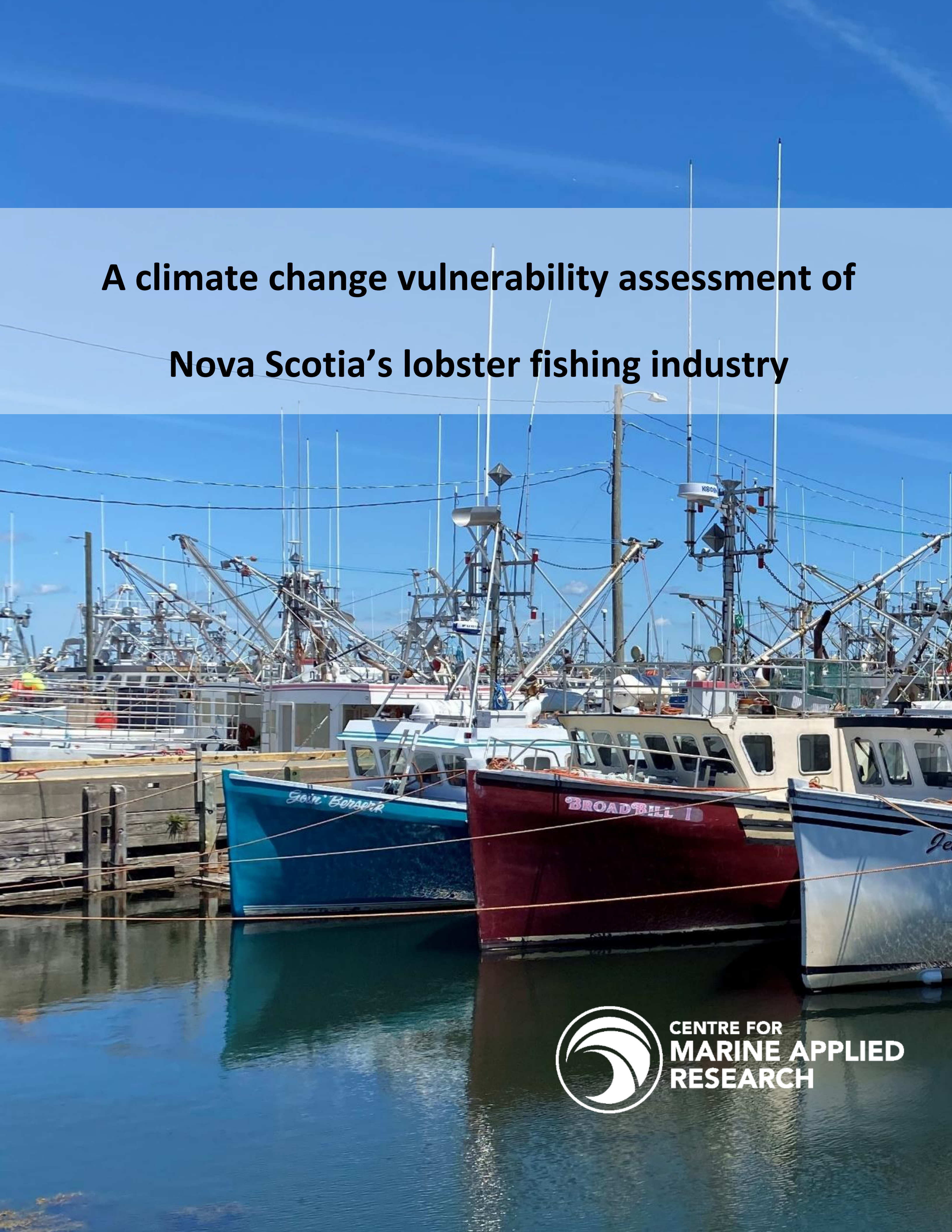
A climate change vulnerability assessment of Nova Scotia's lobster fishing industry



CENTRE FOR MARINE APPLIED RESEARCH

A climate change vulnerability assessment of Nova Scotia's lobster fishing industry

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Table of Contents

1 Executive summary

Climate change is beginning to affect Nova Scotia fisheries, and impacts are expected to increase. Nova Scotia is Canada's number one exporter of seafood, with American lobster (*Homarus americanus*) as the most economically prominent fishery, valued at over $1 billion in 2021. Understanding climate change vulnerabilities of this fishery is an important step to guide planned adaptation. Climate change vulnerability assessments are an internationally recognized process that combines biophysical and socio-economic metrics to estimate relative vulnerability. Data are typically partitioned into three indices: *Exposure*, which describes the magnitude of climate change stressors within a defined area; *Sensitivity*, which considers how much a system or sector responds to stressors; and *Adaptive Capacity*, which describes the ability to adapt in order to reduce *Exposure* and *Sensitivity*. Determining which metrics to include and how to account for them in an assessment, is a function of data type, availability, resolution, scale, and importance. Assessments typically consider both current and projected impacts.

To better expand our understanding of climate change threats to the Nova Scotia lobster fishery, a climate change vulnerability assessment was implemented and partitioned between two models applied to Lobster Fishing Areas (LFA) bordering Nova Scotia. The first model, 'Lobster Vulnerability', assessed lobster temperature thresholds relative to ocean model (BNAM) projections under a high emission scenario (RCP 8.5) for 2055 and published Catch Per Unit Effort (CPUE) relative to the Upper Stock Reference (USR) value, to rate stock heath. The second model, 'Lobster Harvesting', encompassed vulnerability of harvesters, harvesting activity and fishing infrastructure. Metrics for *Exposure* included, lost fishing days due to bad weather and trend perception of lost fishing days. Metrics for *Sensitivity* included fishing infrastructure, fishery management flexibility, financial resilience; and *Adaptive Capacity* metrics included fisheries flexibility, personal flexibility, and perception of climate risk. Data for most metrices in the 'Lobster Harvesting' model were collected through face-to-face interviews with 289 lobster harvesters licenced to fish in Nova Scotia waters. There were insufficient responses from LFA 25, 28, and 35 so these were not assessed within the 'Lobster Harvesting' model. Both models were combined to estimate the climate change vulnerability of the provincial lobster fishery.

Under the 'Lobster Vulnerability' model, projected average bottom and surface temperatures during the warmest 2055 month remained within optimal temperature thresholds, except for LFA 25 and LFA 26A, where juveniles could be exposed to sub-optimal temperatures. Stock status of all LFAs was considered healthy, with CPUE of many LFAs more than twice the USR. This resulted in low and moderately low vulnerability of lobster in LFAs around the province.

Under the 'Lobster Harvesting' model, lost fishing days due to bad weather was greatest in southern LFAs 34 and 33 with almost a 3^{rd} of eligible fishing days lost and a perception that this trend was increasing. LFAs in northeast Cape Breton and 26A in the Northumberland Strait had less than 10% lost days. This resulted in a wide range of *Exposure* scores across the province. *Sensitivity* and *Adaptive Capacity* indices were less diverse. While there were some priority areas for wharf repair in the southwest and parts of Cape Breton, lobster harvesting *Sensitivity* metrics exhibited either moderate or moderately high vulnerability across LFAs. Likewise, *Adaptive Capacity* metrics indicated moderate vulnerability across the province except for LFA 34 which had moderately high vulnerability. While there were some general metric trends, there was also extensive variation of responses between lobster harvesters within individual LFAs.

The overall climate change vulnerability assessment of the lobster fishery indicated moderately low vulnerability in LFAs across the province except 26A, 33, and 34 which had moderate vulnerability. The cumulative outcome suggests that the provincial lobster fishery is not at high risk. Nevertheless, moderately low and moderate vulnerabilities do not mean there is no vulnerability nor an absence of risk. Fortunately, there are actions that can support improvements to *Adaptive Capacity* and reduce *Sensitivity*.

The limited difference of many metrics across LFAs suggests that initiatives to improve the *Adaptive Capacity* of the lobster fishery could be applied province-wide, with a few exceptions. However, LFA specific recommendations are made herein, as a function of a metric or specific index vulnerability. While the province and the lobster fishing industry are currently involved in several initiatives to track and adapt to climate change, rapidly evolving research, climate change velocity, technological developments, and requirements for flexible management suggest ongoing needs for attention and action. This empathises 'having a seat at the table' at interest holder meetings and with organizations that oversee lobster and climate change aspects. This will also help to better track risk around issues being exacerbated by climate change (e.g., marine mammal entanglement, changing bait sources, damage from extreme events, economic drivers, vulnerability of First Nations lobster fishing, and regional specific change). Other recommendations include, exploring opportunities to develop and test clean marine propulsion for lobster vessels, determining climate proofing needs for industry marine infrastructure, and investing in alternative bait development. Finally, climate change vulnerability assessments and research on changing marine environments are rapidly evolving. An update of this assessment would benefit from revisiting in 5 years.

2 Introduction

2.1 Climate change

Atmospheric greenhouse gas concentrations are the highest they have been for the past 800,000 years, due to the burning of fossil fuels and other human activities (IPCC, 2021). The Intergovernmental Panel on Climate Change (IPCC), the official climate science body of the United Nations (UN), is 95% certain that these greenhouse gas emissions are responsible for our changing climate (IPCC, 2014). Similarly, atmospheric concentrations of carbon dioxide (CO_2) are the highest they have been for at least two million years and are responsible for ongoing ocean acidification (IPCC, 2021). Overall, the IPCC considers the manifestation of human driven climate change as 'unequivocal' and that these changes have already impacted human and natural systems (IPCC, 2013). Due to the potential for climate change to impact almost every aspect of humanity, anticipating and planning for climate change is widely considered to be the greatest challenge of our time (Carlin, 2020; The United Nations Refugee Agency, 2020; European Environment Agency, 2021; United Nations, 2021).

In Canada, air temperatures are increasing across the country, while sea level rise[1], ocean acidification[2], and ocean warming[3] are all occurring faster in Nova Scotia than elsewhere in Canada or the global average (Environment and Climate Change Canada, 2019). These changes are already impacting Nova Scotia's fishing industry (e.g., by altering species distribution and timing of key life stages of commercially important species) and coastal communities (e.g., by increasing coastal erosion and flooding). These effects are detailed in Howarth et al., (2021), 'Assessing climate change vulnerability of seafood industry-dependent communities in Nova Scotia'. Determining which fisheries and fishing communities are the most susceptible to climate change impacts is pragmatic, as it can enable decision-makers to focus adaption efforts on those sectors and communities identified to be the most at risk (Adger, 2006; IPCC, 2014; Krishnan et al., 2019). This was explored for provincial fisheries in the report, 'A rapid climate change vulnerability assessment of Nova Scotia fisheries and fishing communities' (Reid et al., 2022). A recommendation from the report, was to investigate climate change vulnerability specific to the Nova Scotia lobster fishery.

2.2 Climate change vulnerability assessments

Vulnerability is defined by the IPCC (2014) as a susceptibility to harm which can be utilized to identify actionable mitigation to support an industry that may be affected by climate change. Climate change vulnerability assessments are common management tools that aim to reduce and address challenges associated with assessing an industry's risk (Füssel and Klein, 2006; Soares et al., 2012; Thomas et al., 2019; Dudley et al., 2021). These assessments can be complex, since they require a diverse range of data inputs (i.e., oceanographic, ecological, fisheries, and socio-economic) with different spatial and temporal domains, and resolution. Given extensive data diversity, assessing vulnerability must often combine quantitative data such as biophysical and economic value, with qualitative data such as interviews and expert opinion (e.g. Soto et al., 2018; Bukvic et al., 2020; Dudley et al., 2021). This complexity must ultimately produce manageable outputs to support management recommendations that are easily communicated to decision makers and interest holders.

Climatic change vulnerability assessments are typically based on three indices: '*Exposure*', '*Sensitivity*', and '*Adaptive Capacity*' (Islam et al., 2019; Krishnan et al., 2019; Soto et al., 2019; Kling et al., 2020; Mafi-Gholami et al., 2020). *Exposure* quantifies the magnitude and frequency of climate change stressors that are occurring or predicted to occur at a defined area or scale (Adger, 2006; Hunter et al., 2015). Examples of *Exposure* metrics in the ocean include warming, acidification, sea-level rise, and changes in primary productivity. Other examples can be weather related, such as hurricanes and surge-driven flooding. *Sensitivity* can reflect social and economic factors that influence how a system (i.e., the lobster fishery) can be affected by climate driven events (Sarkodie and Strezov, 2019). Examples of *Sensitivity* metrics may include structural integrity of fishing infrastructure, financial resiliency, resource vulnerability, and the ability of regulator's management flexibility. Although, *Sensitivity* can also be applied at an individual species level (Section 2.4, Table 1). *Adaptive Capacity* measures how much a system (i.e., the lobster fishery) can respond to climate change effects on a long-term basis (Smit and Wandel, 2006; IPCC, 2014).

[1] Sea level uplift rate is projected at approximate 130 cm by 2100 at Halifax under RCP 8.5. Other modelled locations of Vancouver, BC; Nain, NL; and La Grande, QC had projections of 100 cm, 50 cm, and -50 cm, respectively (James et al., 2014; Zhai et al., 2014; Atkinson et al., 2016).

[2] Due to high inputs of freshwater, ocean acidification is occurring faster on the Scotian Shelf and Gulf of St. Lawrence than the global average (Gledhill et al., 2015).

[3] Temperatures in the Northwest Atlantic have increased over the last four decades and are warming faster than the global average (Wu et al., 2012; Forsyth et al., 2015). The Gulf of Maine has warmed by 0.03 °C per decade since 1982, faster than 99 % of the world's oceans (Pershing et al., 2015).

This could include the ability for harvesters to have flexibility, such as switching fisheries or completely changing careers and the perception of risks. As with *Sensitivity*, *Adaptive Capacity* can also be applied at the species level (Section 2.4, Table 1).

2.3 Nova Scotia's lobster fishing industry

Nova Scotia is Canada's number one exporter of seafood, with American lobster (*Homarus americanus*) being the most economically important fishery valued at over $1 billion in 2021 (Figure 1) (Government of Canada, 2022), representing 63% of the province's total fisheries value (Fisheries and Oceans Canada, 2022a). Lobster landings in Nova Scotia have steadily increased, except during the COVID-19 pandemic-induced market collapse in 2020 and 2021 (Mercer, 2020; Withers, 2021a; Fagan, 2022). Lobster is landed throughout the province, with Shelburne and Yarmouth counties landing approximately 50% of all lobster caught.

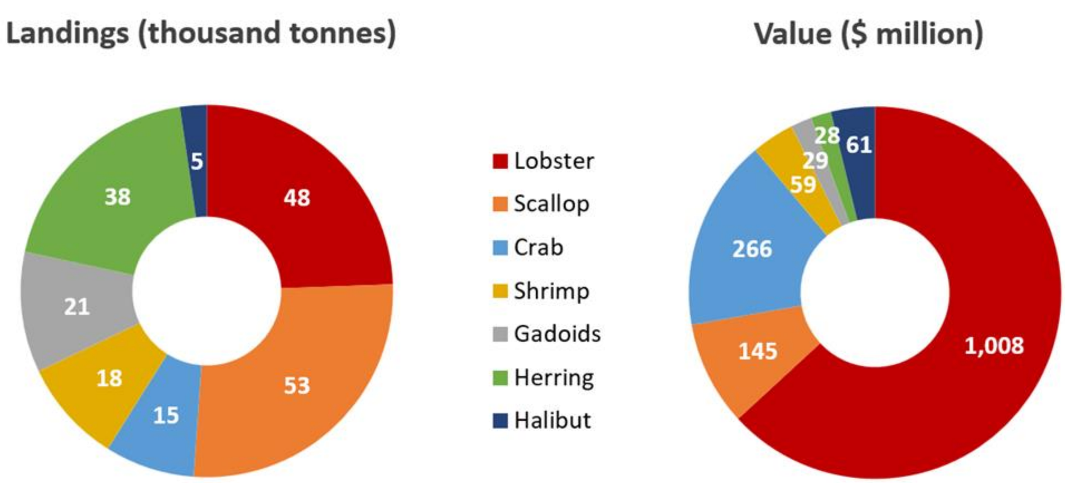

Figure 1 | 2021 seafood landings weight (thousand tonnes) and value for species (million dollars) fished in Nova Scotia (Government of Canada, 2022).

The fishery in Atlantic Canadian waters is managed spatially by Lobster Fishing Area (LFA; Figure 2), to dictate trap limits, fishing seasons, and number of licenses. LFA's may be further subdivided into irregular statistical grids for which harvesters report their landings. In Nova Scotia, LFAs 25 – 35 represent the inshore Nova Scotian lobster fleet with fishing occurring no greater than 90 km from shore while the offshore lobster fleet[4] (LFA 41) fishes beyond these distances. Lobster fishing licenses are issued by Fisheries and Oceans Canada (DFO) and are subject to expiry. The inshore lobster fishery is managed by a finite number of licenses which has remained consistent the past 18 years (D. Eberhard and M. Richard, Fisheries and Oceans Canada, pers. comm. 2022), with the greatest number of licenses represented by LFAs 33 and 34.

[4] There are only 8 offshore lobster licences (Cook et al., 2020a).

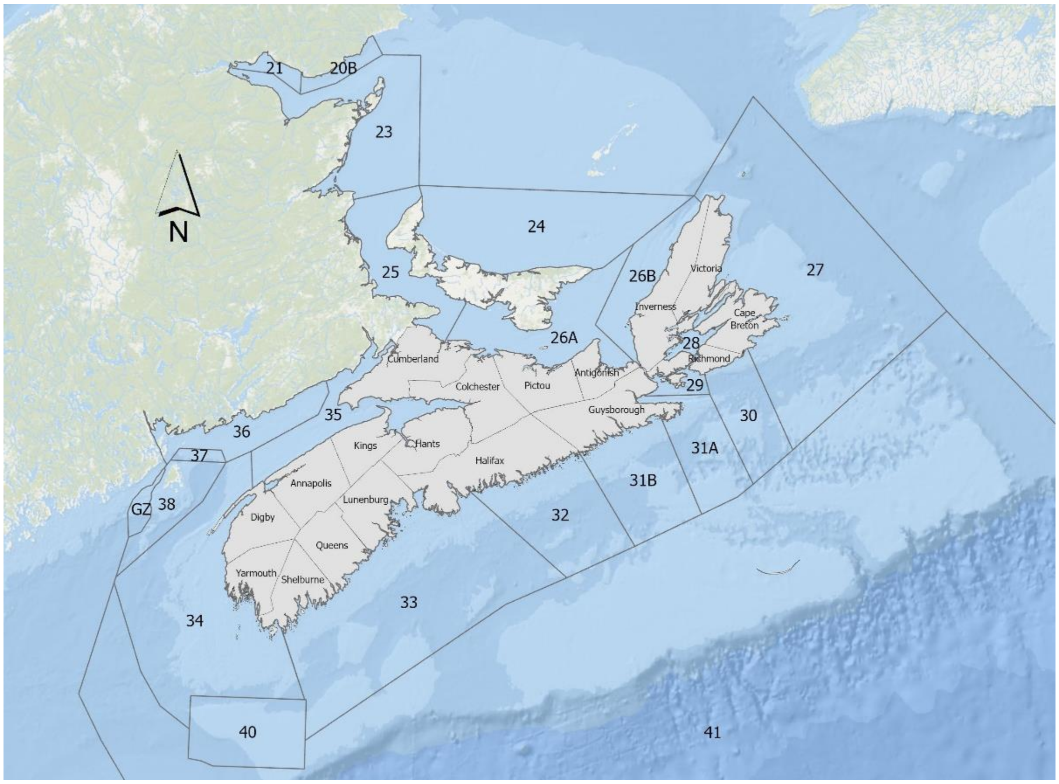

Figure 2 | Lobster Fishing Areas (LFA) around Nova Scotia

While Nova Scotia's lobster fishery has benefited from increased landings within the last decade (~22% since 2011), many threats exist that could endanger the long-term sustainability of this industry. Climate change is one of these threats and research is needed to better understand the vulnerability of the major commercial fishery in Nova Scotia.

2.4 Assessing climate exposure of lobster and lobster fishing

Research on current and anticipated climate change exposure of lobster around Nova Scotia and the surrounding region, has been largely explored as a function of temperature influence, physical habitat availability within changing ranges, water chemistry (e.g., ocean acidification), and trophic changes (e.g., predators, food availability). However, temperature has been the primary driver to assess lobster vulnerability.

At various life stages lobster can be exposed to very different environmental conditions and have different tolerances to temperature. Quinn (2017) reviewed studies investigating the effects of temperature on American lobster, with applicable findings summarized here. Lobster larvae are considered to have greater tolerance to higher temperatures (compared to benthic phases) given they largely inhabit the water column which is frequently warmer than bottom water. Temperatures above 18 – 20 °C are considered sub-optimal for lobster larval growth, with the first signs of stress (e.g., inactivity, irregular movements, elevated heartbeat, and temporary stoppage of the heart) in stage I, III, and IV larvae occurring between 26.0 – 33.8 ◦C and then intensifying at 28 – 34.0 ◦C (Huntsman, 1924). The benthic stages of the American lobster are considered to perform poorly at temperatures ≥ 20 ◦C with lethal temperatures for juveniles after <1 h exposure, between 27 – 35.5 ◦C, while longer-term (120 d) rearing at 24.3 ◦C resulted in lower juvenile survival than at 20.3 ◦C. Lethal upper temperatures of adult lobsters after < 1 h exposure range from 28 to 32 ◦C, while temperatures lethal to ≥ 50 % of adult lobsters (LD50) following 48 h exposure were those ≥ 25.7 – 28.4◦C. Unpublished research by CMAR suggests that adult lobster have an upper temperature threshold of 25.7 – 29.6 ◦C depending on acclimation temperature. See Appendix A; Table 1 for details on literature reported ranges.

One of the first explorations of thermal habitat index for lobster under projected temperature change was pursued by Shackell et al. (2014). A correlative species distribution model was developed by analyzing 41+ years of vessel survey data to estimate changes in 'realized thermal habitat' for 46 North Atlantic species, including American lobster. Under projected temperature changes, lobster in Canadian waters were considered 'winners', with an estimated approximate 20 % gain of realized thermal habitat in 2030 and 110 % in 2060. Utilizing the same spatial temperature projections as Shackell et al. (2014), Stortini et al. (2015) applied a semi-quantitative climate change vulnerability assessment tool which considered warming as the exposure component (Stortini et al., 2015). This was combined with sensitivity metrics (i.e., range, population status, food specificity, habitat specificity, reliance, larval dispersal, and adult mobility) to evaluate the vulnerability of 33 fish and invertebrate species. Lobster in Canadian waters did not have a high vulnerability score, under the mild (+ 0.7 °C) or severe (+ 3 °C) warming scenario.

To evaluate climate risk to marine life, Boyce et al (2022a; 2022b) developed a climate risk index for biodiversity (CRIB) and operationalized it as a unified and spatially explicit index, describing the state of 2,000 species across three ecosystems, including 90 fish stocks in the northwest Atlantic Ocean. The vulnerability component was partitioned into the standard three indices (*Exposure*, *Sensitivity*, and *Adaptive Capacity*) with respective metrics as detailed in Table 1.

Table 1 | Vulnerability indices for marine species (Boyce et al., 2022a)

Exposure	**Sensitivity**	**Adaptive Capacity**
Projected climate velocity	Thermal safety margin	Vertical habitat variability and use
Projected ecosystem disruption	Conservation status	Geographic habitat fragmentation
Projected time of climate emergence from species' thermal niche	Cumulative human impacts	Maximum body length
Projected loss of suitable thermal habitat	Vertical habitat variability and use	Thermal habitat variability and use

On the 2100 horizon under the SSP5-8.5[5] high emissions scenario, LFAs 23-26AB (includes the Northumberland Strait) and LFAs 27-33 (north and east Cape Breton, connecting with the wider Atlantic coast of Nova Scotia) were estimated to have high average vulnerability at ~0.49 and ~0.45 out of 0.90, respectively. LFA 35 in the upper Bay of Fundy and LFA 33 off the southwest shore were estimated to have moderate average vulnerability at ~0.43 and ~0.42 and out of 0.90, respectively.

[5] SSP stands for shared socio-economic pathways and embodies the high emission scenario RCP 8.5 (IPCC, 2023)

Le Bris et al. (2018) estimated Gulf of Maine lobster abundance under RCP[6] 8.5 sea surface temperature (SST) projections for 2050. Graphical results suggest a 2050 decrease in lobster abundance similar to regional population levels of the early 2000s; a reduction of roughly 40% from a peak abundance period (~ 2010–2015). Hindcast simulations demonstrated that the removal of large predators, increase in smaller predators, and increased prevalence of shell disease all had effects on lobster populations, although the primary driver was still temperature. Nevertheless, improved conservation measures such as efforts to preserve the stock's reproductive potential, could dampen the negative impacts of warming. A relative recruitment index was also calculated, applying a Ricker model to estimate recruit numbers from total egg production, then extending the model with a temperature term to consider thermal optima (16.4 °C) for lobster settlement. The spatial domain of the recruitment index model ranged from southern New England to north of Cape Breton. Graphical data suggests 2050 recruitment will increase slightly to > 0.75 in the Bay of Fundy LFAs and most of LFA 34, compared to 2010-2015. Estimated 2050 recruitment in the LFA 33 area with the approximate shore-side half of the LFA will remain > 0.75, but there is an apparent recruitment reduction on the outer half of the LFA to between 0.50 and 0.75. LFAs in the Northumberland Strait and west Cape Breton area appear to have decreased estimates of between 0.25 and 0.50. Recruitment estimates in the remaining LFAs were estimated to reduce from > 0.75, compared to 2010-2015, to between 0.75 and 0.50 in 2050.

Greenan et al. (2019) assessed the vulnerability of Atlantic Canada lobster fishing communities, by combining a coastal infrastructure vulnerability index (climate change exposure, harbour infrastructure status, and socio-economic criteria) with a lobster vulnerability index (exposure and stock status). The lobster exposure sub-index was estimated from loss or gain of offshore thermal habitat, while the stock status sub-index was derived from offshore suitable habitat, occupancy, abundance, and early life stage food availability. BIO North Atlantic Model (BNAM) and coupled model (CM) 2.6 ocean models projected temperatures changes of surface and bottom temperatures for 2055 RCP scenarios[7], 4.5 and 8.5. By mid-century, both future climate model scenarios project a general increase and expansion of lobster thermal habitat suitability, although, the suitability trend was more pronounced under the CM2.6 projections. For Nova Scotia, habitat suitability was calculated for bordering LFAs 35, 34, 33, and offshore LFAs 40 and 41. Of these, graphical data suggested that LFAs 33, 34, 40, and 41 were estimated to increase median suitable habitat in 2055 by approximately, 65%, 5%, 5%, and 20%, respectively, under the BNAM model. LFA 35 was estimated to decrease a few precent. Under the CM2.6 model LFAs, 33, 34, 40 and 41 were expected to increase median suitable habitat by approximately 150%, 10%, 15% and 27%, respectively, with LFA 35 projected to decrease by a few percent.

Tai et al. (2021) modelled the combined effects of ocean warming, acidification, fishing pressure and fishing size limit on lobster survival and lobster catch rates for 2091-2100 under an RCP 2.6[(8)] and RCP 8.5 emissions scenario. Graphical data of simulated temperature effects (accounting for oxygen and primary productivity in absence of acidification) suggested that by the end of the century, catch potential will be reduced around much of Nova Scotia by approximately 50 %, with the exception of the Northumberland Strait to west Cape Breton area, where an increase of approximately 50 % could occur. Simulations applying laboratory-determined pH thresholds, suggested ocean acidification will have limited impact on lobster abundance. Graphical results of an RCP 8.5 warming simulation combined with a doubling of hydrogen ions, suggested increased acidification would cause a minor reduction of maximum catch potential of ~ 2 % around Nova Scotia. The study concluded that while reduced fishing pressure can

[6] Relative Concentration Pathway.

[7] RCP 4.5 is considered the moderately low-emissions, scenario, and RCP 8.5 is considered the high emission scenario.

[8] Lowest emissions scenario.

improve the population to some extent, the magnitude of increased effects of climate change overweighs any population gains made by reduced fishing pressure over this period.

2.5 Scale, projections, and emission scenarios

Methods to account for changes in environmental metrics typically compare a reference period (recent past or present day) to future condition. Projections have been commonly developed for 2030 (Shackell et al., 2014; Stortini et al., 2015), 2050-2060 (Shackell et al., 2014; Stortini et al., 2015; Le Bris et al., 2018; Greenan et al., 2019), 2055 (Greenan et al., 2019), and end of century (Tai et al., 2021; Boyce et al., 2022a; Boyce et al., 2022b).

Climate change assessments on American lobster have been applied at a variety of marine spatial scales. As a number of these initiatives aimed to assess multiple marine species, spatial scales were a function of many considerations and not intended specifically to reflect lobster. Spatial scales in these studies have been applied to lobster at wide regional scale (Shackell et al., 2014) or at NAFO[9] division scales where the assessment covered multiple LFAs (Stortini et al., 2015; Boyce et al., 2022a). Lobster specific assessments that have occurred at higher resolution, have been applied at the LFA scale (Greenan et al., 2019), 0.5° x 0.5° cells (55.66 km x 55.66 km or 3,098 km^2) (Le Bris et al., 2018), and at 0.25° x 0.25° cells[10] (Tai et al., 2021).

Most assessments applied the maximum emission scenario of RCP 8.5 (Le Bris et al., 2018; Tai et al., 2021; Boyce et al., 2022a), which is also embodied within SSP5-8.5 (Boyce et al., 2022a; IPCC, 2022b). Several assessments applied a high mitigation scenario of RCP 2.6 (Tai et al., 2021), also represented within SSP1-2.6 (Boyce et al., 2022a), for comparison purposes. In some instances, temperature change projections in the marine system were not tied to a specific carbon emission scenario, but based on regional extrapolation of warming trend data (Shackell et al., 2014) or exploring outcomes tied to a specific temperature increase (Stortini et al., 2015).

2.6 Objectives

This report aims to conduct a detailed climate change vulnerability assessment of the Nova Scotia lobster industry, within a regional context of lobster fishing areas. The project objectives include:

1. Inform decision makers and stakeholders which LFAs are at greater relative risk to climate change;
2. Provide directional / actionable steps for the lobster industry;
3. Identify knowledge gaps and help guide future research; and
4. Facilitate decision maker and stakeholder adaptation to climate change, by providing information to support action planning, steps, or investment opportunities.

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[9] Northwest Atlantic Fisheries Organization.

[10] That is 27.83 km x 27.83 km or 775 km^2.

3 Methods

3.1 Model approach

This climate change vulnerability assessment of the Nova Scotia lobster fishery combined two vulnerability models, a 'vulnerability of lobster' model and 'vulnerability of lobster harvesting' model (Figure 4). We define 'lobster vulnerability' as vulnerability of lobster as a species, 'vulnerability of lobster harvesting' as vulnerability of harvesters, harvesting activity and fishing infrastructure, with 'vulnerability of the lobster fishery' as a combination of the two models.

