Evaluating Resiliency for American Lobster and its Fishery in a Changing Environment

Cameron Hodgdon[1,6], Noah Hunt[2], M. Conor McManus[3], Burton Shank[1], & Yong Chen[4,5]

[1]*Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, Woods Hole, MA 02543, USA*

[2]*CSS, Inc., Fairfax, VA 20230, USA*

[3]*Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, Narragansett, RI 02882, USA*

[4]*School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794, USA*

[5]*Institute for Advanced Computational Science, Stony Brook University, Stony Brook, NY 11794, USA*

[6]*Corresponding Author; cameron.hodgdon@noaa.gov*

1.0 Abstract

The application of individual-based modeling frameworks has expanded over the last few decades, but their use is still limited in global fisheries management practices. These probabilistic models allow simulation of complex species' life history and fishery-dependent processes. This research sees the advancement and implementation of the Individual-Based Lobster Simulator, an individual-based modelling framework, to simulate American lobster (*Homarus americanus*) stock dynamics in the Gulf of Maine and Georges Bank region under a suite of climate change and management scenarios. With impacts of warming waters directly considered, the stock was projected out to equilibria under scenarios of status quo management and alternative future management schema. This analysis allowed for evaluation of the effectiveness and overall impact of alternative regulatory measures on the stock for a given climate change scenario. We conclude that regulatory changes were generally effective at maintaining spawning biomass and legal biomass under climate scenarios but were less effective at maintaining recruitment and landed catch. Furthermore, a given management action had less effectiveness at maintaining stock levels under increased levels of climate change.

Keywords: Individual-Based Modeling, Management Strategies, Projections, Scenario Exploration, Environmental Effects

2.0 Introduction

The American lobster (*Homarus americanus*) is a high-value crustacean in the northwest Atlantic (NMFS 2024) shown to be sensitive to the region's intense climate change (Mills et al. 2013; Pershing et al. 2015; Kleisner et al. 2017), as ocean temperatures have been found to impact lobster life history, recruitment, suitable habitat, migration timing, molting phenology, and natural mortality (Mills et al. 2013; Boudreau et al. 2015; Staples et al. 2019; Goode et al. 2019; Tanaka et al. 2019; Hodgdon et al. 2021; Hodgdon et al. 2022A; Hodgdon et al. 2022B). Given the significance of this fishery to coastal economies and its historical significance toward cultural identity (GMRI 2012), it has become increasingly important to address the impacts that climate change has on the population and the subsequent fishery in the Gulf of Maine/Georges Bank (GOM/GBK) stock area.

The American lobster fishery in the GOM/GBK stock area has remained predominantly a small-crew, owner-operator fishery for over 150 years, with vessels setting baited traps (known as pots) on the seafloor (Corson 2004; GMRI 2012). Before an official top-down management schema was established, conservation efforts were placed on the fishery by the fishers themselves, who lobbied state legislatures to implement rules such as the minimum legal size and the prohibited harvest of egg-bearing females (Acheson and Gardner 2010; Acheson and Gardner 2011).

A minimum legal size of lobster was put in place to ensure sexual maturity and breeding of a portion of the population before being landed in the fishery (Acheson & Reidman 1982). Lobsters mature at different sizes, with size at 50% maturity (L_{50}) estimated at 90.81 mm carapace length (*CL*) (ASMFC 2015; Mazur et al. 2019B). The minimum legal size has varied over time, but, since 1989, has been 83 mm *CL* in nearshore GOM waters and, since 2008, 89 mm *CL* in offshore GBK waters (ASMFC 2020). Many of these small lobsters that are caught in pots, but not landed, survive the process (Mazur et al. 2019A), resulting in a low handling mortality.

To further ensure the sustainability of the GOM/GBK lobster stock, fishers do not harvest egg-bearing females (called berried females) (Acheson & Reidman 1982; Mazur et al. 2019A; Mazur & Johnson 2020). When intercepted by the fishery, these females are notched with a small "v" on their tail to signal other fishers that may catch them in the near future (~2 molting events of the individual) that they are breeding females and should not be landed (despite the presence of eggs at harvest or not). This practice has proven to be effective (Acheson & Reidman 1982; Acheson & Gardner 2011); however, even though fishers generally agree with the methodology (Acheson & Gardner 2011; Mazur & Johnson 2020), v-notching compliance rates of fishers today are not well known due to perceived decreasing benefits from the conservation measure (Mazur & Johnson 2020).

These conservation measures were designed to protect a proportion of the breeding component of the stock and, in turn, ensure high levels of recruitment to sustain the population. However, the measures themselves are based on what is currently understood about lobster life history, which has been altered and is likely to continue changing under climate change. Thus, there is a strong need to understand how this lucrative fishery will be impacted as warming waters continue to alter the northwest Atlantic large marine ecosystem (LME) (ASMFC 2020). To appropriately address these questions, a modeling or simulation framework must consider climate impacts on the population and management and regulatory impacts on the fishery simultaneously. Such a framework must be flexible to appropriately consider the complex conservation measures and life history characteristics of the species, including non-continuous growth and size-based life history and fishery processes. For U.S. American lobster, one framework used to address such questions has been the Individual-based Lobster Simulator (IBLS), which was recently used to simulate changes to the population and fishery dynamics for the stock under climate-driven life history changes and alternative minimum legal sizes (Mazur et al. 2019A, Hunt et al., 2023).

Using the IBLS, this study examined the cumulative impact of three potential scenarios of future climate change on the life history of GOM/GBK American lobster, and how the stock and associated fishery were impacted. The utility of management changes via altered regulations on the fishery are also assessed under these future climate scenarios to examine the interplay of climate effects and management effects on the stock and fishery dynamics. Through this effort, we aimed to provide insight into how the GOM/GBK lobster population may change under anticipated climate scenarios, and whether prospective management actions may be of use towards mitigating adverse effects on the stock and fishery it supports.

3.0 Methods

3.1 Basecase Stock Projections with the Individual-Based Lobster Simulator

The IBLS was initially developed by Chen et al. (2005), and has been expanded over several iterations (Chang 2015; Mazur et al. 2019B; Hodgdon et al. 2022A). This probabilistic model can capture complex size-dependent life history and fishery processes, and has been used to test the performance of the models used for the American lobster stock assessment conducted by the Atlantic States Marine Fisheries Commission (ASMFC) (Chen et al. 2005; Zhang et al. 2011). The American lobster stock assessment model, like other American lobster population models (e.g., Theberge et al. 2024), is deterministic and estimates parameters on the aggregate population. These types of models are inherently more rigid than probabilistic models like the IBLS, which allows for variability in processes among individuals (nevertheless, both types of models are informative to the successful management of the species). The IBLS simulates a stock of American lobster by implementing both life history and fishery processes on individuals using random Bernoulli trials in each seasonal timestep (Chen et al. 2005; Chang 2015; Mazur et al. 2019B; Hodgdon et al. 2022A). Each Bernoulli trial is informed by previous research on the species and the stock assessments conducted by the ASMFC (ASMFC 2015; ASMFC 2020). Mazur et al. (2019B) gives a full description of the model and this paper presents a brief overview.

The IBLS has seasonal timesteps, operating on four, 3-month long periods per year: Winter (January-March), Spring (April-June), Summer (July-September), and Fall (October-December). At the start of each timestep, every lobster is an independent integer size (the size it was at the end of the previous timestep) between 53 and 223 mm carapace length (*CL*) to match the range of sizes used in the ASMFC American lobster stock assessment (ASMFC 2015; ASMFC 2020). Each lobster then passes through the set of random Bernoulli trials (Figure 1), where probability of the outcome of each trial is sex and size-dependent. At the end of the timestep, each lobster is either dead from natural mortality or handling mortality, landed in the fishery, or alive. Lobsters that survive grow by molting, where they shed their shell and regrow a larger one (Herrick 1911). The frequency of molting occurs once to twice a year (in the Summer or Fall) and is dependent on lobster size (Herrick 1911; Aiken & Waddy 1976; Comeau & Savoie 2001). How much a lobster grows during a molting event is also size-dependent. In the IBLS, the probability a lobster grows in a timestep is molt probability and how much it grows is determined by the molt increment distribution (see section 3.3). After a potential molting event, the lobster then enters the next timestep at the size it is at the end of the previous timestep and continues through this process until it either dies from natural mortality or is landed in the fishery. At the end of the simulation, each lobster has a life history record of its sex, size changes, maturity status, and death disposition, which allow for stock-wide estimates of recruitment abundance, spawning stock biomass (SSB), landed catch, and legal biomass (biomass of lobsters that have the potential to be legally harvested) to be calculated for each timestep (Mazur et al. 2019B; Hodgdon et al. 2022A). Recruitment is an input to the IBLS using data from previous stock assessments (ASMFC 2020). A yearly recruitment value is proportioned across seasons (with Summer receiving ⅔ of the yearly recruitment and Fall receiving ⅓) and equally split between sexes. Each recruited individual starts at a random integer size between 53 and 58 mm CL to match the first 5 mm size bin used by the ASMFC in stock assessments (ASMFC 2015; ASMFC 2020).

