Projections and perceptions:
Predicted impacts of climate change on shellfish mariculture

By

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Abstract

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The impact of climate change on the aquaculture industry is becoming an increasingly relevant topic for farmers, managers, and researchers alike. The growth and expansion of this industry is contextualized by the changes in ocean properties both occurring and predicted to occur, as a result of climate change. In Atlantic Canada, planning for the future of bivalve farming should incorporate predictions of how species will be impacted by climate change, and as well how stakeholders perceive these impacts. This study coupled bioenergetic models for the eastern oyster (*C. virginica*), and the blue mussel (*M. edulis*), with high resolution climate models to predict the performance and growth of these species in the near future (2046-2050), compared to the past (1986-1990). Results indicate that changing sea surface temperatures may benefit *C. virginica* more than *M. edulis* in terms of future growth, due to their differing thermal physiologies. Furthermore, this study identified three main perceptions held by stakeholders regarding how climate change will impact bivalve aquaculture. Although stakeholders recognized the impacts of changing ocean properties on bivalve performance, it was less clear how farming costs, planning, and activities would be impacted. Further, a divide was identified between how farmers and managers perceive the effects of climate change on bivalve aquaculture. Results from this study should be used to plan for the future of bivalve farming in Nova Scotia and Prince Edward Island, two Canadian provinces heavily invested in bivalve aquaculture. Recognizing the importance of bridging the science-policy interface, information from both modelling efforts as well as stakeholder input should be used to create a resilient future for bivalve farming.

Keywords: aquaculture; bivalves; climate change; bioenergetics; dynamic energy budget modelling; stakeholders; perceptions; Q methodology

Acknowledgements

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Chapter 1: General introduction

1.1 Shellfish aquaculture and climate change

Aquaculture, the practice of rearing aquatic organisms, is the fastest growing food industry globally (FAO, 2016). Specifically, demand for shellfish products is increasing globally (FAO, 2016), and over the past two decades, bivalve production value has more than tripled in Canada alone (DFO, 2016). Although a recently industrialized practice, some of the oldest aquaculture practices in Canada were oyster farms in Prince Edward Island (PEI) (Gardner, Pinfold 2013). The mussel industry emerged more recently in the 1970s, and quickly became economically imperative to PEI. Currently, PEI mussels are consistently Canada's leading shellfish product both by weight and value (DFO, 2016). Bivalve aquaculture has the potential to bring both wealth and jobs to rural communities which tend to experience high unemployment rates, and have few opportunities for year-round employment (Statistics Canada, 2016). In 2010, 5500 people were employed by the aquaculture industry in the Maritime provinces (Gardner Pinfold, 2013). Despite its expansive coastline, Nova Scotia (NS) currently produces only 5% of the amount of shellfish that PEI produces (DFO, 2016) (Figure 1). Furthermore, NS has been identified has having suitable ecological and market landscapes for the expansion of their aquaculture industry (Stantec, 2009).

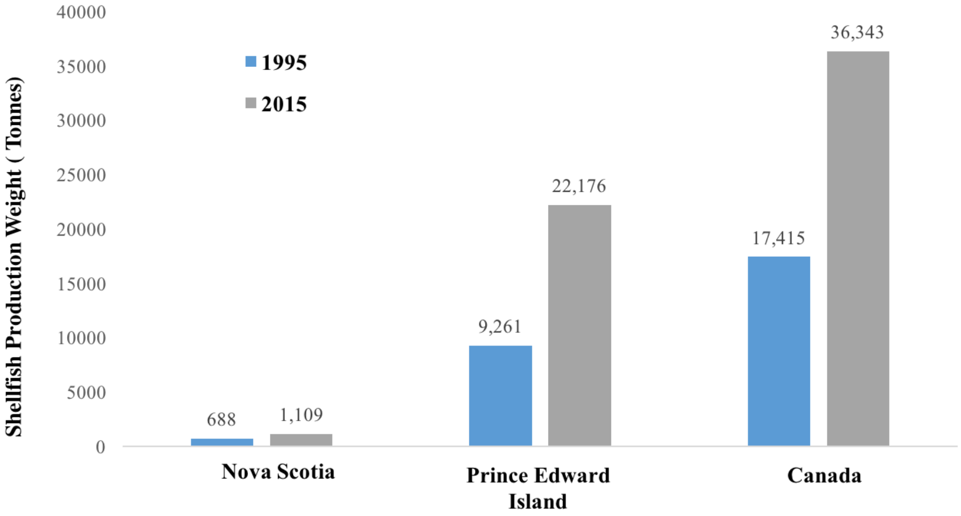


Figure 1. Shellfish production statistics (Tonnes) in 1995 and 2015 for Prince Edward Island, Nova Scotia, and Canada (DFO, 2016).

Many of the communities that rely on bivalve aquaculture are also experiencing and anticipating the effects of climate change (Lemmen et al., 2016). Climate change, as defined by the International Panel on Climate Change (IPCC), is any significant change to either the average state of a particular climate, or its variability (IPCC, 2012). Climate change is impacting Canada's coastlines at accelerated rates compared to global averages (Lemmen et al., 2016), and on the east coast of Canada sea and air temperatures are projected to continue to increase throughout the 21st century (IPCC, 2013). Currently, eroding shorelines, storm surges, and warming water temperatures are being observed on the east coast of Canada, particularly in PEI (Filgueira et al., 2013; Lemmen et al., 2016). These coastal impacts are driven by a multitude of processes including rising sea levels, reduced sea ice (both in thickness and duration), and an increase in frequency and strength of extreme weather events. For example, PEI has been subject to shoreline erosion due to the combination of sand dune composition, rising sea levels, and reduced sea ice (Catto et al., 2002). The provincial government of NS has also recognized the impacts of climate change, particularly threats posed by storm surges and gradual sea level rise (Lemmen et al., 2016). Many of the impacts of climate change, such as warming ocean temperatures and increased storm frequency, are physically linked and will have downstream impacts such as increased ocean acidification and ocean stratification (Lemmen et al., 2016). As the characteristics of oceans gradually change, so too will the biota that inhabit them.

Changes in temperature influences bivalve physiology; as ectotherms, changes in temperature impact basic functions such as heart and filtration rates (Bayne et al., 1976; Kittner and Riisgård, 2005). Changes in temperature will therefore affect survival, phenology, and ultimately distribution (Philippart et al., 2003; Zippay and Helmuth, 2012). The results of the relationship between temperature and bivalves is discussed widely in the body of scientific literature. For example, warming ocean temperatures are currently permitting the northward migration of many marine species (e.g. Diederich et al., 2005; Jones et al., 2009, 2010; Rinde et al., 2016; Shelmerdine et al., 2017). Additionally, temperature may impact the timing of life cycle events (e.g. spawning and overall reproductive effort) which will have downstream effects on population growth and interspecific interactions (Philippart et al. 2003; Filgueira et al., 2015; Thomas et al., 2015). Apart from temperature, climate change may impact bivalves in other ways. Increased storm frequency may alter both the shape and biological productivity of coastal embayments, having an impact on the primary food source of bivalves (Filgueira et al., 2013; Guyondet et al., 2015). With shells made of calcium carbonate, spat survival and growth has been found to be negatively impacted by ocean acidification (Gazeau et al., 2013). Impacts of climate change on bivalves are also often species specific (e.g. Filgueira et al., 2016), meaning that future conditions may have both positive and negative impacts, dependent on the species being farmed.

1.2 Management problem and research objectives

The bivalve aquaculture industry is facing an increasingly uncertain future because of climate change. Changes in abiotic conditions will impact the growth and performance of economically important bivalve species. As environmental changes are predictable, marine planners can anticipate where and how farms will be impacted. Site-selection for new farms, and the management of extant ones is dependent on stakeholder support and engagement. The goals of this research are to predict future growth of bivalves in the coastal waters of NS and PEI (Chapter 2) and to understand how stakeholders perceive the relationship between climate change and shellfish aquaculture (Chapter 3) (Figure 2). Bivalve growth was explored with the two most economically important species in NS and PEI, the blue mussel (*Mytilus edulis*) and the eastern oyster (*Crassostrea virginica*). The perception of key stakeholders, namely farmers, managers, and researchers were analyzed in both NS and PEI using a semi-quantitative interview method (Q methodology). To prepare for the possibility of expanding bivalve aquaculture, modelling techniques can be used to anticipate environmental changes and concomitant effects on cultured species, and stakeholder perceptions can be used by marine planners to adapt to those foreseen changes. Both of these objectives are useful for planning new bivalve farming areas, and evaluating the longevity of current ones. The goals of this study are useful for informing marine spatial planning (MSP) exercises. MSP is a public process by which the use of coastal space and resources is planned to achieve social, ecological, and economic balance (UNESCO, 2017). Being spatially focused and interdisciplinary, this research contributes to key elements of MSP.

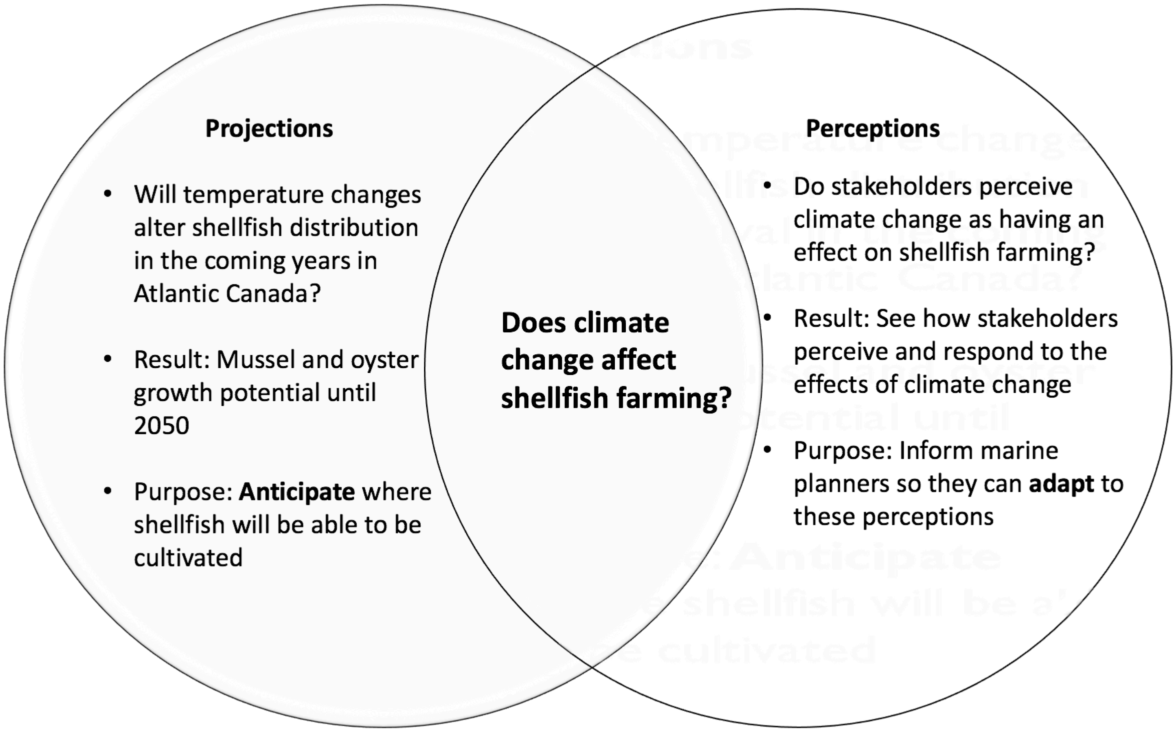


Figure 2. Overview of the central management problem addressed in this report, and its relationship to the two ways this problem was addressed. Each side of the Venn diagram (projections/perceptions) are discussed in chapters two and three, respectively.