Vulnerability model structure is consistent with holistic climate change vulnerability assessments where overall vulnerability is typically partitioned into three indices. These are, *Exposure*, *Sensitivity*, and *Adaptive Capacity* indices (Section 2.2), with each index comprised of individual metrics. If two data sources provided similar information these were considered sub-metrics and averaged to create a single metric. Vulnerability for individual models was calculated by averaging indices. Some vulnerability assessments subtract *Adaptive Capacity* from the combined *Exposure* and *Sensitivity* indices however, since this model ranks the metric scores according to vulnerability severity, this allows for the three primary indices to be combined directly.

Metrics for both models were selected based on the most relevant available data, with an aim to minimize the total number of metrics, to avoid diminishing returns of individual metrics. Incorporating many metrics can reduce the relative contribution of each metric to overall outcomes and this may necessitate a metric weighting system. A weighting system can further reduce the contribution of less important metrics to the extent that they have little influence on model outcomes and consequently, may be difficult to justify inclusion. Consequently, this study aimed to include a modest amount of key metrics, to avoid inclusion of data that may not discernably change model outputs, in accordance with good 'model parsimony' practices (Gori, 2018).

All metric and sub-metric values in this assessment were scored from 1 to 5, where high values were associated with increased climate change vulnerability and low values consistent with reduced vulnerabilities (Table 2). This approach enabled different types of data to be combined to obtain scores (normalizing) for *Exposure*, *Sensitivity*, and *Adaptive Capacity* indices, and overall lobster fishery vulnerability. Vulnerability scores were rounded up for mapping.

Table 2 | Metrics and sub-metric scoring system

Ranking	Index / Metric Score	Vulnerability
1	0.00 – 1.00	Low
2	1.01 – 2.00	Low-Moderate
3	2.01 – 3.00	Moderate Moderate-High
4	3.01 – 4.00	High
5	4.01 – 5.00	Very High

3.2 Vulnerability of lobster

Lobster vulnerability was estimated by averaging an *Exposure* index with a *Stock status* index. *Stock status* was considered to be representative of the species *Sensitivity* and *Adaptive Capacity,* which is a common partitioning approach for assessing vulnerability at a species level (e.g. Stortini et al., 2015), including lobster (Greenan et al., 2019). Given limitations of fishery-independent lobster ecosystem data for most inshore Nova Scotia LFA areas (Section 5.4.5) and extensive multispecies data requirements needed to apply state-of-the-art species vulnerability assessments[11] (Boyce et al., 2022a; Boyce et al., 2022b) at an LFA scale, a more suitable parsimonious approach was needed to estimate lobster vulnerability within the study scope. Consequently, a simplified variant of the lobster vulnerability index by Greenan et al. (2019) was applied, where BIO North Atlantic Model (BNAM) temperature projections were compared with lobster temperature thresholds and data from DFO lobster stock assessments were combined to estimate lobster vulnerability at the LFA level.

3.2.1 Exposure

Sea surface temperature (SST) and bottom temperature projections from the BNAM ocean model by Brickman et al (2016) were used to plot 2055 September temperature projections (as the warmest month) around Nova Scotia. Only an RCP 8.5 high emissions scenario projection was chosen, given this is unfortunately the most likely emissions scenario as greenhouse gas emissions are still increasing (IPCC, 2023). A near-term timeline of the coming three decades was chosen (as opposed to 2075 or end of century projections) due to greater applicability to present day decision making and available data. BNAM projection data was converted from its native MATLAB format to CSV files for analysis in R and plotting in ArcGIS. The 2055 RCP 8.5 projected relative temperature change was added to present condition values to estimate 2055 temperatures. LFA boundaries were overlaid, temperature data was partitioned out per LFA and descriptive statistical values (e.g., mean, median, and variation) were calculated for projected bottom and sea surface temperature (SST) data within each LFA boundary (Section 4.1.1).

To assess potential lobster response to projected LFA temperatures, a table was developed detailing literature reported optimal, sub-optimal, stressful, and lethal temperature ranges for different lobster life stages (Appendix A; Table 1). This data was simplified to assign temperature ranges to vulnerabilities with the upper score of 5 as the lethal range (Table 3). Scores were assigned to LFAs where mean or median projected SST temperature values exceeded upper larval thresholds, or projected 2055 bottom temperature exceeded upper juvenile or adult thresholds during the warmest month, September.

Table 3 | Lobster upper temperature (°C) thresholds. Columns denote assigned vulnerability scores**.**

	Vulnerability score				
	1	2	3	4	5
Life stage	**Temperature (°C) range**				
Larvae	< 20	20.0 – 23.0	23.1 – 25.0	25.1 – 28.0	> 28.0
Juveniles	< 16	16.1 – 20.0	20.1 – 23.0	23.1 – 25.0	≥ 26.0
Adults	< 15	15.1 – 18.0	18.1 – 19.0	19.1 – 27.0	≥ 28.0

[11] The Ecosystem Disruption index of the CRIB approach requires the proportion of all species in the ecosystem that are projected to exceed their thermal tolerances at the scale of interest.

3.2.2 Stock status

DFO fisheries stock assessments apply the precautionary approach to fisheries management decisions where harvest strategies consider healthy, cautious, and critical stock status zones. The Upper Stock Reference (USR) value marks the boundary between the healthy and cautious zones and the lower reference point the threshold between critical and cautious (DFO, 2006). Scoring in this study was assigned as a function of the three-year running catch per unit effort (CPUE) median (Maritimes Regions) or suitable proxy (Gulf Region), relative to stock status reference points, with vulnerability ratings partitioned into 5 bins as detailed in Table 4.

Table 4 | Vulnerability rating for stock status as dictated by catch per unit effort (CPUE). LSR is the limit reference point and USR the upper stock reference.

CPUE	Classification under the fisheries management precautionary approach*	Vulnerability
< LRP	Critical zone	5
> LRP and < 0.50 USR	Cautious zone	4
0.50 USR < and > 0.75 USR	Cautious zone	3
> USR	Healthy zone	2
> USR x factor	Healthy zone	1

*Fisheries management precautionary approach is described in DFO (2006) and Cook et al. (2020a)

CPUE relative to stock reference points is commonly used as a primary indicator to assess lobster stock status in the DFO Maritimes Region (e.g. DFO, 2020a; DFO, 2023a). While standardized CPUE is preferred over simple fishery-reported CPUE to account for effects of fishing behaviour, localized depletion and environmental conditions (DFO, 2023b), the generalized linear model inputs[12] required for standardization are only available for a handful of LFAs such as Nova Scotia's LFA 35 and New Brunswick's LFAs 36 and 38 (Fisheries and Oceans Canada, 2022d; DFO, 2023b). In some instances, CPUE is considered a secondary indicator, with commercial biomass as a primary indicator where fishery independent surveys occur, such as LFAs 34 and 41 (Fisheries and Oceans Canada, 2021a; Fisheries and Oceans Canada, 2022e). However, given that standardized CPUE and fishery independent survey data is not available for most Nova Scotia LFAs, this leaves fishery-dependant CPUE as the most consistently available primary indicator to compare Maritimes Region LFAs. CPUE data was provided by DFO Commercial Data, Policy & Economics group and information from DFO stock assessment reports were used to assess lobster stock status at the LFA level (Table 4).

There are differences in data availability and application of stock status indicators for southern Gulf of St Lawrence LFAs. Lobster stock status indicators are fishing pressure (e.g., proportion of empty traps and nominal effort) and abundance, with landings considered an abundance proxy (DFO, 2016). Currently, the Upper Stock Reference (USR) is applied to the entire region as a landings (MT) threshold, not as a CPUE threshold at the individual LFA level (DFO, 2019b). While there are recent landings data from Gulf Region LFAs, CPUE data for individual LFAs is only available up to 2017 or 2018 depending on the LFA sub-region (DFO, 2019b). Consequently, a modified approach was required to estimate present day stock status vulnerability scores. The most recent DFO stock health classification for Southern Gulf-wide landings

[12] Generalized linear modelling with explanatory variables of Year, Day of Season, Temperature, and the interaction between Day of Season and Temperature.

(2017/2018) relative to the USR, was scored as detailed in Table 4. To establish the relationship of individual LFAs relative to stock performance of the wider southern Gulf during this time period, CPUE and landings data were examined to infer if stock status was consistent with the wider southern Gulf. Ongoing trends of LFA landings since 2017 were then used to approximate current stock health and vulnerability. Where there was greater uncertainty, increased vulnerability was applied as consistent with the precautionary approach.

3.3 Vulnerability of lobster harvesting

The second model assessed climate change vulnerability of provincial lobster harvesting. This encompassed fishing activity, lobster harvesters themselves, and associated fishing infrastructure. This model considered poor weather resulting in lost fishing days and poor weather trend perception to reflect *Exposure*. The *Sensitivity* index included fishing infrastructure (wharf state), fishery management flexibility, and financial resilience of individual lobster harvesters. The *Adaptive Capacity* index considered personal fisheries flexibility and perception of risk. Organization of metrics and sub-metrics are detailed in Section 3.4.

3.3.1 Interview survey metrics

Data for all metrics except for Fishery Management metrics was collected through face-to-face interviews with lobster harvesters or survey forms. The interview survey was designed to obtain qualitative and quantitative data from active lobster harvesters around Nova Scotia. Interview protocols followed Tri-council ethical guidelines (Tri-Council, 2013). Interviewers visited wharves in LFAs 26A, 26B, 27, 29, 30, 31A, 31B, 32, 33, 34, and 35[13], as the 2022 lobster fishing seasons ended to ensure the presence of lobster harvesters but minimize interference with activities. Interviewers accessed wharves with permission of the Harbour Masters, operated in pairs and approached lobster harvesters that appeared available. If harvesters were interested but did not have the time, they were provided with a web address for the online survey they could complete later. At some wharves where the presence of harvesters was intermittent, a kiosk table was set up at the entrance to the wharf to advertise the survey for those interested (Figure 3). Interview questions are detailed in Table 5. Interview responses were partitioned on the Likert scale[14], unless otherwise indicated. While there were several interviews conducted in LFA 35, respondents fished out of other LFAs (such as nearby 34) and their responses were assigned to the LFAs they fished in. Consequently, LFA 35 was not assessed within this model.

[13] As there were no LFA 28 landings data available for privacy reasons (< 5 licenses), and there was only one data point from the BNAM model in the Bras d'Or lakes, there was insufficient data to include LFA 28 in the analyses. There were only 13 licenses from LFA 25 (which staddles New Brunswick and Nova Scotia waters), registered in Nova Scotia ports. Given this small number and an inability to differentiate landings or CPUE only to Nova Scotia harvesters, this LFA was not included in the analysis.

[14] i.e., Strongly disagree, disagree, neutral, agree, or strongly agree.

Figure 3 | Interview surveys with lobster harvesters. Direct approach (left panel) and interview kiosk (right panel).

The *Exposure* index was a function of two metrics, 'Fishing days lost due to bad weather' and perception of bad weather trends over the last 5 to 10 years (Appendix B). The total number of days lost due to bad weather was converted into a percentage of possible annual fishing days within each LFA to calculate a percentage. It was assumed that both metrics accounted for current climate change effects on regional weather, and as a simplifying assumption, that projected increases in extreme weather will occur proportionately across the province's fishing areas.

The 'Fishing Infrastructure' metric was comprised of the sub-metric, lobster harvesters' response to the statement, 'My key fishing wharves are in good repair', and a sub-metric as a survey, asking province Coastal Resource Coordinators (CRCs)[15] about the state of wharves in LFAs under their purview. CRC wharf survey questions cover condition, age, and specific structural issues if they exist (Appendix C; Table 4).

3.3.2 Fisheries management flexibliy

Inputs for the Fisheries Management Flexibility metric were separate from the survey. The fisheries management matrix (Table 6) and conservation measures sub-metrics (Table 7), were combined to create a Fishery Management Flexibility metric. Flexibility and the capacity for dynamic responses to climate-driven changes is widely acknowledged as a pragmatic adaptive strategy (Marshall et al., 2013a; Howarth et al., 2021). Thus, broader fisheries management flexibility has been advocated as a key mechanism to increase resiliency of fisheries under a changing climate (e.g. Stephenson et al., 2019a; Boyce et al., 2021; Woods et al., 2021). While fisheries management flexibility is largely a qualitative metric open to interpretation, spatial, seasonal, bycatch flexibility, and the maximum trap number were jointly considered as a means to formulate a robust scoring matrix (Table 6). Species conservation status is used to inform the *Sensitivity* index in species vulnerability assessments, as species with better conservation status demonstrate greater resiliency to anthropogenic threats (Boyce et al., 2022b). Management measures that improve conservation can therefore be considered to support improvements in conservation and vulnerability reduction. Carapace size, trap window size, and v-notching efforts for each

[15] Regional liaison staff of the Marine Division of the Nova Scotia Department of Fisheries and Aquaculture

LFA were used to develop a conservation measures matrix, where more stringent conservation measures were considered to be less vulnerable (Table 7).

Table 5 | Inputs for the climate change vulnerability of lobster harvesting model.

Category	Metric	Sub-metric	Questions / information
Adaptive Capacity	Fisheries flexibility	Willingness to adjust fishing season	How much do you agree with the following statements? Fishing seasons should be adjusted to account for ocean changes.
		Ability to switch fisheries	How much do you agree with the following statements? If lobster stocks decline, I could switch fisheries.
	Personal flexibility		How much do you agree with the following statements? If needed, I have other skills, experiences, or education which could help me change careers.
	Perception of risk	Perception of climate change	How much do you agree with the following statements? There is no evidence that climate change is occurring.
		Perception of climate change threat to fishery	How much do you agree with the following statements? I am concerned about the impacts of climate change on the lobster fishery.
Sensitivity	Fisheries Management Flexibility	Management flexibility	Matrix combining – Species mean probability, months in season, by-catch flexibility, max. number of traps.
		Conservation measures	Combines – Min legal carapace size, "Female lobster conservation" – Window size females/v-notch program
	Fishing Infrastructure Status	Harvester perception of wharf state	How much do you agree with the following statements? (My key fishing wharves are in good repair)
		CRC perception of wharf state	Major, minor, and no repair required - average scores
	Financial resiliency	Revenue proportion from lobster harvesting	What percentage (%) of your annual income comes from lobster fishing?
		Revenue loss needed to forgo fishing	By what percentage (%) would your fishing income have to decline before you would choose to stop lobster fishing?
Exposure	Fishing safety and extreme weather	Perceived trends in lost fishing days	How much do you agree with the following statements? Over the last five to ten years, I have noticed the number of fishing days lost to bad weather has increased.
		Percentage of season missed	On average, how many fishing days do you lose a year due to bad weather. Answer from survey compared with days in a season to estimate a percentage.
Supporting Information			What are the minimum and maximum distances that you fish from shore?
			What wave heights prevent you from fishing?
			What wind speeds prevent you from fishing?

Table 6 | The fisheries management matrix. Flexibility score was assigned to each fishery based on the average spatial, temporal, by-catch flexibility, and gear flexibility.

Score	*Species probability %	Temporal flexibility	By-catch flexibility	Trap limit
1	81 to 100 %	12 months (all year)	All by-catch can be retained	No trap limit
2	61 to 80 %	8 to 12 months	More than 3 by-catch species can be retained	351 – 400
3	41 to 60 %	5 to 8 months	2-3 by-catch species may be retained	301 – 350
4	21 to 40 %	3 to 5 months	1 by-catch species may be retained	251 – 300
5	0 to 20 %	< 3 months	All by-catch must be returned to the sea	< 250

* The % area within an LFA where lobster inhabit which informs spatial fishing flexibility. Data is from www.aquamaps.org, an online tool for course predictions of species occurrence.

Table 7 | The conservation scores for each lobster fishing area (LFA) based minimum carapace size and female lobster conservation programs.

Score	Minimum Carapace Size	Female Lobster Conservation
1	More than or equal to 84 mm	Both v-notching female lobster and female lobster window size restriction
2	81 – 83 mm	No v-notching of lobster, but there is a female window size restriction
3	78 – 80 mm	V-notching of female lobster and mandatory v-notch program, no female window size restrictions
4	75 – 77 mm	Cannot retain v-notch lobster, no other restriction measures
5	Less than or equal to 74 mm	No v-notching of female lobster or carapace size restriction measures for female lobster

3.4 Vulnerability of the lobster fishery

Overall model structure and organization of metrics and sub-metrics within supporting models are detailed in Figure 4. Model vulnerability scores at the LFA level from the two supporting models, 'Vulnerability of lobster' and 'Vulnerability of lobster harvesting' were averaged to estimate climate change vulnerability of the Nova Scotia lobster fishery.

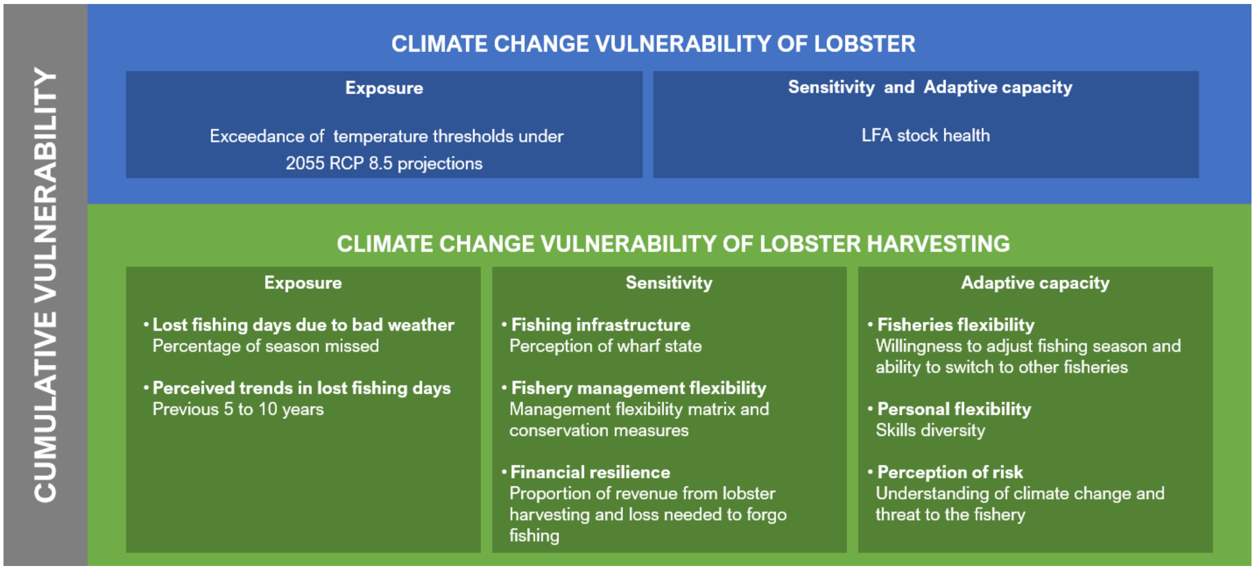


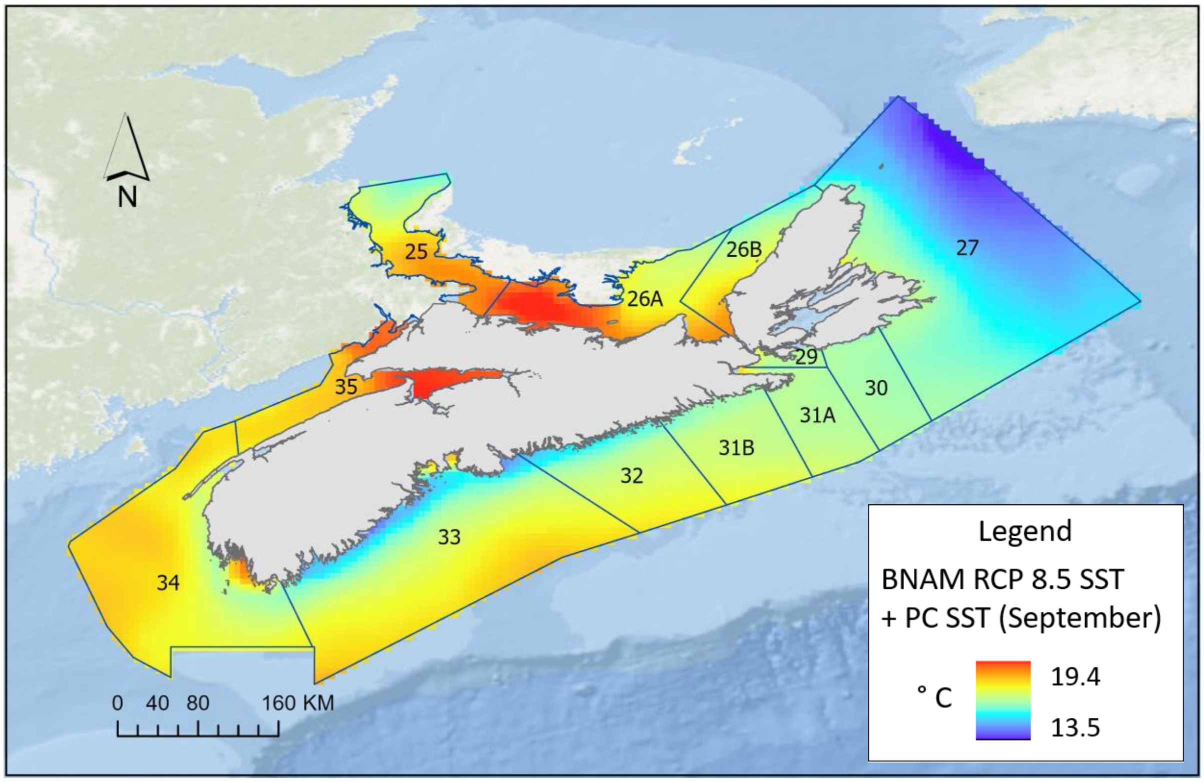
Figure 4 | Vulnerability of the Nova Scotia lobster fishery model structure. Metrics and sub-metrics are detailed under index columns.

4 Results

4.1 Lobster vulnerability model

4.1.1 Exposure

The *Exposure* index assessed whether mean or median LFA temperature of RCP 8.5 projections of 2055 bottom and surface temperatures in the warmest month (Figure 5, Table 6a/6b) transitioned beyond optimal temperatures for larval, juvenile and adult lobster. Despite projected increases, September temperatures remained within optimal ranges for most LFAs except LFA 25 and 26A, where juveniles and adults could be exposed to sub-optimal bottom temperatures. This resulted in most LFAs rated with low vulnerability score of 1 and LFAs 25 and 26A rated with moderately low exposure score of 2.



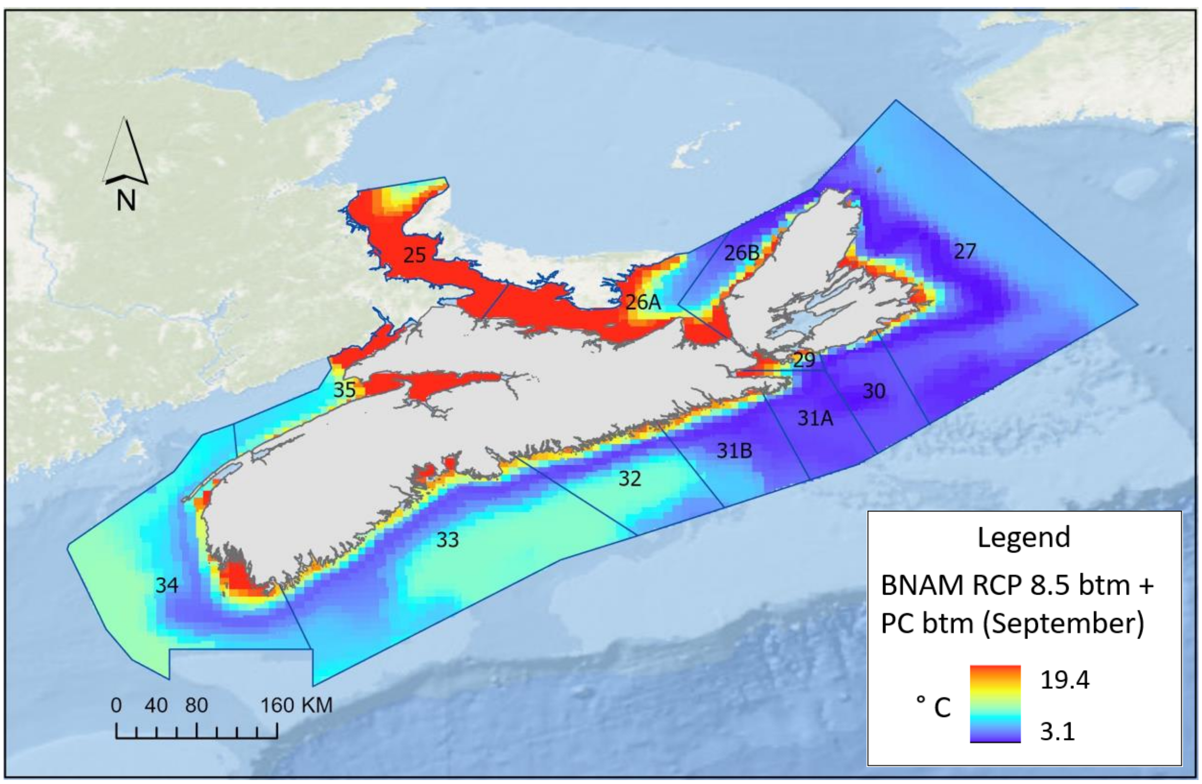


Figure 5 | BNAM September 2055 mean temperature projections for the sea surface (top) and bottom (bottom). Colour scales are different between maps. PC indicates present condition and btm indicates bottom temperature.

Table 5a | Descriptive statistics for spatial BNAM September 2055 bottom temperature projections.

LFA	Minimum	Maximum	Median	Average	St. dev.
25	7.9	19.1	17.9	16.9	2.4
26A	3.8	19.4	17.8	15.0	5.0
26B	3.3	18.6	5.7	7.9	4.9
27	3.2	17.6	5.4	5.5	2.2
29	3.5	17.3	13.4	11.6	5.1
30	3.2	15.3	4.1	4.1	1.2
31A	3.4	17.7	4.0	4.6	2.5
31B	3.5	16.5	4.6	6.0	3.1
32	3.7	16.3	8.1	7.8	2.6
33	3.9	18.7	7.5	7.7	2.3
34	4.5	19.1	8.1	8.3	2.8
35	7.0	19.3	12.0	13.3	5.3

Tables 6b | Descriptive statistics for spatial BNAM September 2055, sea surface temperature projections.

LFA	Minimum	Maximum	Median	Average	St. dev.
25	16.1	19.0	17.8	17.7	0.8
26A	16.3	19.4	18.2	18.1	0.8
26B	15.7	18.6	17.1	17.1	0.6
27	13.5	17.6	15.5	15.6	0.7
29	16.6	17.3	16.7	16.8	0.2
30	16.4	16.8	16.6	16.4	0.1
31A	16.6	17.8	16.7	16.8	0.1
31B	16.2	17.6	16.9	16.9	0.3
32	15.1	17.8	17.0	16.9	0.6
33	14.7	18.7	17.3	17.1	0.8
34	16.3	19.1	17.7	17.6	0.4
35	17.6	19.3	18.1	18.4	0.5

4.1.2 Stock status

Lobster landings for Nova Scotia bordering LFAs are shown in Figure 6. All Maritimes Region LFAs with available data from DFO or most recent published CPUE data were above the USR as a running median for the last three years of reported data (Figure 7). Stock status of most LFAs were well into the healthy zone, with CPUE more than twice the USR and were thus considered to have low vulnerability (score of 1). LFAs 33 and 34 stock status were also in the healthy zone, but not by a factor, so were considered to have moderately low vulnerability (score of 2).

Stock status of Gulf of St. Lawrence-bordering LFAs has been considered largely positive since 2012, with some variability (Rondeau et al., 2014; DFO, 2016). However, recent fishery-dependent CPUE data was unavailable for these LFAs. The most recent DFO Science Response reported that preliminary southern Gulf of St. Lawrence landings in 2017/2018 were three times the long-term median value over the period of 1947 to 2011 and represent the highest value in the time series with stocks considered healthy (DFO, 2019b). Graphical data from the report indicated that regional Gulf lobster landings were approximately twice the USR value or more the previous 3 years of reported data (up to 2017). Based on the DFO stock classification as healthy and given landings were greater than a factor above the USR, this suggests lobster in the southern Gulf of St. Lawrence region in 2017 could be classified as low vulnerability.

Examination of the most recent CPUE data at the LFA level within the southern Gulf, suggests that LFA 25 has either remained constant or increased slightly from 2012 to 2017 and likewise, with at least 2 of 3 sub-regions within 26A (Figure 8). LFA 26B CPUE data from 2015 onwards is absent, but the 2013 and 2014 CPUE values suggest it performed similarly to that of LFA 26A. Landings for LFA 25 and 26A have generally increased since the mid-2000s, and LFA 26B has had a marginal landings increase since 2012 (Figure 6). The general trends of these LFAs are consistent with the wider southern Gulf trend which suggests a healthy stock status[16] for 2017.

DFO supplied data shows increased landing trends in Gulf bordering LFAs have continued beyond 2017 (Figure 6) when southern Gulf-wide landings were already, approximately twice the USR value or more. This ongoing increase in landings for individual LFAs in 25 and LFA 26A beyond 2017 suggests these stocks remain healthy, vulnerability is not increasing, and consequently, a low vulnerability score of 1 is justifiable. Greater data uncertainty and marginal landings increase on LFA 26B suggest a score of 2 (moderately low vulnerability) is better suited, out of an abundance of caution.

[16] Stock status from 'Update of the stock status indicators of the American lobster, *Homarus americanus*, stock of the southern Gulf of St. Lawrence to 2018' (DFO, 2019a) was reported at the regional level, not for individual LFAs.