The IBLS can be used to project indefinitely under static conditions to determine stability points called equilibria. Projections of each individual lobster are conducted through the flowchart in Figure 1 and probabilities of the Bernoulli trials can be kept static or changed in the projection period. In the basecase projections, these probabilities remained constant for both life history and fishery-based Bernoulli trials. Forecasted recruitment is estimated with an updated weak stock-recruit relationship (Mazur et al. 2019B). Here, a moving average of SSB (biomass of all mature lobsters; male and female) is generated across the historical series so that recruitment in year *X* can be matched with an average SSB across years *X*-3, *X*-4, and *X*-5, based on the variable lag time between spawning and model recruitment (Hodgdon et al. 2022B). These three-year SSB averages are binned (roughly equal splitting of data into five bins; e.g., if there were fifty SSB averages, then each bin would represent ten SSB averages, with bin 1 containing the lowest ten SSB averages and bin 5 containing the highest ten SSB averages) and a normal distribution of recruitment is created for each bin using the recruitment values associated with the SSB averages in each bin. In each projection year, recruitment is randomly selected from the normal distribution of recruitment associated with the bin of the forecasted SSB value. A short-coming of this stock-recruit relationship was that it could never generate more recruits than previously observed regardless of how much SSB might be increased in the future. As a result, any climate scenario that decreased recruitment or increased natural mortality could only result in a decrease in stock sizes, regardless of any management actions. To address this, we developed the ‘rising-bin schema’. In this rising-bin schema, recruitment is drawn from distributions associated with extrapolated bins (beyond bin five) which were determined using logistic regression. A logistic function was fit to the midpoints of SSB bins 2, 3, and 4 (these bins having defined bounds of SSB other than zero or infinity). This logistic function was then modelled over SSB values larger than those historically observed. Where the function intersected with bin five (~33000 mt and higher) became the midpoint of the new bin five (~33000 mt to ~73000 mt). The SSB range of this new bin five was then used as the range of SSB for bins six, seven, and so on. The solutions of the logistic function at these new bin midpoints revealed the mean recruitment value used to estimate the recruitment distributions associated with these new bins. The standard deviation of recruitment in the old bin five was used for the new bin five and for all subsequent bins. This rising-bin schema approach (Figure 2) allows recruitment to rise with substantial increases in projected SSB beyond those previously observed, while also limiting the total number of recruits in these extreme scenarios. In this study, results for all projections are presented for both this rising-bin schema and the original schema where recruitment was limited to historically observed ranges, hereafter called the ‘set-bin schema’. Neither of these schemas are deemed more likely than the other as it is unknown whether the ecosystem has the capacity to sustain lobster recruitment at levels higher than previously observed.

3.2 Determining Changes to the Population and Fishery Under Climate Change

To constrain the scope of climate impact and management action scenarios, a team of experts from academia, federal and state agencies, and industry were convened throughout a multi-year process to determine a list of what aspects of American lobster life history are anticipated to be most impacted under climate change, and specifically how these characteristics may change with warming temperatures in the northwest Atlantic. Additionally, a list was generated of what management changes would be most likely considered in the future, both independently and in conjunction with the changes to lobster life history seen from climate impacts. From these lists, a substantial follow-up survey-based assessment was conducted on knowledgeable parties across multiple organizations and states within the New England (U.S.) area: ASMFC, the Maine Department of Marine Resources (MEDMR), the Massachusetts Division of Marine Fisheries (MADMF), and New York State Department of Environmental Conservation (NYSDEC). The aim of this survey was to rank the aforementioned lists and prioritize simulations with changes to key parameters based on future plausibility. The final life history parameters identified as most impacted by climate change were natural mortality, molting probability, molt increment probability, size-at-maturity, and recruitment. The list of final management parameters most likely to be impacted by future fishery regulation changes were those to minimum legal size and fishing effort (see section 3.4).

After an exhaustive sensitivity test of the IBLS to these life history and management parameters, this work was again disseminated to various stakeholders during the American Lobster Initiative Regional Lobster Research and Outreach Summit, a multi-day workshop in early 2023 hosted by Maine Sea Grant (NSG 2023). Feedback from this workshop allowed for the formulation of biologically realistic levels of cumulative impacts of climate change at different levels to the life history parameters and reasonable levels of change to future management regulations.

3.3 Projections Under Future Climate Change

In addition to a basecase projection (which excludes future climate impacts), future climate change projections were conducted under three different levels denoted as "Low", "Moderate", and "Extreme". These levels were not meant to represent specific climate-based projections, but rather cover a range of potential future regimes for the GOM/GBK stock region, with "Low" representing minimal climate change impacts on lobster life history and "Extreme" representing very high levels of impact.

Under climate change, natural mortality is anticipated to increase based on increased shell disease prevalence (Groner et al. 2018). In their work, Groner et al. (2018) assumes a threefold increase in natural mortality if shell disease prevalence becomes very high. Thus, natural mortality in the projections (M_P) was calculated as:

$$M_P = M_T \times M_{P_{Scalar}} \quad (1)$$

where M_T is natural mortality in the terminal year of the hindcasted period and M_{P_Scalar} represents the climate change scalar that varies with each climate scenario: M_{P_Scalar} = 1.5 (Low), M_{P_Scalar} = 2.0 (Moderate), and M_{P_Scalar} = 3.0 (Extreme). It is important to note that this natural mortality is the probability of individual lobsters dying and is not equivalent to the natural mortality rate commonly used in stock assessments.

For climate impacts on growth, molting probability and molt increment distribution were both altered in the IBLS projections following the alterations proposed in Hodgdon et al. (2022A), where molting probability increases and molt increment distribution decreases under climate change. As such, lobsters molt more frequently, but grow less per molting event. Molting probability in the IBLS (P_M) is estimated as:

$$P_M = \frac{P_{M_{Scalar}} + SAS}{k_{CL}} \qquad (2)$$

$$k_{CL} = e^{-8.08127 + 0.076535 \times CL} \qquad (3)$$

where *SAS* is a measure of timesteps (seasons) a lobster has spent at its current size, *CL* is the current carapace length of the lobster in mm, and k_{CL} the longest possible time a lobster of size *CL* can remain at size *CL* before molting. Thus, *SAS* can vary from 1 to k_{CL} seasons (note that for mature individuals, *SAS* varies from 2 to k_{CL} seasons, ensuring no mature individuals can experience a molting event in sequential seasons). P_{M_Scalar} artificially shifts the time spent at current size, increasing the overall frequency of P_M. P_{M_Scalar} was assigned values of 1, 2, or 3 across the Low, Moderate and Extreme scenarios, respectively. For example, in the basecase, the probability of a lobster of size *S* molting in a given timestep if it has gone *T* timesteps without molting becomes the probability of a lobster of size *S* in a given timestep molting if it has gone *T*+1 timesteps without molting in the Low future climate scenario. Additionally, double molt probability (DM_P; the probability of small lobsters molting twice in one year) and molting mortality (*MM*; natural mortality related to a molting event) both increase by a factor of 1.5 under a Low climate scenario, 2.0 under a Moderate climate scenario, and 3.0 under an Extreme climate scenario. Increased shell disease prevalence due to warmer temperatures impacts natural mortality (Groner et al. 2018), but also impacts *MM* directly when the disease causes partial fusion between the new and old shells (Stevens 2009). Throughout all scenarios, lobsters are limited to molting only during the Summer and Fall (and not during Winter and Spring). Molt increment distribution (P_I) was shifted via the equations below:

$$P_I = N(1.2236 + (0.1294 \times CL) - P_{I_{Scalar}}, \sigma^2) \quad \textit{if male; CL<95} \tag{4}$$

$$P_I = N(1.2236 + (0.1294 \times 95) - P_{I_{Scalar}}, \sigma^2) \quad \textit{if male; CL≥95} \tag{5}$$

$$P_I = N(1.2288 + (0.1285 \times CL) - P_{I_{Scalar}}, \sigma^2) \quad \textit{if female; CL<82} \tag{6}$$

$$P_I = N(1.2288 + (0.1285 \times 82) - P_{I_{Scalar}}, \sigma^2) \quad \textit{if female; CL≥82} \tag{7}$$

where *N* is the normal distribution truncated by upper and lower bound probabilities of 0.975 and 0.025, respectively, and σ is the standard deviation of the normal distribution equal to 2.1 (ASMFC 2006; Hodgdon et al. 2022A). P_{I_Scalar} artificially shifts the number of mm *CL* a lobster will grow if it molts, decreasing the overall mm *CL* across the climate scenarios as: P_{I_Scalar} = 1 (Low), P_{I_Scalar} = 2 (Moderate), and P_{I_Scalar} = 3 (Extreme). Lobster size-at-maturity is expected to decrease under climate change as a function of temperature (LeBris et al. 2017; Hodgdon et al. 2022A). Probabilistic size-at-maturity in the IBLS (P_{SAM}) is estimated as:

$$P_{SAM} = \frac{1}{1 + e^{-0.3\times(CL-(L_{50}-P_{SAM_{Scalar}}))}} \tag{8}$$

where L_{50} is the size (*CL*) at 50% sexual maturity. In stock assessment, this number is traditionally 90.81 mm *CL* (ASMFC 2015). Following LeBris et al. (2017)'s findings that lobster L_{50} would decrease 2.8 mm *CL* per degree Celsius rise in environmental bottom temperature, paired with projections of GOM/GBK bottom temperature rising as much as four degrees Celsius in the next 100 years (IPCC 2019; Brickman et al. 2021; Hodgdon et al. 2022A), P_{SAM_Scalar} shifts L_{50} down by 5.6 mm *CL* in a Low climate scenario, *11.2* mm CL in a Moderate climate scenario, and *16.8* mm CL in an Extreme climate scenario.

