1. Introduction

Rapid Arctic warming and ice melt are altering ocean circulation in the North Atlantic. This is triggering ecosystem regime shifts that are impacting the biological productivity of coastal and shelf waters of New England and Atlantic Canada with cascading impacts on the region's iconic fisheries, and in turn, challenging coastal communities and economies that depend on them (**Fig. 1**; Tesdal et al. 2018; Tesdal 2020; Friedland et al. 2020; Gonçalvez Neto et al. 2021; Greenan et al. 2021). These communities seek readily accessible monitoring, analysis, and forecasting capacities that support resilience and adaptation to physical, biological and socio-economic impacts caused by Arctic warming. Our understanding of these impacts is hampered by four challenges: (1) lack of an end-to-end analysis of the connection between Arctic change and its impact on coastal communities at a lower latitude; (2) limited capacity for scenario planning or forecasting to support decisions that account for future conditions in the ecosystem and fishery; ; (3) limited transboundary sharing of socio-ecological data among Atlantic Canada and the Northeast US partners, such as would be needed to support climate risk assessments for fisheries and coastal communities; and (4) few opportunities for early career scientists to learn convergence methodology and conduct convergence research. These challenges would benefit from improved US-Canadian collaboration across disciplines and sectors.

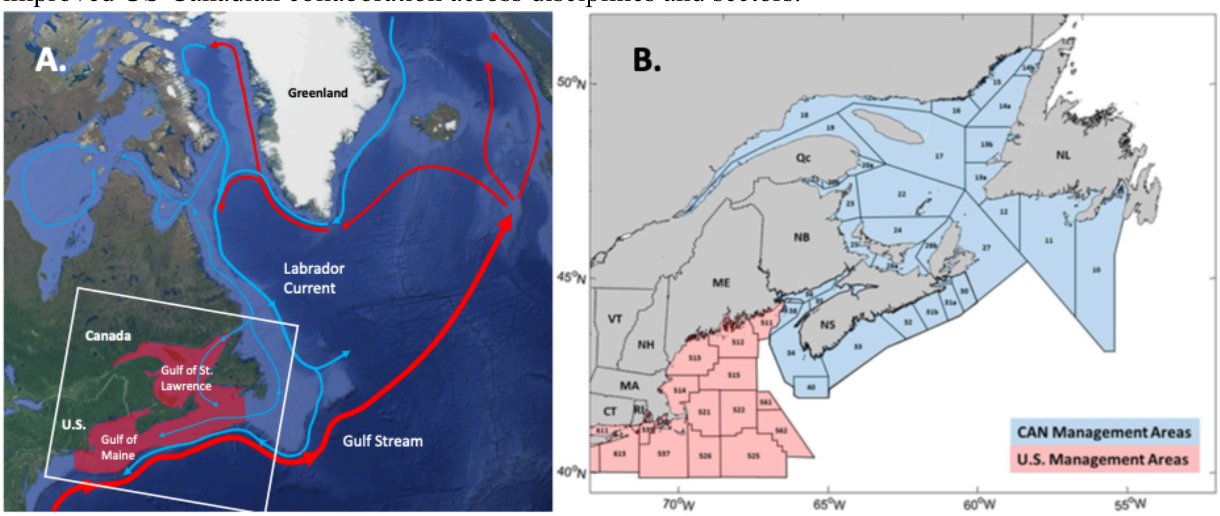

Figure 1. Spatial domain of the proposed NNA Lobster Network project. (A) Geographic range of the American lobster fishery (white box) nested within the Northwest Atlantic Ocean, and (B) Corresponding political boundaries and lobster management and statistical areas in US and Canadian waters.

Planning for the NNA Lobster Network began in February 2021 and in July was energized by support from the University of Maine's Arctic Seed Grant program. Our proposed three-year project focuses on the American lobster (*Homarus americanus*) fishery, the most valuable single-species fishery in both nations, and a well-studied and iconic socio-ecological system (e.g., Steneck and Wilson 2010, Steneck et al. 2011, Wahle et al. 2020). We are building on long-standing partnerships in the US and Canada, across academic institutions, government agencies, and the fishing industry. ***Our overarching goal is to increase the adaptive capacity of marine resource users and managers in the face of changing conditions by advancing understanding of how the cascading effects of rapid Arctic change will affect the lobster fishery and its associated socio-ecological system in coastal New England and Atlantic Canada.*** We will achieve this goal through a convergence research approach that addresses two major elements of the NNA program: *Natural Environment* and *Social Systems,* with project outcomes relevant to the focal areas: *data and observation, forecasting, education* and *global* (lower latitude) *impacts*.

This document is a revised Project Description based on post-review recommendations by the NNA program. The revised project has been downscaled and rescoped from the originally proposed 4-year NNA *Collaboratory* project to 3-year NNA *Research* project we now refer to as the *NNA Lobster*

Network. As recommended by the NNA program, we regard this project as Phase I of a potential two-phase project, the second phase of which will be contingent on the success of the first. This 3-year Phase I project addresses two of the three NNA Venn Diagram elements (*Natural Environment* and *Social Systems*), and reserves for Phase II the development of an originally proposed decision support tool under the *Built Environment* element.

2. Background

***2.1 Linking Arctic change to lower latitudes in the Northwest Atlantic ecosystem**:* Climate warming has resulted in dramatic losses of Arctic sea ice (Sevellec & Fedorov 2017; Putrasahan et al. 2019; Dukhovskoy et al. 2019) and the Greenland ice sheet (Bamber et al. 2012). This, in turn, has hastened the pace of freshening of the upper subpolar North Atlantic Ocean (Bamber et al. 2012), in particular the Western Atlantic Subpolar Gyre (WASG), which has experienced steady increases in upper water column buoyancy and gyre circulation strength (Caesar et al. 2018; Tesdal et al. 2018; Tesdal 2020; Gonçalves Neto et al. 2021). This freshening trend has weakened the branch of the cold, nutrient-rich Labrador current that flows south of Newfoundland, while the Gulf Stream has migrated northwards, causing the piling of warmer, nutrient-poor waters along the mid-Atlantic Bight and New England coast (Gonçalves Neto et al. 2021; Tesdal 2020; **Fig. 1**) and weakening of the Atlantic Meridional Overturning Circulation (AMOC) in recent years (Yang et al. 2016; Caesar et al. 2018). North Atlantic warming is anticipated to continue under future climate scenarios (Alexander et al. 2018; 2020), enhancing stratification, reducing convection and slowing the AMOC (Cheng et al. 2013; Collins et al. 2013), with substantial consequences for large ecosystems of the northern and mid-latitudes (Mills et al. 2013; Pershing et al. 2015; Chen et al 2021). However, the causal chain, and associated lags, that link warming Arctic conditions to oceanographic change in the Northwest Atlantic and subsequent biological and socio-economic consequences for the most valuable single-species fishery in North America has never been explored.

