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The Effect of Temperature on the Supply and Demand for the American Lobster (Homarus americanus) in the State of Maine

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The Effect of Temperature on the Supply and Demand for the American Lobster (*Homarus americanus*) in the State of Maine

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Abstract

The Gulf of Maine (GOM) American lobster (Homarus americanus) stock accounts for 90% of the U.S. American lobster landings. This makes it an extremely valuable and important fishery on a national scale, but also to the state of Maine. In the past decade, the fishery has experienced rapid fluctuation in landings and price due to anthropogenic influences of the water temperature in the GOM. Given the economic importance of the fishery, it is important to understand the future impacts of climate change on the availability of lobster and economic consequences of these shifts. A bio-economic model is used in the analysis of the supply and demand to determine the effect of warmer ocean waters on the American lobster. The current supply and demand for the American lobster is estimated using an ordinary least squares regression. The estimated supply model is simulated under a higher temperature scenario and fed into the demand model to simulate a new lobster price. Overall, it was projected that the higher temperature scenario results in a 9% increase in lobster landings and 8% decrease in the price per pound of lobsters. While this is a preliminary study of an integrated supply and demand model that incorporates the impacts of climate change, the results are robust. This motivates future studies to understand the implications of higher ocean temperature on lobsters and the large economy in the state of Maine that rely on the resource.

I. Introduction

1.1. Overview

The American lobster (*Homarus americanus*) fishery was responsible for 81% of the value of seafood and fish landings in the state of Maine during 2015 (DMR). This makes it extremely important to understand potential exogenous impacts to the lobster population in Maine. Several biological, environmental, and economic factors influence the timing, availability and fishing effort of lobsters. Lobsters rely on their environment as a source of nutrients to maintain physical processes for growth and reproduction. Environmental cues are extremely important for migration and molt patterns of lobster, which consequently influence when they are available to fishermen. Additionally, the supply and demand of lobsters is an important component of the price per pound that fishermen receive. Thus, in order to understand the lobster industry in Maine, biological and economic factors must be accounted for together. This can be done through a bio-economic model that combines biological and economic variables together into a coherent equilibrium model. I believe this model is the best candidate to characterize the lobster industry in Maine.

In this paper, I aim to expand on existing biological and economic models of the American lobster population in Maine to gain an understanding on the impending impacts of climate change to the fishing economy. Recent market shocks in lobster demand and rapid declines in southern states lobster stocks drive the need to understand the economic implications for Maine. I apply a bio-economic analysis through an equilibrium supply and demand model to integrate economic, biological, and environmental drivers in the market for American lobsters. Additionally, I incorporate the current rate of change for in the Gulf of Maine (GOM) ocean temperatures to simulate a future climate scenario. From these equations, I determine the reduced form demand equilibrium under theoretical temperature increases in the GOM to compare market equilibrium price. Analyzing the market with a bio-economic model allows for more informed policy decisions that are able to incorporate several elements and aim to protect market equilibrium. Effective policy is critical given Maine's economic reliance on the American lobster fishery.

I approach this by reviewing the historic and current state of the lobster fishery and environmental changes in Maine to examine the important ecological shifts in the ecosystem.

Next, I build the foundations of a bio-economic model with the essential economic and ecological theory. Building on the theoretical understandings of the model, I outline the research methods used to examine the potential impacts of economic and environmental factors. Finally, I analyze the results of the bio-economic model and conclude with potential uses of this research in the broader context of management policy for the lobster fishery in Maine.

1.2. Management of the American Lobster

The American lobster is found along the Eastern coast of the United States from North Carolina up through Maine. Traditionally, the American lobster population was divided into three biological stocks: the GOM, Georges Bank (GBK), and Southern New England (SNE) (Figure 1). The GOM stock is responsible for more than 90% of the lobster landings in the U.S. and has been on a sharp incline since 2007. Historically, the SNE stock was the second largest, but in the past 15 years it has experienced a decline and now accounts for about 2% of the total U.S. landings (ASMFC 2015). The American lobster fishery is dependent on the stock in the GOM and in order to protect all stocks there are extensive regulations in the industry.

All lobster stocks are carefully monitored and regulated based on stock assessments. All lobster fishermen, both commercial and recreational, must have the proper vessel and trap permits in order to remove any lobsters from the environment. Additionally, these permits may require that you only fish in certain areas. There are a total of seven (1-6 & OCC) areas between the three stocks and seven individual areas within Maine (A-G) (Figure 1). Each zone, along the east coast and in Maine, has slightly different regulations, but there are consistent laws that aim to ensure the abundance and persistence of lobster populations in each region.

The protection of egg-bearing females, juveniles, and mature lobsters in each fishing area aims to reduce declines in stock populations. Every zone of the lobster fishery in the Atlantic has minimum and maximum carapace sizes to ensure that juveniles, who will reproduce in the future, and larger adults, who are fertile, remain in the ecosystem. In addition to size regulations, v-notching is a technique that allows for the identification of egg-bearing females by cutting a v on one of the tail flippers of a lobster (NOAA 2014). This allows for easy identification of females that should remain in the water to release their eggs and allow recruitment of lobster populations in the future. The GOM stock has benefited from these regulations and seen an

increase in the population of lobsters. While strict management is one reason for the increase in abundance, other factors are responsible as well.

(a) (b)

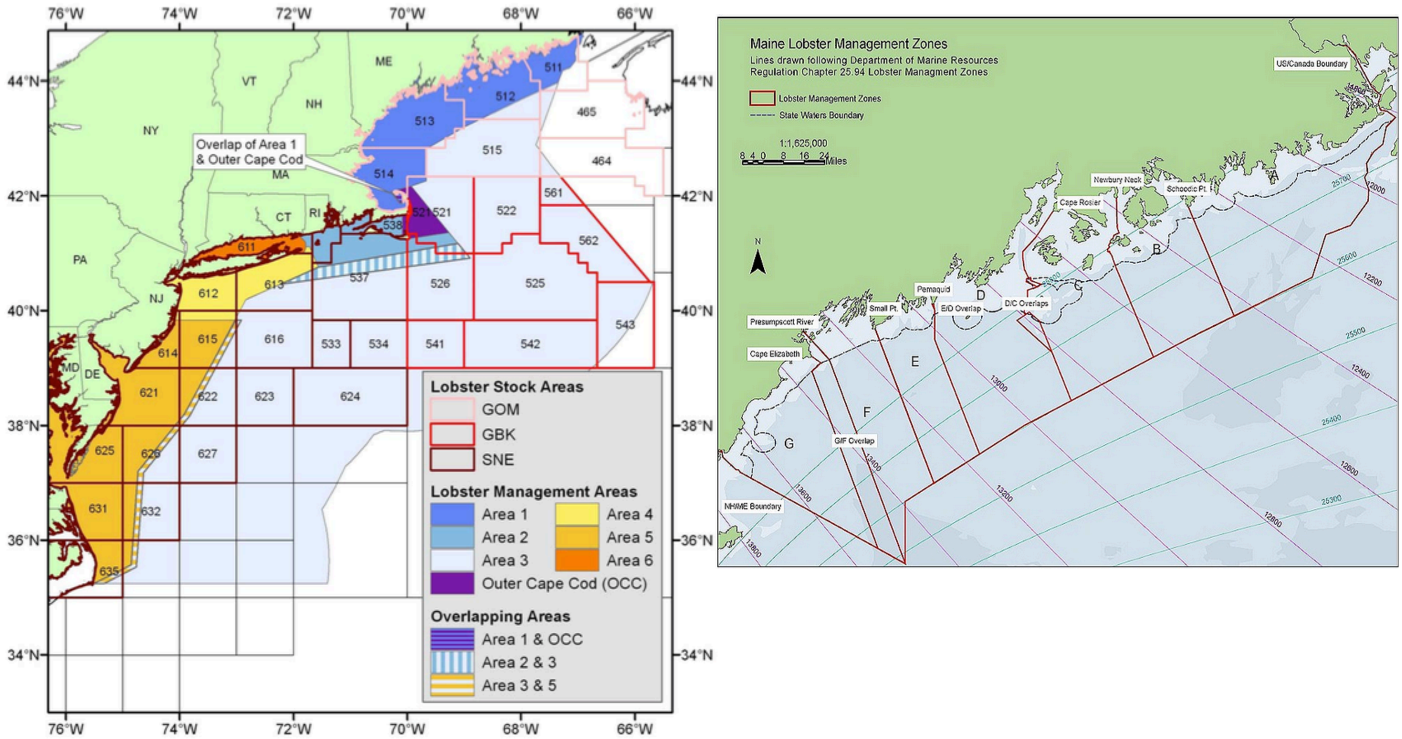

Figure 1 (a) Lobster populations by stock area (GOM, GBK, SNE) and management areas (A1-A6, OCC) **(b)** Seven management zones (A-G) in Maine. Source: American lobster information sheet, NOAA sustainable fisheries 2015)

1.3. Maine's Lobster Abundance

The GOM lobster stock is extremely abundant with increased growth over the past 35 years. Since 1980 the stock has experienced steady population increases, and a rapid acceleration in the number of lobsters since 2007 (ASMFC 2015). This increase in abundance is seen in the acceleration in landings since 1980 and particularly since 2007. High lobster populations are the results of several drivers within the GOM.