Projected recruitment (R_P) in the IBLS is calculated as:

$$R_P = N(R_{SSB_{Bin}}, \sigma^2) \times R_{P_{Scalar}} \quad (9)$$

where N represents the normal distribution truncated by upper and lower bound probabilities of 0.975 and 0.025, respectively, and σ is the standard deviation of the normal distribution. R_{SSB_Bin} and σ vary by SSB_{Bin}, which in turn varies between a set-bin schema and a rising-bin schema for projected recruitment (see section 3.1). In the set-bin schema, SSB_{Bin} is one of five bins of historical SSB (less than ~11000 mt, ~11000 to ~15000 mt, ~15000 to ~26000 mt, ~26000 to ~33000 mt, and larger than ~33000 mt) determined by the number of data points between the bounds. The associated historical recruitment values for the values of SSB within each bin are used to create the normal distribution in Equation 9. Any future value of recruitment is pulled from the historical recruitment normal distribution associated with the SSB_{Bin} that the projected SSB value lies in (Figure 2). This represents a weak stock-recruit relationship, proposed for American lobster by Mazur et al. (2019B) and updated with new data and information on recruitment lags from Hodgdon et al. (2022B). In the rising-bin schema, the methodology for determining projected recruitment is identical to that in the set-bin schema when SSB is under ~73000 mt. However, when SSB exceeds this threshold, recruitment is drawn from a set of extrapolated bins (as opposed to still being drawn from bin five as it is in the set-bin schema), discussed in section 3.1 and summarized in Figure 2. R_{P_Scalar} decreases the overall recruitment across the climate scenarios, effectively changing the relative steepness of the stock/recruit relation and potentially acting as a proxy for increasing pre-recruit mortality, as: R_{P_Scalar} = 0.75 (Low), R_{P_Scalar} = 0.50 (Moderate), and R_{P_Scalar} = 0.25 (Extreme). Forecasted recruitment is particularly difficult to predict due to a myriad of factors including environmental influences (Okamura et al. 2024). The R_{P_Scalar} values used in this study allowed for a wide range of potential future recruitment scenarios to be explored while maintaining biological realism (when these R_{P_Scalar} values were applied to terminal year recruitment, the resulting scaled values were all within historically observed ranges). A summary of all of the scalars above and their values across projection scenarios can be found in Table 1.

3.4 Projections Under Alternative Management Actions

Projections were conducted under a suite of management changes that were enacted upon basecase projections and all climate scenario projections (Low, Moderate, and Extreme) and using both schemas for determining future recruitment (set-bin schema and rising-bin schema) to determine the interaction of climate change and management feedback to the fishery and stock. These management actions included changes to both minimum legal size and fishing effort.

Minimum legal size (representing the smallest size of lobster legally allowed to be landed) at the start of the projection period is set at 83.09 mm *CL*. This value represents a terminal year (2018) average for the regulation across the GOM region (83 mm *CL*) and GBK region (89 mm *CL*) weighted by the landings from each region in the terminal year (ASMFC 2020). A vast majority (>95%) of these landings come from the GOM (ASMFC 2020). Thus, changes to minimum legal size in the projection period were only performed for GOM and no changes were made to GBK. From the stakeholder outreach (see section 3.2), reasonable values that would encompass a range of possible future changes to minimum legal size in the GOM region would be 88 mm *CL* and 93 mm *CL*.

Fishing effort is modeled in the IBLS as the encounter rate or the probability of a lobster being caught in the fishery (caught in a trap and brought up to the boat), but not necessarily landed. Like most parameters in the IBLS, encounter rate is size, sex, and season dependent. Future encounter rate (ER_P) in the IBLS is estimated as:

$$ER_T = \frac{C_T}{P_T \times S_T} \tag{10}$$

$$F_T = -\ln{(1 - ER_T)} \tag{11}$$

$$F_P = F_T \times F_{P_{Scalar}} \tag{12}$$

$$ER_P = 1 - e^{-F_P} \tag{13}$$

where ER_T is the encounter rate in the terminal year of the hindcasted period, C_T is the size, sex, and season specific catch in the terminal hindcasted year, P_T is the size, sex, and season specific population biomass in the terminal hindcasted year, and S_T is the size, sex, and season specific gear selectivity x legal selectivity x conservation selectivity in the hindcasted terminal year. F_T is the size, sex, and season specific fishing mortality in the terminal hindcasted year and F_P is the size, sex, and season specific fishing mortality in the projection period. F_P is proportional to F_T via the F_{P_Scalar}. From the stakeholder outreach (see section 3.2), reasonable values that would encompass a range of possible future effort decreases were determined to be 25% (F_{P_Scalar} = 0.75) and 50% (F_{P_Scalar} = 0.5). After the F_{P_Scalar} is applied, F_P is transformed back into an encounter rate in the projection period, ER_P. This methodology was more appropriate than applying a scalar directly to the encounter rate so that a given scalar of X directly represented (and was not just proportional to) a reduction in fishing mortality of (1-X)%. These changes to fishing mortality would be reflective of changes to regulations that would directly impact effort such as trap limits. However, fishing mortality and effort are not a 1:1 relationship and a moderate reduction in fishing mortality may require more drastic changes in effort to achieve, especially for this particular fishery which may currently be oversaturated with traps (Acheson & Acheson 2010). At sizes smaller than the minimum legal size, C_T is equal to zero (because lobsters smaller than this size cannot be legally landed). For this size range, the ER_T at the minimum legal size is instead used (this same tactic is used for all sizes greater than the maximum legal size). These two changes to future encounter rates and future minimum legal sizes were done alone and in combination, the latter representing management changes that would impact minimum legal size and encounter rate (fishing effort) together. It should be noted that because fishing mortality occurs before growth and maturation processes within a time step (Figure 1), that the true effect on the stock of altering the minimum legal size may be slightly underestimated (i.e., SSB may be slightly underestimated and landed catch may be slightly overestimated).

3.5 Projection Methodologies

A total of 44 projection scenarios were completed (Table 2), with each scenario run for ten iterations in order to generate standard deviations of projected series. Each projection scenario was run for 100 years. Due to IBLS limitations, changes to life history and/or management occurred instantaneously due to the inability of the model to gradually apply these changes. These changes occurred 10 years into the projection period. To test the sensitivity of the model to the location of these changes, additional tests were completed for 20 and 30 years into the projection period. This did not affect the equilibria or overall long-term projection results (see supplemental material; Figure S1). These blocks, before and after the changes were made, can be considered life history regimes that may also incur changes to management practices. For all scenarios outlined in Table 2, hindcasted and projected time series of recruitment abundance, SSB, landed catch, and legal biomass were generated. Additionally, sex-specific equilibria for these same time series were produced, representing the median of the final ten years of the projected time series (and across the ten model iterations for each projection scenario).

4.0 Results

4.1 Climate Projections Under Status Quo Management

GOM/GBK American lobster recruitment abundance, SSB, landed catch, and legal biomass all rose substantially from the 1980s through 2018 (Figure 3). Under the set-bin schema, basecase projections for recruitment showed a relatively stable timeseries. All future values of recruitment appear to have been drawn from the fifth (highest) bin. This steady period of relatively high recruitment led to high and stable SSB, landed catch, and legal biomass over the projected period (Figures 3 and 4). Each subsequent climate scenario (Low, Moderate, and Extreme) negatively impacted recruitment and in the tenth year of the projection, recruitment quickly reached a new, lower equilibrium related to the level of climate change (Figures 3 and 4). This decrease correspondingly impacted both legal biomass and landed catch.

