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The Past, Present and Future of Conservation in the Maine Lobster Fishery

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THE PAST, PRESENT, AND FUTURE OF CONSERVATION IN THE MAINE LOBSTER FISHERY

By

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By Mackenzie Mazur

Dissertation Advisors: Dr. Yong Chen and Dr. Teresa Johnson

An Abstract of the Dissertation Presented
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Understanding both the social and biological factors surrounding conservation is important for informing effective fisheries management. This dissertation examines conservation in the American lobster (*Homarus americanus*) fishery in a changing Gulf of Maine (GOM) using computer simulations informed by interviews with lobster fishers. In this fishery, v-notching, an important conservation measure intended to protect the spawning stock, has been hypothesized to have contributed to the dramatic increase in lobster landings and stock biomass since the 1990s in the GOM. Semi-structured and oral history interviews were analyzed to understand v-notching compliance and lobster fishers' perceptions of v-notching. All lobster fishers interviewed described v-notching as important for the lobster fishery's sustainability, while also reporting that the v-notching practice has been declining in recent years. Interviews suggest that the decline in v-notching was due to a decrease in the net benefits of v-notching resulting from increased lobster abundance. Given this decline in v-notching practice, evaluating the effect of v-notching on the fishery is important. An individual-based lobster simulator (IBLS), which can capture complex processes with a flexible probabilistic approach, was modified, parameterized, and applied to the fishery. To evaluate the impact of v-notching,

scenarios examining different v-notching compliance rates and v-notch definitions were simulated using the IBLS with different recruitment dynamics scenarios. These simulation results suggest that the lobster fishery would not have experienced the observed large positive increases in biomass and landings without a high v-notching compliance rate (i.e. 90 or 100% compliance) or a strict definition of the notch. Although v-notching has contributed to the increases in the fishery and population, to fully understand the role of conservation, the stock-recruitment relationship (SRR) in a changing GOM needs to be better understood. The GOM bottom water temperatures have increased at a rate of 0.2°C per decade, which caused lobster settlement area to expand and size at maturity to change, adding to the complexity of understanding recruitment dynamics. To give more effective advice for fisheries management, the SRR for lobster was further investigated by including bottom water temperature as a covariate. The results showed that temperature had a strong effect on recruitment resulting in a temporal shift in productivity in the SRR in 2009. This dissertation also used a size-structured stock assessment model to assess the effect of a decrease in size at maturity and the resulting change in growth on the American lobster stock assessment model and SRR. Projections of the lobster fishery under different v-notching scenarios show that in the near future, although v-notching does not increase landings, v-notching still preserves the spawning stock. These results show that the v-notching conservation measure is a valuable tool for precautionary management. Overall, these results suggest that input controls, such as protecting the spawning stock, can provide benefits to both the fish population and fishery. The implications of a decline in the v-notching practice may have negative impacts for the future sustainability of the fishery if the spawning stock and productivity were to decline. Additionally, this dissertation demonstrates that climate driven SRRs and biological reference points should be considered for American lobster management. This dissertation highlights the importance of considering changes in compliance and productivity and the interactions between the two factors. The framework proposed in this study can be extended to evaluate the protection of spawning females in many other commercial fisheries influenced by climate change.

DEDICATION

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CHAPTER 1

AN INTRODUCTION TO CONSERVATION IN THE MAINE LOBSTER FISHERY

1.1. The Maine lobster fishery

The American lobster fishery is the most valuable single-species fishery in the United States (NMFS 2018) with around 82% of the American lobster landings coming from the Maine lobster fishery in the Gulf of Maine (GOM) (ACCSP 2019), which is co-managed by lobster fishers and the Maine Department of Marine Resources (DMR). The lobster fishery is the most valuable fishery in Maine. In 2019, over 46 thousand metric tons were landed in the Maine lobster fishery (Maine DMR 2020), making up 73% of the revenue from Maine's fish and seafood landings (over 491 million USD; Maine DMR 2020). Lobsters are caught with wire traps and are managed with gear restrictions, limited entry into the fishery, trap limits, legal sizes, and protection of egg-bearing lobsters. Maine lobster fishers are known for their 'harbor gangs', which are groups of lobster fishers that protect unofficial territories, and typically reside within one 'harbor gang' throughout their fishing career (Acheson 1988).

The state of Maine's dependence on the lobster fishery is significant, and a collapse could disrupt the state's economy and fishing communities (Steneck et al. 2011). Lobster fishers need to prepare for future threats if they are to be resilient in the future (Henry and Johnson 2015), and the fishery is facing a variety of threats. The Maine lobster fleet is aging (Johnson and Mazur 2018), which may affect fishing behavior and operations, as different generations of fishers have different perceptions of the fishery. Shifting baselines and "memory illusions" lead to different perceptions of the fishery that influence fishing behavior (Daw 2010). Furthermore, the Maine lobster fishery is not efficient and has not been efficient for some time; if most lobster fishers decreased their fishing effort, they could increase their profit (Holland 2011). The fishery is also dependent upon herring as bait, consuming 70% of GOM herring landings (Grabowski et al. 2010). However, herring landings have decreased in recent years (ACCSP 2019).

Maine lobster landings and biomass have increased dramatically in the past few decades and are at historic highs (Fig. 1; ASMFC 2015). The Maine lobster fishery has not experienced overfishing or been overfished since 2001 (ASMFC 2015). In the 1920s and 1930s, however, the fishery experienced a bust in landings (Acheson and Gardner 2010). Conservation ethic in the Maine lobster fishery was developed after the low catches in the 1930s. These low catches changed the perceptions of conservation for many lobster fishers and fishers began to report law violations, which increased conservation ethic (Acheson and Gardner 2010). Lobster fishers' conservation ethic continued to grow due to increasing catches and other socioeconomic factors (Acheson and Gardner 2010). For decades after the low catches, conservation became one of the lobster fishers' top priorities (Acheson and Steneck 1997). Lobster fishers' conservation ethic increased because of the high costs of not participating in conservation and the numbers of people accepting the conservation ethic in the lobster fishery (Acheson and Gardner 2010). Decades later, the fishery experienced a boom in landings.

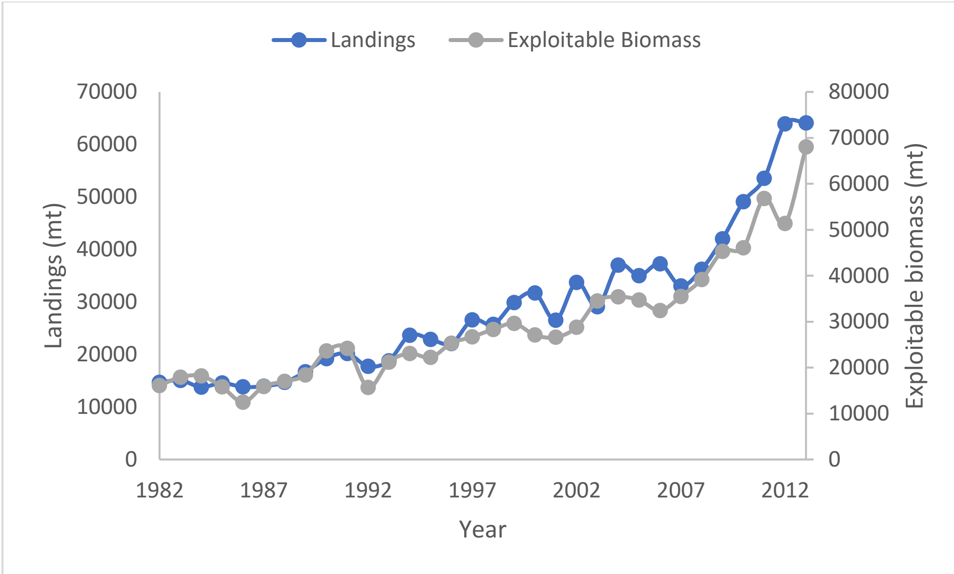

Figure 1.1. Gulf of Maine lobster observed landings and exploitable biomass estimated from the most recent lobster stock assessment (ASMFC 2015) over time.

This all happened under environmental change, including warming water temperatures, in the GOM. Warming water temperature affects lobster growth, reproduction, and behavior. Temperatures at the optimal range for lobster can lead to high recruitment in recent years (Le Bris et al. 2018; Tanaka et al. 2019), but temperatures too warm can lead to recruitment failure (Le Bris et al. 2018). Decreased settlement in young-of-year surveys may indicate a future decline in recruitment (Wahle et al. 2015). Aside from temperature, lobster settlement also depends on the strength and timing of southwesterly winds (Xue et al. 2008). The lobster size at maturity has decreased overtime, possibly due to increasing water temperatures (Waller et al. 2019). As a result, warming water temperatures affect lobster distribution (Tanaka and Chen 2016, Tanaka et al. 2018, 2019). In years where the water temperatures warm up early and in years with warmer average water temperatures, lobster distribution is more north (Henderson et al. 2017; Tanaka et al. 2018). However, the effects of warming water temperatures on the lobster population are not fully understood, and other changes in the ecosystem, such as plankton community changes, can affect lobster population dynamics as well.

Both conservation measures and environmental factors are considered to have led to the increases in the GOM lobster landings and stock biomass (Acheson and Gardner 2010; Acheson and Steneck 1997; Le Bris et al. 2018). Various hypotheses have been developed to explain the increase in the GOM lobster population and fishery landings, such as reduced biomass of major predators leading to increased juvenile lobster survival rates (e.g. Atlantic cod; Crooks and Soule 2010; Hanson and Lanteigne 2000; Zhang and Chen 2011, Zhang et al. 2012), warming water temperature resulting in higher growth rates (Spees et al. 2001), increased herring bait use in the lobster fishery (Grabowski et al. 2010; Zhang and Chen 2011), improved lobster-suitable habitat (Tanaka and Chen 2016), increased spatial variability of lobster larvae (Steneck and Wilson 2001), and conservation measures (Acheson and Steneck 1997). This dissertation focuses on the role of conservation measures in this fishery.

1.2 Conservation and fisheries management

Conservation measures are a large part of the Maine lobster fishery and fisheries management in general. The aim of fisheries management is to ensure sustainable fish stocks under uncertain environmental conditions while balancing social and economic objectives. National Standards require fisheries management to be informed by the best available science. First, a fisheries stock assessment is performed based on the data collected in various fishery-dependent and fishery-independent monitoring programs to estimate fish population biomass, fishing mortality and recruitment. Those estimates are compared to biological reference points (BRPs) to determine fish stock status. BRPs are quantitative measures of stock status that should be targeted or avoided. BRPs can serve as performance guidelines or markers for fishery management regimes (Gabriel and Mace 1999). Currently, ad hoc reference points are used for the GOM lobster fishery (ASMFC 2015).

Various types of regulations and conservation measures have been used in fisheries management, such as input controls (i.e. fishing effort controls, maximum and minimum legal sizes, and protection of specific life history stages) and output controls (i.e. total allowable catch (TAC) or quotas). Output controls, which directly constrain the catch, are often considered to be more efficient and effective in controlling fishing mortality levels than input controls (Kompas et al. 2004). Although input controls do not directly control catch, they can still regulate fisheries. Input controls are also often used to address fishing's impact on the ecosystem (Emery et al. 2012). However, there is not one regulation that meets all management objectives, and a combination of regulations is often necessary (Dichmont et al. 2013). Additionally, with further understanding of how fisheries interact with the surrounding ecosystem, there has been a push for ecosystem-based fisheries management (EBFM), which may also require a combination of regulations (Fulton et al. 2014).

1.3. Conservation in the Maine lobster fishery

Conservation in the Maine lobster fishery is based on the size of lobsters and the protection of egg-bearing females. The first conservation laws in the Maine lobster fishery were the prohibition of taking egg-bearing lobsters in 1872, followed by a minimum size, then v-notching, and then a maximum size, all of which are still in effect today (Acheson and Steneck 1997). Under the v-notching law, when a lobster fisher catches an egg-bearing lobster in a trap, the lobster fisher can choose to cut a 'V' shaped notch in her tail and release her back to sea. Other lobster fishers that catch these v-notched lobsters must release them as well, because it is illegal to land v-notched lobsters. Fishermen's attitudes towards conservation are important when developing effective management strategies (Acheson and Gardner 2010). Conservation measures were established in the Maine lobster fishery due to attitudes towards conservation, political entrepreneurship, and discount rate (Acheson and Knight 2000).

Previous studies have investigated the effects of conservation on the fishery. Conservation measures alone provided a sustainable lobster fishery in Maine but then amplified the effect of more favorable environmental conditions on the lobster abundance in recent decades (Le Bris et al. 2018). Conservation measures are further predicted to mitigate the negative effects of warming water temperatures on the lobster fishery (Le Bris et al. 2018).

1.4. V-notching

One conservation measure that plays a large role in the conservation ethic of the Maine lobster fishery is v-notching. V-notched lobsters are illegal to land, because they are proven breeding stock. A v-notch typically grows out around two molts later, but this depends on the definition of a v-notch. For example, with a strict definition, a lobster with any size of a notch is considered v-notched and is illegal to land. With less strict definitions, lobsters with notches that are less than 1/8th to 1/4th of an inch are not considered v-notched and are legal to land (NOAA 2014). With a less strict definition, a v-notch may only last for one molt.

V-notching is thought to be particularly effective in protecting large female lobsters, which extrude the most eggs (Acheson and Knight 2000). Large female lobsters can have around 100,000 eggs, whereas smaller lobsters have tens of thousands of eggs (Fogarty 1995). In the Maine lobster fishery, v-notched lobsters had nine times more eggs than unnotched lobsters, because v-notched lobsters were larger in size (Daniel et al. 1989). In the Wexford lobster fishery in Ireland, v-notched lobsters contributed to 59% of the population's reproductive potential because of the large abundance and size of v-notched lobsters (Tully 2001). Eggs from large lobsters also have more calories per egg, which may positively affect larval growth and survival (Attard and Hudon 1987). Thus, the v-notch conservation measure can increase the reproductive potential of lobster populations and potentially mitigate the negative effects of climate change on lobster fisheries (Daniel et al. 1989, Tully 2001, Le Bris et al., 2018).

The v-notching conservation measure was initially established from the support of the fishing industry and not scientific evidence (Acheson and Steneck 1997). Lobster fishers are proud of their efforts to get the v-notching conservation measure passed by the legislature in 1947. They usually comply with and self-enforce this measure, because they believe it is the most important conservation measure in the fishery, essential to the sustainability of the fishery, and one of the reasons for the recent increase in landings (Acheson and Steneck 1997; Acheson and Gardner 2010; Acheson and Knight 2000).

The limited understanding of the effectiveness of v-notching has raised some concerns from stakeholders regarding the necessity of this measure. A few decades ago, federal and state scientists argued that the v-notching conservation measure should be eliminated because they thought that v-notching was ineffective at conserving the population (Acheson and Steneck 1997) and that v-notched lobsters could get infected (Acheson and Knight 2000). Maine lobster fishers continued to believe fully in the conservation measure even when v-notching was considered ineffective by others. In 2009, approximately 91% of Maine lobster fishers believed that v-notching was effective in conserving the lobster stock with some wanting even more strict enforcement of the conservation measures and for lobster fishers in other regions (such as Canada) to v-notch as well (Acheson and Steneck 1997; Acheson and Gardner 2010). However, in recent years, compliance with v-notching may be declining (Hall 2014).

As a result, my research focused on evaluating the v-notching conservation measure. Understanding how regulations have contributed to fish population status and fishery output is important for the success of a fishery. To do this, fishery models can be used. Specifically, fishery simulations can be used to ask 'what if' questions in the fishery. One model that is flexible and has been increasingly used for single-species fishery simulations is an individual-based model (IBM). IBMs are commonly used in ecology because they can account for differences between individuals in ecological systems (Judson 1994).

1.5. Environmental impacts

However, evaluating the impact of conservation poses some challenges due somewhat to the impact of environmental factors on population dynamics. Fisheries management needs to consider the effects of environmental variability on growth, reproduction, and mortality (Hofmann and Powell 1998). Environmental variability includes changes in abiotic factors such as temperature, salinity, and pH, and these factors influence population dynamics. Environmental variability can be caused by oceanographic cycles, but long-term trends in environmental variables are often due to anthropogenic forces, such as climate change. Trends in water temperatures are likely to affect the rate of growth for many fish species, as many species are ectothermic. Changes in population dynamics, such as rate of growth, can make fisheries management challenging as the effectiveness of current management regulations may change (Yatsu et al. 2005). If these changes are not considered, management regulations may become detrimental to the resource (Hofmann and Powell 1998). In the face of climate change, fisheries management needs to be adaptive (Mills et al. 2013) and robust to environmental fluctuations (Walters and Parma 1996). By incorporating environmental factors into management frameworks, the effectiveness of management under environmental change can be identified (Froehlich et al. 2017).

Environmental factors impact lobster recruitment (Ennis 1986), and the GOM lobster fishery catch depends on recruitment dynamics (Zhang et al. 2011). Using a stock-recruitment relationship (SRR) to predict the effect of conservation would be valuable. However, SRRs are difficult to define partly because of the influence of environmental factors on lobster life history. As described above, temperature has a large impact on lobster life history and therefore population dynamics and distribution. Because of the effects of the environment, notably temperature, on lobster population dynamics, considering environmental effects on the fishery in simulations is important.

1.6. Objectives

This dissertation research evaluated the v-notching conservation measure in a changing Gulf of Maine. To do this, this dissertation used a variety of statistical and mathematical models, informed by interviews with Maine lobster fishers. Chapter 2 drew on semi-structured and oral history interviews to examine perceptions and behavior related to v-notching. Chapter 3 modified, parameterized, and tuned a previously developed individual-based lobster simulator (IBLS) for the GOM lobster fishery in order to evaluate conservation measures in the fishery. Chapter 4 used the tuned IBLS to examine contributions of v-notching to increases in the lobster fishery landings and biomass. Different v-notching scenarios with varying compliance rates, v-notch definitions, and SRRs were simulated. Chapters 5 and 6 evaluated the effects of a changing environment on lobster recruitment dynamics. Understanding the effect of water temperature on the SRR is critical for understanding the effect of v-notching in the future. Chapter 7 concluded the dissertation by using all the tools and knowledge gained through chapters 2-6, to project different v-notching scenarios for 15 years. The framework developed can be used to evaluate conservation in other fisheries. As many fisheries are heavily exploited and experiencing environmental change, such frameworks are critical.

CHAPTER 2

EFFECTS OF INCREASES IN FISHERY RESOURCE ABUNDANCE ON CONSERVATION COMPLIANCE

2.1. Abstract

Understanding compliance is important for understanding the effectiveness of conservation. This study examines conservation compliance in the American lobster fishery in Maine. In this fishery, an important conservation measure that protects spawning female lobsters, known as v-notching, is primarily self-enforced, but evidence suggests that its compliance rate may be declining. We analyzed semi-structured and oral history interviews to understand v-notching compliance and lobster fishers' perceptions of v-notching. All lobster fishers interviewed described v-notching as important for the lobster fishery's sustainability, while also reporting that the v-notching practice has been declining in recent years. Our analysis suggests conservation compliance changed as the benefits of conservation changed. Lobster fishers are beginning to question whether v-notching is as beneficial as it was in the past. High catches in recent years also have created time constraints, or costs, on board the vessel that limit fishers' ability to v-notch. The perceived benefits and costs of conservation changed with increasing resource abundance, impacting compliance and potentially the future sustainability of the fishery.

2.2. Introduction

Overfishing is a problem in fisheries throughout the world, often due to fisheries management failures. However, some fisheries are sustainably managed partly because of high compliance with conservation measures. Understanding stakeholder perceptions about conservation practices is valuable for the effectiveness of environmental management, including fisheries management (Kellert 1985; Clark and Wallace 2002; Mascia 2003; Sawchuk et al.

2015). It is especially critical to understand conservation compliance, or fishers' compliance with conservation measures, when measures cannot be easily enforced (Gibson et al. 2005). To anticipate the potential of non-compliant fishing behavior, it is important to understand the quality and diversity of motivations for compliance rather than simply the lack of presence of compliance (Boonstra et al. 2017).

Conservation compliance depends on many factors, including benefits, costs, and norms (Hauck 2008). Most notably, resource users are more likely to comply with conservation measures if they benefit from them (Sutinen et al. 1990). Fishers will not comply with conservation if the net benefits from not complying are large enough (Sumalia et al. 2006). Compatibility between conservation measures and fishing practices also influences conservation compliance (Nielsen Raakjær and Mathiesen 2003). This 'rationalist' model assumes that resource users consider costs and benefits of their actions (Hauck 2008). However, conservation compliance is also influenced by a variety of interrelated social, cultural, and psychological factors (Clark and Wallace 2002; Sawchuk et al. 2015). This 'normative' model assumes compliance is influenced by norms, morality, legitimacy, and social and cultural factors (Hauck 2008).

In this chapter, I examine how conservation compliance can change in a fishery under changing resource abundance. The study examines conservation compliance in the American lobster fishery in Maine, where an important conservation measure, known as v-notching, protects spawning female lobsters. This conservation rule has long been considered a norm, but as I illustrate, the perceived benefits and costs of this practice have changed with increasing abundance, potentially impacting compliance and the future sustainability of the fishery.

2.3. Materials and Methods

A trap only fishery, lobsters are managed with gear restrictions, limited entry into the fishery, trap limits, legal sizes, and protection of egg-bearing lobsters. Maine lobster landings, abundance, and value have increased dramatically in the past few decades (ASFMC 2015). Understanding conservation compliance in this fishery is timely given that conservation can improve the resilience of the fishery to climate change (Le Bris et al. 2018) and since changing resource abundance can affect conservation compliance (Santis and Chávez 2015).

Although minimum and maximum legal size regulations are important, the focus of this analysis is on what many lobster fishers believe to be the most important conservation measure in this fishery, the practice known as v-notching, which is a key part of the lobster fishers' conservation ethic (Acheson and Gardner 2010). Acheson (2003) describes v-notching as a conservation norm. Other fisheries have had changes in v-notching compliance. For example, Scottish lobster fishers v-notched less often when the lobster price per pound was higher (Leslie et al. 2006). Before lobster fishers receive their license, they need to fish for a certain amount of days with a licensed lobster fisher or a sponsor (Maine DMR 2019), and it is during this time that many fishers learn their responsibilities to the lobster resource and other fishers, including the practice of v-notching.

Although research on Maine lobster fishers' perceptions of v-notching has shown that Maine lobster fishers view v-notching as effective and the most important conservation measure in the fishery (Acheson and Gardner 2010), an updated analysis is in order. The Maine lobster fishery is facing a variety of social and environmental threats, such as climate change (Le Bris et al. 2018) and graying of the fleet (Johnson and Mazur 2018). There are concerns about lobster fishers' social resilience to future threats (Henry and Johnson 2015). Such changes can affect fishing behavior and the compliance rate of v-notching, which may be declining (Hall 2014).

2.3.1 Interviews and analysis

First, semi-structured interviews (n=5) (Bernard 2011) were conducted with managers, scientists, and lobster fishers. Topics included in the exploratory, semi-structured interviews were the strengths and threats related to the fishery and its co-management system. Next, oral history interviews (n=32) (Ritchie 2003) were conducted with Maine lobster fishers. Analysis of the semi-structured interviews and prior research (Henry and Johnson 2015; Johnson et al. 2014) helped to develop a semi-structured, oral history interview guide that investigated environmental, social, and regulatory changes and concerns in the fishery. Themes that arose from the semi-structured interviews and were incorporated into the oral history interview guide included the industry's conservation ethic, v-notching, and resilience. Oral history interviews compile memories and personal commentaries. These interviews preserve social memory and capture the lived experience of an individual and can be used to understand ecological history, resource use, and management (Crandall et al. 2018), including fisheries management (Colburn and Clay 2012; Package-Ward and Cornell 2014).

A snowball sampling approach (Bernard 2011) was used to collect oral histories from a purposive sample of Maine lobster fishers from March 2017 to March 2018. We asked interviewees if they knew of any other lobster fishers that would be interested in being interviewed. We sought a sample of lobster fishers with diverse experiences (e.g., years in the fishery, size of boat, age, and lobster zone) (Table 2.1). We continued to conduct interviews until we had participants with diverse characteristics. However, there were only male lobster fishers in our sample. Most Maine lobster fishers are male, and most likely as a result, all of the recommended interviewees through snowball sampling were male. All lobster fishers invited agreed to participate. The mean age of interviewed lobster fishers was 46.31 (Table 2.1), which is slightly younger than the mean age (49.5) of lobster fishers in 2015 (Johnson and Mazur 2018). The state of Maine lobster fishing area is split into seven zones from the east to west (zones A – G). Lobster fishers that were interviewed were from five of Maine's seven lobster fishing zones (zones A - E) (Table 2.1). Since most of the lobster fishing occurs off mid-coast Maine, most interviewed lobster fishers were from the mid-coast in zones B (n = 11), C (n = 7) and D (n = 7). Although the sample cannot be considered representative of all experiences in the lobster fishery, it was sufficient for documenting fisher experiences and perceptions examined in this study.

Table 2.1. Attributes of interviewees.

Attribute	Mean	Mode	Range
Years in lobster fishery	30.74	47	5-61
Size of boat (ft.)	36.26	40	20-46
Age (yrs.)	46.31	N/A	18-83
Lobster zone	N/A	B	A-E

Oral history interviews ranged from 20 to 150 minutes and followed a semi-structured guide that still allowed participants to share what was most important to them. Topics such as participants' experience in lobster fishing, changes in the lobster fishery and marine ecosystem, threats to the fishery and marine ecosystem, fishery management, and changes in fishing behavior. The original focus of the interviews was changes, threats, and resilience in the lobster fishery. Since v-notching emerged as an important topic in the key informant interviews, additional questions were asked about this practice. All oral history interviews were audio recorded and transcribed verbatim by a professional transcription service. The interviewer then reviewed and corrected errors with the transcriptions to further ensure accuracy. NVivo 11 software was used for qualitative analysis of the oral history interviews following an inductive coding strategy[1] (Miles 2013). Interview codes examined in this paper focused on v-notching and reasons why lobster fishers do or do not v-notch. For second cycle coding, we followed a pattern coding strategy. As a result, reported themes were overlying themes that relate to individual codes. Codes included sustainability, self-interest, codes relating to lobster abundance, codes relating to lobster health, enforcement, and generational differences. Individual inductive codes were grouped into themes as reflected by the sub-sections in the results (Table A11).

2.4 Results

Four main themes that arose and will be addressed are: 1) general perceptions of v-notching, 2) specific factors affecting compliance (incentives/deterrents), 3) variation in viewpoints on compliance factors across generations, and 4) other, non-compliance related themes.

2.4.1. General perceptions of v-notching

In general, lobster fishers interviewed were taught to v-notch early on in their careers and expressed positive views about v-notching (Codes 4, 7 & 9; Table A11). All lobster fishers interviewed thought that v-notching was important, with some lobster fishers specifically describing it as the most important regulation in the fishery. One lobster fisher described: “The most important thing, I think, is the v-notch. It’s what sustains the catch. It’s got to be.” Most

[1] In an inductive coding strategy, the researcher interprets qualitative data to develop concepts and themes. This differs from a deductive coding strategy which focuses on testing hypotheses.

lobster fishers described having always supported and complied with v-notching since they started fishing.

The importance and practice of v-notching is something that fishers are typically taught very early on in their career. One lobster fisher who was 41 years old recalled how he was taught to v-notch by his father:

> I know that I was kind of raised that way. I remember before there was the mutilation law, people would keep lobsters that were missing half a fin, and my father would never let me. As a kid, he didn't want anything to do with them, and so I always kind of followed that rule anyway because that was the way I was taught.

Many of the lobster fishers interviewed reported that they continue to encourage their children and other lobster fishers to v-notch. As one lobster fisher explained, "I'm gonna continue preaching v-notch 'til I die because I think it's the most important thing we can do to sustain this fishery." Other indicators of the importance of v-notching are stories heard from captains who report that they instruct their crew to v-notch and will re-notch lobsters they have caught with a v-notch, ensuring the lobster remains protected for longer.

However, interviews also indicate a decline in the v-notching practice in recent years. When asked if they always v-notch every egg-bearing lobster caught, some lobster fishers reported that they v-notch less than they used to or do not v-notch at all, and provided reasons for this in the interviews (Fig. 2.1). One lobster fisher explained: "A lot of guys don't do it. They just think it's a waste of time." One lobster fisher explained how the significance of the practice has changed dramatically:

> I can remember in the ‘90s again, you did a female loaded down with eggs and it was almost a reverent moment. You took the time. My grandfather would practically stop the boat, and put a huge notch in it and cradle it back into the water.

This lobster fisher went on to lament that while he still tries to v-notch today, he is not actually able to v-notch every egg-bearing lobster when he is busy, because there are so many lobsters caught. This lobster fishery is busy trying to handle the many lobsters that are legal to land.

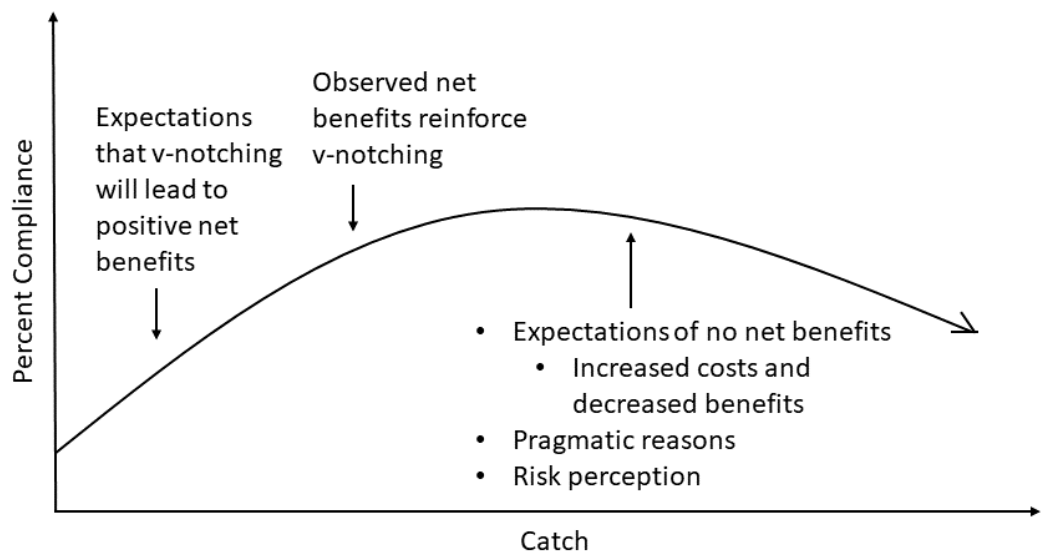

Figure 2.1. Theorized relationship from the interviews between v-notching compliance and catch.

2.4.2. Factors affecting compliance

The top three factors influencing v-notching compliance identified in interviews were (1) sustainability benefit, (2) too many v-notched lobsters, and (3) pragmatic reasons (Fig. 2.1 and Table 2.2). These are described in detail below.

Table 2.2. Factors affecting v-notching compliance and the direction of the effect.

Factors affecting v-notching compliance	**Effect**
Sustainability benefit	Positive
Self-interest	Positive
Free rider problem	Negative
Pragmatic reasons	Negative
Risk to resource	Negative

2.4.2.1. Compliance incentive: Sustainability benefit

Not surprisingly, most lobster fishers explained that they v-notch because they believe the conservation practice keeps the fishery sustainable or maintains the landings (Fig. 2.1; Table 2.2; Code 8a, Table A11). Specifically, lobster fishers explained that by protecting the breeding stock, v-notching allows for more lobsters to enter the population. Lobster fishers attribute the current high landings and lobster abundance to v-notching. Several lobster fishers believed that v-notching and other conservation measures would keep the lobster fishery sustainable in a changing environment.

2.4.2.2. Compliance incentive: Self-interest

Some lobster fishers noted that they v-notch not only to protect the resource, but also because if they cannot catch it, they do not want anyone else to either (Table 2.2; Code 1, Table A11). One lobster fisher described: "If I notch it, I know that guy next to me is not gonna keep it, so I don't have to worry about it." Some lobster fishers will create large pronounced notches, rather than small notches, so that v-notched lobsters cannot be caught by other lobster fishers for a longer period.

2.4.2.3. Compliance deterrent: No benefit for sustainability

The high catches of v-notched lobsters were identified as having an important role in v-notching compliance (Fig. 2.1; Table 2.2; Code 5a, Table A11). Many lobster fishers described that they believed, or knew of other lobster fishers who believed, that there were too many v-notched lobsters in the population. These lobster fishers describe how most egg-bearing lobsters that they catch have already been v-notched. Consequently, they report that some lobster fishers do not v-notch as much because they do not think it is necessary or beneficial. One lobster fisher explained: “A lot of guys don’t do it. They think it’s a waste of time. Just because we’re seeing so much, the mentality is, you know, there’s so many more on bottom, why bother with it?”