Fishing, one potential driver, in the GOM has been a prominent component of the state's economy for over a century. The GOM has seen several booms and busts in fisheries due to

overfishing and exploitation, which has caused widespread ecosystem shifts in species abundance. Atlantic cod was once the most profitable marine resources in Maine during the 1800's. The inshore stock was declared to be depleted around 1950, however the fishery adapted by moving offshore. This sizeable decline in the cod population is thought to be a reason for increasing lobster populations since the 1980's (Steneck et al. 2011). Atlantic cod are a predator of the American lobster, so a decline in their population could lead to an increase in lobsters due to decreased predatory pressure.

More recently, the acceleration in abundance since 2007 may be due to management practices and the strong incentive and willingness of Maine lobster fishermen to conserve (Steneck et al. 2011). Lessons from the cod fishery and historic mismanagement of species in Maine are a reason lobster fishermen may respect and adhere to strict management regulations. Even with strict management and respectful fishermen, the GOM lobster stock is fished to its highest legal potential. The historic increase in abundance and rapid growth has lead to increased fishing effort and landings.

1.4. Lobster Fisheries Link to the Economy

Maine is exceedingly dependent on the value of lobsters and their high abundance to drive the economy. This reliance makes understanding potential future economic impacts imperative to adjust management for the future. The GOM has been severely overfished over the past century, with industry booms concentrating at one species at a time until the resource is no longer available. While several fisheries, such as Atlantic cod and the green sea urchin, played a major role in the fishing economy in Maine, lobster have persisted as the upmost important species through time (Figure 2). This has resulted in a "monoculture" of lobsters for the Maine fishing industry (R. S. Steneck et al. 2011).

The heavy regulations and simplified ecosystem in the GOM have fueled the monoculture of lobsters. The lobster fishery effectively feeds lobsters with their bait, eliminating the need for lobsters to forage on their own (Steneck, Vavrinec, and Leland 2004; Steneck et al. 2011). This further increases their abundance, through a decrease in natural mortality. Moreover, it creates a system that resembles an aquaculture business. The loss of lobsters as a predator on other species in the environment further simplifies the ecosystem. As the lobsters

continue to rely on fisherman as their food source, the fishery is inherently more connected to economic drivers.

Today, more than ever, catch diversification in the Maine fishing economy has decreased significantly (Figure 2). This is described as an economic "gilded trap", in which the appeal of increased lobster abundance prevented stakeholders from realizing the potential social implications of their actions in the long run (R. S. Steneck et al. 2011). If fishermen and other community members involved in the lobster industry continue these practices, they will move deeper into this trap. The substantial decrease in economic diversity within Maine's fisheries calls for motivating research on the need to reestablish a healthy and diversified economy. We can gain insight on the dependence of the fishery and how ecological factors, such as water temperature, may affect economic conditions of Maine's lobster fishery.

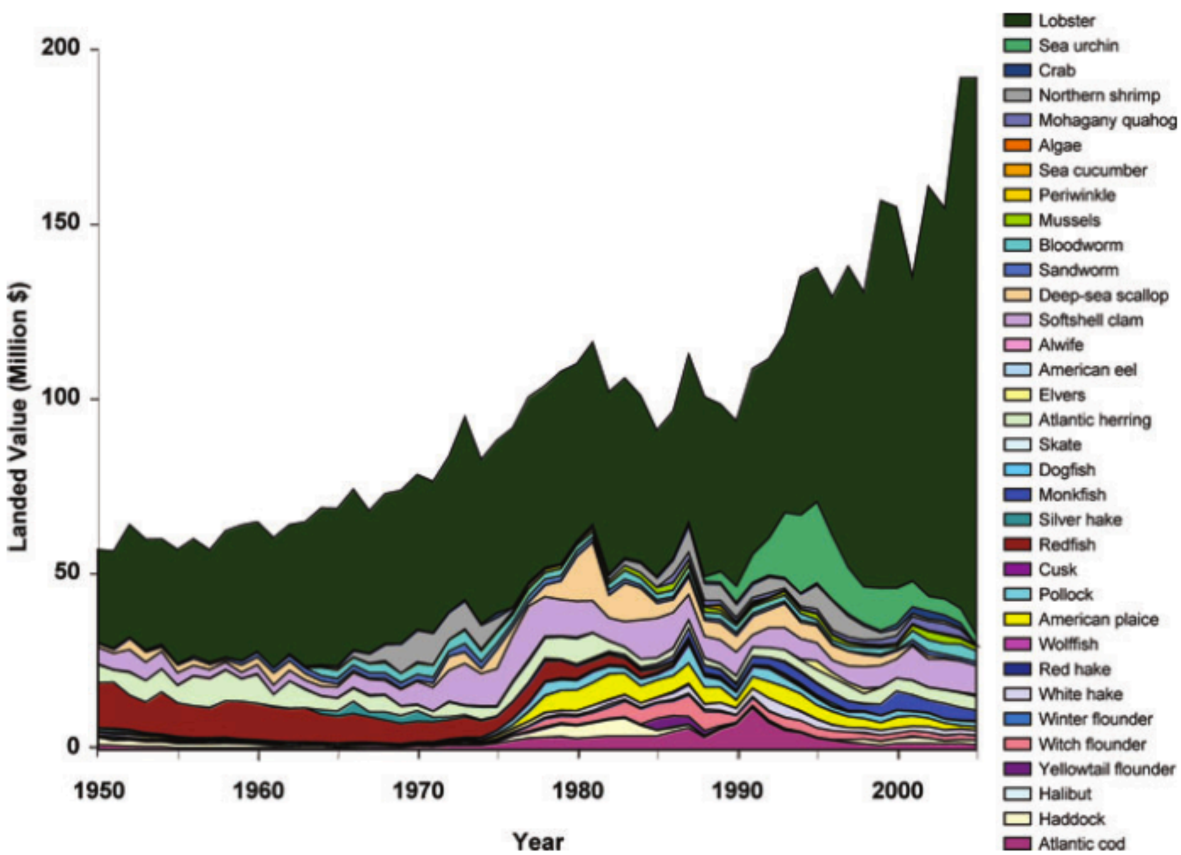

Figure 2. Landed values (corrected for inflation via the Consumer Price Index for 1980) by species for the 34 most important fisheries in Maine from 1950-2005. Source Steneck et al. (2011)

1.5. Lessons from Long Island Sound

In 1999 Long Island Sound experienced a mass die-off of lobsters after two years of difficulties with small declines in the population (Pearce and Balcom 2005; Howell et al. 2005). Just before the die-off event, the landings in Connecticut and New York peaked at 11 million pounds and a value of over $40 million. Two years later, landings declined by over 50% in areas of the Sound leading to a rapid decrease in the value of the fishery (Howell et al. 2005). The primary belief for this massive die-out is persistent increased water temperatures around 1-2° C in Long Island Sound (Pearce and Balcom 2005; Howell et al. 2005; R. S. Steneck et al. 2011).

Changes in water temperature have the potential to alter biological development of lobsters as well as make the species more susceptible to disease. Shell disease in lobster was present in localized areas and the coupled effect of the increase in temperatures weakened their immune systems further, which lead to the die-off (Pearce and Balcom 2005). This event affected all sizes of lobsters resulting in what some scientists refer to as "recruitment failure". The decline in fertile adults limited the number of juveniles, leading to a cyclical loop of reduced recruitment (R. S. Steneck et al. 2011). This extends the recovery time for the lobster stock, further affecting the fisheries overall value.

What occurred in the Long Island Sound is possible in Maine. Temperatures in the GOM are expected to increase from 2-4°C by 2080 (Nye 2010). These future predictions surpass what was observed in the Long Island Sound. Although each lobster population responds differently to anthropogenic changes, predictions for Maine are somewhat alarming. This increase may alter the reproductive capability of lobster in Maine as well as make them more vulnerable to disease, just as in Long Island Sound. For this reason, it is important to understand Maine's economic dependence on the lobster fishery and the potential impacts that similar events may have on the GOM lobster stock and therefore economy.

1.6. Environmental Influences on Lobsters

There is a strong seasonality trend in the lobster fishery due to biological and behavioral adaptations of the American Lobster. During the winter, the first quarter of the year, lobsters are primarily found offshore in deeper water due to warmer temperatures in the open ocean compared to shallow coastal areas (Waterman 2001; Pershing and Mills 2016). Additionally,

weather conditions in Maine make it more difficult for fishermen to stay on the water for extended time periods to haul lobster traps. Both of these factors contribute to low lobster landings during this quarter. Moving into the second quarter, lobsters begin to move inshore as well as shed their shells. A new lobster shell may take month to be complete and develop as a hard outer shell. Lobsters in this stage of their molting process are known as "shedders" and considered soft-shelled (Waterman 2001). At this time, demand for lobsters is at its summer peak. A combination of large quantities of lobster inshore as well as growing, hungry lobsters during the summer makes catching lobsters easiest this time of year. Furthermore, "shedders" do not transport and stay fresh for as long as hard-shelled lobster. This makes the timing of the lobster molt extremely profitable for the fishery, as lobsters can be sold fresh to the influx of summer consumers (Pershing and Mills 2016). As quarter 4 approaches, the increased summer demand begins to fall, water temperatures decrease, and lobster start to migrate back offshore leading to decreased landings.