Landed catch in the projection period was particularly related to recruitment trends (Figures 3 and 4), with a given percent decrease in recruitment during a future climate regime resulting in at least that same proportion decrease of overall catch. This decreasing trend in catch across climate scenarios is also related to the number of legal-sized females being unavailable to the fishery due to decreasing L_{50} and conservation measures. This increase in the proportion of smaller mature females also skews the sex distribution of legal biomass to be more female-dominant under more intense climate change scenarios (Figure 4). Additionally, this increased protection of females due to decreasing L_{50} results in less severe decreases to legal biomass seen across the future climate scenarios than those seen for landed catch (Figures 3 and 4). This disconnect was also partially due to M throughout the year, where an overall larger number of lobsters died due to M between the end of the year and the subsequent fishing season.

Interestingly, SSB seemed to be positively impacted under some of the future climate scenarios (Figures 3 and 4). In the Low and Moderate climate scenarios, SSB equilibria were higher than in the basecase. This is because of the lowered L_{50}, which made a larger subset of the population that is unavailable to the fishery, sexually mature (and female-dominant). This is also the reason for the large spike in SSB seen in the tenth year of the projections (Figure 3); this spike represents a significant number of lobsters that already existed (i.e., not new lobsters), immediately becoming sexually mature (this phenomenon is also seen in the recruitment projections and is a consequence of the limitations of the model and not considered biologically realistic). This trend of increasing equilibria does not continue into the Extreme climate scenario, however (Figure 4). Here, M has become high enough to counteract the positive effect on SSB felt by the decreased L_{50}. Furthermore, most sexually mature females in this future climate scenario are very small in comparison to other climate scenarios, decreasing the overall SSB (even though spawning stock abundance could still be relatively high).

Under the rising-bin schema, there existed similar patterns across climate scenarios for recruitment, SSB, landed catch, and legal biomass (Figures 3 and 4). However, due to recruitment not being constrained to historical levels, SSB increased to much higher levels in both the Low and Moderate climate scenarios. In these instances, recruitment, landed catch, and legal biomass all subsequently rose (with legal biomass equilibria in these scenarios now above that for the basecase). This same pattern was seen to a lesser degree in the Extreme climate scenario. Sex ratios of recruitment, SSB, landed catch, and legal biomass remained relatively consistent between the set-bin schema and the rising-bin schema for all future climate scenarios.

4.2 Climate Projections Under Changes to Future Management Schema

Equilibria for each management scenario are presented in Figures 5, 6, and 7. For time series plots of these management scenarios, see the supplemental material (Figures S2, S3, and S4). Each of the six future changes to management conserved more SSB in long-term projections in comparison to basecase projections (Figures 5, 6, and 7). As was expected, increases to the minimum legal size and decreases to fishing effort both had a positive relationship with SSB. These two management scenarios together (MLS 88 ER 1 and MLS 93 ER 2) had a larger, combined effect on SSB than either management action alone. These relationships were held through all three future climate scenarios (Figures 5, 6, and 7), but the proportion increase in SSB under each scenario changed, with more climate change resulting in less effective management actions. These relationships were also held in both the set-bin and rising-bin schemas. However, because SSB was always greater than the basecase across these management scenarios and recruitment in the set-bin schema could never be larger than values observed in the basecase, projected recruitment across all management scenarios in the set-bin schema were indistinguishable from recruitment under scenarios with status quo management (Figures 5, 6, and 7). In the rising-bin schema, however, recruitment was not as constrained. Thus, under the Low future climate scenario, recruitment was able to rise above basecase values. However, under both the Moderate and Extreme future climate scenarios, recruitment was more negatively impacted by the R_{P_Scalar} and did not rise above basecase projections under any changes to future management. Management actions of reducing fishing effort had a larger impact on recruitment levels than did raising the minimum legal size.

Landed catch, being heavily correlated with recruitment (see section 4.1), had similar trends in the set-bin schema, where projected catch under all management scenarios did not rise above basecase levels. However, also similar to recruitment, landed catch was able to rise above basecase levels in the rising-bin schema under a Low future climate scenario. This same trend did not occur in either the Moderate or Extreme future climate scenario. Furthermore, there does appear to be a disconnect between landed catch and legal biomass. More legal biomass is the result of more conservative management schema, but the proportion of this legal biomass that is caught is also negatively correlated with the same conservative management schema, keeping landed catch at relatively similar levels across different regulatory actions. Thus, SSB and legal biomass appear to be more influenced by management actions, whereas recruitment and landed catch appear to be more influenced by climate change.

Clear relationships emerged between management actions and the sex ratios of SSB, landed catch, and legal biomass. Under status quo management, SSB is female-dominant. However, the proportion of SSB that is female had a positive relationship with changes to minimum legal size, but a negative relationship with fishing effort. When effort was drastically reduced (ER 2 and MLS 93 ER 2), SSB even became male-dominant (Figures 5, 6, and 7). Landed catch was male-dominant across all management scenarios, and legal biomass was female-dominant across all management scenarios (Figures 5, 6, and 7). However, more conservative management actions usually led to a broadening of these ratios, where landed catch became even more male-dominant and legal biomass became even more female-dominant.

5.0 Discussion

Numerous studies qualify and quantify the relationship of specific American lobster life history characteristics to rising temperatures (Mills et al. 2013; Boudreau et al. 2015; Staples et al. 2019; Goode et al. 2019; Tanaka et al. 2019; Hodgdon et al. 2021; Hodgdon et al. 2022A; Hodgdon et al. 2022B). This study expands upon work done by Hunt et al. (2023) by simulating and projecting the GOM/GBK American lobster stock using cumulative effects of climate change on a suite of lobster life history characteristics. The future of American lobster in the northwest Atlantic is highly dependent on future climate conditions.

American lobster recruit survival is adversely affected by climate change via extreme warming (Casey et al. 2022; Hodgdon et al. 2022B) and ocean acidification (Menu-Courey et al. 2019). This relationship formed the assumption in this study that overall recruitment would decline under more intense levels of climate change in the GOM/GBK stock region. Without management interventions, projected catch is directly impacted by these changes in recruitment, and in turn, is adversely affected by warming waters. This is because catch compositions of lobster are highly skewed towards the minimum legal size (Acheson & Reidman 1982; ASMFC 2020) and, thus, there is a strong correlation of catch levels and population size of the individuals nearest minimum legal size. When considering differences between this study's set-bin and rising-bin schemas for estimating recruitment, Low levels of climate change on the stock could lead to higher recruitment and catches if the stock-recruit relationship continues and does not plateau at recently observed recruitment levels. However, under Moderate and Extreme levels of climate change, it becomes more likely that recruitment and catches will decline regardless of whether the stock-recruit relationship continues.

Management actions considered in this study consisted of minimum legal size increases and actions that would reduce fishing effort. These measures are meant to preserve the breeding population of the stock and address growth overfishing (Fogarty & Gendron 2004; Mazur et al. 2019A; ASMFC 2020; Hunt et al. 2023). This feedback in the IBLS projections was apparent, with more conservative measures raising the overall SSB compared to status quo management schema (Figures 5, 6, and 7). Reducing fishing effort had an inverse relationship with the proportion of females comprising SSB, with extreme reductions in effort shifting the sex ratio to male-dominant at equilibrium. This change may be because female lobsters are limited in their growth after reaching sexual maturity, dedicating more energy towards reproduction and away from molting (Attard & Hudon 1987; Koepper et al. 2021). Thus, under highly reduced effort, male lobsters have a greater capacity to reach larger sizes (and grow beyond the maximum legal size), individually contributing more to SSB. This phenomenon is not apparent in management scenarios that only increase the minimum legal size. Increasing the minimum legal size shifts the catch composition to larger individuals. Relatively fast-growing males are still caught in lobster pots (and subsequently landed), there is just a greater delay between model recruitment and reaching minimum legal size. Unlike SSB, landed catch was male-dominant across all management scenarios and legal biomass was female-dominant across all management scenarios. This is most likely due to female lobsters having more protections than males under status quo management (Theberge et al. 2024). Thus, even though more conservative management scenarios promote increases in both male and female legal biomasses, the positive effects on female biomass are compounded. Furthermore, more conservative management scenarios result in a widening of the disparity between males and females in both legal biomass and landed catch. Thus, highly conservative management measures, reductions in effort or increases to the minimum legal size, will result in catches of lobster that are exceedingly male-dominant and will also significantly increase the relative biomass of females that cannot legally be landed. In general, management changes had much larger observable impacts on SSB and those increases in SSB did not always have a proportional impact on catch or recruitment due to climate change impacts on growth and natural mortality.