Chapter 2: Projections: Projected shellfish performance using a dynamic energy budget model

2.1 Introduction

With a growing population expected to surpass 9 billion by 2050, the cultivation of bivalves helps to provide food security as a source of inexpensive protein with low environmental impacts (Shumway et al., 2003; Godfray et al., 2010). Globally, the production of bivalves has been steadily increasing over the past several decades and is expected to continue to do so (FAO, 2016). Considered ecosystem engineers as well as keystone species (Gutiérrez et al., 2003; Zippay and Helmuth, 2012; Han et al., 2017; Sorte et al., 2017), bivalves interact with their environment through both top-down and bottom-up processes (e.g. Coen et al., 2007; Rice, 2008). Top-down control via filter-feeding may significantly curtail phytoplankton populations (Cranford et al., 2003; Newell, 2004; Forsberg et al., 2017) potentially affecting bivalve performance itself (Dame and Prins, 1998; Bacher et al, 2003; Strohmeier et al, 2005), but also impacting other filter-feeders and grazers (Kluger et al., 2017). Filtration activity can also play an important role in regulating water quality and depth of light penetration (Gallardi, 2014; Guyondet et al., 2015). Bivalves can also impose bottom-up control on plankton communities by altering fluxes of nutrients (Menge, 1992; Newell 2004). Bivalves redirect energy from the pelagic environment to the benthos, as faeces and pseudofeces sink creating accumulated organic material below farms or beds (Newell, 2004; Cranford et al., 2007; 2009).

Interactions between bivalves and their environment are bidirectional, meaning the abiotic environment also imposes effects on bivalves. Temperature plays an important role in physiology, gene expression, distribution, and fitness of bivalves (Zippy and Helmuth, 2012; Shelmerdine et al., 2017). The internal body temperature of bivalves usually matches external water temperatures, except when intertidal species are subject to aerial exposure (Zippay and Helmuth, 2012). Although the effect of temperature on physiology is species-specific, generally as temperature increases, physiological rates will increase until a threshold is met, at which point performance will decline (Kooijman, 2010). Due to this relationship between physiological functions (e.g. filtration rates and oxygen consumption) short-term changes (days/weeks) in temperature will predictably impact their survival (e.g. Malham, 2009; Rinde et al., 2016) and long-term changes (years) will impact their reproductive timing and effort, and consequently their spatial distribution (Bayne et al., 1976; Philippart et al., 2003; Kittner and Riisgård, 2005; Toupoint et al., 2012; Zippay and Helmuth, 2012; Filgueira et al., 2014). Accordingly, the relationship between temperature and physiology of bivalves is particularly relevant within the context of climate change.

The Intergovernmental Panel on Climate Change (IPCC) has reported that since 1971 global ocean surface temperatures have increased 0.11°C (± 0.02) per decade (Pachauri and Mayer, 2015). Although temperature will not be the only change to impact bivalves, it has been shown to be the most deterministic factor influencing shellfish growth and distribution, and is one of the most widely studied abiotic factors related to climate change (Zippy and Helmuth 2012; Rodrigues et al., 2015; Buckley and Huey, 2016; Filgueira et al., 2016). Warming ocean temperatures are modifying current natural ranges of many marine species (e.g. Diederich et al., 2005; Jones et al., 2009; 2010; Rinde et al., 2016; Shelmerdine et al., 2017). Despite inherent uncertainty, modelling techniques which incorporate both climate data and organismal bioenergetics are the only tools available to explore the effects of future climate change scenarios on animal populations.

Climate models are quantitative representations of natural processes that make up Earth's conditions, and are often used to predict the effects of climate change (Pachauri and Mayer, 2016). Currently, global emissions of CO_2 are the best predictor of Earth's surface warming, and are directly related to both human population and economic growth (Pachauri and Mayer, 2016). Output from these models include estimated surface, air, and water warming, ice cover, and change in circulation patterns (Pachauri and Mayer, 2016). Refining the scale of global climate models promotes understanding how climate processes and conditions will change on local scales at highly detailed spatial resolutions. This has been done for the Northwest Atlantic shelf region of Canada (Brickman and Drozdowski, 2012), integrating atmospheric and oceanic information to estimate future sea surface temperature (SST) and salinity of the Scotian Shelf and Gulf of Saint Lawrence (Long et al. 2016) (Figure 3A).

Regarding bioenergetics, Dynamic Energy Budgets (DEB) provide a mathematical method for modelling energetic flows through individual organisms (Kooijman, 2010). DEB models breach interdisciplinary boundaries by merging the principles of thermodynamics, physiology, and theoretical biology. The mechanistic nature of DEB models permits its application to a wide range of environmental conditions. DEB has been parameterized for several bivalve species (e.g. Pouvreau et al. 2006; Van der Veer et al., 2006; Filgueira et al., 2014) and used to predict their growth (e.g. Lavaud et al., 2017), and reproductive effort (Montalto et al., 2015). The coupling of climate and bioenergetics models such as DEB is being used under the context of climate change to explore the effect of predicted temperatures on the energy budgets of organisms (e.g. Sará et al., 2011; 2013; Thomas et al., 2011; 2015).

The development of bivalve aquaculture industry is contextualized by climate change and its concomitant effects on the oceans, given its reliance on natural environmental conditions. Climate change is generating uncertainty around future production levels of bivalves, which makes creating resilient government policies increasingly difficult (e.g. Rodriguez-Rodriguez and Ramudo, 2017). On the Atlantic coast of Canada, it has been recognized that sea surface temperatures (SST) are increasing at a rate higher than the global average (IPCC, 2013; Saba et al. 2016). As these changes are predictable, impacts to cultivated bivalve species can be anticipated, and their effects could be mitigated with management plans. In the present study, the future growth of two widely cultivated bivalve species in Atlantic Canada (*Mytilus edulis* and *Crassostrea virginica)* are estimated by coupling their bioenergetics to a high resolution climate model. In this way, bivalve growth and performance can be predicted for the coming decades, to prepare for the impacts of climate change on the industry. The findings of this study are relevant for planning bivalve farming, in terms of both site- and species-selection.

2.2 Methods

2.2.1 Description of study area

The study area for this research is the Scotian Shelf and Gulf of Saint Lawrence, the bodies of water surrounding NS and PEI (Figure 3A). The study area contains widely varying temperatures both seasonally and spatially. Colder waters in the Bay of Fundy reach an average summer high of 13°C, however water temperatures in the sheltered Northumberland Strait (e.g. the body of water between NS and PEI) may exceed 20°C (Feindel et al., 2013). Furthermore, this area is extensively used for bivalve aquaculture, primarily the eastern oyster (*Crassostrea virginica)*, and the blue mussel (*Mytilus edulis*) (Figure 3B). Culture methods consist primarily of long-lines, floating bags, and some oyster bottom culture (DFO, 2003a; 2003b).

2.2.2 Climate change model

The climate change model used in this study was produced by the Department of Fisheries and Oceans Canada, as a part of the Canadian Government's Aquatic Climate Change Adaptation Services Program. Unlike other Global Climate Models (GCMs), this is a high resolution (1/12°) model of regional climate dynamical downscaling system of the Gulf of Saint Lawrence, Scotia Shelf, and Gulf of Maine (Long et al. 2016). The model domain, for the use in this research was restricted to the waters surrounding NS and PEI (Latitude: 42.7130 to 49.0416, Longitude: -67.1065 to -59.0403). The model is constructed of the atmospheric Canadian Regional Climate Model (CRCM), and the oceanic model the Canadian Océan PArallélisé (CANOPA) model. The CANOPA model was developed at the Bedford Institute of Oceanography (Brickman and Drozdowski, 2012), based on the Océan PArallélisé model, version 9 (OPA 9.0; Madec et al., 1998), and the Louvain-la-Neuve ice model, version 2 (LIM2; Fichefet and Morales Maqueda, 1997; Bouillon et al., 2009). The model covers the time period from 1970-2100 under the A1B and Representation Concentration Pathway (RCP) 8.5 scenario (Long et al. 2016). The output is produced in grid cells with dimensions of 5-6 km horizontally. River inputs are included in the model; however tidal forcing is not used. A full description of the model can be found in Long et al. (2016)

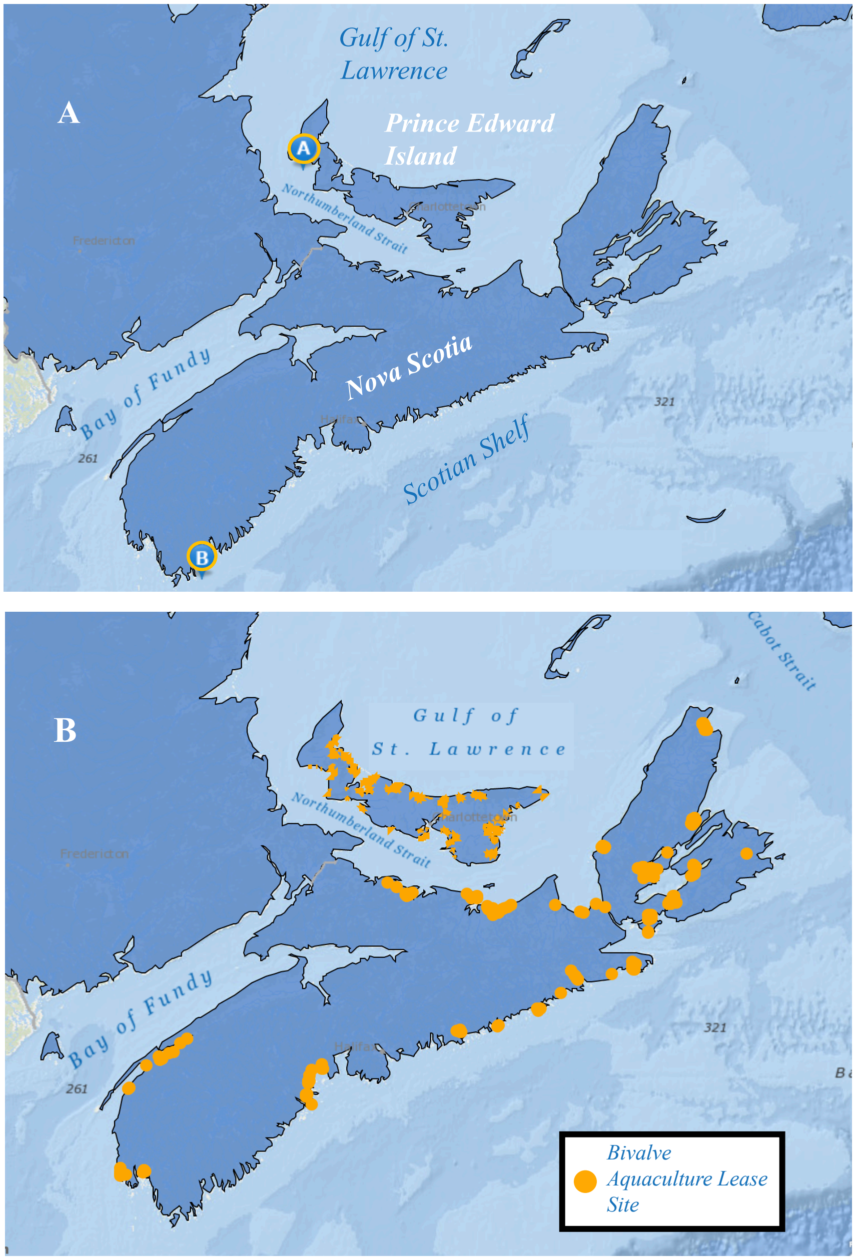


Figure 3. Map of the model domain, A) indicating the relevant waterbodies surrounding Nova Scotia and Prince Edwards Island, with A and B representing the location of represent the warmest and coldest coastal areas relevant for bivalve farming contained within the model domain, respectively, and B) Map of bivalve aquaculture lease sits in Nova Scotia and Prince Edward Island, data retrieved from NSDFA, 2017, and DFO, 2017, respectively (Produced in Esri/ArcGISonline).

