Assessing Climate Change Vulnerability of Seafood Industry-Dependent Communities in Nova Scotia

Informing Adaptation

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Assessing Climate Change Vulnerability of Seafood Industry-Dependent Communities in Nova Scotia

Informing adaptation

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Executive summary

Climate change is increasing the temperature of the oceans and reducing their pH. In addition, global sea levels are rising at an accelerating rate, increasing the risk of coastal erosion and flooding. In this report, the Centre for Marine Applied Research (CMAR) reviews the potential impacts these changes may have on the Nova Scotian fishing and aquaculture industries, and the coastal communities they support, before proposing a vulnerability assessment tool to help prioritize climate change adaptation measures.

The four most economically valuable fisheries in Nova Scotia are: American lobster (*Homarus americanus*), snow crab (*Chionoecetes opilio*), sea scallop (*Placopecten magellanicus*), and northern shrimp (*Pandalus borealis*). Although lobster fisheries in Maine and Nova Scotia are currently benefitting from ocean warming, continued warming could potentially lead to: reductions in habitat; increased variability in the timing of lobster molting; reduced bait availability; and increased risk of disease. Ocean warming has also led to marked declines in snow crab abundance on the western Scotian Shelf, and some research suggests that continued warming could lead to its commercial extinction on the eastern Scotian Shelf by 2070. Northern shrimp is also projected to undergo reductions in abundance on the eastern Scotian Shelf and Gulf of St. Lawrence. Likewise, a variety of finfish species, including groundfish and pelagics, are projected to experience climate-driven declines and distribution shifts. However, the introduction or expansion of previously rare, warm water species could potentially provide new fishing opportunities. Nevertheless, if the fishing industry is to initiate new fisheries, and adapt to climate change in general, the industry may require a greater degree of flexibility than afforded by the current fisheries management framework.

Climate change also has potential to impact the Nova Scotian aquaculture industry. Blue mussels (*Mytilus edulis*) and American oyster (*Crassotrea virginica*) may be negatively affected by ocean warming, ocean acidification, harmful algal blooms, and increased disease. There is also potential for ocean warming to negatively impact the production of Atlantic salmon (*Salmo salmar*) if temperatures rise beyond, and oxygen concentrations decline below, optimal thresholds. Nevertheless, the aquaculture industry may have adaptive advantage over wild fisheries as producers can theoretically choose to grow more suitable or resistant species and strains, and because producers have at least some control over environmental conditions.

Over 70 % of Nova Scotia's population live within 20 km of the coast and 14 % of all jobs in the province are ocean-related. Nova Scotia is, therefore, highly dependent on coastal areas and resources for employment and housing. However, climate change may impact these coastal communities through a wide range of impacts including increased coastal erosion and flooding risk, which may damage infrastructure and alter shipping channels.

There are a wide variety of policies and funding programs aimed at helping industries and communities adapt to climate change. Planning adaptation measures in advance will likely be more effective than attempting to respond to climate change impacts after they occur. A key step for the advanced planning of adaptation measures is to conduct a vulnerability assessment to help decision makers prioritize adaptation efforts. Assessing vulnerability involves estimating three components: exposure, sensitivity, and adaptive capacity. There are many challenges to overcome and numerous methods to collect data for vulnerability assessments. In order to help guide adaption plans, this report reviews current best practices for estimating vulnerability and proposes potential approaches to developing a vulnerability index for Nova Scotian seafood industry-dependent communities.

1. Introduction

Primarily due to fossil fuel emissions and other human activities, greenhouse gas (see Table 1 for examples) concentrations in the Earth's atmosphere are currently higher than they have been for over 800,000 years, (IPCC 2014). The Intergovernmental Panel on Climate Change (IPCC, see Section 1.1) are 95% certain that these greenhouse gas emissions are responsible for global warming.

Table 1 | The most important greenhouse gasses contributing towards global warming.

Greenhouse gas	Chemical formula / acronym
Carbon dioxide	CO_2
Methane	CH_4
Ozone	O_3
Water vapor and clouds	H_2O
Chlorofluorocarbons	CFCs
Hydrofluorocarbons	HFCs

1.1. The Intergovernmental Panel on Climate Change (IPCC)

The IPCC is the official body of the United Nations responsible for assessing science related to climate change. Comprising of 195 member governments and supported by thousands of scientists and experts worldwide (IPCC 2020b), the IPCC is widely considered to be the international authority on climate change (Solomon and Manning 2008, Gupta 2010, Beck and Mahony 2018).

1.1.1. IPCC Assessment Reports

The IPCC produces a comprehensive 'Assessment Report' on climate change approximately every five years (IPCC 2020a). The fifth Assessment Report was released in 2014, with the next due in 2022. The IPCC also frequently publishes 'Working Group Reports' on: (1) the physical scientific basis of climate change; (2) the vulnerability of societies and ecosystems; and (3) adaptation and mitigation (IPCC 2020c). As these reports are widely used by researchers and government agencies around the world, it is important to have a basic understanding of IPCC terminology and projection scenarios.

The IPCC make climatic projections based on several possible emissions scenarios (see Table 2). To communicate the probability of these projections, the IPCC uses a likelihood scale ranging from *exceptionally unlikely* to *virtually certain* (see Table 3). They also use five terms to express the level of confidence they have in their assessments, ranging from *very low confidence* to *very high confidence*. Levels of confidence are determined based on the type, quality, amount, and / or consistency of evidence.

1.2. Climate change in Atlantic Canada

This report describes trends that may occur, or may have occurred, according to scientific research. Although the effects of global warming are relatively well understood at the global scale, model projections at the regional level are associated with much higher levels of variability and uncertainty. The future remains unknown, and we have tried to express this uncertainty throughout this report.

Table 2 | The different emissions scenarios used by the IPCC for their climatic projections. Name = IPCC emissions scenario, where RCP = 'Representative Concentration Pathway' and refers to atmospheric greenhouse gas concentration trajectories. Temperature increases are relative to 1986 – 2005. Adapted from (IPCC 2014).

Scenario	Name	Temperature increase	Key information
Low emissions	RCP 2.6	0.3 – 1.7 °C	Requires CO_2 emissions to start declining by 2020 and reach 0 by 2100.
Intermediate emissions	RCP 4.5	1.1 – 2.6 °C	Requires CO_2 emissions to reach half the level of 2050 by 2100 and CH_4 to stop increasing by 2050.
Intermediate emissions	RCP 6.0	1.4 – 3.1 °C	Greenhouse gas emissions peak around 2080 and then start to decline.
High emissions	RCP 8.5	2.6 – 4.8 °C	Greenhouse gas emissions continue to rise throughout the 21st century.

Table 3 | The likelihood scale used in IPCC Assessment Reports. Adapted from (Mastrandrea et al. 2010).

Term	Probability of outcome
Virtually certain	> 99 %
Very likely	90 – 100 %
Likely	66 – 100 %
About as likely as not	33 – 66 %
Unlikely	0 – 33 %
Very unlikely	0 – 10 %
Exceptionally unlikely	0 – 1 %

1.2.1. Air temperature

It is *virtually certain* that Canada's climate has warmed and will continue to warm in the future (Zhang et al. 2019). Average air temperatures in Canada increased by 1.7 °C between 1948 – 2016 and, depending on the emissions scenario, are projected to increase a further 1.5 – 2.3 °C by 2050 (Zhang et al. 2019). This is approximately twice the global average (IPCC 2014). However, rates of warming are comparatively slower in Atlantic Canada as average air temperatures increased by just 0.7 °C between 1948 – 2016 and is projected to increase a further 1.3 – 1.9 °C by 2050 (Cohen et al. 2019). These changes are beginning to impact Atlantic Canada's coastal and ocean systems (see Sections 1.2.2 – 1.2.11), coastal communities (see Section 4), and fishing (see Section 2.2) and aquaculture industries (see Section 3).

1.2.2. Ocean temperature

Ocean 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, Pershing et al. 2015). For example, 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). It is likely that this trend is mostly due to global warming. However, some research suggests the Gulf Stream may potentially be shifting north (Brickman et al. 2016, Saba et al. 2016), which could further enhance warming by transporting more warm, tropical water from the Gulf of Mexico along the east coasts of the United States of America (USA) and Canada (Talley et al. 2011). Temperatures have also increased in the Bay of Fundy, Scotian Shelf, Cabot Strait, Northumberland Strait, and Gulf of St. Lawrence. Since records first began, three of the five warmest years have occurred in 2012, 2014, and 2015 (Hebert and Pettipas 2016, Bernier et al. 2019). However, some years and regions are more variable than others (Hebert and Pettipas 2016) and 2019 exhibited relatively cool sea surface temperatures (Cyr et al. 2020). Nonetheless, ocean temperatures in Canada are projected to continue increasing over the 21st century, and the waters in Southern Atlantic Canada (Figure 1) are projected to warm faster than the rest of the country (Greenan et al. 2019a, Lavoie et al. 2020). Overall, projections under a high emissions scenario suggest summer sea surface temperatures in Atlantic Canada may increase by up to 4 °C by 2050 (Greenan et al. 2019a).

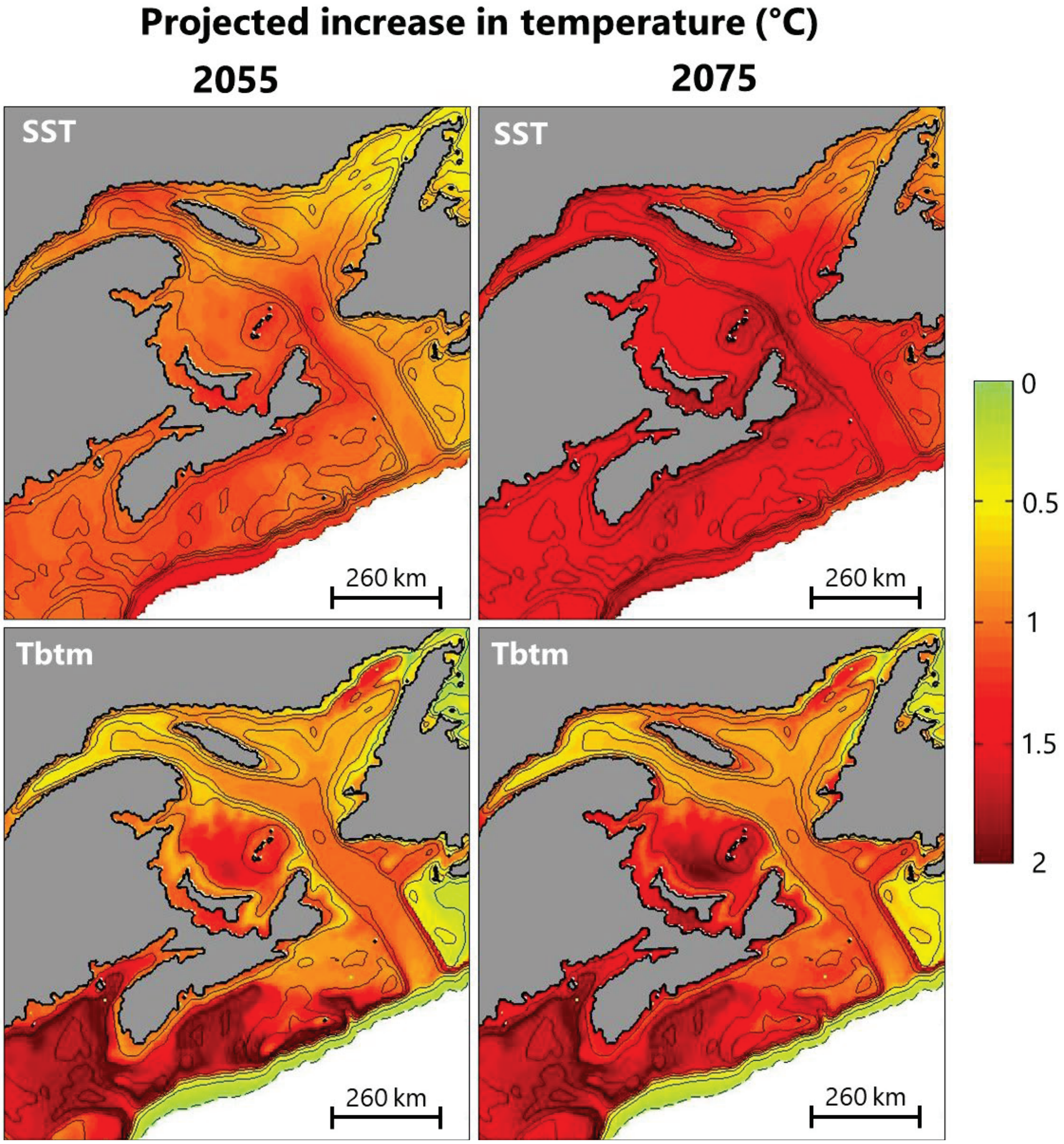

Figure 1 | Projected increase in sea surface temperature (SST) and bottom water temperature (Tbtm) in 2055 and 2075 relative to present conditions under a high emissions scenario. Data were calculated using the Bedford Institute of Oceanography North Atlantic Ocean Model (BNAM), which is documented in Brickman et al. (2016). Source: David Brickman, Fisheries and Oceans Canada (DFO).

As sea surface temperatures increase, marine heatwaves have also increased in duration and frequency in the Northwest Atlantic, and this trend is projected to continue over the coming century (Oliver et al. 2018, Schlegel et al. 2021). Marine heatwaves describe prolonged extreme oceanic warm water events and are typically defined as periods when sea surface temperatures exceed the 90th percentile for at least 5 days. They can persist for weeks or up to several years, and can range in size from an individual bay to several ocean basins (reviewed in Holbrook et al. 2020).

Overall, these general warming trends are beginning to impact the fishing industry (see Section 2.2) through changes in fish distribution, habitat suitability, disease prevalence, and recruitment (i.e. the number of juvenile fish surviving and entering the fishery). Ocean warming may also impair the growth of some shellfish species, and cause an increase in harmful algal blooms, disease, and parasites, which could impact the aquaculture industry (see Section 3).

1.2.3. Sea ice

Atlantic Canada encompasses the most southward extent of winter sea ice in Canada. However, warmer temperatures have reduced the thickness and percentage cover of sea ice, and shortened the duration of the sea ice season (Clarke et al. 2016, Galbraith et al. 2019). In Eastern Canada, average sea ice cover declined by 7.5 % per decade between 1969 – 2016 (Derksen et al. 2019). However, sea ice cover fluctuates from year to year. For example, sea ice cover in the Gulf of St. Lawrence returned to average levels in 2003 and again in 2014 (Galbraith et al. 2017). Likewise, sea ice cover on the Scotian Shelf was higher in 2015 than the 1981 – 2010 average (Hebert and Pettipas 2016). Overall, sea ice is projected to continue declining across Atlantic Canada, and some model projections suggest sea ice will be almost completely absent in the Gulf of St. Lawrence by 2100 (Senneville et al. 2014, Lavoie et al. 2020). Reductions in sea ice will likely increase wave heights (see Section 1.2.6) and coastal erosion (see Section 1.2.8). Also, the melting and break-up of sea ice may pose a navigational risk to shipping and fishing boats, potentially exerting more pressure on search and rescue, and other emergency services (Greenan and Warburton 2013, also see Section 4).

1.2.4. Sea level

Due to the melting of glaciers and ice sheets, as well as the thermal expansion of the oceans, global sea levels increased by an average of 19 cm (1.7 mm per year) between 1901 – 2010 (IPCC 2014). Furthermore, the Nova Scotian land mass is still recovering from the retreat of glaciers during the last ice age (approximately 11,000 years ago) and is currently sinking at a rate of 2 mm per year (Atkinson et al. 2016). Consequently, the relative sea level in Nova Scotia is rising 3.3 mm every year and is projected to increase by a total of 50 – 150 cm relative to present day values by 2100 (James et al. 2014). This is substantially faster than the global average. These small, gradual increases in sea-level are not inconsequential as sea level height tends to have a non-linear relationship with flooding risk. For example, a 10 cm increase in sea level may cause a three-fold increase in flooding frequency (Church et al. 2006, Zhai et al. 2014). Overall, rising sea levels are accelerating rates of coastal erosion (see Section 1.2.8) and are increasing the risk of flooding and damage to coastal infrastructure (see Section 1.2.5 and Section 4).

1.2.5. Extreme high-water levels and storm surge

Rising sea levels (see Section 1.2.4) may increase the frequency and magnitude of extreme high-water levels and storm surge events. In Halifax, for example, a 20 cm rise in relative sea level (projected to occur within 20 – 30 years) could increase the frequency of coastal flooding by a factor of four (Atkinson et al. 2016, Greenan et al. 2019a). The highest recorded water levels in Halifax occurred during Hurricane Juan in 2003 which saw water levels temporarily increase by 1.87 m (Atkinson et al. 2016). This storm surge event resulted in an estimated $300 million of damage, and caused loss of power to over 800,000 for up two weeks (Quon 2017). Under a high emissions scenario, this record high water level is projected to occur every 5 years by 2060 (Atkinson et al. 2016).

1.2.6. Waves and storms

The severity of waves and storms in Atlantic Canada display contradictory trends (Greenan et al. 2019a). Average summer wave heights have increased by 2 cm per decade since 1948 (*medium confidence*) and winter wave heights have increased by up to 20 cm (Rhein et al. 2013, Bromirski and Cayan 2015). Evidence also suggests the frequency of late summer and autumn extreme storms have increased in Atlantic Canada since 1958 (Wang et al. 2016). Conversely, there is evidence that storm tracks have shifted northwards since the 1970's (Wang et al. 2006). This shift is projected to reduce wind speeds and wave heights (*low confidence*) across Atlantic Canada over the coming century (Casas-Prat et al. 2018, Greenan et al. 2019a). However, this will not be true for areas subject to winter sea ice declines (see Section 1.2.3), as sea ice inhibits wave formation. Overall, average wave heights in Nova Scotia are projected to increase between 40 cm to 1.8 m by 2090 under a high emissions scenario. This will accelerate coastal erosion (see Section 1.2.8) and increase the risk of coastal flooding and damage to infrastructure (see Section 1.2.5 and Section 4).