2.4.2.4. Compliance deterrent: Pragmatic reasons

Other reasons identified in interviews for no longer v-notching were coded as pragmatic reasons (Fig. 2.1; Table 2.2; Code 5b, Table A11). Lobster fishers described that the catch of egg-bearing lobsters in recent years has been exceptionally high and that this had prevented them from v-notching. As one lobster fisher lamented, “I have to admit, we don’t v-notch like we used to because there’s so many. Like it gets to a point of ridiculousness. Like I couldn’t have my guys v-notch all day long because we would never get done.”

Indeed, the increase in the catch of egg-bearing lobsters makes it more difficult to v-notch given everything else done during the workday. For every trap haul, the lobster fishers need to haul the trap up to the boat, take the lobsters out of the trap, measure lobsters, release illegal lobsters (i.e., undersized, oversized, notched, or egg-bearing lobsters) back to sea, band the legal lobsters, place the legal lobsters in the holding tank, bait the trap, and release the trap back to sea. One lobster fisher described that when sea conditions are rough, v-notching the large amount of egg-bearing lobsters is even more difficult. V-notching may sometimes be the last priority when there are so many other things to attend to when lobster fishing.

Enforcement of the v-notch law also influences v-notching behavior (Code 2, Table A11). Because it is difficult to v-notch so many lobsters when there are already numerous lobsters on board, some lobster fishers expressed their fears of enforcement. Some lobster fishers set egg-bearing lobsters aside to v-notch later when handling a large catch. However, a couple of lobster fishers were concerned about being caught with a v-notched or egg-bearing lobster on board. The Maine DMR (2019) states "It is against the law to take, transport, sell or possess any lobster that is bearing eggs." As a result, some fishers reported that they released egg-bearing lobsters immediately back into the ocean without v-notching them. Lobster fishers describe how if they were caught with a v-notched lobster on board, they would be fined or lose their license. These lobster fishers do not keep egg-bearing lobsters aside to v-notch later if they are busy. To be safe, one lobster fisher explained that he sometimes throws lobsters with eggs or old v-notches overboard without notching them first: "If you're not sure, when in doubt, throw them over. It's not worth losing the license or getting searched by any wardens and having any issues with them." Lobster fishers further explained how different enforcement officers have conflicting guidelines for what constitutes a v-notched lobster, and this creates additional uncertainty and fear among fishers. Some marine patrol officers consider any sort of mutilation a v-notch, but other marine patrol officers do not consider a small mutilation a v-notch. Interestingly, some lobster fishers are not more likely to v-notch to avoid consequences of being caught not practicing v-notching because the practice is impossible to enforce without observers on board.

2.4.2.5. Compliance deterrent: Risk to resource

Some lobster fishers expressed their belief that v-notching could cause disease or that disease could arise from the large density of lobsters caused by v-notching (Fig. 2.1; Table 2.2; Code 6, Table A11). These lobster fishers believed disease would spread or is already spreading quickly with the large amount of v-notched lobsters in the population. In this view, v-notching could hinder the sustainability of the lobster resource. These lobster fishers believed that increasing the density of lobsters was beneficial, but only until a certain point, at which the large density of lobsters would negatively interact with pathogens. One lobster fisher described:

> What I've been seeing in a lot of the bigger v-notched lobsters with eggs is shell disease. So, ... me and [the warden] talked about it at length one day, and we kind of agreed that, to get rid of the shell disease, get rid of those egged lobsters.

2.4.3. Variations in viewpoints on compliance factors across generations

Another theme in the interviews was a perception that there is a difference in v-notching compliance between the older and younger generations (Code 3, Table A11). Lobster fishers described how the younger generation of lobster fishers tended to fish harder and that there is less camaraderie in lobster fishing communities today than decades ago. Some lobster fishers described that the older generation tended to have a stronger conservation ethic. These lobster fishers believed the younger generation does not v-notch as much as the older generation. One lobster fisher, who was 60 years old, explained:

> The older generation was more worried about the resource. I think more careful, better stewards of the resource. The younger generation, I think, are more greedy. They're buying boats that are 600 to 800 thousand dollars right now, and to make that work,

> you've got to go fast, you've got to go hard, and you don't take the time to v-notch, you don't take the time to handle the lobster properly, and I don't think they see the overall big picture.

2.4.4. Other themes

In addition to v-notching and other conservation measures, lobster fishers described other factors they feel influence lobster abundance (Code 8b, Table A1). Although many fishers pointed to climate change as one factor mentioned that may have contributed to the large increase in lobster abundance, many fishers were uncertain about what effects this would have on the future of the fishery. One lobster fisher explained:

> The global climate change concerns me. I think, personally that the reason why we've had some of these booms is because the temperatures make those kind of creatures more active. They breed more, they eat more, they grow more. And you have a boom. And I think if it goes too far the other way, we'll have a crash.

Interviews suggest that lobster fishers believed that climate change was a 'dread' risk, which invokes a feeling of lack of control, and also an 'unknown' risk, which is difficult to observe and quantify (Fischoff 1987; Langford 2002; Slovic 1987).

2.5. Discussion

For fisheries management to be effective, compliance of conservation measures needs to be high (Dietz et al. 2003). V-notching is perhaps the most important conservation measure in the Maine lobster fishery and fishers historically advocated for v-notching because they viewed it as beneficial to the population. Consistent with what other scholars have noted (Acheson and

Gardner 2010), our study found that Maine lobster fishers continue to view v-notching as important for sustainability of the fishery. However, a decrease in compliance of v-notching was identified in this study. Our analysis further suggests a decline in v-notching compliance has occurred due to changes in the abundance of lobsters resulting in an increasingly high catch of lobsters. We hypothesize that there is a relationship between compliance and fish abundance, but there are other factors that affect compliance. Abundance is one factor that affected compliance in this case, but it was also the factor that seemed to change the most over time. This change in compliance has occurred even though the overall management structure and rules have stayed the same. If compliance continues to decline, the effect of v-notching on future sustainability will change, which may further affect lobster fishers' perception of v-notching. This may be an example of a social trap, in which resource users act for short-term individual benefits, but in the long-term, the net benefits for the fishery are negative. Lobster fishers may be able to handle more catch by not v-notching, but in the long-term this may have negative impacts on the population and fishery.

This increase has created unintended consequences that are challenging the norm such that for some lobster fishers, v-notching is no longer a priority. Before resource abundance dramatically increased, the cost of v-notching compliance was low and relatively easy to do (Abdullah et al. 1998). Today, with a high amount of v-notched lobsters in the population, some lobster fishers question the continued benefit of the practice to the lobster population. Because of the increasing catch, there are now some conflicting views: lobster fishers v-notch because it is important for sustainability, while other lobster fishers do not v-notch because they view it is no longer important for sustainability. In this way, compliance in this fishery with respect to v-notching can still be explained by the normative model of compliance that suggests fishers follow the rule because it is a norm (Hauck 2008). At the same time, compliance for others is explained by the rationalist model that suggests fishers are not following the rule because it either does not provide a benefit or incurs a cost to them (Hauck 2008), which are due to the increasing resource abundance observed in recent years. The pragmatic reasons for v-notching non-compliance were also related to the perceived costs or benefits, because v-notching would be an increased cost as lobster fishers would have less time to catch and handle legal lobsters. However, these constraints would differ with different fishing operations (i.e. number of crew, size of boat, number of traps, etc.).

Resource users can learn to practice conservation through a multitude of pathways (Turner and Berkes 2006). By understanding the environment (ecological understanding), resource users can learn to practice conservation without a collapse in the resource abundance (depletion crisis) (Turner and Berkes 2006). Under the depletion crisis mode of conservation emergence, fishers will practice conservation when the resource is scarce. Under the ecological understanding mode of conservation emergence, fishers will practice conservation not because of a depletion event, but because of ecological knowledge and lessons passed between fishers and generations. Resource users can develop an ecological understanding by learning from lessons and experiences of others (Turner and Berkes 2006). This study highlights the complexity of conservation compliance. Not only was compliance affected by factors relating to the rationalist and normative models (Hauck 2008), but our findings (Fig. 2.1) are also consistent with others who have shown that conservation can emerge as a result of either a depletion crisis or ecological understanding (Turner and Berkes 2006). In the case of the Maine lobster fishery, a depletion crisis seemed to have created the conservation ethic, as v-notching was initiated after low catches of lobsters in the 1930s (Acheson and Gardner 2010). The ecological understanding model explains how v-notching was maintained for some time. Lobster fishers had a shared understanding of the benefits of v-notching, such that everyone followed the rule. The perceptions of v-notching in this study suggest that lobster fishers' perceptions of the fishery and compliance are complex and related to the status of the lobster resource and various social and economic aspects. However, with changing resource abundance, the shared ecological understanding underlying conservation compliance may be changing for some lobster fishers.

Given the compliance deterrents driven by high catches of lobsters (i.e., too many v-notched lobsters, pragmatic reasons, and fear of enforcement), we theorize a feedback loop where v-notching decreases with high catches of lobsters but increases with low catches of lobsters (Fig 2.1). Future research is needed to better understand the underlying dynamics and motivations of the feedback loop.

Additionally, we suggest that differences between the younger and older generations of lobster fishers may create differing perceptions of v-notching. Such division within communities can modify the behavior of fishers to favor short-term over long-term benefits (Grisel 2019). When economic, social, and ecological conditions differ among resources users, there may be less cooperation between users, resulting in less conservation (Waring and Acheson 2018). Cooperation is reduced because there is less solidarity due to increased inequality. For example, Maine lobster fishers from different regions preferred different trap limits due to differences in lobster abundance and distance to markets, resulting in disagreement on state-wide trap limit proposals (Waring and Acheson 2018).

Sharing information and ongoing discussion among fishers, policy-makers, scientists, and enforcement agents about v-notching compliance and conservation is likely to benefit the management of this fishery. For example, marine patrol personnel and lobster fishers would benefit from a strategy that would allow lobster fishers to set aside egg-bearing lobsters to v-notch later without receiving penalties if stopped by marine patrol. Leeway for how long lobster fishers can hold egg-bearing lobsters could be considered. With this leeway, lobster fishers may v-notch lobsters that they would not have v-notched due to fear of enforcement. Education on the benefits of v-notching may also be important if biomass were to decline in the future; lobster fishers would be more likely to remember the benefits of v-notching. Additionally, with a precautionary approach to management, it is important that v-notching is still encouraged to preserve the breeding stock. The findings of this study may also have implications for other conservation regulations (i.e. prohibition of landing egg-bearing lobsters, minimum size), as compliance for these regulations may be changing in similar ways.

Furthermore, our study underscores the value of oral history interviews as a tool for documenting changes in behavior and motivations that can inform fisheries management discussions. Oral histories can also preserve social memory, which can have important implications for the future of the fishery. Social memory can remind lobster fishers of the benefits of v-notching in the past, and this may help sustain a norm that could potentially disappear and will be important should abundance and catch levels decline.

While this study has shed light on some factors influencing v-notching compliance in the Maine lobster fishery, more research is needed to better understand the differences in compliance among different lobster fishers and fishing operations. For example, inshore and offshore lobster fishers have different fishing operations (i.e. offshore lobster fishers tend to have larger boats). Because inshore and offshore lobster fishers have different fishing operations and deal with different proportions of egg-bearing females and sizes of catches and lobsters, the inshore and offshore lobster fishers may have different v-notching compliances. A previous study also hypothesized differences in compliances among different fishing styles and mindsets (Boonstra and Hentati-Sundberg 2016). Compliance may increase if management considers the variety of fishing styles (Boonstra and Hentati-Sundberg 2016). Another important topic for future studies is the impact of climate change on v-notching. Future studies should incorporate these results into fishery simulations. However, integrating qualitative and quantitative data requires a framework that can account for the different underlying assumptions associated with the two sources of data. Future studies should also interview more lobstermen or conduct surveys to increase the sample size, as the sample size in this study was small. This study also provides scenarios and hypotheses to be tested for the Maine lobster fishery. For example, lobster fishers mentioned differences in compliance among generations of lobstermen. Future studies should conduct mail surveys to test this hypothesis. Also, lobster fishers expressed that v-notching, or protecting the spawning stock, may not be as important in the future as it was in the past. Using fishery simulations, this hypothesis can be tested. Compliance can be changing in other fisheries for regulations that are self-enforced and difficult to monitor. Scientists and managers in other fisheries should also consider changes in compliance caused by a change in resource status. Many other fisheries are facing changes in resource abundance due to high fishing pressure and a changing climate, so these fisheries may be facing changing conservation compliance as well.

2.6. Conclusions

American lobster fishers in the state of Maine believed that v-notching provided a sustainability benefit, and historically, this practice has been a norm among fishers. However, conservation compliance has declined for some fishers. This shows that conservation compliance can change even when the management system remains the same. Changing resource abundance can change fisher's behavior through changes in their perceptions of the benefits and costs of the practice. While fish abundance affects compliance, other factors, such as generational differences, fishing styles, and norms, also have effects on compliance, but the changes in these effects overtime is not clear. Moreover, social memory is important for v-notching to continue into the future. Fisheries management should consider the effects of changes in resource abundance on conservation compliance. Changes in conservation compliance are also important to consider in fishery models when modeling the effect of conservation measures.

CHAPTER 3

USING AN INDIVIDUAL-BASED MODEL TO SIMULATE THE LOBSTER FISHERY AND EVALUATE THE ROBUSTNESS OF CURRENT MANAGEMENT REGULATIONS

3.1. Abstract

Individual-based models (IBMs) can capture complex processes with a flexible probabilistic approach, which makes them useful for studying organisms with complex life history and fishery processes such as the American lobster (*Homarus americanus*). This research aimed to modify and parameterize an individual-based lobster simulator (IBLS) to simulate the American lobster fishery in the Gulf of Maine. To simulate the fishery, the IBLS was tuned to match the seasonal catch and size composition from the 2015 American lobster stock assessment by adjusting the values of coefficients for select parameters. With appropriate coefficients for the initial abundance, recruitment, and seasonal encounter probability levels, the tuned IBLS accurately simulated the historical landings. Given the uncertainty in future American lobster recruitment, the tuned IBLS was then used to evaluate the effectiveness of current management regulations under different levels of recruitment.

3.2. Introduction

The importance of the lobster fishery and the uncertainty of its future call for an evaluation of the robustness of current management regulations with a simulation tool. Identifying a simulation tool for the complex American lobster fishery, in which fishery and life history processes vary among individuals, is necessary for such an evaluation. The complexity of American lobster biological and fisheries processes makes the use of traditional mathematical formulation-based models difficult (ASMFC 2000). Growth of the American lobster is not continuous, as lobsters grow by molting, which mainly occurs in summer and fall (Factor 1995).

Molting frequency is dependent on the size and maturation status of the lobster (Factor 1995; Comeau and Fernand 2001).

Additionally, conservation measures used in the GOM fishery, including minimum and maximum legal sizes, prohibition of the taking of egg-bearing lobsters, and protection of ovigerous females through a v-notching program, are difficult to consider as separate processes with traditional fishery models (ASMFC 2000). Consideration of all these fishery processes as separate from one another is important when evaluating changes in one process but not the others. For example, fishery conservation processes need to be considered as separate to evaluate the effect of minimum size but not maximum size and protection of egg-bearing lobsters.

An individual-based model (IBM) may be an alternative modeling approach used to develop a fishery simulator because it can track the detailed life history and fishery processes of individual lobsters. IBMs describe a population consisting of different individuals and changes in the number of individuals (instead of population density) and consider the population dynamics under complex processes (Uchmański and Grimm 1996). With a probabilistic approach, IBMs allow for much more complexity than traditional mathematical-formulation-based models (Uchmański and Grimm 1996). When mathematical methods are used to model complex processes, unrealistic assumptions are often introduced to attain mathematical solutions, whereas IBMs can assume individuals are different from one another (Grimm 1999; Judson 1994). In addition to the incorporation of variability among individuals, IBMs can simulate life cycles of individuals that are not usually included in analytical models.

In this chapter, we modified, parameterized, and tuned an individual-based lobster simulator (IBLS), which is an IBM for a lobster fishery, to simulate the historical GOM lobster fishery. We used the tuned IBLS to evaluate the robustness of current management regulations under different levels of recruitment. We assessed the status of the fishery under different recruitment levels with ad hoc biological reference points. This study includes (i) the description and parameterization of the IBLS that mimics the dynamics of the life history and fishery processes of individual lobsters; (ii) calibration of the IBLS, using coefficients for specific parameters to predict historical landings and population size composition of lobsters; and (iii) application of the simulator to evaluate the robustness of current management regulations under different levels of recruitment. This study also discusses how simulations can highlight uncertainties in input data and model structure.

3.3. Methods

The IBLS was developed by Chen et al. (2005) to test the performance of the stock assessment model and further developed by Chang (2015) for management evaluation. An IBM was used to develop the IBLS for the GOM lobster fishery by expressing numerous components of the model equations as random Bernoulli trials (Chen et al. 2006; Chang 2015; Fig. 3.1). Instead of calculating the number of lobsters that survive a given process such as natural mortality or fishing mortality, we simulate natural or fishing mortality acting on Nt individual lobsters. Because IBMs are not based on traditional mathematical formula, the IBLS cannot be described in one or a few equations. IBMs are bottom-up models in which population-level outcomes emerge from variation among individuals (DeAngelis and Grimm 2014).

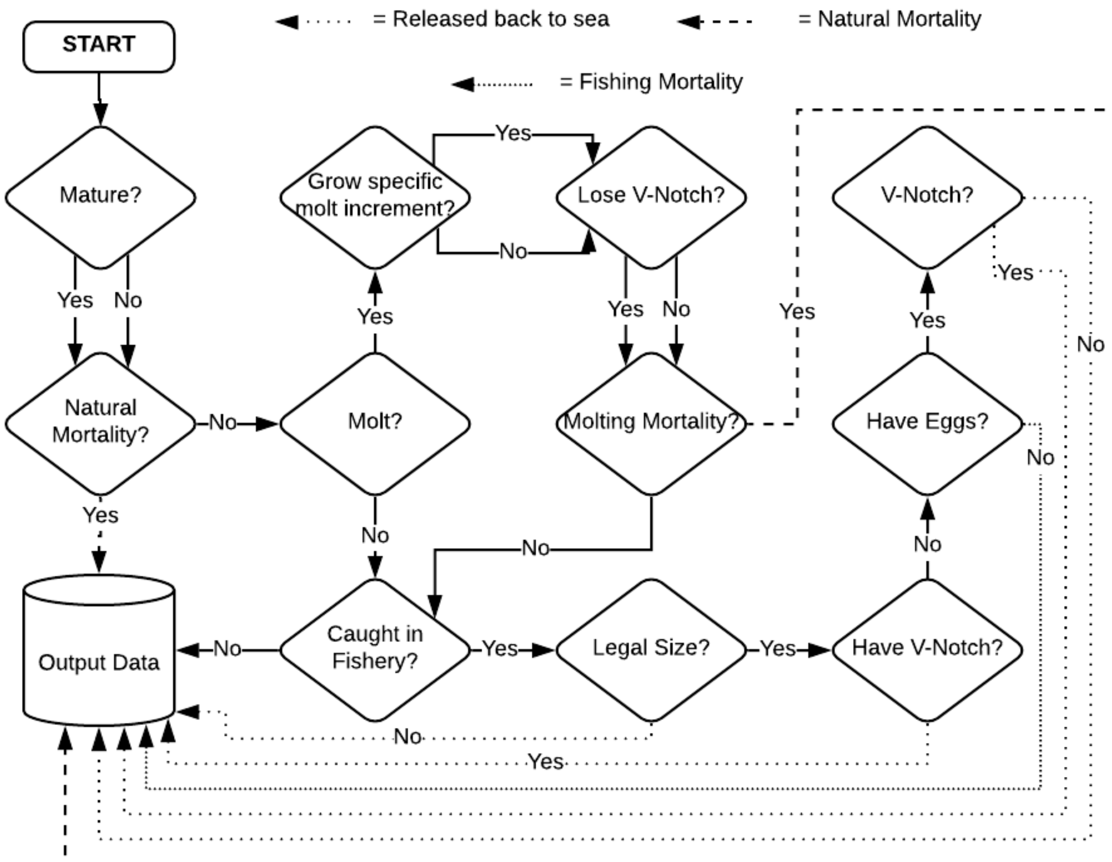

Figure 3.1. Flowchart of the individual-based American lobster simulator. Each lobster has a conditional probability of going through each process, as the probability at each process depends on what processes the lobster previously went through. The diagram was modified from Chen et al. (2005) and Chang (2015). See sections 3.3.1.1. for more details on probabilities and 3.3.1.3. for more details on the life history and fishery processes.

3.3.1. Model Description

3.3.1.1. Input

The IBLS requires abundance, recruitment, and other types of data (Table 3.1). Most of the probabilities and other input data are from the stock assessment data (ASMFC 2015), but fishing effort data are from the Maine Department of Marine Resources (DMR) harvester data, and v-notching information is from personal communication with managers (Table 3.1). These are the best available data representing the GOM lobster fishery dynamics. Most of the probabilities have means that are parameters from stock assessment model. In this case, the stock assessment parameters and output are assumed to be the true state of the lobster fishery. Select input and probabilities are tuned or calibrated as described later.

Table 3.1. Input data for the individual-based American lobster simulator. The most recent American lobster stock assessment is the Atlantic States Marine Fisheries Commission (ASMFC, 2015) source. Personal communication was with Maine lobstermen and Maine Department of Marine Resources staff. Harvester data are from the Maine DMR.

Inputs	Values	Source
Initial abundance	93,200,000	ASMFC 2015
Initial size composition	Differs among sizes	ASMFC 2015
Initial sex ratio	0.546	ASMFC 2015
Recruitment	Differs among years in summer and fall; 0 in winter and spring	ASMFC 2015
Recruit size composition	Differs among sizes	ASMFC 2015
Natural mortality probability	0.025 each timestep	ASMFC 2015
Molting probability	Differs among sizes	ASMFC 2015
Probability of growth increments per molt	Differs among sizes	ASMFC 2015
Maximum interval in between molts	7 seasons	Personal communication
Time between first molt and second molt if there is a double molt in a year	1 season	ASMFC 2015
Maximum molt increment (mm)	20	ASMFC 2015
Number of molts a V-Notch lasts	2	Personal communication

Table 3.1. Continued

Molting mortality probability	0.05	ASMFC 2015
Fishing effort (trap haul set over days)	Average of 1,085,440 in winter, 4,512,963 in spring, 25,485,938 in summer, and 8,606,713 in fall	Harvester data
Landings	Differs among sizes, sexes, seasons, and years	ASMFC 2015
Conservation selectivity	Differs among sizes, sexes, seasons, and years	ASMFC 2015
Legal selectivity	Differs among sizes, sexes, seasons, and years	ASMFC 2015
Abundance	Differs among sizes, sexes, seasons, and years	ASMFC 2015
Maximum legal size (mm CL)	128	ASMFC 2015
Minimum legal size (mm CL)	1982-1987: 81, 1988: 82, 1989-2013: 83	ASMFC 2015

Table 3.1. continued

Number of timesteps until a mature female lobster can have eggs after she molts	4 seasons	Personal communication
Maximum number of timesteps a mature female lobster can keep her eggs	4 seasons	Personal communication
Probability of a lobster caught with eggs being V-Notched by a lobsterman	0.9	Personal communication

Some of the probabilities, such as encounter probability, were calculated from the input data. Encounter probability is the probability that a lobster is caught in a trap and is calculated for each season, year, sex, and size class (Chang 2015). This is conceptually similar to catchability. Encounter probability was calculated as:

$$Enrate_{t,s,k} = \frac{C_{t,s,k}}{C_{t,s,k}+N_{t+1,s,k}} \quad (1)$$

where $C_{t,s,k}$ is the catch on boats before the lobsters that are illegal to be landed are thrown back, or the total number of lobsters that are caught in time *t* for sex *s* and size class *k* and $N_{t+1,s,k}$ is the abundance in time *t+1* for sex *s* and size class *k*. Catch on boats, or the amount of lobsters on the boat before protection from conservation measures occurs, was calculated as:

$$C_{t,s,k} = \frac{L_{t,s,k}}{S^{cons}_{t,s,k} S^{legal}_{t,s,k}} \quad (2)$$

where $L_{t,s,k}$ is the landings (of the fishery) in time *t* for sex *s* and size class *k*, $S^{cons}_{t,s,k}$ is the conservation selectivity in time *t* for sex *s* and size class *k*, and $S^{legal}_{t,s,k}$ is the legal selectivity in time *t* for sex *s* and sizeclass *k*. Conservation selectivity is the proportion of lobster landed from not being protected from having eggs or being v-notched. Legal selectivity is the proportion of lobster landed from being of legal size. $C_{t,s,k}$ plus $N_{t+1,s,k}$ is the abundance of the current timestep before fishing mortality, the last process in the IBLS but after natural mortality and growth, plus the lobsters that are released. The denominator in equation 1 includes lobsters that are released, because in reality, those lobsters could be caught again in a given timestep and need to be included in the total number of lobsters that the catch on boat can be removed from. Encounter probability is then scaled by fishing effort to represent the probability of being caught in the fishery.

3.3.1.2. State variables and scales

Individual lobsters are characterized by the state variables size (carapace length (CL) in millimeters), sex, maturity status, egg status, survival status (if the lobster is alive or dead because of either fishing or natural mortality), and V-notch presence. The temporal range is from the years 1982 to 2013 because the time range of the most recent American lobster stock assessment model output is from 1982 to 2013 (ASMFC 2015). The spatial extent is the GOM lobster stock area (Fig. 3.2). The model has four timesteps: winter (January–March), spring (April–June), summer (July– September), and fall (October–December). There are 35 size classes. The largest size class is a plus group that includes all lobsters larger than or equal to 223 mm CL, and the smallest size class is 53 mm CL; this is the smallest size at which a lobster can grow above legal minimum size in one molt. The size class interval of 5 mm CL was chosen because the minimum molting increment is 5 mm CL (ASMFC 2015).

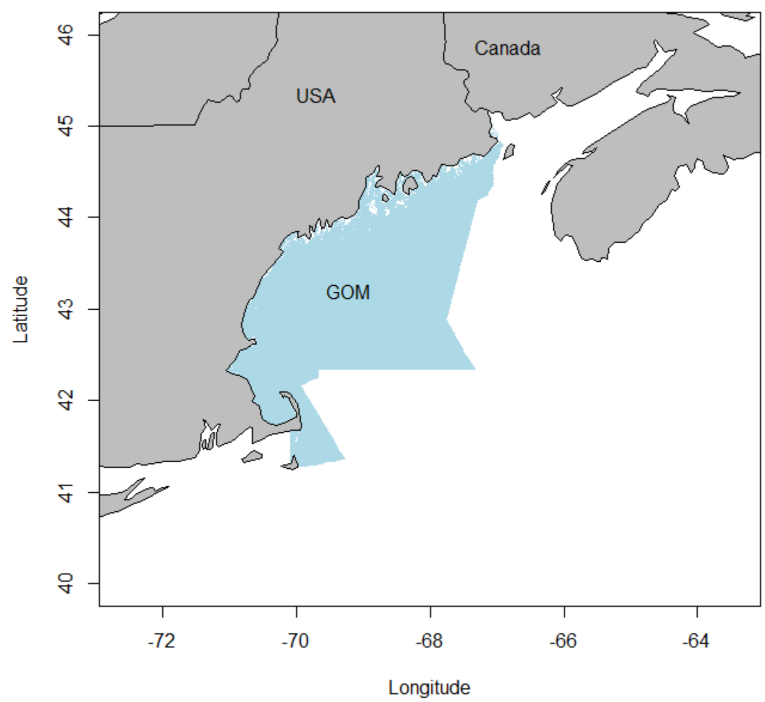

Figure 3.2. The Gulf of Maine (GOM) lobster stock area.

3.3.1.3. Process overview and scheduling

Individual lobsters are traced throughout the simulation, which includes biological and fishery processes, until the individuals die of natural or fishing mortality. At first, 93,200,000 lobsters are traced, but this number changes due to mortality and recruitment. The first part of the IBLS includes the biological processes such as natural mortality and growth. In each time step in the IBLS, each individual lobster is first assessed to see if it is mature; this determines if the lobster is a part of the spawning stock biomass (SSB) and can produce eggs. It then has a probability of dying from natural mortality such as predation. If the lobster does not die, it has a probability of molting and growing a specific molt increment. Larger lobsters molt less frequently and have smaller molt increments. If it has been two molts since its last v-notch, it will lose its v-notch, as the v-notch will grow out with each molt. After molting, the lobster then has a probability of dying from molting mortality.

If it survives or did not molt, it has a probability of being caught in the fishery (encounter probability). Once caught, if it is of illegal size or has a v-notch from a previous timestep, it is released back to the population. There is no mortality when lobsters are released back to the population. If it has eggs, it has a probability of being v-notched by a lobster fisher and then released back to the population. Once v-notched, it is released back to the population and protected from harvest for two molts. The released lobster can be harvested in the next time step if it is legal to be caught. If an egg-bearing lobster is not v-notched, the lobster fisher still releases the lobster back to the population because it is illegal to land lobsters with eggs. If the lobster did not die from fishing mortality, it survives to the next time step.

The lobsters that survive to the next time step plus the recruits into the fishery equals the number of lobsters that go through the life history and fishery processes in the next time step. Each individual lobster entering the IBLS goes through all the processes repeatedly until it dies due to natural mortality or is caught in the fishery. Two recruitment events occur in the summer and fall, when molting occurs. At the end of each discrete time step, the state variables are updated and recorded. The internal process of the IBLS is programmed in C++ (Chang 2015), and the input and output data are handled and analyzed in the R programming environment (R Core Team 2017).

3.3.1.4. Initialization

The initial size composition ($p_{k,1982}^{s}$) and abundance (N_{1982}^{s}) for each sex is specified, so that the number of lobsters for each sex *s* in size class *k* in the first assessment timestep (i.e., winter in 1982 (the first timestep of the stock assessment output)) is:

$$N_{k,1982}^{s} = p_{k,1982}^{s} N_{1982}^{s} \tag{3}$$

The fishery was initially occupied with 93.2 million lobsters with an initial sex ratio of 0.546. There was a burn in period of five years to get the amount of lobsters with a v-notch to the levels of that in 1982.

3.3.1.5. Submodels

3.3.1.5.1. Recruitment

For the historical simulation and calibration parts of the study, historical recruitment was used. For evaluating the current management regulations under different levels of recruitment, we used three different recruitment levels: low, intermediate, and high. Under the assumption that estimated historical recruitment from the stock assessment has some errors, recruitment was drawn from a normal distribution with a given mean and a coefficient of variation (CV) of 10%. The means of the low and high recruitment levels were the means of the five lowest and five highest historical recruitment values, respectively. The intermediate recruitment level mean was the mean of all the historical recruitment values.

3.3.1.5.2. Maturity

The proportion of females that are mature, which make up the SSB, at a certain CL is defined with a logistic equation (ASMFC 2015):

$$P_{matcl} = \frac{1}{1+e^{27.243-0.3CL}} \tag{4}$$

The size of 50% maturity is estimated to be around 91 mm CL (ASMFC 2015). This equation determines the probability that an individual lobster is mature.

3.3.1.5.3. Weight-length relationship

The weight-length relationship used in the IBLS to calculate stock biomass for males is described as (ASMFC 2015):

$$W_L = 5.21\ X\ 10^{-7} CL^{3.07814} \tag{5}$$

For females it is described as (ASMFC 2015):

$$W_L = 8.67\ X\ 10^{-7} CL^{2.97157} \tag{6}$$

where *CL* is carapace length in mm for each lobster (ASMFC 2015).

3.3.1.6. Output

The output from each simulation is carefully documented. The output data can be aggregated into fishery indicators such as year-, season-, and size-specific abundance, biomass, and catch. Biomass can be estimated by summing the weights of individual lobsters after weight is determined from the weight-length models (ASMFC, 2015). Total biomass, $\mathrm{B}_{\mathrm{y}}^{\mathrm{total,s}}$, and legal biomass, $\mathrm{B}_{\mathrm{y}}^{\mathrm{legal,s}}$, in year *y* for sex *s* are estimated as:

$$B_y^{total,s} = \sum_k N_{k,y}^s w_k^s \tag{7}$$

$$B_y^{legal,s} = \sum_{si} N_{k,y}^s p_{k,y}^s w_k^s \tag{8}$$

where w_k^s is the weight of the lobster in size *k*, and $p_{k,y}^s$ is a switch (0 for size classes not of legal size, and 1 for legal size classes).