2.2 An iconic fishery in a changing ecosystem: As North America's most valuable single-species fishery, the American lobster contributes over $US 2 billion in ex-vessel value between the US and Canada annually (Wahle et al. 2020, NOAA 2021, DFO 2022). The Gulf of Maine accounts for 90% of US lobster production. Over the past three decades, the region has witnessed a historic six-fold boom in lobster landings, likely due to the combined effects of favorable warming and the depletion of predatory groundfish (Wahle et al. 2013, Goode et al. 2019). In Maine, about 80% of the state's total landed value of all fisheries comes from lobster alone (ME DMR 2022), signaling a perilous dependence of some coastal communities on this single resource (Steneck et al. 2011). Furthermore, southern New England's fishery is near collapse due to stressfully warm summer temperatures (Le Bris 2018, ASMFC 2020), compounded by the onset of a persistent shell disease epizootic (Glenn and Pugh 2006, Wahle et al. 2009). The strong dependence on lobster, coupled with ongoing climate-driven change fundamentally altering the marine

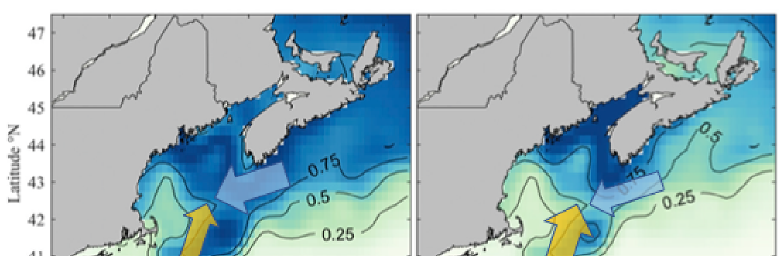

Figure 2. Changing fishing fortunes: Modeled lobster recruitment probability in the Gulf of Maine, Scotian Shelf and southern Gulf of St. Lawrence in 2010-15 (left) and projection for 2050 (right) assuming a 1.5° C increase in ocean temperature. Arrows roughly indicate relative influence of the Gulf Stream (orange) and Labrador Current (blue). (Adapted from Le Bris et al. 2018)

environment, raises pressing questions about the future of the lobster resource and the adaptive capacity of those who depend on it (Stoll et al. 2017). 0

The success of the lobster fishery also owes in part to a tradition of applying the precautionary harvest approach and active participation of stakeholders in decision-making processes that are critical to effective governance of natural resources (Acheson 1988, 2003, Ostrom 1990, Wilson 2007). Such participation has been facilitated by a diverse suite of institutions, at multiple scales, that provide both formal and informal pathways for harvesters to shape the management and stewardship of the lobster fishery. In the US, management responsibilities are split between state (inside 3 miles) and federal waters, while Canada's fishery is divided into 41 Lobster Fishing Areas. The US fishery is largely fished through effort controls with no closed seasons, while the Canadian fishery uses a combination of effort controls, and local quotas and seasonal closures. Given this heterogeneity in management approaches, the question arises as to whether some management institutions are more responsive to a changing environment than others, and whether decisions made by adjacent management areas affect neighboring ones.

As the region's waters warm and experience more frequent marine heatwaves (Mills et al. 2013, Pershing et al. 2015, Chen et al. 2021), lobsters are being affected directly by temperature increases and indirectly by broader ecosystem changes. Lobster larvae are hatching earlier, developing more quickly, have higher energetic demands, and juvenile lobsters are growing faster and maturing at a smaller size (Waller et al. 2017, 2019). Adding to the direct effects of warming is the weakening influence of cold, nutrient-rich water derived from the Labrador Current. The resulting strengthened intrusion of the warm, nutrient-poor, Gulf Stream to the Gulf of Maine (Gonçalves Neto et al. 2021), has altered the composition of the phytoplankton community (Balch et al. 2012, Friedland et al. 2020) and reduced net primary productivity (NPP, Tesdal, 2020). In turn, these changes have caused significant declines of the coldwater copepod, *Calanus finmarchicus*, which have been implicated in the decline of herring stocks, sea birds, and the endangered North Atlantic right whale, all of which depend on *Calanus* as an energy-rich forage food (Friedland et al. 2021, Pershing et al. 2021). Recent evidence also suggests that the downturn in *Calanus* has led to declines in young-of-year lobster recruitment despite record high egg production (Carloni et al. 2018, Wahle et al. 2021). Moreover, under warmer temperatures, southern demersal predators are expanding into the region, heightening predation risk for juvenile lobsters (Nye et al. 2009, Wahle et al. 2013). The net effect is a lobster range shift northward and to deeper, offshore waters (Pinsky et al. 2013) In short, the recent warming that spurred growth of the Gulf of Maine lobster population is now pushing temperatures towards thresholds that jeopardize recruitment success (Le Bris et al. 2018; **Fig. 2**). Understanding potential impact pathways and incorporating them into robust predictive models will be the foundation to support effective forward-looking climate adaptation decisions.