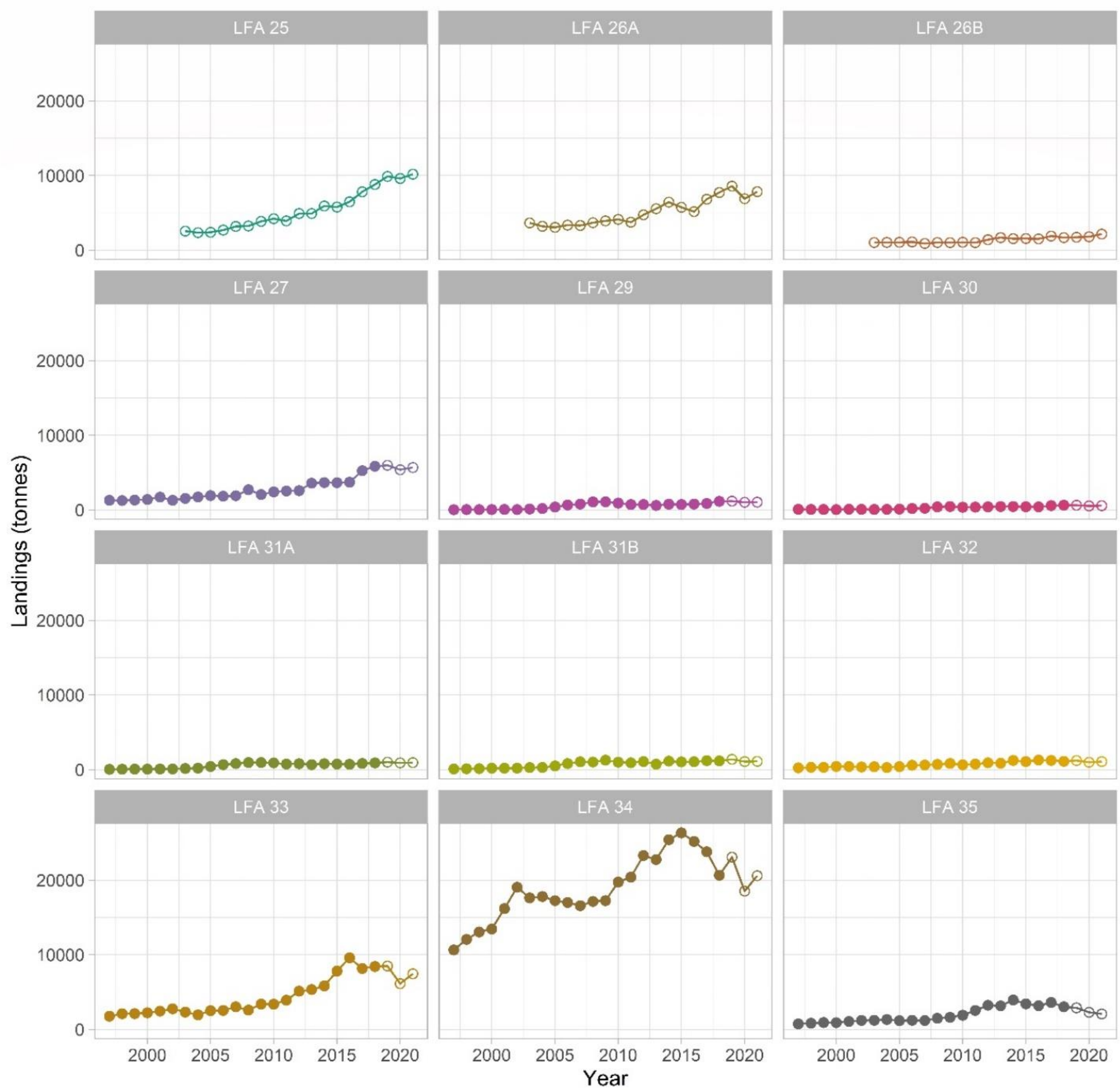


Figure 6 | Lobster landings in Nova Scotia bordering LFAs. Hollow circles are considered preliminary. Data was obtained through a DFO statistics request. LFA 28 data was unavailable due to privacy constraints with a small number of licences.

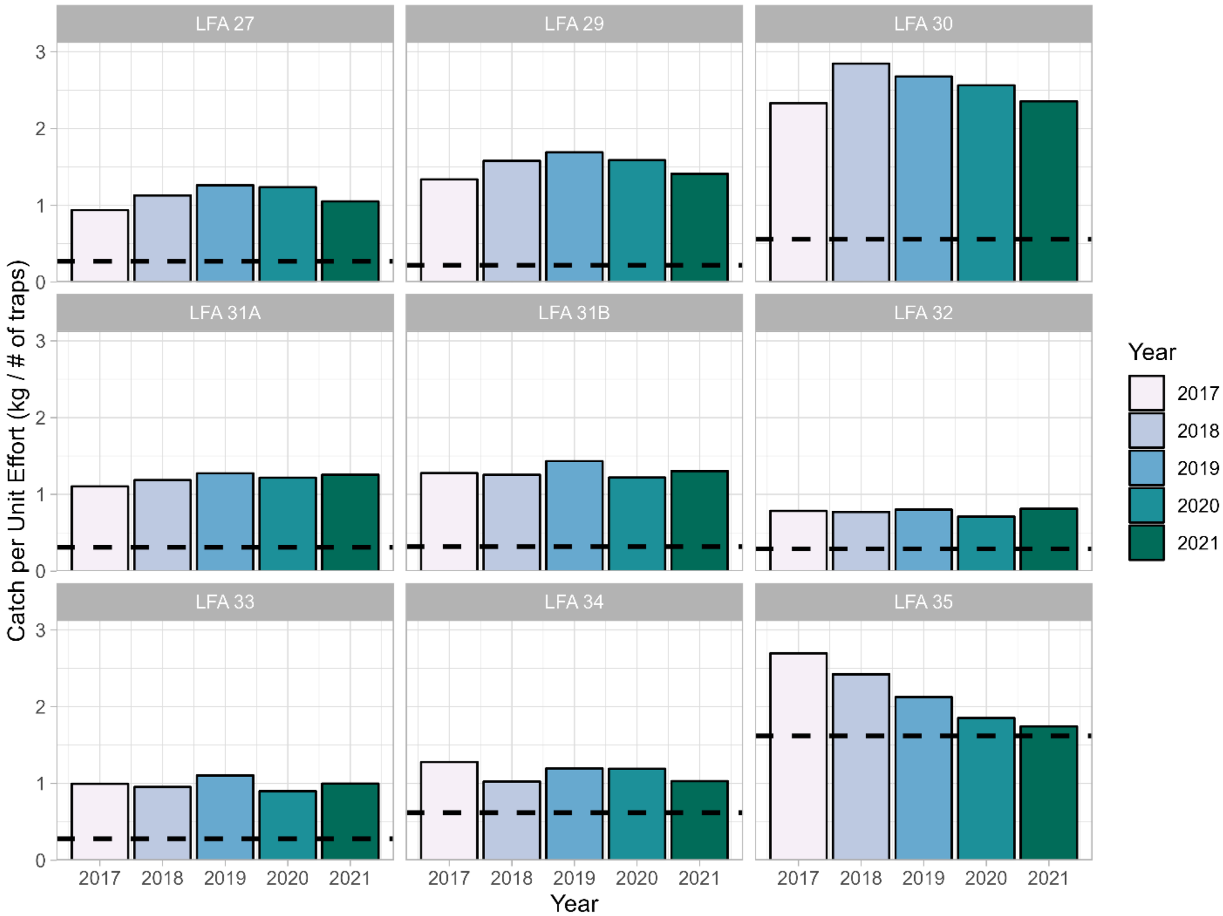


Figure 7 | Commercial catch per unit effort (CPUE) across Maritime Region LFAs. The x axis indicates the most recent available data of the previous 5 years. LFA CPUE data was provided by DFO Maritime Region and data since 2017 is considered preliminary. Dashed lines indicate the Upper Stock Refence (USR) value for respective LFAs (Fisheries and Oceans Canada, 2018; Fisheries and Ocean Canada, 2020; Fisheries and Oceans Canada, 2021c).

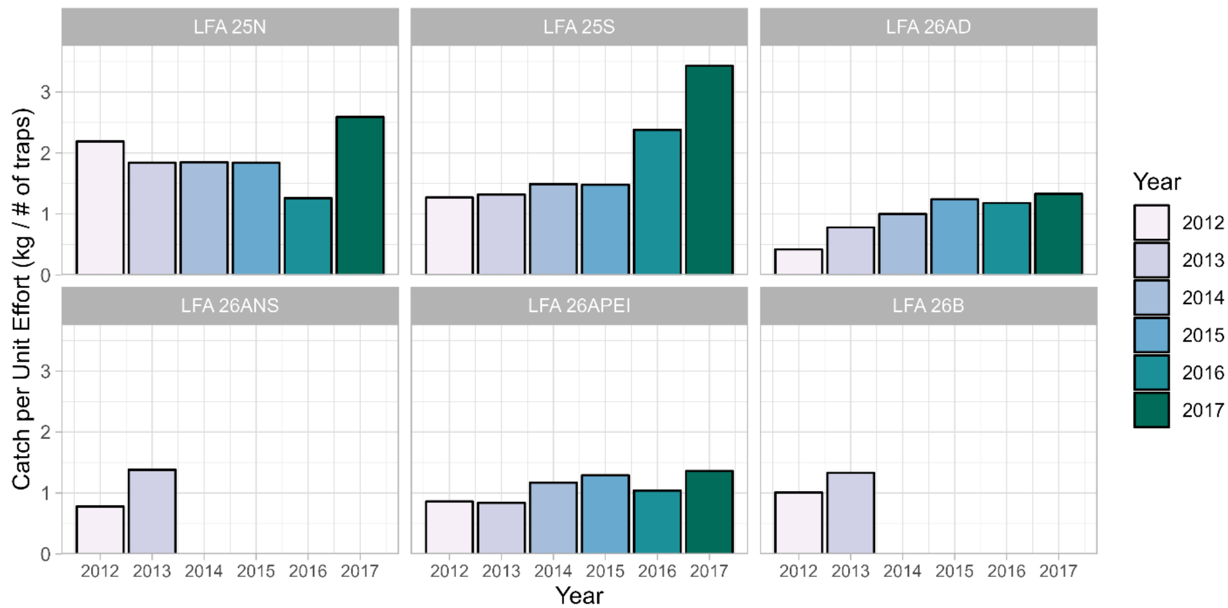


Figure 8 | Catch per unit effort (CPUE) of DFO Gulf Region lobster fishing areas (LFAs). The x axis indicates the last 6 years of available data. Data from 2017 is considered preliminary. LFA sub-regions 25S, 26AD, 26ANS and 26B border Nova Scotia's Northshore and western Cape Breton.

4.1.3 Vulnerability

Given the generally low *Exposure* and healthy stock status, overall lobster vulnerability is likewise low. LFAs in the Northumberland Strait area (25, 26A, and 26B) and 35 in the Upper Bay of Fundy, had moderately low vulnerability (Figure 9). The remaining LFAs around the province had low vulnerability.

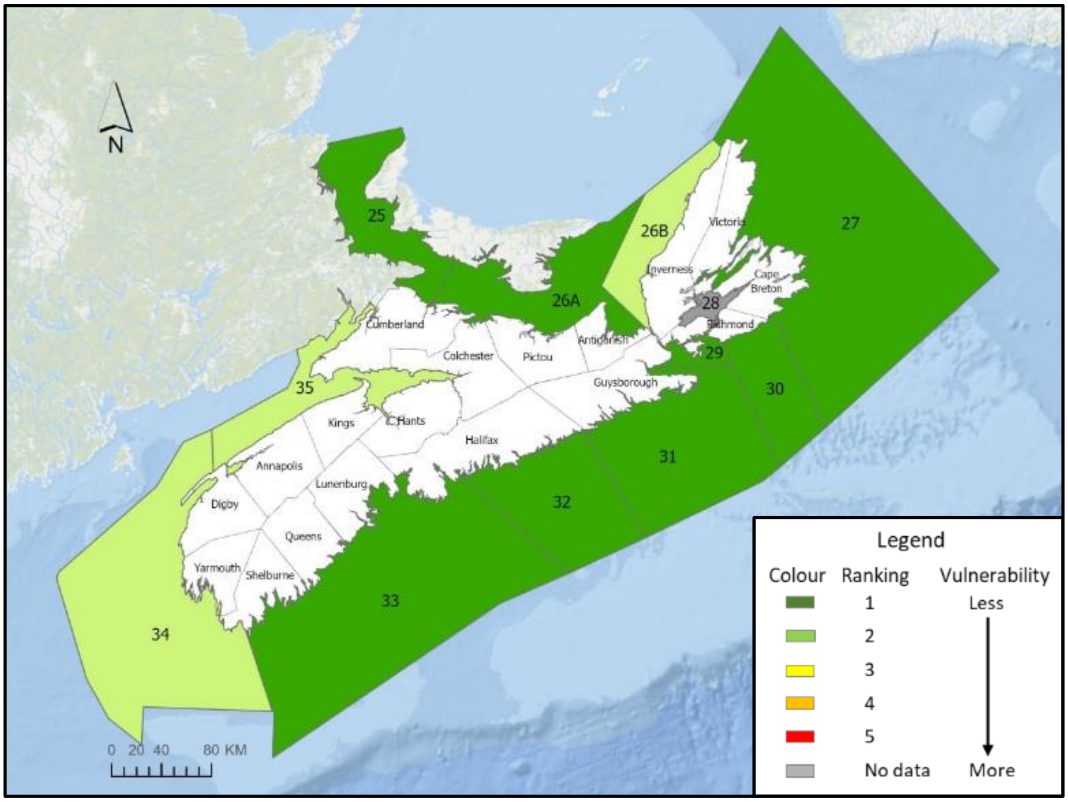


Figure 9 | Lobster vulnerability for LFAs surrounding Nova Scotia. This is a composite of *Exposure* and *Stock status* indices.

4.2 Lobster harvesting vulnerability model

Metrics and sub-metrics for the lobster harvesting vulnerability model were derived from interview survey responses or matrix development (Section 3.3). While attempts were made to get survey representation from all LFAs there were insufficient responses for LFAs 25 (Northwest shore bordering NB), 28 (Bras d'Or Lakes), and 35 (upper Bay of Fundy), and these could not be included in this model. While there were some responses from Digby Harbour, located at the edge of LFA 35 and adjacent to LFA 34, respondents primarily fished in LFA 34. Survey outcomes are detailed in Appendix E. Not all survey responses were applied to the model as some were used to provide context or supporting information. Survey responses of a more socioeconomic nature (e.g., not necessarily climate related) were partitioned out for analysis in a separate study (Flaherty et al., *in preparation*).

4.2.1 Lobster harvester survey

There were 289 lobster harvester survey respondents in total. LFAs had greater than 5 % of respondents in proportion to the number of license holders (Table 7), except LFAs 25, 28, and 35 which had no responses and consequently, were not included in the model. CMAR was able to survey harvesters of a wide range of ages throughout the province. Of the harvesters surveyed, 75% had more than 10 years of experience in the lobster fishery. However, LFAs 26A, 27, 32, and 34 had proportionately more responses from harvesters greater than 45 years old (Appendix E, Figure 3), primarily participating in the fishery as captains or owners/operators.

Table 6 | Number of responses as a proportion of licenses issued in 2020 for each Lobster Fishing Area (LFA).

LFA	No. of Licenses	Responses	Proportion of Responses (%)
25	13*	0	0
26A	314*	23	7
26B	203	26	13
27	452	54	12
28	<5	0	0
29	58	13	22
30	20	7	35
31	128	10	8
32	140	28	20
33	577	34	6
34	934	94	10
35	87	0	0

* Number is representative of licenses only with homeports in Nova Scotia

4.2.2 Exposure

The lobster harvesting *Exposure* index included the two metrics, 'Fishing Days Lost to Bad Weather', and the perception that, 'Fishing Days Lost to Bad Weather Has Increased'. Lost fishing days due to bad weather ranged from approximately 5% in LFA 26A to over 30% in LFAs 33 and 34 (Appendix B, Figure 1). There was a general trend of increasing loss of fishing days moving toward southwest LFAs. Average responses to the statement of, fishing days lost to bad weather has been increasing over the last 5 to 10 years, were generally neutral across LFAs, except for 33 and 34 which generally agreed with the statement (Appendix B, Figure 2). The resulting *Exposure* index indicated low exposure vulnerability of Northumberland Strait and outer Cape Breton LFAs, with the exception of 26B, which had moderate vulnerability (Table 8). Remaining LFAs around the province exhibited moderate *Exposure* vulnerability (Figure 10).

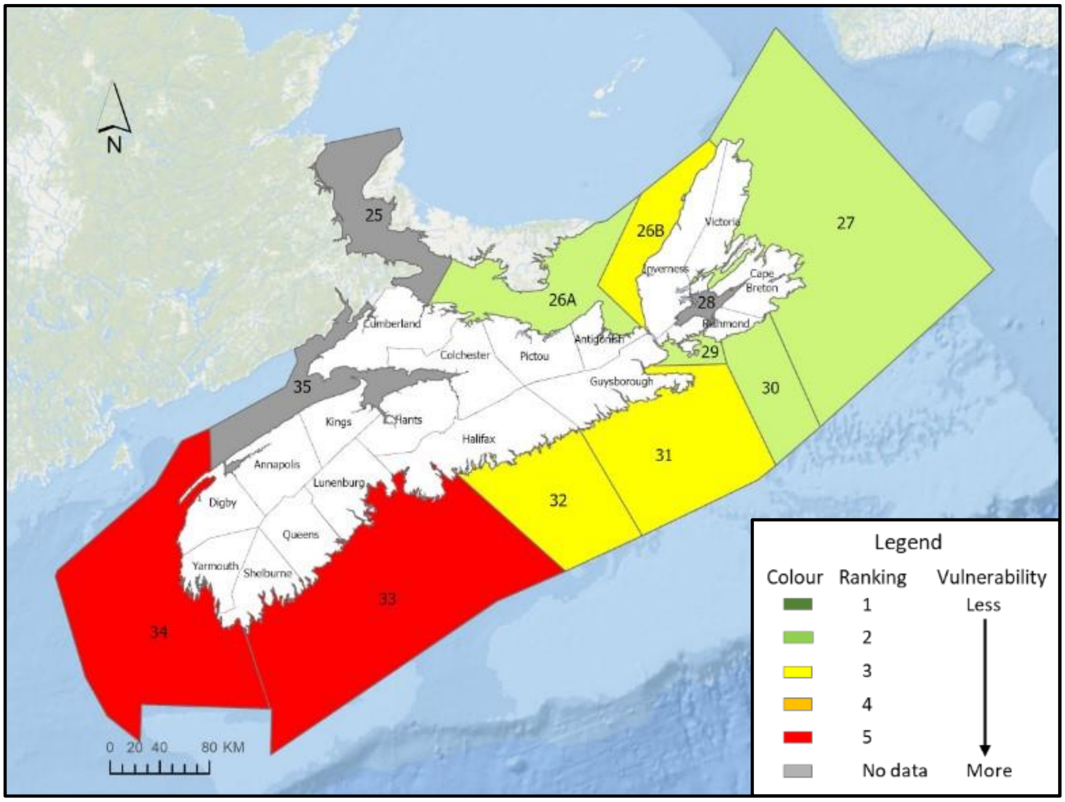


Figure 10 | Exposure index for lobster harvesting. Based on fishing days lost due to bad weather and perception of trends in bad weather fishing days.

4.2.3 Sensitivity

The *Sensitivity* index was comprised of the metrics: Fisheries Management Flexibility, Fishing Infrastructure Status, and Financial Resiliency. LFAs 26A, 29, and 33 scored moderate *Sensitivity*, with remaining LFAs scoring moderately high *Sensitivity* (Figure 11, Table 8).

Fishing Infrastructure Status is the combined lobster harvester (Appendix C, Figure 3) and provincial CRC opinion of wharf conditions (Appendix C, Tables 5 and 6). For all LFAs, lobster harvester and CRC scores of wharf condition were similar to each other, being less than one value apart out of a possible score of five. Combined observations are mapped in Appendix C, Figure 4. Wharves in LFA 26A scored moderately low vulnerability, LFA 30 scored high vulnerability[17], with remaining LFAs scoring between moderate and moderately high vulnerability.

The Fisheries Management Flexibility metric combined the sub-metrics Fisheries Management Matrix (Appendix C, Table 1) and Conservation Measures (Appendix C, Table 2). The Fisheries Management Matrix scores varied widely across different LFAs with a slight trend of greater flexibility on the south shore and Bay of Fundy, and less flexibility in the Northumberland Strait and parts of Cape Breton (Appendix C, Figure 1). Conservation Measures were generally similar across LFAs, with moderate vulnerability scores, except LFA 30 which had relatively strict conservation measures. This resulted in all

[17] Major wharf repairs required in Fourchu Harbour.

LFAs with moderate to moderately high vulnerability scores for Fisheries Management Flexibility (Appendix C, Figure 1).

The Financial Resiliency metric (Appendix C, Figure 5) combined the two sub-metrics Revenue (%) from Lobster Fishing, with Revenue Loss (%) to Stop Fishing. The average proportion of revenue from lobster fishing ranged from 67% in LFA 26B to 85% in LFA 34. Revenue Loss (%) to Stop Fishing ranged from 38% in LFA 31 to 69% in LFA 26A (Appendix C, Figure 6). There was no obvious province wide spatial trend, other than some adjoining LFAs had similar values for the sub-metrics (e.g., 34 and 33, 29 and 30). Financial Resiliency (in the context of *Sensitivity*) across LFAs was scored as moderately vulnerable or as moderately high vulnerability (Appendix C, Figure 5).

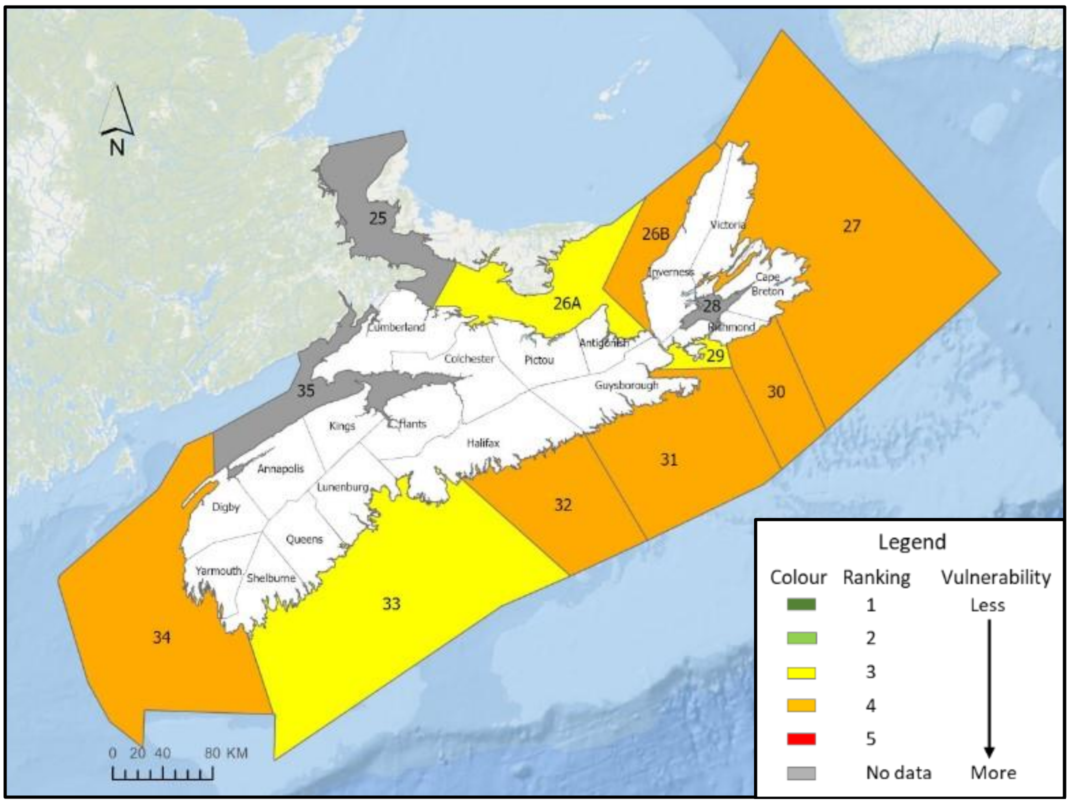


Figure 11 | Relative lobster harvesting *Sensitivity* across LFAs. This index includes the metrics: fisheries management flexibility, status of fishing infrastructure (i.e., infrastructure state), and financial resiliency of lobster harvesters.

4.2.4 Adaptive Capacity

The *Adaptive Capacity* Index was comprised of the metrics Fisheries Flexibility, Personal Flexibility, and Perception of Risk. There was largely consistent *Adaptive Capacity* throughout LFAs across the province with the majority of LFAs having moderate *Adaptive Capacity* (Figure 12, Table 8). The exception being LFA 34 which had moderately low *Adaptive Capacity*.

The Fisheries Flexibility metric (Appendix D, Figure 1) was comprised of the sub-metrics Adjust Fishing Seasons and Could Switch Fishery. The Adjust Fishing Seasons sub-metric describes the response to the statement, 'Fishing seasons should be adjusted to account for ocean change'. Province wide, responses were generally neutral (Appendix D, Figure 2). The Could Switch Fishery sub-metric described the capacity of harvesters to switch fisheries if lobster stocks declined. Average LFA responses around the province generally disagreed that they had the capacity to switch except for LFAs 30 which had a more neutral response (Appendix D, Figure 3). The resultant Fisheries Flexibility metric was between moderate to moderately low across the province.

The Personal Flexibility metric was estimated from the response to the statement, 'If needed, I have other skills to change careers'. Most LFAs had an average neutral response, except LFAs 31, 33, and 34 which generally disagreed with the statement (Appendix D, Figure 4).

The Perception of Risk metric (Appendix D, Figure 5) was the average of the two sub-metrics, Evidence of Climate Change (Appendix D, Figure 6) and Concerns Climate Change Impacts the Fishery (Appendix D, Figure 7). Harvesters in most LFAs agreed that there was evidence that climate change was occurring, with LFAs 27 and 30 strongly agreeing. Average harvester responses from all LFAs agreed they had concerns about climate change impacts on the lobster fishery. Almost half (48%) of lobster harvesters across the province listed climate change or a climate change metric (e.g., warming water, increased storms) as one of the top three threats to the lobster fishery (Appendix E, Figure 11).

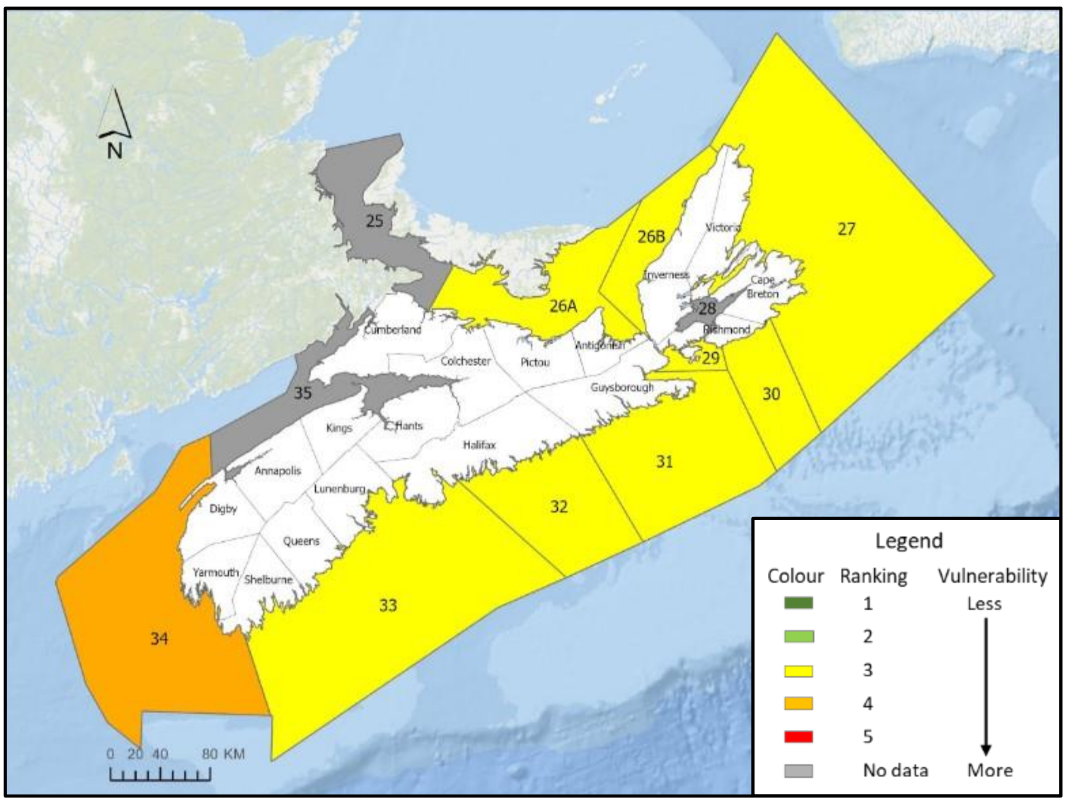


Figure 12 | Relative lobster harvesting *Adaptive Capacity* across LFAs. Higher scores indicate greater vulnerability, with a high score reflecting lower *Adaptive Capacity* and a low score representing higher Adaptive Capacity. This index includes the metrics: fisheries flexibility, personal flexibility, and perception of risk.

4.2.5 Lobster harvesting vulnerability

Vulnerability of lobster harvesting was an average of the *Exposure*, *Sensitivity,* and *Adaptive Capacity* indices. Most LFAs scored moderate vulnerability except the south shore LFAs 33 and 34 which scored moderately high vulnerability (Figure 13; Table 8).

Table 7 | Lobster harvesting vulnerability metric summary across LFAs. Transitioning from dark green, light green, yellow, orange, and red represents an increase from low to high vulnerability, respectively. Grey sections indicate insufficient data.

	Exposure		Sensitivity			Adaptive Capacity		
LFA	**Suitable fishing days**	**Suitable fishing days are decreasing**	**Fishery Management Flexibility**	**Fishing Infrastructure Status**	**Financial Resiliency**	**Fisheries Flexibility**	**Personal Flexibility**	**Climate Risk Perception**
25								
26A								
26B								
27								
28								
29								
30								
31								
32								
33								
34								
35								

Table 8 | Lobster harvesting vulnerability index summary across LFAs. Vulnerability is an average of the *Exposure*, *Sensitivity* and *Adaptive Capacity* indices. Transitioning from dark green, light green, yellow, orange, and red represents an increase from low to high vulnerability, respectively. Grey sections indicate insufficient data.

