmental educator, farming oysters, and back packing through Peru. Ashley is a candidate for the Master of Science degree in Marine Biology and Marine Policy from the University of Maine in May 2020.