3. Proposed Research

3.1 Overarching Goal and Objectives:

This project will address the three-part hypothesis that ***Climate-driven Arctic change will affect the distribution and abundance of American lobster, and in turn, the fishing industry and coastal communities that depend on them, whose resilience to change will be determined by their the magnitude of change and their ability to adapt as changes occur.***

Our proposed NNA research will leverage existing monitoring programs and develop forecasting capacity of how warming Arctic waters will impact lobster populations and fisheries, including an end-to-end modeling framework that integrates oceanographic, population, and economic components. Research products will help the industry and managers develop strategies to ameliorate economic and social impacts. The project is committed to a convergence research approach that builds on a long-standing network of academic, government, and industry stakeholders in the US and Canada.

Our broad scientific objectives span two major elements of an NNA Research project: *Natural Environment* and *Social Systems.*

- ***Natural Environment:*** *Evaluate, model, and forecast how changes in the Arctic cryosphere affect ocean circulation at lower latitudes in the NW Atlantic and the productivity of its lobster populations.*
- ***Social Systems:*** *Model and forecast the effects of lobster population change on the fishery and well-being of the lobster industry.*

These two objectives provide the framework for our research and the specific hypotheses we will address. Details on the NNA Lobster Network team, project timeline, outreach, education and governance activities are described in the *Management and Integration Plan* in supplementary documents. Unfunded collaborators, heretofore referred to as *Project Partners* are listed in *Facilities, Equipment & Other Resources*.

3.2 Natural Environment: Linking Arctic Change to American Lobster Population Dynamics

The Natural Environment element of our proposal is divided into two subsections, the first of which (3.2.1) addresses changes in the physical environment and their impact on primary and secondary productivity. The second (3.2.2) relates to how those changes affect lobster population connectivity and productivity over space and time.

3.2.1 Cryosphere, Atmosphere, Physical and Biological Oceanography (Chassignet, Goes, Gomes, Romero, Stukel, Tedesco): We will test two hypotheses:

H1: *The ongoing and projected loss of Arctic sea ice and Greenland ice sheet will alter transport and composition of the Labrador Current and continue to weaken AMOC, thereby enhancing the northward migration of warmer, oligotrophic Gulf Stream waters into coastal ecosystems of Atlantic Canada and New England.*

H2: *Changes in the fractional contribution of the Labrador Current and Gulf Stream will increase temperature and stratification, as well as alter regional primary and secondary productivity, along the Scotian Shelf and in the Gulf of Maine.*

Our **primary tool** to address **H1 -** the role of Arctic and Greenland ice melt and freshwater fluxes on circulation patterns, nutrient fluxes, and their impacts on lower trophic productivity in the mid-latitudes will be the Northwestern Atlantic HYCOM-NEMURO coupled atmosphere-ice-ocean-biogeochemical model (**Hy**brid **C**oordinate **O**cean **M**odel - **N**orth Pacific **E**cosystem **M**odel for **U**nderstanding **R**egional **O**ceanography). The HYCOM-NEMURO model will be configured with a 1/50° equatorial spatial resolution (~1.5 km mean resolution) and a 41-layer hybrid vertical structure. The bathymetry/landmask is derived from the latest 15-arc second GEBCO v2019 product, providing a well-defined coastline and continental shelf. Deep learning super-resolution methodology based on the Deep Residual Channel Attention Network (RCAN), trained using high-resolution 3-D ocean fields currents at 1/50° (Chassignet and Xu 2017; 2021), will be used to incorporate missing submesoscale processes into the 3-D ocean fields of the HYCOM 1/12° Global Ocean Forecasting System (GOFS, from 1994 to present) analysis and reanalysis. The HYCOM outputs will be: Ocean - sea surface height, temperature, salinity, currents, and other diagnostic products (e.g., mixed layer depth); Atmospheric surface fluxes - air temperature, winds, wind stress, and heat fluxes. HYCOM results will be validated against 8-day and monthly satellite fields of sea surface temperature (Chassignet et al., 2009), NOAA's Integrated Ocean Observing System (IOOS) and the Canadian Integrated Ocean Observing System (CIOOS) data streams of water column temperature (Morrison et al., 2012), and bottom temperature from the environmental monitoring on lobster traps (eMOLT) program (Li et al., 2017). The NEMURO (Kishi et al. 2007) outputs will include 2 classes of phytoplankton, 3 of zooplankton, nutrients, detritus, O_2, CO_2, and alkalinity, and other diagnostic products like chlorophyll a (Chl a) concentration and NPP. NEMURO results will be validated against 8-day and monthly satellite fields of sea surface nitrate (Goes et al. 1999; 2000a,b; 2001, 2004), Chl a (O'Reilly et al. 2019), NPP using the Absorption Based NPP Model (Kiefer and Mitchell, 1983; Wu et al. in review) and phytoplankton size classes (Turner et al. 2021). These maps will be derived using data from SeaWiFS (1998-2010), MODIS-Aqua (2002-present), MERIS (2002-2012) and Suomi-VIIRS (2012-present) with algorithms optimized for the Northeast continental shelf. Modeled nutrients, O_2, CO_2, alkalinity, zooplankton size classes and copepod abundance will be validated using shipboard data available at BCO-DMO, NOAA-NCEI, Canada-DFO, and NOAA Ecosystem Monitoring (EcoMon) programs.