	Indices			
LFA	**Vulnerability**	**Exposure**	**Sensitivity**	**Adaptive Capacity**
25				
26A				
26B				
27				
28				
29				
30				
31				
32				
33				
34				
35				

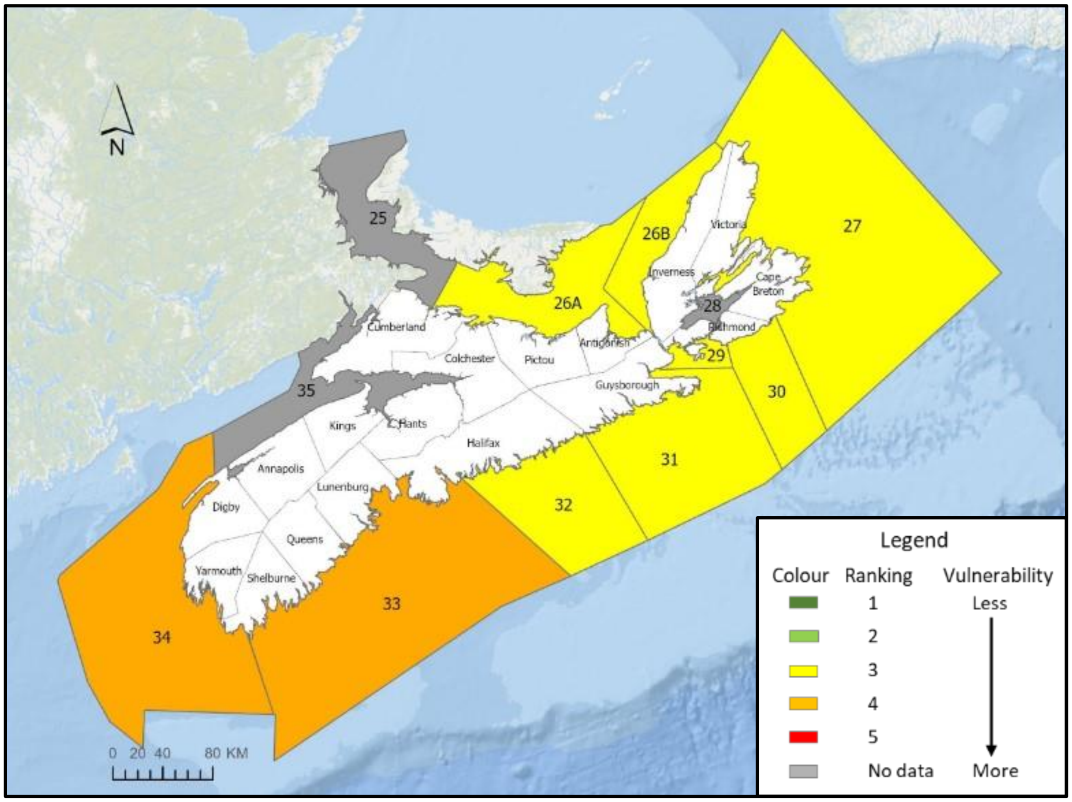


Figure 13 | Lobster harvesting vulnerability of LFAs bordering Nova Scotia. This is a composite of the *Exposure*, *Sensitivity,* and *Adaptive Capacity* indices.

4.3 Cumulative climate change vulnerability of the Nova Scotia Lobster Fishery

Cumulative Vulnerability of the Nova Scotia Lobster fishery was an average of Lobster Vulnerability and Lobster Harvesting vulnerability. Most LFAs around the province had moderately low vulnerability except for LFAs 26B, 33, and 34 which had moderate vulnerability (Figure 14).

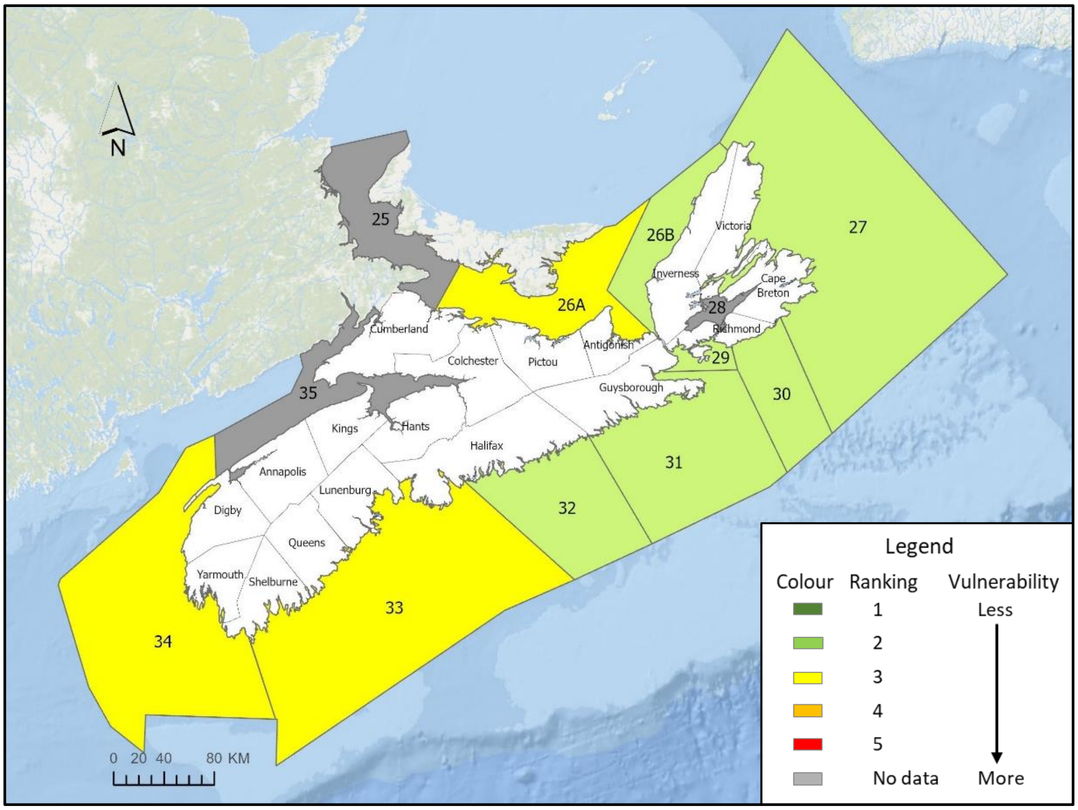


Figure 14 | Cumulative vulnerability of the Nova Scotia lobster fishery. An average of the Nova Scotia Lobster Vulnerability and Lobster Harvesting Vulnerability models.

5 Discussion

5.1 Vulnerability of lobster

The relative *Exposure* of lobster to projected temperatures in this study was relatively consistent with previous research, where is appropriate suitable thermal habitat during the warmest month of the year is still expected in the near term. Indeed, some studies have reported an expected increase in optimal lobster temperatures in this region in the coming few decades (Shackell et al., 2014; Stortini et al., 2015; Le Bris et al., 2018; Greenan et al., 2019). In this study, there was little difference in vulnerability of lobster across the province with only a slight relative increase of *Exposure* vulnerability for Northumberland Strait - western Cape Breton LFAs. This trend of LFAs is consistent with other literature. Graphical data of temperature based recruitment projections by Le Bris et al. (2018) suggest a reduction in recruitment could be expected in those LFAs by 2050. However, the generally exceptional stock status of Maritime LFAs, which are operating above the USR values, and near record landings of bordering Gulf Region LFAs, suggest good population size which helps reduce *Sensitivity* to stressors, and arguably demonstrates good responsiveness to management measures (i.e., capacity to adapt). The combined thermal regimen and healthy stock status drove low vulnerability scores of lobster around Nova Scotia.

5.2 Vulnerability of lobster harvesting

Lobster harvesting vulnerability metrics developed from data collected through face-to-face interviews straddling the last day of the fishing season, proved relatively successful. Many harvesters were still present at wharfs, maintaining their vessel or involved with other 'winding down' tasks. There was good willingness from harvesters to speak during this time and it was estimated from study interviewers that over 95% of harvesters approached were willing to interview. In a few instances where wharf visits could not be timed with the end of the season and there was limited opportunity for direct approach, a kiosk table was set up at the wharf entrance to enable interaction with harvesters coming and going. Nevertheless, face-to-face interviews are more logistically demanding and much more costly than online surveys, but this method resulted in good cross-sectional data and to the best of our knowledge, resulted in the highest response rate for this type of study.

Lobster harvesting vulnerability across LFAs for two of the supporting indices did not differ widely. *Sensitivity* values indicated either moderate or moderately high vulnerability across the province and *Adaptive Capacity* was largely average. This suggests there is scope to improve *Adaptive Capacity* (and thereby reducing *Sensitivity*) and the apparent lack of large differences across provincial LFAs suggest that related initiatives could be province-wide and may not require tailoring for specific regions. It should be noted that this observation is relative to LFA harvesting activity and does not necessarily reflect the economic *Sensitivity* of specific communities to changes in the local lobster fishery or *Adaptive Capacity* of community-based lobster harvesters. Per capita fisheries revenue, the relative contribution of lobster landings to that revenue, and consequently *Sensitivity* at the county level is detailed in Reid et al (2022).

There were greater differences across LFAs within the climate change *Exposure* index, as indicated by lost fishing days, or perceived trends in days lost due to bad weather. There was a greater proportion of lost fishing days reported for south shore LFAs 33 and 34, which drove a slightly higher vulnerability score compared to other LFAs. This difference across LFAs are orders of magnitude, with LFA 26A estimating only 5% days lost and LFAs 33 and 34 more than 6 times that at over 30% (Section 4.2.2). The results from LFA 33 and 34 suggest unsafe weather conditions may be increasing, further supports ongoing flexibility and allowances around the seasonal timing of fishing days, to help reduce *Sensitivity* to these effects. The result from these two LFAs was not surprising given the trend of vessels travelling greater distances and multi-day fishing in these LFAs, despite larger fishing vessels in this region which can accommodate more extreme conditions. These responses are consistent with large portions of LFA 34 having higher wind speeds in winter, fall, and spring compared to other LFAs where fishing occurs closer to shore, as suggested by the Environment Canada and Climate Change Wind Atlas[18]. Changes in trends may be more noticeable with harvesters already operating in high wind areas. Hurricane intensity and duration are expected to increase under climate change, but not necessarily the frequency (Knutson et al., 2020; Knutson et al., 2021) and the province has acknowledged that storms will continue to become more intense around Nova Scotia (Department of Environment and Climate Change, 2022).

5.3 Vulnerability of the lobster fishery

The cumulative vulnerability of the lobster fishery LFAs bordering the province, exhibited moderately low vulnerability, except LFAs 26A, 33, and 34 which had moderate vulnerability. This is somewhat encouraging as it suggests the largest provincial fishery is not at high risk based on the current information available. Nevertheless, moderately low vulnerability and moderate vulnerability does not mean there is no vulnerability. Higher vulnerability scores from the Lobster Harvesting Vulnerability model were largely

[18] Maps - Wind Atlas - Environment and Climate Change Canada

responsible for the moderate vulnerability scores of the lobster fishery in LFAs 26A, 33, and 34. However, action can be taken to improve vulnerability scores (Section 6). Reducing lobster harvesting vulnerability is arguably easier than reducing lobster vulnerability. While adjustments to fishing pressure and conservation can be applied to improve stock status, thereby helping to reduce lobster vulnerability, this is apt to reduce landings. Little apart from climate change mitigation and lobster range change can reduce lobster *Exposure* to biophysical climate changes.

5.4 Potential study limitations

5.4.1 Ocean models

Climate change assessments applying ocean model projections often combine multiple model outputs, thereby creating an ensemble of model projections, with the rationale that collective error will be reduced. However, the assumption of error reduction or cancelation through use of ensemble projections does not always hold (Fennel et al., 2022) and there are currently only a handful of models that project bottom water temperatures at an LFA-friendly resolution for the mid-century time frame. The two primary models, BNAM and CM2.6 were compared by Greenan et al. (2019) who reported that the two models differed marginally with respect to lobster thermal habitat projections at the LFA level, but with the CM2.6 model having slightly increased variation and temperature, which only resulted in larger differences in LFA 33. The scope of this study and parsimony objectives of the simple model prompted the use of accessible and published model projections, and the BNAM model outputs by Brickman et al. (2016). While it is possible there could be differences in vulnerability ratings with application of a different ocean model, it is assumed that at the current state of model developments, these would be minor. It is expected that increased model resolution and knowledge will be available in coming years, and these can be re-run within the model as improved ocean projections are made available. Additional limitations of present-day ocean models are discussed in the following section (5.4.2).

5.4.2 Lobster and temperature

Temperature is considered to be the largest physiochemical driver of lobster abundance and while lobster can be affected by other parameters such as dissolved oxygen and ocean acidification, the timelines in which levels are expected to be problematic for lobster around Nova Scotia, exceed the 2055 timeline (Tai et al., 2021). Therefore, these were not directly considered in the model.

Some temperature thresholds identified as viable conditions for lobster are not without problem. For example, 15°C is considered a near optimal temperature but also corresponds with the greatest progression of shell disease lesions (Tlusty and Metzler, 2012). Nevertheless, the overall gains in lobster recruitment at this temperature seem to offset detriments from shell disease (Le Bris et al., 2018). There are also warming winter temperatures that can affect spawning. Aiken and Waddy (1995) reported, that if water temperatures remain above 6-8°C throughout the winter, the cyclic relationship between molting and spawning can be disrupted and spawning is no longer synchronized within the population. It is unclear how much this could affect lobster abundance at an LFA scale. However, high resolution coastal data collected by CMAR over the last 4 years suggest that upper winter water temperatures at the most southern extent of the province have not yet exceeded 4°C. Increases in February bottom temperatures indicated by BNAM RCP 8.5 projections for 2055 suggest maximum temperature in southern LFA 34 will increase < 1.4°C. This suggests that winter temperatures above 6°C will not be largely manifested by this time. Nevertheless, uncertainty with projections, lack of full coastal coverage of ongoing temperature monitoring, and annual temperature variation associated with the North Atlantic Oscillation suggest warming winter water temperatures and potential affects to lobster warrants further investigation.

It is also important to note, that an assessment based on mean and median projected temperatures at the LFA scale are not necessarily reflective of all locations within an LFA. Some areas may manifest greater extremes compared to the average. This is apparent in LFA 25 and 26A where large portions of these LFAs have September temperatures around 19°C (Figure 5). Consequently, there could be greater vulnerability within an LFA at a finer spatial scale than reported.

An additional challenge with the current state of marine projections, is that they are not yet able to account for the variability of anomalous events such as marine heatwaves. Short-term but acute increases in temperature, such as heat waves, can have major implications for biological functionality. Increasing frequency of marine heatwaves are becoming problematic for marine ecosystems globally (Frölicher et al., 2018; Smale et al., 2019; Guo et al., 2022) and warm water temperature anomalies have been generally increasing in the Atlantic zone (Fisheries and Oceans Canada, 2022c). This current inability to account for anomalous events such as heat waves has been acknowledged as a limitation in vulnerability assessments of marine species (e.g. Greenan et al., 2019; Boyce et al., 2022b).

5.4.3 A simple lobster vulnerability model

One consideration for estimation of lobster vulnerability in this study is that there was no underlying species distribution model to calculate *Exposure,* nor a model to estimate stock status (*Sensitivity* and *Adaptive Capacity*). Greenan et al. (2019) applied a more sophisticated approach where *Exposure* was defined as the percent change in suitable habitat, calculated from thermal preference, presence, depth, bottom temperature, season, and location. Stock status was calculated from potential suitable habitat, occupancy, abundance status, and early life stage food availability. Some of these metrics, such as larval food availability can represent significant drivers of lobster recruitment and abundance. Nevertheless, while there were differences between the simple model output used in this study and more sophisticated model by Greenan et al (2019), differences were not extreme. LFAs in common, assessed for lobster vulnerability by both this study and Greenan et al. (2019) were 33, 34, and 35. The Greenan et al. (2019) lobster vulnerability index scores for 35, 34 and 33 were 2.5, 2.0, and 2.0 out of 5.0, respectively. In this study, 35, 34, and 33 were 1.5, 1.0, and 1.0 out of 5, respectively. This study's vulnerability estimates were about 20% less and the relative trend across those LFAs was the same. This suggests that with the moderate differences between the two models, application of the simple model is not apt to report a drastically different outcome.

5.4.4 Early life stage food availability

Some copepods such as *Calanus finmarchicus* are a major zooplankton component in the North Atlantic and a primary dietary source for larval lobster. Ocean warming has caused this copepod to decline in the Gulf of Maine and Scotian Shelf and this was reflected in an apparent shift of *Calanus finmarchicus* around 2010 (Brennan et al., 2019). These changes could be concerning for lobster populations, as low *C. finmarchicus* abundance in the Gulf of Maine has been correlated with low juvenile lobster abundance, suggesting temperature-driven changes in zooplankton can negatively affect lobster recruitment (Carloni et al., 2018). This copepod has exhibited a northeastward shift in distribution of around 8 km per decade since 1959 (Chust et al., 2013) although model projections suggest *C. finmarchicus* habitat range will still be within Nova Scotia waters by 2080 (Villarino et al., 2015). Any current effects of *C. finmarchicus* on lobster recruitment and abundance since 2010 around Nova Scotia are difficult to attribute, as the stock status and/or landings of LFAs since have generally been improving around the province, albeit with some fluctuation. Nevertheless, a lack of direct consideration of food availability for larval lobster is a potential limitation of this study.

5.4.5 Data gaps in the near shore

Lobster stock status is ideally assessed through a combination of fishery-dependent (commercial data from harvesters) and fishery-independent data (does not rely on commercial catch data) to develop multiple indicators. Generally, the more indicators, the greater the confidence in corroborating trends and stock health classification. Fishery-dependent data typically includes metrics like commercial CPUE, landings and recruitment trap surveys (DFO, 2023a), while fishery-independent data will include data such as georeferenced seasonal abundance, habitat, and lobster morphometrics (Denton, 2023). Trawl surveys have some advantages over commercial data, as they are not reliant on animal behaviour or extraneous factors such as bait choice (DFO, 2020b) and can collect data needed to improve interpretation of commercial catch data [e.g., standardized CPUE (DFO, 2023b)]. While all LFAs have fishery-dependent data reporting requirements to a varying degree, not all LFAs have extensive fishery-independent data. This is partially because much of the fishery-independent data collection occurs with large research vessel trawl surveys (Fisheries and Oceans Canada, 2021b). Larger research vessel surveys cannot collect inshore data around much of the Nova Scotia coastal area and typically operate beyond 100 m depth (Coffen-Smout et al., 2013; Serdynska and Coffen-Smout, 2017). Some trawl surveys are designed to specifically target inshore lobster areas and some LFAs like 34, have good coverage (Denton, 2023). However, many inshore areas around the province such as LFA 27–33 have bottoms unsuitable for trawling (Cook et al., 2020b). Diver surveys are another option (DFO, 2019a), but these are labour intensive and have limited spatial coverage. This challenge of collecting inshore fishery-independent data results in inconsistent application of stock status indicators across LFAs and results in several LFA stock assessments relying on only commercially collected data. Nevertheless, commercial catch data is available for most Maritime and Gulf LFAs and has been consistently used as either primary or secondary lobster stock status indicators across Maritime and Gulf Regions. This suggests that in absence of fishery-independent data, fishery-dependant data is a good approximation of stock health, albeit with greater uncertainty. Comparison of lobster stock indicators, both fishery-independent and dependant data, occurs periodically under DFO framework assessments (e.g. Cook et al., 2020b).

6 Next steps and recommendations

6.1 The need to improve adaptive capacity

Climate change vulnerability assessments help to identify potential sources of risk and needs for adaptation. While these assessments may not necessarily identify prescriptive actions needed to reduce specific vulnerabilities, knowledge gaps and areas requiring attention are highlighted. This is an important step for the development of effective adaptation pathways. Within the context of the three primary vulnerability indices, increasing *Adaptive Capacity* reduces *Sensitivity* and likewise, reducing *Exposure* requires either environmental mitigation or increased *Adaptive Capacity* (Thomas et al., 2019; Reid et al., 2022). Apart from climate change mitigation, initiatives that reduce vulnerabilities will focus on improving *Adaptive Capacity*.

The metrics used to support vulnerability assessments (Section 3) can also be thought of as key performance indicators (KPI) and improving the vulnerability score of these metrics is one approach to measure success of adaption outcomes. Climate change adaptation involves reducing climate risks and vulnerability, primarily through adjustment of existing systems (IPCC, 2022b). In the context of fisheries, improving vulnerability metrics such as economic/financial resilience, fisheries management flexibility, risk awareness, flexibility of harvesters, conservation practices, access to resources, robust marine infrastructure, and longevity of fishing livelihoods are common approaches and these considerations are active fields of study (e.g., Marshall et al., 2013a; Marshall et al., 2013b; Le Bris et al., 2018; Stephenson et al., 2018; Stephenson et al., 2019a; Stephenson et al., 2019b; Boyce et al., 2023).

Defining the timelines for implementation of adaption actions is a global challenge as climate change is a continuum of increasing environmental alteration and frequency of disastrous events. It is now widely accepted that climate change is not a hard-to-predict anomaly[19] but its occurrence is unequivocal (IPCC, 2021); with much greater impacts pending even though predictions and timelines may not be exact[20]. Therefore, the longer the delay in adaptation to climate change, the greater the likelihood of maladaptive coping responses, increased disaster recovery costs and missed opportunities for proactive investment (Reid et al., 2019; The Global Commission on Adaptation, 2019; Howarth et al., 2021).

6.2 Provincial support

The Nova Scotia Department of Fisheries and Aquaculture (NSDFA) has a legislated mandate to manage, promote, support and develop the fishing, aquaculture and seafood processing industries that contribute to the economic, environmental, and social prosperity of Nova Scotia's coastal and rural communities (Province of Nova Scotia, 2023). As an extension of this mandate the department supports proposals, programs, and policies that promote climate change preparedness of the seafood industry (Department of Fisheries and Aquaculture, 2022). This includes plans to partner with industry on a strategy for climate change adaptation and mitigation (Department of Fisheries and Aquaculture, 2022) and the creation of a fisheries and aquaculture climate change information hub (Department of Environment and Climate Change, 2022). Some modest opportunities for industry funding will be made available. In collaboration with the Department of Energy and Climate Change, there will be a new fisheries and aquaculture energy efficiency innovation fund and a climate change adaptation fund (Department of Environment and Climate Change, 2022). The province is also committed to support the seafood industry by pursuing federal funding and contributing to provincial-federal funded programs such as the Atlantic Fisheries Fund (AFF). While these developments are not specific to the lobster fishery, the nature of the fishery as the largest contributor to the seafood economy, warrants proportional consideration under climate adaption and mitigation initiatives.

These funding and partnership opportunities are timely and compliment many of the following recommendations to support planned adaptation of the lobster fishery. While not all the recommendations herein fall under direct provincial oversight, they ultimately aim to support a robust lobster fishery and consequently, the provincial goal of fostering a prosperous seafood industry. In instances where initiatives may not be within the direct jurisdiction of NSDFA or provincial government, a supporting or secondary partnership role may be appropriate, if only to ensure ongoing awareness. Given provincial resource limitations and competing funding demands, cost-benefit considerations may be needed to prioritize recommendations. Such determinations are a challenge for all levels of governance, globally. Application of decision support tools to determine and prioritize climate change adaptation pathways has been one solution advocated by the IPCC (IPCC, 2022a; IPCC, 2023), and this could be a viable option to assist the province.

[19] A 'black swan' event (Taleb, 2010)
[20] A 'grey rhino' event (Wucker, 2016)

6.3 The wider lobster fishery

The following recommendations are intended for the wider provincial lobster fishery to highlight pathways for adaption, mitigation or resolve important knowledge gaps. These considerations aim to help the province and the lobster fishing industry improve *Adaptive Capacity* of the fishery, thereby reducing *Exposure* and *Sensitivity* to the effects of climate change.

6.3.1 Ensure a 'seat at the table' for lobster and climate initiatives

As climate change, technology, and practices in the lobster fishery evolve, *Adaptive Capacity* needs may also change. Given the potential volume of climate information, multiple disciplines involved, and a dynamic fishery, it is an ongoing challenge for stakeholders keep up to date, but it is necessary to stay informed of developments to ensure proactivity. Some initiatives are already in place which can serve as a forum to track developments. For example, the Fisherman and Scientists Research Society coordinates research collaboration between lobster fishermen, scientists, and managers to collect data that supports projects such as improved understanding of climate change effects on lobster and conservation practices. This information can help guide flexibility in fisheries management, which ultimately supports improved *Adaptive Capacity*.

The Lobster Science Partnership Roundtable is a Fisheries and Oceans Canada led initiative which brings together lobster fishery stakeholders to discuss and prioritize important lobster science research through forums such as the Lobster Science Symposium. Having a seat at the table for these and related initiatives will help ensure the province and industry have opportunity for input into climate change adaptation strategies that affect the Nova Scotia fishery. This could extend to wider initiatives like the proposed federal Blue Economy Strategy to help ensure it aligns with provincial and industry interests. While this strategy, currently under development at the time of the report's writing, encompasses more than the lobster fishery and climate change, the disproportionately large contribution of this fishery to the Canadian seafood economy and overarching effects of climate change, suggest these will require careful integration into the strategy.

Recommendation: The province and industry should ensure they have a 'seat at the table' at forums and with organizations that oversee lobster and climate initiatives.

6.3.2 Skills and opportunities diversification

Adaptive Capacity could be increased by improving personal flexibility and options among lobster harvesters. While this metric is largely individualistic and a function of personal choice, availability of additional employment or opportunity for skills development could provide a degree of contingency for additional options. The strategy of diversification is not new and improving personal flexibility will be a difficult sell when the fishery has good returns. Nevertheless, opportunities and skills diversification have many community advantages beyond the lobster fishery. While fostering economic diversification extends beyond the domain of NSDFA this reflects the need to coordinate mandates and incentives from different levels of governance including communities (Reid et al., 2022). Consequently, NSDFA may have a collaborative role in strengthening of the seafood economy and to help steer diversification and value-added initiatives.

Recommendation: Promote wider opportunities within the seafood economy. This might include expansion of college programs, targeted training, internships, value-added initiatives for existing seafood, exploration of new fisheries (e.g., ranges change), and diversification of other local seafood sources such as aquaculture.

6.3.3 Track risk exacerbation by climate change

There are a number of ongoing issues affecting the Nova Scotia lobster fishery, while not brought on by climate change, are being exacerbated by climate change. Tracking these risks will help inform the seriousness of pending developments which relate to not only the industry but also to provincial mandates or objectives, to better enable proactive responses. Some of these ongoing developments include:

Entanglement of marine mammals in fishing gear.

Oceanic changes are altering the distribution of food sources such as plankton, which whales can follow into novel areas with lobster traps. Entanglements may occur in these new areas which were previously considered low risk for entanglements. This has led to temporary closures of harvesting areas (included around Nova Scotia) to roped gear (Fisheries and Oceans Canada, 2022b). Survey responses suggested harvesters are generally not supportive of 'ropeless gear', although impromptu follow up discussions indicated this was largely due to the technical difficulties of existing technology. This suggests a targeted need to support ongoing developments of this technology so that it is practical, functional, and commercially available for the industry.

Changing bait source

Recent restrictions on lobster bait species such as herring and mackerel (Palmeter, 2022) have increased the cost of bait and diversity of sources. Some harvesters we spoke with purchased from buyers that sourced frozen bait from Asia and Africa. Greater bait import distances will increase the carbon footprint of lobster harvesting, which is in contrast to a net zero carbon strategy. Development of local sustainable sources or alternative baits will help reduce the carbon footprint and potentially reduce cost. This would benefit from some investment opportunities for research, development, and commercialization of alterative bait sources.

Increase in extreme environmental events

Fishing and fishing infrastructure have always been at risk from severe storms, but greater storm intensity driven by climate change is increasing this risk. This will not only affect suitable fishing days, but even land-based infrastructure such as lobster processing facilities are not immune (Undercurrent News, 2022). Improving structural integrity of existing infrastructure while ensuring that damaged marine infrastructure 'builds back better' is an important step to reduce *Sensitivity* to climate change. Lobster harvesters can also be at the mercy of terrestrial events such as wildfires, which have destroyed stored fishing gear (Légère, 2023). Events such as these demonstrate the interconnectivity of climate influenced events and multi-jurisdictional overlap, suggesting that planning and response coordination will benefit from the involvement of industry and multiple levels of governance.

Climate change vulnerability of Nova Scotia First Nation lobster fishery

First Nations and lobster harvesting in Nova Scotia, may have different climate change adaption needs than the wider lobster fishery. There is a complex relationship between First Nations and lobster harvesting. Some members hold regular commercial licences, there are communal commercial licences, and other lobster fishing occurs under communal food, social and ceremonial (FSC) licences, and there are ongoing challenges from a lack of definition around the Supreme Court of Canada's 1999 recognition of the Mi'kmaq right to a moderate livelihood fishery (Withers, 2021b; Canada, 2023). Nevertheless, some

First Nation communities are increasing their position in the provincial lobster fishery with acquisition of 2 of the 8 offshore lobster licences (Intrafish Media, 2020) and research initiatives such as, a zero emission lobster boat (Tutton, 2022). DFO is currently developing plans to improve understanding of social-economic conditions surrounding the indigenous lobster fishery (Pourfaraj et al., 2022) and this could be a good foundation for collaborative assessment of climate change risks to this fishery.

Economics assessment of the lobster fishery

An important component beyond the scope of this study, but with potentially profound implications for climate change vulnerability of the lobster fishery, are uncertainties around global economic drivers. Indirect climate change effects like those mentioned above in this section, are expected to influence economic components such as export markets, insurance, logistics, supply chains, product demand and disaster relief. These considerations and others suggest a need to track external economics drivers with the inclusion of gap analysis and scenario modelling to account for climate driven changes in ocean condition and markets. While some of this research is occurring (e.g., Moore et al., 2020), it is in its infancy and not specific to Nova Scotia.

Regional specific change

Casual conversations with lobster harvesters during our interviews hinted at a number of possible environmental changes either not documented or not well documented. Some examples include, increasing tidal speeds across Yarmouth mudflats that are preventing lobster from walking against the current and increased frequency of atypical tidal/wind directions. While such information is anecdotal, it does suggest ongoing engagement with lobster harvesters could be an important early warning tool for pending issues or prioritizing further investigation needs.

Recommendation: Establish a committee of NSDFA Coastal Resource Coordinators to track and document ongoing developments and challenges within the lobster fishery, such as those above. Meet regularly with industry for information exchange, with management to disseminate findings, identify priorities and possible roles. This relates to the previous recommendation (Section 6.3.1) and synergies could be devolved with appropriate coordination.

6.3.4 Clean marine propulsion for lobster vessels with affiliated infrastructure

While tangible actions to reduce vulnerability are largely associated with steps to increase *Adaptive Capacity* and reduce *Sensitivity* to climate change, mitigation is ultimately required. This means largescale reduction of greenhouse gas emissions. All industries including fisheries have a responsibility to pursue this. While reduction of greenhouse gases has implications for all Atlantic Canada fisheries, the large scale of the lobster fishery suggests special consideration for green technologies.

Clean marine propulsion technology is an active topic of investigation in Nova Scotia. NSCC has just established a Clean Marine Propulsion Lab and advancements in the field were recently presented and discussed at the Centre for Ocean Venture and Entrepreneurship in Dartmouth (COVE, 2022). A study between NetZero Atlantic and Oceans North was initiated in 2022 to examine how Nova Scotia's Lobster vessels can achieve net-zero emissions by 2050 (Oceans North, 2022). Oceans North has further partnered with Membertou First Nation to develop an electric lobster boat (Tutton, 2022).