3.3.1.7. Model calibration

With these probabilities and input data, the base case, or historical fishery, was simulated. Additionally, catch and size composition data were aggregated from the American lobster stock assessment, and these data were used to tune the IBLS. The historical fishery simulation is systematically calibrated, or tuned, to minimize the objective function to match the observed data (from the stock assessment) using all possible combinations of coefficients or scalers for specific parameters with equal weight on both catch and size composition. A range of values of coefficients was chosen for initial abundance, recruitment, and season-specific encounter probabilities. The historical fishery was simulated from 1982 to 2013 with every possible combination of coefficients. The coefficients that minimized the objective function, which was the coefficient of variation of the root mean square error (CVRMSE) between the observed (from the stock assessment) and simulated catch and size composition, were chosen (Table 3.2). In this case, parameters are not estimated in a statistical estimation, but coefficients or scalers for predetermined parameters are identified. These variables are tuned with the scalers rather than estimated. Tuning the IBLS with coefficients is necessary to find the optimal coefficient values given the data so that the observed historical fishery can be simulated. With the calibrated IBLS, we then observed trends in the outputs such as catch and abundance. The calibrated IBLS could then be used to evaluate management regulations.

Table 3.2. The optimal coefficients for the parameters that were tuned in the IBM. These coefficients produced the smallest objective function.

Parameter	Coefficient value
Initial abundance	0.7
Recruitment	1.2
Encounter probability	
Winter	1.9
Spring	2.9
Summer	0.7
Fall	0.7

3.3.1.8 Application

To illustrate some of capabilities of the simulator, we evaluated the current management regulations under different levels of recruitment: low, intermediate, and high. The different recruitment levels were projected for the years 2014–2023. Mean encounter rates of the most recent 5 years were used for each of the projection years. The status of the fishery was assessed using ad hoc biological reference points that were used in the most recent lobster stock assessment (ASMFC 2015). The target reference points were the 25th percentile of historical exploitation rate and the 75th percentile of historical reference abundance, and the limit reference points were the 75th percentile of historical exploitation rate and the 25th percentile of historical reference abundance. Reference abundance and exploitation rate are calculated using lobsters greater than 78 mm CL (ASMFC 2015).

By comparing the reference abundance, exploitation rate, and landings of the different scenarios, we can ask (i) how would the fishery and lobster population be different if recruitment were to change, and (ii) are current management regulations robust to variability in recruitment? The simulations were run 50 times for each of the three scenarios: (i) low recruitment, (ii) intermediate recruitment, and (iii) high recruitment.

3.4. Results

3.4.1. Calibration

The parameter coefficients that produced the smallest objective function (Table 3.2) increased recruitment and decreased initial abundance. These coefficients also increased the winter and spring encounter probabilities and decreased the summer and fall encounter probabilities, as encounter probabilities can vary by season. The objective function seeks to minimize the sum of the CVRMSE of observed and predicted catch and size composition by time step. The error indicator (e.g., CVRMSE) was 0.92 with the coefficients and 1.11 without the coefficients.

With these values of coefficients or scalers, the tuned IBLS accurately captured the historical annual and seasonal landings (Figs. 3.3 and 4). Before tuning, the simulated annual landings were lower than the observed landings (Fig. 3.3). Without the coefficients, the simulated seasonal landings were lower than the observed landings in the spring and summer but higher in the winter and fall (Fig. 3.4).

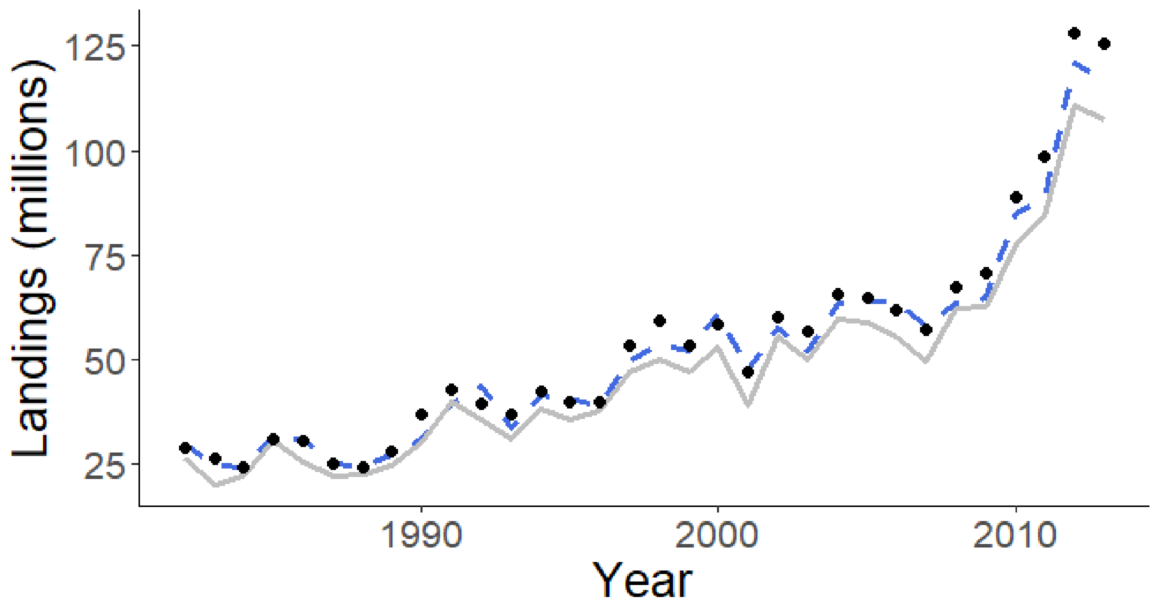

Figure 3.3. Simulated annual landings overtime. Observed = black dots, simulated with coefficients (tuned) = dashed blue line, and simulated without coefficients (not tuned) = grey line.

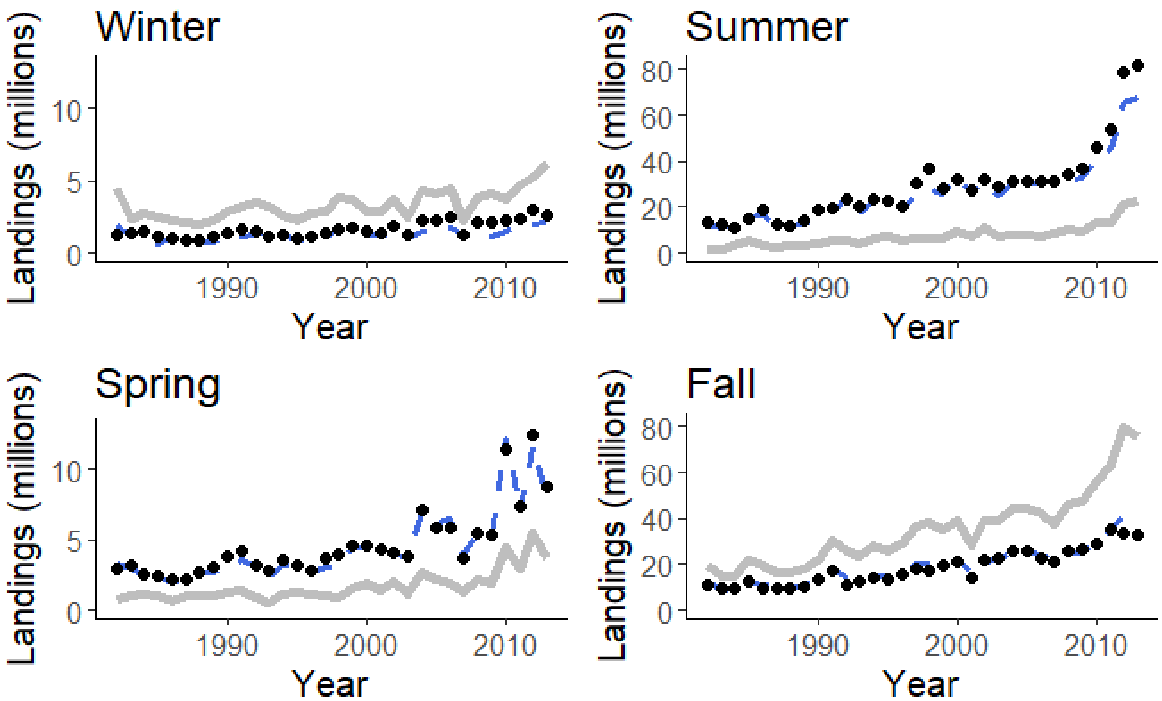

Figure 3.4. Simulated seasonal landings over time. Observed = black dots, simulated with coefficients = dashed blue lines, and simulated without coefficients = grey lines.

The IBLS simulated fewer small lobsters and more large lobsters in all seasons for both sexes but more so in the winter and spring (Figs. 3.5 and 3.6). Also, in the summer and fall, the IBLS simulated more male lobsters just above the legal minimum size (Fig. 3.6). Before tuning, the simulated size composition better matched the size composition from the stock assessment (Figs. 3.5 and 3.6). The biggest differences in size composition before and after tuning were in the winter and spring (Figs. 3.5 and 3.6).

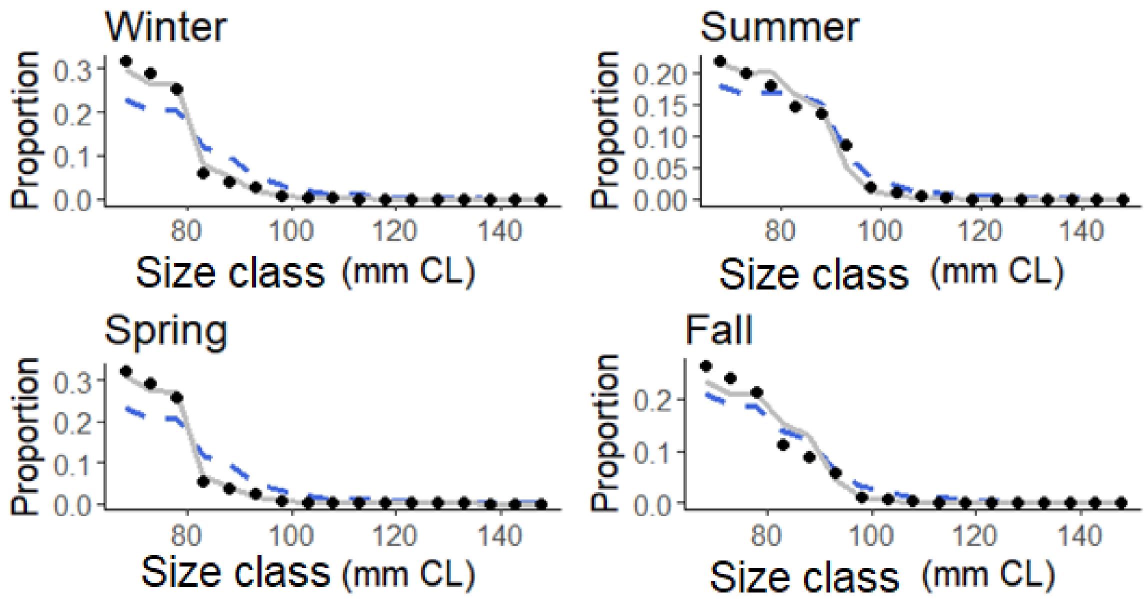

Figure 3.5. Simulated mean seasonal female size composition. Observed = black dots, simulated with coefficients = dashed blue lines, and simulated without coefficients = grey lines.

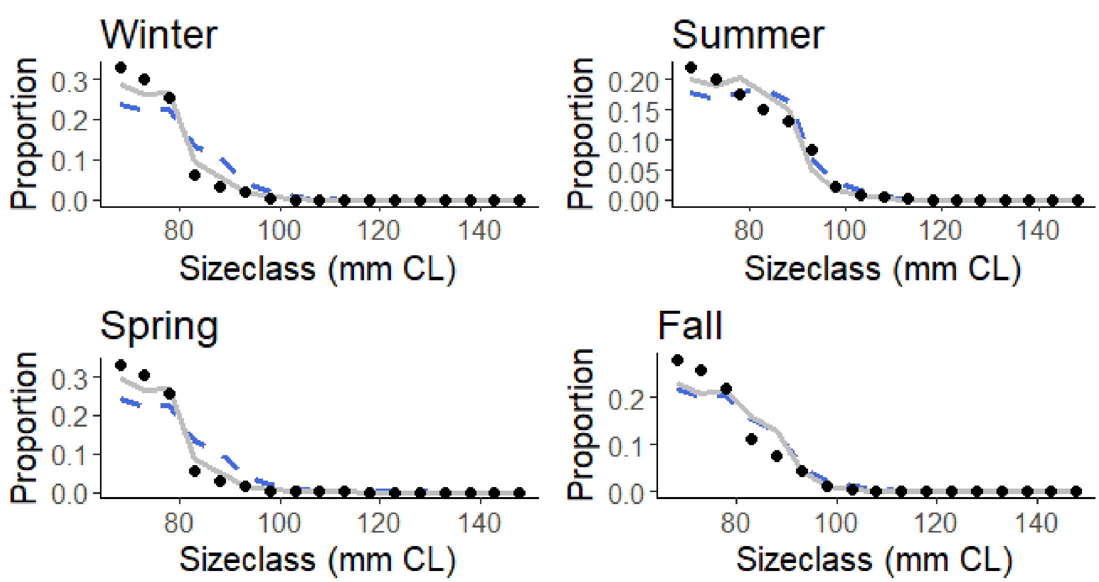

Figure 3.6. Simulated mean seasonal male size composition. Observed = black dots, simulated with coefficients = dashed blue lines, and simulated without coefficients = grey lines.

3.4.2. Application

With high recruitment (average of highest five years of recruitment), reference abundance remained steady and well above the abundance target reference point (124 million) from 2014 to

2023 (Fig. 3.7). With intermediate recruitment (average of historical recruitment), reference abundance declined below the abundance target reference point but remained above the abundance limit reference point (60.7 million) (Fig. 3.7). With low recruitment (average of lowest five years of recruitment), reference abundance declined below the limit reference point (Fig. 3.7). The rate of decline was larger with low recruitment and decreased over time in both the low and intermediate recruitment scenarios (Fig. 3.7).

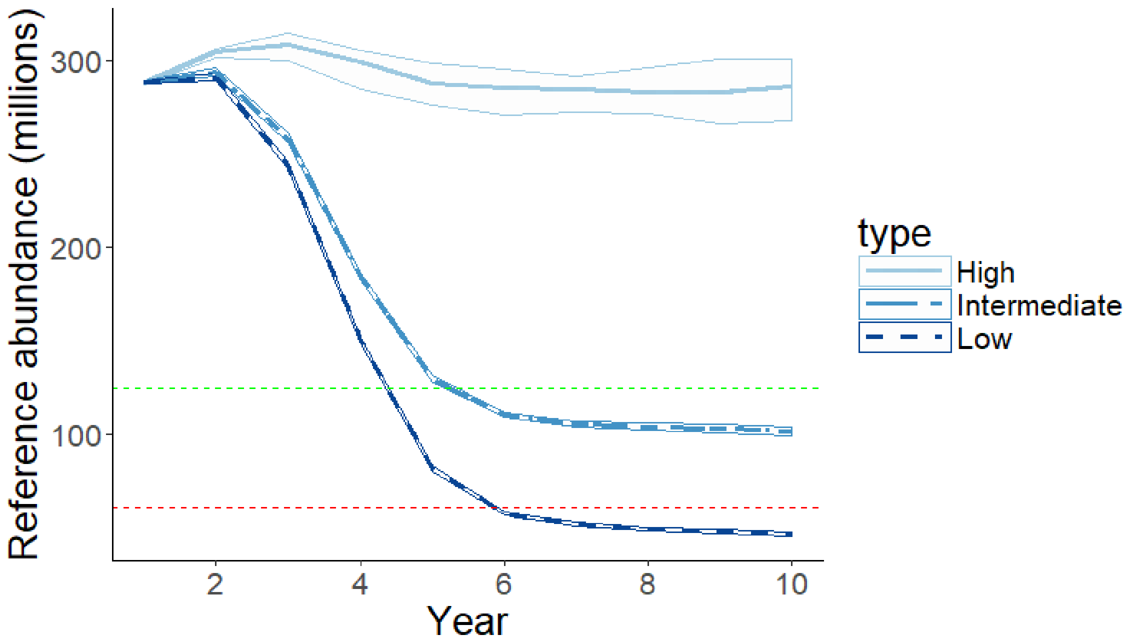

Figure 3.7. Reference abundance from 2014 to 2023 with low, intermediate, and high recruitment. The horizontal dotted green line represents the target abundance reference point (124 million) (75th percentile of reference abundance). The horizontal dotted red line represents the limit abundance reference point (60.7 million) (25th percentile of reference abundance).

Exploitation rate remained steady and above the exploitation rate limit (0.352) with high recruitment (Fig.3.8). With intermediate recruitment, exploitation rate declined to around the limit and then increased (Fig. 3.8). With low recruitment, exploitation rate declined to below the target (0.332) and then increased to just above the target (Fig. 3.8). Exploitation rates were similar across all recruitment levels until the fifth year of the projection (Fig. 3.8).

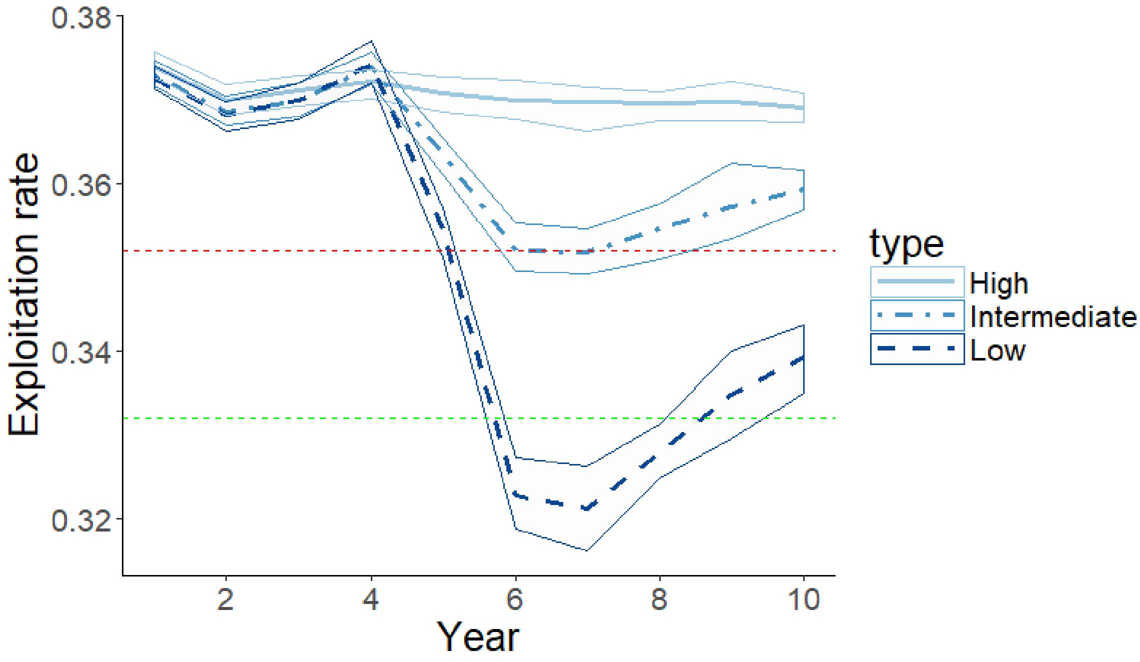

Figure 3.8. Exploitation rate from 2014 to 2023 with low, intermediate, and high recruitment. The horizontal dotted green line represents the target exploitation rate reference point (0.332). The horizontal dotted red line represents the limit exploitation rate reference point (0.352).

With high recruitment, landings only slightly declined (Fig. 3.9). With intermediate recruitment, landings declined to about half of the amount in the first year of the projection (Fig. 3.9). Landings declined even more and at a faster rate with low recruitment (Fig.3.9). With both intermediate and low recruitment, the landings leveled off around year 6 of the projection (Fig. 3.9).

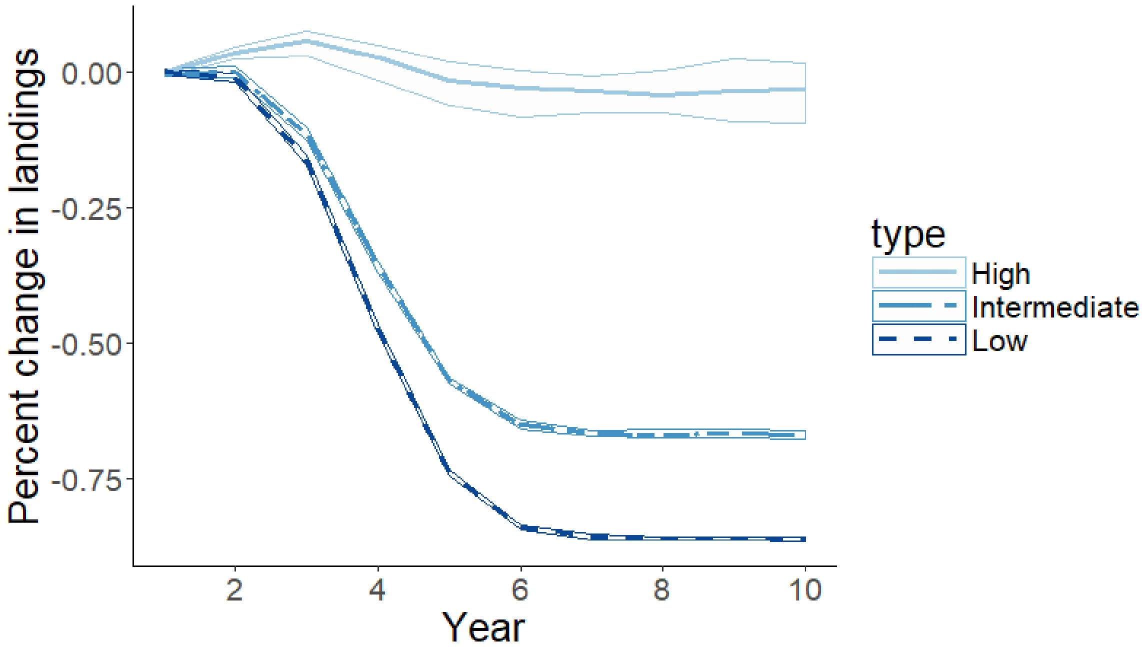

Figure 3.9. Percent change in landings from 2014-2023 with low, intermediate, and high recruitment.

3.5. Discussion

In this study, an individual-based simulation tool that can be used to evaluate fisheries management is described, modified, parameterized, tuned, and applied. In this section, we discuss the lessons learned from calibrating the IBLS, the management implications for the American lobster fishery, and the applicability of this simulator in other crustacean fisheries.

3.5.1. Lessons from calibrating the IBLS

One of the main goals posed by the present study was to tune the IBLS by identifying appropriate values of coefficients for the IBLS parameters. Because fisheries are complex, variable, and difficult to observe, there is substantial uncertainty in fisheries models (Hill et al. 2007). Complex fisheries result in complex models and many assumptions, and data are frequently inadequate for evaluating complex models (Hill et al. 2007). Calibrating a model includes tuning the model by determining a set of parameters that fit the model to its data and can provide insights into the uncertainty of input data, model parameters, and model structure. This is different from estimating model parameters in a statistical model. Results from a simulation model are based on many initial parameter estimates, which are not known. Coefficients can be applied to inputs that are not as certain, and once the simulator is tuned, the more the coefficients deviate from 1, the more uncertainty can be expected from that input or model structure.

In this study, there are discrepancies between results obtained before and after calibrating the IBLS. The large coefficients, or scalers, represent either inaccuracies of the input data or the IBLS structure. Interestingly, the simulated size composition matched the historical size composition better before tuning the model, which may be a result of the model catching more small lobsters to better fit the historical landings. Additionally, structural differences between the stock assessment model (ASMFC 2015) and the simulator may result in bias (Hill et al. 2007). Potential bias may be apparent in the size composition of male lobsters in the summer and fall. The IBLS simulates more male lobsters just above the legal minimum size in these seasons, which may be a result of the IBLS simulating less catch of male lobsters overall to match the catch from the stock assessment. Tuning the IBLS highlights some uncertainties in the lobster stock assessment. The GOM lobster stock assessment model underestimated the amount of large lobsters (ASMFC 2015), and the tuned simulations produced more large lobsters than there were in the stock assessment output data, especially in the winter and spring, when migration to offshore waters occurs. In the IBLS, lobsters cannot migrate, so the large lobsters are kept within the system unless they die. Moving forward, the Atlantic States Marine Fisheries Commission (ASMFC) will combine the GOM lobster stock with the Georges Bank lobster stock because of the migration of large lobsters between the two stocks (ASMFC 2015).

Tuning the IBLS addresses the uncertainty in the fishing effort, as well as other parameters. In this study, fishing effort was estimated from harvester data as trap haul set over days. Simulated landings are sometimes underestimated with no coefficients, which indicates that this may not be the best estimate of fishing effort. The effort data used in this study were obtained from fishing vessels that only target lobster. However, misreporting by lobster fishers is possible, and logbooks are only filled out by 10% of Maine lobster fishers which may not be representative of the fishery. Also, the stock area includes New Hampshire and Massachusetts fishery areas, and fishing effort data from those states were not included in this study. Additional factors such as lobster fisher skill and bait may also play a role. Future research should consider changes in skill and bait over time.

As a result, the simulated annual, spring, and summer landings before calibration were all lower than the landings from the stock assessment, which indicates that the trap haul set over days from the harvester data may be an underestimation of fishing effort. The simulated landings in the winter and fall are higher than the landings from the stock assessment, which suggests that in those seasons, the harvester data may be an overestimation of fishing effort. The values of coefficients for the encounter probabilities had a much higher magnitude in the winter and spring than in the summer and fall, indicating that the harvester data are more reliable in the summer and fall than in the winter and spring. The same amount of trap haul set over days applied in the summer and fall can result in a larger catch than that of the winter and spring because of the differences in spatial distribution of lobster (Chang et al. 2010).

However, the lack of fit to the observed catch and size composition may be an effect of inappropriate model structure and assumptions instead of the data input. For example, the IBLS is structured so that lobsters are only allowed to be caught once in a time step, when in reality, they could be caught and released several times in a time step. This affects the encounter-rate calculation, hence another reason to tune the encounter probabilities. Also, the lobsters and fishing effort are assumed to be distributed evenly across the area, which is not realistic. Lobsters are also assumed not to migrate out of or into the stock. Additionally, natural mortality is assumed to occur before growth and fishing. The response of lobster fishers to changes in the system was not incorporated into the simulator either.

3.5.2. Management implications for the American lobster fishery

The simulations in this study indicate that the robustness of Maine lobster fishery management regulations is dependent upon recruitment. However, the recruitment levels in these simulations are much different from each other because they are based off the historical recruitment, which has a wide range of values. Future studies should include different levels of recruitment that are closer in magnitude.

Nevertheless, according to the simulations, even if recruitment declines to a third of the current recruitment, abundance will still be above the limit abundance. Also, if recruitment were to decline to a tenth of the current recruitment, then exploitation rate would decline to below the target, which indicates that current management regulations allow for a reduction in exploitation rate with low recruitment. Current management regulations also allow for a reduction in exploitation rate with intermediate recruitment. Although catch declines dramatically with low recruitment, it only declines to a level similar to the historical catch in the mid-1990s.

The tuned IBLS replicates the historic data well and therefore can be used to evaluate management regulations in the GOM lobster fishery. Simulators for fisheries management combine the best available data and can evaluate a variety of management scenarios (Grant et al. 1981). The simulator in this study can be a useful tool for management of the American lobster fishery and other lobster and crab fisheries by evaluating management strategies with consideration of varying biological factors.

The simulator used in this study can be adapted to serve as an operating model within a management strategy evaluation (MSE) context. MSE is an emerging approach that can improve fisheries management because it is an adaptable framework for modeling a fishery management system instead of just the fish stock (Cochrane et al. 1998; Smith et al. 2008). MSE uses a simulator as a realization of the truth and can be used to identify management strategies that will fail at meeting objectives before deciding the final management measures (Harwood and Stokes 2003). However, to work towards a complete MSE, future studies should identify management objectives for the GOM lobster fishery with information from stakeholders. Failure in fisheries management is often due to lack of clearly defined management objectives. Future MSE work should involve lobster fishers early in the process. MSEs allow precautionary management to be implemented thoroughly and scientifically (Harwood and Stokes 2003).

Not only can the simulator evaluate management strategies, but it can also be used to identify which factors influence the current lobster abundance and landings. In the GOM lobster fishery, fishers and scientists believe that both conservation measures and environmental factors have led to changes in the Maine lobster fishery and population (Acheson and Gardner 2010; Acheson and Steneck 1997). Future studies should use simulations to help identify the degree to which conservation measures and biological factors have influenced the fishery.

Before the simulator can be used to test management scenarios, it is important that the assumptions of the simulator be understood. Because the conclusions may be incorrect if some of the numerous restraining assumptions are changed, the best performing management scenarios should be viewed with consideration of these assumptions. Some of these assumptions include no variation of population dynamics over space, no migration between stocks, constant natural mortality, and constant size at maturity. For the most part, the simulator is based on similar assumptions and the same equations as those in the stock assessment. Natural mortality and maturity equations used in the simulator are assumed to be known in the stock assessment, which is usually not true.

Additionally, an important assumption of this simulator is that the behavior of the lobster fishers is a response to present management. The response of lobster fishers to new management measures are not considered, although it is important for policy performance (Sanchirico and Wilen 2001). Parameterization of the response of lobster fishers to new management measures is difficult. Currently, the stock assessment also does not consider responses of lobster fishers to management measures (ASMFC 2015). In the stock assessment, no stock–recruitment relationship is assumed, which is why the simulator has multiple options for simulating recruitment. Future work with the simulator should focus on sensitivity analyses to evaluate the robustness of the results by varying these assumptions.

In this study, recruitment is not affected by changes in SSB that result from changes in management because there is no relationship between recruitment and SSB. The stock–recruitment relationship, which is often important in identifying the effects of long-term management scenarios, is difficult to quantify for American lobster. In general, the stock–recruitment relationship and the impact of environmental variability and biological factors on this relationship are unclear (Punt et al. 2014). Although the simulator is based on single-species population dynamics, it can consider some effects of ecosystem variability when simulating recruitment. Rather than trying to identify a single best recruitment estimation method, uncertainty in recruitment can be explicitly and formally accounted for by incorporating a wide range of biologically plausible recruitment scenarios into the tuned IBLS. Other fishery simulators have included a range of structures for recruitment relationships (Punt and Smith 1999). Recruitment can be designated as a function of SSB and bottom-water temperature. Otherwise, recruitment can be drawn from theoretical distributions derived from historical recruitment that correspond to high and low SSBs.

Future studies on simulations of the Maine lobster fishery should not only focus on recruitment estimation, but also on growth and fishing behavior changes. The GOM is experiencing rapid water temperature changes (Le Bris et al. 2018; Mills et al. 2013) and an aging Maine lobster fleet (Johnson and Mazur 2018). Temperature changes may influence lobster population dynamics, as temperature has a large effect on the life history of American lobster, especially on recruitment and growth (Aiken and Waddy 1986). This can be incorporated into the simulator by creating a relationship between temperature and recruitment and a relationship between temperature and growth matrices. An aging lobster fishing fleet may also impact the effectiveness of existing management because fishing behavior may begin to change, as different generations of fishers may have different perceptions of the resource (Nemec 1972; Silva 2016). For example, the percentage of compliance of v-notching may change over time. These changes could be incorporated by testing scenarios with different v-notching ratios. Incorporation of other information such as temperature changes and lobster fishing fleet dynamics may potentially improve the calibration of the IBLS. Incorporating temperature into the development of an SSB and recruitment relationship may improve the calibration of the IBLS and projection of the population. In addition, changing growth may result in changes in the effectiveness of existing size-related management.

3.5.3. Applicability of the IBLS in other crustacean fisheries

IBMs are useful alternatives to statistical models for crustacean management. Although statistical models work well for crustacean population dynamics, IBMs can also accurately simulate crustacean fisheries and can even be used to validate statistical model results. IBMs can be used to supplement stock assessments and inform fisheries management. As the IBLS is flexible, it can be modified for the use of a simulator in other crustacean fisheries as well. Numerous biological and management scenarios can be simulated with small alterations of the parameters.

The IBLS can be especially useful for any lobster or crab fishery, as they have similar life history and fishery processes to American lobster. With an IBM approach, a variety of biological and fishery processes is included in the simulator. Crustacean life history processes such as molting, molting mortality, and bearing eggs are included. The individual-based approach can capture the non-continuous molting processes that vary among individuals.