The NEMURO model provides outputs of calanoid copepods. Targeted sensitivity simulations of calanoid copepods will be undertaken to fine-tune model parameterizations, evaluate model outputs of copepods using data from the NOAA Ecosystem Monitoring and Canada Atlantic Zone Monitoring Program zooplankton surveys. Meltwater fluxes from Arctic sea ice will be estimated from satellite-altimetry derived changes in sea ice volume, obtained from the combination of sea ice extent and thickness. Greenland ice sheet (GrIS) freshwater fluxes will be derived from Gravity Recovery And Climate Experiment (GRACE) and GRACE follow-on (GRACE-FO), which provide ~monthly spatially distributed mass change estimates and uncertainty estimates for 2003 through present (Loomis et al., 2019; Wiese et al., 2019; Watkins et al. 2015). Altimetric mass change estimates from the Ice Cloud and Elevation Satellite (ICESat) and ICESat-2 spanning 2003 through 2019 (Smith et al. 2020) will be used as an additional check on GRACE mass balance measurements. Mass loss accumulated in individual basins will be distributed within ocean grid cells adjacent to the ice sheet basins. Co-PI Tedesco and Dr. Alexander are involved in a National Sea Level Change Team project led by NASA Goddard Institute for Space Studies (GISS) to estimate sea level change associated with various sources including ice sheet melt, results from which will be used to constrain model and satellite estimates. One source of uncertainty in GrIS freshwater flux is that mass balance observations include changes in precipitation, which *van den* Broeke et al. (2016) has shown to be small relative to changes in runoff. Model outputs will be used to assess to what extent interannual variability in freshwater transport in the Labrador Current and/ or atmospheric forcing (e.g., NAO/AO) contribute to the freshening and the strength of the WASG and the Labrador Current itself (Tesdal et al. 2018; Tesdal 2020). As part of this effort, we will quantify (1) the transport and freshwater fluxes in the Atlantic Canada region just upstream of the Gulf of Maine, and (2) how the volume of fresh SSW and cold, nutrient-rich LSW varies as a function of the strength of the Labrador Current. In parallel, we will use machine learning techniques (e.g., random forest) to address attributions of the drivers we are investigating. HYCOM-NEMURO outputs and satellite data products will be used to assess how freshening and changes in circulation influence nutrients and phytoplankton biomass and productivity in the Labrador Sea and Western North Atlantic Ocean.

To quantify the long-term impact of ice melt on circulation patterns, oceanographic conditions, and primary and secondary productivity, HYCOM-NEMURO simulations will be extended to 2050 using the existing 1/50° North and Equatorial Atlantic HYCOM configuration of Chassignet and Xu (2017, 2021) with atmospheric forcing from the downscaled CESM SSP3-7.0 climate projection (Yeager et al., 2018). We will work with the *Built Environment* and *Social Science* teams to provide projections and associated uncertainty relevant to the decision-making timelines of stakeholders (e.g., mortgages on fishing vessels and stock assessments). To further identify (a) the sensitivity of Labrador Current transport to meltwater input, (b) the fraction of the freshwater that is transported southward to the Scotian Shelf or offshore into the WASG, and (c) how meltwater input will influence the transport of different water masses into the Gulf of Maine under future climate scenarios, we will also artificially increase meltwater input as in Luo et al. (2016). The cryospheric component of meltwater change will be estimated from a combination of CMIP6 ensemble estimates of sea ice volume change (e.g., Zanowski et al., 2021) under SSP3-7.0, in conjunction with projections from the Ice Sheet Model Intercomparison Project (ISMIP6) of spatially distributed ice sheet mass balance changes (Goelzer et al., 2020).

3.2.2 Ecosystem and Lobster Population Modeling (Brady, Mills)**:** We will use outputs from the Northwestern Atlantic HYCOM-NEMURO described in 3.2.1 to drive spatio-temporal models of lobster life history and population dynamics in the Northwest Atlantic, essentially step two in the end-to-end modeling framework. After developing, tuning, and testing the models, we will run multiple simulations to generate short- and long-term predictions of American lobster population productivity. We will test two hypotheses:

***H1:** Changing marine ecosystem conditions, including rising temperatures and trophic connections to* Calanus finmarchicus*, are associated with spatial and temporal non-stationarity in lobster life history parameters, the importance of key life history variables, and population outcomes.*

***H2:** Controls on lobster population productivity have shifted from local environmental and human exploitation conditions to large-scale regional and basin-wide factors, and the influence of large-scale drivers will continue increasing as climate change progresses.*

The lobster population modeling framework consists of two components. First, a lobster **larval life history model** will be developed to simulate the drift, growth, and mortality of lobster larvae as determined by coastal flow fields, water temperature at the surface and bottom, and the abundance of the zooplankton *Calanus finmarchicus*. The larval transport model will expand upon earlier larval tracking models (Xue et al., 2008, Chasse & Miller, 2010; Quinn et al., 2017), and inputs (e.g., temperature, currents, prey fields) will come from HYCOM-NEMURO (3.2.1). In Years 1-2, we will advance the larval transport model by including a statistical distribution model that will inform the location of larval release (Chang et al., 2010) and incorporation of spatiotemporal variability of egg hatch phenology (ASMFC, 2020). *Calanus* abundance and distribution will be modeled using HYCOM-NEMURO (3.2.1), and in Years 1-2, the survival of lobster larvae will be modified by their co-occurrence with *Calanus* and mortality rates will be tuned by comparing model output to *in situ* measurements of stage-specific larval lobster abundances (Carloni et al., 2018). Validated larval patterns will be used to generate regional patterns of postlarval settlement to the seafloor using thermally-specific relationships and nursery habitat availability during Years 2-3 (Annis, 2005; Goode et al., 2019), and patterns of postlarval settlement will be calibrated using existing ALSI time series (Wahle et al. 2013). In Years 3-4, validated postlarval settlement densities will inform short-term landings forecasts by implementing temperature-dependent logistic growth of individual year classes to generate indices of recruitment into the fishery, and in turn, these indices will be compared to annual landings to generate recruitment-to-landing relationships that will be used to hind- and forecast regional landings trajectories for a 6-year period, as in Oppenheim et al. (2019).

The second component of this end-to-end framework will be a **population dynamics model**, which will simulate later life stages of lobster in spatially-resolved areas. We will expand upon an existing lobster population model (Le Bris et al., 2018) with Dr. Le Bris under a contract agreement. We will extend the model domain to span from southern New England to Newfoundland-Labrador and enhance the spatial resolution to operate at the scale of statistical areas in the U.S. and management areas in Canadian waters (**Fig. 1B**). Range-wide analyses of U.S. and Canadian biological monitoring data from multiple fishery-dependent and fishery-independent programs will be conducted in Years 1-2 to refine estimates, and characterize variability, of biological parameters (e.g., growth rates, age at maturity, fecundity, natural mortality) in relation to oceanographic and lower trophic level conditions generated from HYCOM-NEMURO. Larval abundance estimates, biological parameter estimates, and thermal influences on biological rates will be incorporated into a size-structured population model (Years 2-4), wherein temperature will influence individual growth, fecundity, and natural mortality (directly and indirectly through the predator size spectrum) at monthly time steps. Outputs of the population dynamics model will be compared to abundance estimates from relevant stock assessments to validate and assess sensitivity of the model.