Transition to no-emission propulsion technology is likely to occur in a stepwise fashion. A recent study on the neighbouring Maine lobster fleet, concluded that full electro voltaic (EV) technology is not yet ready but intermediate transition to diesel-electric hybrids is currently possible and this would reduce emissions by 30-40% (Hagan and Nelson, 2022). Nova Scotia lobster harvesters may be open to this idea. The CMAR survey found that in all LFAs except one, over half of the lobster harvesters were either neutral or at least moderately supportive of government subsidies to promote hybrid engine use (Appendix E, Figure 6). There has also been recent international discussion on hydrogen fuel cell based propulsion, which is powering some ferries in Europe (Hagan and Nelson, 2022) and being tested on a tuna fishing vessel in Japan (FuelCellsWorks, 2019).

While adoption of EV or hydrogen fuel cells to Nova Scotia lobster fishing vessels may seem far off, the rate of development is rapid. It is important to consider now, that accompanying changes are needed for wharf infrastructure to support charging needs for EV vessels or enable supply for hydrogen fuel cells. This is an active area of investigation. Nova Scotia based engineering firm Rimot is currently exploring ways to support how EV marine vessels such as lobster boats will connect to a renewable electrical grid (James Craig, Rimot, pers comm, 2023).

Recommendation: The province and industry associations would benefit from tracking developments in green marine proposition technology to anticipate timelines, pending needs of the lobster harvesters and non-Small Craft Harbours[21], to anticipate future funding and development needs.

6.3.5 Marine infrastructure assessment

Wharf state was largely variable within LFAs, though there were a few 'hot spots' around the province such as the southwest shore and parts of Cape Breton (Appendix C, Figure 4). A previous recommendation from the report, 'A rapid climate change vulnerability assessment of Nova Scotia fisheries and fishing communities' was to recommend professional engineering assessments of key industry (non-Small Craft Harbours) and provincial wharves (and associated infrastructure) to identify climate proofing needs and potential cost expectations of critical seafood infrastructure (Reid et al., 2022). An initiative to help address this is currently under development and supported by NSDFA. Nevertheless, additional information in this report has greater specificity to lobster harvesters, improves resolution needed for infrastructure assessment needs, and can therefore provide additional guidance on where to direct efforts. Depending on the timeline considerations for assessments, green infrastructure needs could be considered as per Section 6.3.5.

Recommendation: Continue ongoing efforts to support assessments of non-Small Craft Harbours marine infrastructure with a focus on 'climate providing' needs.

6.3.6 Reassess climate change vulnerability as new information and research develop

Finally, assessing climate change vulnerability is a rapidly evolving field. Improved ways of calculating and communicating risk are under development. Ocean model projections are also improving and there are research initiatives underway aiming to address near-shore ecology data gaps, to better provide inputs for lobster population models. These developments will ultimately improve our ability to predict lobster population response to direct and indirect climate change drivers. Demographic data from this study suggest many pending retirements of current lobster harvesters over the next several years. An influx of new harvesters will bring new ideas, perception of risk, different levels personal flexibility and understanding of climate change. Other model inputs such as state of marine infrastructure or fisheries flexibility, could change quickly depending on resources and desire for change. Consequently, some input metrics used in this study could become dated relatively quickly.

[21] Harbours co-managed between DFO and local harbour authorities

Recommendation: Reassess climate change vulnerability of the Nova Scotia lobster fishery in 5 years.

6.4 LFA scale

Recommendations at the LFA scale reflect vulnerabilities identified in this study. Addressing vulnerabilities of some metrics (e.g., Fishery Management Flexibility) are not the direct responsibility of the province nor industry. Nevertheless, applicable recommendations are made regardless of jurisdictional authority, as this informs needs for engagement, communication, and collaboration. LFA specific recommendations considered herein primarily reflect metrics or indices with moderately high to high vulnerabilities.

LFA 26A

This area includes the southeastern part of the Northumberland Strait between Nova Scotia and Prince Edward Island, and the western side of Prince Edward Island adjoining Cape Breton (Section 2.3, Figure 2). Lobster fishing *Exposure* had moderately low vulnerability (Section 4.2) and *Sensitivity* and *Adaptive Capacity* were moderately vulnerable (Section 4.2). Fisheries management flexibility scored moderate high vulnerability, largely influenced by limited fisheries management flexibility, such as no flexibility in season start and end dates, low by-catch flexibility, and low trap limits. This LFA would benefit from considerations to improve flexibility of fishing season start and end dates and improved by-catch flexibility assuming minimal effects to stock and ecosystem health.

LFA 26B

This area includes the eastern half of the Northumberland Strait between Prince Edward Island and Cape Breton (Section 2.3, Figure 2). *Exposure* and *Adaptive Capacity* indices of lobster harvesting scored moderate vulnerability, with *Sensitivity* scoring moderately low, resulting in overall moderate vulnerability (Section 4.2). LFA 26B had the highest vulnerability score for fisheries management flexibility. As with adjoining LFA 26A, this vulnerability could be improved by considering greater flexibility of fishing season start and end dates, by-catch flexibility, and trap limits. In making this recommendation it is assumed that any such adjustments, would need to be balanced against considerations of stock health.

LFA 27

This area covers the northeastern coast of Cape Breton, Nova Scotia and approximately three quarters of the Cabot Strait between Cape Breton, Nova Scotia, and Newfoundland (Section 2.3, Figure 2). This LFA had the second highest lobster harvesting *Sensitivity* score (Section 4.2), largely due to moderately high vulnerabilities in fisheries management flexibility, fishing infrastructure status, and financial resiliency (Section 4.2.5, Table 8). This suggests recommendations for improved flexibility around fishing season start and end dates and by-catch, assuming due considerations of stock and ecosystem health. The LFA ranked third most vulnerable for fishing infrastructure status (Section 4.2.5, Table 8) and support for infrastructure improvements should be considered.

LFA 29

This LFA borders eastern Nova Scotia from Guysborough to Point Michaud (Section 2.3, Figure 2). There was a moderately low *Exposure* score, and moderate vulnerability for the *Sensitivity* and *Adaptive Capacity* indices for the lobster harvesting model. (Section 4.2). As with many other LFAs, LFA 29 had a moderately high vulnerability score for fisheries management flexibility, suggesting this area could be improved to reduce *Sensitivity*. Fisheries flexibility (ability to switch between fisheries if needed) also scored moderately high vulnerability, suggesting either limited options or capacity to fish alterative species. Exploring options to diversify fishing opportunities in this LFA would be a logical next step. However, survey respondents reported that an average revenue loss of 62% was needed before they would stop fishing lobster (the 2nd lowest vulnerability sore among LFAs for the financial resiliency metric, Appendix C, Figure 6), which could reflect limited financial motivation among harvesters to explore other fisheries.

LFA 30

This LFA borders eastern Nova Scotia, from Guysborough to Lower Whitehead (Section 2.3, Figure 2). Lobster harvesting *Exposure* and *Adaptive Capacity* had low vulnerability scores, but *Sensitivity* was moderately high (Section 4.2). This was driven largely by the highest fisheries infrastructure vulnerability score across the province (Appendix C, Figure 1, Tables 1-3). Consequently, infrastructure assessment and investment should be a priority.

LFA 31

This LFA boarders eastern Nova Scotia from Whitehead to Ecum Secum (Section 2.3, Figure 2)[22]. With a moderate lobster harvesting vulnerability score for *Exposure*, *Sensitivity* and *Adaptive Capacity*, resulting in moderate overall vulnerability (Section 4.2). There was moderately high vulnerability for financial resiliency (Table 8, Appendix C, Figure 5) with the average revenue obtained from lobster fishing at 84.5% (Appendix C, Figure 6). LFA 31 also had moderately high vulnerability for personal flexibility (largely driven by a disagree response to the statement, 'If needed, I have other skills, experiences, or education which could help me change careers' (Appendix D, Figure 4). This suggests that LFA 31 could benefit from labour and skill diversification opportunities.

LFA 32

This LFA borders eastern Nova Scotia from Ecum Secum to Port La Tour (Section 2.3, Figure 2). *Sensitivity* had moderately high vulnerability (Section 5.2), mainly as a function of Fishery Management Flexibility and Financial Resilience. *Exposure* and *Adaptive Capacity* indices exhibited moderate vulnerability as did Lobster Harvesting (Section 4.2). Exploring options to improve fishery management flexibility, and opportunities for diversification could be a benefit to this LFA. LFA 32 also had the third highest vulnerability for suitable fishing days, suggests anticipation of greater vessel safety needs and modifications to accommodate more extreme conditions.

LFA 33

LFA 33 is large and extends from southeastern Nova Scotia at Cow Bay, southwest to Port La Tour (Section 2.3, Figure 2). This LFA scored moderately high vulnerability for the *Sensitivity* and *Adaptive Capacity* indices and high *Exposure* vulnerability, resulting in moderately high vulnerability for lobster harvesting (Section 4.2). The high *Exposure* score was driven by almost a 3rd of fishing days lost due to bad weather and the perception that suitable fishing days are decreasing. Efforts could focus on pending needs for increased vessel emergency and safety training, flexibility around start and end dates of fishing seasons to account for problematic weather and, anticipate future vessel needs to accommodate more extreme ocean conditions.

[22] It is partitioned into LFA 31A and B, but due to lower response rates in those areas, the data was pooled as one LFA.

LFA 34

This LFA borders southwestern Nova Scotia from Port La Tour to Digby (Section 2.3, Figure 2). LFA 34 had the highest overall vulnerability score for lobster harvesting, largely driven by high vulnerability to *Exposure*, and moderately high *Sensitivity* and *Adaptive Capacity* (Section 4.2). This LFA had high vulnerability for suitable fishing days, with almost a 3rd lost due to bad weather, and a wider perception that suitable fishing days are decreasing (Appendix E, Figure 14). LFA 34 also had moderately high fishing infrastructure vulnerability, financial resiliency, fisheries flexibility, and personal flexibility (Table 8). This resulted in this LFA having moderately high vulnerability for lobster harvesting (Figure 13). LFA 34 could benefit from increased vessel emergency and safety training, flexibility around start and end dates of fishing seasons to account for weather, and anticipate future vessel needs to accommodate more extreme ocean conditions. Investments in infrastructure should be prioritized, as well as diversification of labour and skill development opportunities.

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8 References

Adger, W. N. (2006). Vulnerability. *Global Environmental Change, 16*(3), 268-281. doi:10.1016/j.gloenvcha.2006.02.006

Aiken, D. E., Waddy, S. L. (1976). Controlling Growth And Reproduction In The American Lobster. *Proceedings of the annual meeting - World Mariculture Society, 7*(1-4), 415-430. doi:10.1111/j.1749-7345.1976.tb00079.x

Annis, E. R. (2005). Temperature effects on the vertical distribution of lobster postlarvae (*Homarus americanus*). *Limnology and Oceanography, 50*(6), 1972-1982. doi:10.4319/lo.2005.50.6.1972

Atkinson, D. E. et al. (2016). Dynamic coasts in a changing climate. In D. S. Lemmen, F. J. Warren, T. S. James, & C. S. L. Mercer Clarke (Eds.), *Canada's Marine Coasts in a Changing Climate* (pp. 27-69): Government of Canada.

Bartley, D. M. et al. (1980). Growth and conversion efficiency of juvenile American lobsters *(homarus americanus*) in relation to temperature and feeding level. *Proceedings of the World Mariculture Society, 11*(1-4), 355-368. doi:10.1111/j.1749-7345.1980.tb00130.x

Boyce, D. et al. (2021). Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic. Oceans North. Halifax, Nova Scotia. https://oceansnorth.org/wp-content/uploads/2021/05/Incorporating-climate-change-into-fisheries-management-in-Atlantic-Canada-and-the-Eastern-Arctic.pdf

Boyce, D. et al. (2023). A prospective framework to support climate-adaptive fisheries in Canada. *FACETS, 8*, 1-15. doi:10.1139/facets-2022-0164

Boyce, D. et al. (2022a). Operationalizing climate risk in a global warming hotspot. *bioRxiv*, 2022.2007.2019.500650. doi:10.1101/2022.07.19.500650

Boyce, D. et al. (2022b). A climate risk index for marine life. *Nature Climate Change*, 1-9. doi:10.1038/s41558-022-01437-y

Brennan, C. E. et al. (2019). How transport shapes copepod distributions in relation to whale feeding habitat: demonstration of a new modelling framework. *Progress in Oceanography, 171*, 1-21.

Brickman, D. et al. (2016). High resolution future climate ocean model simulations for the Northwest Atlantic Shelf region. Fisheries and Oceans canada (DFO), Bedford Institute of Oceanography, Dartmouth, Nova Scotia. https://waves-vagues.dfo-mpo.gc.ca/Library/365880.pdf

Bukvic, A. et al. (2020). A systematic review of coastal vulnerability mapping. *Sustainability, 12*. https://www.mdpi.com/2071-1050/12/7/2822

Camacho, J. et al. (2006). Temperature acclimation alters cardiac performance in the lobster *Homarus americanus*. *Journal of Comparative Physiology A, 192*, 1327-1334. doi:DOI 10.1007/s00359-006-0162-1

Aboriginal Communal Fishing Licences Regulations, (2023).

Carlin, D. (2020). Time to tackle humanity's greatest challenge: Climate change. *Forbes Magazine, New Jersey, USA*. https://www.forbes.com/sites/googlecloud/2022/02/24/does-ai-have-the-answer-to-the-customer-experience-riddle/?sh=5029f7236062

Carloni, J. T. et al. (2018). Bridging the spawner-recruit disconnect: trends in American lobster recruitment linked to the pelagic food web. *Bulletin of Marine Science, 94*(3), 719-735. doi:10.5343/bms.2017.1150

Chust, G. et al. (2013). Are *Calanus* spp. shifting poleward in the North Atlantic? A habitat modelling approach. *ICES Journal of Marine Science, 71*(2), 241-253. doi:10.1093/icesjms/fst147

Coffen-Smout, S. et al. (2013). Mapping inshore lobster landings and fishing effort on a maritimes region modified grid system. *Can. Tech. Rep. Fish. Aquat. Sci., 3024*.

Cook, A. M. et al. (2020a). 2017 Assessment of the Offshore American Lobster (*Homarus americanus*) in Lobster Fishing Area (LFA) 41. *DFO Can. Sci. Advis. Sec. Res. Doc., 2018/034*, vi + 82 p.

Cook, A. M. et al. (2020b). 2018 Framework Assessment of American Lobster (Homarus americanus) in LFA 27–33. *DFO Can. Sci. Advis. Sec. Res. Doc., 2020/017*.

COVE. (2022, November 3, 2022). *Advances in Clean Marine Propulsion.* Paper presented at the A COVE NSCC event, Dartmouth, Nova Scotia.

Crossin, G. et al. (1998). Behavioral thermoregulation in the American lobster *Homarus americanus*. *J Exp Biol, 201*(3), 365-374. https://jeb.biologists.org/content/jexbio/201/3/365.full.pdf

Denton, C. M. (2023). Maritimes Region Inshore Lobster Trawl Survey Technical Description. *Can. Tech. Rep. Fish. Aquat. Sci., 3376: v + 52 p.*

Department of Environment and Climate Change. (2022). Our Climate, Our Future Nova Scotia's Climate Change Plan for Clean Growth.

Department of Fisheries and Aquaculture. (2022). Department of Fisheries and Aquaculture Annual Plan 2022-2023. https://beta.novascotia.ca/sites/default/files/documents/1-3045/business-plan-2022-23-department-fisheries-and-aquaculture-en.pdf

DFO. (2006). A Harvest Strategy Compliant with the Precautionary Approach. *DFO Can. Sci. Advis. Sec. Sci. Advis. Rep., 2006/023*.

DFO. (2016). Update of the stock status indicators for the American lobster (Homarus americanus) stocks in the southern Gulf of St. Lawrence. *DFO Can. Sci. Advis. Sec. Sci. Resp.*

DFO. (2019a). Update of the stock status indicators of the American lobster (Homarus americanus) stock of the southern Gulf of St. Lawrence to 2018. *DFO Can. Sci. Advis. Sec. Sci. Resp.*

DFO. (2019b). Update of the Stock Status Indicators of the American Lobster, *Homarus Americanus*, Stock of the Southern Gulf of St. Lawrence to 2018. Canadian Science Advisory Secretariat.

DFO. (2020a). Assessment of the American Lobster (Homarus americanus) in Lobster Fishing Areas 27 - 32. https://publications.gc.ca/collections/collection_2020/mpo-dfo/fs70-6/Fs70-6-2020-026-eng.pdf

DFO. (2020b). Proceedings of the Regional Peer Review of the Stock Assessment of American Lobster in Lobster Fishing Area (LFA) 41; September 27-28, 2017. *DFO Can. Sci. Advis. Sec. Proceed. Ser., 2021/010*.

DFO. (2023a). Stock Status Update for American Lobster (Homarus americanus) in Lobster Fishing Area 33 for 2022. *DFO Can. Sci. Advis. Sec. Sci. Resp., 2023/007*.

DFO. (2023b). Stock Status Update of Lobster (Homarus americanus) in Lobster Fishing Area 35 for 2022. *DFO Can. Sci. Advis. Sec. Sci. Resp., 2023/006*.

Dove, A. D. M. et al. (2005). A prolonged thermal stress experiment on the American lobster, Homarus americanus. *Journal of Shellfish Research, 24*(3), 761-765. https://www.scopus.com/inward/record.uri?eid=2-s2.0-33646758848&partnerID=40&md5=c212f84ccc3332b7d735df009c5e8e5b

Dudley, P. N. et al. (2021). A More Comprehensive Climate Vulnerability Assessment Framework for Fisheries Social-Ecological Systems. *Frontiers in Marine Science, 8*, 674. https://www.frontiersin.org/article/10.3389/fmars.2021.678099

Environment and Climate Change Canada. (2019). Canada's Changing Climate Report. Government of Canada. Ottawa ON. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/Climate-change/pdf/CCCR_FULLREPORT-EN-FINAL.pdf

European Environment Agency. (2021). Climate change is one of the biggest challenges of our times. Accessed March 3, 2022. https://www.eea.europa.eu/themes/climate

Fagan, K. (2022). Lobster industry clawing back from COVID-19 pandemic hits. *SeaWestNews*. https://seawestnews.com/lobster-industry-clawing-back-from-covid-19-pandemic-hits/

Felix, J. R. (1978). *The effects of temperature change on growth and survival of Aamerican lobsters (Homarus americanus).* San Diego State University, USA,

Fennel, K. et al. (2022). Ocean biogeochemical modelling. doi:10.1038/s43586-022-00154-2

Fisheries and Ocean Canada. (2020). Lobster Fishing Areas 27 - 38 Integrated Fisheries Management Plan. https://www.dfo-mpo.gc.ca/fisheries-peches/ifmp-gmp/maritimes/2019/inshore-lobster-eng.html

Fisheries and Oceans Canada. (2018). Stock status update of American lobster (*Homarus americanus*) in Lobster Fishing Area 34. Canadian Science Advisory Secretariat. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2018/2018_044-eng.html

Fisheries and Oceans Canada. (2021a). Assessment of American lobster (*Homarus americanus*) in lobster fishing area 34. Fisheries and Oceans Canada (DFO), Maritimes Region, Ecosystems and Oceans Science. https://waves-vagues.dfo-mpo.gc.ca/Library/40976002.pdf

Fisheries and Oceans Canada. (2021b). Assessment of American Lobster (*Homarus Americanus*) in Lobster Fishing Areas 34. Canadian Science Advisory Secretariat.

Fisheries and Oceans Canada. (2021c). Assessment of American Lobster (*Homarus Americanus*) in Lobster Fishing Areas 35 - 38. Canadian Science Advisory Secretariat.

Fisheries and Oceans Canada. (2022a). Commercial fisheries. https://www.dfo-mpo.gc.ca/stats/commercial-eng.htm

Fisheries and Oceans Canada. (2022b). North Atlantic right whales - 2022 fishery management measures. https://www.dfo-mpo.gc.ca/fisheries-peches/commercial-commerciale/atl-arc/narw-bnan/management-gestion-eng.html

Fisheries and Oceans Canada. (2022c). Oceanographic Conditions in the Atlantic Zone in 2021.

Fisheries and Oceans Canada. (2022d). Stock Status Update of Lobster (*Homarus Americanus*) in Lobster Fishing Areas 36 and 38 for 2021. Canadian Science Advisory Secretariat.

Fisheries and Oceans Canada. (2022e). Stock Status Update of Lobster (*Homarus Americanus*) in Lobster Fishing Areas 41 (4X + 5ZE) for 2021. Canadian Science Advisory Secretariat.

Ford, R. F. et al. (1979). Effects of fluctuating and constant temperatures and chemicals in thermal effluent on growth and survival of the American lobster (*Homarus americanus*). *Proceedings of the World Mariculture Society, 10*(1-4), 139-158. doi:10.1111/j.1749-7345.1979.tb00014.x

Forsyth, J. S. T. et al. (2015). Recent accelerated warming of the continental shelf off New Jersey: Observations from the CMV Oleander expendable bathythermograph line. *Journal of Geophysical Research: Oceans, 120*(3), 2370-2384. doi:10.1002/2014JC010516

Frölicher, T. L. et al. (2018). Marine heatwaves under global warming. *Nature, 560*(7718), 360-364. doi:10.1038/s41586-018-0383-9

FuelCellsWorks. (2019). Japan to Power Fishing Boats with Toyota's Hydrogen Fuel Cells. *FuelCellsWorks*. https://fuelcellsworks.com/news/japan-to-power-fishing-boats-with-toyotas-hydrogen-fuel-cells/#:~:text=Hydrogen%20fuel%20cells%20power%20a%20motor%20by%20producing,in%20fiscal%202019%20to%20test%20safety%20and%20practicality.

Füssel, H.-M., Klein, R. J. T. (2006). Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. *Climatic Change, 75*(3), 301-329. doi:10.1007/s10584-006-0329-3

Gledhill, D. K. et al. (2015). Ocean and coastal acidification off New England and Nova Scotia. *Oceanography, 28*(2), 182-197. http://www.jstor.org/stable/24861880

Gori, M. (2018). Chapter 2 - Learning Principles. In M. Gori (Ed.), *Machine Learning* (pp. 60-121). Cambridge, MA USA: Morgan Kaufmann.

Government of Canada. (2022). Seafisheries landed value by province, 2021. https://www.dfo-mpo.gc.ca/stats/commercial/land-debarq/sea-maritimes/s2021pv-eng.htm

Greenan, B. et al. (2019). Climate change vulnerability of American lobster fishing communities in Atlantic Canada. *Frontiers in Marine Science, 6*, 18. doi:10.3389/fmars.2019.00579

Guo, X. et al. (2022). Threat by marine heatwaves to adaptive large marine ecosystems in an eddy-resolving model. *Nature Climate Change, 12*(2), 179-186. doi:10.1038/s41558-021-01266-5

Hagan, J., Nelson, R. (2022). EV on H2O? The feasibility of electrifying Maine's lobster fleet. Georgetown, Maine. https://maineclimatetable.org/electrifying-the-lobster-fleet/?fbclid=IwAR1DjajUSU1vmSeVhKZ0R_lZ30JI4XxmE_tCARD8gbjoY1DEiFhtwQVfb-0

Harrington, A. M. et al. (2019). Effects of temperature on larval American lobster (Homarus americanus): Is there a trade-off between growth rate and developmental stability? *Ecological Indicators, 96*, 404-411. doi:https://doi.org/10.1016/j.ecolind.2018.09.022

Howarth, L. M. et al. (2021). Assessing climate change vulnerability of seafood industry-dependent communities in Nova Scotia. Centre for Marine Applied Research (CMAR), Dartmouth, Nova Scotia, Canada. https://cmar.ca/2021/01/25/assessing-climate-change-vulnerability-of-seafood-dependent-communities-in-nova-scotia/

Hunter, K. L. et al. (2015). Climate change vulnerability assessment methodology workshop proceedings. *Canadian Manuscript Report of Fisheries and Aquatic Sciences, 3086*, 20 pp.

Huntsman, A. G. (1924). No. 5: Limiting factors for marine animals.: 2. Resistance of larval lobsters to extremes of temperature. *Contributions to Canadian Biology and Fisheries, 2*(1), 89-93. doi:10.1139/f24-005

Intrafish Media. (2020). Clearwater sells lobster fishing licenses to First Nations group for $19 million,. *IntraFish*. https://www.intrafish.com/finance/clearwater-sells-lobster-fishing-licenses-to-first-nations-group-for-19-million/2-1-871557

IPCC. (2014). Climate change 2014: Synthesis report. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. https://www.ipcc.ch/reports/?rp=ar5

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

IPCC. (2022a). Climate change 2022. Impacts, adaptation and vulnerability. Full Report. Intergovernmental Panel of Climate Change (IPCC), United Nations (UN). https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf

IPCC. (2022b). Climate change 2022. Impacts, adaptation and vulnerability. Summary for policy makers. Intergovernmental Panel of Climate Change (IPCC), United Nations (UN). https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_FullReport.pdf

IPCC. (2023). Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6): Summary for Policymakers. 36. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

Islam, M. M. et al. (2019). Vulnerability of inland and coastal aquaculture to climate change: Evidence from a developing country. *Aquaculture and Fisheries, 4*(5), 183-189. doi:10.1016/j.aaf.2019.02.007

James, T. S. et al. (2014). Relative sea-level projections in Canada and the adjacent mainland United States. Geological Survey Canada, Ottawa, Ontario. https://northsaanich.ca/wp-content/uploads/Relative-Sea-level-Project-in-Canada-Adjacent-Mainland-US.pdf

Jost, J. A. et al. (2012). Enhancing thermal tolerance by eliminating the pejus range: a comparative study with three -decapod crustaceans. *Marine Ecology Progress Series, 444*, 263-274. https://www.int-res.com/abstracts/meps/v444/p263-274/

Jury, S. H., Watson III, W. H. (2013). Seasonal and sexual differences in the thermal preferences and movements of American lobsters. *Canadian Journal of Fisheries and Aquatic Sciences, 70*(11), 1650-1657. doi:10.1139/cjfas-2013-0061

Kling, M. M. et al. (2020). Multiple axes of ecological vulnerability to climate change. *Glob Chang Biol, 26*(5), 2798-2813. doi:10.1111/gcb.15008

Knutson, T. et al. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society, 101*(3), E303-E322. doi:10.1175/BAMS-D-18-0194.1

Knutson, T. R. et al. (2021). Climate change is probably increasing the intensity of tropical cyclones. ScienceBrief. https://news.sciencebrief.org/cyclones-mar2021/

Krishnan, P. et al. (2019). Framework for mapping the drivers of coastal vulnerability and spatial decision making for climate-change adaptation: A case study from Maharashtra, India. *Ambio, 48*(2), 192-212. doi:10.1007/s13280-018-1061-8

Laufer, H. et al. (2013). Multiple factors in marine environments affecting lobster survival, development, and growth, with emphasis on alkylphenols: A perspective. *Canadian Journal of Fisheries and Aquatic Sciences, 70*(11), 1588-1600. doi:10.1139/cjfas-2013-0148

Le Bris, A. et al. (2018). Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences, 115*(8), 1831-1836. doi:10.1073/pnas.1711122115

Légère, P. (2023). N.S. fishermen say province isn't doing enough to cover wildfire losses. *CBC News*. https://www.cbc.ca/news/canada/nova-scotia/fishermen-province-not-doing-enough-wildfires-losses-1.6930632

MacKenzie, B. R. (1988). Assessment of temperature effects on interrelationships between stage durations, mortality, and growth in laboratory-reared *Homarus americanus* Milne Edwards larvae. *Journal of Experimental Marine Biology and Ecology, 116*(1), 87-98. doi:https://doi.org/10.1016/0022-0981(88)90248-1

Mafi-Gholami, D. et al. (2020). Vulnerability of coastal communities to climate change: Thirty-year trend analysis and prospective prediction for the coastal regions of the Persian Gulf and Gulf of Oman. *Science of the Total Environment, 741*, 140305. doi:10.1016/j.scitotenv.2020.140305

Marshall, N. et al. (2013a). Climate change awareness is associated with enhanced adaptive capacity. *Agricultural Systems, 117*, 30–34. doi:10.1016/j.agsy.2013.01.003

Marshall, N. et al. (2013b). Social vulnerability of marine resource users to extreme weather events. *Ecosystems, 16*. doi:10.1007/s10021-013-9651-6.

McLeese, D. W. (1956). Effects of temperature, salinity, and oxygen on the survival of the American lobster. *Journal of the Fisheries Research Board of Canada, 13*(2), 247-272.

Mercer, G. (2020). Nova Scotia lobster processors call for a hault to harvesting as market for shellfish collapses amid COVID-19 pandemic. *The Globe and Mail*. https://www.theglobeandmail.com/business/article-nova-scotia-lobster-processors-call-for-a-halt-to-harvesting-as-market/

Nielsen, T. V., McGaw, I. J. (2016). Behavioral thermoregulation and trade-offs in juvenile lobster Homarus americanus. *Biological Bulletin, 230*(1), 35-50. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84958745266&partnerID=40&md5=7efbb71334e02170fac3b113ea6bb4cf

Oceans North. (2022). Fishing for Climate Solutions: New Study Will Examine How Nova Scotia's Lobster Vessels Can Achieve Net-zero Emissions [Press release]. Retrieved from https://www.oceansnorth.org/en/blog/2022/06/fishing-for-climate-solutions-new-study-will-examine-how-nova-scotias-lobster-vessels-can-achieve-net-zero-emissions/

Palmeter, P. (2022). DFO shutting down herring, mackerel fisheries on East Coast. *CBC*. https://www.cbc.ca/news/canada/nova-scotia/dfo-shutting-down-herring-mackerel-fishery-1.6402779#:~:text=The%20Department%20of%20Fisheries%20and,well%20with%20the%20fishing%20community.

Paterson, W. D., Stewart, J. E. (1974). In Vitro Phagocytosis by Hemocytes of the American Lobster (Homarus americanus). *Journal of the Fisheries Research Board of Canada, 31*(6), 1051-1056. doi:10.1139/f74-119

Pershing, A. J. et al. (2015). Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science, 350*(6262), 809-812. doi:10.1126/science.aac9819

Pourfaraj, V. et al. (2022). Workshop on development of an Interactional Map of the Social-Ecological System for American Lobster (Homarus americanus) in the Maritimes region.

Province of Nova Scotia. (2023). Mandate, Vision & Mission. Accessed June 19, 2023. https://novascotia.ca/fish/about/mandate/

Quinn, B. K. (2017). Threshold temperatures for performance and survival of American lobster larvae: A review of current knowledge and implications to modeling impacts of climate change. *Fisheries Research, 186*, 383-396. doi:10.1016/j.fishres.2016.09.022

Reid, G. K. et al. (2019). Climate change and aquaculture: considering adaptation potential. *Aquaculture Environment Interactions, 11*, 603-624.