The current American lobster stock assessment does not implement a stock-recruit relationship (ASMFC 2020; Hodgdon et al. 2022B). It is generally difficult to estimate an explicit stock-recruit relationship for many crustaceans, lobster included, because there are a myriad of environmental factors influencing recruitment trends (Aiken & Waddy 1986; Casey et al. 2022; McManus et al. 2023; McManus 2024). This disconnect is what originally led to the development and implementation of the weak stock-recruit relationship in the IBLS (Mazur et al. 2019B). It is understood that post-larval recruitment dynamics may be strongly mediated by environmental factors (Carloni et al. 2018; Hodgdon et al. 2022B; Carloni et al. 2024; Shank et al. 2024), which presented a problem for the projections. The weak stock-recruit relationship dictates that recruitment is only impacted by relatively large changes to SSB (i.e., when SSB moves from one bin to another; see section 3.3). The terminal SSB bin in the set-bin schema was anything larger than 33000 mt. Projected SSB varied substantially with changes in management in the projected period, but never fell below this threshold (Figures 5, 6, and 7), ensuring an unchanging recruitment pattern over the same period. Due to this disconnect, all projections with the set-bin schema under all alternative management scenarios are to be interpreted as how these regulatory actions would impact the population under the current recruitment regime. This interpretation seems more biologically plausible for management actions that do not drastically alter SSB. In very conservative management scenarios, SSB has the potential to increase more than 25 fold above current levels (Figure 5). It is unlikely that this substantial of an increase in SSB of lobster would have a negligible impact on recruitment (and subsequent catch). However, under less conservative management scenarios, where spawning biomass may only increase marginally, the argument that recruitment and subsequent catch goes unimpacted is more reasonable given: (1) that the management actions used in this study are designed to conserve SSB (Fogarty & Gendron

2004; Mazur et al. 2019A; ASMFC 2020; Hunt et al. 2023), (2) there is a known complex relationship between SSB and post-larval recruitment (Carloni et al. 2018; Hodgdon et al. 2022B; Carloni et al. 2024; Shank et al. 2024), and (3) that catches of lobster are correlated with abundance of the smallest individuals of the legal sizes (Acheson & Reidman 1982; ASMFC 2020).

Future trends of recruitment in the GOM/GBK stock area represent a large source of uncertainty in this study, hence the utilization of both the rising- and set-bin schemas. The set-bin schema represents a suite of future scenarios in which recruitment has already reached a potential upper limit for the stock area and future increases to SSB are offset by declining recruitment (Casey et al. 2022) and female fecundity (Goldstein et al. 2022). However, there's uncertainty about whether future GOM/GBK recruitment will react to thermal changes in the same way as recruitment has in Southern New England (Shank et al. 2024). The rising-bin schema was intended to capture a more optimistic suite of future recruits per spawner scenarios where these negative effects are lessened or non-existent compared to the set-bin schema. Both schemas are presented to represent a more realistic range of potential future recruitment, but neither schema alone represents the bounds for what future recruitment could be for this stock. The rising-bin schema used in this study is perhaps more biologically realistic, allowing recruitment patterns to fluctuate at these very high levels of projected SSB. This claim is substantiated by the recent GOM/GBK stock assessment, where a state-space trajectory of stock-recruit steepness has remained constant in recent years, with no sign of approaching an upper limit (ASMFC 2020), which indicates that recruitment in the GOM/GBK stock could reach higher levels (although not confirming that it actually will). If the rising-bin schema is more biologically plausible, more conservative management actions should lead to greater recruitment and overall catch. It is important to note that, in the rising-bin schema, increases to minimum legal size always led to increased catch compared to status quo management under the same level of climate change, an outcome not seen with reductions in effort. Benefits of more conservative management actions are only observed when considered within a given future climate regime (i.e., when compared to the status quo management schema in the same future climate scenario). The more climate change impacts the GOM/GBK ecosystem, the less effective management actions will become at conserving SSB and keeping recruitment and catches high. This is most likely due to the increasing proportion of smaller individuals comprising the SSB under more intense warming scenarios (i.e., the more waters warm, the less big old fecund females, or BOFFs, in the stock). Broadly, the effectiveness of future management decisions on the lobster fishery may decline as the GOM/GBK stock area continues to warm, a phenomenon not unique to the lobster fishery (Noble et al. 2015; Mason et al. 2023).

The future of the American lobster fishery is predicted to be severely impacted by the region's intense climate change (Mills et al. 2013; Boudreau et al. 2015; Staples et al. 2019; Goode et al. 2019; Tanaka et al. 2019; Hodgdon et al. 2021; Hodgdon et al. 2022A; Hodgdon et al. 2022B). However, the cumulative results of this study should not be interpreted as the range of all possible futures for this stock and fishery. The IBLS framework allows for consideration of a myriad of potential population threats brought about by a warming ecosystem, such as increased predation and shell disease prevalence, via its ability to simulate multitudes of potential future natural mortalities and growth rates. However, it is limited in its capability to appropriately consider sub-stock dynamics, such as migration and recruitment into deeper offshore habitats which could result in lowered reproductive success for this fishery (Goode et al. 2019; Casey et al. 2022). There are also numerous unknowns associated with recruitment growth and survivability, as well as the link recruitment has with the spawning stock (Goldstein et al. 2025), a key limitation surrounding recruitment in this study. Additionally, there are a plethora of unknown factors that could influence this stock under each of the warming scenarios tested in this study and careful consideration should be given to these uncertainties when interpreting results in the context of management. These simulations are based on the observed influences of temperature on lobster life history (e.g., Southern New England stock dynamics) and do not consider emergent and unique GOM/GBK stock responses to climate change (Shank et al. 2024).

Stocks like GOM/GBK American lobster that are projected to be significantly impacted by rising temperatures and other effects of climate change are at risk of less effective status quo management under these new potential futures (Noble et al. 2015; Mason et al. 2023). This relationship between management actions and climate change necessitates adaptive management practices such as the use of dynamic reference points (Subbey et al. 2024; Hodgdon et al. 2022B). For American lobster, environmental considerations are already present in some aspects of the stock assessment process including in the design of regime-based reference points (ASMFC 2020). Nevertheless, the incorporation of truly dynamic, environmentally explicit, reference points have the potential to greatly improve future management of the GOM/GBK lobster stock because management will need to continually adjust (Hodgdon et al. 2022B).

This study has shown that the future of the American lobster fishery is dictated by the warming trends in the GOM/GBK stock area. In the absence of management actions, the equilibrium of projected recruitment and catches declines with more intense climate change. It is important to note, however, that unforeseen impacts of climate change have the potential to mitigate or worsen these effects on the stock and fishery. Furthermore, in the absence of a stock-recruit relationship that allows increasing recruitment rates, conservative regulatory actions have negligible impacts on recruitment trends and catch rates. Conversely, in the presence of a stock-recruit relationship that allows increasing recruitment rates with larger SSB values, conservative regulatory actions do have the potential to sustain and even increase recruitment levels and catch sizes. However, the effectiveness of these management actions on the SSB of the stock appears to decline with greater impacts of climate change. Thus, with higher levels of climate change in the GOM/GBK stock area, more conservative management actions may be necessary to sustain stock levels and catches. This poses a problem for managers that need to make decisions for the future of the fishery. Given the uncertainties surrounding trends in future recruitment, results from both the rising-bin and set-bin schemas should be considered when developing future management actions. Furthermore, to determine the most appropriate management actions given future climate change, a full management strategy evaluation (MSE) should be conducted under varying recruitment levels and climate impacts. The IBLS could act as this MSE framework, but changes would need to be made to include climate effects in ways other than set climate scenarios and to consider more realistic feedback loops between management and climate. Future research towards these MSE frameworks is becoming increasingly important as climate change in the region continues to warm at accelerated rates where management actions are increasingly less capable of sustaining high catch rates.

6.0 Author Statements

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6.2 Competing Interests Statement

The authors declare there are no competing interests.

6.3 Author Contributions Statement

CH: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

NH: Conceptualization, Formal Analysis, Software, Writing – review & editing.

CM: Conceptualization, Methodology, Writing – review & editing, Supervision.

BS: Conceptualization, Methodology, Writing – review & editing, Supervision.

YC: Conceptualization, Funding Acquisition, Methodology, Writing – review & editing, Supervision.

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6.5 Data Availability Statement

All data and code used in this study can be obtained on the following public GitHub repository: https://doi.org/10.5281/zenodo.17792430

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Tables

Table 1. A summary of all scalars applied to life history traits in the IBLS under the basecase and under each of the three future climate scenarios: Low, Moderate, and Extreme. M_{P_Scalar} is applied to natural mortality, P_{M_Scalar} is applied to molting probability, DM_{P_Scalar} is applied to double molt probability, MM_{Scalar} is applied to molting mortality, P_{I_Scalar} is applied to molt increment distribution, P_{SAM_Scalar} is applied to probabilistic size-at-maturity, and R_{P_Scalar} is applied to projected recruitment. Refer to section 3.3 and equations 1 through 9 for how each scalar is utilized.