2.2.3 Bioenergetic model: Dynamic energy budget (DEB)

The bivalve models used in this study are based on DEB theory (Kooijman, 1986; 2010). DEB models define how energy is moved through an individual by describing them with three standard state variables: reserves, structure, and maturity/reproduction (depending on the life stage). Energy moves as organisms assimilate food, which is first stored as reserves. Subsequently, a fraction of reserves (κ) is directed towards growth and maintenance of the structure of the individual, and the rest (1- κ) is allocated to maturity in juveniles, and reproduction in adults (specifically, gametes). The notations and symbols used in this text are consistent with Kooijman (2010) where square brackets [] denote quantities per unit structural volume, braces {} denote quantities per unit surface-area of the structural volume, and rates are defined by dots above their symbol. The model equations are described briefly in Appendix i, and further details of the model can be found in Pouvreau et al. (2006). The models were run for a full year, beginning on January 1st, and were initialized with the same length for both species (2cm) and dry flesh mass (DFM), including structural weight only, of 0.013g and 0.02g for *C. virginica* and *M. edulis,* respectively

The parameterization of the DEB models (Appendix ii) followed existing studies, Lavaud et al. (2017) for *C. virginicia* and Rosland et al. (2009) and Saraiva et al. (2011) for *M. edulis*. The models were calibrated using the scaled functional response (*f*) as a simplified proxy for food availability. This parameter originates from the Holling Type II response used in DEB theory (Kooijman, 2010):

$$f = \frac{X}{X + X_k}$$

Where X is food availability and X_k is the half-saturation coefficient, which represents the time and energy an individual allocates to searching for food. As the value of *f* moves from 0 to 1, increasingly less time and energy is spent looking for food. Using this relationship, *f* was simplified as a proxy ranging between 0-1 for food availability where low values of *f* (i.e. $f = 0$) reflect low food availability, and high values of *f* (i.e. $f = 1$) reflect food availability at saturation (Kooijman, 2010). This proxy was used to calibrate the growth rates of both *C. virginica* and *M. edulis*. Calibration was completed to ensure that growth rates were within biologically reasonable ranges. This was done by comparing *C. virginica* and *M. edulis* growth from the literature with model outputs (Appendix iii). Growth rates were calculated following Clausen and Riisgård (1996):

$$\mu = \left(\frac{X_t}{X_0}\right) \text{x}\, t^{-1}$$

Where X_t and X_0 are the average dry weight or shell length on Day 0 and Day *t* respectively.

2.2.4 Coupled model

The DEB models for *C. virginica* and *M. edulis* were coupled to the high resolution ocean climate model (Long et al., 2016) following an off-line scheme. The forcing variable used from the climate model was seawater temperature. Temperature data was extracted from the model between the years of 1980 to 2050 for each grid square in the region of interest, and then the top two depth measurements (0 and 12m) were daily averaged. Temperature measurements in the model were produced twice a month, and linear interpolation was used to estimate data points between observations. Three periods were studied by averaging five year periods, 1985-1990, 2016-2020, 2046-2050, representing the past, present, and future scenarios respectively. Averages were used to minimize the impact of potential outliers.

2.2.5 Data analysis and numerical experiments

To determine how temperature changed both spatially and temporally, past SST data (1986-1990) was subtracted from future SST data (2046-2050), for the entire region being analyzed. This was done twice, by averaging the temperature for January and August, the coldest and warmest months, respectively. To determine how thermal stress may change over time, the number of consecutive days exceeding physiologically relevant thermal thresholds (°C) were calculated for comparison between the three times periods. This was done for warm temperatures relevant for the upper thermal threshold of *M. edulis* and cold temperatures relevant for the lower thermal threshold for *C. virginica*. The upper thermal threshold used for *M. edulis* in this DEB model is 23°C (Rosland et al., 2009), however increased mortality rates have been observed in laboratory conditions at 22°C (Clements et al., 2017, unpublished data). Similarly, the lower thermal threshold of *C. virginica* used for this model was 2°C (Lavaud et al., 2017), however behavioral changes (e.g. filtration rates decrease by 50%) have been observed at 9°C (Comeau et al., 2008). This was done for the warmest and coldest areas relevant for bivalve aquaculture contained in the model domain (Figure 3A). To explore the species-specific effects of SST changes, growing degree days (GDD) were calculated for both *C. virginica* and *M. edulis* across the three time periods, in the warmest area within the model domain relevant for bivalve aquaculture (Figure 3A, point A). GDD were calculated as follows:

$$\mathrm{GDD} = \sum_{i=start\ date}^{end\ date} (T_i \geq T_{TL}\ , T_i \leq\ T_{TH}) * \Delta d$$

Where T_i is the SST (°C) on day i, and T_{TL} and T_{TH} are the predetermined lower and upper threshold temperatures respectively (°C), and Δd was a determine time-step (1 day). GDD is in units of °C x day, and was calculated for one year (January 1 – December 31). Lower and upper thermal tolerances for *C. virginica* were 2°C and 35°C (Lavaud et al., 2017), respectively, and -1.8°C and 23°C (Saraiva et al., 2011) were used for *M. edulis*.

To estimate the physiological performance of both species, shell length (SL), dry weight (DW), and gonadosomatic index (GSI), were estimated for the present time period, for the warmest and coldest areas relevant for bivalve aquaculture within the model domain (Figure 3A). GSI was calculated as a ratio of reproductive tissue to total dry weight. To determine how these indices changed spatially and temporally, percent change was calculated for both SL and GSI in the entire model domain as follows:

$$\frac{Future\ Value - Past\ Value}{Past\ Value}\ x\ 100\%$$

To estimate changes in phenology across the model domain, the earliest spawning dates of both species were estimated using a combination of temperature and GSI thresholds, wherein both conditions must be met for a spawning event to occur. The temperature thresholds for *C. virginica* and *M. edulis* were 17°C (Nelson, 1928; Loosanoff, 1939), and 14°C (Newell, 1989), respectively. Additionally, GSI thresholds of 0.2 (Choi, 1992) and 0.28 (Troost et al., 2010) for *C. virginica* and *M. edulis,* respectively. On the first day that both thresholds were met, spawning was triggered in the model by emptying reproductive reserves.

All statistical analyses were performed in Rstudio version 3.1.2. For all parametric analyses, tests for normality and homogeneity of variance were performed with Shapirowilk and Barlett's tests respectively. No data transformations were required; all parametric assumptions were met. For GDD comparisons, 2-way ANOVAs were run. When factors yielded significant effects, post hoc testing was done using a Tukey test. All α levels were 0.05. No significant interactions were found.

2.3 Results

2.3.1 Climate model

The climate model indicates that SST warming will be spatially dependent within the model domain. Differential warming rates were observed between the past (1986-1990) and the future (2046-2050) scenarios (Figure 4), with some areas experiencing average August temperatures of 2.5°C higher in the future than in the past. Smaller changes were observed in January, with the highest absolute change being 1.5°C. In the warmest area relevant for farming bivalves in this model (Figure 3A, point A) the number of consecutive days exceeding temperature thresholds relevant to the upper thermal tolerance of *M. edulis* increased over the three time periods (between past and future for all temperatures $p<0.05$) (Figure 5A). In the past (1986-1990), 6 days in a row exceeding 22°C were expected, compared to the future, where 39 consecutive days could exceed this temperature (Figure 5A). For low temperatures relevant to the lower thermal threshold of *C. virginica*, no significant changes were observed in the number of consecutive days falling below these temperatures, calculated for the coldest coastal area relevant for bivalve farming within the model domain (between past and future for all temperatures, $p>0.05$) (Figure 5B). Linking temperature and physiology, in the warm location (Figure 3A, point A) GDD increased between the past and the future for both species ($p<0.05$, Figure 6).

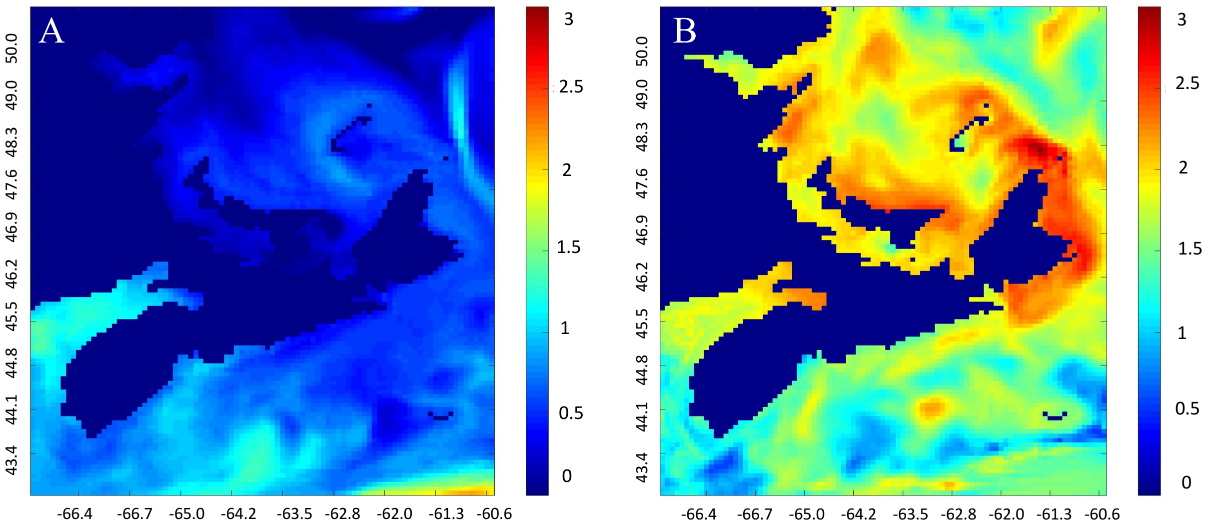


Figure 4. Change in temperature (°C) between the past (1986-1990) and the future (2046-2050) for the Gulf of Saint Lawrence and Scotian Shelf areas within the model domain. Temperatures were calculated by averaging the SST values for the month of January (A) and August (B), the coldest and warmest months, respectively.

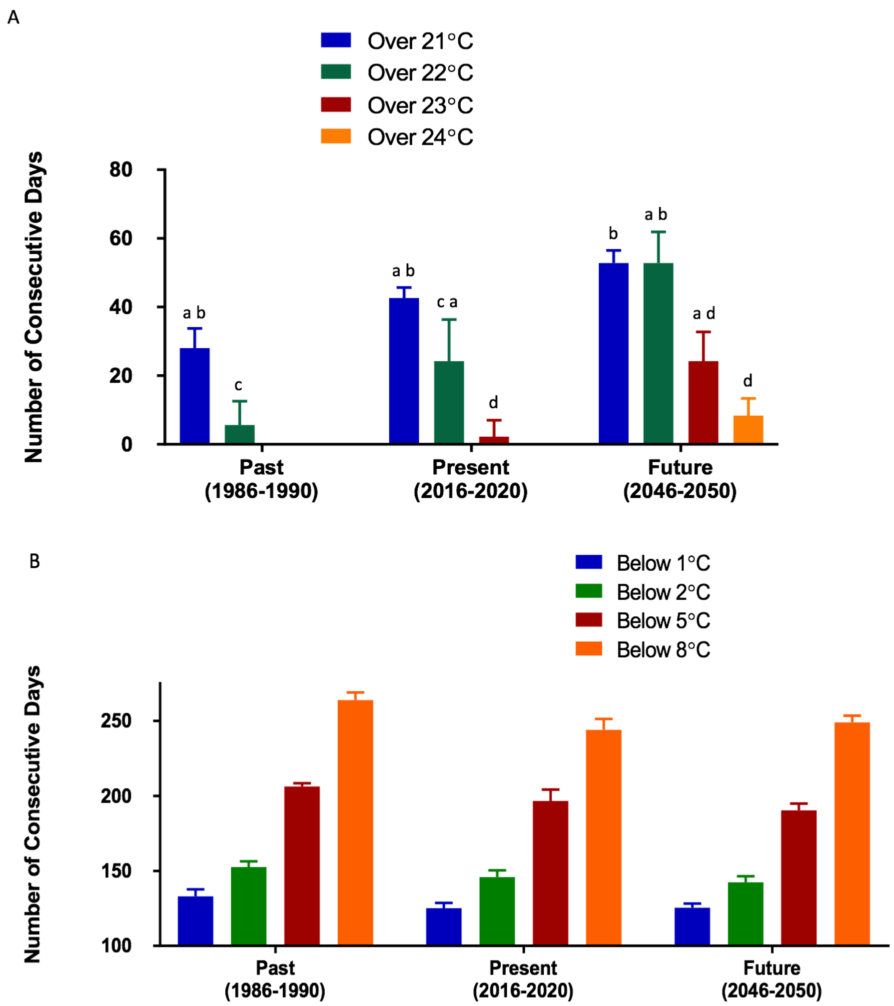


Figure 5. A. Number of consecutive days that exceeded temperatures relevant to *M. edulis'* upper thermal threshold (Rosland et al., 2009). Temperature data was taken from the warmest area relevant for potential bivalve aquaculture (Figure 3A, point A). Bars not sharing the same letter indicate significantly different groups ($p<0.05$). B. Number of consecutive days falling below temperatures relevant to *C. virginica's* lower thermal threshold (Lavaud et al., 2017). Temperature data was taken from the coldest coastal area relevant for bivalve aquaculture included in the model domain (Figure 3A, point B). Within each temperature group, no significant effect of time was found ($p>0.05$).