1.2.7. Precipitation

Average precipitation levels across Canada increased by 20 % (*medium confidence*) between 1948 – 2012 (Vincent et al. 2015, Zhang et al. 2019). In contrast, annual precipitation levels in Atlantic Canada increased by just 11 % (*low confidence*) and are projected to increase by a further 3.8 – 5 % by 2050 (Lemmen et al. 2016, Cohen et al. 2019, Zhang et al. 2019). Although increases in precipitation have been less pronounced in Atlantic Canada, the Maritime provinces are predicted to experience some of the largest increases in extreme rainfall events over the coming century (Simonovic et al. 2017). Extreme rainfall events accelerate erosion and increase the risk of flooding and damage to infrastructure (see Section 4).

1.2.8. Coastal erosion, flooding, and regional differences

Coastal erosion occurs when tides, currents and waves break down and / or carry away rocks and sediment along the coast, resulting in the landward retreat of the shoreline (reviewed in Davidson-Arnott and Ollerhead 2011). Although this is a natural process, rising sea levels (see Section 1.2.4), increasing wave heights (see Section 1.2.6), and increasing risk of coastal flooding (see Section 1.2.5) in Nova Scotia are exacerbating coastal erosion, threatening properties and other coastal infrastructure (see Section 4).

A project by Natural Resources Canada (NRC) known as 'CanCoast' compiled data on the physical characteristics (e.g. geology, slope, tidal range, and projected sea level rise and wave heights) of Canada's coastlines (Manson et al. 2019). These data were then combined in a 'Coastal Sensitivity Index' to assess how susceptible Canadian coastlines are to coastal erosion and flooding. Low sensitivity values indicate areas that are relatively resistant to climate change (e.g. rocky coastlines with steep cliffs, in areas with high tidal range, projected to experience moderate increases in sea level and wave height) and high sensitivity values indicate areas that are very vulnerable to climate change (e.g. silty, flat coastlines, in areas with low tidal range, projected to experience substantial increases in sea level and wave height).

Most of the coastline around Nova Scotia has ‘moderate’, ‘high’ or ‘very high’ sensitivity to projected levels of coastal erosion and flooding (Figure 2). According to the index, Eastern Cape Breton is the most sensitive region in Nova Scotia as relative sea levels are rising faster, and the coastline is predominantly low-lying, made-up of sand and softer sediments (Heather Bay Berry, Université du Québec à Rimouski, pers. comm, December 2020). Similarly, coastlines in the Minas Basin, Cobequid Bay, Amherst, the South Shore, and much of the North Shore and Northumberland Strait have high sensitivity as they are either exposed to strong waves and / or have predominant geology consisting of sedimentary rocks and sands. Conversely, the steep, granite coasts of Northern Cape Breton, as well as the Atlantic coast between Cape Sable Island and Sheet Harbour, are the least sensitive (Environment Canada 2005, Lemmen et al. 2016).

Caution is warranted when interpreting these CanCoast products as coastal geology, morphology, and rates of erosion can vary greatly over small scales of just tens of metres. Thus, the CanCoast data products are only intended for broad-based regional assessment (John Somers, Nova Scotia Environment, pers. comm, December 2020).

1.2.9. Salinity

Long-term trends suggest that the upper ocean in Atlantic Canada has reduced in salinity while deep waters in the Gulf of St. Lawrence have increased in salinity (Greenan et al. 2019a, Lavoie et al. 2020). For example, there is some evidence that surface waters in the Bay of Fundy have reduced in salinity (Hebert et al. 2016). Conversely, greater transport of subtropical waters (see Section 1.2.2) has been observed to have a role in increasing salinity of deep waters (200 – 300 m) in the Gulf of St. Lawrence (Galbraith et al. 2017) and is projected (*medium confidence*) to continue over the coming century (Greenan et al. 2019a). Increases in salinity have potential to increase the risk of disease in mussels and oysters (see Section 3.2.4), while reductions in salinity may increase ocean acidification (see Section 1.2.11).

1.2.10. Oxygen

Despite high levels of variability among basins, the global ocean has lost around 2% of its oxygen since 1960 (Schmidtko et al. 2017). Warmer waters have less capacity to hold oxygen, which may partly explain this trend. Additionally, less saline waters promote stratification, meaning water layers are less likely to mix, preventing the transport of oxygen to deeper waters (Gruber 2011). Oxygen concentrations are declining faster in the Northwest Atlantic Ocean and could potentially be due to: (1) changes in the Labrador current, which transports cold, oxygen-rich waters from the Arctic to the Newfoundland Shelf, Scotian Shelf and Gulf of St. Lawrence; (2) changes in the Gulf Stream (see Section 1.2.2); and (3) elevated nutrient loads in the Gulf of St. Lawrence which may be reducing oxygen concentrations at depth (Petrie and Yeats 2000, Gilbert et al. 2005, Gilbert et al. 2010, Levin 2018). However, all these mechanisms are highly complex and poorly understood (Claret et al. 2018). Nevertheless, deep waters on the Scotian Shelf (150 m), Cabot Strait (250 m), and Gulf of St. Lawrence (320 m) have experienced a reduction in oxygen concentrations of 0.5 – 1.2 μM per year since the early 1960’s (reviewed in Gilbert et al. 2010, Brennan et al. 2016, Claret et al. 2018) which is projected to continue at an increasing rate over the coming century (Claret et al. 2018). Declines in oxygen concentration have the potential to impact several shellfish fisheries in Nova Scotia (see Sections 2.2.4 – 2.2.6) and the aquaculture industry (see Section 3.3).

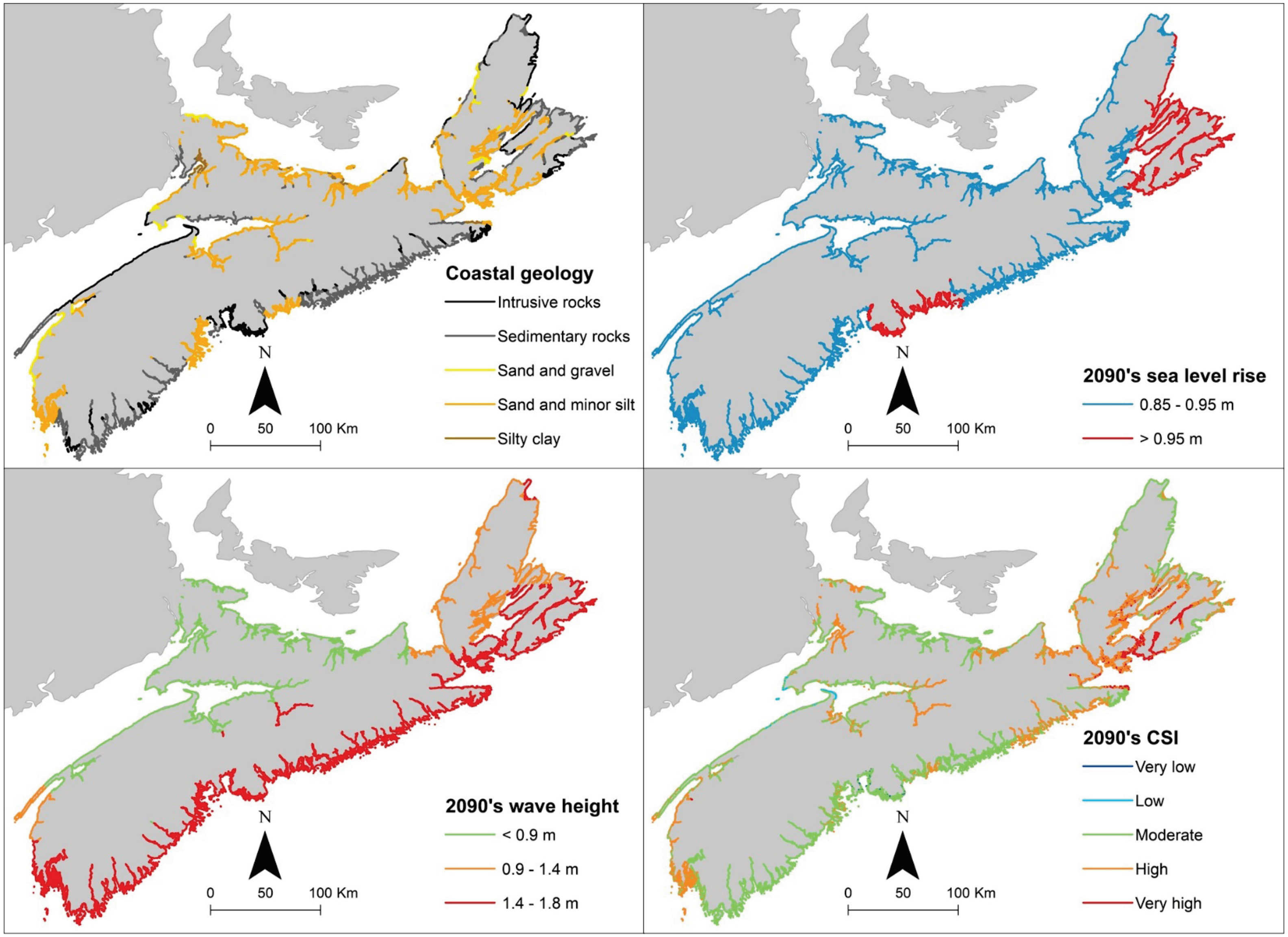

Figure 2 | Coastal geology of Nova Scotia**,** sea level rise, wave heights, and Coastal Sensitivity Index (CSI) projected for 2090. Data and model explanations available in Manson et al. (2019). CSI < -500 = very low, -499 to -150 = low, -149 to 150 = moderate, 150 to 500 = high, > 500 = high.

1.2.11. Ocean acidification

When seawater absorbs CO_2, it triggers a series of chemical reactions which lowers its pH, making it slightly more acidic (Doney et al. 2009). As the oceans have absorbed approximately 30 % of CO_2 emissions since the industrial era, they have experienced a 26% increase in acidity or a pH reduction of 0.1 (Rhein et al. 2013, IPCC 2014). This change in pH is the fastest the oceans have experienced for at least the last 66 million years (Hönisch et al. 2012). 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). Consequently, their surface layers have decreased in pH at a rate of 0.03 – 0.04 per decade since 1934 (WMO 2014, Galbraith et al. 2019, Greenan et al. 2019a). Likewise, deep waters in the lower Gulf of St. Lawrence experienced a decrease in pH of 0.2 – 0.3 between 1934 – 2007 (Mucci et al. 2011). Ocean acidification has potential to impact several shellfish fisheries in Nova Scotia (see Sections 2.2.4 – 2.2.6) and the shellfish aquaculture industry (see Section 3.2.2).

1.3. Significance of Nova Scotia's seafood industry

The coasts, oceans, and their resources have substantial social, cultural, and economic importance in Nova Scotia. It has been estimated that 14 % of all jobs in the province are coastal- or ocean-related (Fisher 2011). In 2019, the fishing and aquaculture industries alone directly employed 18,973 people in Nova Scotia, and supported another 5,479 jobs in the seafood processing industry (Fisheries and Oceans Canada 2020e). Consequently, the total number of people employed by the fishing, aquaculture and seafood processing industries is higher in Nova Scotia than any other province (Boyce 2021). Most fishing, aquaculture, and seafood processing operations in Nova Scotia are located in coastal rural areas, which have been identified as being in need of economic growth and development (oneNS 2014, CRRF 2015). Both aquaculture and fisheries development are viewed as strategic 'inclusive economic growth' opportunities for coastal and rural communities in Nova Scotia (Nova Scotia Department of Fisheries and Aquaculture 2019). Inclusive economic growth describes the provincial government's aim to build and promote a more innovative and diverse economy accessible to all.

1.4. Report aims and objectives

Ocean warming, sea level rise, ocean acidification, and a variety of other climate-driven changes (see Section 1.2) have potential to impact the Nova Scotian fishing and aquaculture industries (see Sections 2–3), and the coastal communities they support (see Section 1.3). This report reviews some of these potential impacts and proposes an approach to assess the vulnerability of different sectors and seafood industry-dependent communities (see Sections 6 – 7). Such an exercise could prove invaluable in guiding climate change adaptation efforts.

2. Wild capture fisheries in Nova Scotia

2.1. Past and present status

Nova Scotia's fisheries can be broadly divided into two general groups: shellfish and finfish. The quantity and value of shellfish landings has greatly increased in Nova Scotia over the last three decades (Figure 3). In 2019, shellfish fisheries represented 66 % of all provincial landings by weight and 87 % by value (Fisheries and Oceans Canada 2021b). Shellfish products generally receive higher value per unit of weight compared to finfish, explaining their disproportionately high contribution towards landings value (Wilson et al. 2020). Nova Scotian shellfish fisheries primarily target American lobster (*Homarus americanus*, see Section 2.2.3), snow crab (*Chionoecetes opilio*, see Section 2.2.4), American sea scallop (*Placopecten magellanicus*, see Section 2.2.5), and northern shrimp (*Pandalus borealis*, see Section 2.2.6), which represent the top four most economically important fisheries in the province (Fisheries and Oceans Canada 2020c). Generally, American lobster makes a greater contribution to landings in the south of Nova Scotia while snow crab tends to be more important in the north (Figure 4).

Nova Scotia's finfish fisheries (see Sections 2.2.7 – 2.2.10) target a wide range of species including several cod-like species (e.g. Atlantic cod, *Gadus morhua* ; haddock, *Melanogrammus aeglefinus* ; pollack, *Pollachius virens* ; silver / Atlantic hake, *Merluccius bilinearis*), flatfish species (e.g. Atlantic halibut, *Hippoglossus hippoglossus* ; American plaice, *Hippoglossoides platessoides* ; yellowtail flounder, *Limanda ferruginea*), small pelagics (e.g. Atlantic herring, *Clupea harengus* ; Atlantic mackerel, *Scomber scombrus*) and large pelagics (e.g. Swordfish, *Xiphias gladius* ; tuna, *Thunnus* spp.). In 2019, finfish fisheries represented 32 % of total landings by weight, 12 % by value, and 42 % of all fishing licenses were for finfish (Fisheries and Oceans Canada 2020c). Historically, the waters surrounding Nova Scotia supported some of the world's most productive fishing grounds for large predatory groundfish (e.g. cod-likes and flatfish) but many of these have been in decline since the mid-1980's (Jackson et al. 2001, Beddington et al. 2005, Frank et al. 2005, Frank et al. 2011, Howarth et al. 2014, Pedersen et al. 2017). Nonetheless, finfish still make a substantial contribution towards fishery landings and to coastal economies in Nova Scotia (Figure 3).

2.2. Potential effects of climate change on fisheries

2.2.1. Distribution shifts

Generally, marine organisms are adapted to survive within a specific range of temperatures, salinity, oxygen concentrations, and other environmental parameters. Since these parameters are changing on a global scale (see Section 1), many species around the world have exhibited shifts (*high confidence*) in their geographic distribution (IPCC 2014) and such changes are projected to continue over the coming century (Cheung et al. 2009). These distribution shifts may result from: (1) organisms moving towards deeper, cooler waters and / or towards the poles, in order to remain within their preferred temperature range; (2) changes in the timing, direction, and extent of their migration movements; (3) increased mortality of eggs, larvae or adults in some parts of their distributional range; and / or (4) broader ecological changes, such as changes in food web dynamics, species invasions, and habitat loss (Parmesan and Yohe 2003, Perry et al. 2005, Nye et al. 2009, Cheung et al. 2010, Wilson et al. 2020). Some of the most important commercially targeted species in Nova Scotia (e.g. snow crab and northern shrimp) may display especially pronounced shifts in their distribution as these species are generally considered to be at, or close to, their southern most extent (see Sections 2.2.4 and 2.2.6).

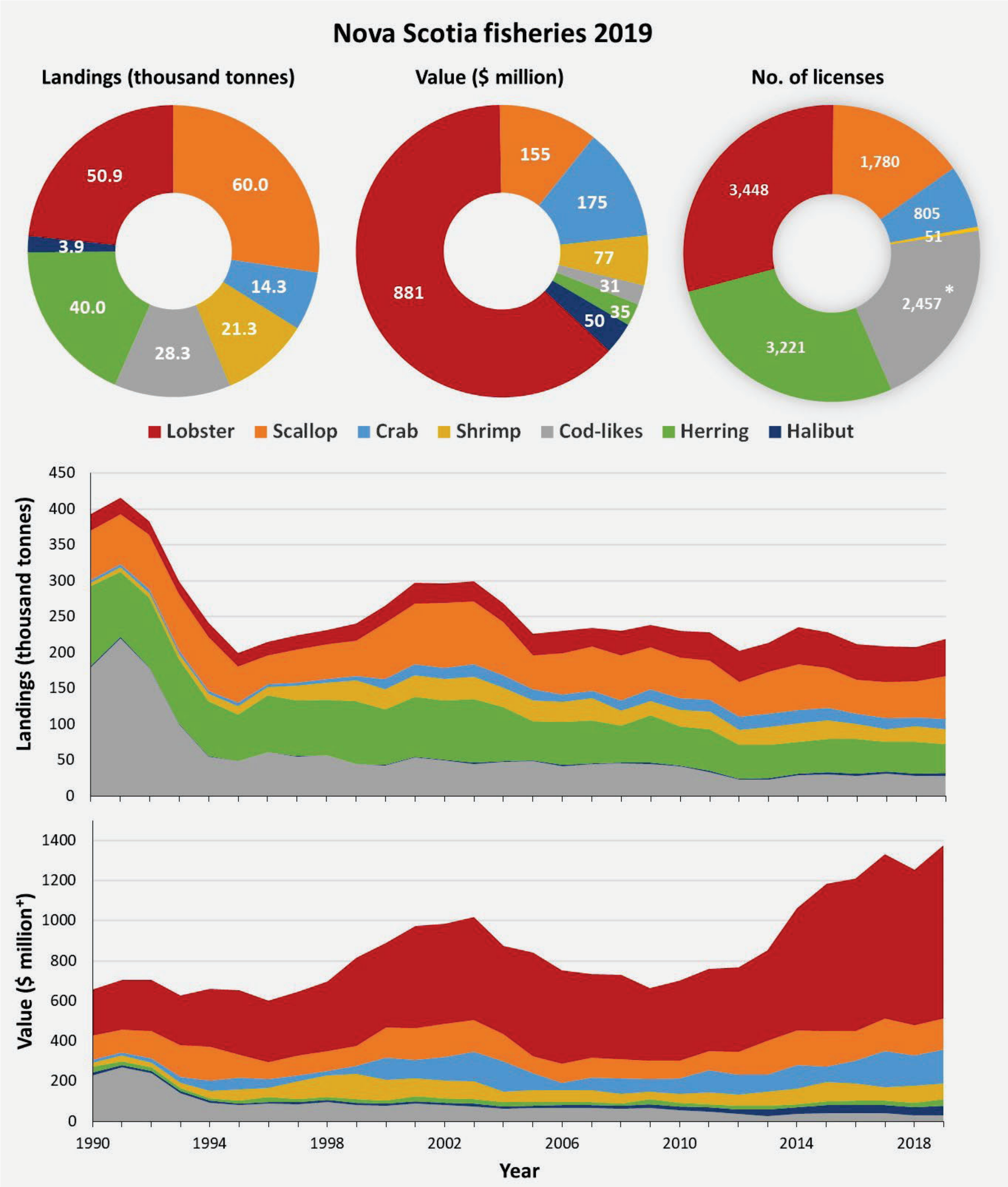

Figure 3 | The landings, value, and number of licenses of some of the most prominent wild capture marine fisheries in Nova Scotia, by species in 2019 (Top), and over time (Bottom). Lobster = American lobster, Scallop = sea scallop, crab = snow crab, shrimp = northern shrimp, herring = Atlantic herring, halibut = Atlantic halibut, and cod-likes = cod, pollock, haddock and silver hake. (*) = all groundfish species including cod-likes, redfish, halibut, turbot, cusk, catfish, skate, and dog fish. ($^+$) = inflation adjusted to 2018 values (Bank of Canada 2020). Source: Fisheries and Oceans Canada (2020c).