Reid, G. K. et al. (2022). A rapid climate change vulnerability assessment of Nova Scotian fisheries and fishing communities. Dartmouth, Nova Scotia.

Rondeau, A. et al. (2014). Assessment of the American Lobster (Homarus americanus) Stock Status in the Southern Gulf of St. Lawrence (LFA 23, 24, 25, 26A and 26B). *DFO Can. Sci. Advis. Sec. Res. Doc., 2014/036. xii*, 92 p.

Sarkodie, S. A., Strezov, V. (2019). Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: Evidence from 192 countries. *Science of the Total Environment, 656*, 150-164. doi:10.1016/j.scitotenv.2018.11.349

Serdynska, A., Coffen-Smout, S. (2017). *Mapping Inshore Lobster Landings and Fishing Effort on a Maritimes Region Statistical Grid (2012–2014)* [Vector Shapefile]. Retrieved from: https://open.canada.ca/data/en/dataset/64f741d7-1129-49dd-9e5c-2b1de79024f0

Shackell, N. L. et al. (2014). Thermal habitat index of many Northwest Atlantic temperate species stays neutral under warming projected for 2030 but changes radically by 2060. *Plos One, 9*(3), e90662. doi:10.1371/journal.pone.0090662

Smale, D. A. et al. (2019). Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change, 9*(4), 306-312. doi:http://dx.doi.org/10.1038/s41558-019-0412-1

Smit, B., Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change, 16*(3), 282-292. doi:10.1016/j.gloenvcha.2006.03.008

Soares, R. et al. (2012). Mass spectrometry and animal science: Protein identification strategies and particularities of farm animal species. *Journal of Proteomics, 75*(14), 4190-4206. doi:http://dx.doi.org/10.1016/j.jprot.2012.04.009

Soto, D. et al. (2019). Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. *Reviews in Aquaculture, 11*(2), 354-374. doi:10.1111/raq.12336

Soto, D. et al. (2018). Climate change and aquaculture: vulnerability and adaptation options. In M. Barange, T. Bahri, M. C. M. Beveridge, K. L. Cochrane, S. Funge-Smith, & F. Poulain (Eds.), *Impacts of climate change on fisheries and aquaculture* (pp. 465-490): Food and Agricultural Organization (FAO), Rome, Italy.

Spees, J. L. et al. (2002). Thermal acclimation and stress in the American lobster, Homarus americanus: Equivalent temperature shifts elicit unique gene expression patterns for molecular chaperones and polyubiquitin. *Cell Stress and Chaperones, 7*(1), 97-106. doi:10.1379/1466-1268(2002)007<0097:TAASIT>2.0.CO;2

Steneck, R. S., Wahle, R. A. (2013). American lobster dynamics in a brave new ocean. *Canadian Journal of Fisheries and Aquatic Sciences, 70*(11), 1612-1624. doi:10.1139/cjfas-2013-0094

Stephenson, R. L. et al. (2019a). A practical framework for implementing and evaluating integrated management of marine activities. *Ocean & Coastal Management, 177*, 127-138. doi:10.1016/j.ocecoaman.2019.04.008

Stephenson, R. L. et al. (2018). Evaluating and implementing social–ecological systems: A comprehensive approach to sustainable fisheries. *Fish and Fisheries, 19*(5), 853-873. doi:https://doi.org/10.1111/faf.12296

Stephenson, R. L. et al. (2019b). Integrating diverse objectives for sustainable fisheries in Canada. *Canadian Journal of Fisheries and Aquatic Sciences, 76*(3), 480-496. doi:10.1139/cjfas-2017-0345

Stortini, C. H. et al. (2015). Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. *ICES Journal of Marine Science, 72*(6), 1731-1743. doi:10.1093/icesjms/fsv022

Tai, T. et al. (2021). Modelling ocean acidification effects with life stage-specific responses alters spatiotemporal patterns of catch and revenues of American lobster, *Homarus americanus*. *Nature Scientific Reports, 11*, 14.

Taleb, N. N. (2010). The Black Swan: The Impact of the Highly Improbable (2nd ed.). London, England: Penguin.

The Global Commission on Adaptation. (2019). Adapt now: a global call for leadership on climate resilience. 81. https://gca.org/wp-content/uploads/2019/09/GlobalCommission_Report_FINAL.pdf

The United Nations Refugee Agency. (2020). Climate change is the defining crisis of our time. Accessed March 3, 2022. https://www.unhcr.org/news/latest/2020/11/5fbf73384/climate-change-defining-crisis-time-particularly-impacts-displaced.html

Thomas, K. et al. (2019). Explaining differential vulnerability to climate change: A social science review. *Wiley Interdisciplinary Reviews Climate Change, 10*(2), e565. doi:10.1002/wcc.565

Tlusty, M. F., Metzler, A. (2012). Relationship between temperature and shell disease in laboratory populations of juvenile American lobsters (Homarus americanus). *Journal of Shellfish Research, 31*(2), 533-541. doi:10.2983/035.031.0213

Tri-Council. (2013). Annotated guidelines for completing the joint UVIC/VIHA application for ethics approval for human participant research. SSHRC: Social Sciences and Humanities Research Council; NSERC: National Sciences and Engineering Research Council; and CIHR: Canadian Institute of Health Research. https://www.uvic.ca/research/assets-old/docs/ors/forms/ethics/human/Joint_UVic_VIHA_Annotated_Guidelines.pdf

Tutton, M. (2022). Mi'kmaw First Nation, environmental group work on creating zero-emission lobster boat. *Global News*. https://globalnews.ca/news/9320551/membertou-oceans-north-electric-lobster-boat/

Undercurrent News. (2022). Hurricane Fiona damage estimates ratchet up for Nova Scotia lobster plant. https://www.undercurrentnews.com/2022/10/05/hurricane-fiona-damage-estimates-ratchet-up-for-nova-scotia-lobster-plant/

United Nations. (2021). The climate crisis – a race we can win. Accessed March 3, 2022. https://www.un.org/en/un75/climate-crisis-race-we-can-win

Villarino, E. et al. (2015). Modelling the future biogeography of North Atlantic zooplankton communities in response to climate change. *Marine Ecology Progress Series, 531*, 121-142. https://www.int-res.com/abstracts/meps/v531/p121-142/

Waller, J. D. et al. (2017). Linking rising pCO_2 and temperature to the larval development and physiology of the American lobster (*Homarus americanus*). *ICES Journal of Marine Science, 74*(4), 1210-1219. doi:10.1093/icesjms/fsw154

Withers, P. (2021a). Global pandemic took double-digit bite out of Nova Scotia seafood exports. *CBC*. https://www.cbc.ca/news/canada/nova-scotia/nova-scotia-seafood-exports-pandemic-1.6047713

Withers, P. (2021b). Sipekne'katik pivots on controversial lobster fishery in southwest N.S. *CBC*. https://www.cbc.ca/news/canada/nova-scotia/sipekne-katik-pivots-on-controversial-lobster-fishery-1.6043018

Woods, P. et al. (2021). A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change. *ICES Journal of Marine Science*. doi:10.1093/icesjms/fsab146

Worden, M. K. et al. (2006). Temperature dependence of cardiac performance in the lobster *Homarus americanus*. *Journal of Experimental Biology, 209*, 1024-1034.

Wu, L. et al. (2012). Enhanced warming over the global subtropical western boundary currents. *Nature Climate Change, 2*(3), 161-166. doi:10.1038/nclimate1353

Wucker, M. (2016). The Gray Rhino: How to Recognize and Act on the Obvious Dangers We Ignore. London, England: Macmillan.

Zhai, L. et al. (2014). Estimating sea-level allowances for the coasts of Canada and the adjacent United States using the fifth Assessment Report of the IPCC. Fisheries and Oceans Canada.

Appendix A: Temperature thresholds and lobster stages

Table 1 | Water temperature tolerance for various life stages of lobster.

Lobster Stage	Optimal	Sub-optimal	Stressful	Lethal
Larvae	15 - 18 [1]	18 - 20 [2]	23°C - 26 [3]	26.0 - 33.8 [4]
Juveniles	15 - 17 [5]	18 - 20 [6]	16 - 26.3 [7]	27 - 35.5 [8]
Adults	12 - 15 [9]	16 – 20 [10]	≥20 [11]	25 - 32 [12]

Note: studies encompass a wide range of lobster research, which may include assessment of a lobster stage or a specific aspect (within a stage), such as a physiological or immune parameter. 'Optimal' is classified as ideal or best performance. 'Sub-optimal' are ranges which are not optimal, but not necessarily considered as stressful or damaging. The 'Stressful' category includes ranges which are associated with stress responses or damage. 'Lethal' describes conditions where mortality can occur.

References

[1] Ford et al., 1979; MacKenzie, 1988; Quinn, 2017; Waller et al. 2017; Harrington et al. 2019

[2] Huntsman, 1924; Felix, 1978; Ford et al., 1979; Nielsen and McGaw, 2016; Quinn, 2017

[3] Ford et al., 1979; Quinn, 2017

[4] Huntsman, 1924; Quinn, 2017, Annis et al. 2022

[5] McLeese, 1956; McLeese and Wilder, 1958; Jost et al., 2012; Quinn, 2017

[6] McLeese and Wilder, 1958; Ford et al., 1975; Aiken and Waddy, 1976; Crossin et al., 1998; Jury and Watson III, 2013; Nielsen and McGaw, 2016; Quinn, 2017

[7] Huntsman, 1924; Bartley et al., 1980; Nielsen and McGaw, 2016; Quinn, 2017

[8] Huntsman, 1924; Felix, 1978; Ford et al., 1979; Nielsen and McGaw, 2016; Quinn, 2017

[9] Crossin et al., 1998

[10] McLeese and Wilder, 1958; Ford et al., 1975; Aiken and Waddy, 1976; Crossin et al., 1998; Jury and Watson III, 2013; Nielsen and McGaw, 2016; Quinn, 2017

[11] Laufer et al., 2013; Steneck and Wahle, 2013; Quinn, 2017

[12] Paterson and Stewart, 1974; Spees et al., 2002; Dove et al., 2005; Camacho et al., 2006; Worden et al., 2006; Jost et al., 2012, McLeese, 1956; Quinn, 2017

Appendix B: Lobster harvesters exposure metrics and sub-metrics

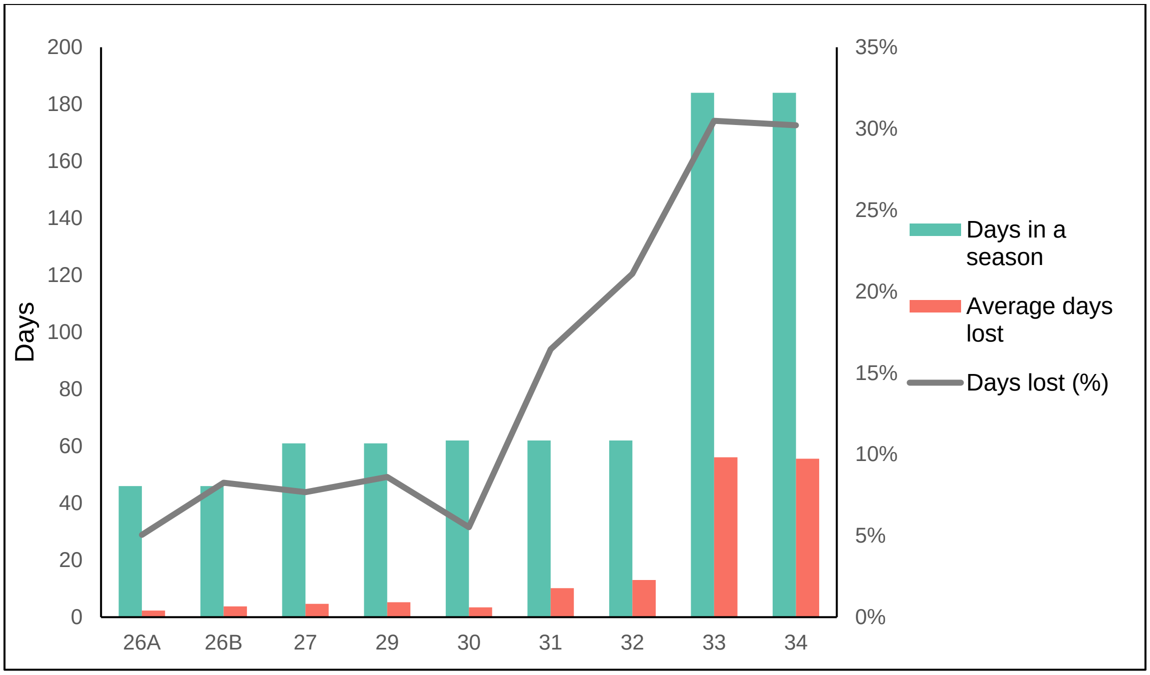

Figure 1 | On average, how many fishing days do you lose a year due to bad weather?

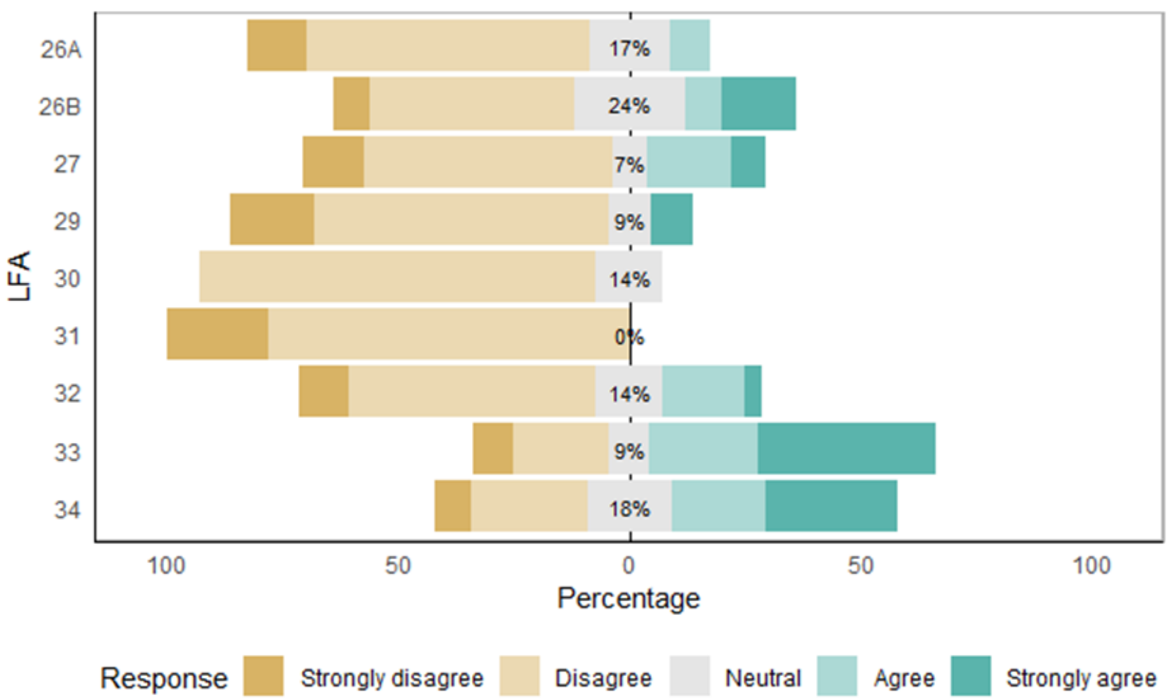

Figure 2 | Number of fishing days lost to bad weather has increased:

Appendix C: Lobster harvesters sensitivity metrics and sub-metrics

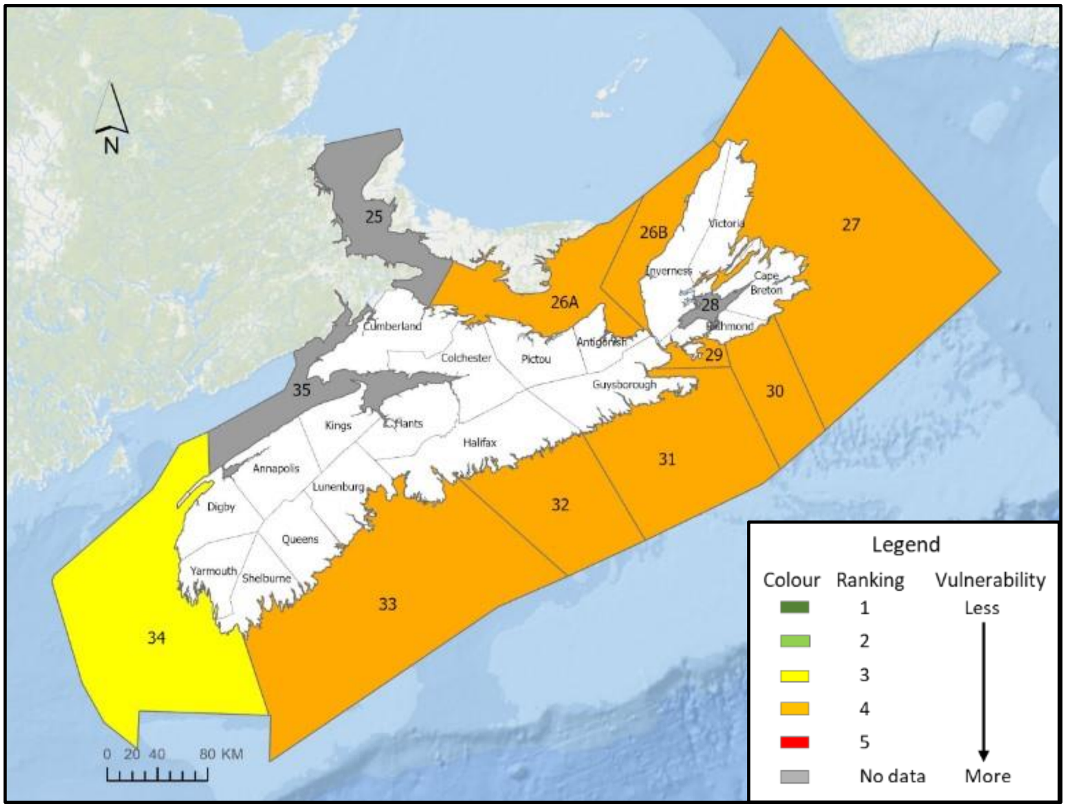

Figure 1 | Fisheries management flexibility. An average of fisheries management matrix sub-metric and conservation score sub-metric.

Table 1 | Fisheries management matrix sub-metric inputs and scores

LFA	Species probability of occurrence (%)	Species flexibility score	Season Months	Season flexibility score	By-catch flexibility	By-catch flexibility score	Maximum number of traps	Maximum number of traps	Final score
25	48.50%	3	2.1	5	Male Rock Crab by-catch may be landed and sold in all areas	4	225	5	4.3
26A-1			1.5	5		4	280	4	4.3
26A-2	32.00%	4	1.5	5		4	255	4	4.3
26A-3			1.5	5		4	250	5	4.7
26B South	73.00%	2	1.5	5		4	250	5	4.0
26B North			1.5	5		4	250	5	4.0
27	87.53%	1	2.0	5		4	275	4	3.5
28	100.00%	1	2.0	5		4	250	5	3.8
29	21.91%	4	2.0	5		4	250	5	4.5
30	99.00%	1	2.1	5		4	250	5	3.8
31A	100.00%	1	2.1	5		4	250	5	3.8
31B	98.00%	1	2.1	5		4	250	5	3.8
32	91.67%	1	2.1	5		4	250	5	3.8
33	87.64%	1	6.1	3		4	250	5	3.3
34	91.82%	1	6.1	3	Some: Male Jonah Crab may be used as bait or landed and sold in LFAs 34-38. Male Rock Crab by-catch may be landed and sold in all areas.	3	375/400	2	2.3
35	90.00%	1	7.8	3		3	300	4	2.8
36	96.17%	1	5.3	3		3	300	4	2.8
38			7.8	3		3	375	2	2.3
38B	84.14%	1	4.3	4		3	375	2	2.5
41	76.12%	2	12.0	1	Male Rock Crab by-catch may be landed and sold in all areas	4	No trap limit (TAC)	1	2.0

Table 2 | Conservation sub-metric inputs and scores

LFA	Minimum legal carapace size (mm)	Minimum legal carapace size (mm)	Window size females (mm)	V-notch female lobsters	Conservation	Score
25	79	3	>/= 115	N	2	2.5
26A-1	75	4	115-129	N	2	3.0
26A-2	76	4	115-129	N	2	3.0
26A-3	76	4	115-129	N	2	3.0
26B South	82.5	2		N	5	3.5
26B North	82.5	2		N	5	3.5
27	82.5	2		N	5	3.5
28	84	1		Y	4	2.5
29	84	1		Y	4	2.5
30	82.5	2	Max. CL-135mm (female)	Y	1	1.5
31A	82.5	2	114-124	N	2	2.0
31B	82.5	2		Y * v-notch program	3	2.5
32	82.5	2		Y * v-notch program	3	2.5
33	82.5	2		Y	4	3.0
34	82.5	2		Y	4	3.0
35	82.5	2		Y	4	3.0

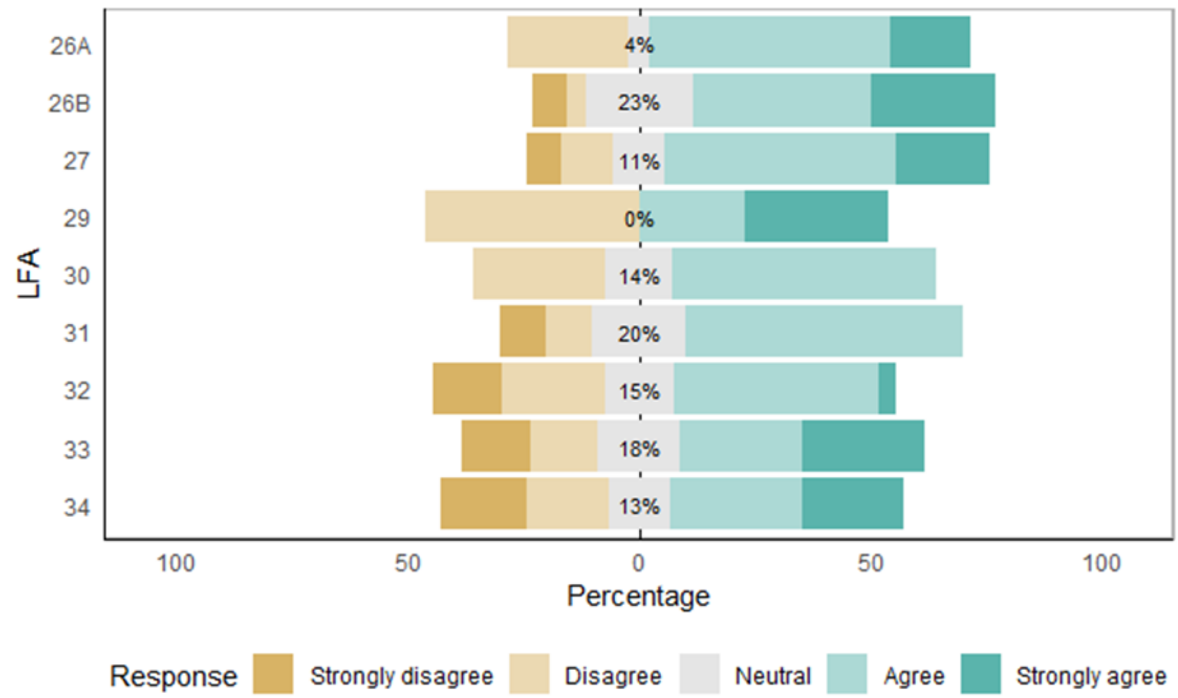

Figure 2 | Fishing seasons should be adjusted to account for ocean changes by LFA:

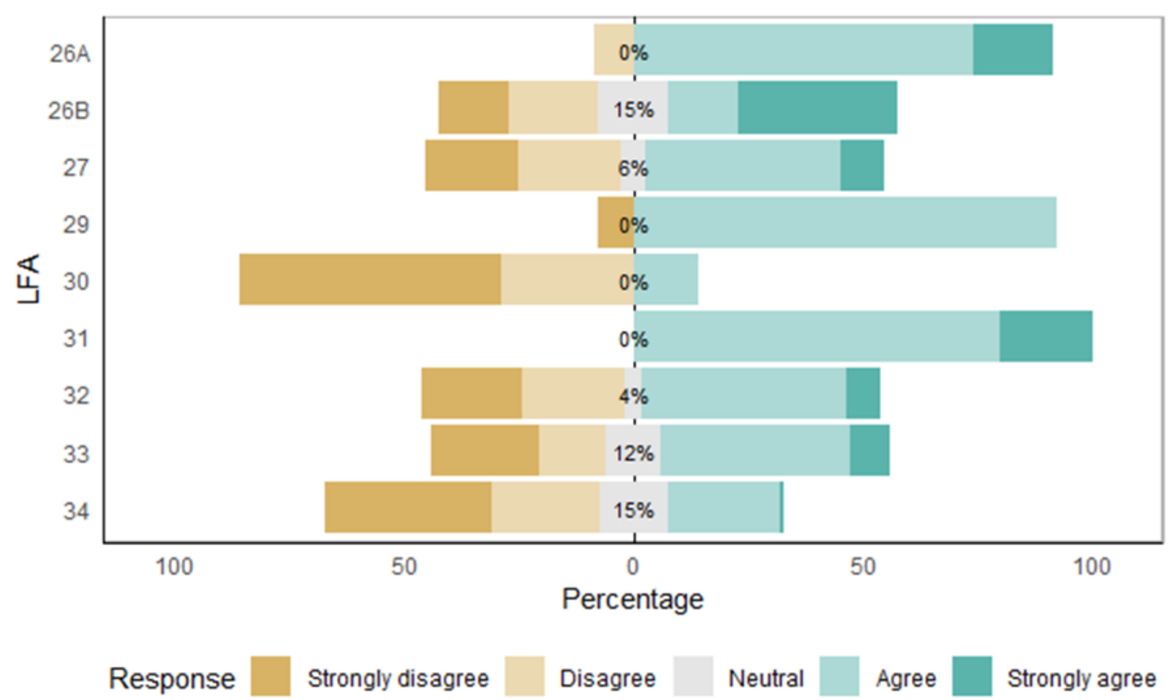

Figure 3 | Survey responses for “My key fishing wharves are in good repair by LFA”

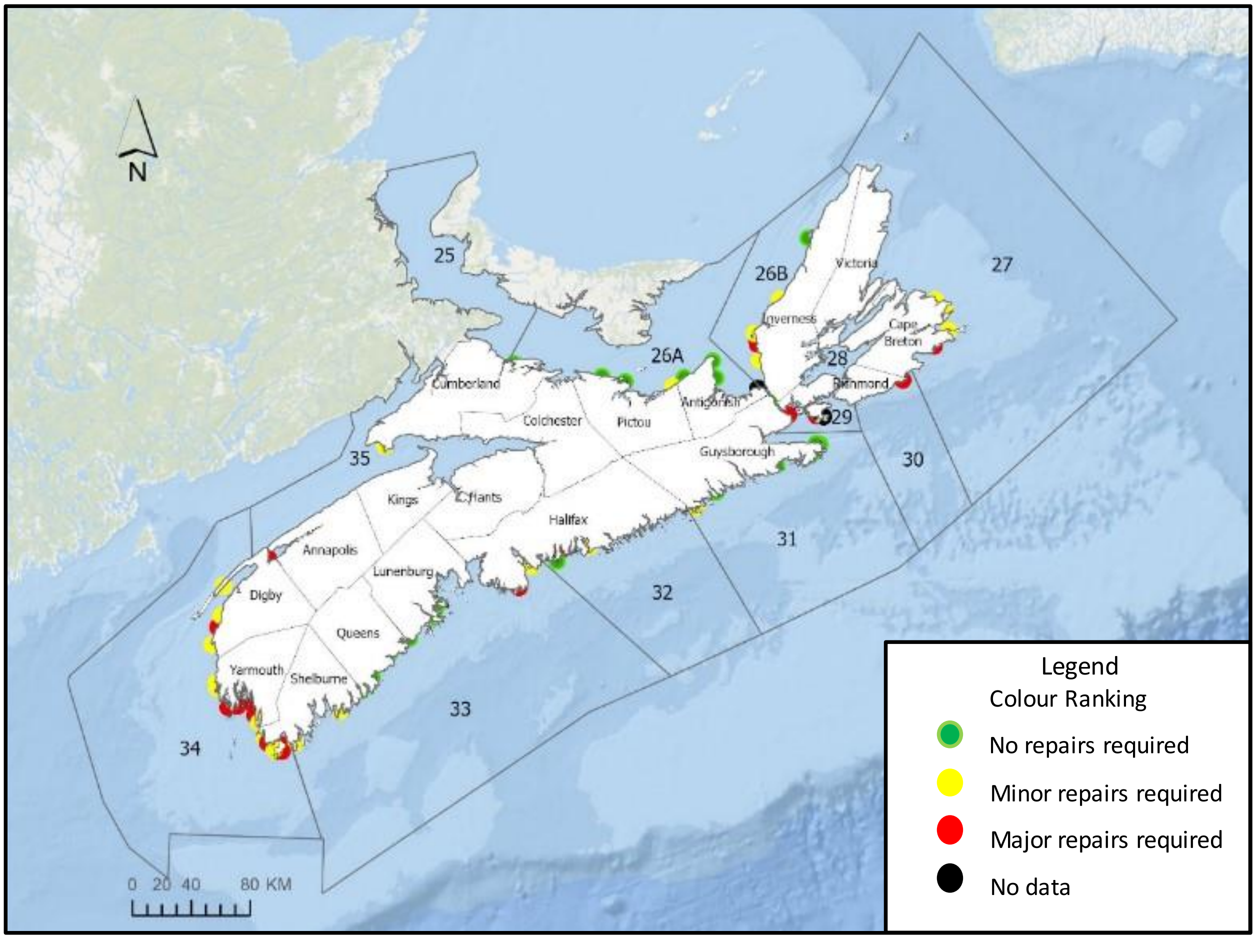

Figure 4 | Relative fishing infrastructure status across Lobster Fishing Areas (LFA), ratings are a combination of CRC and lobster harvester opinions.

Table 4 | Wharf state queries posed to Department of Fisheries and Aquaculture's Coastal Resource Coordinators (CRCs).