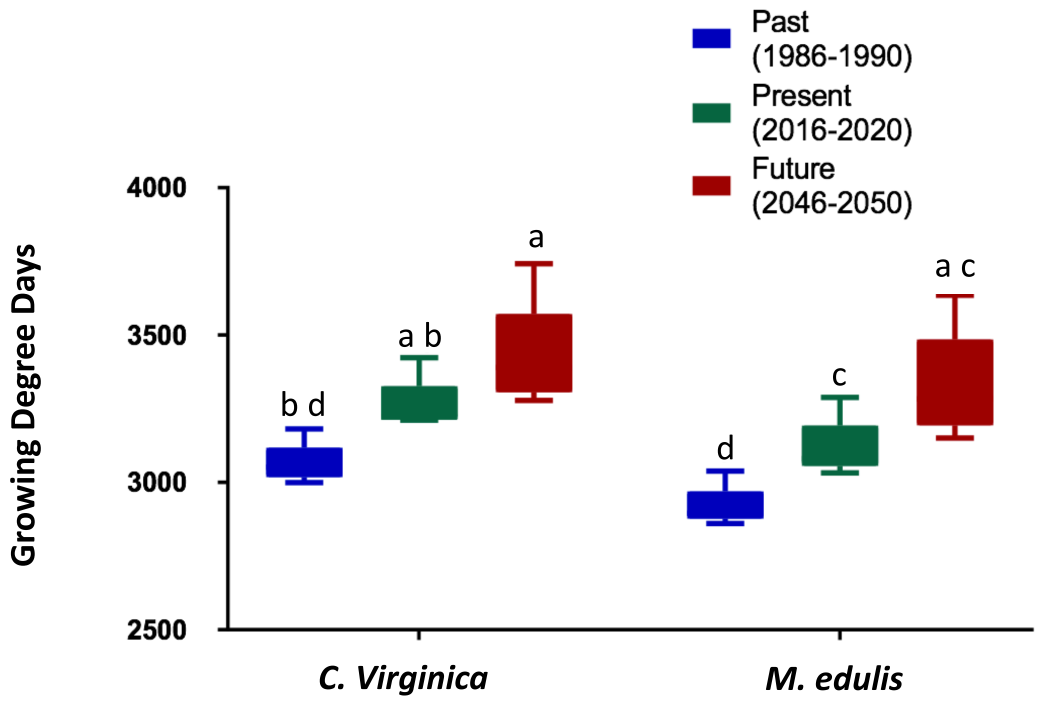


Figure 6. Growing-degree days for *C. virginica* and *M. edulis* for each time period analyzed. Upper thermal tolerances were 35°C and 23°C, and lower thermal tolerances were 2°C and -1.8°C, respectively. This was done for the warmest coastal pixel within the area analyzes (Figure 3A, point A). Bars not sharing the same letters indicate significantly different groups ($p<0.05$).

2.3.2 DEB model validation

The performance of both DEB models was assessed by comparing growth rates (calculated using shell length) to those observed in the literature for similar geographic regions as those used in this study (Appendix iii). Using the present output (2016-2020), *M. edulis* growth rates ($0.00233 \pm 3.65\text{x}10^{-5}$ cm/day) matched those observed in the literature ($0.00265 \pm 3.65\text{x}10^{-5}$cm/day) (Appendix iii). For *C. virginica,* growth rates produced for the present ($0.00198 \pm 5.1\text{x}10^{-5}$cm/day) were below those observed in the literature ($0.00340 \pm 9.2\text{x}10^{-4}$cm/day) (Appendix iii).

2.3.3 Coupled DEB-climate model

The performance (DW, SL, and GSI) of both species varied depending on the thermal regimes of the area they were located in (Figure 3A, points A and B) and within the same area the performance of bivalves was species specific (Figure 7A-H). Generally, the performance of both species were greater in the area with warmer temperatures (Figure 3A, point A). Performance of both species was also visualized for the entire geographic region (Figure 8). The predicted temperature increases are likely to have more observable effects on *C. virginica* than *M. edulis* in terms of both length and GSI, over one year of growth (Figure 8). In the first year of growth, it was found that *C. virginica* did not meet the GSI thresholds needed to spawn (Figure 7D, H) either in the present or the future. For *M. edulis*, the spawning date occurred earlier in the future than in the past, with the largest differential being observed in the Bay of Fundy region (Figure 9).

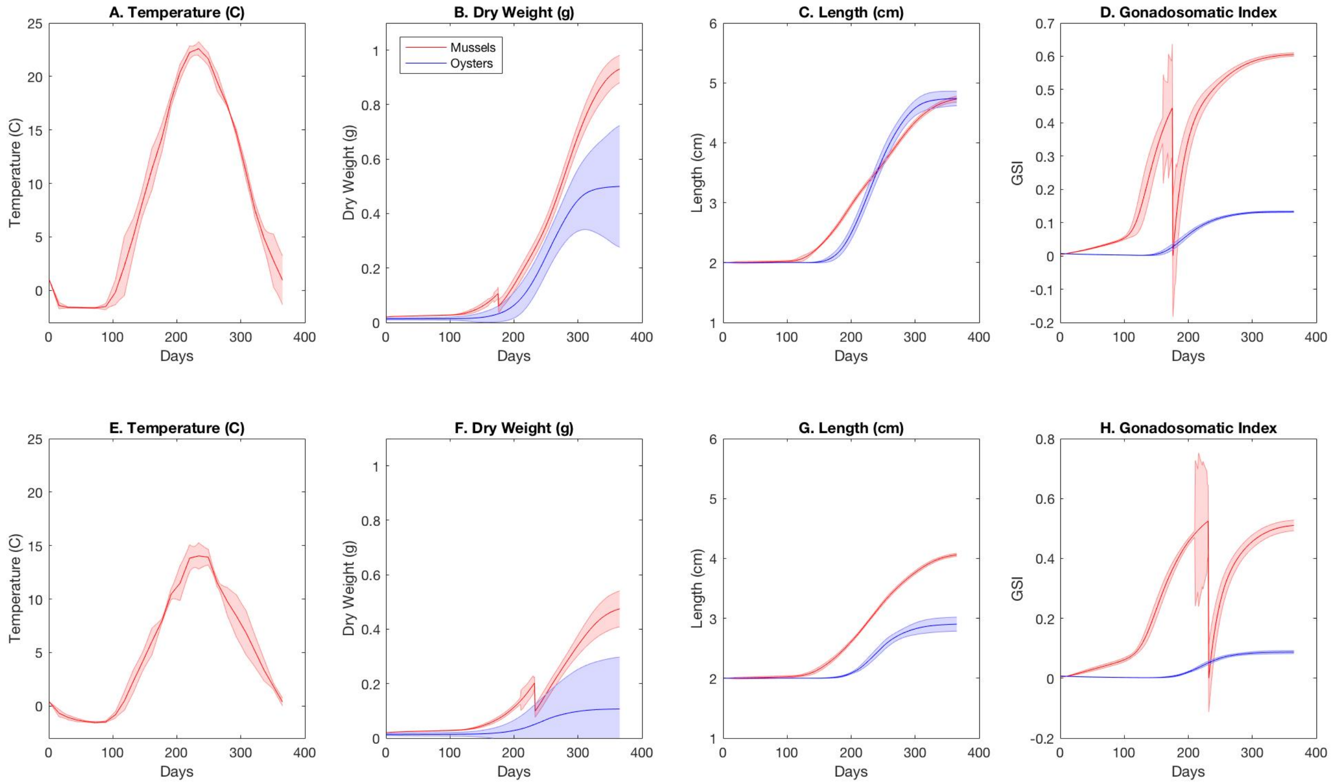
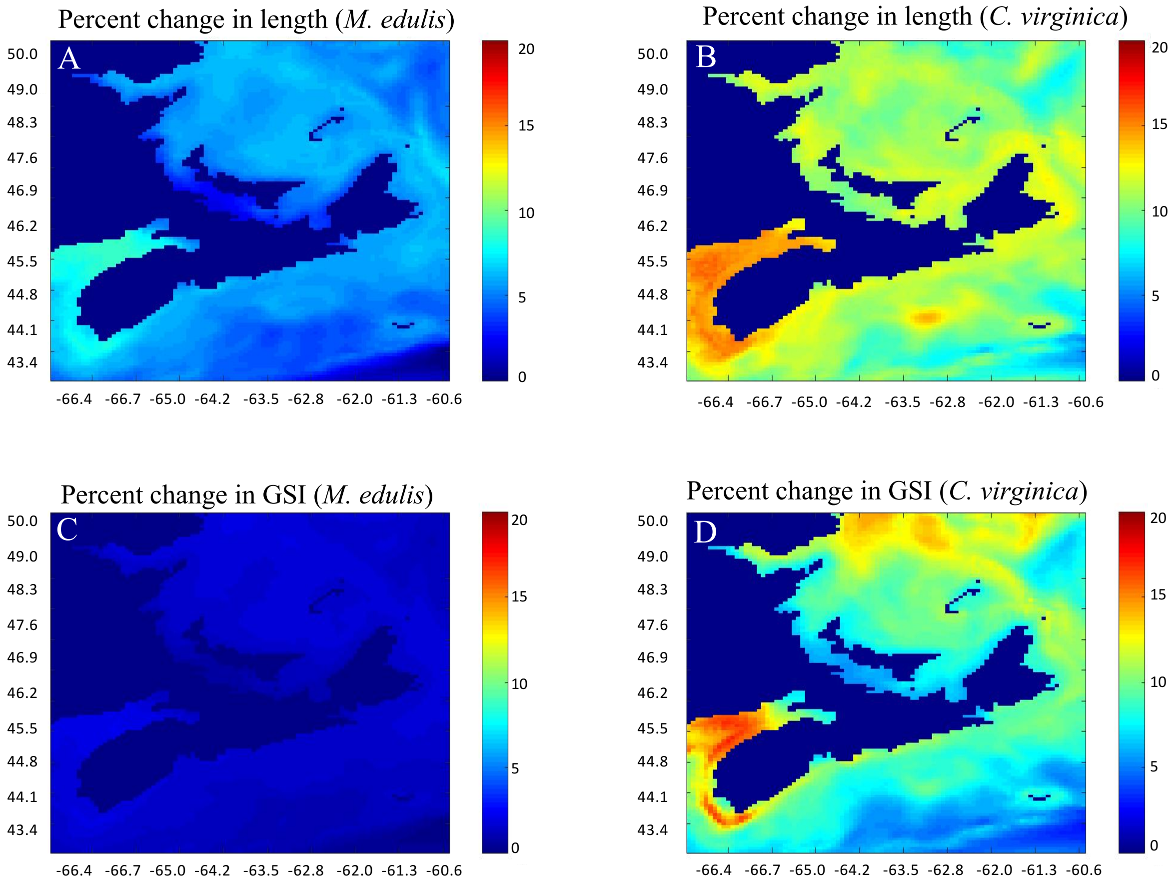


Figure 7. Plots of DEB output indicating *C. virginica* and *M. edulis* growth and performance over one year (beginning on January 1st), replicated for two areas with differing thermal regimes for the current time period (2016-2020). Locations of A-D and E-H can be found in Figure 3A, points A and B, respectively.


Percent change in length (*M. edulis*)

Percent change in length (*C. virginica*)

Percent change in GSI (*M. edulis*)

Percent change in GSI (*C. virginica*)

Figure 8. Percent change in length (SL) (A, B) and gonadosomatic index (GSI) (C, D) of *C. virginica* and *M. edulis* between the past (1986-1990) and the future (2046-2050), calculated after one year of growth.