The results from the present study are encouraging for the simulation of crustacean fisheries; however, additional explorations are needed. The simulator can integrate enhanced knowledge about the fishery and changes in some model assumptions, including changes in size at maturity or natural mortality over time. The IBLS also has functionality that allows uncertainties in recruitment to be addressed, which should be used in future studies.

Management measures that are common in crustacean fisheries such as legal sizes and protection of egg-bearing individuals are included in the simulator. IBMs are useful because they can treat each of the many complex management measures as separate processes rather than one combined selectivity. This differs from models in which total allowable catches or fishing effort levels are the only management measures included. An important feature of the IBLS is that it does not have fishing mortality as a parameter; instead, it is estimated. Using encounter probabilities as a proxy for fishing effort is important for the American lobster fishery, which does not have harvest control rules, so in testing management regulations, there should be no predetermined fishing mortality. Additionally, v-notching is not practiced in all lobster fisheries. This simulator can be used as a tool to test this conservation measure in other fisheries. In the simulator, the compliance of v-notching can be set at different rates, which is important to consider for a management measure that cannot be fully enforced, as it occurs on the boat. Maximum size is another management measure not used in all lobster fisheries and can be tested with the simulator as well. In the IBLS, the number of fisheries and management measures is not a limitation. Many different management measures can be simulated alone and in combinations within the simulator such as marine protected area, total allowable catch, and different legal sizes. A combination of numerous management measures is more realistic. The seasonality of the simulator also allows evaluation of seasonal management measures.

New knowledge can be easily integrated and updated in the simulator without recompiling the code. Economic variables, including price and price decreasing with landings, can also be incorporated into the fishery dynamics. Many bioeconomic models have been developed for crustacean fisheries and could be linked with the simulator (Clarke et al. 1992; Maynou et al. 2006; Holland 2011; Chang 2015). Currently, the IBLS is only parameterized for one area, but this is not fixed. Additional areas can be designated according to the data available. With the necessary data, IBMs have the flexibility to include multiple areas (Grimm 1999). Adaptive management simulations are also a valuable ability of the simulator, as management can be simulated as more conservative or less conservative when the fishery or fish population passes a reference point. Another innovation in this model is the inclusion of the ability to select different compliance rates for conservation measures. Another advantage that IBMs have over statistical models is the process-based design. This allows for easier communication to stakeholders about how the model works. A flowchart (such as in Fig. 3.1) may be easier for stakeholders to understand than mathematical equations.

Lobster fishery management can have effects that extend past the species and into the ecosystem. Future studies should address potential missing ecosystem processes in the simulator. Because of modeling limitations, not all effects of fisheries management can be examined with a single simulation tool. In many cases, adding extra details into the model to address these limitations may not be essential; as Walters et al. (1997) describe, we should not "go to too much detailed models without stopping to ask whether the extra is necessary". The results from simulations will become less useful if additional uncertainties are integrated (Grant et al. 1981; Somers and Wang 1997). This may cause managers to not implement management measures that would have positive influences on the fishery (Grant et al. 1981). Adding multiple areas would require all of the input data for each area and the migration of lobsters among areas, which are often not available or difficult to quantify. Spatially explicit models are often not developed because of the sensitivity of fishery dynamics to migration coefficients and the difficulty of estimating the coefficients (Pelletier and Mahévas 2005). Because there is usually not enough detailed data compared with model complexity, parameter estimation for spatially explicit models is difficult (Pelletier and Mahévas 2005). Here, a trade-off between parsimony and complexity must be made.

In this study, an individual-based approach captures the necessary details of the life history and fishery processes of the American lobster. With the simulation tool that has been modified, parameterized, and calibrated in this study, the GOM American lobster fishery can be simulated. The process of tuning the IBLS highlights the uncertainty in the input data and model structure. This study begins to evaluate the robustness of current management regulations with variability in recruitment, but the simulator has the potential to explore more questions. This simulator can be used to evaluate the robustness of management regulations not only in the GOM lobster fishery but can also be modified for use in other lobster and crab fisheries.

CHAPTER 4

CONTRIBUTIONS OF V-NOTCHING TO DRASTIC INCREASES IN THE LOBSTER FISHERY

4.1. Abstract

V-notching, a conservation measure intended for the protection of mature female lobsters, has been hypothesized to have contributed to the dramatic increase in American lobster, *Homarus americanus*, landings and stock biomass in the Gulf of Maine. To evaluate the impact of this conservation measure, scenarios examining different v-notching compliance rates and v-notch definitions were simulated using an individual-based lobster simulator (Chapter 3) with different recruitment dynamics scenarios. In the model, v-notching with a high compliance rate and a strict definition of the ‘notch’ increased spawning stock biomass by 33−632%. Without a stock− recruitment relationship, v-notching with high compliance and a strict definition decreased landings by 2%. With a weak or strong stock−recruitment relationship, v-notching with high compliance and a strict definition increased landings by 33−85%. Without a high v-notching compliance rate (i.e. 90 or 100% compliance) or a strict definition of the notch, the lobster stock and fishery would not have experienced such large positive increases in biomass and landings. These results suggest that input controls, such as protecting the spawning stock, can provide significant benefits to both the fish population and fishery. The framework proposed in this study can be extended to evaluate the protection of spawning females in other fisheries.

4.2. Introduction

The lack of understanding of v-notching calls for a careful evaluation of this conservation measure and dissemination of results to the industry if v-notching is critical to the sustainability of the fishery. When conducting such a study, variability in fishing behavior, v-notch definitions, and lobster recruitment dynamics should be considered. Because the v-notch conservation measure is voluntary, it is important to consider variability in compliance rates (i.e., the percent of lobsters caught with eggs that will be v-notched by a lobster fisher). Also, different American lobster management areas have different v-notch definitions; some areas have less strict v-notch definitions, while other areas have strict v-notch definitions. Additionally, stock-recruitment dynamics are often difficult to define in a changing environment, which adds the uncertainty in our effort to evaluate the effectiveness of v-notching (ASMFC 2015).

Given the changing environmental conditions in the GOM which may greatly influence the lobster recruitment and growth dynamics (ASMFC 2015; Mcmahan et al. 2016; Tanaka and Chen 2016), an improved understanding of the effectiveness of v-notching in regulating the lobster population dynamics becomes urgent and necessary. However, no systematic and comprehensive study has been done to evaluate and quantify the measure's contribution to the improved lobster stock and landings with consideration of multiple stock-recruitment relationships, variability among individual lobsters, variation in management compliance, and variation in v-notch definitions.

4.3. Methods

In this chapter, the IBLS was used to simulate the Maine lobster fishery.

4.3.1. Recruitment dynamics

In this chapter, four different recruitment scenarios were considered, including scenarios with no relationship between recruitment and SSB, because the American lobster stock-recruitment relationship is not clear (Fig. A21). In the first recruitment simulation scenario, recruitment was drawn from estimated historical recruitment of the corresponding year from the stock assessment (ASMFC 2015), assuming no stock-recruitment relationship. Under the assumption that estimated historical recruitment from the stock assessment has some uncertainty, recruitment was drawn from a normal distribution with the estimated historical recruitment value of the corresponding year from the stock assessment as the mean and a coefficient of variation (CV) of 10%.

Recruitment is estimated annually in the stock assessment and divided into summer and fall portions (ASMFC 2015); therefore, in all the recruitment simulation scenarios, annual estimated recruitment values are used and then the resulting recruitment values are divided into summer and fall portions. Around 66% of recruitment occurs in the summer, and 33% of recruitment occurs in the fall (ASMFC 2015).

The second recruitment simulation scenario was to randomly assign recruitment values from normal distributions, with means and standard deviations estimated from the stock assessment output, that correspond to five levels of SSBs (ASMFC 2015; Fig. 4.1 and Table 4.1). Higher recruitment values correspond with more recent years (Fig. 4.2). This approach partially considered the possible relationships between SSB and annual recruitment. SSB was the SSB in the summer, because this is when lobster eggs hatch (Ennis 1995). SSB was lagged by six years, which is considered as the average time a young of the year lobster takes to reach size at recruitment (Campbell and Robinson 1983; Fogarty and Idoine 1986). To simulate recruitment of a given year, a random number was drawn from the normal distribution of recruitment values that corresponded with the SSB from six years before. For the first six years (1982-1988), the first recruitment simulation scenario, in which recruitment values are drawn from a normal distribution with a mean of the estimated historical recruitment of the corresponding year from the stock assessment, was used. Historical recruitment was assumed for the first six years, because a change in v-notching would not affect recruitment until six years later; therefore, these scenarios simulate a change in v-notching in 1982. As this approach incorporates a relationship between recruitment and SSB, but not a theoretical stock-recruitment relationship, from here on, these scenarios are referred to as weak stock-recruitment relationship scenarios.

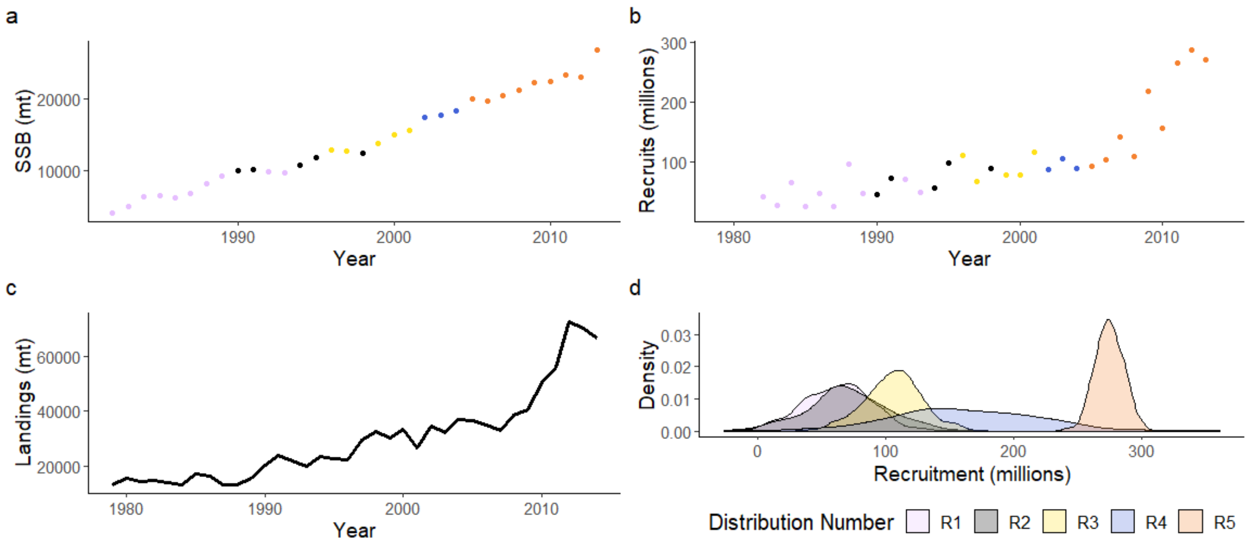

Figure 4.1. Time series of spawning stock biomass, recruitment, and landings and the weak stock-recruitment relationship (SRR) distributions. a) Simulated spawning stock biomass (SSB) over time. Colors correspond to the distributions in the weak SRR. b) Estimated recruitment from the stock assessment over time. Colors correspond to the distributions in the weak SRR. c) Estimated landings from the stock assessment over time. d) The normal distributions of recruitment from the stock assessment that correspond to five different SSB levels. R1 corresponds to SSB that is below 10,000 mt, R2 corresponds to SSB that is above 10,000 mt but below 12,500 mt, R3 corresponds to SSB that is above 12,500 mt but below 16,000 mt, R4 corresponds to SSB that is above 16,000 mt but below 19,000 mt, and R5 corresponds to SSB that is above 19,000 mt.

Table 4.1. Recruitment and spawning stock biomass (SSB) means and SDs of the normal distributions of recruitment values that correspond to five levels of SSB.

SSB level (mt)	**Recruitment mean (millions)**	**Recruitment SD (millions)**	**SSB mean (mt)**	**SSB SD (mt)**
<10000	62.05	25.84	7232.45	1968.92
>10000 <12500	69.32	32.57	11050.11	1025.5
>12500 <16000	107.18	21.18	14061.74	1308.39
>16000 <19000	161.67	55.15	17831.86	436.64
>19000	274.67	10.97	20035.9	394.27

The third recruitment simulation scenario was to use a stock-recruitment model, because stock-recruitment models are commonly used to predict recruitment. To define a stock-recruitment model, the SSB lagged by six years and recruitment data from the stock assessment were fit to a variety of Ricker and Beverton-Holt models (Chang et al. 2016). With a stock-recruitment model, recruitment continuously increases with SSB. This differs from the weak stock-recruitment relationship scenarios, which suddenly switched recruitment distributions with increasing SSB. To find the best stock-recruitment model, four different stock-recruitment models were developed: Ricker and Beverton-Holt models with no temperature and with average bottom water temperature in the summer and fall. The model with the lowest Akaike information criterion (AIC) was chosen for this recruitment simulation scenario. The temperature was the annual average GOM bottom water temperature in the summer and fall months (July- December) from 1982 to 2013 from Finite-Volume Community Ocean Model (FVCOM) stations (Chen et al. 2006). Bottom water temperature was chosen, as it has a large role in driving lobster distribution (Chang et al. 2010). Temperature from the summer and fall was chosen, because recruitment occurs in these seasons (ASMFC 2015).

The Ricker model with no temperature was $R = \alpha S e^{-\beta S} e^{\varepsilon}$ (Ricker 1954, 1958), and the Ricker model with temperature was $R = \alpha S e^{-\beta S} e^{\gamma T} e^{\varepsilon}$ (Penn and Caputi 1986). The Beverton-Holt model with no temperature was $R = \frac{S}{\alpha + \beta S} e^{\varepsilon}$ (Beverton and Holt 1957), and the Beverton-Holt model with temperature was $R = \frac{S}{\alpha + \beta S} e^{\gamma T} e^{\varepsilon}$ (Quinn and Deriso 1999). R is the number of recruits, S is the SSB, T is the average bottom water temperature of the GOM in the summer and fall months, α is the density-independent parameter proportional to fecundity, β is the density-dependent parameter, γ is a coefficient expressing the magnitude of the effect of temperature, and ε is the multiplicative error term. The parameters: α, β, and γ had a range of values, based on 90% confidence intervals determined by bootstrapping. In the v-notching scenarios, these parameters were chosen for each iteration by randomly selecting the parameters from these ranges of values. For the first six years (1982-1988), the first recruitment simulation scenario was used. The fourth recruitment simulation scenario was a stock−recruitment model with an increased density dependence effect. The purpose of this recruitment simulation scenario was to determine how sensitive the results were to density-dependence effects. This recruitment scenario followed the same methods as the third recruitment scenario, except the distribution of the β parameter was modified so that all values were several orders of magnitudes larger those in the bootstrapped β distribution.

4.3.2. V-notching scenarios

Within the IBLS, we addressed effect of v-notching on lobster landings and biomass. We simulated different v-notching conservation compliance levels (0, 50, and 100%) and different numbers of molts until a v-notch grows out (1 or 2 molts) with the 4 different recruitment simulation scenarios from 1982−2013 (Table 4.2). These simulations focused on the long-term effects of different notch definitions and compliance regimes.

Table 4.2. The different v-notching scenarios.

Scenario	Compliance rate (%)	Definition	Time until a v-notch grows out (years)
Reference	90	Strict	4
0	0	N/A	N/A
50-S	50	Strict	4
100-S	100	Strict	4
50-L	50	Less strict	2
100-L	100	Less strict	2

Tully (2004) pointed out that determining the contributions of v-notching and other conservation measures would be impossible if the measures were concurrent. However, with the IBLS, it is possible to identify the contribution of concurrent conservation measures, because each conservation measure is simulated as a separate process. Indeed, many conservation measures can be applied concurrently to the fishery. This approach may lend itself to handling more complex management problems in situations involving varying compliance rates and enforcement criteria.

Conservation measures can be evaluated with different enforcement criteria with the IBLS. This is realistic for measures that are not easily and consistently enforced, such as v-notching. In this case, the size of a notch that is considered a v-notch can differ, so considering different criteria or v-notch definitions is necessary for understanding the measure’s impact on the fishery and population.

The number of molts until a v-notch grows out depends on how strict the v-notch management definitions are; from here on, 2 molts will be referred to as a strict definition and 1 molt will be referred to as a less strict definition. With a strict definition, more molts are needed for the v-notch to grow out because any size notch is considered a v-notch. Lobster fishers can keep the lobsters after approximately 2 yr with a less strict definition and 4 yr with a strict definition, since mature female lobsters tend to molt every other year. The state of Maine currently has a zero tolerance v-notch definition, meaning that a lobster with any notch depth is illegal to land; however, in other lobster management areas a lobster with a notch of less than 1/4th to 1/8th of an inch (3− 6 mm) can be landed.

When evaluating conservation measures, a benefit of using the IBLS is that different compliance rates can be applied in the simulation. Instead of only considering scenarios of implementing a conservation measure or not, conservation measures can be implemented with varying degrees of compliance, which is more realistic. Compliance may differ based on fishermen's reactions to management measures, so consideration of the response of fishermen is necessary when evaluating the impact of management. Maintaining varying degrees of compliance is especially realistic in cases where the conservation measure is difficult to enforce.

In these simulations, the probability of a legal sized lobster being v-notched by a lobster fisher if it is caught with eggs represents the v-notching compliance rate, meaning that 0, 50, or 100% of legal sized lobsters caught with eggs are v-notched. If the lobster is v-notched, it is released back to the population and protected from harvest for 1 or 2 molts. If the lobster is not v-notched, it is released back to the population and can be harvested in the next timestep. Simulations were performed 50 times for each scenario from 1982−2013 due to computational demands.

The results from these simulations were compared with those for the reference scenario, which is the historical scenario. The reference scenario simulates what occurred in the fishery using the first recruitment scenario, or historical recruitment. Historically, there was a 90% v-notching compliance rate and a strict v-notching definition (Mazur et al. 2018), and these were implemented in the reference scenario as well.

Because changes in the v-notching compliance and v-notch definition may not always have a detectable effect on the fishery and population, we used independent samples t-tests to determine if the final SSBs and cumulative landings were significantly different ($\alpha < 0.05$) between scenarios.

4.4. Results

In general, v-notching positively affected American lobster SSB, but more so with a stock−recruitment relationship (Fig. 4.2). V-notching positively affected cumulative landings with a stock−recruitment relationship but negatively affected cumulative landings without a stock− recruitment relationship (Fig. 4.2). Both high compliance and a strict definition increased the positive effect of v-notching (Fig. 4.2). Because the Ricker models did not predict recruitment well (Fig. A21), determining the effect of v-notching from these scenarios was difficult.

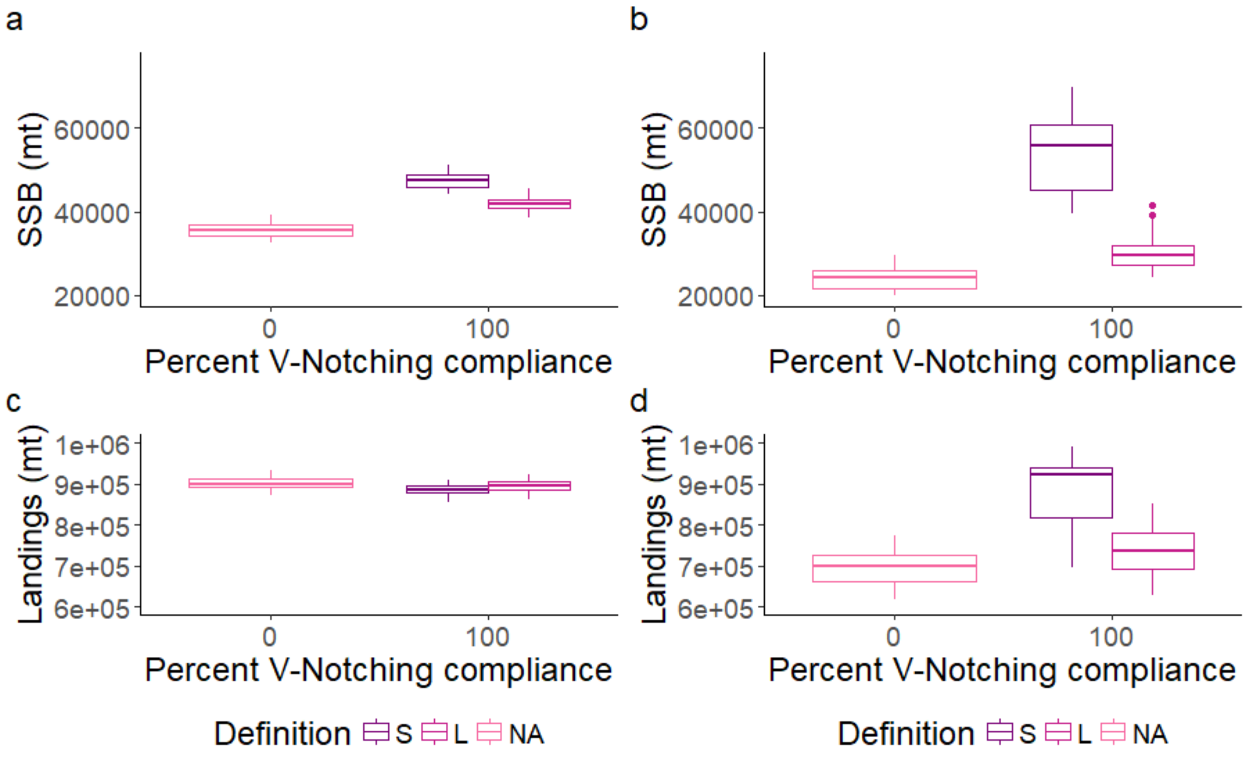

Figure 4.2. American lobster v-notching scenario results. (a,b) Spawning stock biomass (SSB) in the last year of simulations (2013) of 0% and 100% v-notching compliance rates with different definitions and with (a) historical recruitment and (b) recruitment from the weak stock–recruitment relationship. (c,d) Cumulative landings of scenarios with 0% and 100% v-notching compliance rates with different definitions and with (c) historical recruitment and (d) recruitment from a weak stock–recruitment relationship. S: strict; L: less strict; NA: no v-notch definition because there was 0% compliance. Box midline = median; upper box limit = 75% quartile, upper hinge; lower box limit = 25% quartile, lower hinge; lower whisker: smallest observation greater than or equal to lower hinge – 1.5 × interquartile range (IQR); upper whisker = largest observation less than or equal to upper hinge + 1.5 × IQR. These are the same for all boxplots in the figure.

4.4.1. Results with fixed, historical recruitment

With the historical recruitment scenario, higher v-notching compliance and a stricter v-notch definition significantly (p-values < 1.60 × 10–5) positively affected SSB (33% higher with 100% compliance and a strict definition than with 0% compliance) (Fig. 4.3, Table 4.3, Table A21). However, the difference in SSB between the 100% compliance with a strict definition scenario and the reference scenario (i.e. what occurred in the fishery) was negligible (p = 0.79)

(Fig. 4.3, Table A21). The SSBs with 100% v-notching compliance with a less strict definition were slightly less than the SSBs with 50% v-notching compliance with a strict definition (Fig. 4.3, Table 4.3).

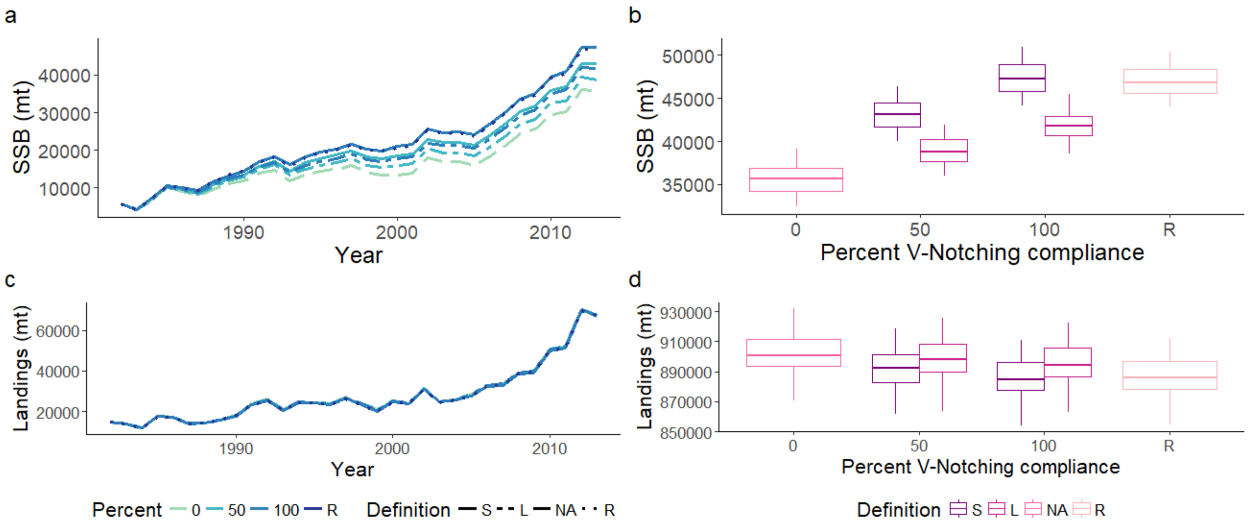

Figure 4.3. V-notching scenarios with historical recruitment. Median American lobster (a) spawning stock biomass (SSB) and (c) landings from 1982−2013 with 0, 50, and 100% v-notching probabilities, with strict (S) and less strict (L) definitions, and with historical recruitment. (b) SSB and (d) cumulative landings in the last year of the simulations (2013) of 0, 50, and 100% v-notching compliance rates with different definitions and with historical recruitment. Results from the reference or historical scenarios are also included. NA: no v-notch definition because there was 0% compliance; R: reference scenario with 90% compliance and a strict definition.

Table 4.3. The median, lower confidence interval (C.I.) (80%), and upper confidence interval (C. I.) (80%) of the spawning stock biomass (SSB) in metric tonnes from the last year of each of the recruitment, V-Notching compliance, and V-Notch definition scenarios.

Scenario	**Median (mt)**	**Lower C.I. (mt)**	**Upper C.I. (mt)**
Reference Scenario (90% compliance with a strict definition)	46868	44863	48991
Historical recruitment			
0%	35600	33273	37698
50% with a strict definition	43096	40924	45715
100% with a strict definition	47316	44920	49262
50% with a less strict definition	38755	36592	40905
100% with a less strict definition	41817	39653	44202
Weak stock-recruitment relationship			
0%	13674	11455	15555
50% with a strict definition	24321	21621	29264
100% with a strict definition	52616	33188	59172
50% with a less strict definition	18026	14865	21115
100% with a less strict definition	22192	20016	25773
Ricker model recruitment			
0%	4049	4671	5314
50% with a strict definition	19141	16787	21522
100% with a strict definition	29631	27161	32844
50% with a less strict definition	10769	9202	12269
100% with a less strict definition	15733	14633	18212
Ricker model recruitment with increased density-dependence			
0%	4266	3794	5103
50% with a strict definition	16250	14861	17873
100% with a strict definition	24224	22534	26945
50% with a less strict definition	9578	8755	11104
100% with a less strict definition	14085	12681	15469

The landings of the different scenarios did not notably differ from each other over time in the historical recruitment scenarios (Fig. 4.3). However, v-notching had a negative effect on cumulative landings (1.9% higher with 0% compliance than with 100% compliance and a strict definition). Most of the cumulative landings of the various scenarios differed significantly (p-values < 0.04), except for the cumulative landings of the strict definition scenarios and reference scenario (p-values > 0.05), the 50% compliance with a strict definition and the 100% compliance with a less strict definition scenarios ($p = 0.228$), and the less strict definition scenarios ($p = 0.348$) (Table A25). The scenario with no v-notching had the highest cumulative landings, followed by the scenarios with less strict definitions, then the scenario with 50% compliance with a strict definition, and then the 100% compliance with a strict definition and reference scenarios (Fig. 4.3, Table 4.4).

Table 4.4. The median, lower confidence interval (C.I.) (80%), and upper confidence interval (C. I.) (80%) of the cumulative landings in metric tonnes of each of the recruitment, V-Notching co mpliance, and V-Notch definition scenarios.

Scenario	**Median (mt)**	**Lower C.I. (mt)**	**Upper C.I. (mt)**
Reference Scenario (90% with a strict definition)	885641	866906	902586
Historical recruitment			
0%	900705	881989	920561
50% with a strict definition	892349	872429	1176305
100% with a strict definition	884293	867689	903623
50% with a less strict definition	897743	877295	913353
100% with a less strict definition	894253	877563	913492
Weak stock-recruitment relationship			
0%	700318	645521	741212
50% with a strict definition	753058	674208	812215
100% with a strict definition	928331	742080	995844
50% with a less strict definition	709219	644956	782125
100% with a less strict definition	736278	667777	801478
Ricker model recruitment			
0%	347086	332866	366472
50% with a strict definition	525284	502732	563015
100% with a strict definition	624020	605157	675085
50% with a less strict definition	440004	416481	468897
100% with a less strict definition	494312	468181	529320
Ricker model recruitment with density-dependence			
0%	279149	264276	290662
50% with a strict definition	431833	408764	458245
100% with a strict definition	515884	488519	548969
50% with a less strict definition	362657	341657	379928
100% with a less strict definition	403271	385252	435226

4.4.2. Simulation results for weak stock-recruit relationships

For the weak stock–recruitment relationship scenarios, v-notching positively affected SSBs (285% higher with 100% compliance and a strict definition than with 0% compliance) (Fig. 4.4, Table 4.3). The SSBs from the reference scenario (i.e. what occurred in the fishery) were slightly below the SSBs from the 100% compliance with a strict definition scenario (Fig. 4.4, Table 4.3). The final SSBs were highest with the 100% v-notching compliance with a strict definition (Fig. 4.4, Table 4.3). Scenarios with strict definitions resulted in an increase in SSB that was not observed in the less strict definition scenarios (Fig. 4.4). Also, the final SSBs in each of the scenarios differed significantly (p-values < 4.17 × 10–5), except for the difference between the 100% compliance with a strict definition and reference scenarios ($p = 0.79$) (Table A22).

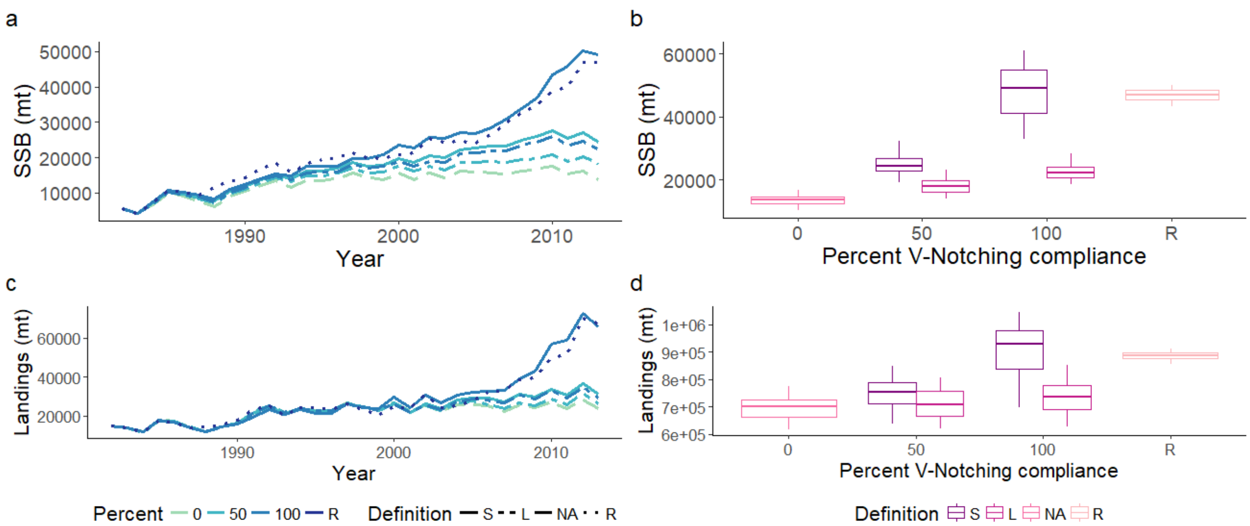

Figure 4.4. Same as Fig. 4.3, but showing the results of the simulations with the weak-stock recruitment relationship.