	Basecase	**Low**	**Moderate**	**Extreme**
M_{P_Scalar}	1.00	1.50	2.00	3.00
P_{M_Scalar}	0.00	1.00	2.00	3.00
DM_{P_Scalar}	1.00	1.50	2.00	3.00
MM_{Scalar}	1.00	1.50	2.00	3.00
P_{I_Scalar}	0.00	1.00	2.00	3.00
P_{SAM_Scalar}	0.00	5.60	11.20	16.80
R_{P_Scalar}	1.00	0.75	0.50	0.25

Table 2. All projections done for this study. Basecase projections of the IBLS represent no future climate impacts on lobster life history and no changes to future management regulations. Projections for each future climate scenario, Low, Moderate, and Extreme, were done in the absence of changes to future management and under six different future management scenarios, representing changes to minimum legal size (MLS), encounter rate (ER), or both for a total of 44 projections (22 projection scenarios each run with a set-bin schema and with a rising-bin schema for recruitment). *CL* is carapace length and mm is millimeters. Note that ER is decreased by applying a scalar to F, not ER directly. The rightmost column lists the names of the future management scenarios used in Figures 5-7.

Basecase	**Low**	**Moderate**	**Extreme**	**Name:**
No Management Changes	No Management Changes	No Management Changes	No Management Changes	-
	Decrease ER by decreasing F 25%	Decrease ER by decreasing F 25%	Decrease ER by decreasing F 25%	*ER 1*
	Decrease ER by decreasing F 50%	Decrease ER by decreasing F 50%	Decrease ER by decreasing F 50%	*ER 2*
	Raise MLS to 88 mm *CL*	Raise MLS to 88 mm *CL*	Raise MLS to 88 mm *CL*	*MLS 88*
	Raise MLS to 93 mm *CL*	Raise MLS to 93 mm *CL*	Raise MLS to 93 mm *CL*	*MLS 93*
	Raise MLS to 88 mm *CL* and decrease ER by decreasing F 25%	Raise MLS to 88 mm *CL* and decrease ER by decreasing F 25%	Raise MLS to 88 mm *CL* and decrease ER by decreasing F 25%	*MLS 88 ER 1*
	Raise MLS to 93 mm *CL* and decrease ER by decreasing F 50%	Raise MLS to 93 mm *CL* and decrease ER by decreasing F 50%	Raise MLS to 93 mm *CL* and decrease ER by decreasing F 50%	*MLS 93 ER 2*

Figures

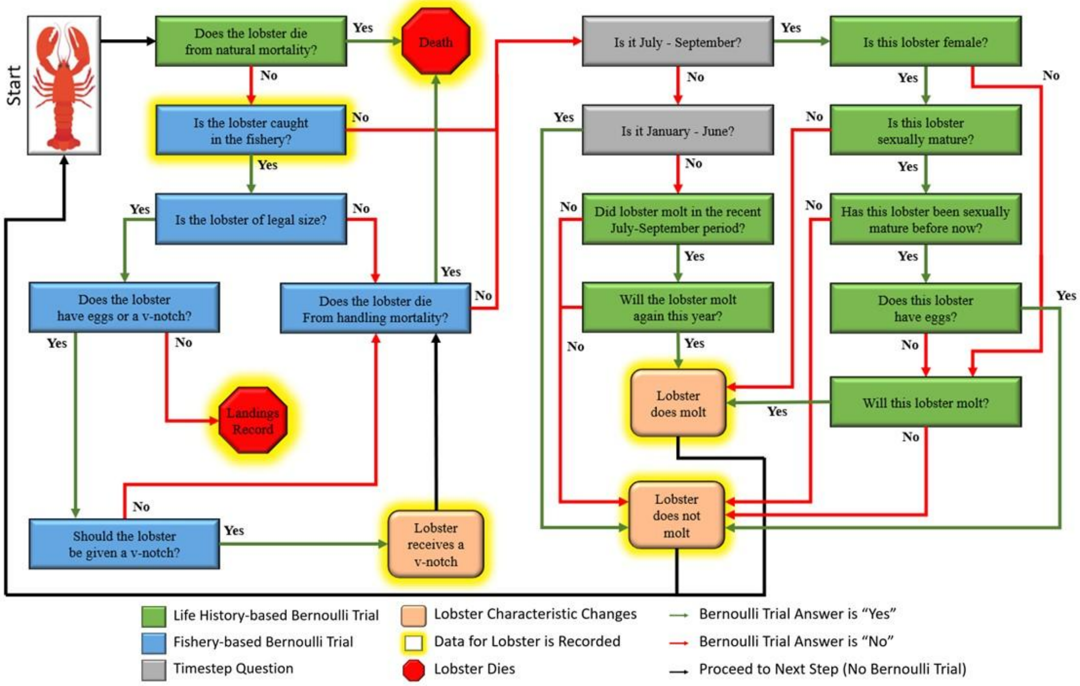

Figure 1. Flowchart of the Individual-based Lobster Simulator (IBLS). Each individual American lobster starts their simulated life and proceeds through each random Bernoulli trial represented as a either a green box (Bernoulli trial pertaining to life history), a blue box (Bernoulli trial pertaining to the fishery), or a gray box (Bernoulli trial pertaining to seasonality). If the outcome of the Bernoulli trial is "yes/true", the green arrow is followed to the next trial. If the outcome of the Bernoulli trial is "no/false", the red arrow is followed to the next trial. An orange box designates an action done on the lobster (either molting or receiving a v-notch). From these boxes, there is only one outcome, and the black line is followed to the next Bernoulli trial. Red octagons represent the end of the iterations and yellow outlines on boxes represent when information is recorded on the life history record of the individual lobster.

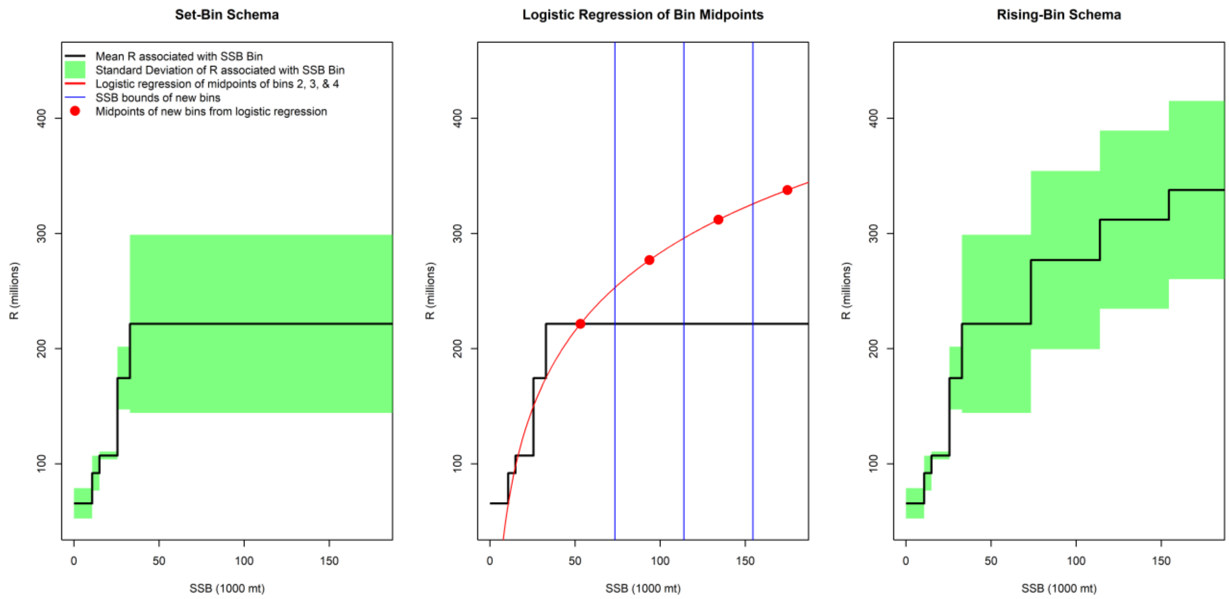

Figure 2. A comparison of the set-bin schema and the rising-bin schema used to project recruitment in the IBLS. Each plot represents recruitment (R) in millions of individuals on the y axis and spawning stock biomass (SSB) in thousands of metric tons (mt) on the x axis. The left plot depicts the set-bin schema, where the black line is the mean R associated with each SSB bin and thus follows the weak stock-recruit function through five bins. Here, the fifth and final bin is ~33000 mt SSB and higher. Green bounds represent the standard deviation of R within each bin. The middle plot depicts the logistic regression (red line) fit to the midpoints of bins two, three, and four. The leftmost red dot shows where the regression intersects with bin five from the set-bin schema, which now represents the midpoint of the new bin five in the rising-bin schema. The leftmost blue line represents the SSB value associated with the upper bound of this new bin five used in the rising-bin schema. The range of SSB in this new bin five is the range used for each subsequent bin in the rising-bin schema and each red dot on the regression depicts the solution of the logistic regression at each new bin midpoint. The left plot depicts the rising-bin schema, where the black line is the mean R associated with each SSB bin and thus follows the weak stock-recruit function through the first five bins. After bin five, each new bin is generated using the bounds (blue lines) and mean R values (red dots) from the middle plot. Green bounds represent the standard deviation of R within each bin. The standard deviation of bin five from the set-bin schema is used as the standard deviation of bins five and higher in the rising-bin schema.