Temperature plays a large role in the lobster's migratory patterns as well as the timing of their molt cycle. Higher temperatures can also cause earlier lobster shedding, altering the typical timeline of the lobster fishery, causing severe economic impacts (Steneck et al. 2011). The heat wave of 2012 confirmed these expectations as increased landings brought in lower profits. The lobster fishery was more successful earlier in the season with soft shell lobsters being caught in traps two months earlier than expected. A combination of limited processing plants and lower average price for soft-shell lobster lead to a dramatic per pound decrease in price and overall profitability of the fishery in 2012. Moving forward, it is important to consider that timing cues, such as temperature, are an important spatial component of the lobster fishery. Successful mating depends on spatial distribution and increased temperature has the potential to cause disconnect between shedding and mating (Murphy 2013). Combined effects of warmer water could reduce reproduction for long-term lobster populations.

The GOM is a unique environment because it is heavily influenced by ocean and atmosphere exchanges due to its enclosed shape, strong seasonal temperature differentials, and cold and warm water currents. From 1900 to 2014 the mean SST in the GOM increased at a rate of 0.01°F/year. Since 1982 this rate has accelerated to 0.05 °F/year. Most recently between

2004 and 2014 the GOM has seen the most dramatic increase in temperature at a rate of 0.41 °F/year (Figure 3) (Fernandez et al. 2015). Additionally, in 2012 the GOM experienced its

highest average water temperature in the 150 years on record, thus coining it the "Northwest Atlantic Ocean heat wave" (Woodard 2015). As the warming trend continues in the GOM the seasonality of the lobster fishery may change as well. Given the economic importance of temperature on biological processes in lobster, it is important to understand the impacts of temperature on the American lobster in Maine.

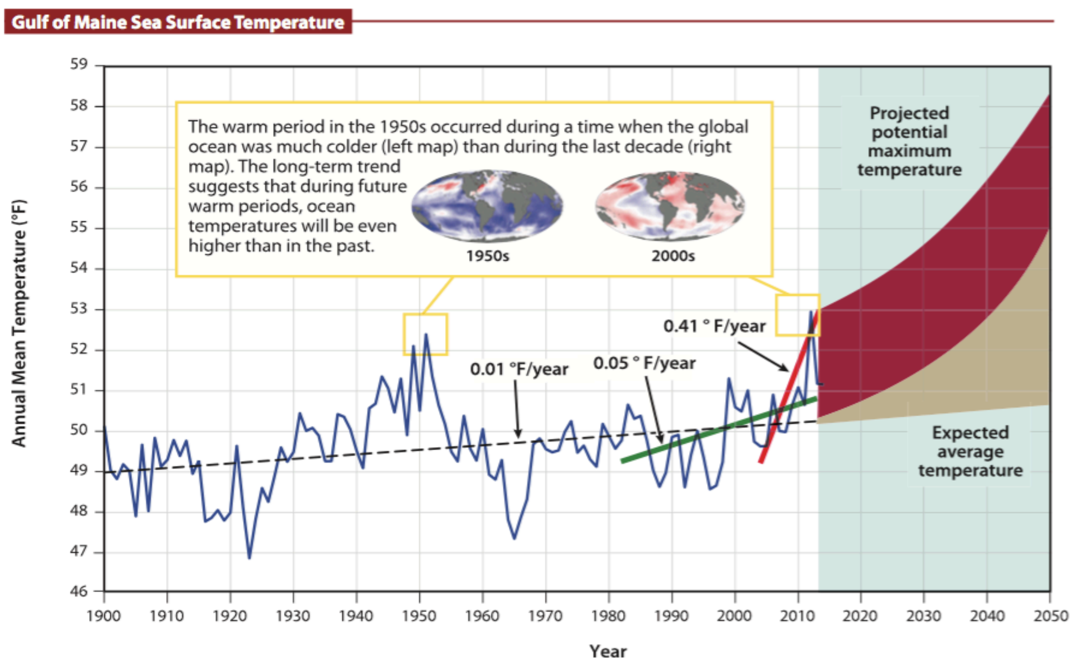

Figure 3. Gulf of Maine sea surface trends from 1900 to 2014 and projected sea surface temperature trends. Source: Fernandez et al. 2105

Maine's economic reliance on the lobster fishery and future potential environmental changes makes understanding impacts extremely important. As the fishery changes under the face of climate change it will be crucial that management adapts as well. In order to do this, we need to understand the potential impact that warmer ocean water will have on the lobster species as well as the economic market, as both are intertwined. This motivated the current study, which

is a preliminary attempt to quantify the effect that warmer ocean temperatures will have on the supply and demand of the American lobster in Maine using a bio-economic model.

II. Literature Review

2.1. Bio-economic Model

The use of bio-economic models to inform management decisions in the American Lobster fishery dates back to the 1970's. In the early practices of bio-economic models, the aim was to establish a baseline to characterize the lobster fishery from a biological and economic perspective at a time when there were no management practices in place (Bell and Fullenbaum 1973). Important management decisions and fishery predications are estimated using the model.

Bio-economic models can be the driver behind several ecosystem conservation measures. Marine reserves are an important example of this method used by policy makers to increase fishery biomass and harvest. A bio-economic model can be used to determine the optimal location for a reserve with the goal to maximize biological and economic yields (Sanchirico and Wilen 2001). Similarly, bio-economic models are used in the Maine lobster fishery to determine optimal quota levels for management policies (Holland 2011). In both of these conservation efforts, a bio-economic model provided a more holistic view of the fishery and accounted for effects on multiple stakeholders.

The insight from a bio-economic model comes from properly modeling the biological and economic factors in a fishery. The biological model aims to quantify the biomass of a fishery using key indicators for the population. The economic model complements the biology by estimating the behavioral factors, such as demand, that drive the economic indicators in the fishery. I examine the current literature on the American lobster from a biological and economic lens to build a model that is able to incorporate both factors together.

2.2. Lobster Supply Models

The supply of lobsters in the GOM can be viewed through two different lenses. The first is the biological supply of the lobster available in the ocean. The second is the supply based on fishing effort. In an early model of the supply of lobsters, water temperature, willingness of

fishermen to fish, and the number of snow days in a year determined the supply of lobsters in Maine (Acheson and Reidman 1982). What is available to consumers is inherently driven by both of these motivators of supply, but I focus the literature review on the most relevant biological models because under current regulations fishermen extract as much of the resource as they physically and legally are able to.

2.2.1. The UMaine Model

The Atlantic State Marine Fisheries Commission monitors the American lobster in the GOM through peer reviewed stock assessments. The most recent peer reviewed stock assessment occurred in 2015 at the Northeast Fisheries Science Center in Woods Hole, MA. The assessment contains topics ranging from data input, life history analysis, model results, reference points, and the current stock status. The biological model used in the assessment to characterize the current state of the lobster stock and the fishery is the University of Maine (UMaine) statistical catch-at-length model that was developed in 2005 (Chen et al. 2005, ASMFC 2015). This model is an important tool for policy makers to determine the availability of lobsters in the GOM within the legal catch limits of the fishery and determine the optimal amount of fishing effort. In this model, I study the abundance of lobsters presented by the UMaine model.

The supply of lobster for a bio-economic model can be estimated by the abundance of lobsters in the GOM. I will focus on lobsters that are within legal catchable size ranges to determine the supply of lobster, since this is the population affecting the economic drivers. The UMaine model examines this subset of the population through a “reference abundance” and “effective exploitation” of lobsters in the GOM. The reference abundance refers to the number of catchable lobsters in a year, which is defined as individuals that are greater than 78mm on January 1 as well as those that will molt and recruit to this size during the calendar year. The effective exploitation is the modeled number of lobsters landed in a year divided by the reference abundance (ASMFC 2015). I use this model because unlike other stock indicators this model is not based solely on official reports and surveys. This allows me to incorporate this model of supply into a model of demand.

The reference abundance will be the primary input for the supply of lobsters in the GOM. The UMaine model determines the reference abundance as a function of several biological population dynamics. The model breaks up the population of lobsters into 35 size bins and

estimates a sex and season specific output for each population dynamic. The dominant factor used to determine the reference abundance of lobster is the abundance at size, which is a function of the survivors at the end of the previous quarter, a sex and season specific growth transition matrix, and a vector of the number of recruits. The growth matrices are only used in the model at the end of the fall and winter quarters under the assumption that no growth takes place in the winter and spring. The number of survivors is based on a function of the abundance as well as mortality due to fishing and natural causes. The number of recruits is modeled as expectations of recruitment that varies over time to determine the proportion of individuals recruited each quarter. The proportion of recruits is assumed to be zero in the winter and spring since lobsters are not molting at this time. The major lobster molt occurs in the summer, making the proportion of recruits highest that quarter. The secondary molt at the beginning of the fall also contributes a smaller proportion of recruits to the reference abundance. UMaine's biologically driven model for the reference abundance of legal size lobster in the GOM is the model for the effective supply of lobsters available to the fishery. This supply is an important market driver along with the demand for lobsters.