For the weak stock–recruitment relationship scenarios, v-notching had a positive effect on cumulative landings (33% higher with 100% compliance and a strict definition than with 0% compliance) (Fig. 4.4, Table 4.4). The landings of the 100% compliance and strict definition and reference scenarios increased dramatically after 2005, unlike the landings from the other scenarios (Fig. 4.4). Like the SSBs, the landings were highest with 100% compliance and a strict definition, followed by the reference scenario landings, landings with 50% compliance and a strict definition, landings with 100% compliance and a less strict definition, landings with 50%

compliance and a less strict definition, and then landings with 0% compliance (Fig. 4.4, Table 4.4). The landings from the reference and the 100% compliance and strict definition scenarios were similar throughout the time series (Fig. 4.4). In the scenarios with 100% compliance and a less strict definition and 50% compliance and a strict definition, the landings were similar (Fig. 4.4, Table 4.4). Most of the cumulative landings differed significantly (p-values < 0.04), except for the cumulative landings from the 100% compliance with a strict definition and reference scenarios ($p = 0.74$), from the 50% compliance with a strict definition and 100% compliance with a less strict definition scenarios ($p = 0.33$), and from the 50% compliance with a less strict definition and 0% compliance scenarios ($p = 0.08$) (Table A26).

4.4.3. Simulation results with strong stock-recruit relationships

When theoretical stock−recruitment models estimated recruitment, the best model was the Ricker model without temperature. The AIC value for the Ricker model without temperature was the lowest (57.6), followed by the AIC value for the Beverton-Holt model with temperature (58.9394), and the Ricker model with temperature (58.9396). The Beverton-Holt model without temperature did not converge. The predicted recruits from the best model overall followed the same trend as the historical recruits; however, the model tended to overestimate recruits at intermediate levels of SSB and underestimate recruits at high and low levels of SSB (Fig. A21). The bootstrapped β parameters were all small negative numbers close to zero, so the modified β parameter distribution for increased density-dependence was the positive transformation of the bootstrapped distribution.

Because the Ricker model could not accurately estimate lobster recruitment at low and high SSBs, the SSBs in all scenarios with recruitment estimated from the Ricker model and the Ricker model with an increased density-dependence effect were lower than the reference SSB

(Figs. 4.5 & 4.6, Table 4.3). With the Ricker models, v-notching had a positive effect on SSB (468–632% higher with 100% compliance and a strict definition than with 0% compliance) (Figs. 4.5 & 4.6, Table 4.3); 100% compliance with a strict definition most positively affected SSB, and the SSBs with no v-notching decreased over time (Figs. 4.5 & 4.6). The SSBs in the other scenarios did not increase drastically over time (Figs. 4.5 & 4.6). With an increased density-dependence effect, the results were similar to that of the regular Ricker model, but the differences between the compliance and definition scenarios were smaller (Fig. 4.5, Fig. 4.6, Table 4.3). All the final SSBs significantly differed from each other (p-values < 2.71 × 10–13) (Tables A3 and A4).

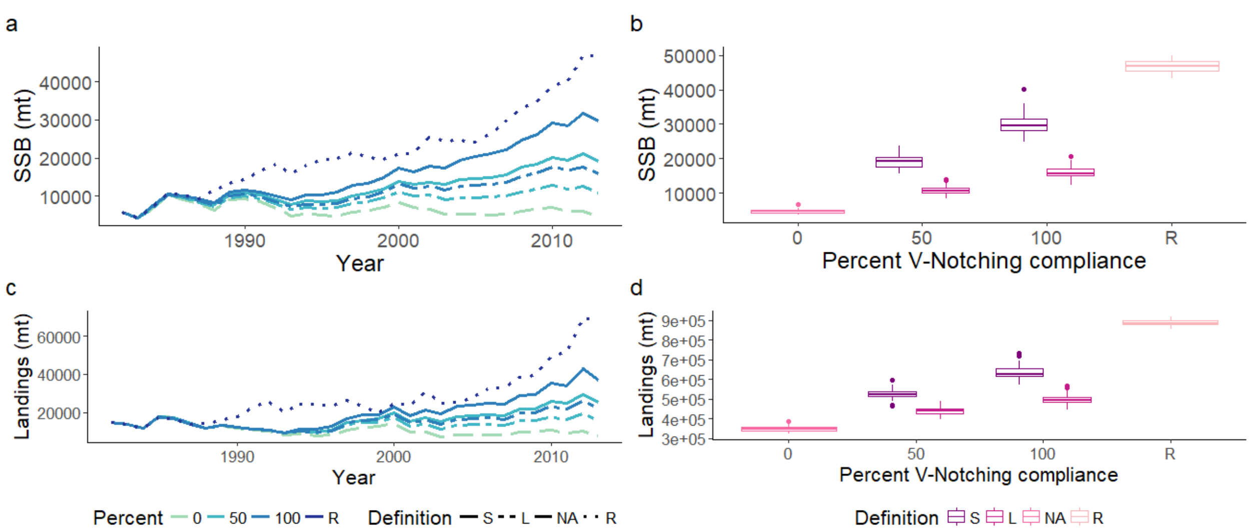

Figure 4.5. Same as Fig. 4.3, but showing the results of the simulations with the Ricker stock-recruitment model.

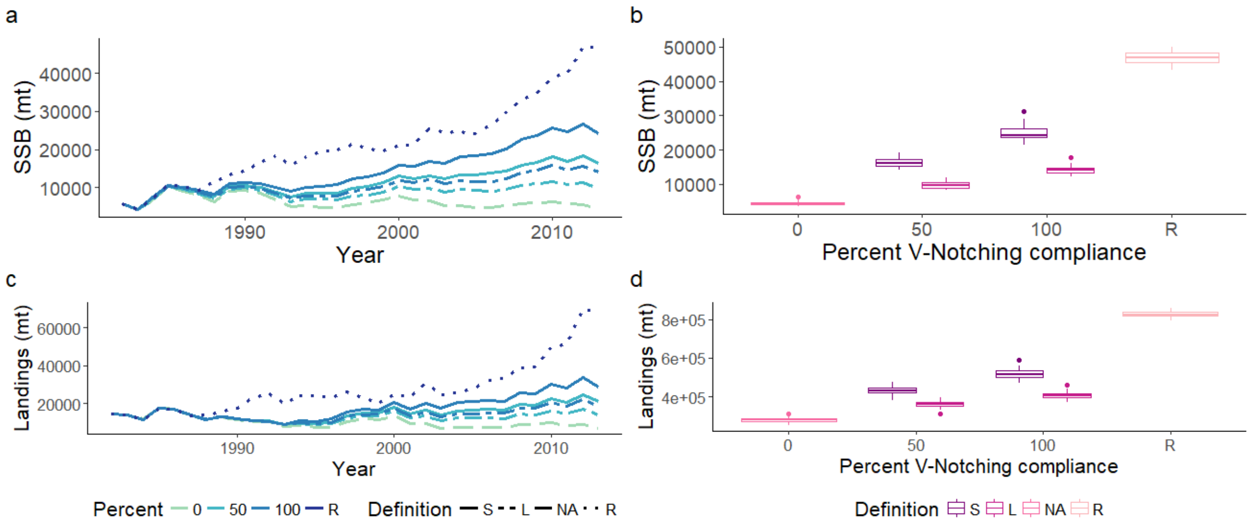

Figure 4.6. Same as Fig. 4.3, but showing the results of the simulations with the Ricker stock-recruitment model with an increased density-dependence effect.

Like the SSBs, cumulative landings were positively affected by v-notching with recruitment from the Ricker models (80–85% higher with 100% compliance and a strict definition than with 0% compliance) (Figs. 4.5 & 4.6, Table 4.4). Cumulative landings from the reference scenario were higher than that of all the different v-notching scenarios with recruitment estimated from the Ricker models (Figs. 4.5 & 4.6 , Table 4.4). Regardless, the landings increased with 100% compliance (Figs. 4.5 & 4.6). Similar to the SSBs with recruitment from the Ricker model, the landings also decreased with no compliance (Figs. 4.5 & 4.6). V-notching significantly positively affected landings (p-values < 4.10 × 10–8) (Tables A7 & A8). There were no large differences between the cumulative landings of the regular Ricker model and the Ricker model with an increased density-dependence effect, but there were larger differences between the compliance and definition scenarios with the regular Ricker model than with the Ricker model with an increased density-dependence effect (Figs. 4.5 & 4.6, Table 4.4).

4.5. Discussion

The results of this study support the consensus among lobster fishers (Acheson and Gardner 2010) that the protection of spawning female American lobsters, in this case by v-notching, has had a positive impact on the GOM lobster population and fishery. The magnitude of the positive impact of v-notching depended on the assumptions of the stock−recruitment relationship, compliance rate, and v-notch definition. V-notching always had a positive impact on SSB, and the impact on cumulative landings depended on the stock−recruitment relationship.

In all scenarios, v-notching preserved SSB, which can act as a buffer if there were a downturn in the fishery or population. With historical recruitment, even if only half of the egg-bearing lobsters that were caught were v-notched, there would still be a significant positive impact on the population (21% larger with 50% compliance and a strict definition than with 0% compliance). With the assumption of a weak stock−recruitment relationship, v-notching had even greater impacts on the population, as the protected spawning stock contributed recruits into the fishery (285% larger with 100% compliance and a strict definition than with 0% compliance). Under this weak stock−recruitment relationship recruitment scenario, there were even more advantages to a higher v-notch compliance rate and strict v-notch definition. SSB did not experience such a dramatic increase without high compliance rates and a strict definition. With the assumption of a stock−recruitment model, a higher v-notch compliance and a strict v-notch definition had a significant large positive impact as well (468–632% higher with 100% compliance and a strict definition than with 0% compliance). Preserving SSB becomes increasingly important in the face of climate change, since warming waters may have deleterious effects on the lobster population. Le Bris et al. (2018) projected the American lobster fishery with warming water temperatures and found that management measures for conserving the reproductive potential can help mitigate the negative effects of climate change.

The impact of v-notching on landings depended on the compliance, definition, and recruitment scenario. In historical recruitment scenarios, no v-notching produced the highest cumulative landings (1.9% higher with 0% compliance than with 100% compliance and a strict definition). With the assumption of a stock–recruitment relationship, v-notching had a positive impact on landings (33–85% higher with 100% compliance and a strict definition than with 0% compliance).

The results from these simulations also suggest that the v-notch definition had an important role. In all recruitment simulation scenarios, even 100% compliance with a less strict definition did not produce more SSB than 50% compliance with a strict definition. In the weak stock–recruitment relationship scenarios, even with 100% compliance rate but with a less strict definition, the SSB and landings would not have experienced a dramatic increase. However, this does depend on the assumptions in this study. One assumption is that the lobsters v-notched stay in the GOM stock area. If they were to go to another area, they could be landed with a less strict v-notch definition. Also, if egg production were used as a metric instead of SSB, there is the possibility that a lobster could be v-notched and never contribute more eggs under a less strict assumption, because mature lobsters bear eggs every other year.

A strict definition of a v-notch only benefits SSB and does not reduce landings with a stock–recruitment relationship, suggesting that all areas should use a strict definition of a v-notch (i.e. takes at least 2 molts to grow out). Without high compliance and a strict definition, there is a risk of a negative impact on the fishery. The state of Maine has the strictest definition of a v-notch, but other US states and Canada currently have a less strict definition of a v-notch.

The v-notching conservation measure sustained viable levels of fishery activity and is appropriate assuming that one objective of management is to maximize yield, under sustainability restraints. With conservation of biomass and an increase in landings, v-notching can be considered a tool for community-based conservation, in which both conservation and development are achieved (Berkes 2004). These results suggest that input controls, such as v-notching, can significantly benefit fish populations and fisheries.

However, v-notching compliance has decreased in recent years in the Maine lobster fishery. In this study, we simulated constant compliances to determine the effect of v-notching; currently, the magnitude of the change in compliance and when this change began to occur is unknown. Future studies should focus on lobster fishers' behavior regarding v-notching—more specifically, when the v-notching compliance began to decrease and how v-notching compliance changes with the status of the lobster population.

Future studies should also focus on understanding lobster recruitment, as the model results are dependent upon recruitment assumptions. This is especially important in understanding the effects of a conservation measure that protects the spawning stock with the long-term objective of increased recruitment. It was difficult to compare the results from the Ricker model recruitment scenarios to the reference scenario, because the Ricker model did not accurately capture historical recruitment. In general, the Ricker models were unable to represent the observed data, especially at high and recent SSBs. As a result, the results from the Ricker model scenarios could not be easily used to determine the effect of v-notching. However, if there were no stock−recruitment relationship, regulations that protect the spawning stock would not be important for the future of the fishery. In reality there is a stock−recruitment relationship that the data cannot show because of possibly large measurement errors, spatial differences in stock−

recruitment relationships, and influences from environmental factors aside from temperature (Hilborn and Walters 1992). Chang et al. (2016) found that different stock−recruitment relationships existed at different spatial scales for the American lobster, possibly resulting from retention of pelagic larvae by oceanic circulations in the GOM (Xue et al. 2008), and the best model was at a medium spatial scale. Additionally, the productivity of American lobsters in the GOM may be changing due to increasing water temperatures which has caused an increase in suitable habitat (Tanaka and Chen 2016). In this study, the average temperature of FVCOM stations was used, but FVCOM stations are not distributed evenly throughout the GOM, which could have led to bias in the temperature averages. Temperature can also affect the stock-recruitment process at many different stages. At the larval stage, sea surface temperature may impact larval survival by increasing larval growth and therefore shortening the length in the water column (Incze and Naimie 2000) and decreasing larval vulnerability to predation. At the settlement stage, if waters are above 12°C, settlement habitat expands (Steneck and Wahle 2013). Increasing water temperatures also cause lobsters to molt more frequently (Comeau and Savoie 2001), which could decrease the lag between SSB and recruits, but it could also increase the number of recruits entering the fishery each year, as more lobsters are molting. This partially explains why a stock−recruitment relationship was difficult to find at a large spatial and temporal scale, such as the whole GOM from 1982−2013.

4.6. Conclusions

The IBLS model results showed that v-notching has a significant positive impact on the GOM lobster SSB (33–632% higher with 100% compliance and a strict definition than with 0% compliance) regardless of the stock−recruitment assumption and a significant positive impact on landings (33–85% times higher with 100% compliance and a strict definition than with 0%

compliance) with a stock− recruitment relationship. The higher the compliance rate and the stricter the v-notch definition, the greater the positive impact on the fishery and population. The stock− recruitment relationship assumed in the model can influence the magnitude of the positive effect of v-notching. The framework proposed in this study can be extended to evaluate conservation and management measures in other fisheries.

CHAPTER 5

IDENTIFYING THE IMPACT OF BOTTOM WATER TEMPERATURE ON STOCK-RECRUITMENT RELATIONSHIPS

5.1. Abstract

The Gulf of Maine (GOM) American lobster landings have increased dramatically in the past few decades, as a result of substantially increased recruitment, making it the most valuable fishery in the United States. Although the increased recruitment is related to high spawning stock biomass (SSB) resulting from various conservations measures, a functional stock-recruitment relationship (SRR) is difficult to define. The GOM bottom water temperatures have increased at a rate of 0.2ºC per decade, which caused lobster settlement area to expand, adding to the complexity of understanding recruitment dynamics. To give more effective advice for fisheries management, this paper’s aim was to further investigate the SRR for American lobster by including bottom water temperature anomalies as a covariate. We first estimated a grid of SSB using bottom trawl survey data in a generalized linear mixed model. Using the estimated SSB and recruitment data from a ventless trap survey, we developed modified Ricker stock-recruitment models that accounted for spatial heterogeneity and dependence with varying coefficient generalized additive models. The results showed that temperature had a strong effect on recruitment. Additionally, a temporal shift in temperature mediated productivity in the SRR was identified in 2009. Our study demonstrated that climate driven SRRs and biological reference points should be considered for American lobster management. These methods can be applied to many other commercial fisheries to understand recruitment dynamics influenced by climate change.

5.2. Introduction

Stock-recruitment relationships (SRRs) are critical for understanding fisheries population dynamics (Cobb and Caddy, 1989). Recruitment dynamics are greatly influenced by many biotic and abiotic factors that affect survival from the eggs to the juveniles in the population (Ulltang, 1996). Because there are large inter-annual variabilities in these factors and susceptibility of early life history processes, SRRs often have large variability and are difficult to define (Subbey et al., 2014). However, quantifying SRRs is important for determining biological reference points (BRPs), projections of alternative fishery management scenarios, and sustainable harvest rates in fisheries management (Van Poorten et al., 2018). Large uncertainty in defining SRRs is often considered a major obstacle for developing and identifying effective fisheries management. Sometimes, SRRs are difficult to identify, because recruitment processes occur at a spatial scale smaller or larger than the stock area (Chang et al., 2015) and environmental conditions change over time. Scales of recruitment variability in marine species often correspond with large-scale environmental variables (Myers et al., 1997). Changes in environmental conditions, including temperature, can affect the productivity of the stock-recruitment (SR) process (Tang, 1985; Jacobson and MacCall, 1995; Ratz and Lloret, 2003). This makes biological sense, as temperature influences energy used for metabolism and respiration (Whiteley et al., 2001) and diet composition (D'Abramo, 1979).

Previous studies have incorporated environmental effects into SRRs (Tang, 1985; Fiksen and Slotte, 2002; Mikkelsen and Pedersen, 2004; Yatsu et al., 2005; Kienzle and Sterling, 2017) to reduce the unexplained SR variation (Subbey et al., 2014). Including temperature in SR models (i.e. blue crab in the Chesapeake Bay (Tang, 1985), Norwegian herring (Fiksen and Slotte, 2002), Japanese sardine and chub mackerel (Mikkelsen and Pedersen, 2004), and brown tiger prawn in Moreton Bay in Australia (Kienzle and Sterling, 2018)) has improved recruitment prediction power and provided a basis for fishery management under different stock-recruitment productivities caused by changing environmental conditions and regime shifts.

The American lobster fishery is the most valuable single-species fishery in the United States (NOAA, 2017), worth more than 624 million USD in 2018 (ACCSP, 2019). Around 82% of the American lobster landings come from the Maine lobster fishery (ACCSP, 2019). In the Gulf of Maine (GOM), lobster recruitment, as well as landings and biomass, have increased dramatically in the past few decades (ASMFC, 2015). However, a SRR has not been defined in the most recent benchmark stock assessment (ASMFC, 2015) because of uncertainty in the lag between spawning stock biomass (SSB) and recruitment and the lack of flexibility in estimating recruitment. American lobster recruitment is also influenced by environmental factors, including temperature (Ennis, 1986). Bottom water temperatures in the GOM are increasing at a rate of 0.2ºC per decade (Kavanaugh et al., 2017). With increasing bottom water temperature, lobster settlement area expands (Annis, 2005; Goode et al., 2019). Other lobster recruitment processes are also affected by temperature. As sea surface temperature rise, larval duration decreases and vulnerability to predators decreases as a result (Incze and Naimie 2000). Increasing water temperatures also decreases the brooding duration of eggs, which results in a earlier hatch and a longer summer for first-year growth. Additionally, GOM lobster recruitment processes are likely occurring at a smaller spatial scale than the whole GOM lobster management area (Chang et al., 2015). The spatial scale at which SRRs are analyzed impacts the possibility of identifying a SRR, the estimation of SR model parameters, the type of SRR, and the predictive performance of SR models (Chang et al., 2015).

The GOM represents an excellent test site for studying nonstationary SRRs because of the differences in oceanography between the western and eastern GOM. This study focuses on inshore waters off the Maine coast, as these waters make up most of the inshore GOM. The Western Maine Coastal Current (WMCC) is characterized by strong stratification and weaker than the Eastern Maine Coastal Current (EMCC). The EMCC is a strong coastal current that creates a well-mixed water column. During the summer, the bottom water in the west can be colder than the bottom water in the east, while the west has relatively warm sea surface temperature (Pettigrew et al., 2005). The GOM is also an ideal system to examine the effect of temperature on a SRR because of the wide range of bottom water temperatures experienced in the region. The goals of this study are to 1) estimate temperature mediated productivity, or temperature mediated reproduction rate in the SR, for American lobster in the GOM and 2) evaluate changes in temperature mediated productivity over time. The principles and methodologies underlying our analysis suggest ways to identify the impact of environmental variables on spatially varying SRRs.

5.2. Materials and Methods

Datasets are assembled so that SRRs can be fit in the inshore Gulf of Maine over space with the incorporation of temperature. Fitting the desired temperature mediated SRR requires co-located estimates of SSB and temperature for each location and time where recruitment is observed.

Lobster recruitment data were obtained from the state of Maine's Ventless Trap Survey (VTS) (Maine DMR, 2019a) (Figs. 5.1, A31, and A32). This random stratified survey has been running since 2006 from June to August. The collaborative, fishery-independent survey is conducted by the Maine Department of Marine Resources (DMR) and contracts lobster fishers along the coast of Maine. Three ventless traps are deployed at each site which are in the three federal statistical areas in the GOM and stratified by depth (1-20, 21-40, 41-60 m). Biological parameters (including carapace length (CL in mm), sex, egg status, cull status, and disease status) and effort parameters (including depth, set over days, latitude, and longitude) are recorded during the survey. Set over days is the number of days that the trap was in the water. In some traps, not all the lobsters were measured, but a quantity was reported. Unmeasured lobsters were usually a result of voice recorder complications. In these rare cases, we applied the same size frequency for the unmeasured lobsters as the measured lobsters in each trap, because length frequencies in inshore areas are very stable (Maine DMR, pers. comm.). Although different definitions of lobster recruits have been used in previous studies, such as young of year lobsters, lobsters at 53 mm CL (minimum size of lobsters in the stock assessment), and lobsters around 83 mm CL (minimum size of lobsters in the fishery). In this paper, define recruits as lobsters smaller than 50 mm CL, because lobsters under 50 mm CL are not migrating seasonally with reproductive lobsters and can be assumed to be near the location that they initially settled (Lawton and Lavalli, 1995). This way, recruits can be assumed to be generated from the SSB in the surrounding area four years prior.

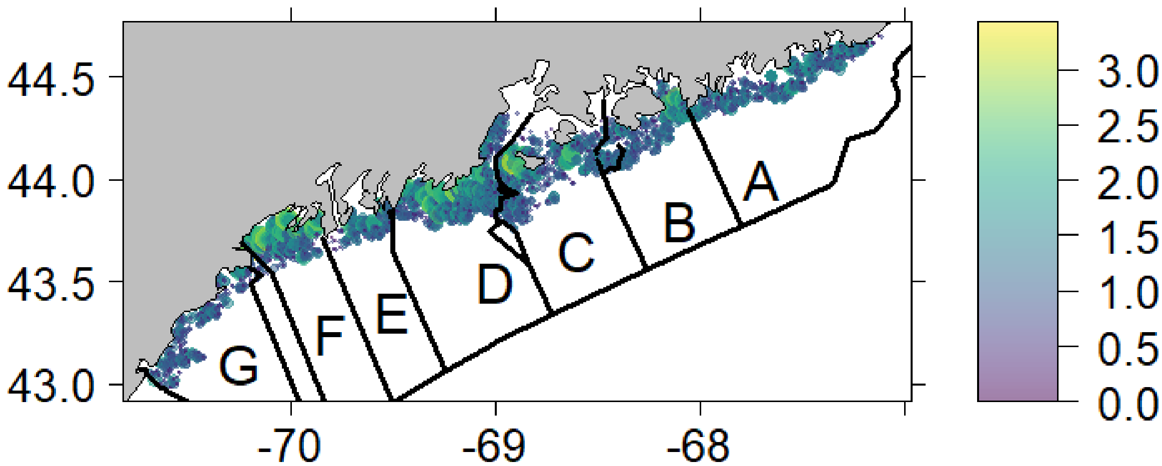

Figure 5.1. Log-transformed mean values of recruitment catch from the Maine DMR Ventless Trap Survey from 2006-2018. Lobster management zones are labeled (A-G). Lobster zones A-C (not including the zone C/D overlap) make up the eastern GOM and lobster zozones D-G (including the zone C/D overlap) make up the western GOM (Chang et al. 2016).

Lobster SSB data were from the Maine-New Hampshire (ME-NH) (2000-2018) fall inshore trawl survey data (ASMFC, 2015 & 2018). These surveys are fishery-independent scientific bottom trawl surveys that employ stratified random sampling by 4 depth strata and 5 regions. To estimate SSB across space and time, we fitted a delta generalized linear mixed model (GLMM) to the trawl survey data using the *VAST* (version 3.2.2) package in R (Thorson 2019; Figs. A33, A34, A35, and A36). SSB was the weight of mature female lobsters. The proportion of mature female lobsters at each size was determined by the logistic equation (ASMFC 2015):

$$P_{matcl} = \frac{1}{1+ e^{25.76-0.29*CL}} \quad (10)$$

SSB density is inferred throughout the study area with this two-stage model. The first stage estimates the probability of encountering female catch, and the second stage estimates catches of

SSB when SSB is present. The delta GLMM allowed us to estimate a continuous field of SSB. Variables in the GLMM included annual intercepts, vessel effects, spatial random effects, and spatio-temporal random effects. We offset SSB by 4 years to account for lobster growth to around 50 mm CL, which can range from 3 to 5 years (McCay et al., 2003; Kilada et al., 2012). Fall SSB was used as a proxy for SSB in the summer, during which egg release occurs, because fall SSB should be similar to summer SSB, as lobsters have not begun their migration yet in the fall.

For environmental data, we used spring and fall bottom water temperature data at a spatial resolution of 0.1° based on an interpolation procedure described in Friedland et al. (2018) (Fig. A37). This procedure combines a kriged interpolation of annual data with climatological data to estimate a complete temperature field, preserving the observational nature of the data. Temperature was collected with conductivity/temperature/depth (CTD) instruments, with most sample coverage in the spring (February-April) and fall (September-November), associated with the trawl survey that is the source of the SSB data. Differences in the date of collection between years were corrected by standardizing to the spring and fall mean dates for collection. Temperature affects lobster settlement, which occurs in the first year of a lobster's life during late summer or early fall, because warming waters increase settlement success in deeper waters (Annis, 2005). Temperature also affects the catchability of lobsters, because lobsters become more active as temperature increases (McLeese and Wilder, 1958). Additionally, lobsters grow at different rates, due to size and maturation status; therefore, the age of lobsters is difficult to determine (Factor, 1995; Comeau and Savoie, 2001). To account for these factors, we offset the average of spring and fall bottom water temperature anomalies by four years and then took a moving average of offset SSB and offset bottom water temperature anomalies with a three-year window. Anomalies were calculated as the difference from the mean temperature at a given grid. Anomalies were used, because the purpose of including temperature was to identify how temperature mediated productivity has changed overtime. As a result of offsetting and averaging SSB and temperature anomalies, it was assumed that the recruits during a given year derive from the SSB of 3 to 5 years earlier and are affected by temperature at settlement, which occurred 3 to 5 years earlier. We also used current bottom water temperature anomalies, which was the average of the spring and fall bottom water temperature anomalies for the current year, to account for the effect of bottom water temperature on catchability in the VTS. We assume the average of fall and spring bottom water temperatures affect the catchability of the VTS, because we did not have access to bottom water temperatures in the summers. Set over days was also included to account for its effect on catchability.

Because Ricker SR models predicted recruitment the best at small spatial scales for lobster in the GOM in a previous study (Chang et al., 2015), we chose to modify Ricker SR models in this study. A Ricker SRR has the general format of $R = \alpha S exp^{-\beta S}$, where R is recruitment, S is the SSB, α is a parameter related to productivity or rate of reproduction, and β is a parameter related to density-dependent effects (Ricker, 1954). The explanatory variables used in this study include offset average SSB, offset average bottom water temperature anomalies, current bottom water temperature anomalies, and set over days. Including offset average SSB forms the basis of the SRR. Including offset average bottom water temperature anomalies identifies the effect of offset temperature on productivity (α). Including current bottom water temperature anomalies and set over days accounts for the effect of these variables on the catchability of recruits. Before fittng SRR models, we conducted a Variance Inflation Factor

(VIF) test, which quantifies the degree of multicollinearity among explanatory variables. All VIFs were under 3 (Table A31), indicating that multicollinearity was acceptably low.

Spatial scales of the SRRs for GOM lobster are smaller than the whole GOM management area and differ between the eastern and western GOM (Chang et al., 2015). To account for this spatial nonstationarity, we modified Ricker SR models using variable coefficient generalized additive models (GAMs) to allow coefficients to vary across latitude and longitude, which accounts for spatial heterogeneity and dependence. In a variable coefficient GAM, the relationship between the response and designated model covariates is spatially variable and locally linear. SRRs are likely to differ throughout the GOM due differences in settlement habitat and differences in currents and therefore larval transport. A variable coefficient GAM allows the relationships to vary over space and accounts for the influence of nearby locations. This accounts for larval movement from locations of SSB in addition to local larval supply and differences in settlement habitat. To linearize the Ricker model, we included the log of recruits per SSB as the response variable (Fig. A38). We developed three different modified Ricker models:

$$log(R_{it}/S_{it-4}) = \beta_0(X_i, Y_i) + \beta_1 S_{it-4} + \beta_2(X_i, Y_i)(T_{it-4}) + f(T_{it}) + f(SOD_{it}) \quad (11)$$

$$log(R_{it}/S_{it-4}) = \beta_0(X_i, Y_i) + \beta_1 S_{it-4} + f(T_{it}) + f(SOD_{it}) \quad (12)$$

$$log(R_{it}/S_{it-4}) = \beta_0 + \beta_1 S_{it-4} + f(T_{it}) + f(SOD_{it}) \quad (13)$$

where R_{it} is the number of recruits at location *i* and year *t*, and S_{it-4} is the averaged offset SSB at location *i* and year *t-5, t-4,* and *t-3*. $\beta_0(X_i, Y_i)$ is the intercept at location *i*s, or the log of the density-independent SRR parameter (α), which allows for a spatially-varying SR productivity. β_0 in equation 13 does not allow for a spatially-varying intercept. β_1 is the coefficient for the effect of SSB, or the density- dependent effect. $\beta_2(X_i, Y_i)$ is the coefficient for the effect of offset average temperature anomalies at location i, which identifies the effect of offset temperature on productivity. e.,., T_{it-4} is average offset bottom water temperature anomaly at location *i* and year *t-5, t-4,* and *t-3*, T_{it} is the current bottom water temperature at location i, representative of catchability effects, and SOD_{it} is set over days at location *i,* and year *t,* also representative of catchability effects. Each location is a VTS site. From these models, spatially varying productivity (α) and spatially-varying effect of offset temperature on αare estimated. This creates a linear effect of offset bottom temperature anomalies at each location. By taking the exponent of the estimated intercept, intercepts can be transformed into the α parameter of the Ricker model. Coefficients for density-dependence and catchability effects current do not vary over space. The spawning stock biomass coefficient is the $-\beta$ parameter of the Ricker model, which is a linear effect. Catchability effects are nonlinear. Equation 11 is the modified Ricker model with an effect of lagged temperature anomalies, and equation 12 is the modified Ricker model without an effect of lagged temperature anomalies. Equation 13 is the Ricker model with no spatial variation or effect of lagged temperature anomalies. We used the Gaussian distribution for each of the models. All GAMs were fitted for the time series 2006- 2018 using the R package *mgcv*. Variables that were not significant were removed from the models.

To find the best model, we used a variety of criteria, including Akaike Information Criterion (AIC), mean squared error (MSE), and deviance explained. Parsimonious GAMs were identified using AIC and MSE. We found MSE using 10-fold cross-validation. To do so, the dataset was randomly split into 10 different groups and cross-validation was performed. We then used ordinary kriging to create spatial plots for productivity (α) and the effect of offset temperature on productivity.

We calculated changes in mean temperature mediated -productivity over time, using α and the effect of offset temperature anomalies(Mantzouni et al., 2010):

$$Temperature\ mediated\ productivity = exp^{(\log(\alpha)+(\beta_2 * T_{it-4}))} \quad (3)$$

If there were to be no effect of offset temperature anomalies, productivity would be based solely on α. Thus, changes in temperature mediated productivity over time are based solely on temperature anomalies and the estimated temperature effect.

Based on the historical temperature data (Friedland et al., 2018) from 1982 to 2018, we hindcasted temperature mediated productivity from 1982, which is the start of the most recent lobster stock assessment model time series (ASMFC, 2015). We then performed a segmented regression to find the year at which temperature mediated productivity in the lobster SRR shifted in the GOM. All statistical analyses were conducted in the R programming environment (v 3.5.3.; R Core Team, 2019).

5.4. Results

In all models, set over days were not significant and removed. The GOM lobster SRR was best explained with spatially varying productivity an effect of offset temperature anomalies (i.e., the lowest AIC, the lowest MSE, and highest deviance explained, Table 5.1). However, there were some patterns in the residuals (Fig. A39). The Ricker model without spatially-varying productivity or the effect of offset temperature anomalies had the highest MSE, highest AIC and the lowest deviance explained (Table 5.1).

Table 5.1. Generalized additive model (GAM) structures and selection criteria. See methods for description of model terms. AIC, Akaike Information Criterion; MSE, mean squared error; Dev expl, % deviance explained.