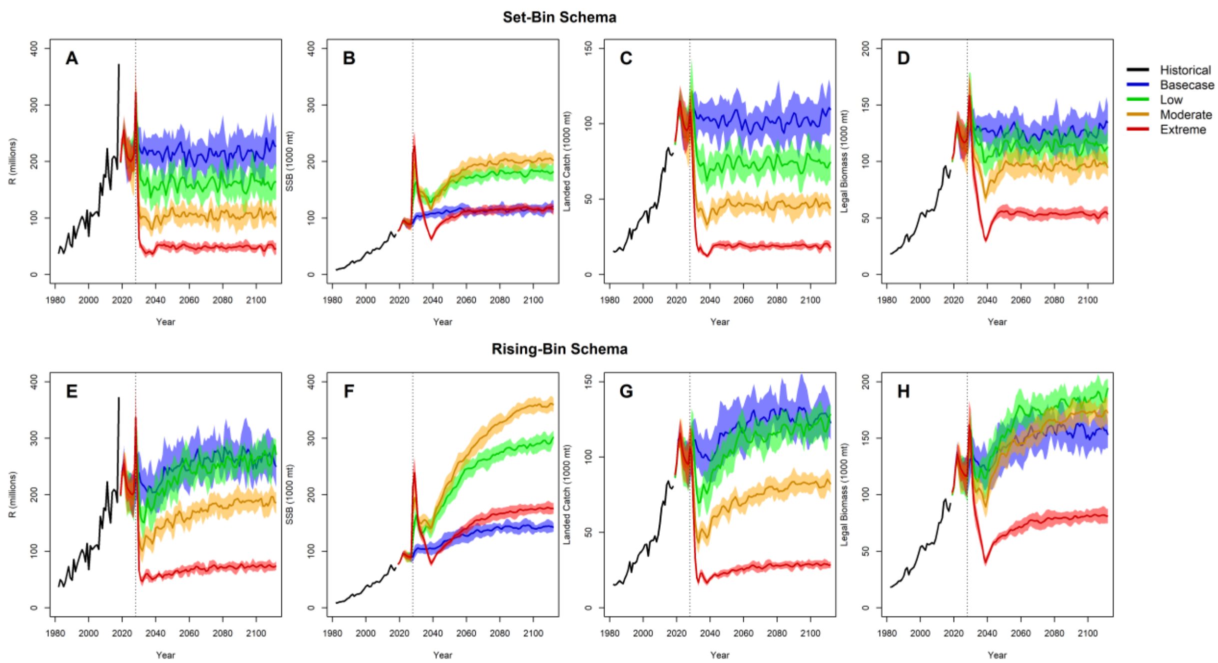

Figure 3. Projections under status quo management. Historical and projected recruitment abundance (R) in millions of individuals (A & E), spawning stock biomass (SSB) in thousands of metric tons (B & F), landed catch in thousands of metric tons (C & G), and legal biomass in thousands of metric tons (D & H). Results are presented for the historical period (black), and the projected period under four future climate scenarios: Basecase (blue), Low (green), Moderate (orange), and Extreme (red). Projections were conducted under both the set-bin schema (top; A-D) and the rising-bin schema (bottom; E-H) under status-quo management. Colored bands represent the standard deviation of the projected series under each future climate scenario. The dotted vertical line represents the projection year when the life history changes brought about by climate change occurred (2028).

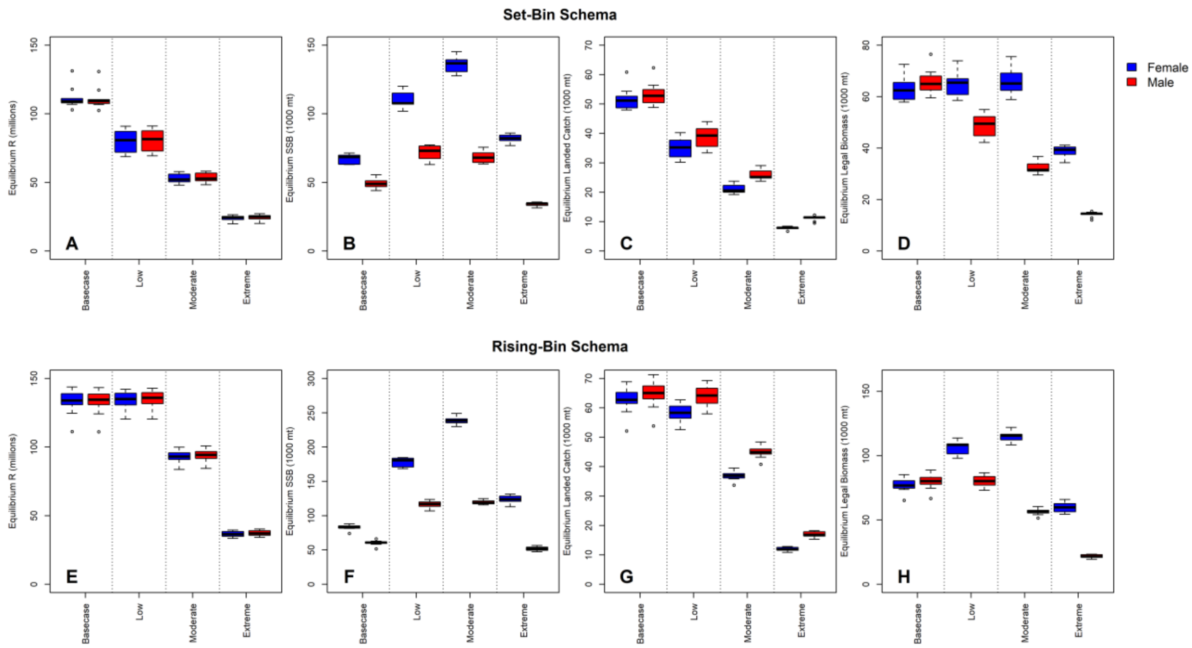

Figure 4. Equilibria under status quo management. Sex-specific equilibrium recruitment abundance (R) in millions of individuals (A & E), spawning stock biomass (SSB) in thousands of metric tons (B & F), landed catch in thousands of metric tons (C & G), and legal biomass in thousands of metric tons (D & H). Equilibria are the median values across the final ten years of the projection period (and across the ten model iterations) under the four future climate scenarios: Basecase, Low, Moderate, and Extreme, each of which was projected under status-quo management. Each box displays the sex-specific estimated equilibrium (solid line), the interquartile range of the estimated equilibrium (colored box), minimum and maximum values of the series in the last ten years of the projection period across the ten model iterations excluding outliers (whiskers), and any outliers in the last ten years of the projection period across the ten model iterations (points). Note any changes of scale between the set-bin schema (top; A-D) and the rising-bin schema (bottom; E-H).