Outputs of the larval life history and population dynamics models will be used to evaluate both hypotheses specified above and assess their impacts to future trajectories of lobster populations across the U.S. and Canada. Through a combination of dynamic factor analysis (Zuur et al., 2003), generalized additive models, and breakpoint detection methods, we will test our first hypothesis by investigating whether the spatiotemporal variability in population-ecosystem relationships remains stationary over time within the larval life history and population dynamics models. The results of these analyses will be used to evaluate our second hypothesis by determining how non-stationarity in population-ecosystem relationships are associated with ecosystem regime shifts (Litzow et al., 2018; Friedland et al., 2020) and whether drivers have shifted from local (e.g., local temperature and catch) to regional (e.g., Gulf Stream North Wall index, aggregate catch) factors. These relationships will be used to tune each model and project population outcomes and uncertainty estimates associated with future climate conditions to 2050 using outputs from HYCOM-NEMURO (3.2.1). Climate (3.2.1), management (3.3.2), and economic (3.3.1) scenarios will be evaluated within the model to quantify their influence on lobster population trajectories at the spatial scale of statistical and management areas in the U.S. and Canada. If our second hypothesis holds under climate projections, an erosion of local fishery management influence on lobster population outcomes should be expected as the influence of regional climate drivers strengthens.

The research conducted herein will support several applications. First, we will routinely meet with lobster stock assessment scientists in the U.S. and Canada, and the postdocs will participate in relevant technical committees to ensure that our analyses of biological parameters, biological-ecosystem relationships, and population trajectories support their information needs and can contribute to modeling efforts that align with fishery management processes. Our findings will also underpin near-term and long-range planning for climate adaptation in the fishery, and we will work closely with industry organizations and community practitioners involved in the *US-Canada Climate and Fisheries Futures Collaborative* (section 4) to apply results to adaptation and resilience planning efforts.

3.3 Social Systems: Linking Ecosystem Change to Resource Users and Fisheries Governance

Leveraging outputs from the ecosystem and lobster population modeling framework described in Section 3.2.2, the overall goal of the Social Systems element of our proposal is to evaluate the resilience of the lobster fishery as it responds to region-wide impacts of climate change through bio-econometric modeling (3.3.1) and the development of socioeconomic indicators (3.3.2).

3.3.1 Bio-economic Modeling (Takunaga): We hypothesize that,

H1: *The American lobster fishery consists of a diverse set of agents whose harvesting decisions (i.e., the amount and location of effort) are shaped by the current and future resource availabilities and fishery governance decisions*.

Bio-economic models are often used to evaluate or simulate the impacts of alternative management regimes or ecological conditions on harvested volumes, revenues, and resource abundance (Clark 2005, Squires et al. 2017, Tokunaga et al. 2019, Wilson et al. 2007, Wilson et al. 2013). Previous bio-economic models of the American lobster fishery found substantial economic gain through economically optimal exploitation (i.e., profit maximization) with individual transferable quota (ITQ) management (Holland 2011a, Holland 2011b). Conventional bio-economic models, including the ones developed for the American lobster fishery, build on constrained optimization, where an individual harvester maximizes profit by choosing harvest amount given resource constraints. These models often assume homogeneous harvesters, fixed prices, uniformly distributed resources, and logistic growth of the resource. Alternatively, agent-based models (ABM) can describe individual and spatial heterogeneities (Burgess et al. 2018, Arthur 2006). ABM has also been used to describe fisheries with spatial and management heterogeneities (e.g., Yu et al. 2013) and spatial expansion of the fisheries (e.g., Hogrenning and Eide, 2021).

This project proposes a bio-economic modeling approach using an ABM framework. Motivation for this approach stems from the fact that despite the economic model showing improved profits under ITQs, the research team's previous interactions with the industry and management stakeholders suggests industry's preference for co-management with effort controls over ITQs and a fishery objective to maximize employment rather than profit maximization. ABM contributes to this project's overall objective by unpacking how ecological and technical (e.g., vessel and engine size, gear) heterogeneities may influence fishing and resource outcomes.

The bio-economic model will constitute the final component of the end-to-end modeling framework. It will draw on the lobster population modeling (3.2.2) to identify and incorporate dynamics of the resource under expected changes in Arctic circulation. To support spatially explicit fishery analyses, the hindcasted and projected lobster population abundances will be distributed over the high-resolution HYCOM spatial grid using statistical relationships between abundance and environmental conditions established from distribution models that are currently under development in Mills' lab. Using this as the status quo, we will introduce bio-economic interactions to simulate scenarios using ABM. Fleet dynamics (i.e., production functions) will be informed primarily by economic theory and recent economic studies of the American lobster fishery (e.g., Bisack et al. 2021) as well as by the social science research (3.3.2 and 3.3.3). Specifically, interviews and surveys conducted as part of socioeconomic indicators work (3.3.2) will inform characterization of alternative fishing objectives, future expectations, adaptive capacities, and resulting harvesting behaviors.

Our model simulates the spatial and temporal changes in fishing effort and resulting harvested volume and value at individual and aggregate levels under Arctic change. The research team will co-develop and ground-truth the model construction and scenarios with stakeholders in Maine in the US and New Brunswick and Nova Scotia in Canada. To achieve this, the team will run two sets of focus group meetings attended by industry experts (approx. 10 experts) from these regions. The first set of focus group meetings, held at the beginning of year two, will introduce the ABM approach and participants will deliberate on i) types of vessels (e.g., vessel size, gear configuration) and associated operational characteristics (e.g., trip frequency, areas of operation) present in each region, aided by initial findings from the empirical data analysis; ii) possible harvester responses (e.g., change harvesting location, change harvest timing, exit fishery) to ecosystem changes; and iii) fishing objectives, future expectations, and adaptive capacities identified by socioeconomic indicators work (3.3.2). Following the first set of focus group meetings, the team will model fleet dynamics. The second set of focus group meetings, held in year three, will test the developed ABM with the same set of industry experts. The participants will present ABM simulations and deliberate on i) whether the results are surprising or as expected, ii) validity of model assumptions and scenarios, and iii) whether there are seemingly unattainable but possible harvest response options that need to be considered. The final model will serve as a basis for an educational tool to be developed in the subsequent phase of the project to engage industry and management stakeholders.