Model	AIC	MSE	Dev expl
$log(R_{it}/S_{it-4}) = \beta_0(X_i, Y_i) + \beta_1 S_{it-4} + \beta_2(X_i, Y_i)(T_{it-4}) + f(T_{it}) + f(SOD_{it})$	**27942.86**	**0.462**	**61.90**
$log(R_{it}/S_{it-4}) = \beta_0(X_i, Y_i) + \beta_1 S_{it-4} + f(T_{it}) + f(SOD_{it})$	28152.71	0.470	61.20
$log(R_{it}/S_{it-4}) = \beta_0 + \beta_1 S_{it-4} + f(T_{it}) + f(SOD_{it})$	30535.98	0.560	53.50

The density-dependent effect (β_1) was estimated to be -0.03. Productivity (α) varied over space (Fig. 5.2). Productivity was highest in the inshore western GOM and off the midcoast. Productivity was the lowest in the far western GOM and eastern GOM.

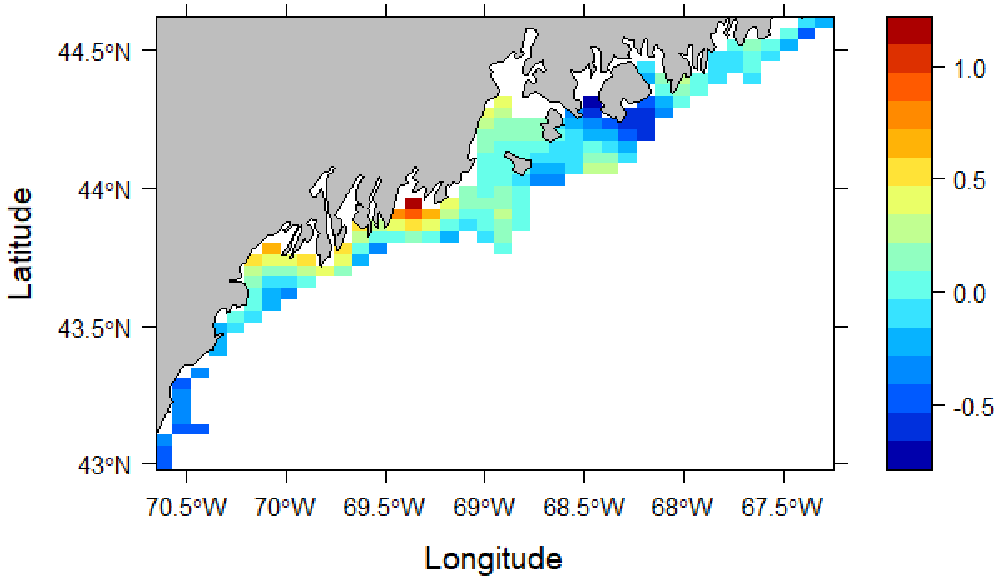

Figure 5.2. Logged productivity (α) parameters (intercepts) in the SRRs over space in the inshore Gulf of Maine.

The effect of offset temperature anomalies on the reproduction rate also varied over space (Fig. 5.3). The effect of offset temperature anomalies was highest closer to the offshore eastern GOM and lowest in the inshore western GOM. Although some of these coefficients are negative, when converted to the effect on productivity in the SRR by taking the exponent, these values become positive.

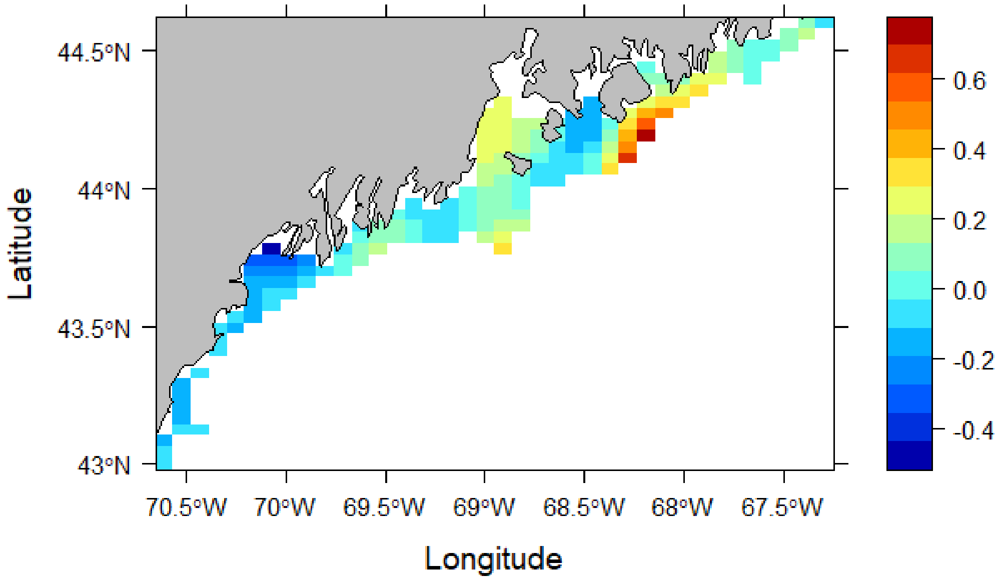

Figure 5.3. Coefficients of offset temperature anomalies in the SRRs over space in the inshore Gulf of Maine.

Mean temperature mediated productivity varied throughout space, but with highest temperature mediated productivity in the western GOM and off midcoast Maine (Fig. 5.4a). Changes in temperature mediated productivity varied throughout the inshore GOM (Fig. 5.4b). The largest increases in temperature mediated productivity were in the eastern GOM. Temperature mediated productivity decreased in the portions of the western GOM.

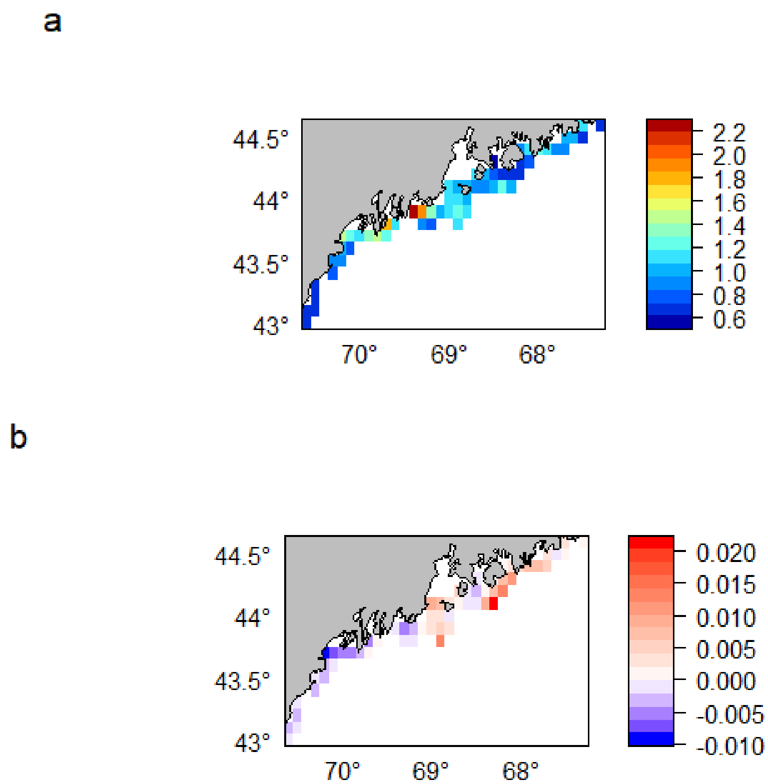

Figure 5.4 Mean and change in temperature mediated productivity. a) Mean temperature mediated productivity (calculated using α and the effect of offset temperature anomalies) and b) slope of the change in temperature mediated productivity in the stock-recruitment relationship from 1982-2018 in the Gulf of Maine.

In the whole GOM, temperature mediated productivity increased overtime, although there was variability (Fig. 5.5a). According to the segmented regression, the shift in increase of temperature mediated productivity occurred in 2008. After 2008, temperature mediated productivity increased faster. The segmented regression had an R squared value of 0.00089, and the difference in slopes was not significant (p-value=0.3528). Stock recruitment curves tended to be steeper later in the time series (Fig. 5.5b).

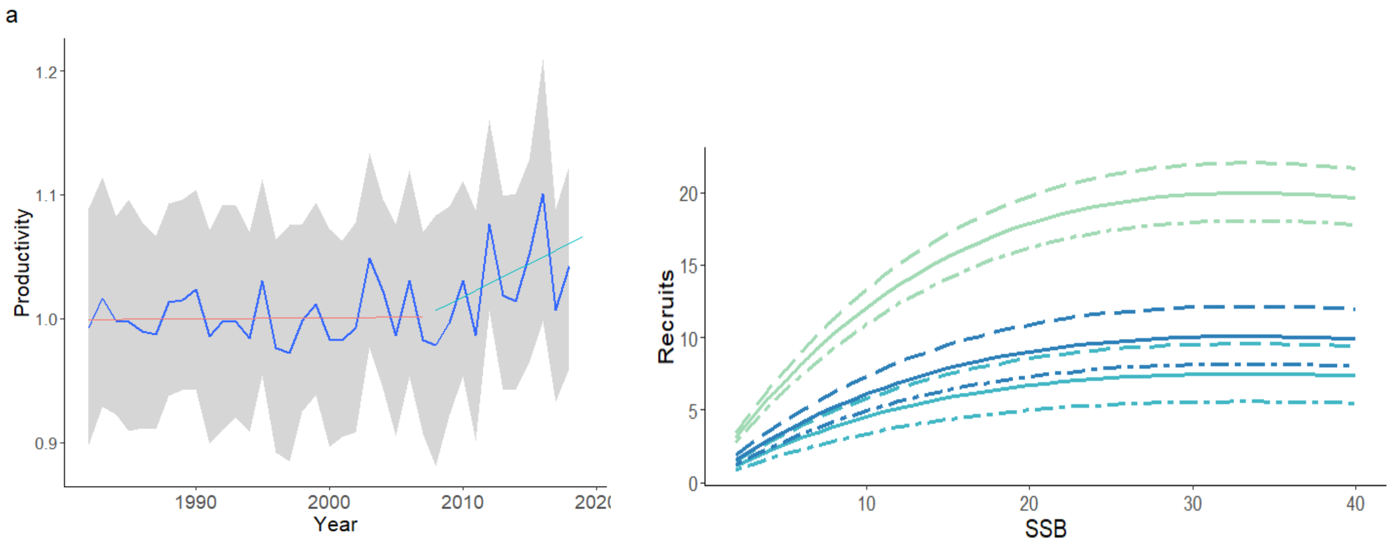

Figure 5.5. Temperature mediated productivity overtime and temperature mediated stock-recruit curves. a) Temperature mediated productivity in the stock-recruitment relationship over time (1982-2019) in the Gulf of Maine. The red line represents the fitted regression before 2008 (slope=0.000082) and the blue line represents the fitted regression from 2008 to 2019 (slope=0.0054). b) Estimated stock-recruitment curves in the inshore Gulf of Maine with the 5th, 50th, and 95th percentiles of productivity over space (solid lines) and with applied effects of temperature anomalies (5th and 95th percentiles) (dotted lines)

Trends in temperature mediated productivity in the eastern and western GOM differed (Fig. 5.6). In the western GOM, temperature mediated productivity stayed similar overtime. Although there is a slight decrease in temperature mediated productivity in the western GOM near the end of the time series, temperature mediated productivity in the western GOM was usually higher than that in the eastern GOM. In the eastern GOM, temperature mediated productivity was variable overtime but increased overall. Near the end of the time series, temperature mediated productivity in the eastern GOM seems to increase to the level in the western GOM.

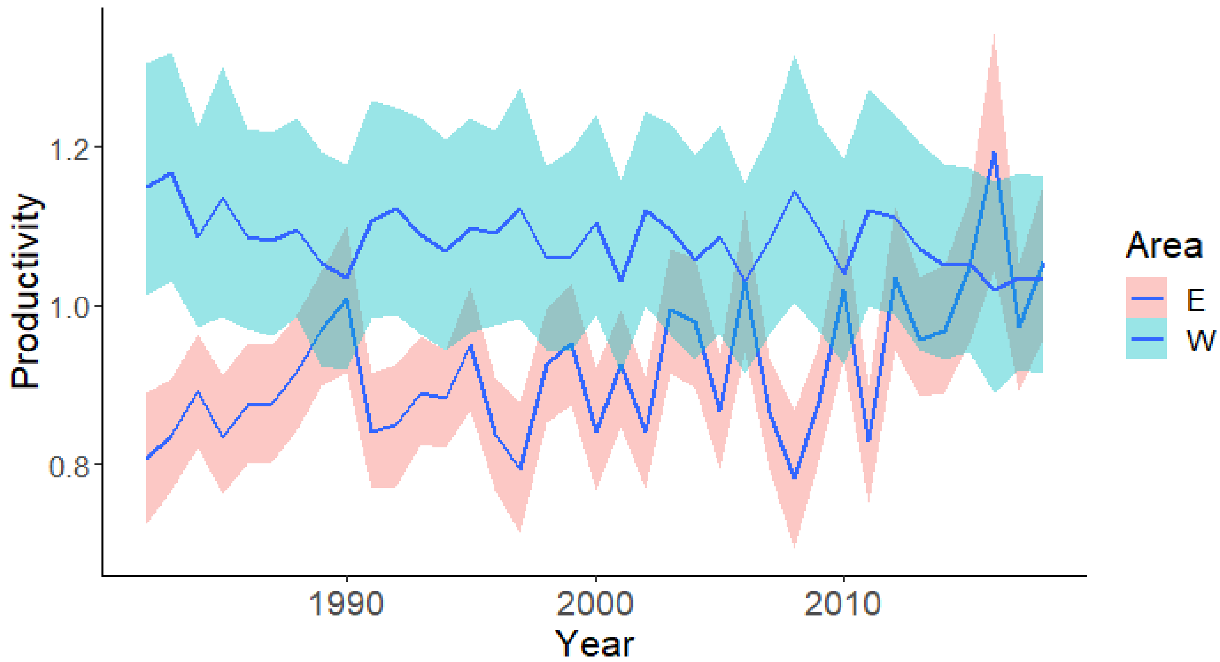

Figure 5.6. Temperature mediated productivity in the stock-recruitment relationship over time (1982-2018) in the in the western and eastern Gulf of Maine

5.5. Conclusions

Our study suggests there is an advantage in incorporating spatial non-stationarity and environmental impacts to predict recruitment for the GOM lobster stock. A previous study found that Ricker models with non-stationary assumptions, the most frequent being a change in the productivity parameter overtime, performed better for many species in the North Atlantic (Ottersen et al., 2013). In this study, the SRR has not only changed over space, which agrees with the findings of Chang et al. (2015), but also time due to climate change. We found that the Ricker models with an effect of offset temperature anomalies performed well. American lobster has exhibited a shift in recruitment dynamics resulting in higher temperature mediated productivity. Likewise, warming water temperatures are predicted to have a positive impact on American lobster abundance (Tanaka et al., 2018). However, if waters become too warm, there are likely to be negative impacts on lobster reproduction, as observed in Southern New England

(ASMFC, 2015). Given the observed shift in temperature mediated productivity, using the whole time series for American lobster SRR in the GOM may lead to biased estimates. The effect of offset temperature anomalies on α is positive in most areas in the inshore GOM. Mean temperature mediated productivity and changes in temperature mediated productivity vary over space, however. Such regional difference in population dynamics can arise from both oceanographic and biological processes. Differences in bottom type between the eastern and western GOM can result in differences in productivity. There is more gravel in the western GOM (Pope et al. 1986), which presents potentially better shelters for early stage juvenile lobsters (Potter and Elner 1982). Changes in temperature mediated productivity differ between the eastern and western GOM due to differences in the rate of temperature increase. Temperature has been increasing faster in the eastern GOM, which would result in higher rates of increase of temperature mediated productivity. However, the difference in slopes in the segmented regression of productivity overtime was not significant. Predation and prey may also be affecting recruitment dynamics, lessening the effect of temperature in the western GOM. Li et al (2018) found that temperature had a smaller impact on juvenile lobster distribution in the western GOM than in the eastern GOM and hypothesized that predators may have an impact on juvenile lobster distribution in the western GOM. Survival of lobsters after settlement is affected by predators, as well as habitat quality and body size (Wahle, 2003). Productivity can be influenced by many factors not directly represented in the data. Aside from environmental factors affecting productivity, there are other reasons that SRRs vary over space. Size at maturity for American lobster varies spatially (Watson et al. 2013), which would affect the proportion of mature lobsters over space. Variation in size at maturity over space was not considered in this study due to lack of data.

Changes in the SRR have important implications for BRPs. Currently, the American lobster stock assessment uses ad hoc BRPs based on modeled abundance and exploitation (ASMFC, 2015). These ad hoc BRPs are the 25th and 75th percentiles of exploitation rate and reference abundance with a reference period of 1982 to 2003 (ASMFC, 2015). Estimating environmentally adaptive BRPs likely requires non-equilibrium assumptions to account for changes in the system. Environmentally adaptive BRPs are important, because they account for the effects of environmental change on the productivity of populations. For example, changing environmental conditions can delay the rebuilding of depleted fish stocks, which would need to be accounted for in BRPs (Britten et al., 2017). Traditional BRPs are often based on MSY, which are calculated with SRRs and assume equilibrium. BRPs estimated from SRRs formed at a large spatial and temporal scale without consideration of environmental variables may be biased due to spatial differences in SRRs and the impact of environmental variables on SRRs. However, in this study, MSY-based reference points are difficult to calculate, because we cannot assume equilibrium and lobsters in this study are smaller than the smallest lobsters in the stock assessment. For American lobster MSY based reference points, recruits in the SRR need to be the same size of the recruits in the stock assessment (53-78 mm CL) and not 50 mm CL or smaller.

More understanding of migration is needed to estimate MSY based reference points over space. American lobsters larger than 50 mm CL begin to migrate seasonally with larger lobsters (Lawton and Lavalli, 1995). Spatially varying MSY based BRPs would only be estimated correctly with information on the migration patterns of lobsters between 50 mm CL and the size of recruits in the stock assessment. Lobsters at this size are migrating, so MSY based reference points defined at the spatial scale in this study would not be meaningful. Therefore, to calculate MSY based BRPs over space, a better understanding of lobster migration is needed.

The results from this study can help inform BRPs by identifying temperature mediated productivity regimes. The most recent lobster stock assessment uses a reference period that begins in 1982 (ASMFC, 2015). However, reference points from this reference period are likely unsuitable, because they assume relative equilibrium and we found that a shift in temperature mediated productivity occurred in 2009.

Because the shift in temperature mediated productivity is based on a stock-recruitment relationship, any reference points based on a new reference period of higher temperature mediated productivity address recruitment overfishing. As this shift in temperature mediated productivity occurs at the settlement stage (around four years earlier), the new reference period could start in 2005. In 2005, the shift in temperature mediated productivity occurred at the settlement stage; at this point, the spawning stock would provide more recruits, because temperature mediated productivity is higher. Fishing pressure on lobsters could increase and still result in high abundance. Comparing the lobster stock status to reference points identified in a lower temperature mediated productivity regime would not be biologically accurate. If ad hoc BRPs are continued to be used for the GOM lobster stock, the reference period should start in 2005. This is the first time a shift in productivity for the GOM lobster has been identified for this time period. Between the 1980s and 1990s, the GOM has experienced a regime shift from a system dominated by high trophic groundfish to a system dominated by low trophic crustaceans, including lobsters (Zhang and Chen, 2007). However, in this study, a shift in temperature mediated productivity in the lobster SRR was not identified between the 1980s and 1990s, but predators were not included in the SRR. Managing with reference points from a higher temperature mediated productivity regime, which would produce higher abundance reference points, would allow the fishery to act sooner if abundance were to decline. Furthermore, the results of this study suggest that lobster fishery managers should directly consider environmental drivers impacting stock status.

An important assumption in this study is that changes in temperature mediated productivity in the SRR are based solely on offset temperature anomalies. As a result, hindcasted temperature mediated productivity from 1982 onwards was based only on offset temperature data. Although we do know that temperature has influenced lobster productivity, the GOM ecosystem has changed substantially since 1982, and other factors probably influenced lobster productivity as well, such as predators, prey, and fishing pressure, which should be considered in future studies. In this study, we considered a direct effect of climate change, but climate change can also indirectly affect the SRR. Climate change can also affect spawning stock age and size composition (Ottersen et al., 2006). For example, the size at maturity for American lobster is decreasing (Waller et al., 2019), which will affect the SSB estimates. Aside from bottom-up controls, such as temperature, top-down controls can also affect lobster productivity in the SRR. A previous study hypothesized that predators may be affecting juvenile lobster distribution in the western GOM (Li et al., 2018). We also hypothesize that there may be other top down and bottom up factors besides temperature and SSB affecting recruitment in the western GOM (i.e. predators and prey), which should be considered in future studies. Variation in life histories due to adaptation to maximize recruitment success under high fishing pressure can also cause nonstationary SRRs (Hidalgo et al., 2014); therefore, future studies should consider nonstationary assumptions not only over space but also time.

Additionally, future studies should consider temperature estimates at a finer temporal resolution. In this study, we assume the average of fall and spring bottom water temperatures affect the SRR, because we did not have access to bottom water temperatures in the summers. Another limitation of this study is that the trawl and VTS surveys do not completely overlap spatially. The trawl survey covers deeper areas than the VTS, which may result in some bias when estimating SSB in shallower areas covered by the VTS with the delta GLMM. Because of this mismatch, modeling SSB in shallow waters at a smaller spatial scale, such as that used in Chang et al. (2015) would was not possible with the current delta GLMM configuration and would introduce even more assumptions that may not be realistic given the data sources. Additionally, most lobsters caught in the VTS are larger than 50 mm CL, but if selectivity is consistent, then the results should be accurate.

In conclusion, temperature mediated productivity in the GOM lobster SRR has increased over time with a shift in temperature mediated productivity in the SRR in 2009. We found that lobster recruitment dynamics in the GOM differ over space and are influenced by temperature, a key environmental variable. Considering differences in SRRs across space and temperature in fisheries modeling has important implications for fisheries management. SRRs can be difficult to define for multiple species with similar recruitment dynamics, and this framework could be applied to other fish populations. Shrimp in the GOM and Australia are a good candidate for these methods, because shrimp are also significantly impacted by temperature (Richards et al. 2012; Roberts et al. 2012). When the water temperature is warmer, the shrimp population productivity declines. Another potential candidate for these methods could be cod in the eastern Atlantic Ocean, as cod recruitment shows different relationships with temperature among different stocks. Cod recruitment in the eastern Atlantic Ocean is positively related to temperature in northern regions and negatively related to temperature in southern regions (Ottersen, 1996). If recruitment, SSB, and temperature data are available across space, this framework can be used. Management implications resulting from this framework are especially important for recruitment fisheries. These methods can quantify spatial differences in recruitment dynamics, which can be useful in spatial management. In the face of climate change, other fish populations are likely to have experienced a shift in temperature mediated productivity in their SRRs as well, and these methods can quantify such shifts.

CHAPTER 6

THE EFFECT OF TIME-VARYING SIZE AT MATURITY ON STOCK STATUS AND STOCK-RECRUITMEN RELATIONSHIPS: A CASE STUDY OF THE AMERICAN LOBSTER IN THE GULF OF MAINE

6.1. Abstract

Environmental conditions are often changing, which can result in changes in key life history processes, which contradicts assumptions of constant biological parameters in fish stock assessments. Time-varying life history parameters are important to consider given evidence that species biology is changing over time because they can have an impact on population dynamics and stock status determination. In the most recent Gulf of Maine American lobster (*Homarus americanus*) stock assessment (ASMFC 2015), size at maturity is assumed to be constant, but there is evidence of a decreasing size at maturity over time. This study uses a size-structured stock assessment model to assess the effect of a decrease in size at maturity and the resulting change in growth on the American lobster stock assessment and stock-recruitment relationship.

6.2. Introduction

Fishery stock assessment models often assume constant parameters for species biology. For example, many stock assessments assume constant natural mortality (Caddy 1991; Hilborn and Liermann 1998; Johnson et al. 2015). However, in many cases, assumptions in stock assessment models are not true in reality (Kolody and Hoyle 2015). Life histories of fish species are often affected by climate change, which may violate the assumption of constant parameters for species biology.

With rapidly changing environmental conditions apparent in many marine ecosystems, parameters for species biology, such as parameters for size at maturity and natural mortality, are likely to change overtime. For example, natural mortality was estimated to vary dramatically over time in the red king crab fishery in Alaska (Zheng et al. 1995). Size at maturity can change in species due to changing environmental conditions and high fishing pressure. Many fish stocks have had declines in age and length at maturity (Beacham 1983, Morgan et al. 1994, Rijnsdorp 1993). Cardinale and Modin (1999) found that size at maturity was negatively correlated with environmental stress. Furthermore, declining sizes at maturity with increasing temperature has been observed for multiple lobster stocks (Templeman 1936, Sutcliffe 1952, Melville-Smith and De Lestang 2006). Aside from climate change, fishing pressure can also affect species biology. Melville-Smith and De Lestang (2006) hypothesized that the selective fishing of large lobsters can also contribute to a decline in size at maturity. Incorrect assumptions about population dynamics in stock assessments can have significant impacts on the stock status and resulting fisheries management. A change in size at maturity would affect the spawning stock biomass (SSB) estimate and therefore, the stock-recruitment relationship (SRR). Previous studies have begun to incorporate time-varying biological parameters, such as natural mortality, in fish stock assessment models (Deroba and Schueller 2013).

In this study, American lobster in the Gulf of Maine (GOM) is used as a case study to examine the effect of a decrease in size at maturity on the stock assessment and SRR. The American lobster, which is endemic to the Atlantic coast of the Canadian Maritimes and the Northeastern United States, forms the basis of a very significant fishery, worth over 630 million USD in 2019 (ACCSP 2019). Environmental conditions in the GOM are changing rapidly, but the American lobster stock assessment assumes constant biological parameters, one of those being size at maturity. In the most recent lobster stock assessment (ASMFC 2015), the 50% size at maturity value and maturity ogive are from a Maine Department of Marine Resources study conducted from 1994 to 1998 (Nutting 1999). Previous studies (Landers et al. 2001; Watson et al. 2013; Waller et al. 2019) found that the size at maturity has changed over time for American lobster. In Boothbay Harbor, Maine, the size at maturity decreased by 5 mm in the last 25 years (Waller et al. 2019). A change in size at maturity will also affect growth, as female lobsters molt less often when mature, because they are carrying eggs every other year (Wilder 1953; ASMFC 2015).

These findings suggest that the assumption of no change in size at maturity over time needs to be changed; calculations of spawning stock biomass (SSB) and egg productions have been made under this assumption (Phillips and Melville-Smith 2005). Changing size at maturity can have effects on growth, stock status, and the SRR for the GOM lobster fishery. For the American lobster stock assessment, no SRR is currently assumed, because the relationship is unclear (ASMFC 2015). In this study, a decrease in size at maturity is hypothesized to improve the stock assessment model and stock-recruitment model fit for the GOM American lobster.

6.3. Methods

6.3.1. Stock assessment model

A length-structured stock assessment model (Tanaka et al. 2019; Cao et al. 2017) was used to examine the effect of a change in size at maturity on the lobster population. This model can use multiple data sources; the data used in the model are seasonal fishery catch, catch size compositions, survey abundance indices, and survey size compositions from 1984 to 2013 (Tanaka et al. 2019). Data from four surveys that implemented stratified random designs were used: 1) the Northeast Fisheries Science Center bottom trawl survey, 2) the Maine/New Hampshire bottom trawl survey, 3) the Massachusetts bottom trawl survey, and 4) the ventless trap survey (Tanaka et al. 2019). The time step in the model is seasonal (i.e. winter, spring, summer, and fall). The overall objective function is the sum of the log likelihood functions linking observed and predicted values of several life history and fishery processes. The configurations in this study follow the base case configurations in the most recent American lobster stock assessment (Tanaka et al. 2019; ASMFC 2015). The lobster population considered in this study includes the Gulf of Maine and Georges Bank stock. In this study, only the female population was considered, as a change in size at maturity would only affect female lobsters.

6.3.2. Maturity matrices

New maturity matrices were estimated for a decrease in size at maturity. The original maturity matrix of American lobster was from the most recent American lobster stock assessment (ASMFC 2015). The proportion mature at size matrices are based of the logistic equation:

$$P_{matcl} = \frac{1}{1+ e^{\alpha+\beta*CL}} \tag{13}$$

The original parameters for the logistic equation are α = 25.7603 and β = -0.2897. A change in size in maturity was incorporated by shifting the proportion mature per size class bin to the left, so that the lobsters mature at a size bin earlier. The parameters for the logistic equation where lobsters mature a size class smaller (83-88 mm CL instead of 88-93 mm CL) are α = 24.3117 and β = -0.2897.

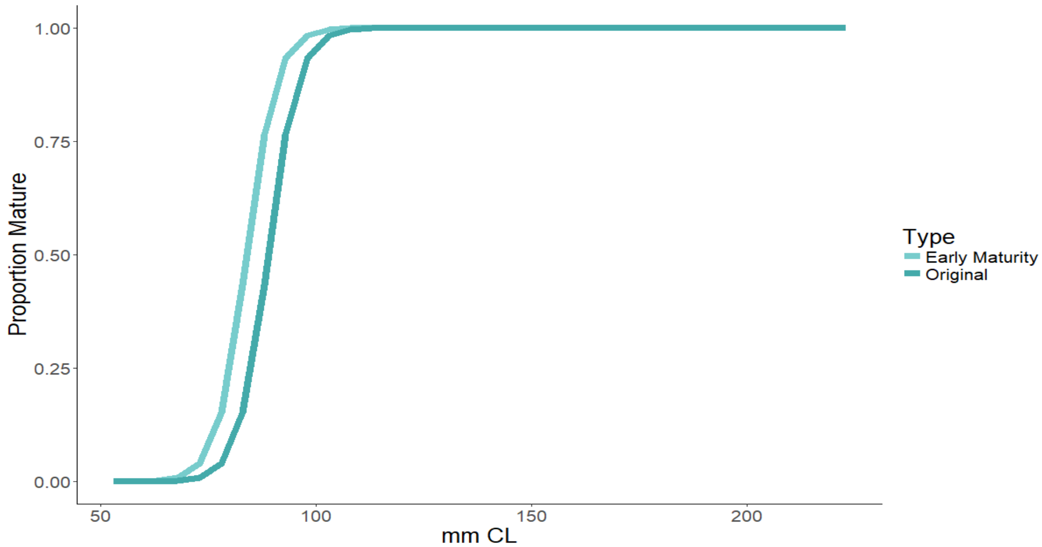

Figure 6.1. Proportion of lobsters mature at each carapace length (CL) using the original maturity matrix and the maturity matrix with 50% size at maturity a size class smaller.

6.3.3. Growth matrices

Adjusted growth matrices that captured the change in growth after maturity at a smaller size (85 mm CL instead of 91 mm CL) were also used when size at maturity decreased. Lobster growth slows after sexual maturity, because females alternate between molting and bearing eggs each year (ASFMC 2015). To create new growth matrices, the probabilities of lobsters at different sizes completing an annual molt cycle were calculated. Maturity curves are assumed to be known without error. From the maturity curves, the probability mature was calculated. Because mature lobsters molt on alternating years, the probability of molting was calculated as

$$Probability\ of\ molting = 1 - \frac{Probililty\ mature}{2} \quad (14)$$

A logistic model is fit for the probability of molting at sizes smaller than L50, but when molting slows down even further after maturity, a minimum molt probability (33%) is applied to larger sizes.

We then built a growth matrix based on the molt probability model. Molting can occur twice in a year for smaller lobsters. For the first molt in the summer, the growth transition matrix is based on a combination of probability of molting, the mean molt increment at size, the variance of molt increment at size. According to tagging data, molt increment increases up to lobsters at 77 mm CL, after which, molt increment is assumed to be 13 mm. Variance of molt increment at size is also based on tagging data. The fall double molt growth matrix was determined by multiplying the probability of molting to a given size by the ratio of the new to historic molt probability.

6.3.4. Scenarios

We ran three scenarios with the stock assessment model: the base case, a decrease in size at maturity for the whole time series, and a decrease in size at maturity half way through the time series (change in 1999). The base case assumes the maturity and growth matrices are the same as in the most recent lobster stock assessment (ASMFC 2015). The constant size at maturity scenarios have one time block for growth and maturity matrices. The scenario with a change in size at maturity in 1999 has two time blocks for growth and maturity matrices. A gradual change in size at maturity would be more realistic, but the stock assessment model cannot incorporate gradual changes in size at maturity.

We then compared the assessment model diagnostics, SSB trends, and SRRs between scenarios. For assessment model diagnostics, likelihoods and retrospective patterns, including Mohn's Rho, were compared. For the SRRs, Ricker stock-recruitment functions were fit to the SSB and recruitment output from the model.