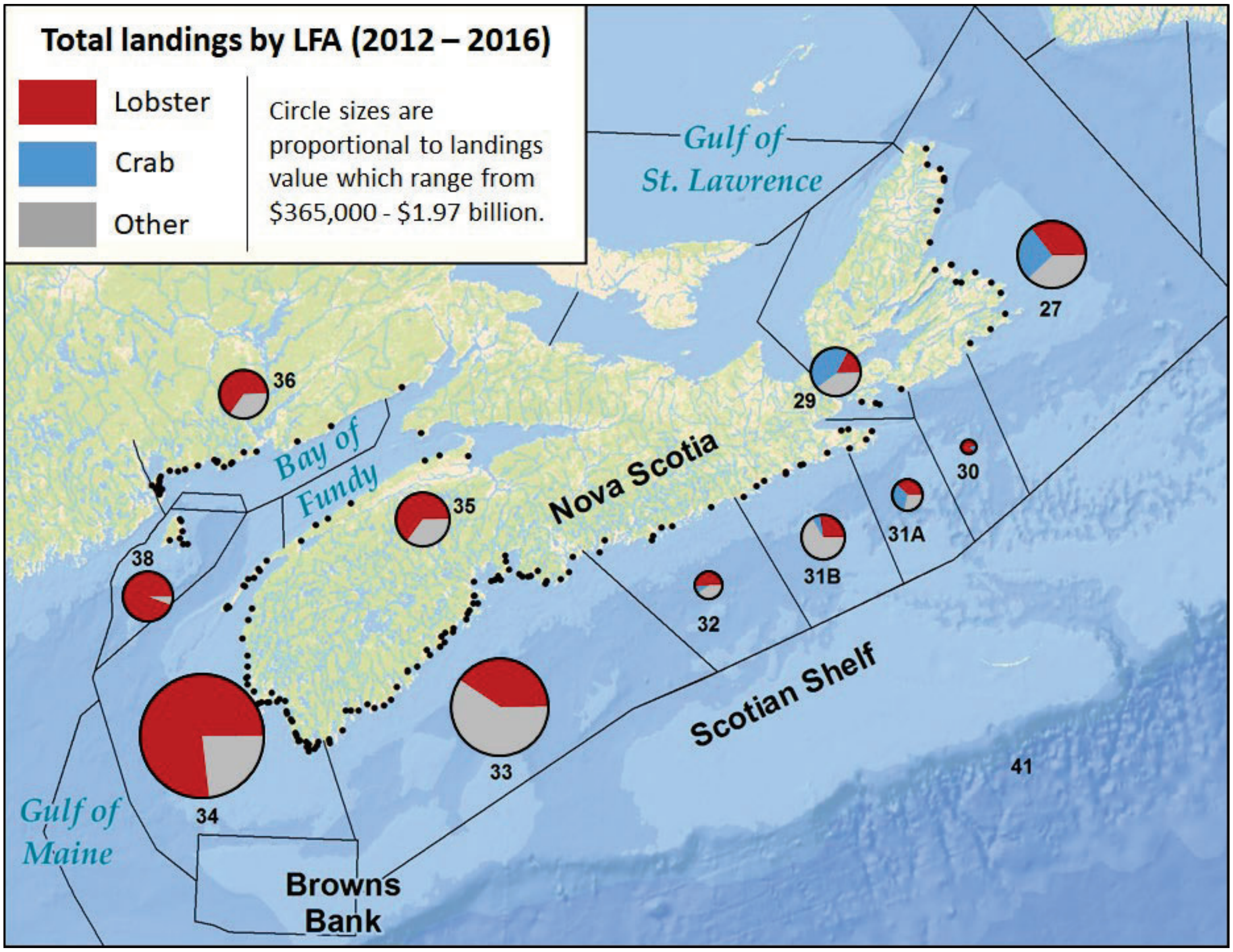

Figure 4 | The proportion of landings (in terms of weight per functional group) within each Lobster Fishing Area (LFA) in Nova Scotia. Pie chart size is scaled by the total value of landings. Data is representative of DFO Maritimes region only and does not include the Northumberland Strait or Gulf of St. Lawrence. DFO Small Craft Harbor locations are represented by black dots. Adapted from Greenan et al. (2019b).

2.2.2. Ocean acidification and fishery interactions

When CO_2 dissolves in seawater, the pH of seawater decreases (see Section 1.2.11). This reduces the amount of carbonate ions available to organisms for shell / exoskeleton growth (Doney et al. 2009, Billé et al. 2013), particularly for bivalves (e.g. scallop, clams, oyster and mussels), crustaceans (e.g. lobster, crab and shrimp) and other calcifying organisms (e.g. plankton and corals). The availability of carbonate in seawater is often measured as the 'saturation state' (or Ω) of aragonite or calcite; the two most common forms of carbonate (Gledhill et al. 2015). Lower aragonite and calcite saturations mean more energy is required by calcifying organisms to grow their shells (Morse et al. 2007, Waldbusser et al. 2015). Most shellfish species require Ω values greater than 1.0 to optimally produce their shells (Gledhill et al. 2015) and Ω values less than 1.0 can negatively affect their growth (Greenan et al. 2019a). Projections reported in a draft white paper (see Salisbury et al. 2019), based on models developed by Lavoie et al. (2019), suggest that subsurface waters in the Gulf of Maine may become persistently undersaturated in aragonite (i.e. $\Omega \leq 1$) over the next 30 – 40 years under a high emissions scenario, and that calcite Ω will also decline in Southern Gulf of Maine to a lesser extent. Overall, aragonite and calcite Ω values can be reduced by cooler temperatures and freshwater inputs, which is why the waters surrounding Nova Scotia are more susceptible to ocean acidification than the global ocean as a whole (see Section 1.2.11). This, combined with the province's high economic dependency on shellfish, means Nova Scotia's fisheries may be particularly vulnerable to ocean acidification.

Finfish may also be affected by ocean acidification. Laboratory studies have shown low pH values to cause a variety of fish species to exhibit signs of tissue damage, malformations, increased egg and larval mortality, and impaired swimming, foraging, predator avoidance and olfactory (i.e. sense of smell) performance (Munday et al. 2010, Frommel et al. 2012, Leduc et al. 2013, Frommel et al. 2014, Stiasny et al. 2016). However, most of these experiments exposed fish to acidification levels at, or greater than, what is projected for the end of this century under the highest emission scenarios. Therefore, it is unknown how well these studies may actually reflect future environmental conditions. There is also substantial variation between species, with many showing no impact from reduced pH (e.g. Munday et al. 2009, Frommel et al. 2013, Damsgaard et al. 2015).

2.2.3. American lobster

Lobster is the most economically important fishery in Nova Scotia and the province's most valuable seafood export (Nova Scotia Department of Fisheries and Aquaculture 2020c). In 2019, landings reached over 50,850 tonnes and generated over $880 million in value, representing 19 % of all landings by weight and 58 % by value (Fisheries and Oceans Canada 2020c). However, warming ocean temperatures (see Section 1.2.2) have contributed to some recent and dramatic changes in lobster fisheries across the eastern coasts of USA and Canada. While lobster catches have reached a record high in the Gulf of Maine and on the Scotian Shelf, catches in southern New England have reached a record low and the fishery has effectively collapsed (ASMFC 2015, Le Bris et al. 2018, Fisheries and Oceans Canada 2020c). The large disparity between these regions is mostly due to differences in temperature, as well as the adoption of stronger fisheries conservation measures in the Gulf of Maine and Nova Scotia (reviewed in Greenan et al. 2019b).

American lobster is distributed across a wide range of temperatures, from -1 to 26 °C (Lawton and Lavalli 1995, Quinn 2017), however, studies indicate an optimal range of around 12 – 18 °C (Crossin et al. 1998). Within this temperature range, lobster larvae display greater survival and faster developmental growth (MacKenzie 1988, Annis et al. 2013, Quinn 2017). In contrast, temperatures above 20 °C have been linked to higher physiological stress, disease, and mortality (Pearce and Balcom 2005, Glenn and Pugh 2006). Bottom temperatures in southern New England now frequently exceed this 20 °C threshold for several months at a time (Wahle et al. 2013). Correspondingly, lobsters in this region have experienced a reduction in habitat suitability, higher incidences of disease, and widespread recruitment failure (Glenn and Pugh 2006, Howarth et al. 2014, Tanaka and Chen 2015, Wahle et al. 2015).

Compared to southern new England, water temperatures are cooler in the Gulf of Maine and Scotian Shelf, meaning ocean warming has increased lobster habitat suitability at a wide range of depths (Wahle et al. 2009, Steneck and Wahle 2013, Tanaka and Chen 2016, Goode et al. 2019). Consequently, lobster populations in this region have expanded further north and offshore (Pinsky et al. 2013, Wahle et al. 2013, Wahle et al. 2015, Goode et al. 2019) and these temperature-driven distribution shifts are a key factor underlying the recent increase in lobster in Maine and Nova Scotia (Le Bris et al. 2018). However, sudden increases in catches can have negative, indirect effects on lobster fisheries. For example, a marine heatwave (see Section 1.2.2) in 2012 led to prolonged period of exceptionally high lobster catches in Maine, which unintentionally led to a collapse in lobster prices both in the USA and Canada (reviewed in Mills et al. 2013).

Overall, lobster habitat suitability is projected to continue increasing in Nova Scotia over the next 30 years (Greenan et al. 2019b), while greatly reducing in southern New England (Rheuban et al. 2017), and the Gulf of Maine to a lesser extent (Le Bris et al. 2018, Allyn et al. 2020). Although these changes are benefiting the Nova Scotian lobster fishery, there are also some potential causes for concern:

- **Southward decline:** Model projections suggest lobster habitat suitability may begin to decline in the Bay of Fundy by the middle of this century (Greenan et al. 2019b, Allyn et al. 2020). Chabot et al. (2013) also speculated that continued ocean warming may cause lobster abundance to decline in the Bay of Fundy, the south shore of Nova Scotia, and in the southern Gulf of St. Lawrence, as bottom temperatures are already higher in these regions than surrounding areas (Figure 1). As coastal communities are more economically dependent on lobster fisheries in southern Nova Scotia (Figure 4), even a small decline in lobster abundance could have large consequences.
- **Disease:** Lobster are more susceptible to epizootic shell disease at temperatures above 10 °C, which can be fatal above 15 °C (Stewart 1980). In addition to reducing their survival, this disease can reduce catch value as infected lobsters possess corrosive brown-black lesions (Figure 5) on their shells (Glenn and Pugh 2006, Castro et al. 2012). The prevalence of this disease is strongly linked to warmer temperatures and is, therefore, currently more of a problem in southern New England than in the Gulf of Maine and Scotian Shelf (reviewed in Shields 2019, Mazur et al. 2020). However, as temperatures continue to warm in the Northwest Atlantic, epizootic shell disease could potentially spread further north into Nova Scotia (Maynard et al. 2016, Greenan et al. 2019b).

Figure 5 | Lesions caused by epizootic shell disease are eroding the external carapace of this American lobster from southern New England. This disease is currently not an issue in Nova Scotia, but it has potential to spread further north as water temperatures continue to rise. Source: Prof. Jeff Shields.

- **Increased molting:** Lobsters tend to molt more frequently in warmer waters (Waddy et al. 1995, Mills et al. 2013, Schmalenbach and Buchholz 2013, Staples et al. 2019). This could be problematic as recently molted lobsters have softer shells, higher water content, and reduced meat yield, meaning they have reduced survivability during capture and transport, and tend to command lower prices as they are less desirable to consumers (reviewed in Thakur et al. 2017). Soft-shelled lobster, and lobster infected with epizootic shell disease, would also fail to meet standards for the '45° N / 63° W' Nova Scotia Seafood Brand (www.nsseafood.com). The relationship between temperature and molting frequency could potentially explain why catches of soft-shelled lobster on the south shore of Nova Scotia increased by 10 % between 2004 – 2014 (Thakur et al. 2017).

- **Reduced fecundity:** Lobsters in warmer waters tend to reach maturity at smaller sizes and younger ages, which may potentially reduce the overall fecundity of the population (Waller et al. 2017). An analysis of 30 years of survey data collected from southern new England and the Bay of Fundy found that, for every 1 °C increase in bottom temperature, lobster size at maturity decreased by 2.8 mm (Le Bris et al. 2017).

- **Reduced food availability:** The copepod, *Calanus finmarchicus*, is a major component of zooplankton in the North Atlantic, and provides food to a wide range of commercially important species (Grieve et al. 2017). However, ocean warming has caused this copepod to decline in the Gulf of Maine and Scotian Shelf (see Section 2.2.11). In the Gulf of Maine, years of low *C. finmarchicus* abundance have been correlated with low juvenile lobster abundance, suggesting temperature-driven changes in zooplankton may be contributing towards regional reductions in lobster recruitment (Carloni et al. 2018). If *C. finmarchicus* abundance continues declining, it could potentially have a negative impact on lobster and other fisheries in Nova Scotia.

- **Bait shortages:** Overfishing and temperature-driven declines in herring and mackerel abundance have resulted in bait shortages for the American lobster and snow crab fisheries (see Section 2.2.7).

In summary, the lobster fishery in Nova Scotia is generally benefitting from ocean warming. However, the simultaneous collapse of the southern New England lobster fishery emphasizes the precariousness of this situation as warmer temperatures suggest increased stress, disease, mortality, and recruitment failure. If lobster populations in Nova Scotia were to decline, the social and economic consequences would be severe given the large contribution towards fishery landings and value.

2.2.4. Snow crab

Snow crab is the second most economically important fishery in Nova Scotia. In 2019, landings reached over 14,270 tonnes and generated $175 million in value, representing 5 % of all landings by weight and 12 % by value (Fisheries and Oceans Canada 2020c). Snow crab is considered to be highly vulnerable to climate change as the range of temperatures it can tolerate is very narrow, and because many aspects of its physiology (e.g. growth rate, body size and fecundity) can be strongly affected by small changes in temperature (Tremblay 1997, Chabot et al. 2013, Zisserson and Cook 2017, Wilson et al. 2020).

Snow crab occupy waters ranging in temperature between -1.8 °C to 6 °C (reviewed in Chabot et al. 2013, Zisserson and Cook 2017), however, temperatures below -1 °C and above 4 °C can comprise their long-term survival (reviewed in Sainte-Marie et al. 2005). Adult snow crabs display a negative energy balance at temperatures above 7 °C (Foyle et al. 1989) and temperatures above 12 °C can be lethal within 96 hours

(Hardy et al. 1994). Evidence suggests juvenile snow crabs have a narrower temperature range between 0 – 1.5 °C (Dionne et al. 2003) but that larvae can tolerate a much broader temperature range of 8 – 15 °C (Kon et al. 2003, Chabot et al. 2013).

Generally, higher temperatures within their tolerable range can promote larger body sizes and faster larval development in snow crabs (Burmeister and Sainte-Marie 2010, Chabot et al. 2013). In addition, female crabs typically reproduce just once every two years in waters colder than 1 °C but reproduce annually in temperatures above 1.8 °C (Moriyasu and Lanteigne 1998). Thus, a small increase in temperature could potentially lead to a two-fold increase in reproductive output in some areas. However, despite the potential for snow crab fisheries to benefit from ocean warming, most evidence indicates snow crab will be negatively impacted by climate change (Chabot et al. 2013, Stortini et al. 2015, Zisserson and Cook 2017).