2.3. Demand Models for Lobster

Demand models for lobster have been used since the early eighties to determine the optimal policy decisions for lobsters in the GOM. Understanding the demand is equally as important as understanding the supply because the price of lobsters has a large economic impact. A year of high landings and low price can be valued the same as a year of low landings and higher prices. The price of lobster can be modeled using an inverse demand function that accounts for economic market drivers.

In an early model, consumer income, substitutes for lobster, and Canadian lobster demand were the basis for a Maine lobster demand model. This model examined the effects of increasing the minimum legal catch size of the American lobster in Maine on the biology of the species and the states economy. The underlying assumption in this demand model is that the supply of lobsters is highly inelastic and changes in price are the result of demand changes (Acheson and Reidman 1982). This is still believed to be the case today because lobster supply is abundant and there have not been observed supply side effects large enough to impact price.

More recently, a similar demand model was used to determine the optimal exploitation of lobsters using a individual transferable quota (ITQ) system. This model used lobster landings, consumer income, U.S. gross domestic product (GDP), and the U.S./ Canadian exchange rate to determine a demand model. This method, however, does not model the supply and demand simultaneously because the argument is that price does not affect the supply of lobsters. Rather, lobster supply is determined by the availability, which is a result of the time of year (Holland 2011). In both models, the supply of lobsters is presented as inelastic because of the strong population of lobsters available in the GOM.

III. Analytical Foundations

3.1. Bio-economic Model

A bio-economic model allows for ecological and economic influences to be considered when analyzing potential impacts and policy. Economic and ecological factors across industries resemble two important themes: (1) ecosystems and economies are determined together and (2) both systems are in general equilibrium in nature. The themes presented are a result of economic and ecological literature that converged on the importance of joint determination and applications of the general equilibrium theory within these two fields. These topics illustrate that ecosystems and economies are adaptive systems that are highly connected (Finnoff and Tschirhart 2008). These themes are especially important when managing a resource, such as the American lobster, because both factors need to be taken into account. The economic and ecological determinants of the lobster fishery are analyzed in this study through a supply and demand model. For the American lobster, the supply is driven by ecological factors that determine the population size, while demand is driven by economic market conditions motivated by consumers. The interactions between the ecological and economic sides of the lobster fishery are extensive and crucial determinants in the market (Figure 4).

Historically, the population of lobsters was dependent on the available nutrients in the ecosystem. This is represented through the transfer of energy from their prey, algae and sea urchins (Robert S. Steneck, Vavrinec, and Leland 2004). However, the most important piece to understand is that there is a transfer of energy from the fishermen to lobsters in the current ecosystem state (Figure 4). This represents the effective aquaculture production that has taken

form in the lobster industry. Not only is this important biologically, but it enhances the interconnectedness and reliance on the ecosystem and economy in the GOM.

Understanding the theoretical energy and monetary drivers in the market sets up the bio-economic model that is used in this study. Conventional ecosystem and economic models are not linked, as the market is, thus they fail to properly inform decisions to maximize profits and ecosystem health (Tschirhart 2000). A bio-economic model allows for the interaction of these systems, linking their drivers. This paper will use the theory of supply and demand to make this bio-economic link.

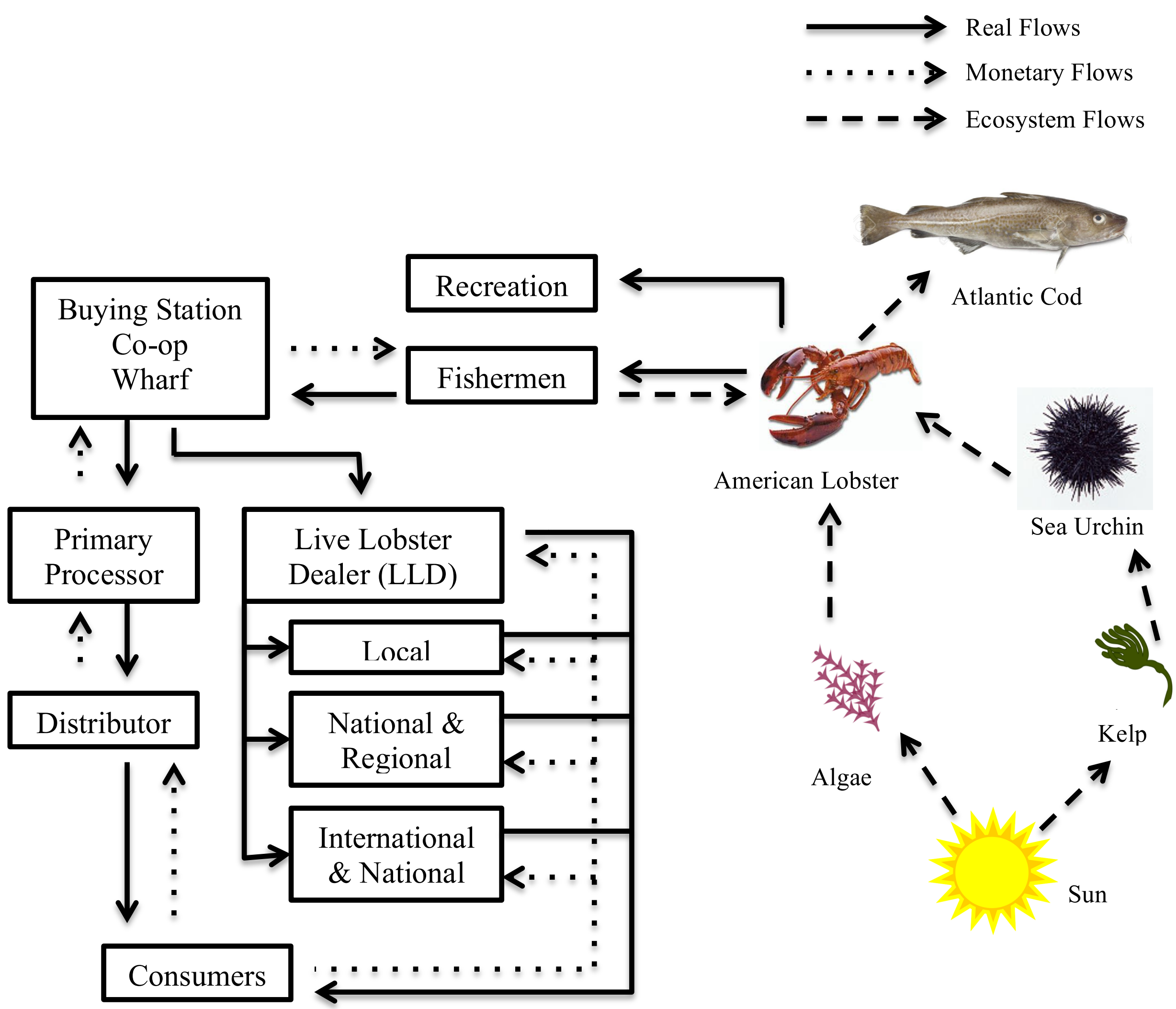

Figure 4 Interactions between simplified GOM ecosystem and economy with respect to the lobster fishery. Graphic modified from (Finnoff and Tschirhart 2008) and commodity chain modified from *John Norton of Cozy Harbor Seafood.*

3.2. Supply and Demand for Lobsters

In general, since 1980 landings have increased with the value of the fishery. However, around 2006 the value of the fishery declined rapidly, resulting in a dis-equilibrium point in the market. Specifically, there was excess of supply, causing the price of lobster to decrease dramatically. This disparity was deepest in 2012 when the industry experienced an increase of 18% in landings and a decline of $3.7 million in value. Since then, the price per pound, and therefore value of the lobster fishery, has recovered. From 2013 to 2014 the price per pound increased by 79 cents, even as landings were at record highs, resulting in the largest recorded per pound increase in one year (DMR 2015). These periods disproportional landings and value motivate the need to examine the ecological and economic drivers causing disparities in the supply and demand for the American lobster in Maine. Analyzing motivators of change may help prevent future market impacts and help understand the relative importance of ecological and economic factors that drive the market equilibrium.

The first assumption of this model is that all past landings and corresponding fishery values represent the market equilibrium. This is supported by the theory of supply and demand, which implies that the availability of lobsters coupled with consumer's desire to purchase lobster will set a market price. In this model, I allow the supply of lobster to change based on the belief that supply shifts due to future anthropogenic changes are possible. These changes in the market may lead to new equilibrium quantities of supply, demand, and price. In fact, this could result in dramatic increases or decreases in price if demand remains constant. For example, an increase in landings may result in excess supply of lobsters, which can be visually represented as a shift of the Q_S line to the right. This shift causes the price for lobsters to decreases and reduces the

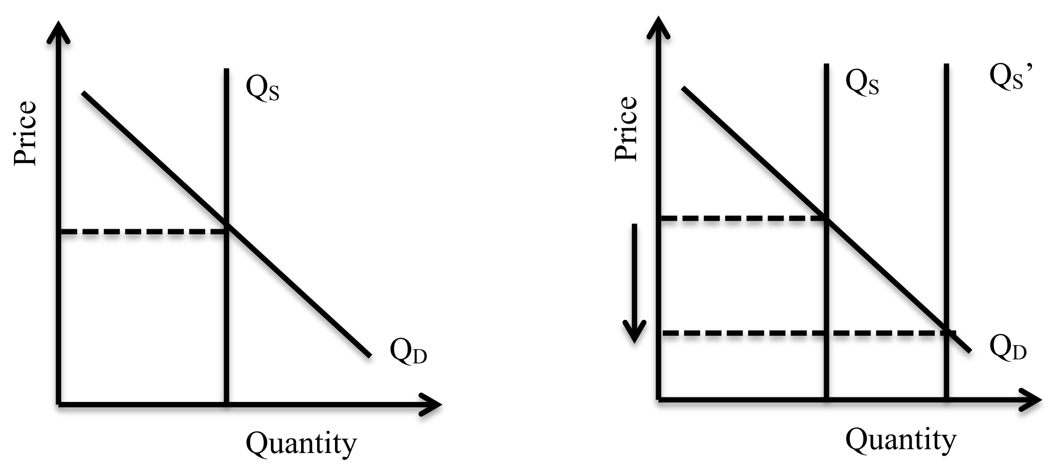

Figure 5 Supply and demand for lobsters and the effect of changes in supply on price.

overall value and profitability of the industry (Figure 5).