6.4. Results

6.4.1. Model diagnostics

The best total likelihood was with the base case, or no change in size at maturity (Table 6.1). The worst total likelihood was with the decrease in size at maturity for the whole time series (Table 6.1). Total catch likelihoods were the same between scenarios.

Table 6.1. Likelihoods of the base case model, the decrease in size at maturity model, and the model with a change in size at maturity in 1999.

Scenario	Total Likelihood	Total Catch Likelihood	Proportion Catch Likelihood	Recruit Likelihood
Base case	53,322.40	-262.49	6792.60	-22.54
Decrease in size at maturity	54,640.30	-262.49	6929.64	-18.66
Change in size at maturity	54,208.70	-262.49	6837.31	-17.46

Retrospective patterns did not increase with a decrease in size at maturity (Table 6.2). The base case scenario had the least retrospective bias for SSB and fishing mortality. However, the scenario with a change in size at maturity had the least retrospective bias for recruitment. Because the base case had better SSB and fishing mortality retrospective patterns, and the change in size at maturity scenario had better recruitment retrospective patterns, these two scenarios are used for the rest of the analysis.

Table 6.2. Mohn's rho values for SSB, recruitment, and fishing mortality for each of the scenarios. These are based on a six year peel.

Scenario	SSB rho	Recruitment rho	Fishing mortality rho
Base case	**0.063**	0.19	**-0.074**
Decrease in size at maturity	0.099	0.42	-0.13
Change in size at maturity	-0.087	**0.13**	0.74

6.4.2. Spawning stock biomass trends

A change in size at maturity increased final SSB slightly (Fig. 6.2). With a change in size at maturity, the SSB increases faster until 1999 (Fig. 6.2). After 1999, the SSB with a change in size at maturity decreases faster than that in the base case (Fig. 6.2).

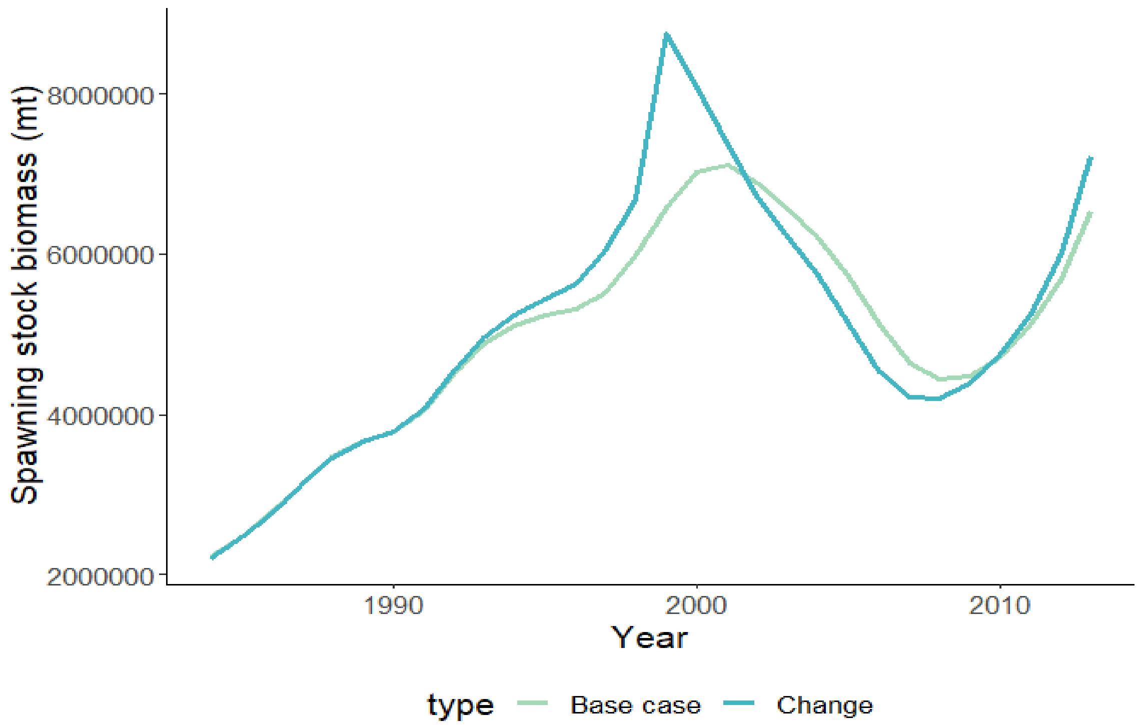

Figure 6.2. Spawning stock biomass over the years for the base case and change in size at maturity scenarios.

6.4.3. Stock-recruitment models

The Ricker model fit to the output data of the change in size at maturity scenario explained more than the Ricker model fit to the base case output data (Table 6.3). However, the Ricker model fit to the base case output data had less error than the Ricker model fit to the change in size at maturity scenario output data.

Table 6.3. R-squared and mean squared error (MSE) values for the two Ricker models from the base case and change in size at maturity output data.

Scenario	**R-squared**	**MSE**
Base case	0.47	0.12
Change in size at maturity	0.62	0.14

A theoretical Ricker curve is not apparent in either scenario (Fig. 6.3). Both models underestimate recruits at intermediate SSBs and overestimate recruits at low and high SSBs. The model formed from the output data from the change in size at maturity scenario had more density-dependent effects.

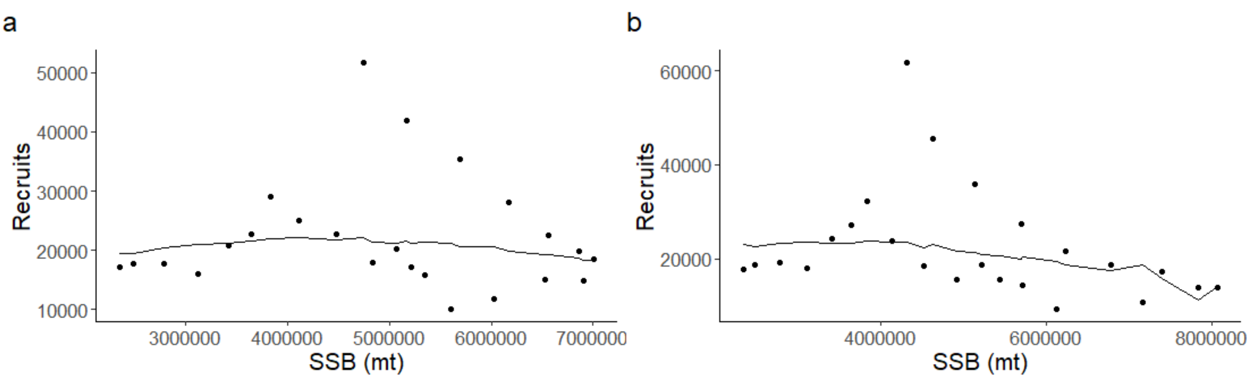

Figure 6.3. Observed recruits (black dots) and predicted recruits (black line) vs spawning stock biomass (SSB) lagged by 6 years for the a) base case and b) change in size at maturity scenarios.

6.5. Discussion

Including time-varying growth and maturity is uncommon in fisheries stock assessments (Patterson et al. 2001). Nevertheless, time-varying life history parameters have improved stock assessment model fits and decreased retrospective patterns for Gulf of Maine northern shrimp (Richards and Jacobson 2016). However, that was not necessarily the case in this study. Likelihood did not improve, and retrospective patterns only improved for recruitment, but got much worse for fishing mortality. Growth may not have been estimated well in the change at size at maturity scenarios.

Changing the size at maturity also changes the spawning stock biomass estimates throughout the time series. If a decrease in size at maturity is not accounted for, SSB is underestimated, resulting in steeper and higher SRRs (Enberg et al. 2010). In this study, SSB did change due to a changing size at maturity. These results agree with a previous study (Cardinale and Modin 1999), which collected Baltic cod and found that spawning stock biomass was correlated with size at maturity. A decrease in size at maturity also changes the SRR. However, neither of the SRRs explained much of the variation in recruitment and did not match theoretical Ricker curves. Stock-recruitment relationships are often difficult to determine sometimes due to short time ranges of data or data without large differences in SSB or recruitment over time. When a population has only increased in the range of the data, functional stock-recruitment relationships tend to appear linear. A variety of reasons can make stock-recruitment relationships unclear, but one reason is an incorrect determination of SSB. Solutions to determining a stock-recruitment relationship are often sought for outside of the SSB and recruitment data. To find the relationship, many different models are tested, and new parameters are often introduced. To find a clear stock-recruitment relationship, revisiting the SSB and recruitment data may be necessary.

Because a change in size at maturity has effects on the assessment and stock-recruitment relationship, a change in size at maturity also has important implications for fisheries management. Any reference points and stock status estimations from a stock assessment will be impacted by a change in size at maturity. Stock-recruitment relationships are important in stock assessment projections and in simulating alternative management strategies. Stock-recruitment relationships are also vital to estimating maximum sustainable yield based biological references points. As the stock-recruitment relationship changed with a decrease in size at maturity, any resulting biological reference points would change as well. Therefore, changes in size at maturity may have important consequences for fisheries management.

A decrease in size at maturity of American lobster would lead to higher egg production which would partly explain why lobsters have been so resilient although exploitation rates have been high (Landers et al. 2001). Watson et al. (2013) found that a change in size at maturity for lobster in Nova Scotia at least doubled the eggs-per-recruit and tripled the percentage of females that reach maturity before legal size.

Future studies should consider other time blocks that begin before or after 1999 for a change in size at maturity. Maine Department of Marine Resources sea sampling data can be used to analyze the size composition of egg-bearing females. A change in this size composition over time may indicate the years for time blocks in the stock assessment model. Survey data may provide evidence for a shift in size at maturity experienced by the whole Gulf of Maine lobster population, rather than a subset of the population in a specific location, which is the focus of many of the biological size at maturity studies. Future studies should also consider incorporating a gradual change in size at maturity in this size-structured stock assessment framework. Aside from a changing size at maturity, other factors may affect the stock assessment and stock-recruitment relationship. Additionally, changes in the environment, such as increasing water temperature, may also affect growth (Thakur et al. 2017). Changes in bottom water temperature does not only affect size at maturity but will also affect molting frequency in general, because increased temperatures cause lobsters to molt more often (Hughes and Matthiessen 1962). Water temperature also affects larval development and possibly recruitment of postlarvae to the benthos (Cobb and Wahle 1994). These factors should be considered in future studies.

Changes in size at maturity can cause differences in spawning stock biomass, and ultimately differences in stock-recruitment relationships. A change in size at maturity impacted the size-structured stock assessment and resulting SRR in this study. However, the impacts were not that strong and did not make the SRR clearer. Incorporating time blocks into stock assessment models can be important when parameters are changing over time. However, multiple parameters can vary over time, making it difficult to decide what should be accounted for (Johnson et al. 2015). Future studies should consider different time blocks in the stock assessment model for changes in size at maturity. As other crustacean species are experiencing changes in size at maturity, other crustacean fishery stock assessments should include time-varying size at maturity.

CHAPTER 7

THE ROLE OF CONSERVATION IN THE FUTURE AND CONCLUSIONS

7.1. The role of conservation

Conservation has been important in the Maine lobster fishery. Historically, conservation compliance was high in the fishery. Today, Maine lobster fishers still have positive views of v-notching (Chapter 2). However, due to high lobster catches in recent years, some lobster fishers question the benefits of v-notching, and conservation compliance has decreased (Chapter 2). Conservation compliance can change even if the management system remains the same. If lobster catches continue to increase, v-notching participation can be expected to decline. This may have significant impacts on the sustainability of the fishery, given how important v-notching has been for sustainability in the past.

V-notching was shown to have contributed to the increases in lobster fishery biomass and landings (Chapter 4). Historically, v-notching has been effective for two reasons: nearly all lobster fishers participate in the activity by making the v-notches, and the state of Maine has a strict no-tolerance policy, in which a lobster with any size of a notch is illegal to land. High v-notching compliance is important in protecting the lobster population. According to the simulations in chapter 4, there would have been 15% fewer landings and 48% less biomass of breeding lobsters in 2013 if only half of lobster fishers had v-notched from 1982 to 2013. The strict definition that the state of Maine uses is also important to the success of v-notching. Even if 100% of lobster fishers participated in v-notching, but there was a less strict definition of a v-notch, there would have been 17% fewer landings and 53% less biomass of breeding lobsters in 2013. In chapter 4, we found that v-notching is a valuable tool for the sustainability of the Maine lobster fishery. However, other conservation measures and fishing factors may also play a role in the increase in lobster landings and biomass. Minimum size is necessary for lobsters to be protected until they are able to mature and produce eggs, and hence, be v-notched. The large amount of herring used as bait may be increasing lobster growth, as many lobsters enter a trap, feed on the bait, and then leave the trap before the trap is hauled.

Changes in the environment also play a role in the lobster fishery, which will affect population dynamics (Chapters 5 and 6), and as a result, potentially change the effect of conservation on the fishery. Because the GOM water temperatures are increasing, several current lobster life history traits are different than those of the past. The present lobster fishery is now in a new productivity regime, beginning in 2008 (chapter 5). In chapter 5, we found that temperature has a strong influence on recruitment dynamics and due to the increasing temperatures, lobster recruitment dynamics have entered a higher productivity regime. This means that the same amount of SSB will provide more recruits. These changes in the SRR can have an effect on the role of conservation. We also explored the effect of a decrease in size-at-maturity, but we did not find that it improved the lobster stock assessment. This leads to another research question: what is the future role of conservation in the fishery?

7.2. Projection scenarios

To predict the future of the Maine lobster fishery, we used all the knowledge and tools gained in chapters 2-5. In chapter 2, v-notching compliance was decreasing, different compliance scenarios of 50% and 90% compliance were projected. In chapter 4, a ‘weak’ stock-recruitment relationship that captured what happened historically was identified, so this assumption was used. Also, in chapter 5, productivity increased overtime in the SRR, so although it does not fit the data the best at a large spatial scale, to see the effect of increased productivity a Ricker SRR with increased productivity was also used (Fig.7.1) Because density-dependence effects are estimated to be near zero, recruits continuously increase with SSB in this Ricker SRR. The IBLS tuned for the Gulf of Maine fishery from chapter 3 was used. Each projection scenario was ran for 15 years 50 times. Encounter rate was assumed to be the average of the five most recent years.

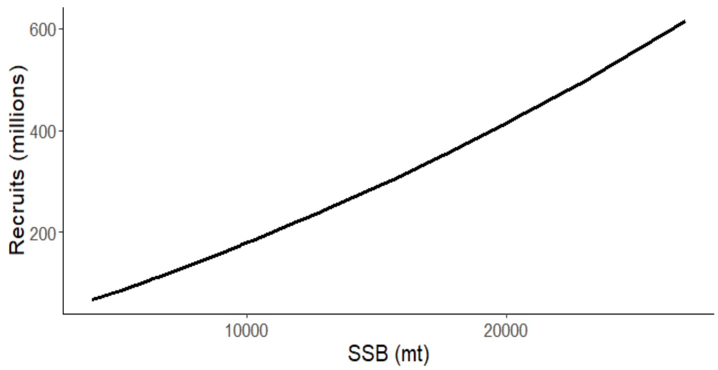

Figure 7.1. Stock-recruitment curve for the Ricker SRR with increased productivity.

Under a weak SRR, none of the landings were significantly different from each other in the projections (Fig. 7.2). Landings increased and then leveled off. Landings no longer increased as a result of the assumptions of the weak SRR, which has a maximum recruitment distribution after which recruitment values no longer increase (chapter 4).

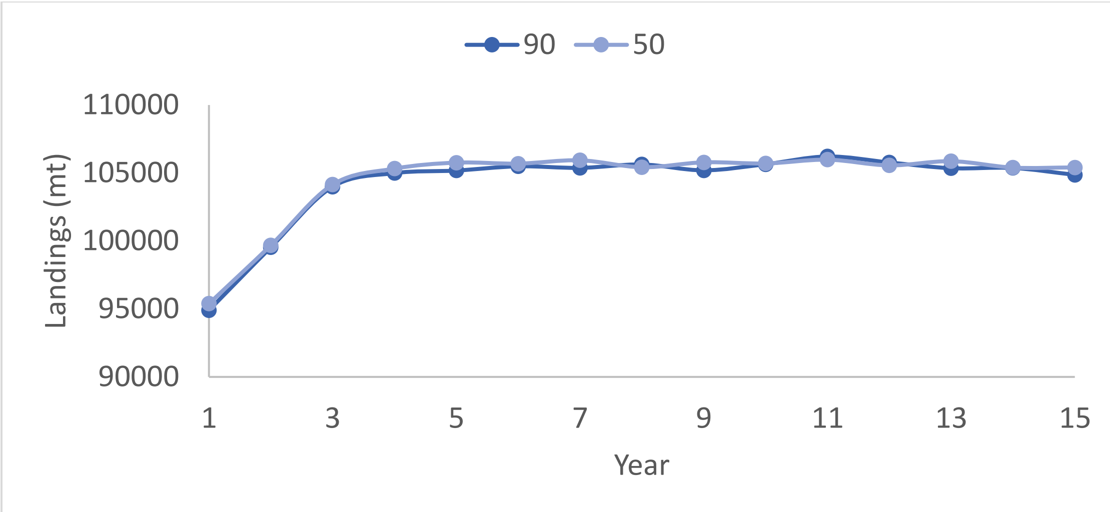

Figure 7.2. Projected landings under a weak stock-recruitment relationship. Median of the projected landings for ten years with different v-notching compliances with a weak stock-recruitment relationship.

Projected SSB with a weak SRR increased overtime (Fig. 7.3). SSB increased more so with 90% v-notching compliance than with 50% v-notching compliance. The differences between median SSB of the two scenarios increase overtime.

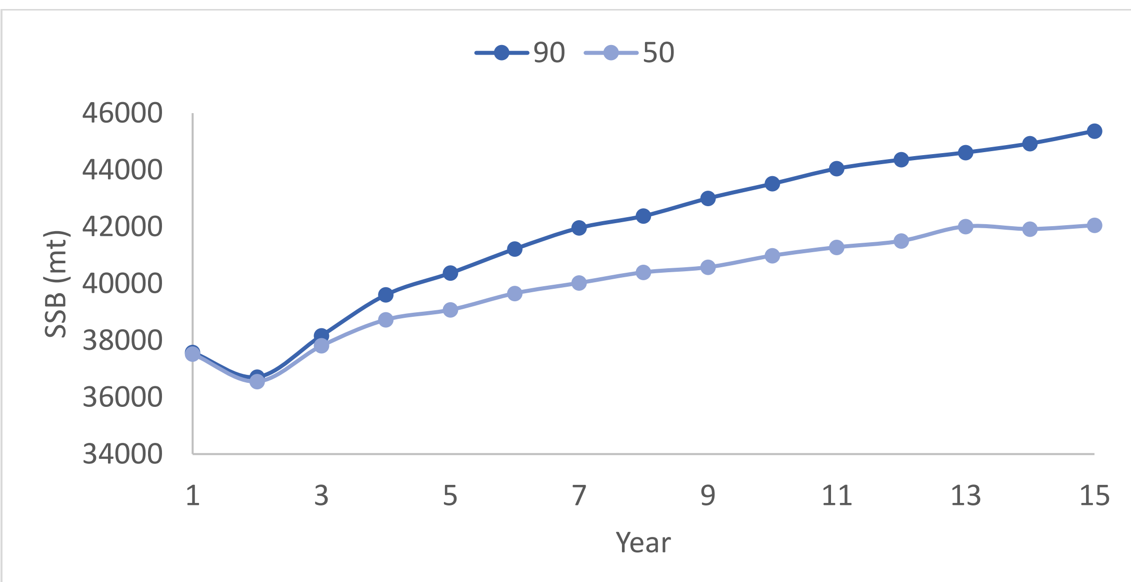

Figure 7.3. Median of the projected spawning stock biomass (SSB) for 15 years with different v-notching compliances with a weak stock-recruitment relationship.

With a Ricker SRR with increased productivity, landings in both scenarios increase (Fig. 7.4). Landings are slightly higher with high compliance than with 50% compliance. The difference in landings between the two scenarios increases overtime.

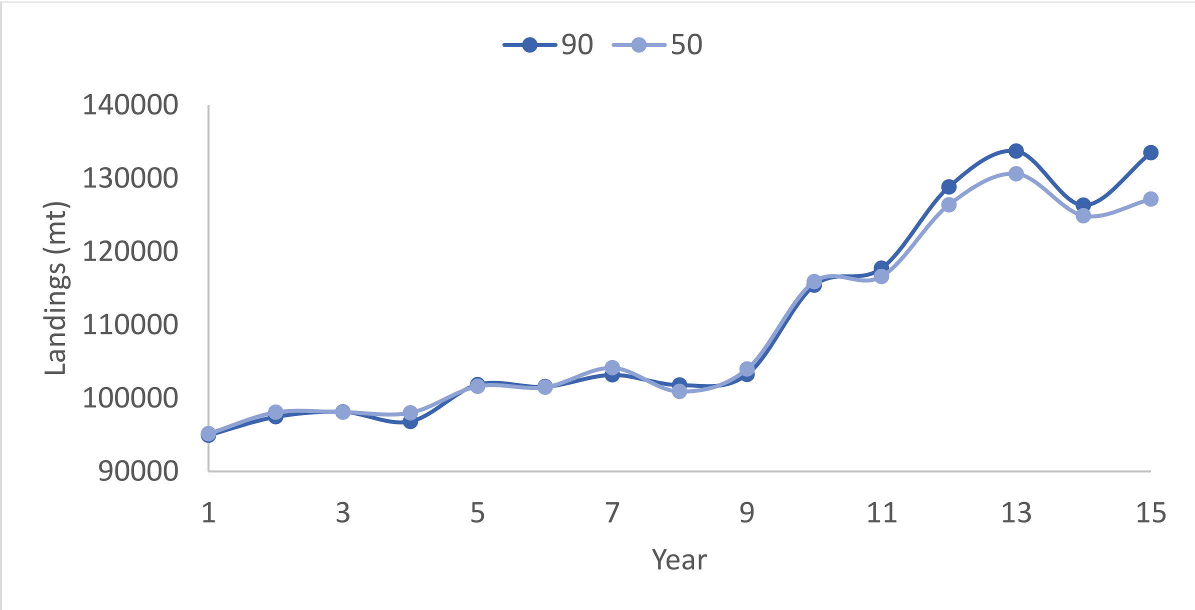

Figure 7.4. Median of the projected landings for 15 years with different v-notching compliances with a Ricker stock-recruitment relationship with increased productivity.

With a Ricker stock-recruitment relationship with increased productivity, SSB increases in both scenarios (Fig. 7.5). At the end of the projection, SSB is higher in the 90% compliance scenario than in the 50% compliance scenario. The differences between SSBs in the two scenarios increases overtime.

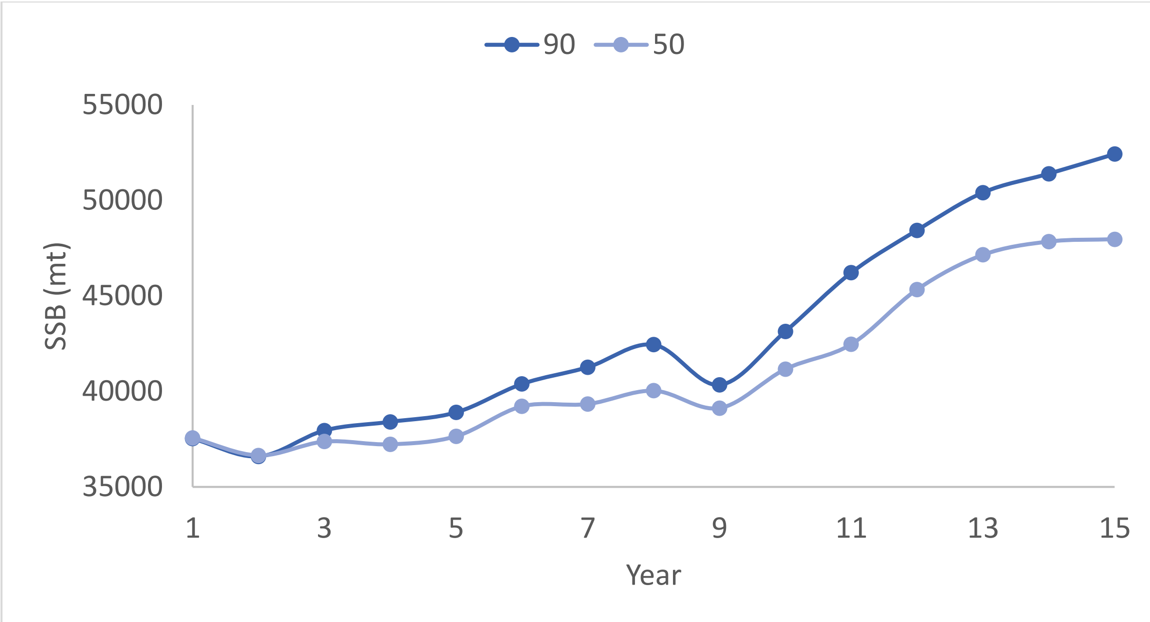

Figure 7.5. Median of the projected spawning stock biomass for 15 years with different v-notching compliances with a Ricker stock-recruitment relationship with increased productivity.

Overall, projections suggest that the effect of a change in v-notching on landings may be negligible in the near future, but v-notching still protects SSB. Lobster fishers also described that v-notching may not be as beneficial anymore (chapter 2). One lobster fisher explained:

> I also know that, even though there's less of a percentage, if there was less of a percentage being notched, there's still so many more lobsters that we still have a growing population of V-notched. So, I think—you know, overall, we're in pretty darn good shape. Now, if people just stop altogether, then that would become a problem for us, but that isn't the case.

From the simulations, it seems that v-notching may have a smaller influence on landings in the immediate future due to high resource abundance and high productivity. Interviews and simulations from chapter 4 suggest under conditions with lower spawning stock biomass, v-notching becomes more important. If biomass were to decline, v-notching may have more of an impact on the fishery like it did in the past. The American lobster settlement index (Wahle and Carloni 2016) show decreases in lobster settlement, which may lead to a decrease in lobster biomass in the future. Trawl surveys show increasing trends in adult lobster biomass, but trends in survey indices could also be a result of changes in migration timing (Henderson et al. 2017).

In the interviews, it seemed that the change in v-notching compliance was a *de facto* management strategy; when biomass increased past a threshold, compliance declined, and we can possibly expect from the history of v-notching compliance, that if biomass were to decline past a threshold, compliance may increase. However, there may be a lag between biomass decline and compliance increase. V-notching may allow biomass to recover if it were to decline in the future. However, if social memory disappears, v-notching may not be practiced in the future. If fishers understand the previous benefits of v-notching, fishers may embrace v-notching again. Additionally, the effects of v-notching on the lobster fishery landings are not immediate. Once a lobster is v-notched, it takes at least another year for it to be protected from being v-notched. After another year, the protected lobster can produce eggs. Around eight years after the eggs hatch and larvae settle, some of the larvae will have grown into lobsters that are above minimum size and can be landed. So, it takes at least ten years for a change in v-notching to affect landings. Lobster fishers may not be aware of this lag or the lag may make some lobster fishers less likely to v-notch if only short-term gains are important.

7.3. Future research and applications

Future studies focusing on lobster fishery projections should also consider a decrease in size at maturity, which was not considered in these projections. Changes in size at maturity can cause differences in spawning stock biomass, and ultimately differences in stock-recruitment relationships (chapter 5). However, multiple parameters can vary over time, making it difficult to decide what should be accounted for (Johnson et al. 2015). Also, the effects of the ecosystem considered in these models are limited. If at all, only the effect of temperature is considered, but there are many other factors in the ecosystem that affect lobster population dynamics. Future research should consider including effects of other environmental factors, such as prey and predators of lobster.

Scientists and managers in other fisheries should also consider changing compliance caused by a change in resource status. The framework proposed in this study can be extended to evaluate conservation and management measures in other fisheries. Specifically, the v-notching measure can be evaluated with this framework in the Canadian and Irish lobster fisheries (Collins and Lien 2011; Tully 2001).

7.4. Application to a management strategy evaluation framework

The tools and information developed in this dissertation can be useful in a MSE framework (Fig. 7.6). Aside from stock assessments and BRPs, management strategy evaluation (MSE) is a simulation tool that can further inform fisheries management by evaluating the performance of alternative management strategies. A management strategy, also known as a management procedure, includes data collection, stock assessment, and a harvest control rule (HCR), which determines the fishing pressure based on the stock status in reference to the BRPs (McAllister et al. 1999). Fishing fleet or fishers' behavior should be included in MSE, because management compliance is often a challenge in fisheries (Bunnefeld, Hoshino, & Milner-Gulland, 2011). Additionally, habitat modeling can also be used to inform fisheries management (Xue et al. 2017), through information on spatial distribution and spatial population dynamics that can help identify optimal management areas (Booth, 2000). Stakeholder engagement is also critical in fisheries management, from stock assessment through the decision-making process (Smith et al. 1999). Chapter 2 identified a decline in compliance which informs parameters and uncertainties for the simulated fishery in a MSE. Chapter 3 focused on the IBLS which can simulate the fishery and management decisions. Chapter 4 identified the effect of v-notching on the fishery, which is important to consider when developing management decisions. Chapters 5 and 6 identified the effect of a key environmental variable, temperature, on the SRR, which will affect the fishery, assessment, and management outcomes.

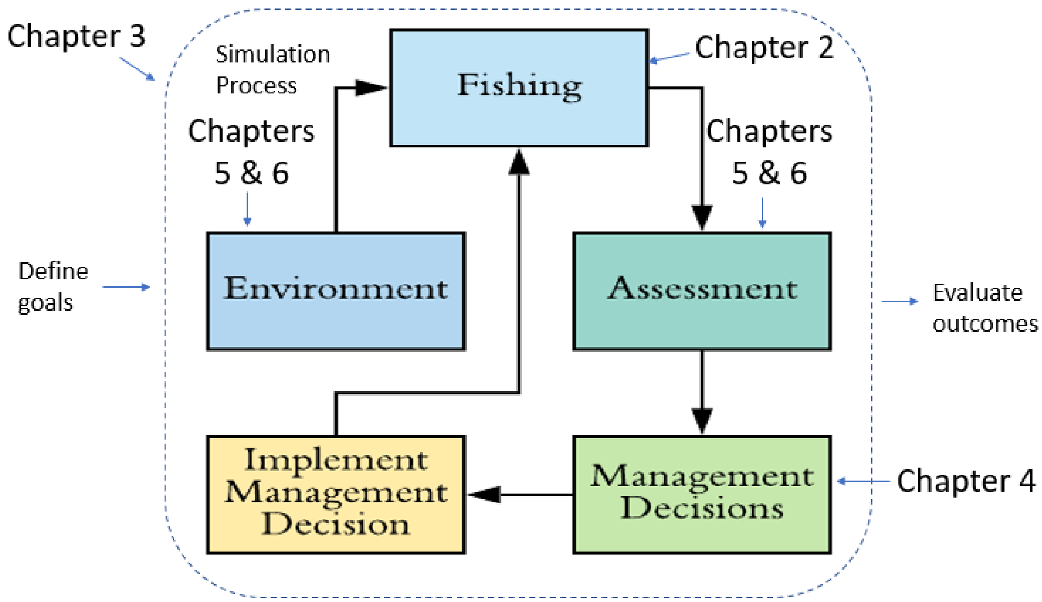

Figure 7.6. Simplified schematic of a management strategy evaluation framework and how the chapters of this dissertation fit into such framework

7.5. Concluding statement

In conclusion, conservation has an important role in the Maine lobster fishery and has contributed to the increases in lobster landings and biomass. This role depends on the environment and resource abundance. Regardless, v-notching is a useful tool for precautionary management that should be continued to be used. V-notching never negatively affects landings in any scenario. Currently, the GOM fishery is at high biomass and productivity levels, but it is uncertain how long this will last. If temperature continues to increase, the fishery might experience negative impacts as observed in Southern New England's lobster fishery (ASMFC 2015). V-notching provides a buffer by preserving SSB, and this dissertation provides quantitative evidence of this.

As the British statistician George Box used to write: "All models are wrong, but some are useful." Many different models are used in this dissertation with a lot of uncertainty and assumptions, which is normal in modeling natural resource systems. Some of these assumptions may be eventually found to be inaccurate, but these models still provide useful information for fisheries management, which is the ultimate goal of this dissertation.

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APPENDIX 1

Table A11. Codebook for this study.