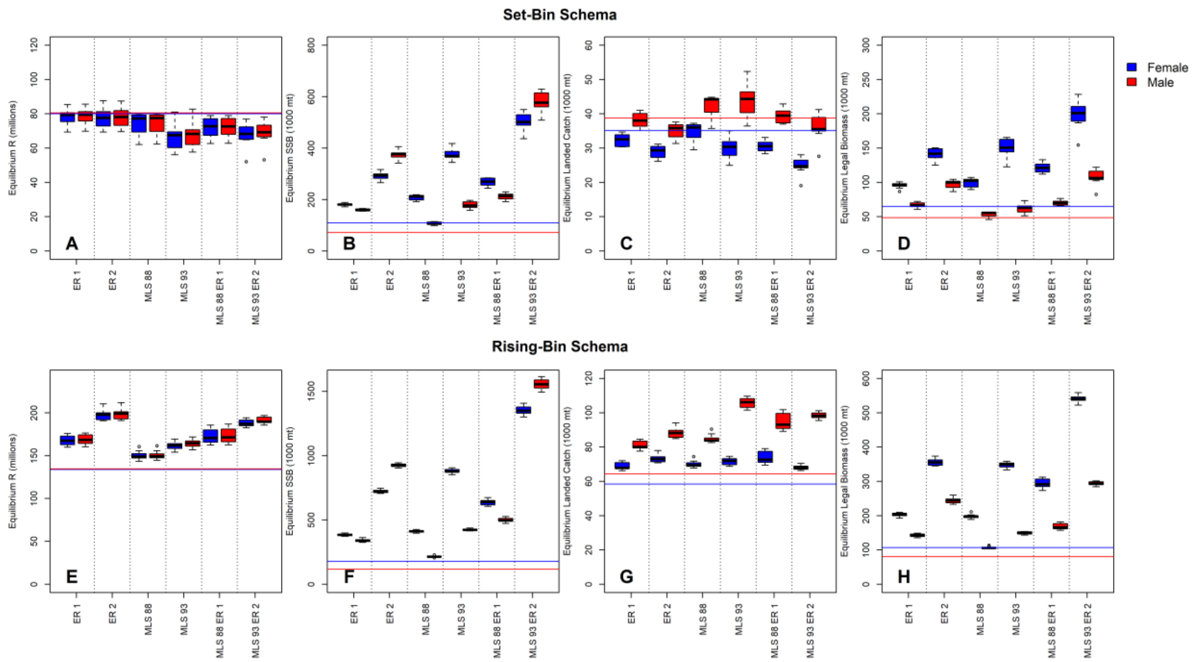

Figure 5. Impacts of management relative to status-quo management for the Low future climate scenario. Sex-specific equilibrium recruitment abundance (R) in millions of individuals (A & E), spawning stock biomass (SSB) in thousands of metric tons (B & F), landed catch in thousands of metric tons (C & G), and legal biomass in thousands of metric tons (D & H). Equilibria are the median values across the final ten years of the projection period (and across the ten model iterations) for the management schema described in Table 2 under the Low future climate scenario. Each box displays the sex-specific estimated equilibrium (solid line), the interquartile range of the estimated equilibrium (colored box), minimum and maximum values of the series in the last ten years of the projection period across the ten model iterations excluding outliers (whiskers), and any outliers in the last ten years of the projection period across the ten model iterations (points). Note any changes of scale between the set-bin schema (top; A-D) and the rising-bin schema (bottom; E-H). The blue and red lines in each plot are the female and male equilibria, respectively, of the Low future climate scenario under the status quo management schema (see Figure 4).

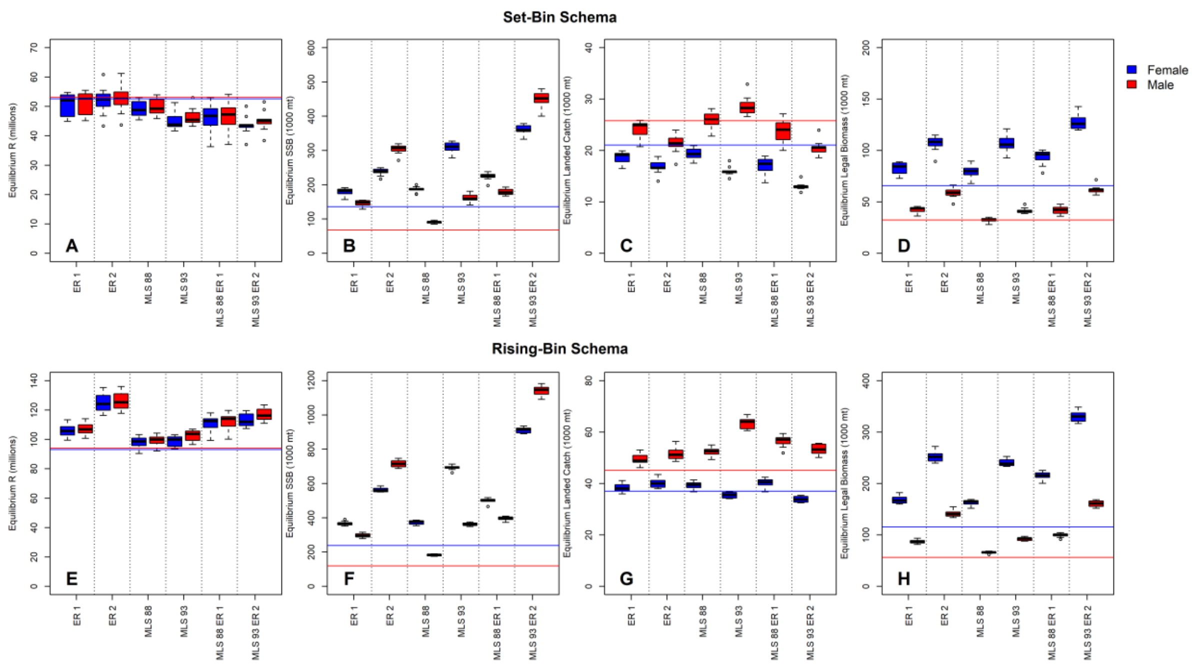

Figure 6. Impacts of management relative to status-quo management for the Moderate future climate scenario. Sex-specific equilibrium recruitment abundance (R) in millions of individuals (A & E), spawning stock biomass (SSB) in thousands of metric tons (B & F), landed catch in thousands of metric tons (C & G), and legal biomass in thousands of metric tons (D & H). Equilibria are the median values across the final ten years of the projection period (and across the ten model iterations) for the management schema described in Table 2 under the Moderate future climate scenario. Each box displays the sex-specific estimated equilibrium (solid line), the interquartile range of the estimated equilibrium (colored box), minimum and maximum values of the series in the last ten years of the projection period across the ten model iterations excluding outliers (whiskers), and any outliers in the last ten years of the projection period across the ten model iterations (points). Note any changes of scale between the set-bin schema (top; A-D) and the rising-bin schema (bottom; E-H). The blue and red lines in each plot are the female and male equilibria, respectively, of the Moderate future climate scenario under the status quo management schema (see Figure 4).

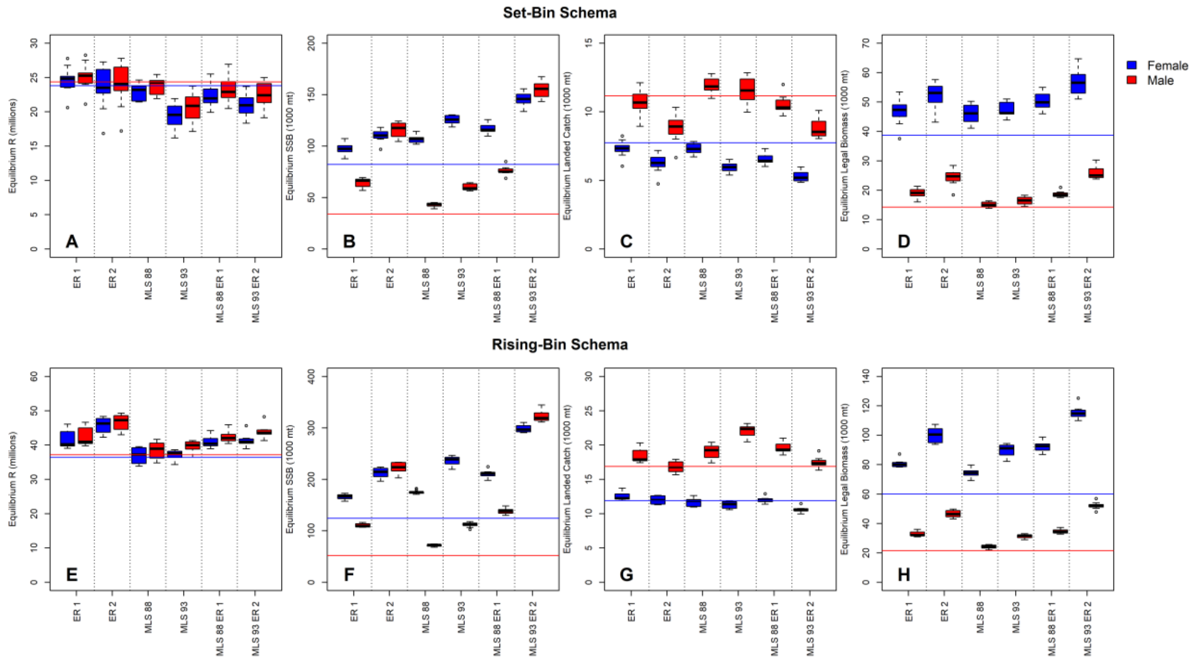

Figure 7. Impacts of management relative to status-quo management for the Extreme future climate scenario. Sex-specific equilibrium recruitment abundance (R) in millions of individuals (A & E), spawning stock biomass (SSB) in thousands of metric tons (B & F), landed catch in thousands of metric tons (C & G), and legal biomass in thousands of metric tons (D & H). Equilibria are the median values across the final ten years of the projection period (and across the ten model iterations) for the management schema described in Table 2 under the Extreme future climate scenario. Each box displays the sex-specific estimated equilibrium (solid line), the interquartile range of the estimated equilibrium (colored box), minimum and maximum values of the series in the last ten years of the projection period across the ten model iterations excluding outliers (whiskers), and any outliers in the last ten years of the projection period across the ten model iterations (points). Note any changes of scale between the set-bin schema (top; A-D) and the rising-bin schema (bottom; E-H). The blue and red lines in each plot are the female and male equilibria, respectively, of the Extreme future climate scenario under the status quo management schema (see Figure 4).