I argue that future climate conditions will affect the availability of lobsters and thus influence the supply in the market. Previous studies do not model supply and demand together because the supply of lobsters is determined solely by availability and time of year, rather than price (Holland 2011). Additionally, the supply of lobsters appears to be extremely inelastic because fishermen will extract the most they can based on effort and legal catch allowances (Acheson and Reidman 1982). While the current belief in the lobster fishery is that the price fishermen receive does not impact their decision to fish, a persistent decrease in price, as environmental conditions change, has the potential to alter this mindset. For this reason, the second assumption of the model is that supply and demand can be modeled together under higher SST projections. This assumption explains that as the price of lobsters decreases, the amount fishermen will receive will fall. Thus, there is a level at which fishermen will be influenced to move into other markets and dedicate time to alternate profitable industries.

Past equilibrium levels of landings and price are used to estimate the effect water temperature has on lobster landings and price. Because of this, the model assumes the markets historical equilibrium conditions are the best estimate of the relative importance of supply and demand factors driving the lobster fishery. I believe this to be the case based on the several shocks that have occurred to the lobster industry during this time period. The equilibrium conditions of 2012 contained in this time series are reflective of how the market acts under extreme temperature events.

Based on these three assumptions, a system of equations is used to solve for a reduced form demand equation that estimates the effect of water temperature on the price of lobsters in Maine. A reduced form demand equation is based on the principle that price contributes to the supply available through a fisherman's decision to catch lobster based on the price received. With this assumption, a complete bio-economic model would account for the ecological factors affecting the abundance of lobsters as well as drivers of consumer demand given potential impacts of increased water temperature. This model achieves this by using current economic conditions, but substituting projected temperature changes. In this way, I will explain the impacts conceivable changes in the supply of lobsters, due to higher ocean water temperatures,

would have on conditions experienced in the lobster fishery from 2004-2013. These findings are used to explain potential future impacts on the market equilibrium in the lobster fishery.

IV. Research Methods

4.1. Data Collection

In order to model the supply and demand of lobsters in Maine, time series biological and economic data was collected. The Atlantic States Marine Fisheries Commission (ASMFC) 2015 *American Lobster Benchmark Stock Assessment and Peer Review* was used to collect the annual reference abundance (millions of lobsters) estimated by the UMaine model from 2004-2013. I applied estimated seasonal factors based on actual landings to determine monthly reference abundance in order to capture the seasonality trends that occur due to migration and growth patterns of lobsters and therefore the accessibility of lobsters to fishermen. To determine these effects, the monthly landings are divided by annual landings to calculate a monthly percentage. Reference abundance was then multiplied by the monthly percentage seasonality factor to estimate a monthly figure (Figure 6). Daily sea surface temperature (°C) means in Boothbay Harbor were collected from the Maine Department of Marine Resources (DMR). Daily means were summed to monthly means and converted to °F for the supply model. Projected SST is based on annual GOM warming trends observed since 2004 that were converted to monthly rates and applied to DMR means (Fernandez et al. 2015). The DMR was also the primary source for monthly landings (millions of pounds) and value (millions of dollars) of the American lobster fishery from 2004-2013 (Figure 7). The price was derived by dividing the value of the fishery by landings, to receive a monthly price per pound. Quarterly data from 2003-2014 on GDP growth (billions of dollars) and U.S./ Canadian exchange rate was collected from Haver Analytics (Figure 8), while Maine non-agricultural employment was collected from the U.S. Department of Labor. Monthly estimates for landings were summed to quarterly figures when used in the demand model.

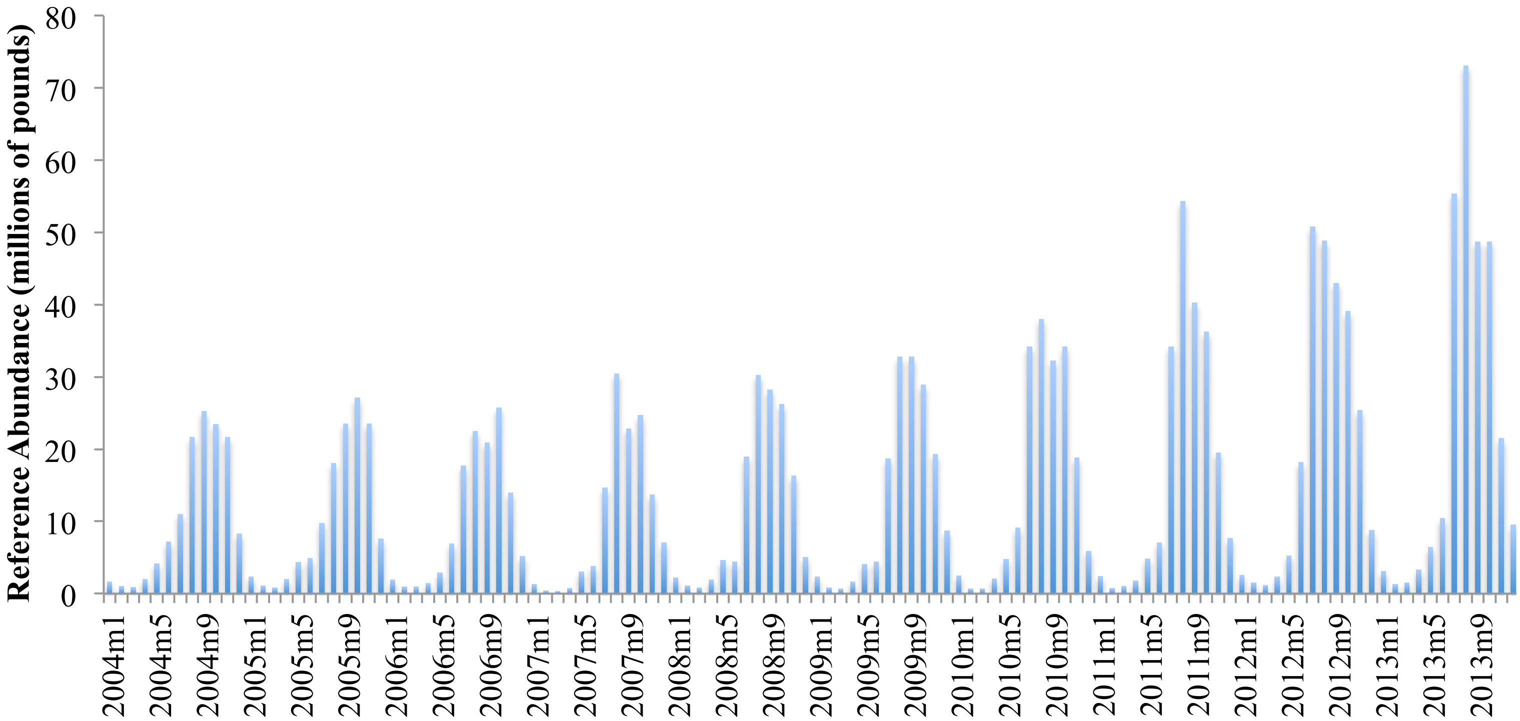

Figure 6. Monthly reference abundance values calculated from yearly values reported in the AMSFC stock assessment and peer review. Indicates the available supply of lobsters within legal catch limits in the GOM.