V-Notching codebook

1. Competition or Self-interest
2. Enforcement
   - 2.a. Uncertainty
3. Generational differences
   - 3.a. Older generation
   - 3.b. Younger generation
4. Industry-Initiated
   - 4.a. Conservation ethic
5. Lobster abundance
   - 5.a. No longer beneficial/not effective
   - 5.b. Too many lobsters on boat
6. Lobster health
   - 6.a. Disease
   - 6.b. Too cold/stress
7. ReNotch
8. Sustainability
   - 8.a. V-notching
   - 8.b. Climate change
9. Transmission of Practice

APPENDIX 2

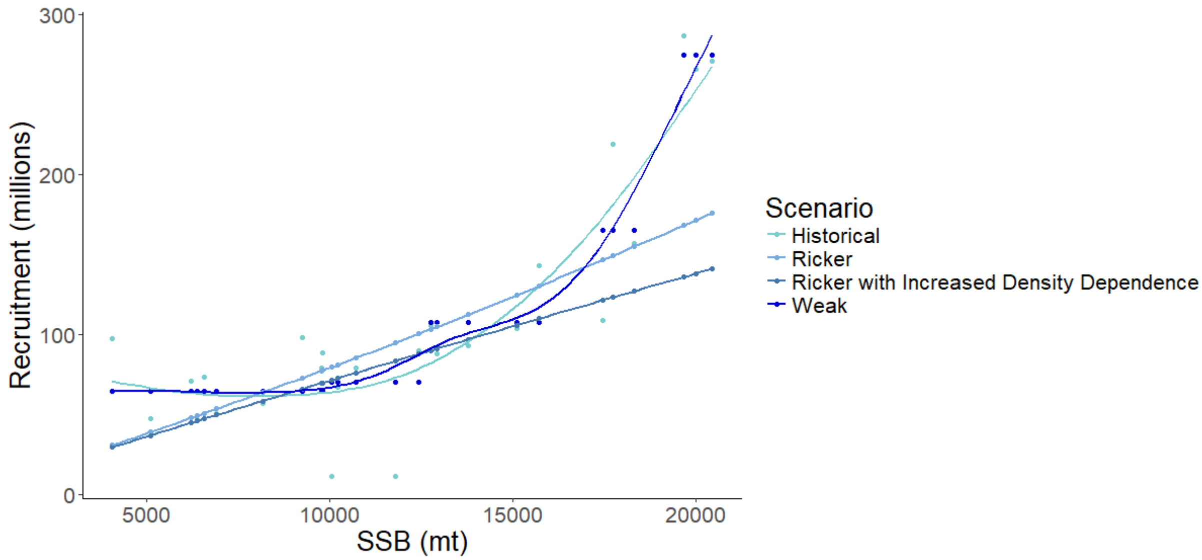

Figure A21. Estimated recruitment (dots) from the 4 different recruitment dynamics scenarios versus spawning stock biomass (SSB) lagged by 6 years. Historical represents the historical recruitment (recruitment estimated from the stock assessment), Ricker represents the recruitment estimated with the Ricker stock-recruitment model, Ricker with Increased Density Dependence represents recruitment estimated with the Ricker stock-recruitment model with an increased density-dependence effect, and Weak represents the recruitment estimated from randomly selecting a recruitment value from normal distributions of recruitment values that correspond to 5 different levels of SSB (hence the 5 levels of recruitment values; weak stock-recruitment relationship). The curves are estimated with a generalized additive model.

Table A22. The results of the independent samples t-tests for the final spawning stock biomasses of each of the V-Notching compliance and V-Notch definition scenarios with historical recruitment. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S represents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	47296	97.7	1.16	0.248
R	46898			
100-S	47296	97.9	11.7	<2.2e-16***
50-S	43140			
100-S	47296	98	15.4	<2.2e-16***
100-L	41899			
100-S	47296	97.2	25	<2.2e-16***
50-L	38874			
100-S	47296	98	33.8	<2.2e-16***
0	35505			
50-S	43140	97.4	-10.8	<2.2e-16***
R	46898			
50-S	43140	97.9	-3.5	0.0007***
100-L	41899			
50-S	43140	96.7	12.5	<2.2e-16***
50-L	388874			
50-S	43140	97.8	21.6	<2.2e-16***
0	35505			
100-L	41899	97.8	-14.6	<2.2e-16***
R	46898			
100-L	41899	97.3	9.02	1.68e-14***
50-L	38874			
100-L	41899	98	18.4	<2.2e-16***
0	35505			
50-L	38874	97.8	-24.5	<2.2e-16***
R	46898			
100-L	41899	98	18.4	<2.2e-16***
0	35505			
0	35505	97.9	-33.5	<2.2e-16***
R	46898			

Table A23. The results of the independent samples t-tests for the final spawning stock biomasses of each of the V-Notching compliance and V-Notch definition scenarios with a weak stock-recru itment relationship. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S r epresents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	47636	9.12	0.27	0.79
R	46785			
100-S	47636	9.35	7.20	4.16e-5***
50-S	24960			
100-S	47636	9.22	7.97	1.99e-5***
100-L	22640			
100-S	47636	9.22	9.39	5.05e-6***
50-L	18163			
100-S	47636	9.10	10.9	1.60e-6***
0	13568			
50-S	24960	78.3	-43.4	<2.2e-16***
R	46785			
50-S	24960	92.7	4.19	6.30e-5***
100-L	22640			
50-S	24960	93.4	12.2	<2.2e-16***
50-L	18163			
50-S	24960	74.1	23.2	<2.2e-16***
0	13568			
100-L	22640	90.0	-57.0	<2.2e-16***
R	46785			
100-L	22640	98.0	9.19	6.85e-15***
50-L	18163			
100-L	22640	85.6	22.1	<2.2e-16***
0	13568			
50-L	18163	89.1	-66.8	<2.2e-16***
R	46785			
50-L	18163	84.7	11.0	<2.2e-16***
0	13567			
0	13567	97.2	-97.9	<2.2e-16***
R	46785			

Table A24. The results of the independent samples t-tests for the final spawning stock biomasses of each of the V-Notching compliance and V-Notch definition scenarios with recruitment from a Ricker model. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S repres ents a strict definition, and L represents a less strict definition. R represents the reference or histo rical scenario.

Group	M	df	T	p
100-S	30054	85.0	-36.8	<2.2e-16***
R	46785			
100-S	30054	89.1	23.4	<2.2e-16***
50-S	19145			
100-S	30054	79.5	31.6	<2.2-16***
100-L	16144			
100-S	30054	68.7	46.0	<2.2e-16***
50-L	10883			
100-S	30054	53.4	65.5	<2.2e-16***
0	4698			
50-S	19145	97.3	-74.6	<2.2e-16***
R	46785			
50-S	19145	94.4	8.50	2.70e-13***
100-L	16144			
50-S	19145	83.0	25.6	<2.2e-16***
50-L	10883			
50-S	19145	57.3	50.8	<2.2e-16***
0	4698			
100-L	16144	96.8	-91.2	<2.2e-16***
R	46785			
100-L	16144	92.3	18.6	<2.2e-16***
50-L	10883			
100-L	16144	61.3	48.2	<2.2e-16***
0	4698			
50-L	10883	87.1	-117.8	<2.2e-16***
R	46785			
50-L	10883	68.9	32.4	<2.2e-16***
0	4698			
0	4698	58.9	-159.9	<2.2e-16***
R	46785			

Table A25. The results of the independent samples t-tests for the final spawning stock biomasses of each of the V-Notching compliance and V-Notch definition scenarios with recruitment from a Ricker model with an increased density-dependence effect. In the Group column, 0, 50 or 100 re presents 0, 50, or 100 % compliance. S represents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	24839	96.8	-58.3	<2.2e-16***
R	46785			
100-S	24839	82.7	25.4	<2.2e-16***
50-S	16407			
100-S	24839	76.2	33.4	<2.2e-16***
100-L	14126			
100-S	24839	71.2	48.1	<2.2e-16***
50-L	9795			
100-S	24839	56.7	70.0	<2.2e-16***
0	4408			
50-S	16407	88.2	-98.9	<2.2e-16***
R	46785			
50-S	16407	96.2	9.70	6.42e-16***
100-L	14126			
50-S	16407	92.3	29.5	<2.2e-16***
50-L	9795			
50-S	16407	67.6	61.9	<2.2e-16***
0	4408			
100-L	14126	81.6	-110.9	<2.2e-16***
R	46785			
100-L	14126	96.7	20.9	<2.2e-16***
50-L	9795			
100-L	14126	72.8	56.0	<2.2e-16***
0	4408			
50-L	9795	76.0	-129.4	<2.2e-16***
R	46785			
50-L	9795	78.0	34.0	<2.2e-16***
0	4408			
0	4408	58.6	-161.2	<2.2e-16***
R	46785			

Table A26. The results of the independent samples t-tests for the cumulative landings of each of t he V-Notching compliance and V-Notch definition scenarios with historical recruitment. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S represents a strict definitio n, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	885432	98	-0.22	0.828
R	886042			
100-S	885432	98	-2.2	0.03*
50-S	891573			
100-S	885432	98	-3.4	0.001***
100-L	894999			
100-S	885432	98	-4.4	3.33e-05***
50-L	897690			
100-S	885432	97.8	-5.8	7.71e-08***
0	901968			
50-S	891573	98	2	0.0524
R	886043			
50-S	891573	98	-1.22	0.228
100-L	894999			
50-S	891573	98	-2.2	0.0329*
50-L	897690			
50-S	891573	98	-3.6	0.000436***
0	901968			
100-L	894999	98	3.1	0.00217**
R	886043			
100-L	894999	98	-0.94	0.348
50-L	897690			
100-L	894999	98	-2.4	0.0175*
0	901968			
50-L	897690	98	4.1	8.77e-05***
R	886043			
100-L	894999	98	-2.4	0.0175*
0	901968			
0	901968	98	5.5	2.52e-07***
R	886043			

Table A27. The results of the independent samples t-tests for the cumulative landings of each of the V-Notching compliance and V-Notch definition scenarios with a weak stock-recruitment relationship. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S represents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	898319	9.06	0.35	0.74
R	886043			
100-S	898319	9.88	4.23	0.002**
50-S	745655			
100-S	898319	9.91	4.53	0.001**
100-L	734893			
100-S	898319	9.87	5.20	0.0004***
50-L	710888			
100-S	898319	9.49	5.72	0.0002***
0	694142			
50-S	745655	55.6	-17.6	<2.2e-16***
R	886043			
50-S	745655	98.0	0.98	0.33
100-L	734893			
50-S	745655	98.0	3.20	0.002**
50-L	710888			
50-S	745655	90.8	5.34	6.69e-7***
0	694142			
100-L	734893	55.3	-18.6	<2.2e-16***
R	886043			
100-L	734893	97.9	2.19	0.03*
50-L	710888			
100-L	734893	90.0	4.17	6.88e-5***
0	694142			
50-L	710888	55.7	-22.1	<2.2e-16***
R	886043			
50-L	710888	91.2	1.75	0.08
0	694142			
0	694142	60.6	-31.4	<2.2e-16***
R	886043			

Table A28. The results of the independent samples t-tests for the cumulative landings of each of the V-Notching compliance and V-Notch definition scenarios with recruitment from a Ricker model. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S represents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S	635638	68.0	-50.3	<2.2e-16***
R	886199			
100-S	635638	93.1	18.5	<2.2e-16***
50-S	528043			
100-S	638638	92.7	23.8	<2.2e-16***
100-L	497869			
100-S	635638	83.9	35.9	<2.2e-16***
50-L	440726			
100-S	635638	66.2	57.9	<2.2e-16***
0	348924			
50-S	528043	77.6	-86.5	<2.2e-16***
R	886199			
50-S	528043	98.0	5.94	4.09e-8***
100-L	497869			
50-S	528043	94.3	18.8	<2.2e-16***
50-L	440726			
50-S	528043	75.1	43.8	<2.2e-16***
0	348924			
100-L	497869	78.1	-94.5	<2.2e-16***
R	886199			
100-L	497869	94.6	12.4	<2.2e-16***
50-L	440726			
100-L	497869	75.6	36.7	<2.2e-16***
0	348942			
50-L	440726	87.4	-124.2	<2.2e-16***
R	886199			
50-L	440726	84.7	26.0	<2.2e-16***
0	348942			
0	348942	97.7	-190.7	<2.2e-16***
R	886199			

Table A29. The results of the independent samples t-tests for the cumulative landings of each of the V-Notching compliance and V-Notch definition scenarios with recruitment from a Ricker model with an increased density-dependence effect. In the Group column, 0, 50 or 100 represents 0, 50, or 100 % compliance. S represents a strict definition, and L represents a less strict definition. R represents the reference or historical scenario.

Group	M	df	T	p
100-S **R**	517335 826237	78.9	-76.2	<2.2e-16***
100-S **50-S**	517335 431650	93.0	19.2	<2.2e-16***
100-S **100-L**	517335 406539	90.8	25.4	<2.2e-16***
100-S **50-L**	517335 360492	83.6	37.7	<2.2e-16***
100-S **0**	517335 278753	70.1	61.6	<2.2e-16***
50-S **R**	431650 826237	90.3	-114.9	<2.2e-16***
50-S **100-L**	431650 406539	97.7	6.60	2.13e-9***
50-S **50-L**	431650 360492	94.2	20.0	<2.2e-16**
50-S **0**	431650 278753	90.5	47.4	<2.2e-16***
100-L **R**	406539 826237	92.5	-126.4	<2.2e-16***
100-L **50-L**	406539 360492	95.8	13.3	<2.2e-16***
100-L **0**	406539 278753	83.1	41.2	<2.2e-16***
50-L **R**	360492 826237	97.7	-153.3	<2.2e-16***
50-L **0**	360492 278723	90.4	29.2	<2.2e-16***
0 **R**	278753 826237	94.2	-207.7	<2.2e-16***

APPENDIX 3

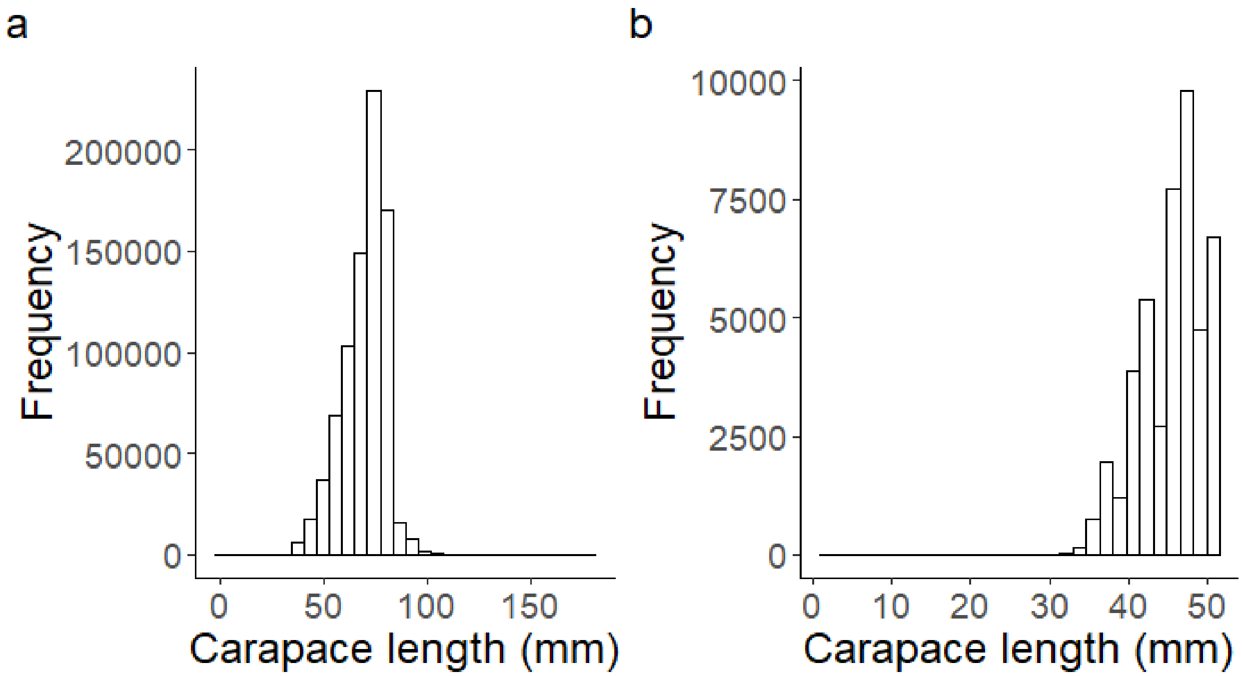

Figure A31 Size frequency of Ventless Trap Survey data with all lobsters (a) and lobsters 50 mm CL and under (b)

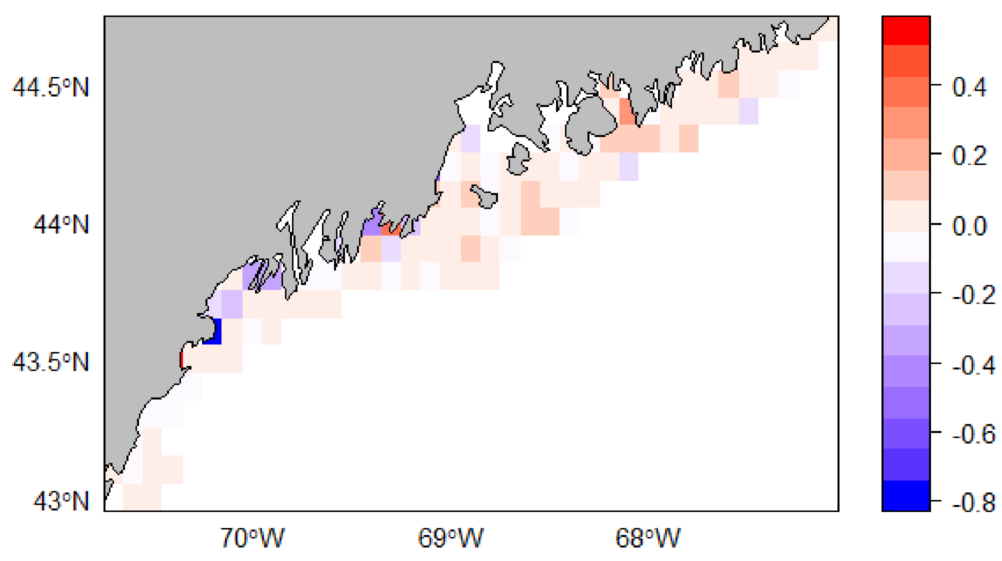

Figure A32 Rate of change in recruit catch in the Ventless Trap Survey from 2006 to 2018 in the Gulf of Maine

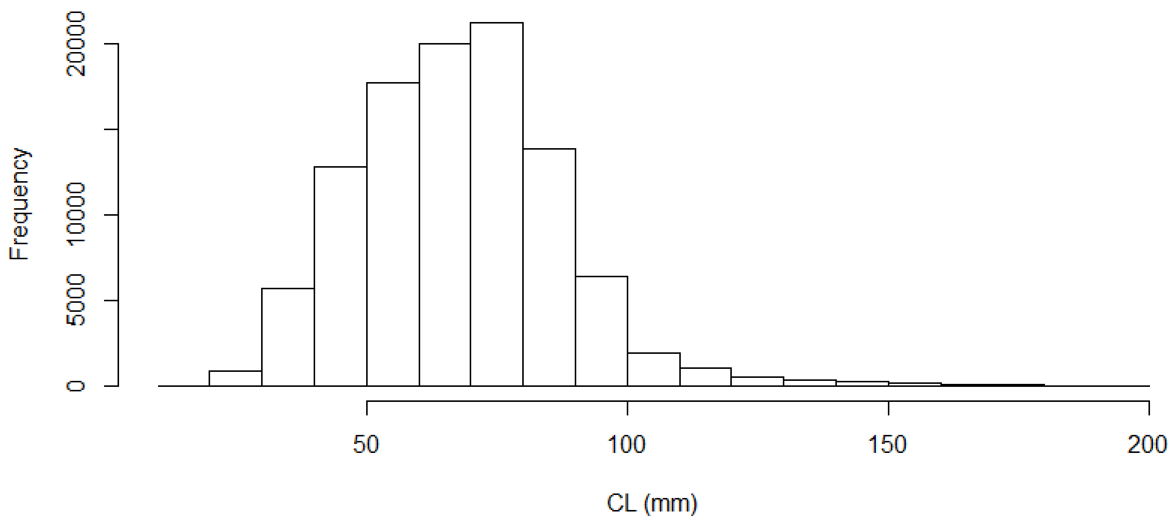

Figure A33 Size frequency of trawl survey data with all lobsters

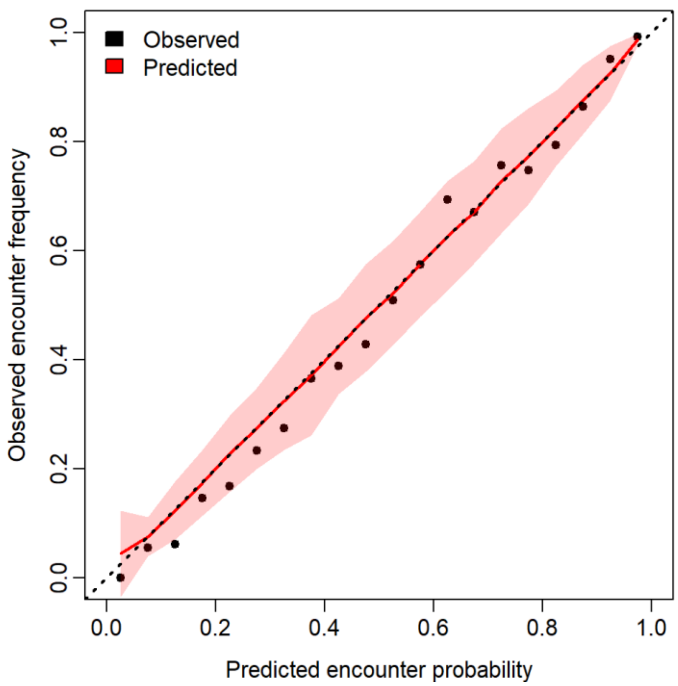

Figure A34 Observed encounter probability versus predicted encounter probability for the first stage of the delta generalized linear mixed model for fall spawning stock biomass

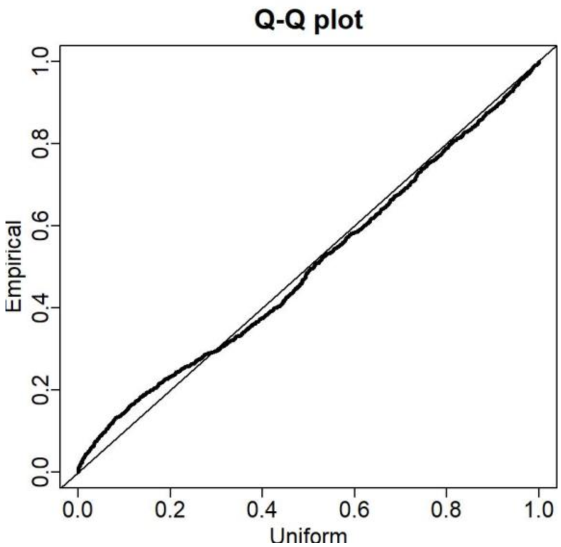

Figure A35 Q-Q plot for the second stage delta generalized linear mixed model output for fall spawning stock biomass

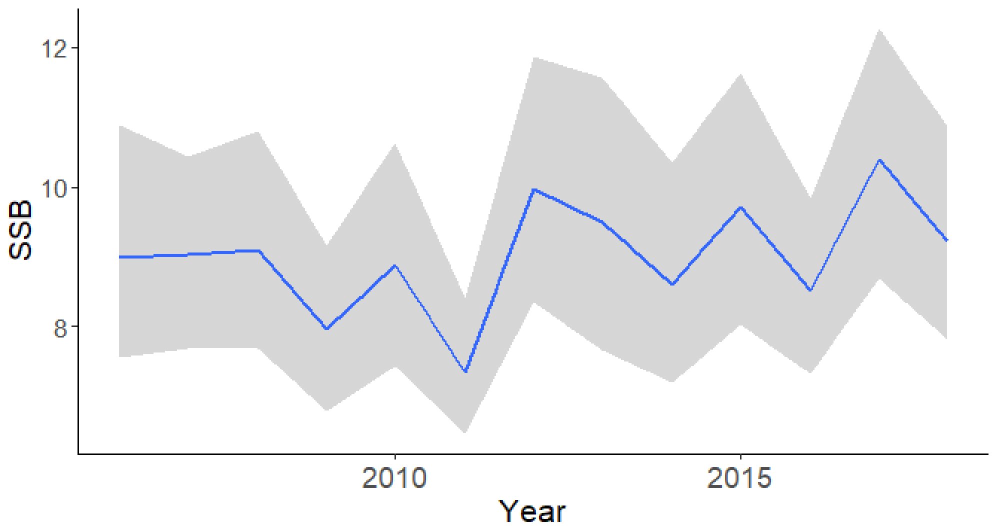

Figure A36 Average estimated spawning stock biomass (SSB) over time in the inshore Gulf of Maine

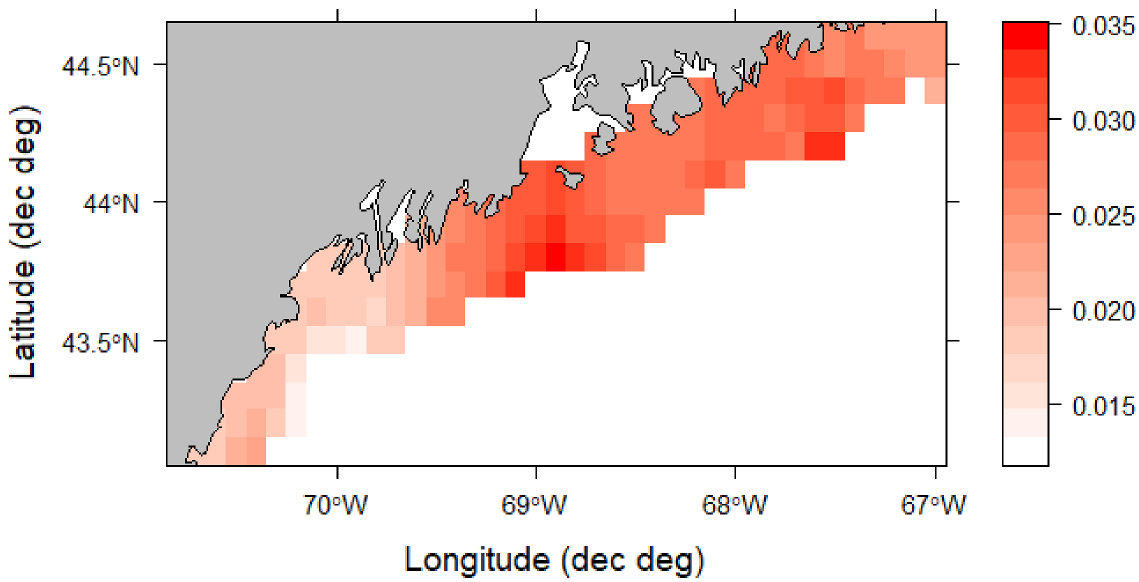

Figure A37 Rate of increase in bottom water temperature from 1982 to 2018 in the Gulf of Maine

Table A31 Variance inflation factors for each of the explanatory variables

Variable	**Variance inflation factor**
Spawning stock biomass	1.01
Set over days	1.01
Unlagged temperature anomalies	1.02
Lagged temperature anomalies	1.02

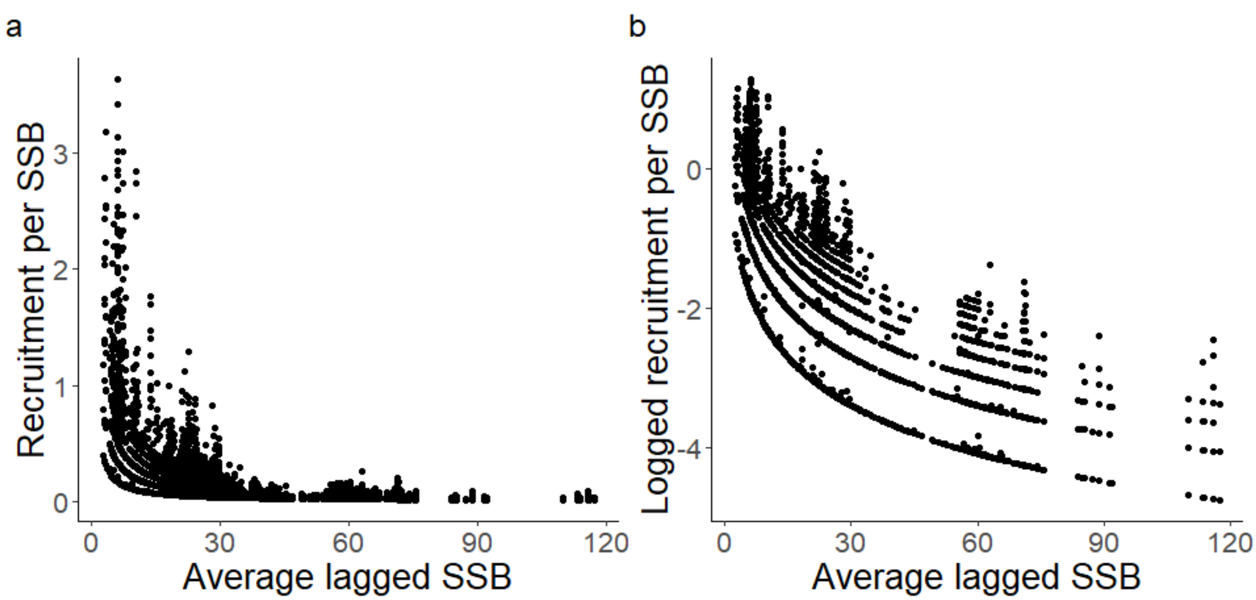

Figure A38 Recruits per SSB vs SSB and log recruits per SSB vs SSB

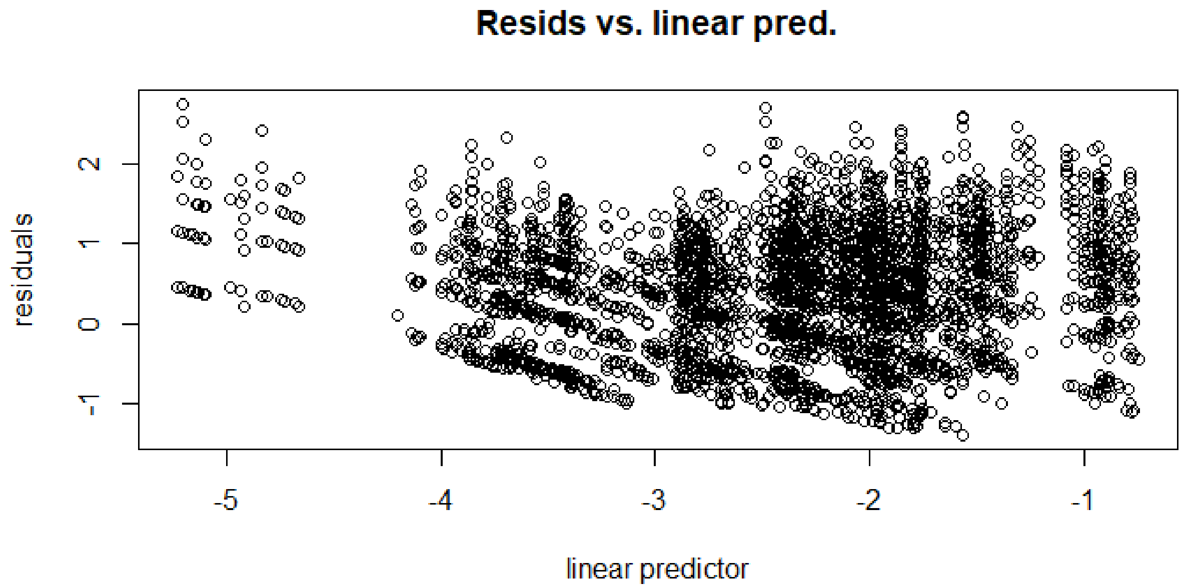

Figure A39 Residuals vs. linear predictor of the Ricker model with an effect of lagged temperature

BIOGRAPHY OF THE AUTHOR

Mackenzie Mazur was born in Halifax, Nova Scotia, Canada in 1993. She then moved to Toronto, followed by Nebraska, and then Massachusetts, where she graduated from high school. She then attended the University of Maine and received a B.S. in Marine Science with a concentration in Marine Biology and a minor in Fisheries with high honor's in 2015. She enrolled in graduate school in 2015 at the School of Marine Sciences at the University of Maine in Dr. Yong Chen's and Dr. Teresa Johnson's labs. She is a candidate for the Doctor of Philosophy degree in Marine Biology from the University of Maine in May 2020.

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