3.3.2 Socioeconomic Indicators (Stoll, Beitl, Leslie**)**: Here we advance two interconnected hypotheses:

H1: *Changing socioeconomic and environmental conditions in the lobster fleet will have differential impacts on livelihoods and wellbeing within and across coastal fishing communities in the Gulf of Maine and Atlantic Canada; and*

H2: *Signs of economic vulnerability can be tracked and anticipated using social indicators of resilience*.

Although the biological status of lobster populations is closely monitored in the Gulf of Maine and Canada, there are currently no social indicators to detect vulnerability among industry participants. We propose to develop a parsimonious suite of socioeconomic indicators that the lobster industry, coastal communities, and managers can use to monitor resilience of the fleet and detect early signs of vulnerability among harvesters. In this context, we define resilience as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (Adger et al. 2000). This effort expands an ongoing initiative led by UMaine in collaboration with the lobster industry and responds directly to recent calls for the creation of social metrics for the lobster fishery by policymakers, scientists, and industry participants alike. Specifically, we will establish a replicable, theoretically grounded, and contextually relevant set of indicators for monitoring resilience of participants in the fishery during a period of rapid change. These indicators will also directly support the ABM (3.3.1).

Social indicators are "quantitative measures of social conditions designed to guide choices at several levels of decision making" (Sawhill 1969 in Andrews & Withey 1976). Unlike discrete variables such as fish size or number of participants in a fishery, some variables, like resilience, cannot be measured directly. These variables, called *latent constructs*, require the identification of indicators that represent the underlying phenomena of interest (Byrne 1998). Indicators for fisheries have been developed in a range of places and at different scales (Colburn & Jepson 2012; Colburn et al. 2016; Himes-Cornell & Kasperski 2016; Jacob et al. 2013). Although indicators cannot replace the richness or depth of information from traditional ethnographic methods, one important advantage is that they provide quantitative data about the social and economic conditions that can be more readily integrated into decision-making processes (Jacob et al. 2013, Leslie et al. 2015).

We propose a mixed-methods approach, drawing on multiple peer-reviewed methods for identifying, reviewing, and validating indicators. In developing socioeconomic indicators for resilience in the lobster fishery, we will follow a three-step process that involves: (1) mapping the latent construct of resilience; (2) identifying quantitative resilience indicators; and (3) collaborating with the industry to validate the indicators (inter-rater reliability). The first step will be to define the suite of variables that underlie resilience in the context of the Maine lobster fishery. Scholars have used a range of strategies to accomplish this step, including literature reviews (Breslow et al. 2018), consensus-based expert elicitation (Stoll et al., 2017), and conceptual mapping with stakeholders (Andrews and Withey, 1976). Irrespective of the approach, there is strong agreement that latent constructs should reflect the lived experiences of the study population. Towards this objective, we will identify the variables associated with our latent construct (resilience) through semi-structured interviews with members of the lobster industry using a “mobile” interview method where participants are interviewed while going about their daily activities (Büscher & Urry 2009). We will start by interviewing lobstermen and then expand to include other actors who are indirectly involved in the fishery, such as scientists, managers, technical assistance providers, community leaders, and shoreside industry representatives. These interviews will be audio recorded and detailed field notes will be taken that are descriptive and reflective. Both the recordings and the fieldnotes will be subsequently coded in NVivo Pro 12 using an inductive approach to identify variables related to resilience. To identify quantitative indicators in the second step, we will draw primarily on datasets that are near real-time and therefore of higher temporal resolution. This addresses a widely acknowledged limitation of previous studies that have used a variety of secondary data sources to measure latent constructs using macro-level socioeconomic data that often has poor temporal resolution, making it difficult to use to detect early signs of change or sudden shifts (Jacob et al. 2013). By focusing on the lobster fishery, we can utilize industry-specific datasets that are directly related to the latent construct of resilience. These datasets will be identified with the support from members of the industry during one-on-one meetings throughout the first year of the project and during a focused data workshop. In these workshops, we will present variables identified during the first step and any preliminary datasets that could be used to inform indices. The final step involves validation through a series of stepwise statistical methods described by Jacobs et al. (2013) and adopted by others (Colburn & Jepson 2012, Himes-Cornell & Kasperski 2016). The continued work on the development of social resilience indicators in partnership with industry members will allow us to advance our capacity to co-design a diagnostic tool for the analysis of co-management institutions. This diagnostic analysis of existing institutions would enable us to assess the participation of harvesters in decision making processes concerning their adaptive capacity in the face of rapid change.

3.4 Planning for User-Driven Information Infrastructure (Dickes and Young Morse)

This project will generate a plethora of data, model outputs, and research products. Although beyond the scope of this Phase I project, a next-stage goal is to contribute to the ‘Built Infrastructure’ element of the NNA by developing data access and decision support infrastructure to make information accessible to and usable by a variety of stakeholders in the lobster industry and management bodies. However, these diverse stakeholders will have different levels of prior knowledge, technical capabilities, and modes of reasoning–all of which affect how they prefer to access, reason with, and apply data and information to decisions. In this project, a learning scientist (Dickes) and data infrastructure developer (Young Morse) will participate in team meetings and stakeholder interactions to develop an understanding of data, products, and stakeholder needs as a basis for planning a second-phase proposal to develop and build a data infrastructure and information dashboard designed based on end-user needs.