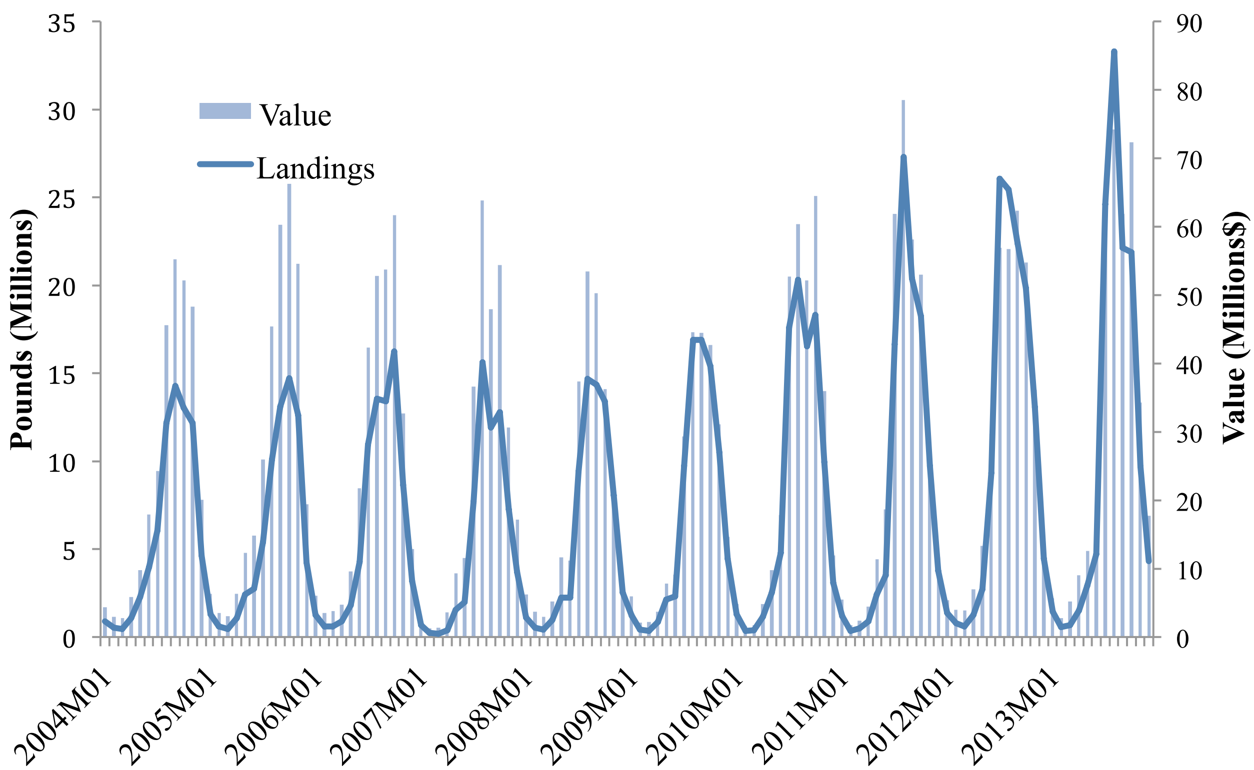

Figure 7 Summary of landing and value of the American lobster fisher in Maine from 2004 to 2014. Data collected from Maine Department of Marine Resources.

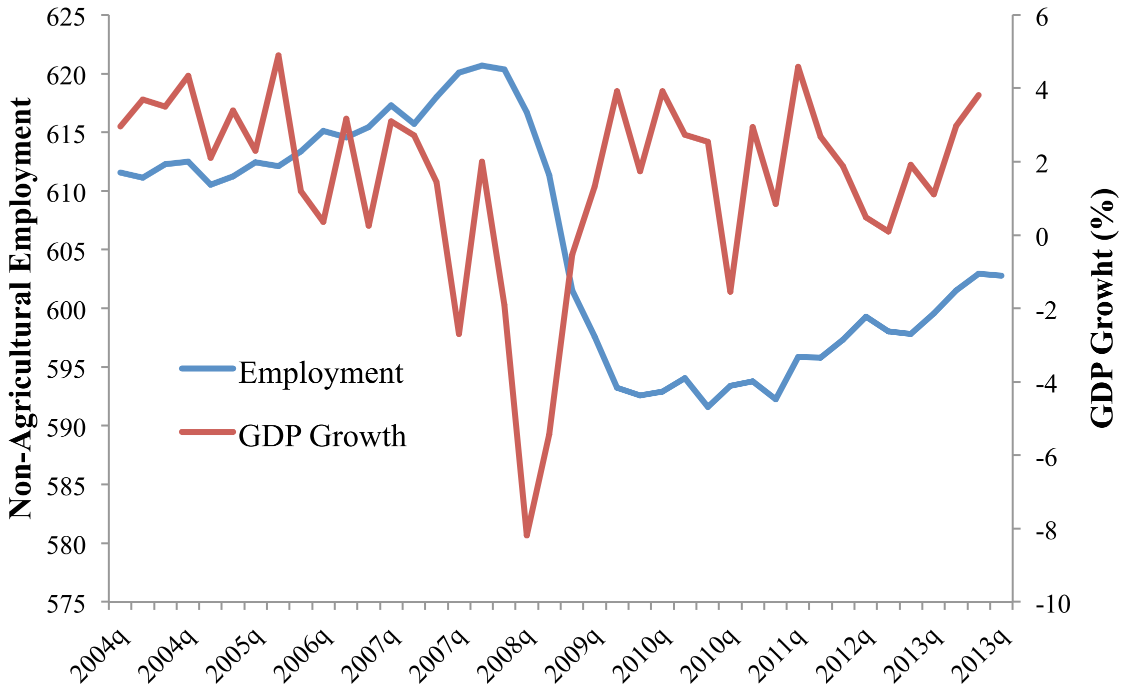

Figure 8. Economic indicators used from 2004-2013: Maine non-agricultural employment (blue), U.S. GDP growth (red). Source: Haver Analytics

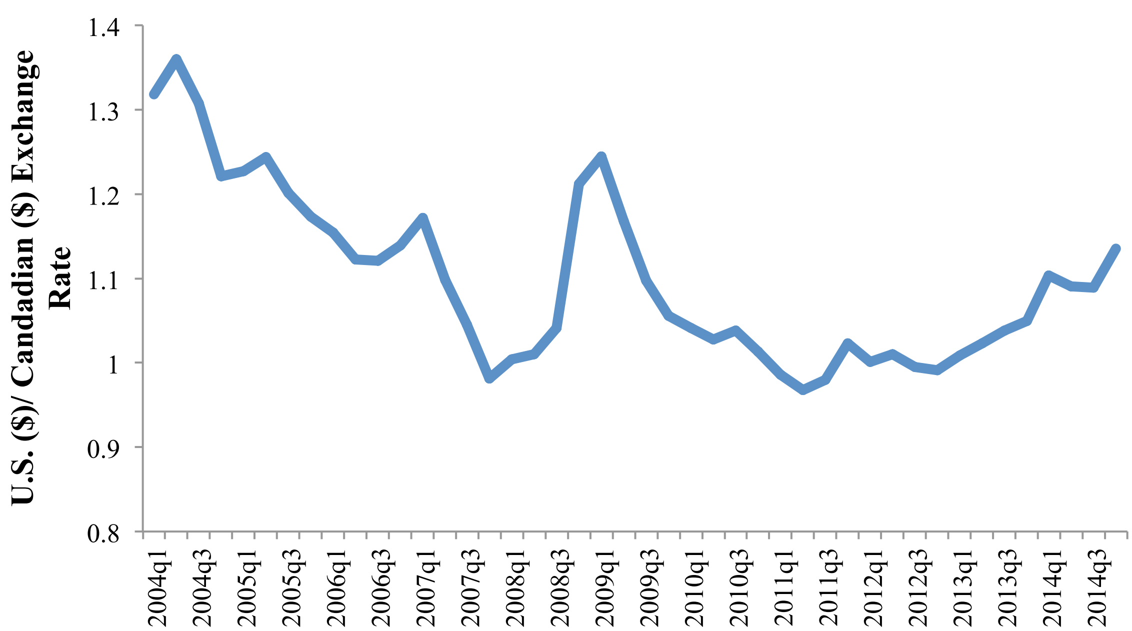

Figure 9. The quarterly U.S./ Canadian dollar exchange rate from 2004-2013. Source: U.S. Department of Labor

4.2. Research Overview

In order to account for future changes I estimate a supply and demand model using an ordinary least squares regression and then simulate this model under a higher temperature scenario. This allows me to understand the supply and demand of lobsters separately and determine the accuracy of my model by comparing the supply of lobsters to reported landings and the inverse demand model to reported market price. With this error in mind, I simulate the supply model first to determine a new level of landings under the higher temperature scenario. I feed this simulated supply model into the estimated demand model to simulate a new price per pound of lobsters in Maine.

4.3. Model Estimation

I build a model for the supply of lobsters using the estimated reference abundance from UMaine as well as an environmental factor, temperature, which affects the growth of lobsters. Additionally, I include monthly dummy variables to incorporate the effects of seasonality on the availability of lobsters. The supply of lobster available to fishermen, given as the pounds of lobsters landed in Maine is:

$$\text{Landings} = \beta_0 + \beta_1 \text{ Reference Abundance} + \beta_2 \text{ SST} + \beta_3 \overrightarrow{\text{month}} + \varepsilon \qquad (1)$$

This provides the base model for available lobsters of legal size limits for commercial fishermen and incorporates the effect of temperature on the availability in the GOM. I hypothesize that an increase in both the reference abundance and SST will cause an increase in landings because both factors will increase the total availability of legally sized lobsters. I estimate a model for demand after building a base model for the supply of lobsters.