To remain within their tolerable temperature range, adult snow crabs on the Scotian Shelf tend to be limited to cold waters located at depths between 60 – 280 m (Choi et al. 2013). However, as these waters are projected to warm over the coming century (see Section 1.2.2), there is a possibility that snow crab on the Scotian Shelf will experience a large reduction in habitat suitability and recruitment, which could potentially lead to their commercial extinction by the year 2070 (Chabot et al. 2013). The marine heatwave in 2012 (see Section 2.2.3) may provide some insight into the future of snow crab fisheries. During this event, water temperatures reached a record high on the western Scotian Shelf, which led to the near disappearance of snow crab, and the population is yet to recover (Stortini et al. 2015, Zisserson and Cook 2017). The heatwave also led to substantial reductions in snow crab abundance on the eastern Scotian Shelf and resulted in several years of unexpectedly low catches (Zisserson and Cook 2017). Such declines may become more common as research suggests marine heatwaves may increase in frequency and duration (see Section 1.2.2). Snow crab in the Gulf of St. Lawrence are also projected to decline in abundance (Chabot et al. 2013) due to ocean warming and decreasing oxygen concentrations (see Section 1.2.10). In addition, warming may initiate earlier spring algal blooms, potentially causing a mismatch in the timing of snow crab larval hatching, reducing larval food availability, growth rates and survival (Kuhn et al. 2011, Chabot et al. 2013).

2.2.5. Sea scallop

Sea scallops are the third most economically important fishery in Nova Scotia. In 2019, landings reached over 59,960 tonnes and generated over $155 million in value, representing 23 % of all landings by weight and 10 % by value (Fisheries and Oceans Canada 2020c). The potential effects of climate change on Nova Scotian scallop fisheries are largely unknown but evidence from neighboring regions suggests there is some potential cause for concern.

Sea scallops are widely distributed from North Carolina up to the Gulf of St. Lawrence in temperatures ranging between 0 – 17 °C in depths of 2 – 110 m (reviewed in Cooley et al. 2015, Torre et al. 2018). Adult sea scallops display optimal growth rates at 10 – 15 °C but temperatures above 21 °C can be lethal (Stewart and Arnold 1994). Most scallop species display faster growth and higher reproductive output at warmer temperatures (reviewed in Shephard et al. 2010).

Studies have investigated the effects of ocean acidification on a variety of scallop species and largely report contradictory trends, as some indicate low pH waters can have negative (Andersen et al. 2013, White et al. 2013, White et al. 2014, Lagos et al. 2016), positive (Ramajo et al. 2016) and neutral effects (Sanders et al. 2013) on scallop survival and growth. Consequently, model projections for New England suggest that, under a high emission scenario, warming will increase sea scallop growth rates until around 2030, at which point ocean acidification will counter the positive effects of warming by causing a reduction in scallop growth and body size (Cooley et al. 2015, Rheuban et al. 2018). Conversely, species distribution models suggest climate change will have little impact on sea scallop biomass in the Gulf of Maine (Allyn et al. 2020). Other models suggest warming temperatures will have a negative effect on habitat suitability across most of New England but trends will be less clear around Nova Scotia, with gains in habitat suitability projected inshore, but a combination of gains and losses projected further offshore (Tanaka et al. 2020). Overall, the variability in these responses suggests further investigation into the potential effects of ocean warming and acidification on sea scallops is warranted.

2.2.6. Northern shrimp

Northern shrimp is the fourth most economically important fishery in Nova Scotia. In 2019, landings reached over 21,320 tonnes and generated over $76 million in value, representing 8 % of all landings by weight and 5 % by value (Fisheries and Oceans Canada 2020c). As temperature can affect most aspects of its life cycle (e.g. fecundity, longevity, growth, sex ratios), northern shrimp could potentially be negatively impacted by climate change (Richards et al. 2012, Chabot et al. 2013).

Northern shrimp occur in water temperatures ranging between -1.6 °C to 12 °C (Shumway et al. 1985) but are considered to have an optimal range of approximately 0 – 6 °C (Koeller 2000). Juveniles are thought to be tolerant to a wider temperature range (Garcia 2007) but temperatures above 16 °C can be lethal to larvae (Shumway et al. 1985). In Nova Scotia, northern shrimp abundance is generally highest on the eastern Scotian Shelf where waters are suitably cooler (Koeller 2000). In contrast, this species is at, or close to, its southern most extent in the Gulf of Maine and western Scotian shelf, and therefore usually only occurs in commercially viable densities when temperatures drop to favourable levels (Koeller 2000, Richards et al. 2012). In fact, the development of northern shrimp fisheries in the Gulf of Maine and western Scotian shelf in the early to mid-1960's coincided with a 10-year period of below-average temperatures (Koeller 2000). However, both fisheries collapsed during a 10-year period of above-average temperatures in the early 1970's. To this day, the fishery on the western Scotian Shelf has never recovered, whereas the fishery on the Gulf of Maine has closed multiple times, and recruitment and spawning stock biomass reached a record low in 2017 (ASMFC 2020). As northern shrimp recruitment is negatively affected by higher temperatures, it is likely that ocean warming is at least partly responsible for these trends (Tande et al. 1994, Koeller 2000, Richards et al. 2012).

It is speculated that future warming will reduce northern shrimp recruitment, larval survival, and egg size on the eastern Scotian Shelf and Gulf of St. Lawrence (reviewed in Chabot et al. 2013). There is also a possibility that warming will create a mis-match between the timing of spring algal blooms and the hatching of shrimp larvae (Chabot et al. 2013, Brosset et al. 2019). Lastly, as northern shrimp are less tolerant to low oxygen levels at higher temperatures (Dupont-Prinet et al. 2013), shrimp abundance is projected to decrease by 3 – 19 % in the Gulf of St. Lawrence by 2060 (Stortini et al. 2016) depending on the extent of ocean warming and oxygen decline (see Section 1.2.10).

2.2.7. Atlantic herring, Atlantic mackerel, and bait shortages

Atlantic herring is the 8th most economically valuable fishery in Nova Scotia ($34.5 million in 2019 ; Fisheries and Oceans Canada 2020c) but the third largest in terms of landings (39,961 tonnes in 2019). In contrast, the Atlantic mackerel fishery is the 18th most economically valuable ($1.9 million in 2019) and the 14th largest in terms of landings (1,047 tonnes in 2019). Both fisheries traditionally supply bait to the lobster and crab fisheries. However, Atlantic herring landings have decreased three-fold since the 1970's (Fisheries and Oceans Canada 2017) and Atlantic mackerel has declined five-fold since the early 2000's (Fisheries and Oceans Canada 2019a). Consequently, the price of bait has increased from around $0.10 to $1 per pound in recent years, and is now a key concern for lobster and crab fishermen in Nova Scotia. In response, several fishermen now have licenses to harvest invasive European green crab (*Carcinus maenas*) for bait (SaltWire 2015), and investigations have begun to test the feasibility of using invasive freshwater fish in the Great Lakes as bait (Gibson 2018) and factory-made baits from fish oil and fish by-products (McCarthy 2019).

In addition to overexploitation (Stephenson et al. 1999, Overholtz 2002, Boyce et al. 2019), evidence suggests that ocean warming may also be partly responsible for these declines as the distribution of the Northwest Atlantic mackerel stock shifted 250 km north- and eastwards between 1968 – 2008 (Overholtz et al. 2011), and similar trends have been reported for Atlantic herring (Rose 2005). Both species are predicted to become increasingly scarce around Nova Scotia, and spring spawning herring may disappear altogether in the Bay of Fundy and Gulf of St. Lawrence (reviewed in Chabot et al. 2013, Lemmen et al. 2016). Consequently, herring and mackerel fisheries are likely to undergo further declines in catches and quota, meaning access to affordable bait could become a growing issue for crab and lobster fisheries.

2.2.8. Groundfish

Although groundfish fisheries have declined in Nova Scotia (see Section 2.1), they still have significant commercial value. Haddock is the 6th most important fishery in terms of landings (22,331 tonnes in 2019) and 9th most important in terms of economic value ($22.3 million in 2019). Silver hake is the 9th most important in terms of landings (5,291 tonnes) and 14th most valuable ($2.8 million). While Atlantic cod is the 13th most important in terms of landings (1,066 tonnes) and 16th most valuable ($2.6 million ; Fisheries and Oceans Canada 2020c).

Model simulations by Shackell et al. (2014) suggest that over 25 species of finfish (mostly groundfish) on the Scotian Shelf will experience a significant reduction in habitat availability due to ocean warming by 2060. Likewise, Atlantic cod is projected to undergo a 30 – 50 % reduction in habitat suitability by 2100 in the Gulf of Maine and Scotian Shelf under a high emissions scenario (Morley et al. 2018, Morato et al. 2020), and a reduction of 26 % is projected for haddock (Morley et al. 2018). Similarly, species distribution models for the Gulf of Maine and southern New England project broad decreases in the biomass of Atlantic cod, haddock, pollock, and several species of hake and flounder (Allyn et al. 2020). Likewise, models constructed by Stortini et al. (2015) identified several populations of pollack, silver hake, Atlantic cod, and cusk (*Brosme brosme*) on the Scotian Shelf to be vulnerable to climate change under a high emissions scenario. Lastly, Greenland halibut (*Reinhardtius hippoglossoides*) is projected to lose up to 55 % of its high density areas in the Gulf of St Lawrence due to ocean warming and oxygen depletion (Stortini et al. 2016).

Conversely, climate change may benefit groundfish fisheries in some respects. Both haddock and Atlantic cod are expected to experience increased growth and survival in response to future warming (Chabot et al. 2013). While Atlantic halibut is projected to shift northwards away from its southern most extent in southern New England (Allyn et al. 2020), potentially resulting in higher catches in Nova Scotia and Newfoundland (Chabot et al. 2013).

2.2.9. Large pelagics

Nova Scotia has several fisheries for large pelagic fish including swordfish (*Xiphias gladius*) and tuna (Atlantic bluefin, *Thunnus thynnus* ; yellow fin, *Thunnus albacares* ; big eye, *Thunnus obesus* ; albacore, *Thunnus alalunga*). Although swordfish landings are small (996 tonnes in 2019), it is the 10th most valuable fishery ($12.9 million in 2019) in Nova Scotia (Fisheries and Oceans Canada 2020c). Similarly, tuna landings only reached 730 tonnes in 2019 but represent the 12th most valuable fishery ($8.1 million in 2019). Atlantic bluefin tuna is also the focus of a live-release sports fishery, which was estimated to have generated over $1.8 million in revenue in 2012 (Ecology Action Centre 2014).

Tuna and swordfish are highly migratory and can travel up to several thousand kilometers every year (Sperling et al. 2005, Fisheries and Oceans Canada 2018b). Due to their complex life histories and long migratory routes, their exact spatial distribution, reproductive behaviour, and other aspects of their ecology are largely unknown (Neilson et al. 2014, Collette 2017). Thus, there is considerable uncertainty regarding the potential effects of climate change on these fisheries.

The few studies which have investigated the potential effects of climate change on North Atlantic swordfish report contradictory trends. For example, two studies found no evidence that the distribution of North Atlantic swordfish had changed between the 1960's – 2000's (Worm and Tittensor 2011, Erauskin-Extramiana et al. 2020). However, Schirripa et al. (2017) concluded that the distribution of North Atlantic swordfish had significantly shifted northwards since 1996 and may be at least partly related to changes in environmental conditions. Overall, the global abundance of swordfish is projected to decline by over 21 % at the end of the century under a high emissions scenario, but increase slightly in the waters surrounding Nova Scotia (Erauskin-Extramiana et al. 2020). In contrast, almost all (89 %) temperate tuna stocks have exhibited a poleward shift in distribution since 1958 as a result of climate change and is projected to continue (Erauskin-Extramiana et al. 2020). Under a high emissions scenario, most tuna stocks in the North Atlantic are projected to decrease over the coming century and Eastern Canada is projected to experience the largest reductions in Atlantic bluefin tuna (Erauskin-Extramiana et al. 2020). However, the abundance of big eye tuna may increase slightly.

2.2.10. Redfish

The Nova Scotian redfish fishery targets two closely related, morphologically similar species (deepwater redfish, *Sebastes mentella* ; and the Acadian redfish, *S. fasciatus*) (COSEWIC 2010). Together, redfish represent the 8th most important fishery in Nova Scotia in terms of landings (8,662 tonnes in 2019) and the 11th most economically valuable ($9.4 million in 2019; Fisheries and Oceans Canada 2020c). Following the near collapse of the fishery during the mid-1990's, a series of strict management measures have been in place to help protect stocks (reviewed in Fisheries and Oceans Canada 2018a). However, the stock has shown significant signs of recovery since 2014 and new experimental licenses have recently been issued to test the viability of reopening the fishery (Fisheries and Oceans Canada 2020g). Thus, the redfish fishery has scope for further expansion.

The potential impacts of climate change on the redfish fishery are not well studied. However, both species of redfish are likely to expand further north into northern Quebec, Labrador, and Nunavut waters (Hollowed et al. 2013, Morato et al. 2020). In addition, a 61 % reduction in habitat suitability has been projected for Acadian redfish in Eastern Canada by 2100 under a high emsisions scenario (Morley et al. 2018), and a reduction of 45 % is projected for the deepwater redfish in the Northeast USA (stocks in Eastern Canada were not assessed). Species distribution models for the Gulf of Maine also suggest the biomass of Acadian redfish will decline (Allyn et al. 2020). These projected declines, combined with the species' slow life history (e.g. lives up to 75 years and reaches sexual maturity at 18 years) and highly episodic recruitment (strong year classes only occur every 5 – 12 years) could make redfish even more susceptible to overexploitation (COSEWIC 2010), and make it difficult to achieve a long-term, stable, sustainable fishery.

2.2.11. Whale trends and potential fishery interactions

There is growing consensus that ocean warming is at least partly responsible for a recent change in the distribution of North Atlantic right whales (*Eubalaena glacialis*). This distribution shift means right whales now frequently appear in major shipping lanes, and fishing grounds for snow crab and American lobster, on the Scotian Shelf and Gulf of St. Lawrence (Davis et al. 2017, Davies et al. 2019). Consequently, since 2017, approximately 20 right whales have been killed or injured in Atlantic Canada as a result of ship strikes and / or entanglement with fishing gear (Davies and Brillant 2019, Bourque et al. 2020, Fisheries and Oceans Canada 2021a, NOAA 2021). As there may be as few as 360 North Atlantic right whales remaining worldwide, there are strong concerns these mortality events could place the species closer to extinction (Pettis et al. 2019, Moore et al. 2021). In response, the Canadian federal government imposed a series of mandatory regulations in 2018, including: a reduction in snow crab quota and trap limits; a large fishery closure within the Gulf of St. Lawrence; and dynamically managed fishery closures in any areas where whales are detected. As a result, the presence of North Atlantic right whales has greatly impacted crab and lobster fisheries operating within the region (Fisheries and Oceans Canada 2020a).

Evidence suggests that increased temperatures in the Gulf of Maine and Scotian Shelf has reduced the abundance of *C. finmarchicus*, a species of copepod which forms a key source of food for North Atlantic right whales (Sorochan et al. 2019). This copepod has also exhibited a northeastward shift in distribution of around 8 km per decade since 1959 (Chust et al. 2013) and model projections suggest these trends will continue over the coming century (Villarino et al. 2015). Therefore, it is thought that the whales may have moved into the Gulf of St. Lawrence in search of greater food availability (Record et al. 2019, Sorochan et al. 2019). As *C. finmarchicus* density in the Gulf of Maine and Scotian Shelf is projected to decrease by as much as 50 % by 2081 – 2100 under a high emissions scenario (Grieve et al. 2017), higher latitude feeding sites, such as the Gulf of St. Lawrence, could increasingly be used by north Atlantic right whales, as well as other species of baleen whale (Davis et al. 2020). However, uncertainty in these projections is very high, and this topic very remains a very active area of research.

2.3. New fishing opportunities

This report has described a variety of potential climate change-related issues facing the Nova Scotian fishing industry (see Section 2.2). However, there is also a possibility that the introduction or expansion of previously rare, warm water species could provide new fishing opportunities, particularly if markets for these species already exist (Ojea et al. 2020).

Annual DFO bottom trawl surveys are catching an increasing number of warm water species on the Scotian Shelf and Bay of Fundy (Withers 2021), and between 1 – 6 new species are captured every year (Shackell and Frank 2003, Bernier et al. 2018, 2019). Increasingly common species include, the American John Dory (*Zenopsis ocellata*), armored sea robins (Family: *Peristediidae*), spotted tinselfish (*Xenolepidichthys dalgleishi*), and the blackbelly rosefish (*Helicolenus dactylopterus*). The blackbelly rosefish, in particular, could provide a potential commercial opportunity as fisheries already exist in the southern United States, Europe, and the Mediterranean (White et al. 1998, Ribas et al. 2006, Santos et al. 2020). Furthermore, this species is predicted to experience an increase in habitat suitability around Nova Scotia as water temperatures continue to warm over the coming century (Morato et al. 2020). Some members of the Nova Scotian fishing industry have already started the process of initiating new fisheries for some of these emerging species (see Section 2.3.1).

Species distribution models for the Gulf of Maine (Allyn et al. 2020) also suggest climate change will lead to a substantial increase in the biomass of weakfish (*Cynoscion regalis*), black seabass (*Paralichthys dentatus*), Atlantic striped bass (*Morone saxatilis*), scup (*Stenotomus chrysops*), golden tilefish (*Lopholatilus chamaeleonticeps*), Atlantic menhaden (*Brevoortia tyrannus*), summer flounder (*Paralichthys dentatus*), clearnose skate (*Raja eglanteria*), and rosette skate (*Leucoraja garmani*). Whether these species will also increase in Nova Scotian waters is currently unknown, but if they did, they could provide new economic opportunities as fisheries already exist for many of these species in the USA (NOAA 2020). Paradoxically, although black seabass is highly valued as food and as game fish, some concerns have been raised that it could increase predation pressure on juvenile American lobster and other commercially important species (MLCA 2018, The University of Maine 2019). Overall, more scientific and market research is required to help determine:

- How species composition is changing in Nova Scotia;
- The potential ecological implications of these changes;
- Whether any new or previously untargeted species may exist in commercially viable quantities;
- What technologies could help fishermen target these species; and
- Whether there are existing or potential new markets.