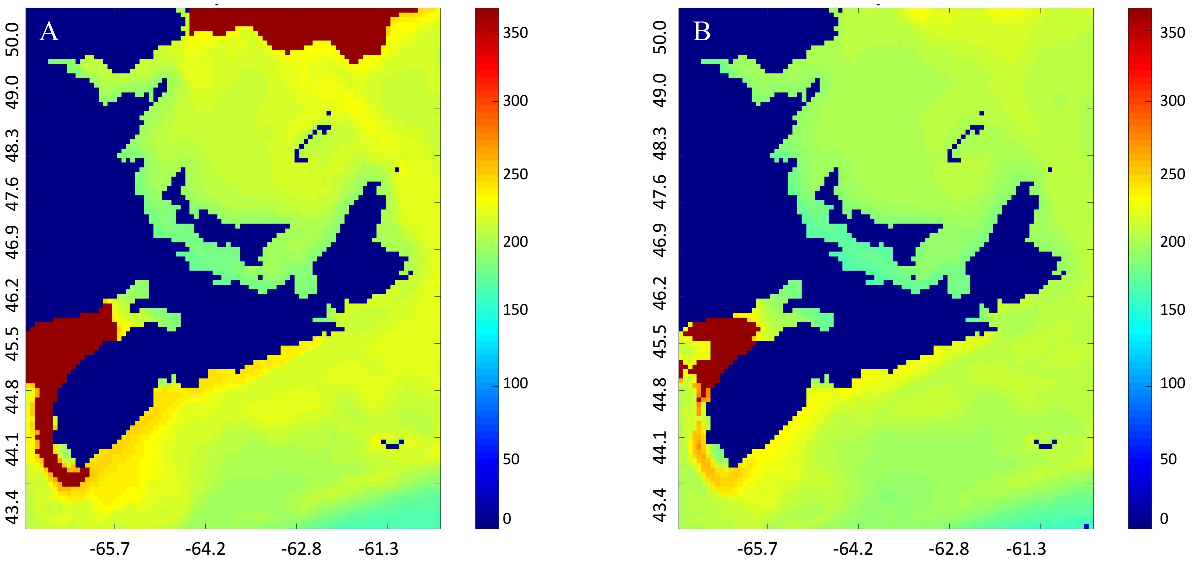


Figure 9. The spawn date of *M. edulis* indicated in Julian day for the past (1986-1990) and the future (2046-2050). Spawn date was calculated as combination of temperature (14°C) (Newell, 1989), and GSI (0.28) (Troost et al., 2010) thresholds. Spawn dates above day 365 indicate that spawning did not occur in the first year of growth.

2.4 Discussion

Water temperature impacts the physiology of bivalves in species specific ways for *C. virginica* and *M. edulis*. Downstream effects of temperature changes on these species have the potential to impact distribution, performance, and phenology (Zippy and Helmuth, 2012; Shelmerdine et al., 2017). In this study, a high resolution climate model was coupled to bioenergetic models of *C. virginica* and *M. edulis* to explore the differential effects of predicted SST changes on these commercial species in the coming decades. By simulating the growth of both of these species over a year, throughout different time periods, the effect of temperature on performance in terms of dry weight, shell length, and reproductive effort was examined for both species.

2.4.1 Climate model

Results from the climate model indicated variable rates of warming within the model domain. Temporally, between the past (1986-1990) and the future (2046-2050), SST warmed for all areas. Seasonally, in terms of absolute warming, larger changes are predicted for the summer compared to the winter (Figure 4). Spatially, SST increased differentially; in January, the southern Scotian Shelf region experienced the most warming, and in August higher rates of absolute warming were observed in coastal areas around northern NS and the northern shore of PEI (Figure 3A, Figure 4). These results match predictions for Canada's mid-high latitude waters in the Scotian Shelf and Gulf of Saint Lawrence (Feindel et al., 2013; Bush et al., 2014). The climate model used in this research has a high spatial resolution, however it does not capture inner coastal bays where aquaculture is carried out. Although it is difficult to create climate change models at high enough resolution to capture the temperatures in these bays (e.g. Stobart et al., 2016), adding 1°C to coastal temperatures in PEI may provide a closer estimation to current bay/inlet temperatures (Filgueira et al., 2015). This variability in SST warming both spatially and temporally indicates that climate change, in terms of ocean warming, will have variable impacts on bivalve bioenergetic processes.

2.4.2 DEB model

DEB models, as mechanistic tools, currently require calibration to the local environmental conditions where they are applied (e.g. Bernard et al., 2011; Picoche et al., 2014). The application of DEB to future scenarios is then limited to the availability of projected climate data, namely temperature and food availability. Inherently, these estimations are impacted by uncertainties as outlined by Skogen et al. (2014): scenario uncertainty (the unknown future socioeconomic climate), model uncertainty (flaws within model estimations), and internal uncertainty (inability to detect change until variability of a signal flattens out). Although these uncertainties have been shown to decrease as models are applied to more local scales (Hawkins and Sutton, 2009), they still limit the ability to integrate environmental data into locally calibrated DEB models. This may explain the lower growth rates produced by the *C. virginica* model in this study, compared to those observed in the literature (Appendix iii). The DEB model used in this study was originally calibrated using field data from the Gulf of Mexico (Lavaud et al., 2017), where the scaled functional response the only parameter that was calibrated in this study. Potential ecophysiological (Casas et al. submitted) or genetic (Murray and Hare 2006) variability from oyster populations from different latitudes could be missed in the current parameterization of the model and consequently explain these lower growth rates. This lower growth may also be exacerbated by the conservative temperature estimates of coastal bays, as discussed above.

Although methods for estimating some environmental variables (e.g. temperature) are clearly defined, others (e.g. food availability) are less clear. Defining food availability for bivalves is frequently done using proxies such as phytoplankton concentration (e.g. Riisgård et al., 2012), often represented by chlorophyll (e.g. Lesser et al., 2010). These methods for defining food availability are associated with inherent model uncertainty for current conditions (Smith, 1980), and become even more uncertain when estimating future chlorophyll *a* concentrations (Elliott et al., 2005). Filgueira et al. (2016), using a spatially explicit model combining the physical environment, aquaculture practices, and climate change drivers, have suggested that climate change (increased SST) may cause a decrease in chlorophyll *a* concentration in coastal embayments, where bivalve aquaculture is present. There is also potential for the abundance of specific size classes of phytoplankton to shift temporally (Agirbas et al., 2015), indicating the possibility for both the quantity and quality of food availability to change over time. Although temperature has been suggested to be the most deterministic factor for bivalve performance under climate change conditions (Filgueira et al., 2016), forcing predicted food availability onto the bioenergetic model would provide a more comprehensive understanding of how bivalve performance will change over time. As predicting chlorophyll *a* in climate change modelling is inherently difficult, food availability was held *ad libitum* for the entire year in this model, following the methods of Lavaud et al. (2017). By limiting the forcing variables in the model to temperature, the results of this study are restricted to the impact of temperature on bivalve physiology.

2.4.3 Coupled climate-DEB model

Predicted changes in SST coupled to bivalve physiology have shown to benefit to *C. virginica* over *M. edulis* in terms of growth, due to their differing thermal physiologies. For *M. edulis* a maximum SL increase of 8.7% was predicted for the future (2046-2050), compared to 16.0% for *C. virginica* (Figure 8). Growth rates of these ectothermic species are highly temperature dependent (Zippy and Helmuth, 2012; Feindel et al., 2013), and although growth rates are predicted to increase, thermal stress associated with ocean warming must be considered. The upper thermal limit of *M. edulis* used in this model was 23°C (Saraiva et al., 2011), but temperatures above 20°C are associated with increases rates of mortality (Newell, 1989; Mallet and Myrand, 1995), and significantly reduced growth rates (Gonzalez and Yevich, 1976).

Specifically, in the southern Gulf of St Lawrence, mortality associated with summer heat stress has recently been observed (Myrand et al., 2000). Although mortality is not predicted by the model, an analysis of predicted temperature could be used as an indicator of mortality risk. For mussels, the number of consecutive days per year at temperatures above 22°C would increase from ~7 in the past (1986-1990) up to ~50 in the future (2046-2050) (Figure 5A). The potential for increased mortality rates at this temperature is highly relevant; in a recent laboratory experiment, mussels held at 22°C for a 30 day period experienced significantly higher mortality rates than a control group held at 16°C (Clements et al., unpublished data). This suggests significantly increased mortality rates for *M. edulis* in the future, compared to past conditions (Figure 5A). Note that, as discussed above, mortality risk would become even higher in aquaculture areas, that is, sheltered bays which cannot be captured with the spatial resolution of the climate model. In this way, these predictions are a conservative estimate of mortality risk in highly coastal, sheltered bays.

Contrastingly, *C. virginica* has the potential to grow to market size at an expedited rate under future scenarios (Figure 8), with no adverse effects from high temperatures due to their high thermal tolerance. Although there was no significant decrease observed in the number of consecutive days below temperatures relevant to the lower thermal threshold of *C. virginica* (Figure 5B), increased growth rates are still likely due to warming summer temperatures. *C. virginica* growth becomes observable in water temperatures around 9°C (Shumway, 1996), a temperature threshold which is likely to be met earlier in the year in the future. Food availability (recorded as timing of phytoplankton blooms) is currently not temporally synced to the seasonal initiation of *C. virginica* growth. In waters contained within the model domain, spring phytoplankton blooms occur in water temperatures between 4°C and 9°C, creating a mismatch between the timing of peak food availability and the seasonal initiation of *C. virginica* growth (Pernet et al., 2007; Comeau et al., 2008; Feindel et al., 2013). As the temporal match between food availability (phytoplankton blooms) and temperatures suitable for growth could become more closely linked under climate change scenarios, the production potential for *C. virginica* would be further benefitted.

In addition to the effects on growth and mortality, SST can also affect phenology, in terms of both reproductive timing and distribution (Thackeray et al., 2010; Feindel et al., 2013). Warming ocean temperatures and the expanded northward distribution of the oyster *Crassostrea gigas* has been extensively studied in European waters (Laugen et al., 2015; Shelmerdine et al., 2017). Spawn dates were estimated in this study using a combination threshold of both temperature and GSI, a common method to trigger spawning in DEB modeling (e.g. Bourlès et al., 2009). The application of this threshold suggested that in the future *M. edulis* will spawn earlier in the year (Figure 9B), and there is potential for oysters to demonstrate a similar trend, however they did not spawn in the first year (Figure 8). For all areas in which spawning occurs, the dates fall within the currently observed spawning times for the Gulf region (between May and August) (DFO, 2003b). GSI calculations (Figure 8) indicate that for both species, proportionally more energy will be allocated to reproduction in the future, although a greater increase was observed in *C. virginica.*

2.4.4 Limitations

The predictions of these DEB models are forced by temperature, the most significant variable for bivalve ecophysiology (Filgueira et al., 2016); however, the effects of other drivers such as ocean acidification, food availability and ecosystem dynamics should not be ignored (Feindel et al., 2013). Ocean acidification, although difficult to predict, has been incorporated into DEB models (e.g. Klok et al., 2014). The waters included within this model have experienced changes in their pH, showing an average pH decline of 0.1-0.2 units since the 1930s (Stewart and White, 2001). Gledhill et al. (2015) have also suggested that the coastal waters of NS have a reduced buffering capacity due to significant freshwater inputs. Acidification has the potential to negatively affect fertilization, larval settlements, and spat shell formation (Curren and Azetsu-Scott, 2013; Gurney-Smith, 2015). Negative impacts have been reported on *M. edulis* larvae in terms of slow growth rates and shell deformities (Gazeau et al., 2010; 2013), and also for recruitment (Brown et al., 2016). For *C. virginica* and *M. edulis* in North America, negative impacts to shell calcification are expected under marine pH conditions predicted for 2050 and 2100, respectively (Gazeau et al., 2007; Whitman-Miller et al., 2009). Despite this, most studies show few impacts of elevated CO_2 on growth or mortality rates of adult bivalves (Keppel et al., 2015; Celements et al., 2017 unpublished data). The impacts of acidification on larval mortality may be particularly important for the aquaculture industry in NS and PEI, where spat are primarily harvested from the wild and therefore rely on unbuffered water (Fiendel et al., 2013). However, rearing spat in hatcheries may help to mitigate the impact of acidification on bivalve aquaculture (Clements and Chopin, 2016)

Culture conditions, where bivalves are grown at high densities are also not represented in these models, which are individual based. Local effects caused by high culture density, such as competition, can have significant impacts on bivalve performance (Cubillo et al., 2012). The primary culture method of bivalves in NS and PEI is in-shore and on long-lines, which increases the risk of thermal stress, and requires cultivation at high densities due to limiting space. Off-shore aquaculture avoids high summer temperatures experienced in coastal bays, potentially reducing thermal stress on *M. edulis* (Myrand et al., 2000; DFO, 2017). Additionally, less competition for space could permit cultivating bivalves at lower stocking densities. Although off-shore aquaculture lacks the physical protection of sheltered bays, by lowering long-lines several meters into the water column, abrasive wave action can be avoided, and more stable temperatures can be achieved (DFO, 2017; Klinger et al., 2017). Preliminary results from *M. edulis* grown off-shore in Newfoundland indicated that off-shore growth rates were comparable to in-shore growth, and that spawning occurred less often, but was more predictable (DFO, 2017). Deeper cooler waters have the potential to avoid thermal stress and increased mortality rates predicted by this model for *M. edulis* under climate change conditions in sheltered inlets (Figure 5A). Compounding stressors such as low food availability, reproduction, and summer heatwaves can act to simultaneously increase mortality rates. For example, previous summer mortalities of *M. edulis* has been explained by the combined effects of high water temperatures, low food availability, and high reproductive output (Tremblay et al., 1998; Myrand et al., 2000).