Survey details	Wharf details	Wharf usage	Condition details	Condition summary
- Date assessed - Name of surveyor	- Wharf common name - County - Location/Community - Ownership - If private, include contact information - Estimated age of the facilities (years)	(user numbers partitioned 0-10, 10-20, >20; or uncertain) - Harvesters - Recreational - Tourism - Sport fishing - Ferry - Other	- Gaps/ broken decking - Broken pilings - Missing clears - Missing bumpers - Underpinning damage - Other	- Minor repair required - Major repair required - No repair required

Table 5. Coastal Resource Coordinator (CRC) evaluation of wharf condition[1]

LFA	Wharf Name	Condition	Condition Details
26A	Arsaig	No repair required	
26A	Ballantynes Cove	No repair required	
26A	Caribou Ferry	No repair required	
26A	Cribbons Point	No repair required	
26A	Havre Boucher	Not completed	Not completed
26A	Lismore/ Baileys Brook	Minor repair required	Broken pilings
26A	Pugwash	No repair required	
26A	Toney River	No repair required	
26B	Baxter Cove	Minor repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage, Armour stone needed for breakwater, Need major overhaul, Electrical
26B	Cheticamp/ La Digue	No repair required	
26B	Inverness	Minor repair required	Dredging, Slipway repairs, Electrical, Floating dock repairs
26B	Little Judique Ponds	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage, Dredging, Electrical, Tidal surge upgrade
26B	Murphy's Pond	Minor repair required	Gaps / broken decking, Broken pilings, Tidal surge upgrade, Parking lot undermining through to wharf, Armour stone needed for breakwater
27	Bay St. Lawrence	No survey response	
27	Glace Bay	Minor repair required	Gaps / broken decking, Missing bumpers, Dredging required every 3-5 years
27	Louisbourg	Major repair required	Gaps / broken decking, Missing bumpers, Outermost T section of wharf has significant undermining
27	Main-À-Dieu	Minor repair required	Missing bumpers, Corner of wharf has significant undermining, Additional berths needed
27	Port Morien	Minor repair required	Missing bumpers, Dredging required every 4-5 years, Breakwaters require extension and widening, Sediment build-up from storms
29	Arichat	Major repair required	Gaps/ broken decking, Broken pilings, Missing bumpers, Underpinning damage
29	Canso	No repair required	
29	Mulgrave	No repair required	
29	Petit de Grat	Not completed	Not completed

30	Fourchu	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage, Dredging, Electrical, Tidal surge protection with Armour stone
31	Country Harbour	Major repair required	Possible undermining
31	Larry's River	No repair required	
31	Little Dover	No repair required	
31	Sandy Point	Major repair required	Broken pilings, Missing cleats, Missing bumpers
31	Sonora Harbour	No repair required	
31	Tickle Wharf	No repair required	
32	East Chezzetcook Harbour	Major repair required	Damage to the underside of the wharf, Gaps / broken decking
32	East Jeddore	Minor repair required	Possible undermining
32	Eastern Passage	Minor repair required	Broken pilings
32	Marie Joseph	Minor repair required	Gaps / broken decking, Damaged deck plankings
32	Three Fathom Harbour	No repair required	
33	East Port L'Herbert	No repair required	
33	Gunning Cove	No survey response	
33	Ingomar	No survey response	
33	LaHave (Clearwater)	No repair required	
33	Liverpool (Mersey Seafood)	No repair required	
33	Lockeport	Minor repair required	Gaps / broken decking, Old pilings, Missing bumpers
33	Lower Sandy Point	No survey response	
33	Port Mouton	No repair required	
33	Riverport (Kraut Point)	No repair required	Missing cleats
33	Sambro	Major repair required	Gaps / broken decking, Broken pilings, Underpinning damage
33	F. Pierce Atlantic Seafood Ltd.	No survey response	
33	Voglers Cove West	No repair required	
34	Abbotts Harbour	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage
34	Argyle	Major repair required	Missing bumpers, Underpinning damage, Extensions
34	Bear Point	No repair required	
34	Cape Saint Mary's	Minor repair required	Lights and winch
34	Chegoggin Point	Minor repair required	Gaps / broken decking
34	Clam Point/ Cripple Creek	Major repair required	Gaps / broken decking, Broken pilings, Missing bumpers, Underpinning damage
34	Clarks Harbour/Swims Point	Minor repair required	Gaps / broken decking, Missing bumpers

34	Digby	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers
34	East Pubnico	Major repair required	Underpinning damage, Approach, Sheeting
34	Falls Point	Major repair required	Gaps / broken decking, Broken pilings, New breakwater needed, Piers stressed past their life cycle
34	Freeport Fish Point Wharf	No survey response	
34	Little River	Major repair required	Underpinning damage
34	Little River Harbour	Minor repair required	Missing bumpers
34	Lower Argyle	No survey response	
34	Lower Woods Harbour	Minor repair required	Gaps / broken decking, Small floating dock
34	Meteghan	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage
34	Newellton	Major repair required	Gaps / broken decking, Broken pilings, Missing bumpers
34	Pinkneys Point	Major repair required	Gaps / broken decking, Broken pilings, Missing bumpers, Underpinning damage
34	Port la Tour	Minor repair required	Unknown
34	Sandford	Not completed	
34	Saulnierville	Minor repair required	Clean up, Signage
34	Shag Harbour	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage
34	South Side	Major repair required	Gaps / broken decking, Broken pilings, Missing bumpers, Underpinning damage
34	Wedgeport	Major repair required	Broken pilings
34	West Head	Minor repair required	Unknown
34	West Pubnico	Minor repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage
34	Westport	Not completed	
34	Yarmouth	Major repair required	Gaps / broken decking, Broken pilings, Missing cleats, Missing bumpers, Underpinning damage, Dredging
34	Yarmouth Bar	Minor repair required	Cable system
35	Advocate Harbour	Minor repair required	Broken pilings, Underpinning damage
35	Lower East Pubnico	No survey response	

Table 6. Coastal Resource Coordinator (CRC) wharf ratings[1]

LFA	Mean condition rating
26A	1.29
26B	3.00
27	3.50
29	2.33
30	5.00
31	2.33
32	2.60
33	1.75
34	4.04

[1] Coastal Resource Coordinators were asked to rate wharves in their domain on a scale of 1 (no repair required), 3 (minor repair required), and 5 (major repair required).

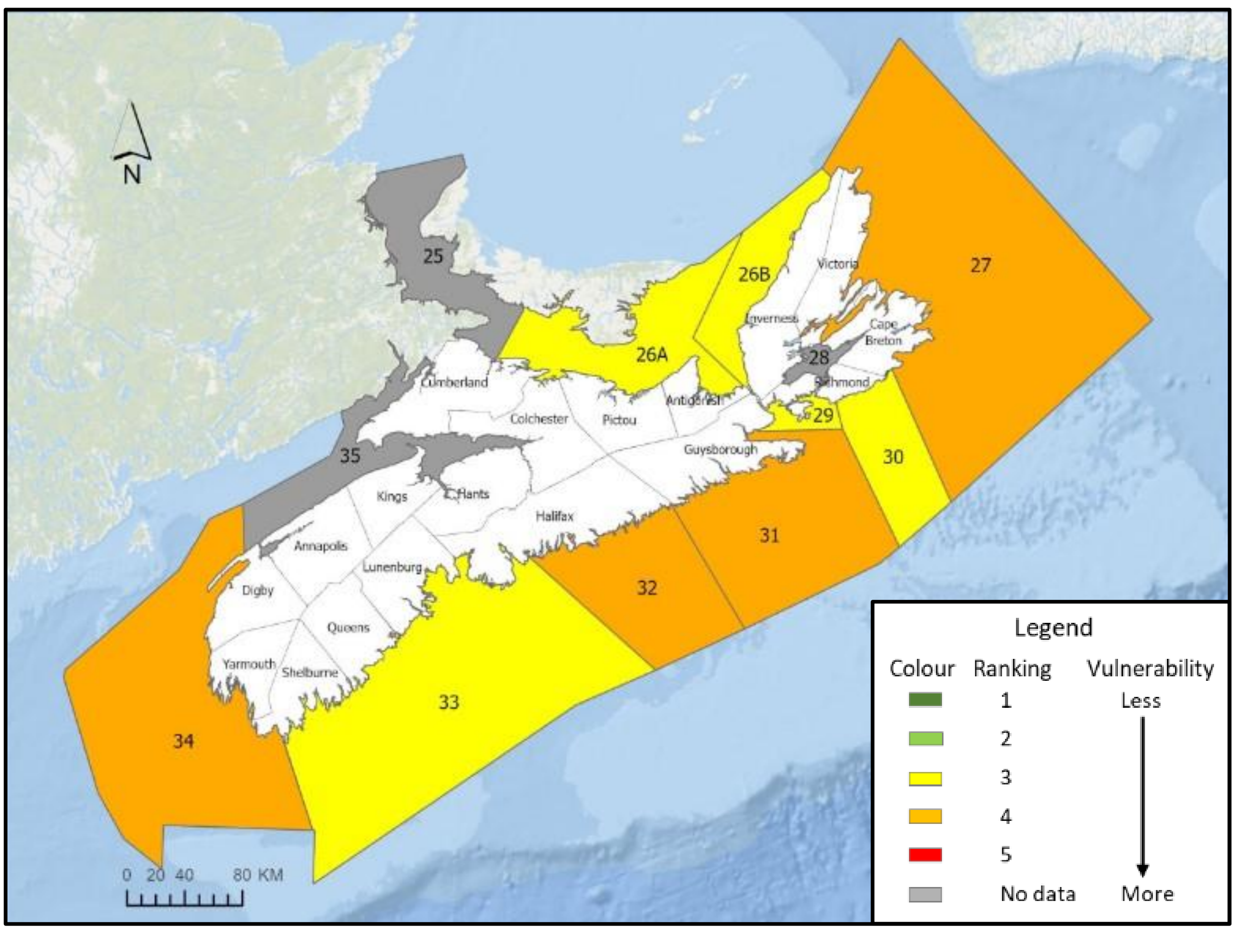

Figure 5 | Relative financial resiliency across LFAs. Average scores of revenue proportion from lobster harvesting and percent loss needed to stop fishing.

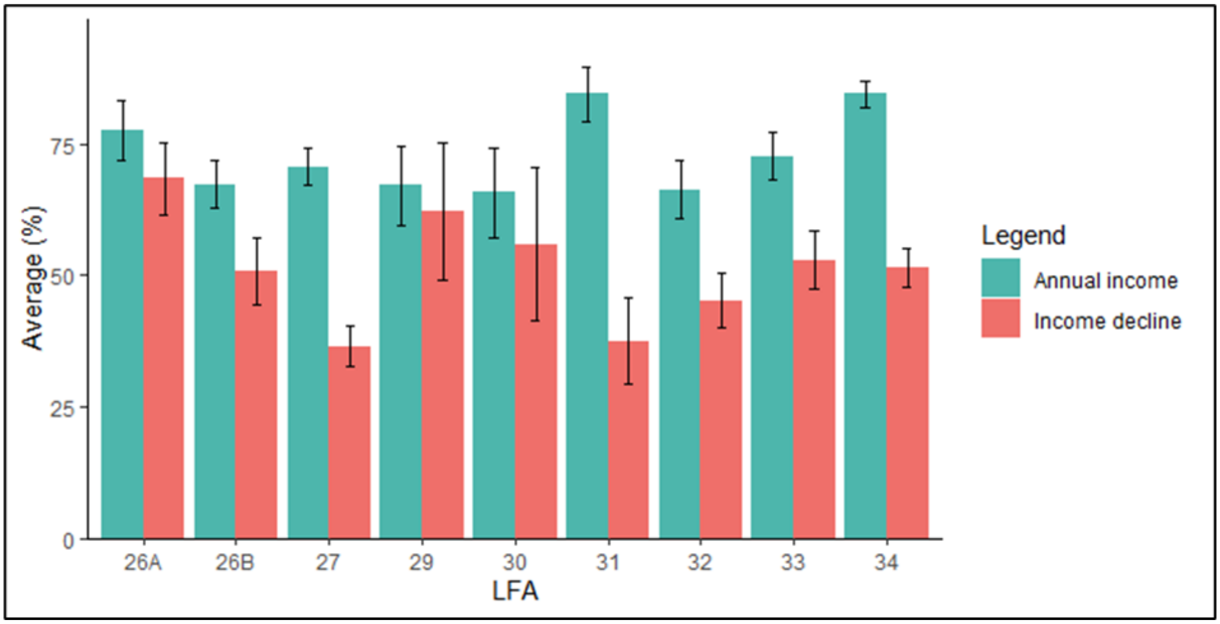

Figure 6 | Revenue from fishing and percent loss needed to stop fishing.

Appendix D: Lobster harvesters adaptive capacity metrics and sub metrics

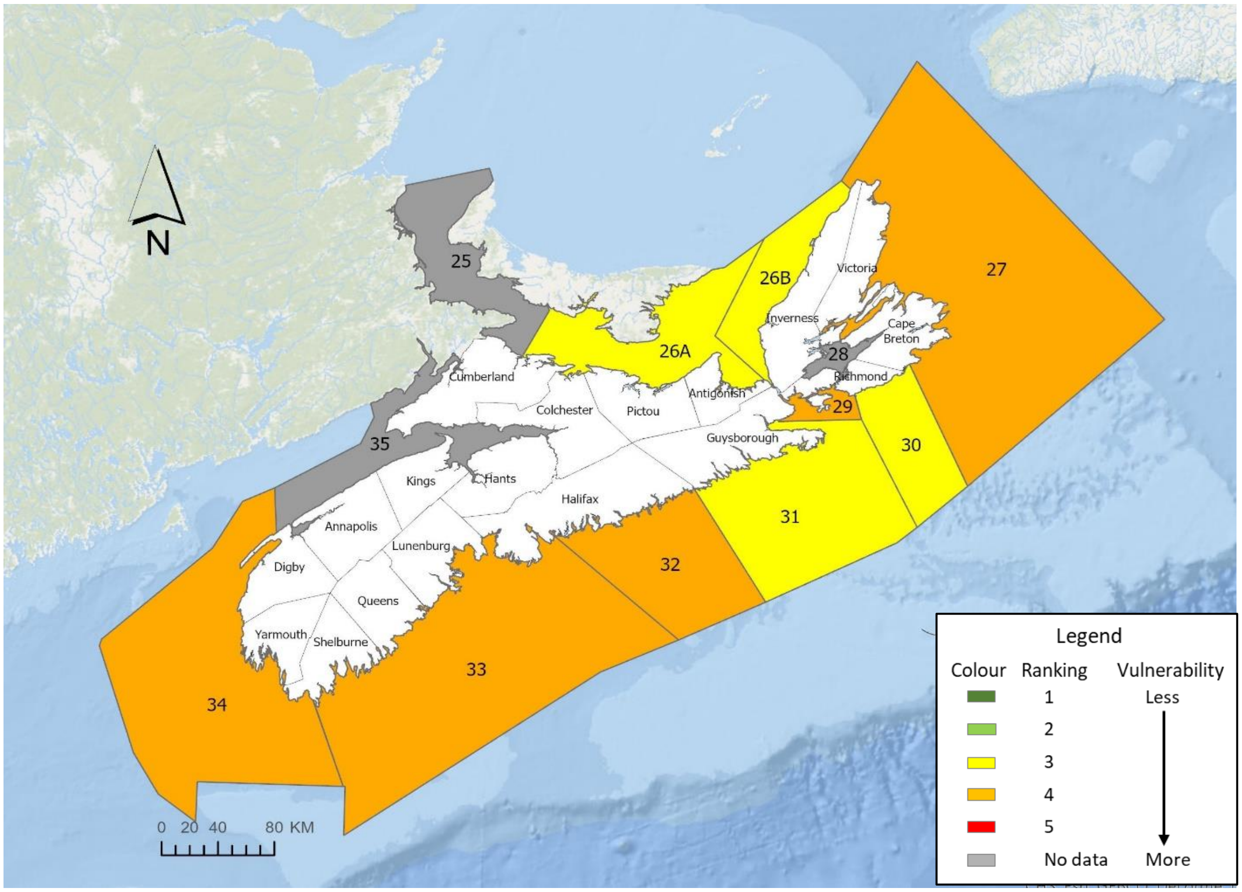

Figure 1 | Relative fisheries flexibility metric across LFAs. A combination of the two sub-metrics, willingness to adjust fishing season and ability to switch to other fisheries.

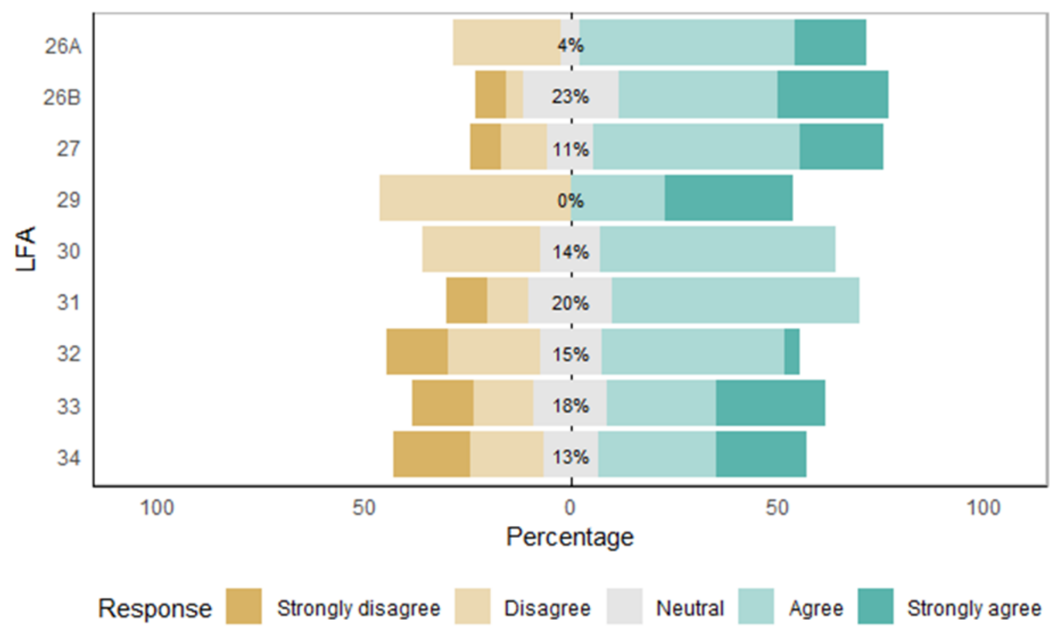

Figure 2| Survey responses for "Fishing seasons should be adjusted to account for ocean changes".

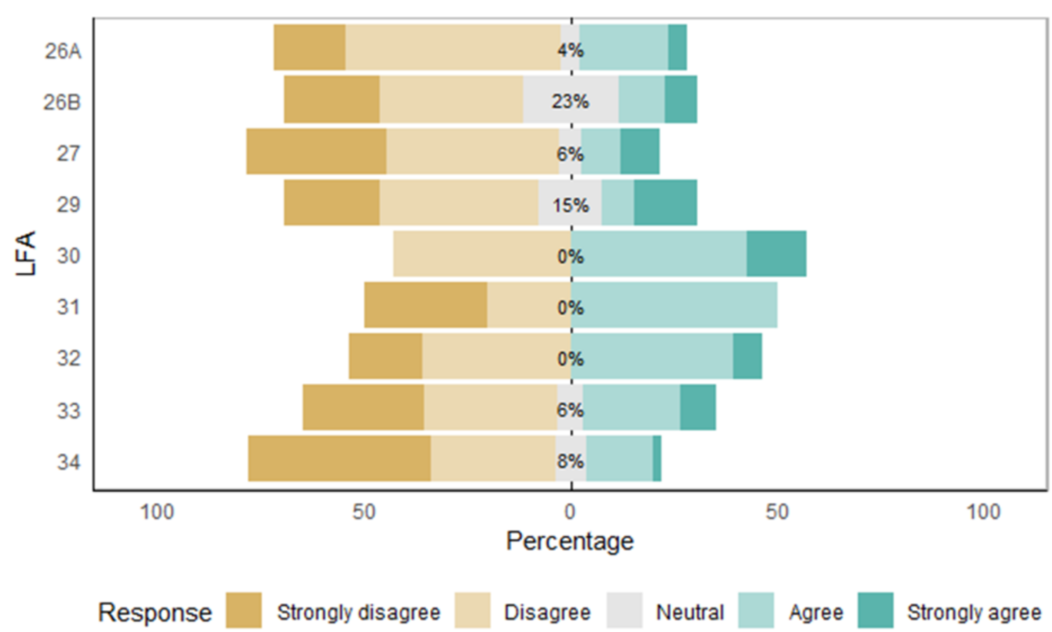

Figure 3 | Lobster harvester survey response to "If lobster stocks decline, I could switch fisheries".

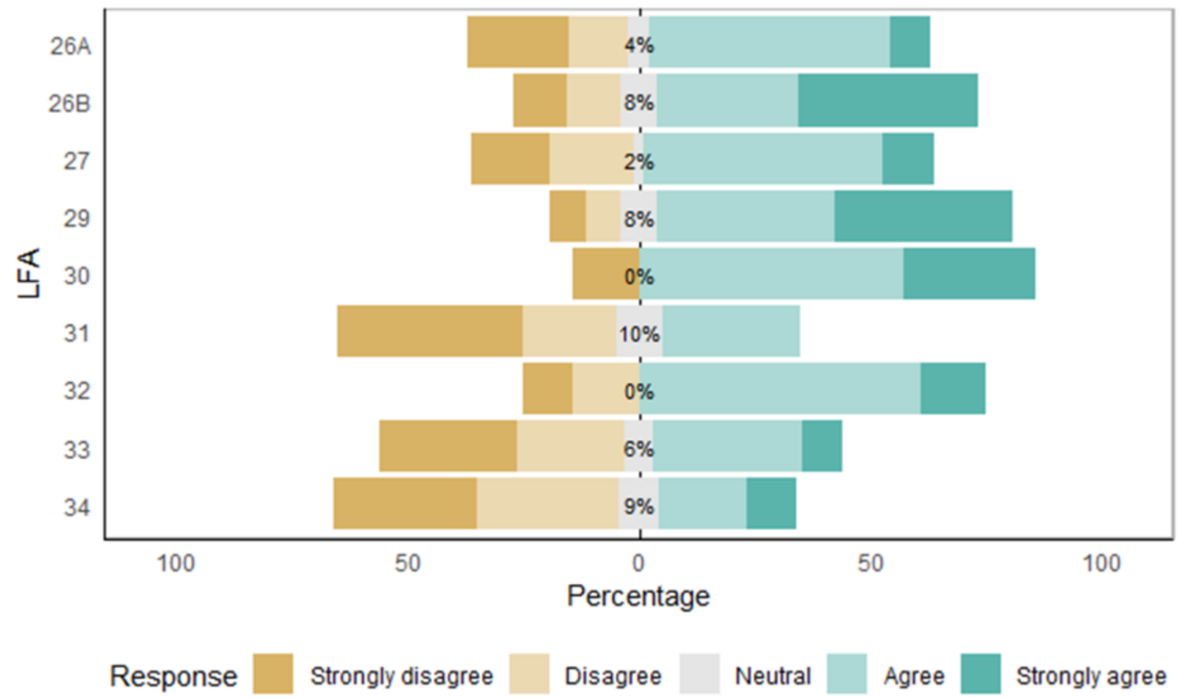

Figure 4 | Lobster harvester survey responses to "If needed, I have other skills, experiences, or education which could help me change careers".

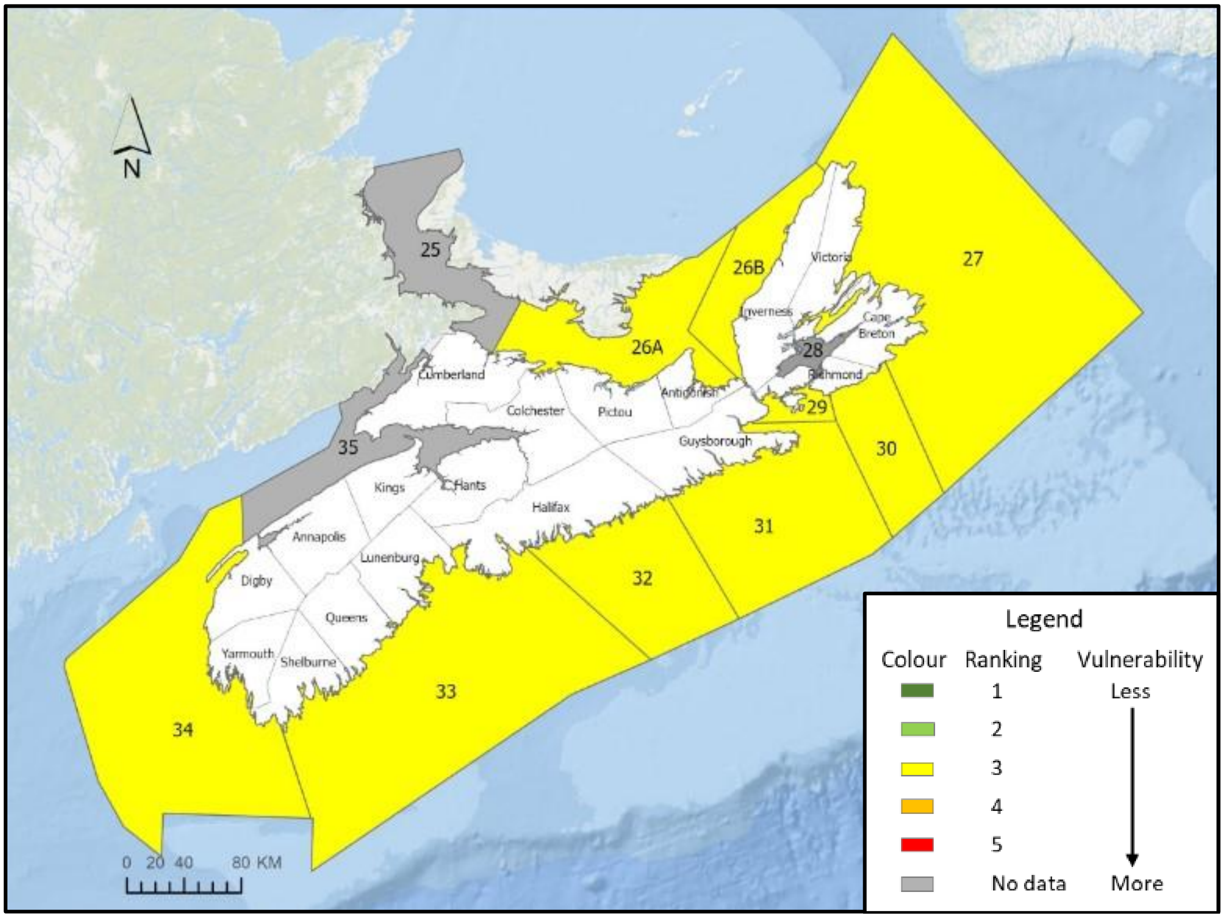

Figure 5 | Relative perception of risk across LFAs. An average of responses to 'There is no evidence that climate change is occurring' and 'I am concerned about the impacts of climate change on the lobster fishery".

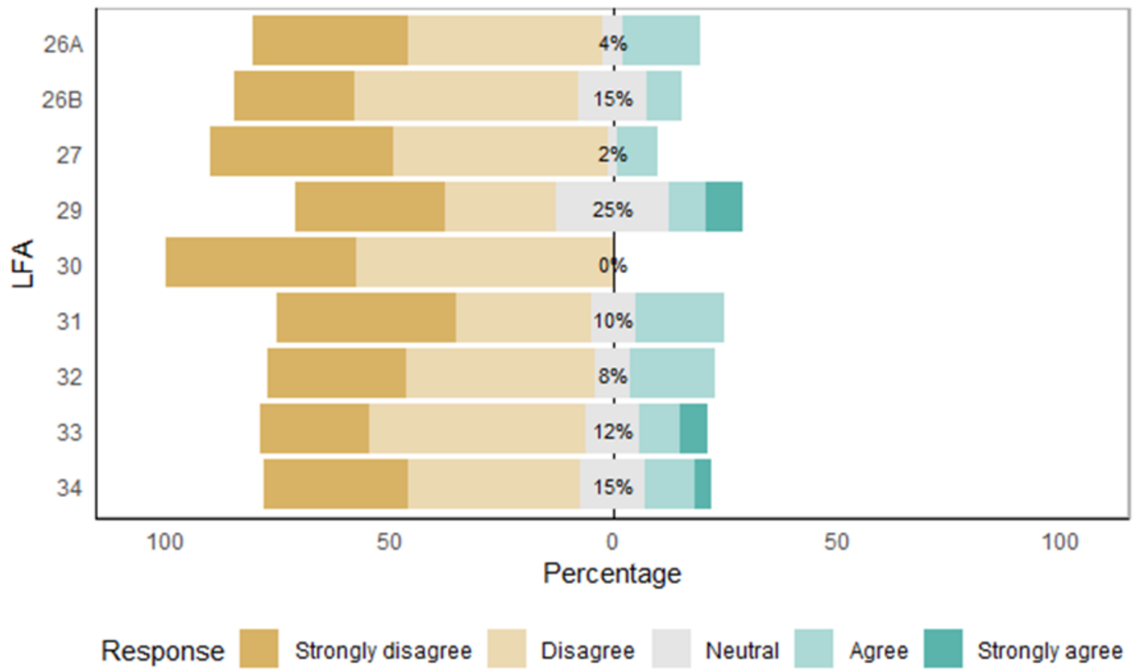

Figure 6 | Lobster harvesters survey response to “There is no evidence that climate change is occurring”.

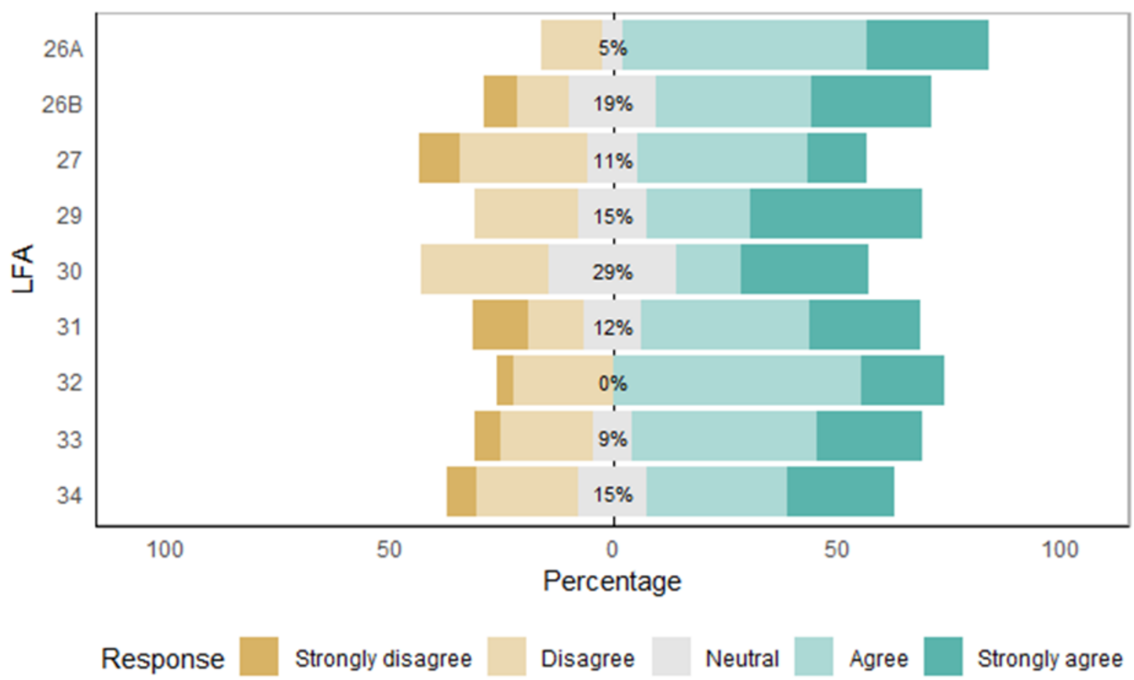

Figure 7 | Lobster harvesters survey response to “I am concerned about the impacts of climate change on the lobster fishery”.