2.3.1. Management of secondary stocks in the DFO Maritimes Region

Initiating new fisheries for emerging species could provide one avenue for fishermen to diversify their income / catches and help the fishing industry be more flexible and adaptable to climate change. DFO's Emerging Fisheries Policy outlines the requirements and procedures for initiating a new fishery (Fisheries and Oceans Canada 2008). In the Maritimes Region, a new fishery will either be managed by DFO's Secondary Species Section or assigned a new unit specific to the species (Melanie Barrett, DFO, pers. comm, March 2021). A 'secondary species' refers to stocks that contribute less than 2000 tonnes in landings a year, or generate less than $2 million in value, however, these thresholds are currently under review (Michelle Greenlaw and Melanie Barrett, DFO, pers. comm, February 2021). A key difference in how DFO manage primary and secondary fisheries is that DFO prioritize personnel and financial resources towards the research, management and enforcement of primary fisheries (Fisheries and Oceans Canada 2008). Thus, for secondary fisheries, the responsibility for collecting fisheries data, and proposing management strategies, reference points, and monitoring and assessment frameworks, falls almost entirely to the fishing industry (Fisheries and Oceans Canada 2015). DFO Science provide advice and peer-review, and DFO Resource Management communicate and provide support to industry. Establishing a secondary fishery within the Maritimes Region generally undergoes three stages:

1. **Experimental fishing:** The industry reviews all existing knowledge and submits an experimental fishing proposal. If approved by DFO, the industry is then permitted to commence non-commercial fishing and the collection of data.

2. **Exploratory fishing:** Based on information attained during the experimental phase, the industry submits an exploratory fishing proposal. If approved by DFO, the industry can commence small-scale commercial fishing and more in-depth data collection (e.g. studies of biology, distribution, and exploration of management strategies).

3. **Commercial fishing:** DFO issues a full-commercial license under strategies and tactics identified in in the experimental and exploratory phases that promote a long-term, sustainable fishery (Fisheries and Oceans Canada 2015).

As the industry is responsible for collecting these data and proposing management strategies, initiating a new fishery requires substantial investment from industry, with no guarantee a commercial license will be issued at the end of the process. During the creation of this report, conversations were held with several fishing industry representatives who have recent experience with initiating secondary fisheries in Nova Scotia. All felt the process was overly complex, unclear, inconsistent, slow, and under-resourced / under-prioritized which often caused the process to stall for undetermined, prolonged periods of time. Consequently, greater support, and a more streamlined bureaucratic processes may be required to help promote the development of new fisheries in Nova Scotia. Overall, this process is currently under revision and DFO is aiming to establish an improved, more collaborative and timely system (Michelle Greenlaw and Melanie Barrett, DFO, pers. comm, February 2021).

2.4. Fisheries management in Canada

DFO is responsible for providing scientific advice to the Government regarding the management of fishery resources. Typically, this advice includes an evaluation of: resource status (e.g. through single species stock assessment, see Section 2.4.1); the impacts of fishing and other processes; and how these compare to targets and objectives (reviewed in Fisheries and Oceans Canada 2019b).

2.4.1. Single species stock assessments

Single species stock assessments are one of the primary activities of DFO fishery scientists (reviewed in Pepin et al. 2020). In general, these:

- Assess the status of populations (e.g. spawning stock biomass, size / age structure);
- Evaluate the sustainability of different harvest strategies;
- Project probable patterns of change on relatively short time scales (usually 1–5 years); and
- Quantify the uncertainty and risks regarding these changes.

Importantly, these types of stock assessments usually assume the distribution of the population is stationary and that the external environment is constant or varying randomly (Pepin et al. 2020). However, as discussed (see Section 1.2), climate change can cause directional, non-random changes (e.g. persisting increases in temperature and decreases in pH) that can strongly affect the distribution and productivity of fish populations (see Section 2.2). Consequently, climate change has the potential to invalidate single species stock assessment models and hamper DFO's management advice (Duplisea et al. 2020, Pepin et al. 2020). Presently, this issue is partially addressed through peer-review meetings (see Section 2.4.2) and several policies (established or emerging), tools, approaches and associated research programs (see Section 2.4.3).

2.4.2. Current avenues for incorporating climate change into DFO fisheries advice

In addition to stock assessments, peer-reviewed meetings overseen by the Canadian Science Advisory Secretariat (CSAS) are an integral component of the DFO fishery advisory process (Fisheries and Oceans Canada 2020b, d). These meetings provide several avenues for climate change to be considered in DFO's management advice. However, Pepin et al. (2020) reviewed 178 DFO stock assessment documents published between 2000 – 2017, and found that only 46% described hypotheses or conceptual linkages between population dynamics and climate, oceanographic or ecological variables. Furthermore, only 21 % of stock assessments quantitatively included oceanographic or ecological parameters, and 31 % did so qualitatively. Lastly, only 27 % included climate, oceanographic or ecological information in their advisory reports (see also, Boyce 2021). This gap may hinder the ability of fisheries management to respond to climate change based on science advice provided by DFO (Fisheries and Oceans Canada 2019b, Duplisea et al. 2020, Pepin et al. 2020).

2.4.3. Sustainable Fisheries Framework and other programs

There are several established or emerging policies, tools and approaches aimed at transitioning fisheries management towards a more holistic ecosystem-based approach (reviewed in Paul and Stephenson 2020). The Sustainable Fisheries Framework (see Fisheries and Oceans Canada 2009c) encompasses a suite of policies which, among others:

- Established a **Precautionary Approach to Fisheries Management**. This policy requires DFO to be cautious in providing advice when scientific knowledge is uncertain, and to not use the absence of adequate scientific information as a reason to delay action for preventing serious harm to fish stocks and their ecosystem (Fisheries and Oceans Canada 2009a);
- Provides the foundation for implementing an **Ecosystem Approach to Fisheries Management**. This aims to replace single species approaches and requires management decisions to consider the wider ecological impacts of fishing and to take into account climate change and other ecological and environmental changes (Fisheries and Oceans Canada 2009b).

DFO is also leading several large research programs on the effects of climate change including the 'Aquatic Climate Change Adaptation Services Program' (ACCASP, Fisheries and Oceans Canada 2020f) which investigates: (1) ocean chemistry (e.g. by collecting field and remote sensing data on ocean circulation); (2) vulnerability of fisheries and coastal infrastructure to climate change (also see example in Section 6.4); and (3) refining oceanographic models (e.g. for temperature, currents and ocean chemistry). The knowledge gained from these research programs aims to improve DFO's understanding of how climate change is affecting fishery resources and will eventually be integrated in their stock management advice through the CSAS peer-review process (Kristian Curran, DFO, pers. comm, December 2020).

2.4.4. Integrating economic, social, and institutional objectives in fisheries management

Fisheries management is moving towards a broader, more holistic, and conservation-oriented management approach in Canada (see Section 2.3.3). This transition is intended to help improve fisheries sustainability and promote management decisions that better consider the impacts of climate change on ecosystems and fishery resources. However, it has been argued that such 'Ecosystem Based Fisheries Management' cannot truly be implemented until management accounts for all four of the following Sustainability Objectives (these are commonly referred to as the "four pillars of sustainability" and are reviewed in much greater detail in Stephenson et al. 2019a, Stephenson et al. 2019b):

1. **Ecological:** Fisheries management should maintain fisheries productivity while protecting other biodiversity and habitats.
2. **Economic:** Fisheries management should promote long-term economic prosperity for commercial, recreational, and aboriginal fisheries, and ensure an economically viable and competitive fishing industry that is adaptable to changing markets. Managers should also consider promoting aquaculture to diversify income and diets.
3. **Social / cultural:** Fisheries management should cater for the well-being of the entire fishing workforce within communities and promote the development of new sustainable economic opportunities.
4. **Institutional:** Fisheries management should be an effective decision-making process that is transparent, democratic, and adaptive. It should include effective policies and agreements that specify roles, responsibilities, legal obligations, and governance structure, while promoting resource stewardship.

At present, fisheries management in Canada, and most other countries, does not fully address all these Sustainability Objectives. Ecological Objectives are by far the key focus, but some Economic Objectives are also addressed. For example, federal and provincial agencies track economic revenue from fishing and seafood processing (e.g. Fisheries and Oceans Canada 2020e, Nova Scotia Department of Fisheries and Aquaculture 2020d, Fisheries and Oceans Canada 2021b), and make efforts to track, maintain and / or increase employment in these sectors (e.g. Food Processing Skills Canada 2019). However, the Social, Institutional, and other Economic Sustainability Objectives receive much less attention, and tend to be considered, if at all, very late through the management advice process (also see Section 2.3.2), or through political decisions (reviewed in Stephenson et al. 2019b). This narrow focus, combined with the following factors, may impede flexibility of the fishing industry to adapt to climate change (also see Section 6.1.2 on Adaptative Capacity):

- **High economic dependence on shellfish:** American lobster, northern shrimp, sea scallop and snow crab represent over 88 % of all fisheries value in Nova Scotia (Fisheries and Oceans Canada 2021b). However, climate change will likely impact the productivity and distribution of these fisheries, as well as a wide range of finfish fisheries, in Nova Scotia (see Section 2.2). Consequently, this economic dependency on a narrow range of resources means any climate-driven changes could have serious socioeconomic consequences for communities which are highly dependent on marine fisheries (Barnett et al. 2017, Mombourquette 2019, Stephenson et al. 2019b).

- **High entry costs:** Many commercial fisheries are 'limited entry', where the number of licenses is limited. This usually means a prospective fisher must purchase a license from an existing license holder, sometimes at the cost of several hundred thousand dollars or more. Such a large investment could deter fishermen from attempting to secure other licenses and diversify their catches.

- **Spatial and seasonal rigidity:** Fishing licenses are often spatially and seasonally restricted, meaning fishermen are only permitted to fish specific areas during certain times of the year. However, as discussed (see Section 2.2), climate change is impacting the productivity, distribution, timing of molting, and other key life stages, of many fisheries in Nova Scotia. Thus, the current licensing system may be too rigid to allow fishermen to adjust their practices in response to any climate-driven changes.

- **Barriers to new fisheries:** As discussed (see Section 2.3.1), establishing a new fishery in Nova Scotia requires a high level of investment from the fishing industry, and usually imposes high levels of uncertainty / investor risk. Therefore, it could be challenging for a small, independent fishing operation to secure the resources necessary to conduct the scientific research, and regularly consult with DFO, during the licensing process for initiating a new secondary fishery.

The examples in this section highlight the need for fisheries management to operate on both short- and long-time scales, and to consider all four sustainability objectives, especially from the perspective of entire coastal communities. Broader, socio-ecological questions must be addressed, such as:

- What are the primary fishery resources in a community?
- How are these likely to change over the coming decades?
- What is the current state of the fishing fleet and what licenses are currently held?
- What other species are available to catch?
- How easily can fishermen track distribution changes in targeted stocks?
- Will licensing systems and legislation need to be less prescriptive to improve flexibility, in light of changing species' distributions, productivity, moulting, and other key life stages?
- What can be done to help coastal communities diversify their income and catches?

Although this will be a highly complex task, integrating ecological, economic, social, and institutional aspects into fisheries management is considered critical for their sustainable development, and for management to operate effectively in light of climate change (Garcia et al. 2014, Stephenson et al. 2017, Stephenson et al. 2018, Foley et al. 2020, Paul and Stephenson 2020). The Canadian Fisheries Research Network, comprising of DFO scientists, and international experts and industry leaders, proposed an integrated management framework that could achieve this ambitious but highly important goal (Stephenson et al. 2019a, Stephenson et al. 2019b).

3. Aquaculture in Nova Scotia

3.1. Past and present status

The aquaculture industry in Nova Scotia has seen substantial growth since the early 1990's, with production increasing five-fold since 1995 (Figure 6). This growth is mostly due to the recent expansion of the Atlantic salmon (*Salmo salmar*) industry, and to a much lesser extent, steelhead / rainbow trout (*Oncorhynchus* *mykiss*) and brook trout (*Salvelinus fontinalis*). Consequently, finfish aquaculture now represents 81 % of all aquaculture production by weight (8,201 tonnes in 2019) and 93 % by value ($69.5 million in 2019).

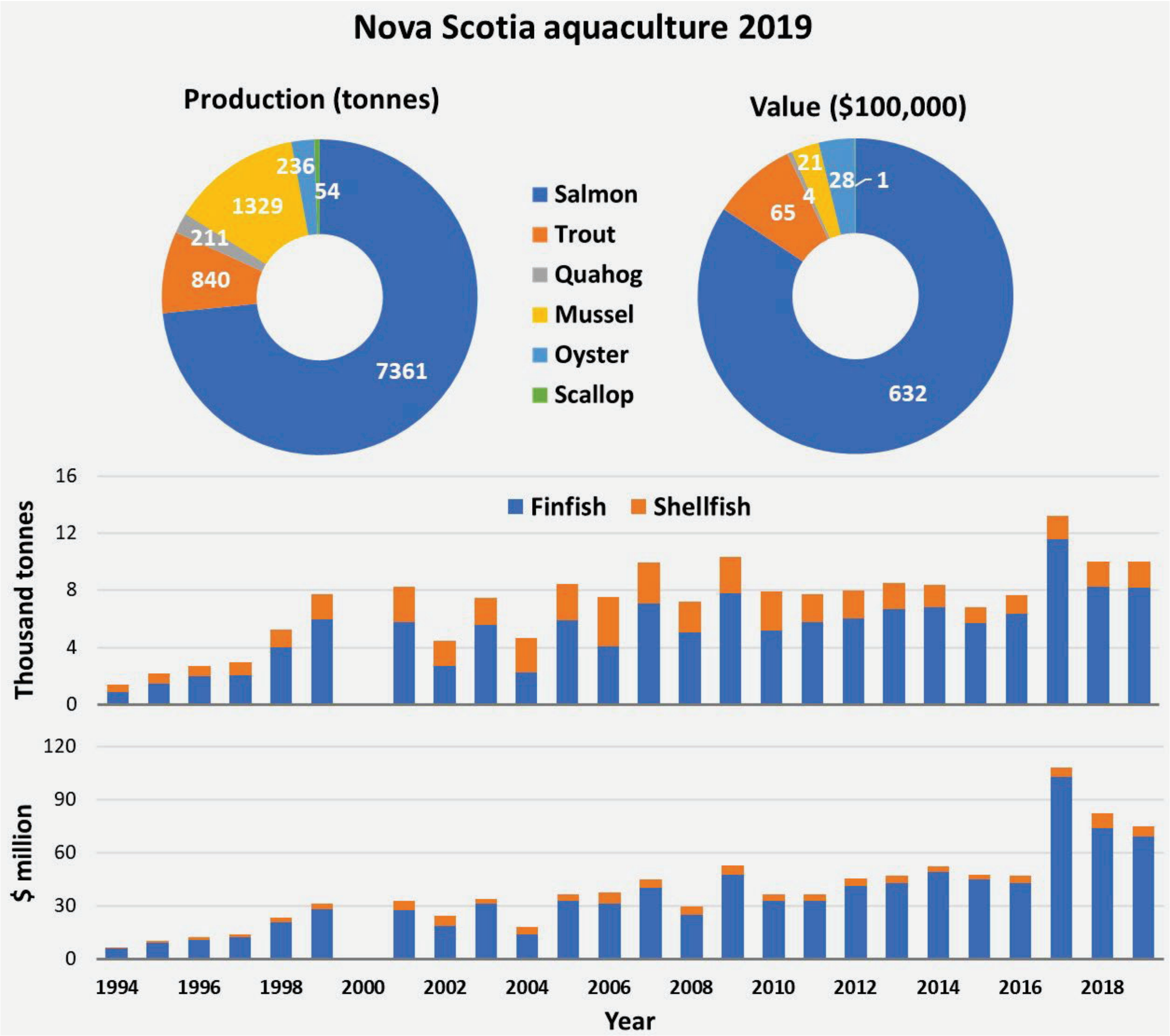

Figure 6 | Aquaculture production levels and value in Nova Scotia for 2019 divided by species (top), and over time (bottom) divided by finfish and shellfish. Salmon = Atlantic salmon, trout = rainbow and brook trout, mussel, = blue mussel, oyster = American oyster, scallop = sea scallop. Source: Nova Scotia Department of Fisheries and Aquaculture (2020b). Gaps represent years with no available data.

Blue mussels (*Mytilus edulis*) make-up the majority of shellfish production in Nova Scotia, representing 13 % of all aquaculture production by weight (1,329 tonnes in 2019) and 3 % by value ($2.1 million in 2019). Production of American oyster (*Crassostrea virginica*) generates comparatively more value ($2.7 million in 2019) than blue mussel, despite production being substantially lower (just 236 tonnes in 2019). A small number of shellfish growers in Nova Scotia produce quahog (*Arctica islandica*), sea scallop, bay scallop (*Argopecten irradians*), and soft-shelled clam (*Mya arenaria*).

Although finfish aquaculture dominates production and value in Nova Scotia, the shellfish aquaculture industry is also economically and socially important. For example, there are currently many more aquaculture leases issued for the production of shellfish (169 leases) than finfish (33 leases) (Nova Scotia Department of Fisheries and Aquaculture 2020a). The shellfish aquaculture sector also employs more people than the finfish sector (Nova Scotia Department of Fisheries and Aquaculture 2020b). Furthermore, there are initiatives underway to facilitate growth of the shellfish aquaculture industry such as the proposed Aquaculture Development Area (ADA) in Lobster Bay. This is currently under assessment by the Nova Scotia Department of Fisheries and Aquaculture (NSDFA) and the Municipality of the District of Argyle (www.aquacultureargyle.com) for shellfish and marine plants culture. The aim of ADA's is to attract investment from growers to establish new operations within pre-defined areas that have already been assessed, including a public process, to ensure aquaculture development is socially, environmentally, and economically suitable (Matthew King, NSDFA, pers. comm, July 2020).

Finally, there are a small number of land-based aquaculture operations in Nova Scotia which culture finfish or marine plants. There is also growing interest in developing new aquaculture facilities in Nova Scotia, including new land-based aquaculture systems for finfish, and new open water facilities for culturing seaweed and / or kelp. Interestingly, some seaweed species might benefit from increased concentrations of atmospheric and dissolved carbon dioxide (Beardall et al. 1998), while other species (e.g. those with calcium-based structures) might be negatively affected by ocean acidification (Kroeker et al. 2010). Similarly, several studies suggest a variety of seaweed and kelp species will undergo climate-driven shifts in distribution and abundance in the Northwest Atlantic (Khan et al. 2018, Wilson et al. 2019), which could have consequences for marine plant aquaculture and wild harvesting in Nova Scotia.