2.4.5 Conclusions

Results of this study indicate that SST in coastal waters will undergo differential rates of warming both spatially and seasonally. Due to the variable thermal physiologies of *C. virginica* and *M. edulis*, these predicted changes in SST will create species specific risks and opportunities in terms of growth and phenology. Summer heat stress may pose an increased threat to *M. edulis*, due to their lower thermal tolerance. This can impact performance in terms of growth, but also potentially increase the risk of mortality. *C. virginica,* with a higher thermal tolerance, is unlikely to experience negative impacts to growth rates, but instead is likely to show an increase in performance. Additionally, as SST warms there may be an increased temporal match between food availability and the growing period of *C. virginica,* which may in turn impact growth and phenology. When planning for the future of cultivating bivalves in Nova Scotia and Prince Edward Island, these results provide information on which areas will become stressful for *M.*

edulis, and concomitantly where opportunities will arise to cultivate *C. virginica* more effectively. The continued success of this industry is dependent upon the careful selection of species and farming sites. To avoid increased temperature related mortality of *M. edulis* from thermal stress, off-shore aquaculture could be considered as a cultivation method. Furthermore, *C. virginica* could be opportunistically grown in areas where warming SST could promote increased growth rates compared to colder areas. To build upon these results, future studies should incorporate environmental variables such as seasonal food availability, and how it will be impacted by climate change, into bioenergetic models.

Chapter 3: Perceptions: Stakeholder perceptions of climate change and impacts on bivalve aquaculture

3.1 Introduction

Globally, climate change is altering abiotic properties of our oceans, and subsequently the living conditions for aquatic organisms (Zippay and Helmuth, 2012; IPCC, 2013). Specifically, warming ocean temperatures combined with increased acidification and storm frequency may create new opportunities and threats for the bivalve aquaculture industry (DeSilva and Soto, 2009). Changing sea surface temperatures (SST) are having observable effects on the distribution of economically important bivalve species, such as mussels, oysters, and scallops (e.g. Shelmerdine et al., 2017). These ectothermic organisms are grown in marine aquaculture (mariculture) farms across the globe, and in 2015 over 14 million tonnes of bivalves were produced (FAO, 2015). Climate change (e.g. changing sea surface temperatures, ocean acidification, and storm frequency) will impact how bivalves perform in terms of growth and survival, and subsequently determine where we are able to culture them (Callaway et al., 2012; Waldbusser et al., 2014). For example, Filgueira et al. (2016) have suggested that in coastal waters of PEI climate change projections will create growing conditions in which oysters may outperform mussels. Due to the dynamic nature of the interaction between bivalve aquaculture and climate change, the flexibility of stakeholders to develop shellfish mariculture in new and innovative ways may be required to maintain a viable industry (Diana et al., 2013).

As stated above, the effects of climate change on bivalve aquaculture are commonly explored from a biological perspective (e.g. Montalto et al., 2016; Shelmerdine et al., 2017). However, in terms of industry development it is also relevant to understand how key stakeholders of bivalve aquaculture ranging from farmers and regulators to academic researchers, understand and perceive the emerging relationship between bivalve aquaculture and climate change. Exploring stakeholder perceptions as they relate to aquaculture (e.g. Mazur and Curtis, 2006; Whitmarsh and Palmieri, 2009; Chu et al., 2010; Rivera et al., 2017), and climate change (e.g. Etkin and Ho, 2007; Spence et al., 2011; Jørgensen and Termansen, 2016) is an emerging topic in the literature. As mariculture relies on local conditions (e.g. water temperature), local knowledge within an industry has been recognized as important capital for aquaculture management (Diana et al., 2013). Perspectives, as they relate to stakeholder groups, are useful for creating successful and sustainable management of aquaculture (Bacher et al., 2014). Not understanding how stakeholders perceive management problems can lead to mismanaged resources, and decreased public trust (Buanes et al., 2004). Furthermore, understanding the perceptions of stakeholders can assist governments in creating policies/mitigation strategies that are accepted by the consulted groups (Sevaly, 2001; Bacher et al.,2014;). Although the body of social science literature on the topic of aquaculture and climate change is growing, often focus is placed on consumer and public groups (Altintzoglou et al., 2010; Fernández-Polanco and Luna, 2010; Freeman et al., 2012; Bacher et al., 2013). Recent studies (e.g. Bacher et al., 2014; Weitzman and Bailey, 2018) instead focus on key stakeholders within the industry, to gain an in-depth understanding of the perceptions of a select group.

Vulnerability of coastal resources and livelihoods to climate change is highly spatially dependent because of both natural processes (e.g. climate), and local governance of coastal resources (Handisyde et al., 2017). Bivalve aquaculture is an important economic contributor to Eastern Canadian provinces, in terms of revenue and job creation (DFO, 2012; NSDFA, 2015). PEI is consistently Canada's largest producer of blue mussels, by both value and mass (DFO, 2016). Additionally, NS has almost doubled its production value of bivalve aquaculture between 1995 and 2015 (DFO, 2016), and recently invested $2.8 million in aquaculture research and development (Government of Nova Scotia, 2017). Bivalve aquaculture contributes indirectly to the maritime economy through its provision of jobs in rural communities which tend to experience high levels of unemployment, and have few sources of year-round income (DFO, 2012; Statistics Canada, 2016). For example, in NS in 2014, almost half of all employees of the aquaculture industry were working in the bivalve aquaculture industry (NSDFA, 2015).

The expansion and success of this industry is contextualized by our changing climate, how it will impact the industry, and what mitigation strategies we employ to ameliorate those impacts. Engaging with stakeholders is important in the planning process, both for the establishment of new farms, and renewing leases for established farms. Many stakeholders (e.g. farmers, researchers) have firsthand experiences with the effects of climate change. The experiences and perceptions that stakeholders have will be important for determining the willingness of farmers to move farm locations, switch the species that they are cultivating, or to accept the risk of investing in an economic activity that could be affected by a changing climate. This topic is particularly relevant for maritime provinces of Canada such as NS and PEI; it has been recognized that sea surface temperatures in these regions are increasing at a rate higher than the global average (IPCC, 2013; Saba et al., 2016). This research aims to determine how stakeholders perceive the relationship between climate change and shellfish farming in NS and PEI. This relationship was explored with stakeholders from research, farming, and management backgrounds. This knowledge is useful for creating marine policy anticipating changes in bivalve farming in terms of adapting current sites (e.g. farming more thermally tolerant species) and new sites can be developed (e.g. in colder waters). This study used a mixed-method interview, Q methodology, to gain in-depth information on the perspectives of bivalve aquaculture stakeholders on the relationship between bivalve mariculture and climate change.

3.2 Methods

Q methodology, originating in the field of psychology, is a semi-quantitative interview method, which has recently been applied to studies of both aquaculture (Rudell and Miller, 2012; Bacher at al., 2014; Weitzman and Bailey, 2018), and climate change (Shackley and Deanwood, 2002). Q methodology is used for collecting data about diverse opinions on a single topic, as a way to assess the subjectivity of individuals (Brown, 1980; 1996). Results help to define thematic perspectives on a topic, and groups participants based on how similar their responses were (Cross, 2005). One of the strengths of Q methodology is that it does not require large sample sizes to produce significant results, as survey methods often do (Du Plessis, 2005; McKeown and Thomas, 2005). Q methodology aims for depth above breadth – it delves deeply into an individual’s perception of a topic, but makes no statements about a broader population (Cross, 2005). Similarly to traditional survey methods, participants are presented with a number of statements that they must place on a form of a Likert scale (Likert, 1932), however each position on the scale has a limited number of spaces (Figure 10) Participants must rank statements against each other, to prioritize their answers. Once the sort is completed, statistical analyses are applied to interpret the prevailing discourses (Schmolck, 2017).

3.2.1 Concourse survey and selecting statements

Q methodology follows a set of discreet steps, as outlined by Du Plessis (2005). To begin, a concourse survey is conducted to provide the researcher with a comprehensive understanding of all of the range of opinions that exist on the topic at hand. The concourse survey entails a thorough review of the relevant literature on the topic, and creating a list of all represented opinions. This was done by surveying both scientific and grey literature (e.g. peer-reviewed journal articles and newspaper articles, respectively), on the topic of climate change and bivalve aquaculture. Once the concourse survey had saturated all existing perceptions on the topic, repeated opinions were removed from the list of statements, so no views were represented more than once. Next, the statements were grouped into categories by relevance: 1. Climate change 2. Shellfish biology and climate change 3. Farming cost 4. Farming logistics and 5. Roles of government and policy. In order to work with a manageable number of statements, similar statements were combined. Statements were also balanced to reflect pro, neutral, and con opinions about the topic. There final grouping of statements is termed the Q-Sort, and for this study contained 40 statements (Table 1).

Table 1. Q-sort statements (n=40) used in the Q methodology interview, organized by corresponding categories.

Category	*Statement*
Climate Change	Warming of oceans has been accelerated in recent history
	There is no scientific consensus that climate change is occurring
Shellfish Biology and Climate Change	Warming ocean temperatures will not have an impact on the growth rate of shellfish species
	Ocean temperatures will not warm enough to impact shellfish distribution
	Warming ocean temperatures will not have an impact on the mortality rates of shellfish species
	Increased water temperatures have no relationship to the presence or abundance of invasive tunicates
	There is no relationship between warming ocean temperature and an increase in frequency of harmful algal blooms
	Increased water temperatures will not lengthen the growing season for shellfish
	Ocean acidification is having a negative impact on the survival of marine shellfish larvae
	Warmer water temperatures will cause an increase in the frequency of MSX outbreaks
	Climate change will be related to new kinds of disease outbreaks on shellfish farms
	Shorter/warmer winters will decrease mortality rates for some shellfish species
	Longer/warmer summers will increase mortality rates for some shellfish species
	Increased and intensified storms will cause increased run-off that may negatively impact shellfish
	Increased temperature will cause suppressed immune system function in some shellfish
	Climate change will alter the timing of food availability and food requirements for some shellfish species
	The effects of climate change on shellfish farming are too uncertain to accurately predict
Farming Costs	Climate change will increase the costs of shellfish farming
	Climate change will not impact the cost of operating a shellfish farm
	Climate change impacts will have no impact on the price of shellfish spat
	The market price of shellfish will be unaffected by warming ocean temperatures
	As water temperatures warm, the cost needed to produce shellfish will decrease
	Climate change will cause an increase in insurance costs for shellfish farming
Farming Logistics	Water temperatures warming beyond the tolerable ranges of shellfish species will cause the closure of currently operating farms in some areas
	Warmer water temperatures will permit the opening of new shellfish farms where previously the water was too cold to do so
	Emergency response plans to extreme storm events will be increasingly necessary in the coming years for shellfish farms
	It would be unlikely that a farm should move to a new location because of the effects of climate change
	Farm management plans should not consider the predicted effects of climate change
	Risk associated with climate change should be integrated into new lease proposals
Role of Policy and Government	Leasing applications should not have to consider the expected water temperature changes in the area
	The government should compensate shellfish farmers for their positive effects on the environment
	Adaptation measures for shellfish farms to deal with climate change conditions must be created at the bay scale
	When planning for new shellfish farms, it is not necessary to consider climate change
	The government should prioritize shellfish research on invasive tunicates
	The government should prioritize shellfish research on the ability of shellfish species to adapt to climate change conditions
	The government should prioritize shellfish research on shellfish disease risk in response to climate change
	The government should prioritize shellfish research on technology to prevent predation (i.e. sea ducks)
	The government should prioritize shellfish research on seed security and domestication
	The government should prioritize shellfish research on the risk of MSX and *Vibrio parahaemolytics*
	In light of climate change, the government should promote shellfish farming as an industry with positive environmental impacts

3.2.2 Survey participants

Participants were identified and selected for this reached based upon two criteria, 1. That they were stakeholders in the bivalve aquaculture industry in NS or PEI and 2. That they related to the bivalve aquaculture industry in diverse ways. Participants were grouped based on their stakeholder role into three categories: 1. Shellfish farmers (n=6) 2. Shellfish researchers (n=10) and 3. Marine planners (referred to as managers) (n=4). Although other stakeholder groups could be identified (e.g. consumers, retailers), this study aims to inform management/regulations, and they were therefore excluded. The number of participants (n=20) fits within the standard of the literature (e.g. Webler et al., 2009; McKeown and Thomas, 2013; Weitzman and Bailey, 2018).