The demand for lobster in Maine can be modeled as a function of several economic indicators that affect price and consumer's purchasing decisions. The following model is adapted from Holland 2011 to model the price of lobsters in Maine:

$$\text{Price} = \alpha_0 + \alpha_1 \text{ Landings} + \alpha_2 \text{ Employment} + \alpha_3 \text{ GDP Growth} + \alpha_4 \text{ Exchange Rate} + \varepsilon \qquad (2)$$

Price is the dollar per pound value of lobsters determined from DMR reports. Landings are the reported pounds by the DMR. I predict that landings and price are negatively correlated so price decreases when landings increase and create excess supply in the market. Employment represents the total non-agricultural employment in Maine and GDP growth is the annualized rate of U.S. real GDP growth. I expect that increases in Maine employment and U.S. GDP growth will increase the price of lobsters because lobsters are generally viewed as a luxury consumer good. Given this, increases in these economic variables would be indicators of higher consumer income, raising the demand and price for lobsters. The real exchange rate between the U.S. and Canada is used because Maine lobster is exported to Canada for processing. I hypothesize that an increase in the U.S./Canadian exchange rate will decrease the price of lobster because this makes it relatively less expensive for the U.S. to export lobsters for processing, reducing the domestic price for lobsters.

4.4. Model Simulation

To examine future effects of rising ocean temperatures in the GOM, I use the estimated parameters in equation (1) and projected sea surface temperature (SST*) values to calculate the new landings. This new equation is:

$$\text{Landings*} = \beta_0 + \beta_1 \text{ Reference Abundance} + \beta_2 \text{ SST*} + \beta_3 \overrightarrow{\text{month}} \tag{3}$$

Where landings* are the predicted values for lobster landings under warmer ocean water. These two equations together provide me with current landings as well as a higher temperature scenario of landings to compare the pure effect of warmer ocean waters on the landings of lobsters in Maine.

The estimated coefficients in equation 2 are used to determine the effect of temperature on the price of lobsters. Using the modeled landings under warmer ocean temperature calculated in equation 3, I simulate the price using the estimated regression coefficients from equation 2 and the same economic indicators. This is given by the equation:

$$\text{Price*} = \alpha_0 + \alpha_1 \text{ Landings*} + \alpha_2 \text{ Employment} + \alpha_3 \text{ GDP Growth} + \alpha_4 \text{ Exchange Rate} \tag{4}$$

Where price* represents the new price and landings* denotes the estimated landings of lobsters under higher SST. A comparison between demand equations results in an estimated price differential under future climatic conditions in the GOM.

4.4. Reduced Form Equilibrium Condition

The final equation represents the market equilibrium for the Maine lobster fishery under projected ocean temperatures. This bio-economic model implies that the price of lobsters will factor into fishermen's decisions to catch lobsters based on the price they will receive. Additionally, the U.S./Canadian exchange rate is a supply side factor because it affects the price fishermen will incur for exporting lobsters to be processed. Employment and GDP growth are pure demand side effects that will determine consumers purchasing decisions. The combined effects of supply and demand drivers feed into the bio-economic model to estimate an equilibrium price on a quarterly basis from 2004-2013. The final result of the model is a reduced form demand equation that uses observed rates of temperature change in the GOM to simulate future conditions. The calculated equilibrium of equation 4 incorporates the projected landings under higher temperatures to solve for a new price. This is the new market equilibrium price that is projected, based on the relative factors that affect the current equilibrium of the fishery.

It is hypothesized that exogenous ecological shocks to the supply of lobsters, which would decrease their availability, will result in negative economic impacts. Specifically, the expected increase in lobster landings under high ocean temperatures will decrease the price of lobsters. As this trend continues, price will become a more important factor in fishermen's decision to catch lobster as well as potentially alter the belief of lobster as a luxury consumer good.

V. Empirical Evidence

5.1. Model Estimation

A combination of the UMaine reference abundance model, SST, and monthly seasonal variables explain 99% of the variance in Maine lobster landings. In line with the predictions,

both increases in reference abundance and SST result in an increase of lobster landings. An increase of one million lobsters inside legal size regulations results in a 441,131-pound increase in lobster landings, *ceteris paribus* (p<0.01). Additionally, a one degree Fahrenheit increase in the SST results in a 127,076-pound increase in landings, *ceteris paribus* (p<0.01). Compared to reported monthly landings provided by the DMR, the modeled monthly landings are 15.48% higher on average.

Parameter	Coefficient	Standard Error
Intercept	-5432863	1154094
Reference Abundance	0.44**	0.01
SST	127076.1**	25810.58
$R^2 = 0.99$		

* Significant at the 5% level; **Significant at any reasonable level

Table 1. Coefficient estimates for the estimated supply model using OLS regression.

The model for lobster demand in Maine demonstrated a strong relationship between the price of lobsters, commercial landings, and economic indicators. Lobster landings, non-agricultural employment in Maine, GDP growth, and the U.S./Canadian exchange rate explain 81.5% of the variance in the price per pounds of lobster. All hypothesized impacts on price were validated and each parameter is at least significant at the 5% level of confidence. A one percent increase in landings results in a 0.16% decrease in the price per pound, *ceteris paribus* (p<0.01). A one percent increase in Maine employment yields a 6.61% increase in price per pound, *ceteris paribus* (p<0.01). A one-percentage point increase in GDP growth results in a 1.40 percentage point increase in the price of lobsters, *ceteris paribus* (p=0.018). Lastly, a one percent increase in the exchange rate results in a 0.85% decrease in the price of lobsters, *ceteris paribus* (p=0.029).

The results of this model confirm that the price of lobsters will decrease due to excess supply in the market, based on commercial landings. Additionally, positive effects of employment and GDP support the notion that lobsters are a luxury good and as consumer's income increases they will tend to purchase more lobsters. Finally, the exchange rate does have

a comparatively large impact on the price of lobsters indicating that Maine fisheries export a substantial amount of their catch to Canada. The modeled price per pound of lobsters is 8% higher on average than the price given by the DMR.

Parameter	Coefficient	Standard Error
Intercept	-38.34	7.05
Log(Landings)	-0.16**	0.01
Log (Employment)	6.61**	1.10
U.S. Real GDP Growth	0.01*	0.01
Log (U.S./Can Exchange Rate)	-0.85*	0.49
$R^2 = 0.82$		

* Significant at the 5% level; **Significant at any reasonable level

Table 2. Coefficient estimates for the estimated demand model using OLS regression.

5.2. The Effect of Temperature Based on the Reduced Form Model

The model incorporates temperature as a factor of supply to represent exogenous environmental factors that will impact the economic equilibrium of the lobster fishery in Maine. The equilibrium of this market is rapidly adjusting as consumer's preferences for lobster fluctuate along with the availability of lobsters. The model predicts at 9% increase in landings if ocean temperatures rise at the rate observed since 2004 (Figure 9). This figure represents the pure effect of temperature on the supply of lobsters, which in turn has large economic impacts for the lobster fishery. Specifically, the projected price of lobsters decreases by 8% on average when higher SST vales are used to model supply and solve for a equilibrium market price (Figure 10).