3.2. Shellfish aquaculture and climate change

3.2.1. Temperature

Generally, blue mussels and American oyster exhibit higher feeding rates and faster growth at warmer temperatures (Steeves et al. 2018). However, the extent of warming projected for Atlantic Canada (see Section 1.2.2) is only predicted to improve growing conditions for American oyster (Filgueira et al. 2016, Steeves et al. 2018, Steeves and Filgueira 2019). American oyster can survive a wide range of temperatures (approximately -2 to 36 °C for adults) and tolerate temperatures up to 32 °C without any negative effects on their growth and physiology (reviewed in Talmage and Gobler 2011, Brennan et al. 2016, Filgueira et al. 2016). In contrast, blue mussels tolerate a narrower range of temperatures (approximately -1.5 to 25 °C for adults) with their feeding and growth rates declining sharply above 20 °C, while temperatures above 27 °C can be lethal (LeBlanc et al. 2010, Feindel et al. 2013). Therefore, ocean warming may pose an increasing threat to the blue mussel aquaculture industry in Atlantic Canada. Steeves et al. (2018) suggests the blue mussel aquaculture industry could avoid the potentially negative effects of ocean warming by relocating further offshore in deeper and cooler waters.

3.2.2. Ocean acidification

Laboratory studies suggest lower pH values can reduce growth rates (Berge et al. 2006) and shell thickness in blue mussels (Gazeau et al. 2010), potentially increasing their mortality and susceptibility to predation (Feindel et al. 2013, Reid et al. 2019b). Ocean acidification can also weaken mussel attachment to hard surfaces (O'Donnell et al. 2013), which could increase the risk of their dislodgment from aquaculture gear.

Although similar effects of acidification have been reported for American oyster (Miller et al. 2009, Waldbusser et al. 2011, Gobler and Talmage 2014), this species is considered to be relatively resistant to ocean acidification (Gobler and Talmage 2014, Lemasson et al. 2017). In general, shellfish larvae tend to be more vulnerable to ocean acidification than juveniles and adults (reviewed in Talmage and Gobler 2011, Reid et al. 2019b), which could pose a risk to aquaculture operations which primarily rely on collecting wild seed (also see Section 3.2.5).

3.2.3. Harmful algal blooms

Harmful algal blooms are events of high phytoplankton abundance, comprised of species which can produce toxins harmful to humans, fish, and other organisms (Landsberg 2002). As mussels, oysters, and other bivalve species feed on plankton, they can accumulate these toxins within their tissues, which can lead to severe, or even lethal shellfish poisoning if consumed by humans (Hégaret et al. 2009, Griffith and Gobler 2020). In Atlantic Canada, there are three main types of shellfish poisoning (reviewed in Feindel et al. 2013):

1. **Paralytic shellfish poisoning:** by the dinoflagellate alga, *Alexandrium fundyense*.
2. **Diarrhetic shellfish poisoning:** by dinoflagellates in the genus *Prorocentrum* or *Dinophysis.*
3. **Amnesic shellfish poisoning:** by the diatom alga, *Pseudo-nitzschia pungens.*

Evidence suggests that ocean warming has increased the duration, frequency, growth rates, and spatial extent of these harmful algal blooms in the Northwest Atlantic (Gobler et al. 2017). In some regions, the duration of these blooms has increased by 3 – 8 weeks and are developing 3 weeks earlier in the year compared with the 1990's. However, there is little risk to public health as federal and provincial agencies continually monitor shellfish and impose strict harvesting closures in areas with high toxin levels (CFIA 2019, Department of Fisheries and Oceans 2020). Nevertheless, increasing harmful algal blooms may lead to more frequent and longer shellfish harvest closures, which could prevent the shellfish aquaculture industry from getting their products to market (Feindel et al. 2013). Thus, harmful algal blooms may become more of a problem to the shellfish aquaculture industry as ocean temperatures continue to rise in Atlantic Canada (see Section 1.2.2).

3.2.4. Disease

Two diseases in American oyster have spread northwards from the southern United States since the 1940's – 1950's (Figure 7), and are likely being driven by warmer temperatures and higher salinities (reviewed in Soniat et al. 2008, Burge et al. 2014):

1. **Dermo disease** is caused by the single-cell protozoan, *Perkinsus marinus*. It caused 50 % mortality in American oyster populations across the Gulf of Mexico but is yet to reach as far north as New Brunswick or and Nova Scotia, (Soniat et al. 2008).
2. **MSX disease** or 'Multinucleate Sphere X' is caused by the protozoan, *Haplosporidium nelson*, and can cause mortality rates up to 90 – 95 % (reviewed in Levinton et al. 2011). In 2002, MSX disease arrived in the Bras d'Or lakes region in Cape Breton, where it had a devastating impact on the American oyster aquaculture industry, the local economy, and First Nation communities (Vercaemer et al. 2010, AAC 2012, Lavoie 2012). As this region is responsible for the majority of oyster production in Nova Scotia, provincial production of oyster declined by 62 % between 1999 – 2006

(Nova Scotia Department of Fisheries and Aquaculture 2020b). The Nova Scotian oyster aquaculture industry is yet to fully recover and mortality from MSX is estimated to cost the industry approximately $1 million every year (Omand 2013). Interestingly, preliminary investigations in Nova Scotia suggest suspended bag production methods may reduce oyster susceptibility to MSX (Rod Beresford, Cape Breton University, pers. comm, 19th November 2020) which may have an added advantage of causing less disturbance and shading to seagrass (reviewed in Howarth et al. 2021).

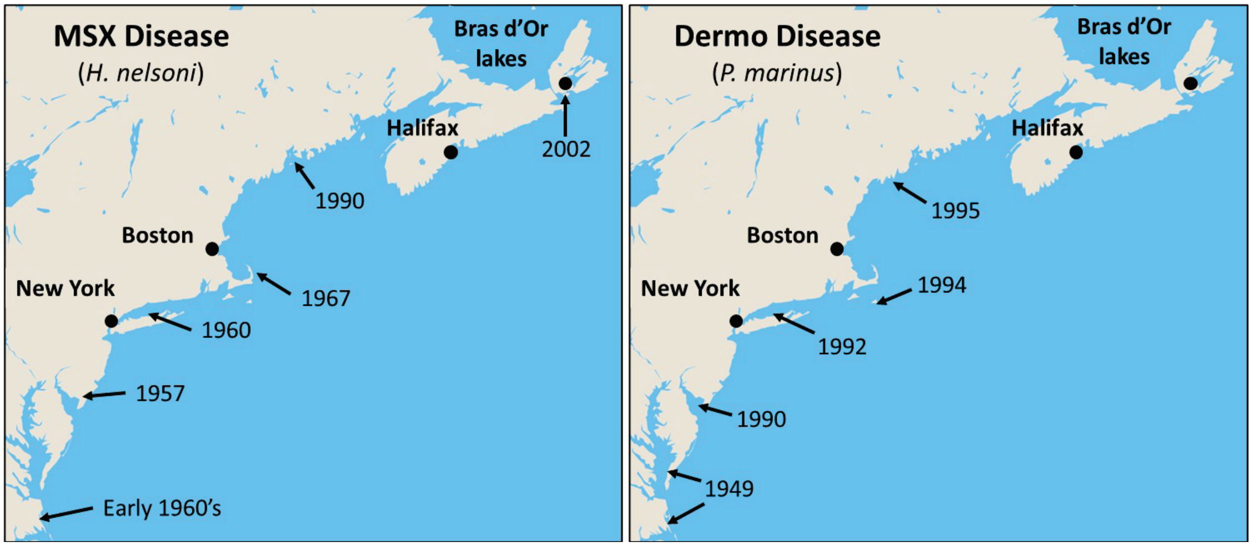

Figure 7 | Years of first reported cases of MSX and dermo disease in American oyster. Trends suggest a gradual northward spread of infection across the eastern coast of USA and Canada. Adapted from Burge et al. (2014).

Overall, ocean temperatures and salinity in the Northwest Atlantic are projected to continue increasing (see Section 1.2) which will likely improve the growth of these protozoan diseases. Thus, there is potential that both diseases will continue spreading northwards and for dermo to reach Nova Scotia sometime in the future (Rod Beresford, Cape Breton University, pers. comm, November 2020).

3.2.5. An increasing demand for oyster hatcheries

The effects of ocean warming, acidification, and increased disease prevalence may partly explain why the collection of wild oyster seed has become increasingly unreliable in Nova Scotia (Rod Beresford, Cape Breton University, pers. comm, November 2020). In fact, consistent and reliable access to seed is one of the biggest concerns for oyster growers in Nova Scotia (Mayer 2019). While there are some oyster hatcheries in New Brunswick and Prince Edward Island, government regulations state that growers in the Bras d'Or lakes cannot import or export seed, in order to reduce transmission of MSX disease (AAC 2012). Growers in this region are, therefore, perhaps in the greatest need of an oyster hatchery. Ideally, multiple oyster hatcheries would be developed in Nova Scotia. This would help ensure: (1) growers have a reliable source of seed; (2) growers in the Bras d'Or lakes have access to their own hatchery; and (3) multiple hatcheries should promote genetic diversity, greater disease resistance and reduced transmission risk (Rod Beresford, Cape Breton University, pers. comm, November 2020).

3.3. Finfish aquaculture and climate change

As temperature and oxygen strongly influence fish growth, physiology and mortality, there is potential that ocean warming and declining oxygen concentrations could impact the finfish aquaculture industry in Nova Scotia (reviewed in Feindel et al. 2013, Reid et al. 2019a, Reid et al. 2019b).

When reared in open net-pens, Atlantic salmon generally display optimal rates of feeding and growth at water temperatures between 8 – 12 °C (reviewed in Elliott and Elliott 2010, Feindel et al. 2013). Both feeding and growth decline above 16 °C, temperatures of 22 – 28 °C can cause 50 % mortality after 7 days, and temperatures above 30 °C are lethal after 10 minutes (Handeland et al. 2003, Handeland et al. 2008, Elliott and Elliott 2010). Higher water temperatures can also increase oxygen consumption in salmon and trout (Forsberg 1994) which could impact their feeding and growth (Remen et al. 2016). Oxygen concentrations above 8 mg L^{-1} are generally considered to be optimal for salmon production (Forsberg and Bergheim 1996, Thorarensen and Farrell 2011); concentrations below 6 mg L^{-1} are stressful; concentrations below 2.5 mg L^{-1} can asphyxiate fish and cause them to surface for air; while oxygen concentrations below 1.7 mg L^{-1} are lethal (Kazakov and Khalyapina 1981, Burt et al. 2012). Environmental parameters for rainbow and brook trout are largely similar to those for Atlantic salmon (reviewed in Feindel et al. 2013).

Higher temperatures reduce the capacity for seawater to hold oxygen (Gruber 2011) which can further exacerbate the physiological effects of low oxygen and high temperatures on finfish. For instance, the combined effects of high water temperatures and low oxygen concentrations led to the death of approximately 2 million farmed salmon in Newfoundland during an unusually warm November in 2019 (Bundale 2019, CBC 2019, Montgomery 2019). Conversely, temperatures below -0.7 °C are also lethal (Saunders et al. 1975) and such 'super chill' events have been linked to the death of large numbers of farmed fish in Nova Scotia (CBC 2015, CTV 2015, Willick 2019). Therefore, warming ocean temperatures in Atlantic Canada may reduce the exposure of salmon to critically low winter temperatures and increase the length of the optimal growing period. However, it may also increase fish stress and mortality if temperature and oxygen levels rise / drop below lethal thresholds (Feindel et al. 2013).

In attempt to reduce the risk of extreme temperature and oxygen events, growers in Nova Scotia are currently testing the viability of lengthening the period of time in which salmon spend in land-based facilities, thus reducing the time they spend at sea from two years to one (Duchene 2017). Growers are also trialing the use of aeration units to increase oxygen concentrations at farm sites. However, preliminary evidence suggests that, while these units can increase oxygen levels above the lethal threshold, they are not enough to restore normal rates of feeding and growth (Meredith Burke, Dalhousie University, pers. comm, November 2020).

Warmer temperatures may also increase the occurrence and duration of harmful algal blooms in Atlantic Canada (see Section 3.2.3), which can cause stress and mortality in farmed finfish (reviewed in Bates et al. 2020). There is also potential that warming ocean temperatures might increase the risk of sea lice infection as higher temperatures can increase sea lice growth, speed up their life cycle (Stien et al. 2005, Groner et al. 2014), and exacerbate the negative effects lice have on salmon growth, physiology, and mortality (Boxaspen 2006, Godwin et al. 2020, Medcalf et al. 2021). Furthermore, the use of hydrogen peroxide is a common treatment method used to remove sea lice, but it can only be applied in temperatures up to 14 °C, as temperatures above this can increase mortality risk during treatment (Kiemer and Black 1997). Thus, warmer temperatures may result in a shorter period when hydrogen peroxide treatments can be applied safely (Feindel et al. 2013). Fortunately, sea lice levels are low in Nova Scotia, meaning minimum treatment thresholds have not been exceeded, and that no treatments for sea lice are currently required (Roland Cusack, NSDFA, pers. comm, June 2020; Anthony Schnyder, NSDFA, pers. comm, March 2021).

3.4. Interactions between wild stocks and aquafeed production

Farmed salmon and trout are fed aquafeeds that are high in protein, omega-3 fatty acids, and other natural oils. These ingredients are partly derived from small, wild fish such as herring, mackerel, sardine, and anchovy (Tacon 2020). As many of these wild species are expected to shift and decline under climate change, there is potential for climate change to affect supplies of key ingredients for aquafeed production (Reid et al. 2019b). However, the aquafeed industry are increasingly sourcing alternative ingredients including soybeans, wheat, livestock by-products, and oils derived from plants and algae (Tacon 2020, Naylor et al. 2021). Given current and anticipated ingredient alternatives, climate change is not expected to limit the production of aquafeeds (World Bank 2013).

3.5. Potential for adaptation in the aquaculture industry

Compared to wild capture fisheries, the aquaculture industry may have an adaptive advantage over wild fisheries as producers have some control of their stock and environmental conditions. Land-based facilities have almost full control of water temperatures, salinity, and oxygen concentrations, while open water facilities have potential to site in (or relocate to) areas with more suitable environmental conditions. Furthermore, the industry is increasingly utilizing real time monitoring technologies, allowing farmers to track oxygen, temperature, and a wide range of other parameters to inform their management and mitigation strategies. Technologies are also being developed that can allow open water producers to supplement oxygen levels and upwell deeper, cooler waters to mitigate the effects of harmful algal blooms. Growers can also select for disease resistant strains, use vaccines, and treat stock for disease and parasites. Finally, the industry also has potential to select and grow alternative species if some species become non-viable under climate change (see Reid et al. 2019a and references therein).

3.6. Effects of multiple stressors on fisheries and aquaculture

The previous sections of this report describe how fisheries and aquaculture in Nova Scotia may be affected by a wide range of climate change-related stressors. However, these stressors are not occurring in isolation. Multiple stressors can interact, and the effects of one may cause organisms to become more sensitive to another. As these interactions are complex and under studied, the impacts of multiple stressors on the aquaculture and fishing industries are largely unknown (reviewed in Reid et al. 2019a, Reid et al. 2019b).

4. Climate change impacts on coastal communities

The previous sections of this report review how climate change may impact fishery and aquaculture resources in Nova Scotia. However, climate change will also affect the towns and communities in which these industries, and their workers, are based (Table 4). For example, it has been estimated that:

- Over 58,000 properties are located on Nova Scotia's coastline and over 80,000 properties are within 50 m of the high water mark (Nova Scotia Environment 2018);

- 70 % of Nova Scotia's population live within 20 km of the coast (Nova Scotia Environment 2019b); and
- There are more than 360 coastal communities in Nova Scotia, many of which have less than 1000 inhabitants (Environment Canada 2005).

Table 4 | Potential impacts of climate change on Nova Scotian coastal communities, excluding impacts to fisheries (see Section 2) and aquaculture (see Section 3). Sources: Environment Canada (2005), MacCallum (2010), Fisher (2011), Greenan and Warburton (2013), Lemmen et al. (2016), Greenan et al. (2019b).

Category	Threat
Housing	Increased risk of property damage due to coastal flooding and erosion, potentially increasing insurance prices.
Power supply	Increased risk of power outages due to coastal flooding, erosion, higher wave heights, storms and falling trees.
Water and sewage	Increased risk of saltwater intrusion, contamination to aquifers and wells from flooding and sea level rise, affecting groundwater supplies.
	Increased risk of damage / failure of sewer systems due to coastal flooding and sea level rise.
Roads and related infrastructure	Increased risk of road damage and road closures due to coastal flooding, erosion, and higher wave heights.
	Warmer air temperatures may increase the frequency of freeze-thaw cycles, potentially causing more damage to roads and sidewalks.
Emergency Services	Damages to infrastructure could restrict emergency access.
	Increased demand for emergency search and rescue, and emergency responses, to extreme winds, waves, floods, storms, and sea ice changes.
Harbours and waterways	Increased risk of damage and maintenance costs of ports, harbours, marinas, and slipways due to coastal flooding, erosion, sea level rise, storms, and changes in sea ice.
	Increased need to repair, relocate, or replace fixed and floating navigational aids (e.g. buoys, lighthouses, breakwaters, and repeater stations) due to sea level rise, coastal erosion, flooding and storms.
	Increased need for channel dredging due to sediment transport caused by changes in sea level and coastal erosion.

All the threats described in this section are interconnected and will likely impact both the fishing and aquaculture industries. For example: increased road closures could impact the ability for fishermen and producers to get their products to domestic and international markets; power cuts and impacts to groundwater supplies could impact food processing operations; damage to harbours could impact access to boats and ability to land catches / product; while weather changes and damage to navigational aids could impact worker safety.