4. Broader Impacts

The broader impacts of our proposed NNA Lobster Network are evident in our educational and training opportunities, and our stakeholder engagement across sectors of the fishing industry and government marine resource agencies in the US and Canada. The proposed project supports fishing industry and community climate adaptation planning and lobster resource management. Our activities address priorities stated by the United Nations Oceans Decade Implementation Plan (Ryabinin et al. 2019), the US Multi-agency Research and Development Priorities (OPUS 2021), and the State of Maine's Climate Action Plan (MCC 2020). It also trains the next generation of scientists to address complex issues through convergence research approaches. We highlight five outcomes that especially address the challenges listed in the proposal Introduction that limit the ability of coastal communities to understand and respond to a changing environment associated with rapid Arctic warming:

- **End-to-end integration:** It integrates outcomes from research in two elements of the NNA Program by conducting the first end-to-end, integrated analysis of the impacts of Arctic change to a marine socio-ecological system at a lower latitude.
- **Scenario analysis and forecasting:** It creates the capacity to evaluate the impact of future scenarios of environmental change on the lobster fishery and communities that depend on it, and to understand the relative ability of coastal communities to adapt to these changes at different spatial and temporal scales.
- **Strengthened cross-border, cross-sector collaboration:** It strengthens long-standing transdisciplinary collaborations between US and Canadian researchers by capitalizing on parallel, but independent, convergence research initiatives - the *NNA Lobster Network* in the US, and the *Lobster Node II* in Canada, whose joint activities will be coordinated by the newly formed *US-Canada Climate and Fisheries Futures Collaborative* (CFFC).
- **Education:** The project will train two graduate students and four postdoctoral associates, creating a cohort of scholars grounded in convergence methodology and ethos.

Below we expand on the stakeholder outreach and educational components of the project that will lead to these Broader Impacts.

4.1 Regional and International Scientist-Stakeholder Collaborations: Our cross-border, cross-sector, collaborations build on long-standing and enduring partnerships. The project engages more than 15 stakeholder partners from the fishing industry and government agencies and academia in the US and Canada. Some are more directly involved in the research than others (see *Facilities, Equipment and Other Resources)*. As stated in section 3.0, our project expands existing monitoring programs supported by government agencies, fishing industry and academia in the US and Canada, including the American Lobster Settlement Index (ALSI), initiated in 1989, and eMOLT, initiated in 2001. In addition, our work complements research and outreach conducted through NOAA Sea Grant's American Lobster Initiative, begun in 2019 to address critical knowledge gaps in our understanding of the lobster fishery and population dynamics in a changing environment. Through our work with Maine Sea Grant's marine extension lead and the Lobster Institute's outreach staff, we will foster engagement of industry and resource manager stakeholders to meet project objectives, especially to develop products that facilitate data integration to meet their information needs and support their decision making. Iterative stakeholder engagement throughout the project will enable us to target research results and products that most effectively meet the needs of stakeholders. We also acknowledge that it is not possible to foresee how stakeholder priorities and interests may change over the 3-year course of our project, and that they are likely to evolve over time. Our outreach methods must therefore be nimble enough to evolve in tandem.

Our collaboration will have a forum in ongoing periodic outreach events. UMaine's Lobster Institute will host the *US-Canada Lobster Town Meeting* as it has for 17 years, a two-day in-person event held alternately in the US and Canada to provide a facilitated town hall forum for industry and scientists to voice perspectives on priority topics. Other annual fora include the Maine Fishermen's Forum, American Lobster Initiative meetings, and Canada's Fishermen and Scientist Research Society meeting.

In collaboration with our state, federal, industry, and Canadian partners through the ALSI program, we will also expand a regional fishery-integrated monitoring program to create a distributed bottom water temperature validation dataset. The eMOLT program utilizes *in situ* ocean sensors and satellite technology to monitor seafloor conditions that are not easily monitored by other conventional sampling practices. To date, this program has been limited mostly to southern New England. Expansion of eMOLT will offer a new, unique dataset of seafloor temperatures in the eastern Gulf of Maine and Canada that can be used for model validation in nearshore waters and provide a new venue for industry involvement in ocean monitoring and modeling in the rapidly changing Northwest Atlantic continental shelf.

As we have developed our NNA Lobster Network project over the past year, a core strategy has been to complement a parallel effort under way in Canada to reinstate the highly successful Canadian Fisheries Research Network's *Lobster Node*. From 2010-2015 Canada's *Lobster Node* established a successful track record of co-constructed and convergent research (Rochette et al. 2017). In 2022 our Canadian colleagues aim to reinstate their very successful Lobster Node, and we envision establishing a cross-border, transdisciplinary research network focused on enabling coastal communities to foresee and adapt to climate impacts. The governance structure of the NNA Lobster Network is further described in our *Management and Integration Plan*.

4.2 Graduate and Postdoctoral Experience: The NNA Lobster Network engages four postdocs and two PhD level graduate students over the course of the project. Our educational goals are to train the next generation of leaders to (1) advance an understanding of the effects of rapid Arctic warming at lower latitudes, (2) conduct inter- and transdisciplinary research, and (3) develop communication skills to effectively engage with stakeholders, partners and policy makers on environmental and societal challenges posed by the changing environment. Students and postdocs will emerge from this program with a grounding in the theory and practice of convergence science through their research collaborations, course work, internships, facilitated US-Canada workshops and retreats. Plans to implement the graduate and postdoc experience appear in the *Management and Integration Plan* and *Postdoc Mentoring Plan*.

5. Results of Prior NSF Research

We have assembled a team with extensive experience in Arctic and mid-latitude ocean climate impacts, oceanographic variability, fish distribution and population dynamics, modeling, the socio-economics of coastal communities in the Northeast US and Atlantic Canada, and the learning sciences. Our proposed research builds on our prior research.