3.2.3 Q methodology interviews

Q methodology interviews were conducted from June 2017 – September 2017, with the approval of the Dalhousie Research and Ethics Board (REB-2017-4125). These interviews were face-to-face and took place at locations chosen by the participants. To begin, participants read through the Q-sort statements (Table 1) which were randomly numbered and then printed out on individual index cards (Figure 10). Numbering ensured that all participants read the statements in the same order. After reading each card, the participant was encouraged to sort it into a pile based on whether or not they agreed, disagreed, or felt neutral about the statement. Next, each card in the Q-sort was further sorted onto a grid chart (Figure 10), which ranged from -4 (most disagree) to + 4 (most agree), where 0 represented neutrality. This grid is a forced "quasi-normal" distribution, where participants must rank statements against each other to determine the perspectives they feel the most strongly about. The grid contains exactly as many cells as Q-sort statements (Curry et al., 2013). The finalized placement of statements on the board for each participant is referred to as their Q-sort. Once the participant had finalized their Q-sort, there was an opportunity for him/her to discuss their choices with the researcher. This information contextualized the rationale of participants, and was used in interpretation of the results.

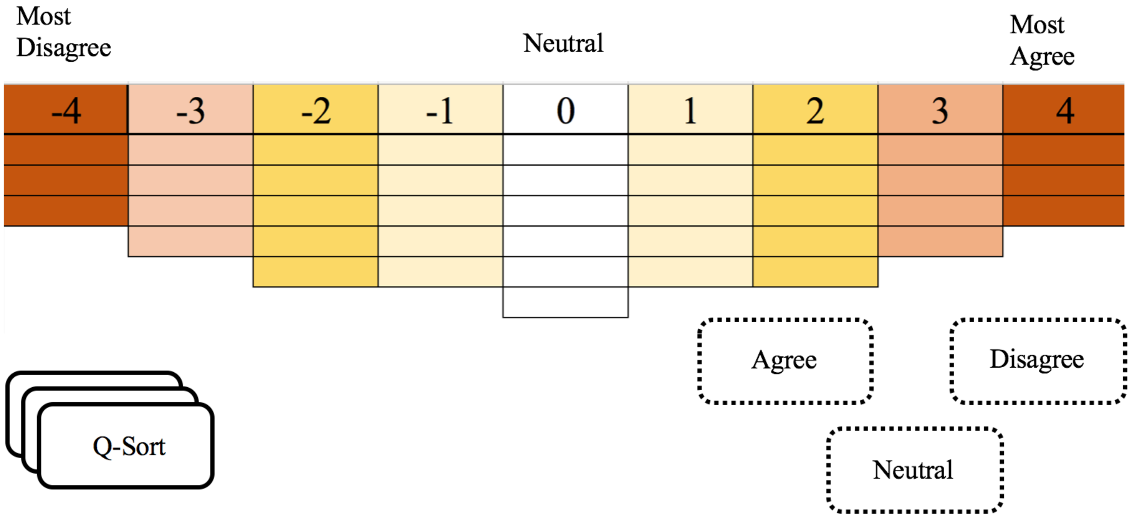


Figure 10. Q Methodology interview set-up. Participants read through the deck of Q-sort cards (n=40), dividing them into piles of "agree" "disagree" and "neutral." Piles were then further subdivided onto the matrix, based upon subjective rankings of the statements by the participant (Adapted from Weitzman and Bailey, 2018).

3.2.4 Statistical analyses

All Q-sorts were analyzed in the statistical software PQMethod 2.35 (Schmolck, 2017), to find patterns in responses both between and within stakeholder groups. The interview data were imported into the PQMethod software and a factor analysis was performed (Schmolck, 2017). First, to determine how correlated the Q-sorts were, a correlation matrix was created where a correlation of 1 represents two participants who sorted the statements identically. Next, a principal component analysis (PCA) was done to group similar Q-sorts together using the correlation matrix. These groups are statistically referred to as "factors", which represent groups of participants who had similar perspectives about climate change and shellfish farming (McKeown and Thomas, 2013). These factors (hereafter referred to as perspectives) were rotated using varimax orthogonal rotation to determine which perspectives explained most of the variance in the data. Although many perspectives can be produced, only those which are statistically relevant were chosen to be further analyzed. To meet these criteria, only perspectives which explained >10% of the variance in the data, and had eigenvalues of >2.00 (e.g. at least two Q-sorts correlated significantly with each other).

To begin the factor analysis an idealized Q-sort is created for each perspective, which was done using an averaged of all Q-sorts which loaded significantly for that perspective (Watts and Stenner, 2005). Using this idealized sort, another correlation matrix was made between each participant, and the perspective with which they were most closely correlated. To determine if the factor loadings for each participant were significant upon a perspective, the following equation was used:

$$s = 2.58 * (\frac{1}{\sqrt{N}})$$

Where N is the number of statements (Curry et al., 2013), producing an s of 0.4 at the 0.1 level of significance (Brown, 1980). This significance level was then increase to 0.5, a method used by other authors (e.g. Weitzman and Bailey, 2018), to create more stringent criteria. Perspectives were then analyzed qualitatively, to determine if the statements contained within each perspective were logical groupings (Weitzman and Bailey, 2018). Confounding Q-sorts were those in which participants loaded significantly either on multiple factors, or no factors.

3.3 Results

From the factor analysis of the Q-sorts three distinct perspectives emerged from the data. Cumulatively, these perceptions explained over 68% of the variance between the 20 Q-sorts (Table 2) (P1 = 32%, P2=11%, P3=25%). These perspectives indicated that all stakeholders interviewed can be grouped into three categories, each with distinct perceptions about bivalve aquaculture and climate change. All stakeholders grouped significantly into at least one perspective, and three stakeholders were grouped into two perspectives (i.e. confounding sorts) (Table 2). For each perspective, an "idealized sort" was created, indicating where each Q-statement would be sorted if the stakeholder fit perfectly with that perspective (Table 3). The following sections list areas of consensus between all stakeholders, and analyze each perspective, based upon its idealized sort, and the stakeholders who matched significantly with it. To ensure that only statements which stakeholders felt strongly about are being interpreted, only extreme statements (ranked -4, -3, +3, +4), and distinguishing statements (p-values < 0.05), will be discussed in relation to each factor. Interpretations of perspectives will be supported by statement numbers indicated in parentheses (e.g. (12)). Perspectives were given titles, interpreted from their idealized sorts, and are as follows: Perspective 1: The Theorist, Perspective 2: The Pragmatist, and Perspective 3: The Middle Ground

Table 2. Summary of Q-sort factor loadings. Values of -1 and +1 represent complete disagreement and complete agreement, respectively. Bold numbers represent significant values (factor loading coefficient > 0.5).

Stakeholder	**P1**	**P2**	**P3**
Perspective 1 (P1)			
Manager	**0.8304**	0.0710	0.2367
Manager	**0.7235**	0.2230	0.4708
Researcher	**0.7160**	-0.0161	0.3278
Researcher	**0.7231**	0.1714	0.4191
Researcher	**0.7337**	0.4011	0.2462
Researcher	**0.7388**	0.4077	0.1840
Researcher	**0.7515**	0.1855	0.3447
Researcher	**0.5420**	-0.0194	0.4169
Manager	**0.6853**	0.2506	0.4987
Perspective 2 (P2)			
Farmer	0.0684	**0.7689**	0.0800
Researcher	0.4541	**0.5254**	0.3088
Perspective 3 (P3)			
Farmer	0.3938	-0.2588	**0.5285**
Farmer	0.2625	0.4648	**0.6201**
Researcher	0.3656	0.1687	**0.7963**
Researcher	0.3779	0.2176	**0.6942**
Farmer	0.4275	0.2975	**0.6700**
Researcher	0.3067	0.2152	**0.7686**
Confounding Sorts			
Manager	**0.5316**	0.1237	**0.6188**
Farmer	**0.6636**	0.1979	**0.5226**
Farmer	0.1638	**0.5252**	**0.5669**
Explained Variance (%)	32	11	25
Total Defining Q-Sorts	9	2	6
Total Q-Sorts	11	3	10

*Table 3. Idealized sort for each perspective descried by each category of Q-statements. * = significant at p<0.05 **= significant at p<0.01*

Category	**Statement**	**P1**	**P2**	**P3**
Climate Change				
	25. Warming of oceans has been accelerated in recent history	4	1**	4
	10. There is no scientific consensus that climate change is occurring	-4	-2**	-4
Shellfish Biology and Climate Change				
	20. Warming ocean temperatures will not have an impact on the growth rate of shellfish species	-4	-2	-3
	26. Ocean temperatures will not warm enough to impact shellfish distribution	-3	0**	-3
	11. Warming ocean temperatures will not have an impact on the mortality rates of shellfish species	-4**	-2	-2
	30. Increased water temperatures have no relationship to the presence or abundance of invasive tunicates	-2*	-4	-4
	2. There is no relationship between warming ocean temperature and an increase in frequency of harmful algal blooms	-3	-4	-4
	38. Increased water temperatures will not lengthen the growing season for shellfish	-1	2**	-2
	37. Ocean acidification is having a negative impact on the survival of marine shellfish larvae	3	4	3
	18. Warmer water temperatures will cause an increase in the frequency of MSX outbreaks	0	2	1
	39. Climate change will be related to new kinds of disease outbreaks on shellfish farms	1	1	2
	36. Shorter/warmer winters will decrease mortality rates for some shellfish species	-1	2	0
	40. Longer/warmer summers will increase mortality rates for some shellfish species	1	-2**	1
	1.Increased and intensified storms will cause increased run-off that may negatively impact shellfish	2	3*	2
	35. Increased temperature will cause suppressed immune system function in some shellfish predict	1	-1**	1
	12. The effects of climate change on shellfish farming are too uncertain to accurately	0	-1	0
	9. Climate change will alter the timing of food availability and food requirements for some shellfish species	2	0*	3
Farming Costs				
	21. Climate change will increase the costs of shellfish farming	0	1	1
	27. Climate change will not impact the cost of operating a shellfish farm	-2	-3	-2
	29. Climate change impacts will have no impact on the price of shellfish spat	-2*	-4	-3
	4. The market price of shellfish will be unaffected by warming ocean temperatures	-2	0**	-2

8. As water temperatures warm, the cost needed to produce shellfish will decrease	-1*	-3	-3
17. Climate change will cause an increase in insurance costs for shellfish farming	0	-3**	0
Farming Logistics			
23. Water temperatures warming beyond the tolerable ranges of shellfish species will cause the closure of currently operating farms in some areas	4**	-1	0
13. Warmer water temperatures will permit the opening of new shellfish farms where previously the water was too cold to do so	3*	1	1
7. Emergency response plans to extreme storm events will be increasingly necessary in the coming years for shellfish farms	2	2	0*
28. It would be unlikely that a farm should move to a new location because of the effects of climate change	-1	0	-1
34. Farm management plans should not consider the predicted effects of climate change	-3	-3	-1*
22. Risk associated with climate change should be integrated into new lease proposals	2**	-2*	-1*
Role of Policy and Government			
33. Leasing applications should not have to consider the expected water temperature changes in the area	-2	-1	-1
14. The government should compensate shellfish farmers for their positive effects on the environment	-1	3**	0
6. Adaptation measures for shellfish farms to deal with climate change conditions must be created at the bay scale	-1	4**	-1**
16. When planning for new shellfish farms, it is not necessary to consider climate change	-3**	1**	-2**
32. The government should prioritize shellfish research on invasive tunicates	0*	0*	3**
31. The government should prioritize shellfish research on the ability of shellfish species to adapt to climate change conditions	4	2	3
24. The government should prioritize shellfish research on shellfish disease risk in response to climate change	3	-1**	2
15. The government should prioritize shellfish research on technology to prevent predation (i.e. sea ducks)	0**	3	2
5. The government should prioritize shellfish research on seed security and domestication	3	3	4
19. The government should prioritize shellfish research on the risk of MSX and *Vibrio parahaemolytics*	1*	0*	4**
3.In light of climate change, the government should promote shellfish farming as an industry with positive environmental impacts	1	4**	2

3.3.1 Areas of consensus

Statements that were not ranked significantly different between perspectives were not used as defining statements, and instead are termed areas of consensus. Eight statements were non-significant for all perspectives at $p>0.05$, meaning that these statements could not be used to define any perspective, because all groups felt similarly. All perspectives felt strongly that the government should prioritize shellfish research on both seed security (5), and the ability of shellfish to adapt to climate change (31). Furthermore, all perspectives agreed that warming water temperatures would impact shellfish growth rates (20). All perspectives thought that climate change would impact the cost of operating a farm (27), however the directionality of this impact was unclear (21). It was either unclear, or neutral, to all stakeholders whether or not farms would have to move to new locations because of climate change (28). Finally, the link between climate change and disease outbreaks was mostly unclear to all stakeholders (18,39) with statements about diseases being sorted into 0, +1, or +2 by all groups.