5. Climate change policies and strategies

5.1. International and federal policies

Climate change and related environmental issues have become a key policy focus for governments as well as the United Nations. Canada, among many other countries, has signed / ratified numerous international treaties aimed at reducing global greenhouse gas emissions. Presently, Canada is engaged in 116 international environmental agreements and agreements (a full list is available at Government of Canada 2020g). Appendix 1 provides an overview of Canada's major international climate change agreements, and details how Canada is on track to fail most of its international emissions targets.

5.2. Provincial climate change strategies

Although Canada is failing to meet most of its international emissions targets, Nova Scotia achieved a 26 % reduction in greenhouse gas emissions between 2005 – 2018, the second largest reduction in the country after New Brunswick (Canadian Institute for Climate Choices 2020). Consequently, Nova Scotia has already surpassed its emissions targets (Hughes 2016) made under the Pan-Canadian Framework (see Appendix 1). Some of the key provincial policies which helped Nova Scotia achieve this are summarized in Appendix 2. There are also several provincial policies which aim to assist Nova Scotian communities adapt to the impacts of climate change, as described below.

5.2.1. Municipal Climate Change Action Plans (MCCAPs)

Nova Scotia is the first Canadian province or territory to mandate the development of Municipal Climate Change Action Plans (MCCAP; Fisher 2011, Philp and Cohen 2019). This mandate requires municipalities to investigate their greenhouse gas emissions sources and local climate hazards, and to prioritize developing solutions that help their communities mitigate and adapt to climate change (reviewed in Cohen et al. 2019). This exercise promoted direct engagement between municipalities and local businesses, property owners, and citizens, and combined with municipal jurisdiction over local public services, has distinctively positioned municipalities as an impetus for action on climate change in Nova Scotia (reviewed in Cohen et al. 2019).

5.2.2. Coastal Protection Act

The provincial *Coastal Protection Act* was passed in 2019 and will impose vertical (i.e. distance below sea level) and horizontal (i.e. distance from high water) setbacks for future construction developments to safeguard them from sea level rise, coastal flooding, storm surge, and coastal erosion (Nova Scotia Legislature 2019). These regulations are currently being developed through an extensive public and stakeholder consultation process (Province of Nova Scotia 2020).

5.3. Climate change adaptation and mitigation funding programs

There are several funding programs in Canada to help reduce greenhouse gas emissions, improve / build new infrastructure, and provide education and training programs relating to climate change. However, many of these are very specific to certain sectors, communities, or levels of government, and are not aimed at the seafood industry.

5.3.1. Federal funding programs

- **Disaster Mitigation and Adaptation Fund** supports large-scale infrastructure projects to help communities across Canada better manage the risks of natural disasters (Government of Canada 2020b). So far, Nova Scotia has received over $56 million to upgrade 64 km of dykes, which will help protect over 60 communities in Hants, Annapolis, Cumberland and Colchester counties from flooding (Fairclough 2019).

- **Low Carbon Economy Fund** aims to promote greenhouse gas emission reductions across Canada (Government of Canada 2020e). Nova Scotia received $56 million in 2019, which was invested in Efficiency Nova Scotia (see Appendix 2)

- **Federal Gas Tax Fund** provided more than $114 million to Nova Scotia between 2019-2020 for local infrastructure projects (Government of Canada 2020d). Communities select how best to direct the funds and have the flexibility to make strategic investments across 18 different project categories including: drinking water; community energy systems; local roads and bridges; and disaster mitigation.

- **Climate Adaptation Leadership Program** overseen by Natural Resources Canada (NRCan), $1 million has been allocated to train Nova Scotian decision-makers and business leaders on the development, implementation and evaluation of climate change adaptation strategies to help ensure climate change adaptation considerations are integrated into existing business practices (Government of Canada 2020a).

- **EcoAction Community Funding Program** is overseen by Environment Climate Change Canada (ECCC) and provides financial support (maximum of $100,000) to non-profit and non-government organizations for local action-based projects that produce measurable, positive effects on the environment (Government of Canada 2021).

5.3.2. Provincial funding programs

- **Green Fund** was established in 2019 to receive and distribute revenues under Nova Scotia's Cap and Trade Program (Nova Scotia Environment 2019a, Climate Change Nova Scotia 2020). It will generate about $27 million in revenue in 2020, increasing to $32 million in 2023. These funds will be used to support measures that reduce greenhouse gas emissions, promote climate change adaptation, and reduce economic and social impacts.

- **Sustainable Communities Challenge Fund** will be created under the *Environmental Goals and Sustainable Prosperity Act* (see Appendix 2) to support community climate change projects. The regulations to accompany the Act are currently being developed and will outline details of the funding program (Province of Nova Scotia 2019c).

5.3.3. Funding for Municipalities

- **Green Municipal Fund** supports capital projects that improve air, water and soil quality, and reduce greenhouse gas emissions (Federation of Canadian Municipalities 2020a).
- **Municipalities for Climate Innovation Program** provides funding, resources, and training for municipalities to adapt to climate change (Federation of Canadian Municipalities 2020c).
- **Municipal Asset Management Program** offers funding, training and resources to help municipalities make decisions about maintaining, replacing and repairing municipal infrastructure (Federation of Canadian Municipalities 2020b).

6. Planning and guiding climate change adaptation measures

The fishing (see Section 2) and aquaculture industries (see Section 3), and the communities in which they are based (see Section 4), are set to experience a large number of changes over the next 30 – 80 years as a consequence of climate change. Anticipating and planning for these changes will likely be less disruptive for communities and businesses, and more economically effective for governments and decision makers, than reacting to changes after they occur (Reid et al. 2019a, Takakura et al. 2019, Jacques 2020). For example, reinforcing, repairing, relocating, or replacing coastal infrastructure before they are damaged would require less expenditure of public funds, and be less disruptive to commercial activities. In the same way, identifying which fishery resources will be negatively affected by climate change, and assisting the fishing industry target and market new species, would have less socio-economic impacts than introducing new management measures after resources decline. Therefore, it is important to consider adaptation measures sooner rather than later.

6.1. Vulnerability assessments

'Vulnerability assessments' can aid the advanced planning of adaptation measures by identifying which communities or sectors are the most vulnerable to climate change, thereby allowing decision makers to prioritize adaptation efforts (Adger 2006, IPCC 2014, Krishnan et al. 2019). Generally, vulnerability assessments are based on three components: 'exposure', 'adaptive capacity', and 'sensitivity' (Islam et al. 2019, Krishnan et al. 2019, Soto et al. 2019, Kling et al. 2020, Mafi-Gholami et al. 2020), as described in the following sections.

6.1.1. Exposure

Exposure measures how much a community, sector, or resource will be impacted by future climatic stressors based on their scale, frequency, duration, and extent (Adger 2006, Hunter et al. 2015). 'Risk' is closely related to exposure and the two terms are often used interchangeably (e.g. Soto et al. 2019). However, 'risk' is usually used to describe the potential of an adverse outcome and is defined by the IPCC as the probability of a hazardous event multiplied by its impacts (IPCC 2014). Of the three vulnerability components, exposure arguably benefits the most from quantitative data. Although, some form of qualitative and subjective weighting system is usually applied to scale the resulting exposure values. For example, Kim et al. (2019) assessed the vulnerability of the Korean aquaculture industry to climate change and made comparisons between different regions, species, and years. They did this by calculating exposure index scores (ranging between 1 – 7) based on projected changes in temperature and salinity for 2030, 2050, and 2100, under two IPCC emissions scenarios.

6.1.2. Adaptive capacity

Adaptive capacity measures how much a community, sector, or resource, can adjust to change (Smit and Wandel 2006, IPCC 2014). For example, Stoll et al. (2017) identified that 88 % of fishermen in Maine had low to medium adaptive capacity due to their high dependency on lobster, and that the limited entry licensing system in place for many fisheries makes it difficult for fishermen to target different species and diversify their catches. Colburn et al. (2016) reported similar findings (Figure 8). Adaptive capacity is also strongly influenced by human behaviour. For example, low perceptions of risk in high exposure areas can lead to reduced preparation and protective behavior, which has led to catastrophic consequences at times (e.g. Messner and Meyer 2006, Rufat et al. 2015, Medina et al. 2020). Given the influence of human behaviour, adaptive capacity is not easily quantifiable. Marshall et al. (2010, 2013) developed an adaptive capacity index for coastal communities based on the percentage of survey respondents that agreed or disagreed with statements related to four topics:

1. How risk and uncertainty are perceived and managed;
2. The development of skills for planning, learning, reorganizing, and experimenting;
3. The degree of financial and emotional flexibility; and
4. The level of interest and willingness to undertake change.

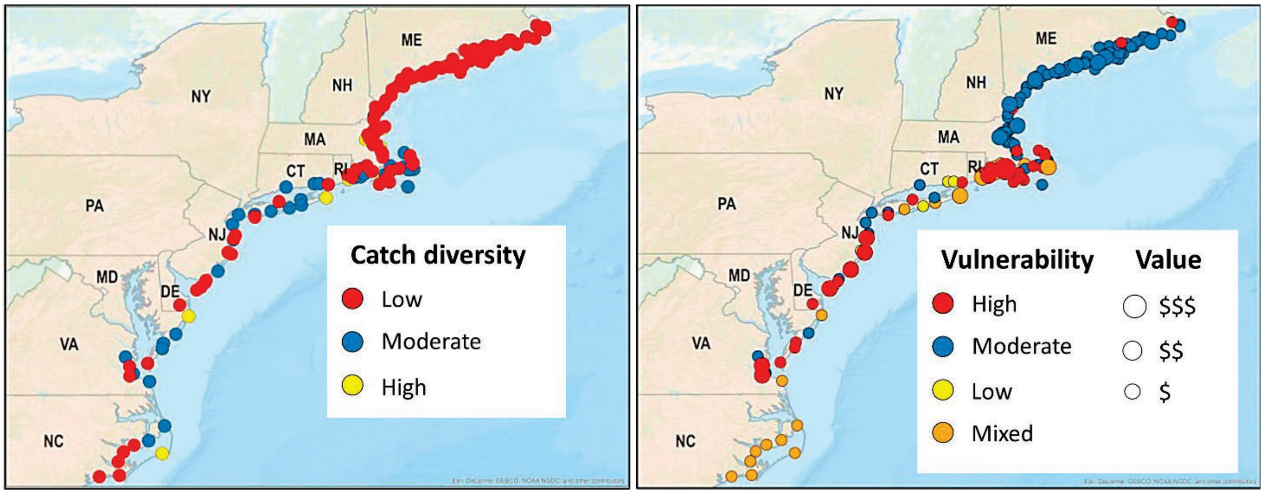

Figure 8 | The diversity, value, and vulnerability of fishing-dependent communities along the Eastern Coast of USA. Fishing communities in the Gulf of Maine were only moderately vulnerable to climate change despite their high dependency on lobster (i.e. low catch diversity). Adapted from Colburn et al. (2016).

6.1.3. Sensitivity

Sensitivity measures how much a community or sector will be affected by climate change based on socio-economic factors (Sarkodie and Strezov 2019) and is often closely associated with levels of resource-dependency (Marshall et al. 2013). Sensitivity can also be a function of affluence as economically developed areas are likely to have higher adaptive capacity (Krishnan et al. 2019, Thomas et al. 2019). For example, well-designed and well-financed coastal infrastructure are likely to better withstand extreme events compared to those that are poorly designed and poorly financed. This means areas with higher sensitivity are not necessarily the most vulnerable as sensitivity can be offset by adaptive capacity (Figure 9 ; Marshall et al. 2013).

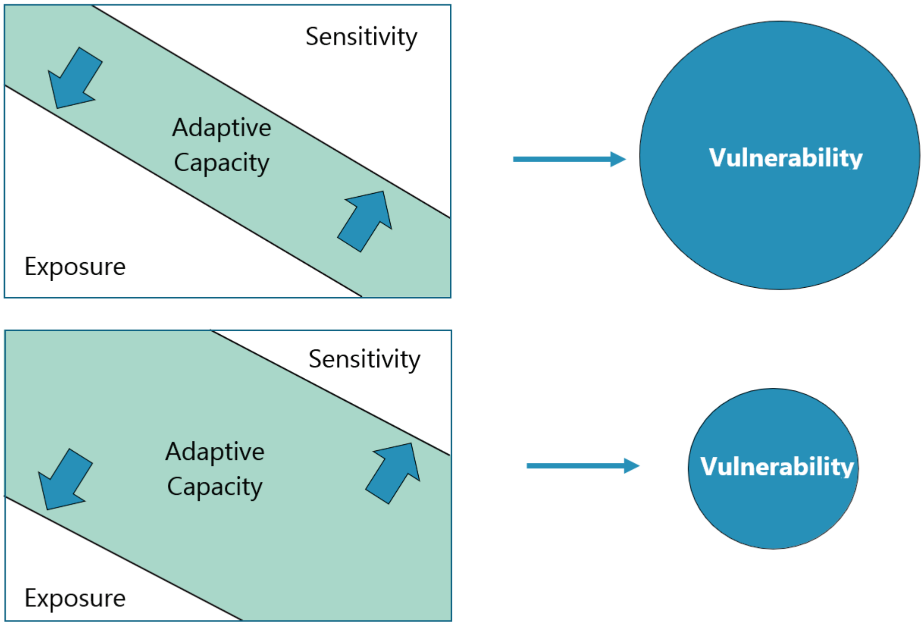

Figure 9 | Figurative diagram showing how adaptive capacity can reduce vulnerability by offsetting sensitivity and exposure. Adapted from Thomas et al (2019).

Although sensitivity often has a strong socio-economic focus, it can also utilize biophysical data. For example, Johnson and Welch (2009) measured the sensitivity of several commercial fisheries in Australia to climate change. They did this by scoring quantitative data on key fishery variables including changes in species' distribution, reproduction, physiology, growth, phytoplankton, and larval survival and transport. Overall, they identified that inter-reef trawl fisheries for small crustaceans and molluscs were the most sensitive to climate change and should, therefore, be a priority for future management efforts.

6.2. Approaches for assessing climate change vulnerability

There are many different ways to assess climate change vulnerability (e.g. Fu et al. 2019, Rakib et al. 2019, Sarkodie and Strezov 2019, Medina et al. 2020), and at present, no approach is considered to be better or more suitable than any other (Hunter et al. 2015). The earliest climate change vulnerability assessments focused solely on the evaluation of exposure but have evolved to become more holistic and to make recommendations for the advanced planning of adaptation measures (Figure 10).

A common approach for assessing vulnerability is to create indices of exposure, sensitivity, and adaptive capacity, which are then combined to form an overall index of vulnerability. For example:

Cumulative vulnerability index = Exposure index + Sensitivity index + Adaptive capacity index

The data used to calculate indices of exposure, sensitivity, and adaptive capacity can be quantitative, semi-quantitative and / or qualitative, and can come from a variety of sources such as biophysical data, questionnaires and interviews (Avelino et al. 2018, Xu et al. 2020). These various data are usually known as indicators and are typically organized into a list, rubric, or table, to help organize and assign scores (Table 5). As many different indicators can be identified and examined, it can be difficult to determine which are the most important in determining vulnerability. In these circumstances, principal components analysis (PCA) and other analyses may be used to identify the most important drivers and reduce the number of factors included in subsequent analyses (e.g. Macusi et al. 2020, Medina et al. 2020).

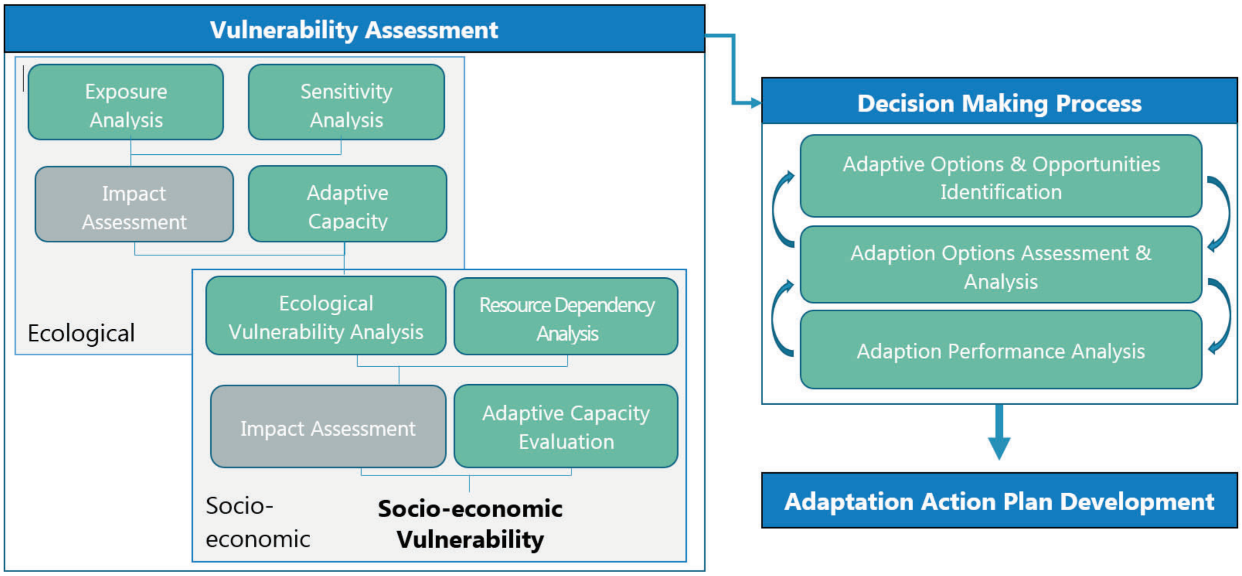

Figure 10 | A conceptual approach for assessing climate change vulnerability of coastal communities dependent on ocean resources. Adapted from Marshall et al. (2013).

Table 5 | Example of a vulnerability indicators organised as a rubric. Adapted from Sarkodie and Strezov (2019).