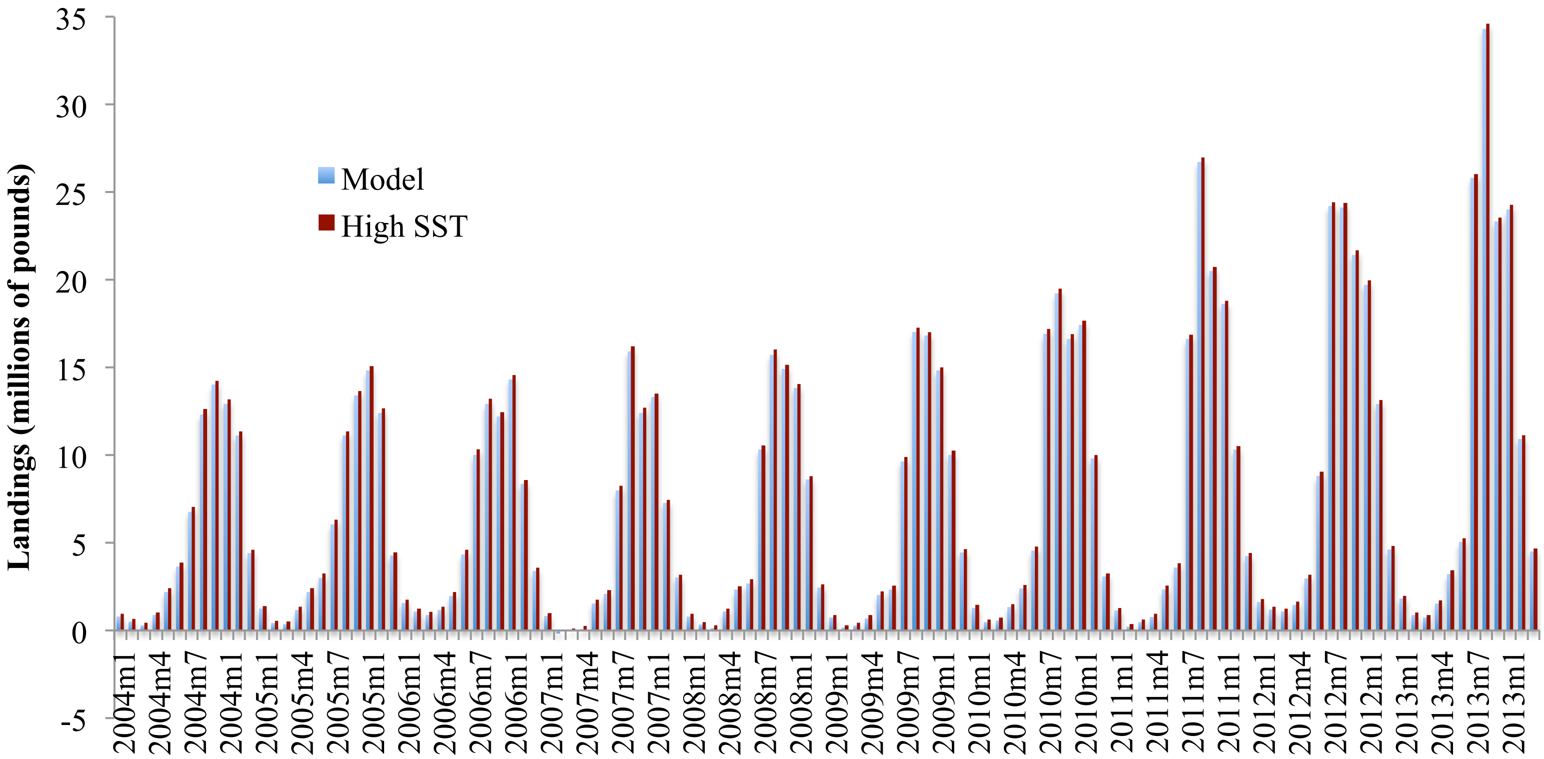

Figure 10. Supply model estimates for lobster landings from 2004-2013 and supply model simulation results under higher temperature scenario.

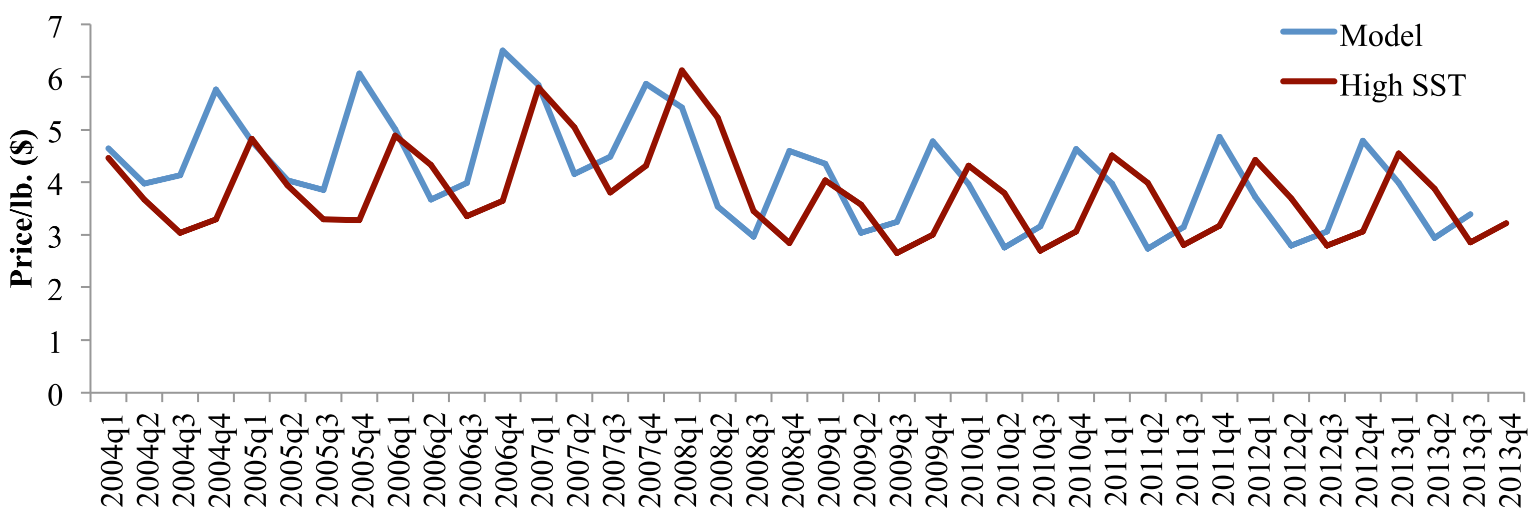

Figure 11. Demand model estimates for lobster landings from 2004-2013 and demand model simulation results under higher temperature scenario.

VI. Conclusions

6.1. Supply Model

Based on the evidence from this model of lobster supply in Maine, ocean temperature factors into the availability of lobsters to commercial fishermen. These findings align with previous observations during warm years, such as 2012, and biological expectations of lobster growth. It is important, however, to note that extreme increased water temperatures may result in declines or crashes in the lobster population. Evidence from Long Island Sound shows that increases in water temperature, especially over long time periods, can have negative effects on lobster availability. The belief that increased temperature may increase susceptibility to shell disease is a large concern, particularly in Maine, as we see warming trends. Additionally, the seasonality of the lobster fishery is extremely valuable for the Maine economy given its reliance on tourism. Temperature affects lobster migration from deep offshore water to shallow inshore waters as well as their molting cycle. Both of these behavioral patterns are factors that determine when lobsters are available to fishermen and the subsequent market price due to meat quality and consumer demand. Potential earlier migrations and molts over extended time periods will influence the market equilibrium through both the availability and demand for lobsters.

Moving forward, it will be important to understand the biological threshold that lobsters have to temperature. While several factors such as rate of change and lobster size will affect the organisms' threshold, examining a tipping point will allow for a more in-depth analysis. The point at which lobsters no longer increase in abundance, but crash, due to temperature change will be an important economic factor in the market. The predicted increases are expected to reduce the price of lobsters, but if a tipping point is included the market price may rapidly increase due to limited availability. This is especially important in the GOM fishery because it makes up for the majority of American lobster supply globally.

6.2. Demand Model

The demand model for lobsters indicates that increased landings in Maine will decrease the price of lobsters. This is consistent with economic theory that more abundant resources are less valuable. The price is especially important in a fishery because it may affect the supply of lobsters as well as demand. Similar to the understanding of a temperature threshold on the

availability of lobster, the point at which fishermen consider price as a factor in their decisions to fish is extremely important. While this is not believed to influence the current market, it has the potential to affect future conditions, especially given effects of anthropogenic impacts on lobsters' habitat. Incorporating a price level that influences supply will enhance the accuracy of equilibrium market conditions in the fishery.

6.3. Effect of Temperature

Overall, the combined supply and demand effects of temperature on the price of lobsters indicates that projected ocean temperatures will have a negative economic impact on the fishery through an 8% decrease in price. In 2015, the lobster fishery accounted for 81% of the $616, 522,118 value of Maine's commercial fisheries. If this projected decline of 8% occurred in 2015 Maine would have lost almost $40 million dollars in revenue assuming no change in landings. The size of the fishery triggers small changes to have large impacts.

It is important to acknowledge that the temperature scenario used to affect the supply of lobsters is an extreme case. While it is the observed rate of change in the GOM over the past decade, the Earth is in a warm period that is further exacerbated by current anthropogenic impacts. Expectations for future ocean temperature are projected to increase at a rate slower than what we have seen in the past decade and what was used in this study. However, periods of accelerated temperature increase at this rate are not unrealistic and occur in intervals through time. Additionally, periods of dramatic warming will affect lobster populations the most and have the potential to create irreversible damage to the stock. As an economy that depends heavily on one resource, it is imperative to understand conceivable extreme conditions.

6.4. Broader Implications

The decline in the value and landings of lobster in the Maine market drives the need for bio-economic approaches. The need for this research is motivated by the impending anthropogenic changes that will affect the Gulf of Maine in the foreseeable future. A severe decline in the lobster fishery in Maine has the potential to have a strong multiplier effect. The most obvious impacts will result from direct declines in the value of the fishery and fishermen's revenue. These declines may also be felt in other layers of the economy as a large number of

fishermen could experience a rapid decrease in income, decreasing demand for other goods. Additionally, Maine is known worldwide for their seafood products, in particular lobster. A rapid decline in the population of Maine lobster would decrease exports as well as result in possible losses in tourism.

The current gilded trap that Maine's fishing economy developed is not a healthy equilibrium. Management and fishermen should understand the current state of Maine's fisheries and the projected impacts for the future. As the GOM continues to change due to anthropogenic impacts the dynamics of the lobster fishery, and other Maine fisheries, will change as organisms respond and adapt to new conditions. Economic conditions are an important motivator to understand the impacts facing the fishery. This model shows that while an increase in lobster availability may appear to be a positive effect that will allow the fishery to grow, the negative impact on price may result in an overall loss in revenue. For this reason, it is important that the fishing economy diversifies to buffer potential changes to lobster populations. Moving away from the monoculture, and even lobster aquaculture, that developed will create a fishing economy more likely to be resilient to future impacts.

Maine lobster is a resource that is on the forefront of research, however I believe that a more holistic approach that incorporates all of the factors, both ecological and economic, must be considered. Furthermore, it is important to consider the future impacts that this industry will face with impending anthropogenic changes. Current models focus on answering questions of lobster management and population changes that will be effective immediately. However, the GOM is an ecosystem that is experiencing the most climate driven changes in the world. These changes encourage the need to examine future impacts that are likely to be seen within the next century. Quantifying the potential economic damages is imperative to motivate actions towards protecting fishery economies and the communities that rely on them.

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