Appendix E: Additional lobster harvesters survey responses

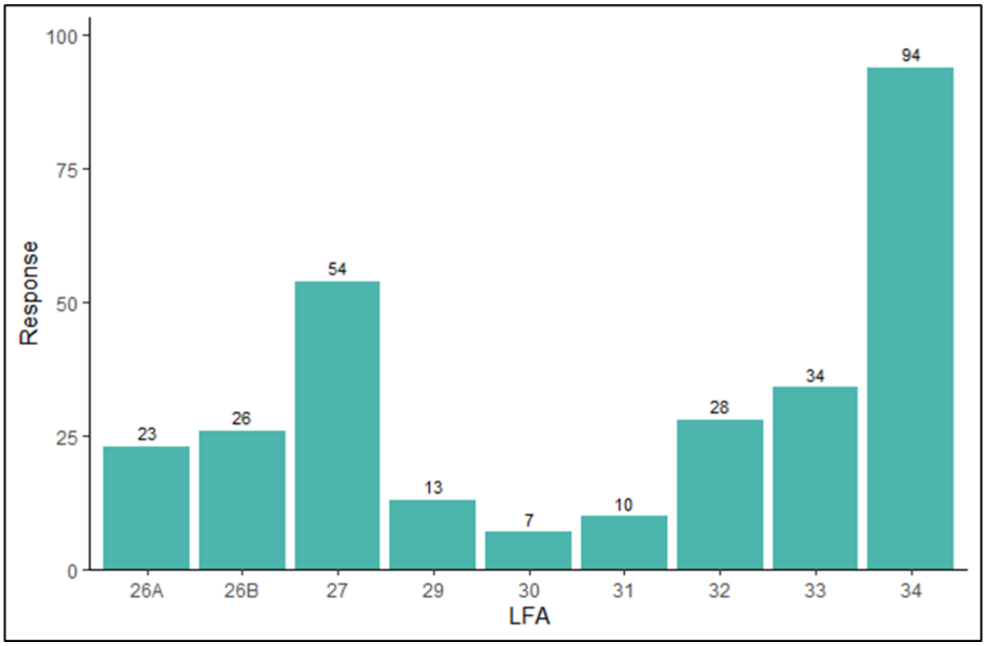

Figure 1 | Question: Which LFA do you fish in? LFAs 28, 25 and 35 were removed from model inputs as responses represented less than 5% of the issued licences in 2021.

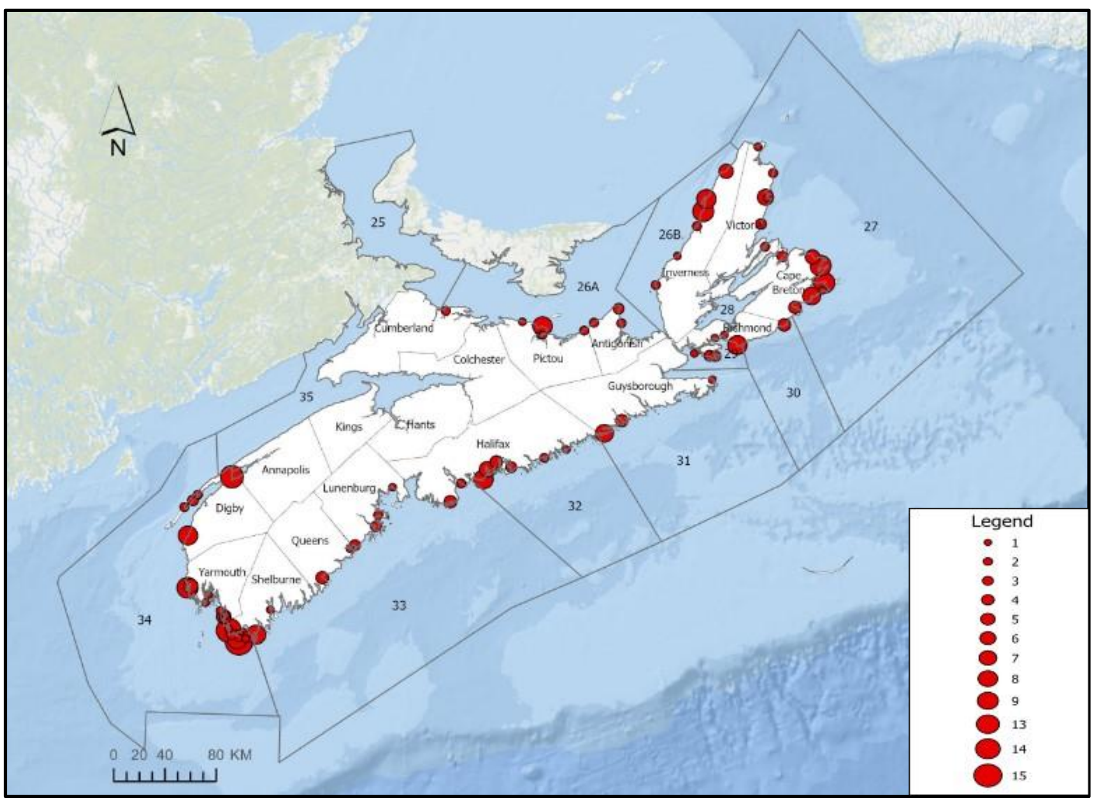

Figure 2 | Question: Which harbour is your vessel based? The proportion of surveys taken at each harbour surveyed across Nova Scotia.

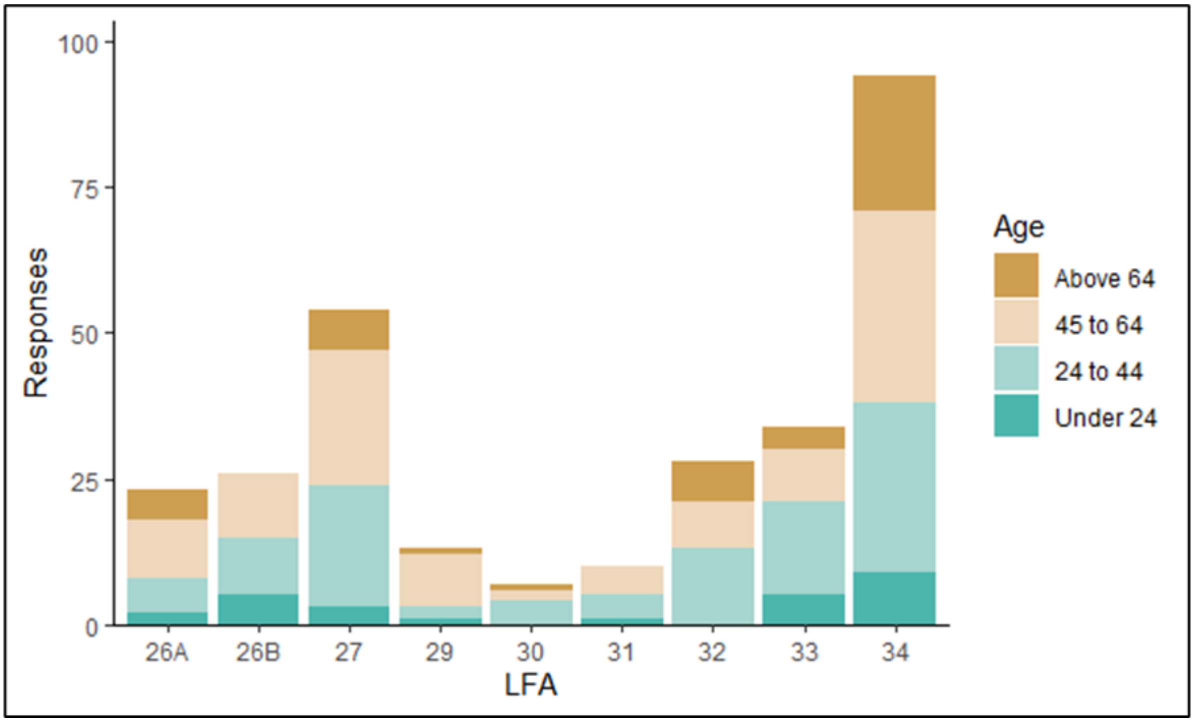

Figure 3 | Question: What is your age range?

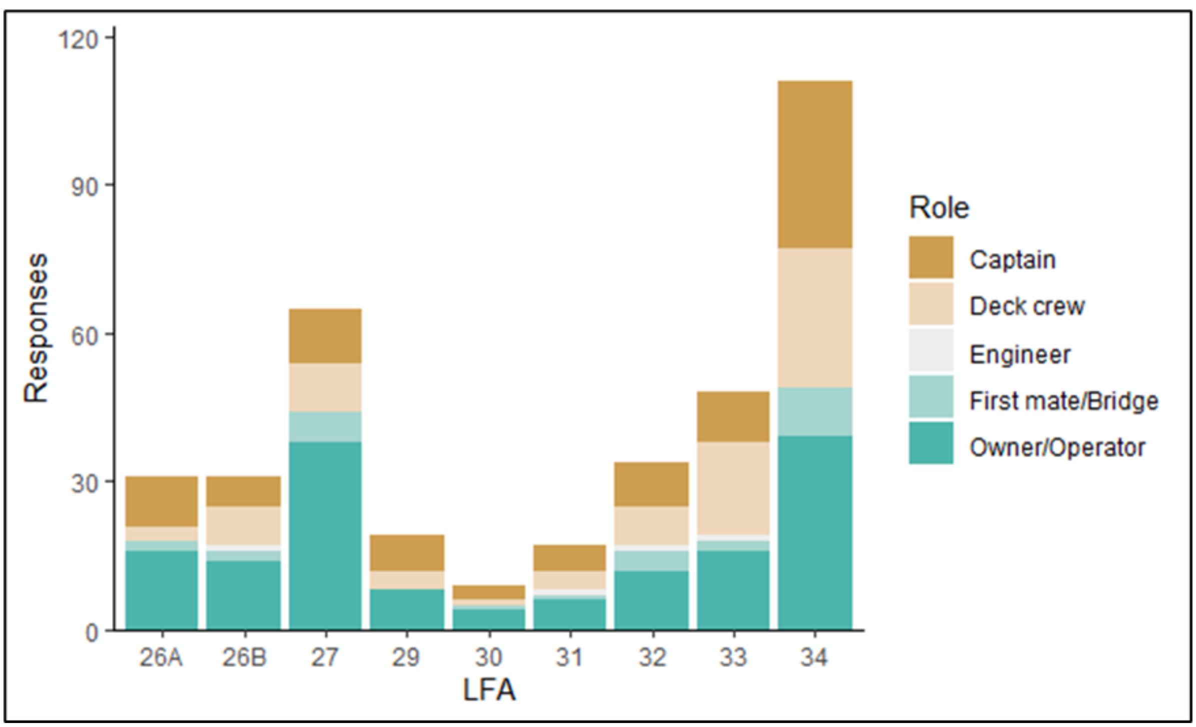

Figure 4 | Question: What best describes your role?

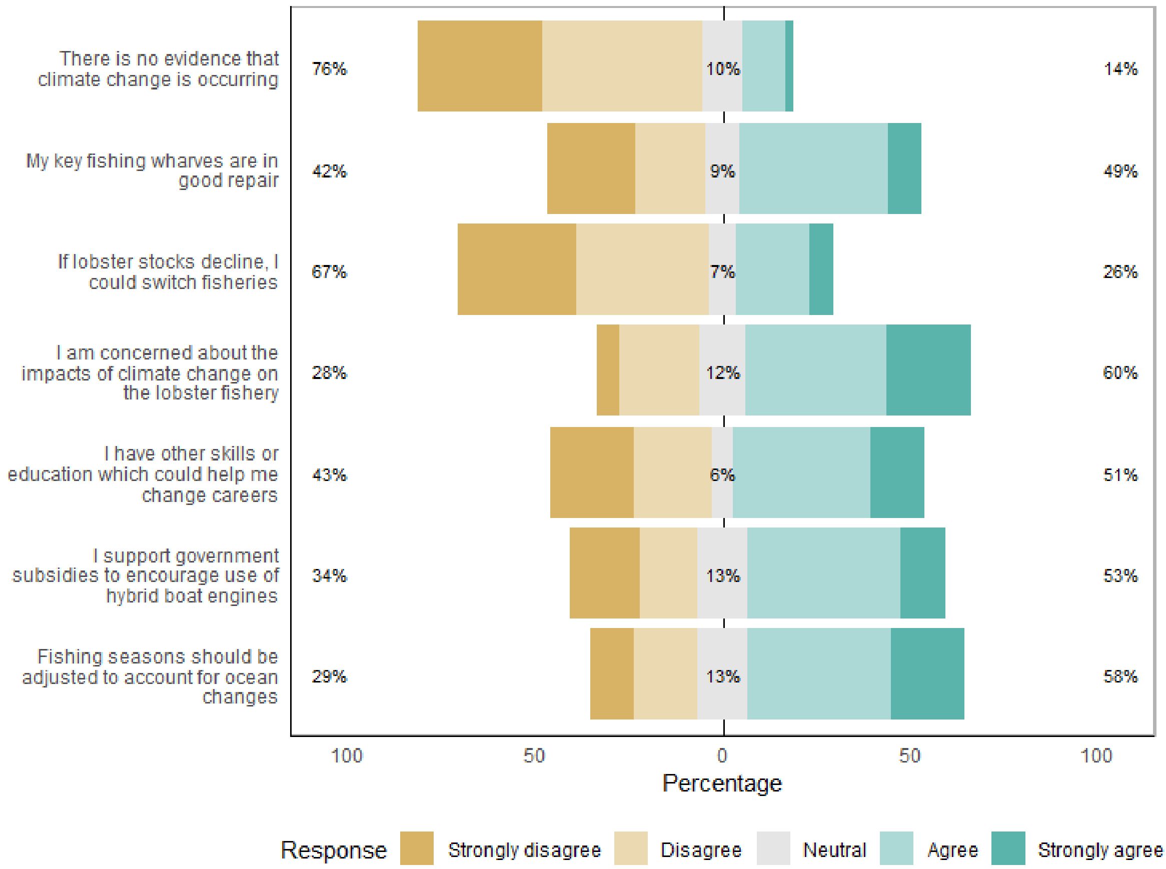

Figure 5 | Question: How much do you agree with the following statements? All LFAs combined.

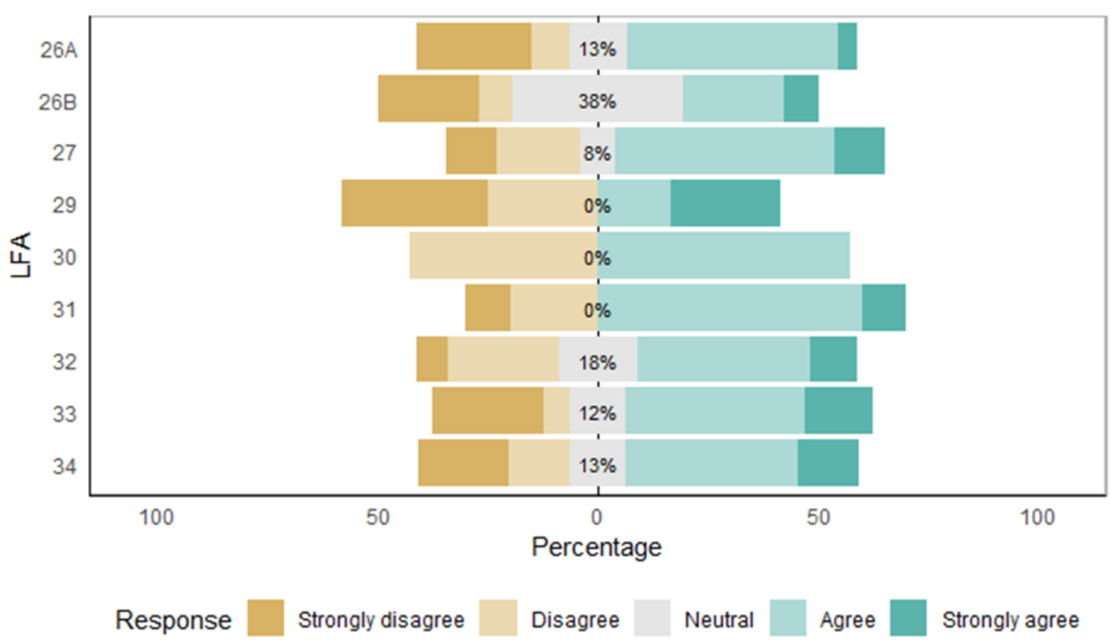

Figure 6 | I support government subsidies to encourage use of hybrid boat engines.

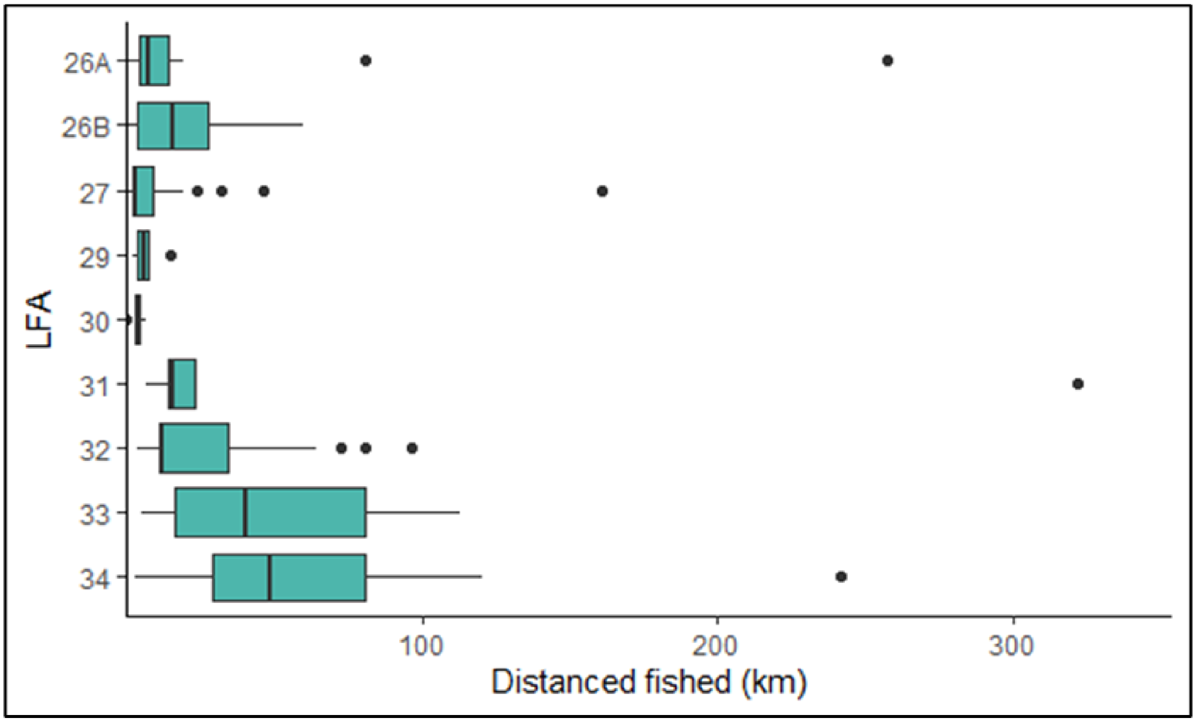

Figure 7 | Question: What are the minimum and maximum distances that you fish from shore? Plots show only average max distance.

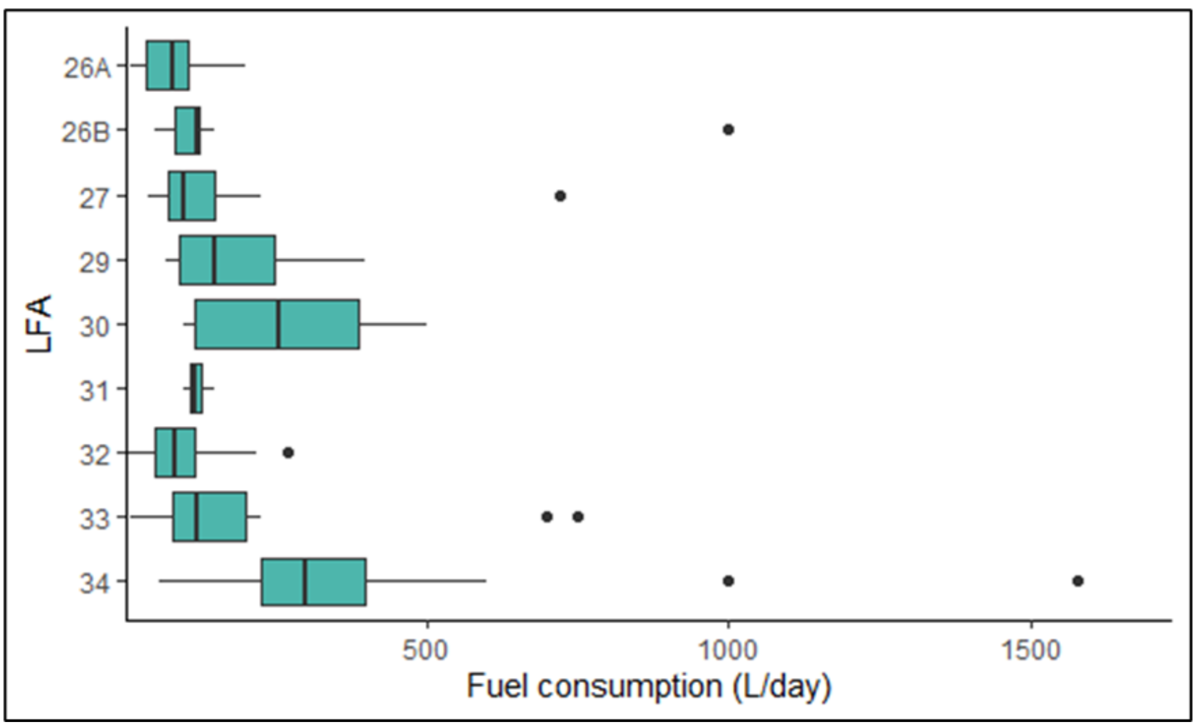

Figure 8 | Question: What is your vessel's average fuel consumption per day?

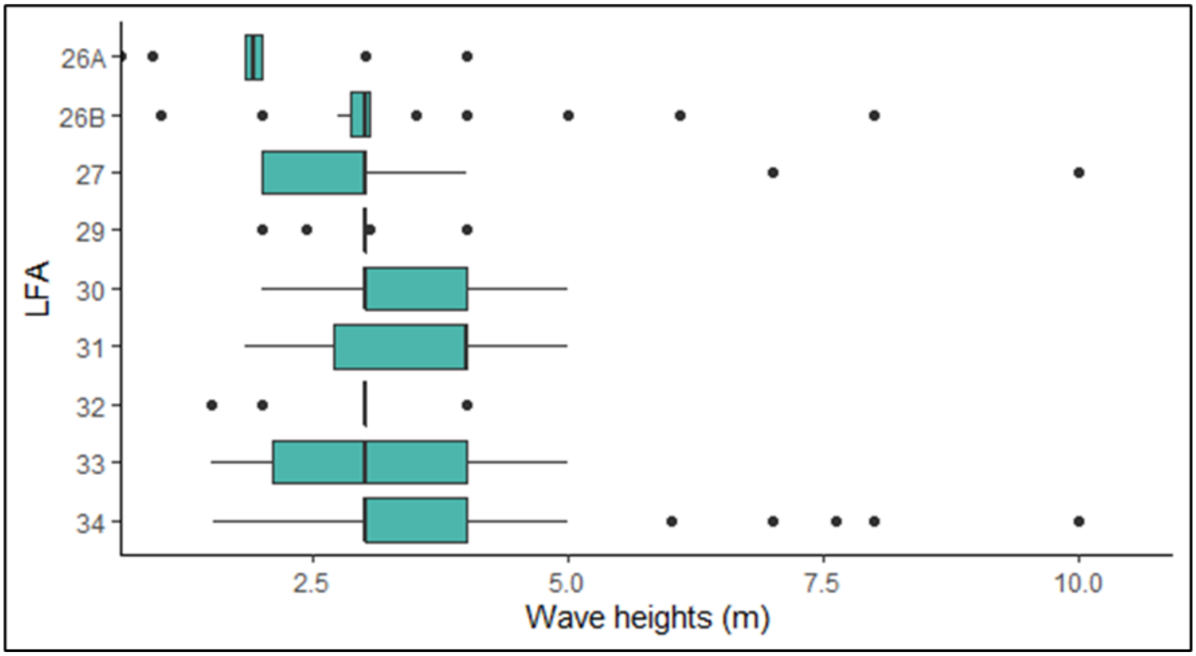

Figure 9 | Question: What wave heights prevent you from fishing?

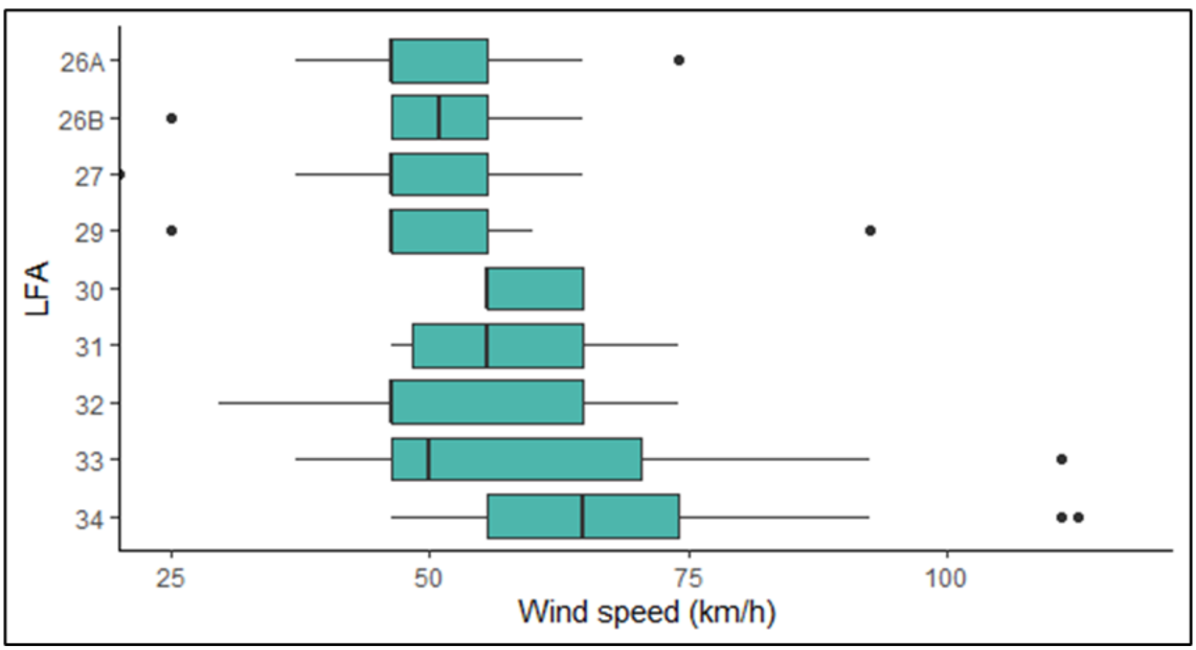

Figure 10 | Question: What wind speeds prevent you from fishing?

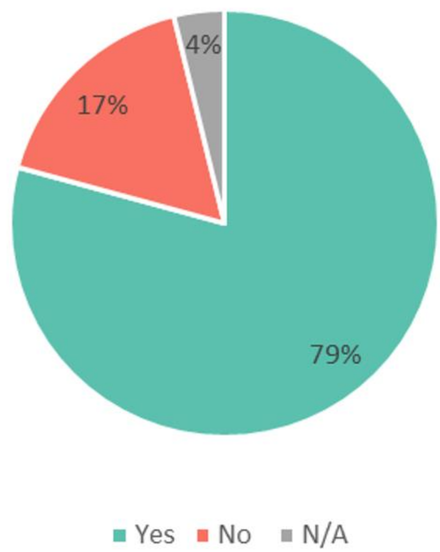

Figure 11 | Question: Do you think ocean conditions are changing?

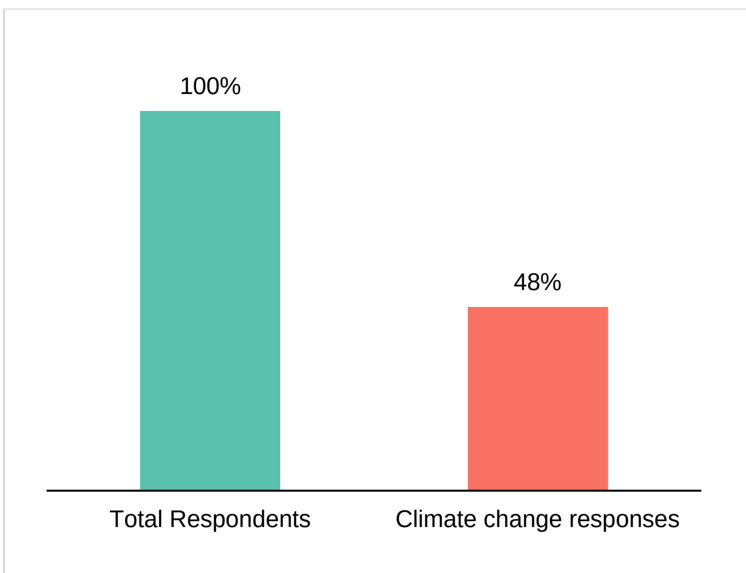

Figure 12 | Question: What do you think are the three greatest threats to the lobster fishery? Approximately 48% of respondents felt climate change (or climate change effect such as bad weather, or warming water temperature) was one of the top three threats to the lobster fishery.

Figure 14 | Question: If ocean conditions are changing, how are they changing? How does this effect the lobster fishery? Relative proportion of answers grouped by category.