Index	Fishery resources	Coastal infrastructure
Exposure	Projected changes in species abundance and distribution.	Projected sea level rise and wave heights.
Sensitivity	Level of dependency upon the resource.	Percentage income from fishing.
Adaptive capacity	Ability to target alternative species.	Gross Domestic Product (GDP) of municipality.

Communities with greater dependency on ecological resources, such as wild capture fisheries, are inherently more vulnerable to climate change. Consequently, the level of resource dependency dictates the potential for socio-economic impacts (Marshall et al. 2013, Greenan et al. 2019b). In these instances, assessing the vulnerability of the resource (e.g. how likely will the resource experience a reduction in abundance) is a prerequisite for assessing the vulnerability of the resource-dependent community (Hunter et al. 2015).

One example where the three components of vulnerability (i.e. exposure, sensitivity, and adaptive capacity) were assessed in the context of fishery-dependent communities is provided by Ekstrom et al. (2015), who assessed the vulnerability of shellfish fisheries in the USA to ocean acidification. Exposure was based on models of projected carbonate availability (see Section 2.2.2). Sensitivity was determined by resource dependency and proportion of income from shellfish fisheries. While adaptive capacity was based on the proximity of coastal communities to scientific laboratories and research institutions, as well as the current state and progressiveness of climate change legislation and policy. The most socially vulnerable communities were identified to be on the US East Coast and in the Gulf of California, however, the reasons for their high vulnerability were very different. East Coast fisheries were identified as being highly dependent on shellfish, particularly molluscs, which are more at risk to ocean acidification. In contrast, the Gulf of California was identified as having low adaptive capacity due to low political engagement in acidification and climate change related issues, low diversity of shellfish catches, and relatively low science accessibility.

6.2.1. Challenges with assessing vulnerability

Vulnerability assessments can be challenging for several reasons. Firstly, data inputs are often combinations of quantitative and qualitative data, with the resultant model often described as semi-quantitative (Soto et al. 2018). For example, inputs such as wind and wave exposure may have magnitude and frequency data generated from climatic models. While other inputs, such as fisherman's perception of risk, are equally important but are subjective and qualitative. This means that a vulnerability assessment must stitch together different types of information and translate these into a single understandable value.

Another challenge is differences in data availability or scale. For example, high resolution storm surge models, capable of projecting flooding risk under different emissions scenarios, may be available for some coastal communities but not others. In this case, investigators cannot simply exclude storm surge risk, so instead they must pursue a more qualitative approach such as relying on expert opinion. This raises a third challenge; the difficulty of comparing vulnerability across communities that have been assessed using different data and vulnerability methods. Nevertheless, such comparisons are still necessary for guiding decision making on a large scale.

6.3. Recommendations for future vulnerability assessment studies

Bukvic et al. (2020) reviewed 65 international studies which mapped the vulnerability of communities to coastal hazards. They found that many studies were limited in their inclusion of social considerations and provided little discussion of their relevance to policy. Consequently, they made six recommendations that would improve future vulnerability assessment studies:

1. **Customize the approach to match the context.** There is no single right way of assessing vulnerability. The methods will depend on the aim of the project, and the types of data available.
2. **Determine an appropriate scale and select appropriate datasets.** Vulnerability can be assessed at the scale of towns, counties, municipalities, provinces, states, and even countries.
3. **Apply the assessment holistically.** There are many socio-economic, geographical, and ecological factors that determine vulnerability.
4. **Pre-define information needs for policymaking.** This is critical as the key rationale of most assessment studies is to improve-decision making.

5. **Inclusion of participatory input, where appropriate.** Input from experts and stakeholders can provide important information not captured by traditional empirical data.
6. **Quantify uncertainty and validation.** Many data and model outputs carry a level of uncertainty which, if possible, should be conveyed in the final vulnerability index.

Following these recommendations, we propose to develop a climate change vulnerability index for seafood industry-dependent communities in Nova Scotia (see Section 7). This would help determine which coastal communities and seafood sectors are most at risk to climate change, which could prove invaluable in guiding climate change adaptation efforts.

6.4. Examples of vulnerability assessments in Nova Scotia

Previously cited vulnerability examples are from the international literature. There have also been several vulnerability assessments in Nova Scotia, however, very few have examined all three components: exposure, sensitivity, and adaptive capacity.

Environment Canada (now Environment Canada and Climate Change) conducted a province-wide vulnerability assessment in 2005 which included a review of coastal hazards such as sea-level rise, flooding, coastal erosion and potential damage to properties and infrastructure (Environment Canada 2005). From this, a series of climate change adaptation options were then recommended to various sectors. Later, in 2011, Nova Scotia mandated municipal climate change adaptation planning (see Section 5.2.1). As all municipalities in Nova Scotia have coastal communities, various aspects of coastal vulnerability were incidentally included to support these climate change adaptation plans.

Several vulnerability studies in Nova Scotia have focused on exposure. Halifax Regional Municipality, implemented a public vulnerability mapping exercise that primarily focused on flood risk (Sustainable Environment Management Office 2011). Mapping of flood risk has also has been conducted for Annapolis Royal (Webster 2010) and the LaHave river estuary in Bridgewater (Webster et al. 2014). A recently developed interactive web-based visualization tool can be used to display flood exposure maps for Shelburne, Lockeport, and Barrington (Minano et al. 2018). While a full vulnerability assessment on Little Anse, Isle Madame, in Cape Breton, investigated breakwater effectiveness under projected storm scenarios (Mostofi Camare and Lane 2015). Finally, Chang et al. (2018) compared the vulnerability of Yarmouth, Lunenburg, and Halifax by developing a 'Hazard Vulnerability Similarity Index'.

There are only a few studies that have explicitly explored vulnerability linkages between fishery resources and fishing infrastructure in Nova Scotia. Greenan et al. (2018) assessed coastal vulnerability of four small craft harbours (SCHs) in Nova Scotia and 13 others in Atlantic Canada. Indices (scored from 1 – 5) were created for infrastructure, exposure, and socioeconomics, which were combined to create a Coastal Infrastructure Vulnerability Index (CIVI). The four harbours assessed in Nova Scotia (Pinkneys point, Aulds cove, Meteghan and Centreville) had some of the highest CIVI scores, suggesting harbours were relatively more vulnerable to climate change. Greenan et al. (2019b) also examined climate change vulnerability of lobster fishing communities by combining the CIVI measure with an offshore Lobster Vulnerability Index (LVI). The LVI was a function of exposure (i.e. gain or loss of optimal temperatures) and stock status (e.g. suitable habitat, abundance food availability). LFAs 35 and 36 were ranked as the most vulnerable with 33, 34 and 38 identified as moderately vulnerable (see Figure 4 for a map of LFAs in Nova Scotia).

7. Proposal to assess climate change vulnerability of seafood industry-dependent communities in Nova Scotia

The information presented in this report supports the need to develop a vulnerability index for Nova Scotian seafood industry-dependent communities to guide adaptation planning. This should follow the recommended practices outlined in Section 6.3 to develop all three vulnerability components:

1) Exposure index

To measure the degree of risk to coastal communities and their resources, we propose to:

- Review the potential for damage to wharves, processing plants, and other coastal infrastructure.
- Evaluate potential impacts to fisheries and aquaculture from environmental stressors including ocean warming, acidification, reduced oxygen, and interactive effects.
- To link projections with IPCC emissions scenarios (see Section 1.1.1).

2) Sensitivity index

To measure degree of ocean resource dependency, and how these will be affected by climate change (i.e. the exposure component), we propose:

- A community level socio-economic assessment of the:
    - Degree of seafood industry dependency (e.g. percentage income from seafood industries);
    - Diversity of seafood resources being utilized; and the
    - Scale of economic inputs such as fisheries landing and aquaculture production.
- Review the current status of seafood industries and make projections under emission scenarios.

3) Adaptive capacity index

To measure the potential for the fishing and aquaculture industry to adapt to potential changes and take advantage of new opportunities, we propose to:

- Review fisheries management under climate change.
- Quantify community perception of risk, motivation to adapt, and financial flexibility.
- Investigate developing technologies to sustain or augment aquaculture under climate change.
- Identify and evaluate applicable climate change initiatives, funding opportunities, and governance that can support climate change adaptation.

7.1. Proposed deliverables

Project deliverables will include a final report on the vulnerability of seafood industry-dependent communities in Nova Scotia to climate change under a range of emission scenarios and time frames. This report would comprise:

- A vulnerability map of Nova Scotian coastal communities, including sub-maps for each of the vulnerability components.
- Detailed community level descriptions of exposure, sensitivity, and adaptation capacity.
- An inventory of community and regional level data gaps needed to define vulnerability and / or support the planning of adaptation measures.
- Adaptation recommendations for fisheries and aquaculture sectors in Nova Scotia.

7.2. Project scope and scale

Project scope will be a function of resource ability, time allotment, data availability, model development and other factors:

- A **smaller project** could assess the vulnerability of a handful of representative communities in each region by compiling existing data (physical, ecological, and socio-economic). Fisheries projections are more regional and may have applicability across multiple communities.
- A **larger project** could assess the vulnerability of almost all seafood industry-dependent communities in Nova Scotia and collect new data, and make new projections, where needed.

7.3. Project approach

Based on the literature examined in this report, we propose the following approaches:

- Develop specific methodologies for indices as a function of data availability, quality, scale, and format.
- Appropriate data and projection resolution requirements (spatial and temporal) will be identified for measures within each support index.
- A rating and ranking exercise will also be developed for measures within each index.
- Existing data and projections will be used where data is available, and key gaps will be identified. New data will be collected as resources allow.
- Data uncertainty will be estimated at the scales applied.
- Quantitative data will take priority over qualitative data, where available.
- A large portion of project information that will need to be acquired through surveys, interviews and engagement with community and experts so participatory input is crucial.
- Policy developers and decision makers should be included the process at the project onset.
- Given overlapping interests and mandates, key collaborations will be necessary to ensure project effectiveness:
    - Provincial departments with overlapping responsibility and mandates, such as Nova Scotia Department of Fisheries and Aquaculture, Nova Scotia Environment, Nova Scotia Department of Municipal affairs, and housing.

  - Federal Departments such as DFO and Environment and Climate Change Canada.
  - Municipal organizations such as the Federation of Canadian Municipalities and the Nova Scotia Federation of Municipalities
  - Environmental organisations, where applicable.
  - Fisheries and aquaculture industry associations.

8. Summary

Climate change is increasing ocean temperatures, sea levels, coastal erosion rates, ocean acidification and flooding risk. These changes have the potential to impact a variety of fishery and aquaculture resources in Nova Scotia. As many fishery resources are projected to undergo shifts in distribution, abundance, and timing of key life stages, fishing communities will require a greater degree of flexibility than possible under current fisheries management practices. There is also potential that warming temperatures, increased risk of disease, and harmful algal blooms may impact the aquaculture industry. Planning adaptation measures in advance will likely be more effective than trying to reactively respond to climate change impacts after they have occurred. Vulnerability assessments are a key step for the advanced planning of adaptation measures as they can allow decision makers to prioritize adaptation efforts to sectors and communities most at risk to climate change. This report proposes the development of a climate change vulnerability index for seafood industry-dependent communities in Nova Scotia. This would help determine which coastal communities and seafood sectors are the most at risk to climate change, which could prove invaluable in guiding climate change adaptation efforts.

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Appendix 1: Canada's major climate change agreements

United Nations Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) aims to prevent "dangerous human interference" with the climate system, and has been ratified by 197 different countries (United Nations 2015b). Some of the most important international agreements to reduce greenhouse gas emissions have been made under the UNFCC. However, as this section details, Canada has repeatedly failed to meet its emission targets.

Kyoto Protocol

In 1998, Canada signed onto the Kyoto Protocol (United Nations 1998), the first international agreement that mandated country-by-country greenhouse gas emission reductions. In 2002, Canada ratified its participation in the Kyoto Protocol with the objective of reducing Canada's greenhouse gas emissions by 6 % below 1990 levels by 2012 (Government of Canada 2005). However, with shifts in governments and climate change priorities, no meaningful legislation was implemented during the Kyoto timeframe and Canada's greenhouse gas emissions increased by over 30 % (Curry and McCarthy 2011). In 2011, when the greenhouse gas reduction target became unobtainable, and Canada was facing $14 billion in penalties under the agreement, it officially withdrew from the Kyoto Protocol (CBC News 2011)

Copenhagen Accord

In 2009, Canada signed the Copenhagen Accord at the UN Climate Change Conference (United Nations 2009), agreeing to reduce greenhouse gas emissions to 17 % below 2005 levels by 2020. However, several reports suggest it is unlikely that Canada met this target (Environment Canada 2014, Office of the Auditor General of Canada 2018b).

Paris Agreement

In 2015, Canada renewed its focus on climate change and took an active role in the development and ratification of the United Nations' Paris Agreement which includes limiting global temperature rise to below two 2 °C above pre-industrial levels, and endeavors to create a carbon-free world by 2100 (United Nations 2015a). However, a report published in 2018 by the United Nations shows that Canada will likely miss its 2030 Paris Agreement targets by a wide margin (United Nations 2018). Likewise, a report released in March 2018 by the Federal Environmental Commissioner and Auditor Generals concluded that most provinces are not on track to meet their commitments to reducing greenhouse gas emissions (Office of the Auditor General of Canada 2018a).

Federal policies

Clean Air Act and the Canadian Environmental Protection Act

The *Clean Air Act* was established in 2006 and aims to improving the health of Canadians (Parliament of Canada 2007). The Act introduced new regulations pursuant to the *Canadian Environmental Protection Act* (Government of Canada 1999) to address air pollutants from certain consumer products and vehicles. Under these Acts, the government committed to reducing greenhouse gas emissions by up to 65 % from 2003 levels by 2050.

Pan-Canadian Framework

After signing the Paris Agreement in 2016, the Canadian Government established the Pan-Canadian Framework on Climate Change and Clean Growth which is built on four pillars: (1) pricing carbon pollution; (2) complementary actions to reduce emissions; (3) adaptation and climate resilience; and (4) clean technology, innovation, and jobs (Government of Canada 2020f). It includes over 50 tangible actions that both federal and provincial governments will take to reduce greenhouse gas emissions by 30 % below 2005 levels by 2030, which is Canada's targets under the United Nations Paris Agreement.

The Pan-Canadian Framework introduced a carbon pricing strategy which mandated carbon pricing by all provinces and territories by 2018, and committed to phase out coal-fired electricity generation by 2030. Through this, the Federal Government introduced a carbon tax of $20 a tonne in 2018 which will increase by $10 a year until it reaches $50 in April 2022 (Government of Canada 2019). The price will continue to rise by $15 each year starting in 2023 until it hits $170 per tonne in 2030 (Tasker 2020). However, there has been minimal support from the provinces since its introduction. Ontario, Alberta and Manitoba took the federal government to court in 2019 over the constitutionality of the carbon tax, and are currently appealing the decision to the Supreme Court of Canada (Rabson 2020).

Healthy Environment and a Healthy Economy

A new climate plan, Healthy Environment and a Healthy Economy, was announced in December 2020 and aims, among others, to introduce new measures to reduce greenhouse gas emissions (Government of Canada 2020c).

Appendix 2: Nova Scotia's climate change policies

Nova Scotia has emerged as a leader in delivering energy efficiency programs and for initiating programs to help municipalities adapt to the impacts of climate change. This appendix details some of the most important of these that have not already been covered by this report.

Environmental Goals and Sustainable Prosperity Act

In 2007, Nova Scotia passed the *Environmental Goals and Sustainable Prosperity Act* which established clear goals focused on integrating environmentally sustainability with economic well-being (Minister of Environment and Labour 2007). It included 25 goals centred around greenhouse gas reductions, renewable energy development, improved air and water quality, and protection of ecosystems. It establishes criteria to measure social and economic prosperity along-side environmental sustainability, and details mechanisms to help make continuous improvements. It remains the only Act in Canada that links environmental goals directly to economic outcomes.

Most of the goals of the *Environmental Goals and Sustainable Prosperity Act* have been achieved (Province of Nova Scotia 2019b) and were, therefore, replaced with the *Sustainable Development Goals Act* in 2019 (Province of Nova Scotia 2019a). This Act sets new goals for climate change and Nova Scotia's economy environment. It also requires Nova Scotia to reduce greenhouse gas emissions by 53 % below 2005 levels by 2030 and reach net-zero emissions by 2050. This is currently the most ambitious greenhouse gas emission reduction target in Canada.

Greenhouse Gas Emissions Regulations

Nova Scotia's *Greenhouse Gas Emissions Regulations* set hard, declining caps on greenhouse gas emissions from the electricity sector (Province of Nova Scotia 1994). These regulations prompted Nova Scotia Power (www.nspower.ca) to plan an affordable transition away from fossil fuels and towards cleaner electricity. In 2015, Nova Scotia legislated that Nova Scotia Power must invest in energy efficiency when it is the most cost-effective option for ratepayer (Climate Change Nova Scotia 2019). Nova Scotia is the only province with such a law, but as a result, $35 million per year from electricity rate payers is invested in energy efficiency programs in the province.

Efficiency Nova Scotia (www.efficiencyns.ca) was established in 2011 to deliver energy efficiency programs. It is Canada's first energy efficiency utility. This independent organization aims to deliver regulated energy efficiency programs to meet provincial climate change targets. Efficiency Nova Scotia programs help homeowners, businesses and communities with energy efficiency upgrades that prevent the release of more than one million tonnes of greenhouse gas emissions annually. These programs have also created more than 1,400 full-time jobs (Effiency Nova Scotia 2020).

Marine Renewable Energy Act

In 2015, Nova Scotia passed the *Marine Renewable Energy Act*, a legal framework for the development of the marine renewable energy industry (Province of Nova Scotia 2017). Nova Scotia's 'Renewable Electricity Plan' sets targets for renewable electricity generation like wind, tidal, biomass, and hydro (Nova Scotia Department of Energy 2010). In 2015, Nova Scotia surpassed the provincial target of 25 % of electricity from renewables and is projected to reach up to 40 % by the end of 2020 (Climate Change Nova Scotia 2019).