- ***K. Mills*** and ***R. Wahle*** were co-PIs on Coastal SEES (Track 2), Collaborative Research: Resilience and Adaptation of a Coastal Ecological-Economic System in Response to increasing Temperature, NSF-OCE 1325484; $1,125,752, 9/1/2013-8/31/2017 (NCE 8/31/2018). ***Intellectual Merits:*** This project investigated how rapid warming and heat waves affected the Gulf of Maine ecosystem and its lobster and cod fisheries, including projections of future changes. It produced 21 papers (* in references). ***Broader Impacts:*** Warming and fishery impacts characterized through this project placed the Gulf of Maine in the international climate change conversation. PI Mills incorporated insights into the "Northeast" chapter of the 4th National Climate Assessment. The project funded a climate change station for GMRI's LabVenture program, which is experienced by 10,000 5th-6th graders annually. The project trained one postdoc, 5 graduate students, and 2 undergraduates. ***Data Availability:*** This project analyzed publicly available data. Derived data products were delivered to BCO-DMO. Data and code to reproduce findings are available from GMRI's GitHub and publications.
- ***D.Brady, H. Leslie,*** and ***R. Wahle*** are contributing to the collaborative research grant to Maine EPSCoR, RII Track-1: Molecule to Ecosystem: Environmental DNA as a Nexus of Coastal Ecosystem Sustainability for Maine (Maine-eDNA). OIA-1849227. $20M: 07/2019-06/2024. ***Intellectual Merits:*** Maine-eDNA is a 5-year research, education and outreach program that is transforming understanding and sustainability of Maine's coastal ecosystems via ecological and eDNA knowledge through transdisciplinary team science on the population, community, and ecosystem processes. ***Broader Impacts:*** Through program-wide data sharing and partnerships with more than 20 organizations throughout Maine, Maine-eDNA is contributing to knowledge and solutions related to sustainable fisheries and emerging harmful species and building capacity for convergent STEM research and education. More than 20 graduate students and four postdocs have been trained thus far. ***Relevant Publications:*** Bayer et al.

(2019), McGreavy et al. (2022). ***Data Availability:*** We have set up the infrastructure to make all the sample data and metadata available. A small set of test sequences have been generated to date, and will be available to national/international repositories.

- ***E. Chassignet*** and ***X. Xu*** collaborated on *Subpolar-subtropical connectivity of the North Atlantic Circulation*, NSF-OCE- 1537136, $451,170 09/01/2015-08/31/2019: ***Intellectual Merits:*** The primary objective of this research was to elucidate the physical dynamics that control the circulation into the transition region between the subpolar and subtropical North Atlantic, especially the Gulf Stream-North Atlantic Current and the deep western boundary current, and to document the role of the transition region on the larger scale circulation. ***Broader Impacts:*** Coupled global climate model simulations used to predict climate change differ greatly in their Atlantic air-sea heat and freshwater fluxes, particularly in the transition region. Our focus on the transition region serves to clarify this complex warm/cold and fresh/saline exchange process. The project trained one postdoc. ***Relevant Publications:*** Xu et al. (2016, 2018a, b, c), LaCasce et al. 2019, Chassignet and Xu (2017, 2021). ***Data Availability:*** Model outputs are available via the HYCOM server (hycom.org/dataserver).
- ***J. I. Goes and H. R. Gomes*** collaborated on *RAPID - Assessing the response of the Seychelles-Chagos Thermocline Ridge Ecosystem to an Indian Ocean Dipole Event*, NSF #2019983, US$191,842, 03/1/2020–02/28/2021. ***Intellectual Merit:*** This study aims to understand the effects of Indian Ocean Dipole on phytoplankton community structure and primary productivity in Seychelles-Chagos Thermocline Ridge in the western equatorial Indian Ocean. Due to Covid-19 restrictions, with approval from NSF the location was shifted to the Eastern Equatorial Region/ ***Broader Impacts*:** This will be a US contribution to the 2nd International Indian Ocean Expedition. Currently 1 Graduate Student from India and 4 high school students from the USA are working on climate change and IOD related impacts on marine life. ***Relevant Publications:*** Work on this project has resulted in 1 publication Rixen et al. (2020). ***Data Availability:*** Data are being collected on cruises during Jan-Mar, 2022 to be deposited at BCO-DMO by mid-June 2022.
- ***A. Dickes and K. Tokunaga*** are co-PIs on *ITEST - Developing underserved elementary students' systems thinking and economic literacy through investigations of local ecological-economic systems*, NSF #2048828, US$477,058, 1/1/2021-12/31/2022. ***Intellectual Merit***: This project engages Maine elementary students from rural and immigrant/refugee communities in an integrated learning experience that includes aquaculture workforce mentorship and classroom-based activities which foreground the affordances of scientific modeling as a means to represent, test, and understand relationships within the natural world. ***Broader Impacts***: This project will establish a bridge between the classroom and a regional workforce, and develop multiple areas of skill and knowledge that can be flexibly deployed across a students' entire academic career and across evolving future work environments. ***Relevant publications:*** The project timeline was significantly altered due to Covid-related school closures and has plans to begin classroom research in Spring 2022. ***Data Availability:*** Subject to human protection and confidentiality standards, learning tools, curricular and professional development resources will be made available by GMRI. Coded, blinded assessment and survey data may be used as archival data at project end.
- ***M. Tedesco*** is leading and ***P. Alexander*** *(Early Career Scientist)* is contributing to *Collaborative Research: Closing the Gaps in Climate Models' Surface Albedo Schemes of Processes Driving the Darkening of the Greenland Ice Sheet*, NSF #1713072, US$506,727: 9/15/17-8/31/22 ***Intellectual merit:*** The objective of this project is to develop an understanding of the impact of key processes driving surface albedo variability on the Greenland Ice Sheet surface energy and mass balance. These processes, including distribution of biological impurities on the ice sheet surface, are important in simulations of ice sheet mass balance. ***Broader impacts:*** The project helps reduce uncertainties of the contribution of Greenland to sea level rise and will also improve our understanding of interactions between the ice sheet, oceans and atmosphere. The project has trained Drs. Patrick Alexander and Shujie Wang, former postdocs at LDEO. ***Relevant publications:*** Tedesco & Fettweis (2020), Alexander et al. (2019), Wang et al. (2018). ***Data Availability:*** Model simulation results and other data used and produced as part of the project have been made available online through ftp or https and as supporting information as noted in the above publications.