3.3.2 Perspective 1: The Theorist

The Theorist perspective was most concerned with long-term impacts of climate change on shellfish biology. To begin, this perspective strongly agrees that climate change is impacting ocean temperatures at an accelerated rate (25, 10). This group is most concerned about the effects of warming temperatures on shellfish biology, particularly increased growth and mortality rates (20, 26, 11). Furthermore, this was the only group that felt strongly that warming ocean temperatures had the potential to close currently operating farms in some regions (23), and also to create opportunities to open new farms in areas that were previously too cold to do so due to impacts on bivalve physiology (13). Furthermore, this perspective thought that the government should prioritize research on the ability of bivalves to adapt to climate change conditions (4). This group did not feel strongly about any statements related to price, however they did agree that climate change will alter the price of shellfish spat (29). Stakeholders in this group believed most strongly of all the perspectives that farm planning should consider the predicted effects of climate change (34, 22, 33, 16). Additionally, this group did not hold strong opinions on the potential to compensate farmers/promote shellfish farming for its positive environmental impacts (14, 3). This group also felt the most strongly that when planning for new sites, climate change should be considered (16). The most stakeholders were sorted into this perspective, six researchers and three managers.

3.3.3 Perspective 2: The Pragmatist

Stakeholders in the Pragmatist perspective seemed to perceive climate change as less of an immediate threat to shellfish farming, and therefore saw fewer opportunities for mitigation strategies. This group viewed climate change as occurring, but not as important an issue as other perspectives (25, 10). However, strong links were made between increased water temperature and invasive tunicates (30), as well as harmful algal blooms (2). This group also recognized the importance of storm runoff as having potential to negatively impact shellfish (1). Apart from acidification (37), this group felt the most neutral about the effects of climate change directly on bivalve physiology (e.g. 26, 38). This group felt the most strongly that climate change would impact the price of spat (29). Regarding the role of policy/government, this group agreed the most that shellfish farmers should be compensated for their positive effects on the environment (14), and similarly that the government should promote shellfish farming as an industry with positive environmental impacts (3). Stakeholders in this group did not believe that research should focus on disease risk and climate change (24), but instead should focus on seed security and domestication/ as well as predation mitigation (15,5). This was the only group that felt strongly that climate change would not increase the insurance costs for shellfish farming (17), and that adaptation measures for farms to deal with climate change should be created at the bay scale (6). Only two stakeholders were grouped in this perspective, one researcher and farmer.

3.3.4 Perspective 3: The Middle Ground

The Middle Ground perspective recognized diverse impacts of climate change on bivalve farming, however they prioritized the impacts differently than the first perspective. This group strongly agrees that climate change is impacting ocean temperatures at an accelerated rate (25, 10). Furthermore, this group saw the effects of increased water temperatures as having similar effects on shellfish biology (26, 37,9), as the first perspective, although they viewed them as slightly less important. Instead, this group more strongly agreed with the effect of warming water temperatures on the presence/abundance of invasive tunicates (4), harmful algal blooms (2), and the timing of food availability (9). In terms of cost, this group saw climate change as having potential to impact the price of spat (29), and that generally as water temperatures increase, the cost needed to produce shellfish will also increase (8). This group did not feel strongly about the need to integrate climate change risk/impacts into lease proposals or farm management plans (34, 16). Of all groups, this perspective felt that most strongly that the government should prioritize research on MSX and *Vbirio* (19), and the impact of invasive tunicates (32). Three farmers and three researchers were sorted into this perspective.

3.3.5 Confounding Sorts

Not all stakeholders were clearly sorted into one perspective (Table 2). These sorts are called confounding sorts, and represent stakeholders who shared perspectives of two or more groups. Three confounding sorts were identified, one manager and one farmer overlapping with perspective 1 and 3, and one farmer overlapping with perspective 2 and 3 (Table 2).

3. 4 Discussion

Stakeholder perspectives have long been viewed as important input in policy creation processes for aquaculture (Sevaly, 2001). Often, stakeholders hold diverse opinions which can be difficult to capture. Q methodology provides a way to explore how stakeholders group together, based not on occupation, but by their perceptions on a topic (Cross, 2005). This research explored how stakeholders understand the relationship between climate change and bivalve aquaculture in Nova Scotia and Prince Edward Island. As two provinces with extensive capacity for bivalve aquaculture (Stantec, 2009), the successful management of this industry should reduce uncertainties generated by climate change, and identified by stakeholders.

3.4.1 Manager-Farmer divide

The perspectives found from this research provide information about overlap (or lack thereof) between farmers, researchers, and managers. Notably, some perspectives lacked certain stakeholders, which may be indicative of topics most relevant to each perspective. Perspective 1 (The Theorist) contained the majority of stakeholders (n=11), however no farmers were sorted into this group. Furthermore, Perspective 1 placed the most emphasis on the importance of climate change impacts to shellfish biology. Perspective 3 (The Middle Ground) had the second largest grouping of stakeholders (n= 6) and notably no mangers. This group recognized the importance of both short- and long-term impacts of climate change on biology. Perspective 2 (The Pragmatist) contained just one farmer and one researcher, and of the three significant perspectives identified using Q methodology, viewed the impacts of climate change on shellfish biology as the least important. None of the farmers or managers interviewed shared perspectives on climate change and bivalve aquaculture. Furthermore, researchers tended to either share perspectives with managers or farmers, but not both.

These results suggest that there is a potential disconnect between the perceptions of managers and farmers, in terms of their understanding of the relationship between bivalve aquaculture and climate change. The discourse between resource users and policy-makers is particularly important for the development of an industry in times of increasing uncertainty (Kaiser and Stead, 2002). Bridging the knowledge gap between managers and farmers may require a knowledge broker, or a person/organization whose responsibility it is to mobilize information from researchers to user groups (Bandola-Gill and Lyall, 2017). Knowledge brokers often exist at the boundaries of organizations, for example, where policy ends and farming begins (MacDonald et al., 2016). Although knowledge brokers cannot be excepted to solve all of the problems at this interface, they have been shown to assist with increasing trust between two ideologically divided groups (MacDonald et al., 2016; Bandola-Gill and Lyall, 2017). This study shows that researchers (governmental, academic, and industrial) have the potential to act as knowledge brokers between managers and farmers.

3.4.2 Climate change and shellfish biology

Stakeholders generally agreed with the mounting evidence surrounding climate change, and its effects on shellfish biology. All stakeholders acknowledged that the processes of climate change are important for any further exploration of its effect on shellfish farming. All stakeholders recognized that changing water temperatures will impact shellfish growth rates (20), and the impacts of ocean acidification on spat survival (37). Only the two stakeholders sorted into Perspective 2 (The Pragmatist) felt neutrally, or slightly supportive of these ideas. What divided stakeholders on these issues was not recognizing processes, but to what extent they were important. Perspective 1 ranked effects on shellfish biology as highest, Perspective 3 in the middle, and Perspective 2 felt the least strongly about these statements in general. For example, the idea that warming ocean temperatures would warm enough to impact shellfish distribution (26), Perspective 2 felt neutrally about, whereas the other two perspectives strongly supported. Variable ranking may indicate that some stakeholders place priority on immediate and observable impacts, as opposed to long-term impacts. Interestingly, managers sorted primarily into Perspective 1, representing longer-term effects, such as temperatures related impacts to shellfish mortality and growth rates (20, 11). Contrastingly, farmers who mostly aligned with Perspective 2 and 3, placing a greater concern on immediate impacts, such as harmful algal blooms and tunicate abundance (30, 2). This people-policy gap is not uncommon for aquaculture (Jones et al., 1999; Krause et al., 2015), and is another area that could benefit from a knowledge broker.

3.4.3 Stakeholder uncertainty and resulting risk

Statements which were sorted similarly by all stakeholders into low rankings (i.e -2 -1 0 +1 +2), may be interpreted as areas of uncertainty. These were statements which stakeholders either did not feel strongly about, or felt they did not have enough information to make an informed decision about the relationship stated on the card (Weitzman and Bailey, 2017; Cross, 2005). For example, all perspectives ranked the statement “Warmer water temperatures will cause an increase in the frequency of MSX outbreaks” (18) either as 0, +1, or +2 (Table 3). MSX, a disease which *C. virginica* is susceptible to, has been identified as a research priority for the Department of Fisheries and Oceans Canada, and has as well been discussed in the media as a major concern for farmers (Charlton, 2017). It is therefore unlikely that the median ranking of this statement represents neutrality on the subject, but an uncertainty about the relationship between MSX and temperature (18).

Other statements which may indicate uncertainty from stakeholders primarily related to either farming practices, planning, or cost. In contrast to the impacts of climate change on shellfish biology, these relationships appear much less clear. Although most stakeholders believed that climate change will increase the price of spat (29), it was not clear to any stakeholders if climate change would impact the market price of shellfish (4), or if climate change would impact the price of farming (21). Regarding farm planning, most researchers and managers felt strongly that climate change has the capability to both close currently operating farms (23), and also create opportunities to open new farms (13), however no farmers supported these notions. Furthermore, no stakeholders were certain about the possibility of moving a currently operating farm to avoid the impacts of climate change (28). No stakeholders held strong opinions about the need to integrate potential risk associated with climate change (22), or expected water temperature changes (33) into lease proposals. As previously mentioned, the neutral ranking of these statements may indicate that stakeholders either do not believe them to be important topics, or that they do not have sufficient knowledge to rank the statement. If the latter is true, it may indicate stakeholder uncertainty, which can pose risks to the shellfish farming industry.

3.4.4 Managing the effects of climate change on aquaculture

It has been recognized that global aquaculture industries will be impacted by climate change, and that those impacts will be specific to both location, culture method, and culture species (DeSilva and Soto, 2009; Doubleday, 2013). By employing a set of synergistic management tools, it will be possible to reduce uncertainties and create a more resilient industry (DeSilva and Soto, 2009). By reducing uncertainty, these tools aim to decrease the risk that stakeholders incur by investing in an industry expected to be impacted by climate change (Shelton, 2014). The following paragraphs outline management tools that can be used to manage aquaculture in the context of climate change. These management tools: ecosystem approach to aquaculture, required insurance, and adaptive management, are recognized on an international level by the Food and Agricultural Organization (DeSilva and Soto, 2009), and on a national level in Canada by the Department of Fisheries and Oceans Canada (DFO, 2009), however provincial legislation also plays a large role in aquaculture management in Canada.

The ecosystem approach to aquaculture (EAA) emphasizes the importance of integrating aquaculture practices into their surrounding ecosystem to support sustainable practices between ecological and social systems (Soto et al., 2008). EAA requires the input of stakeholder experiences and attitudes to manage aquaculture (De Silva and Soto, 2009). EAA also emphasizes the need to manage resources on a waterbody scale, which was identified by Perspective 2 as being important for planning for climate change impacts (6). Managing at this scale would promote effective use of management programs such as biosecurity, and water monitoring at clustered levels, which may be beneficial for small-scale farming activities (De Silva and Soto, 2009). The overall concern that stakeholders indicated for the effects of climate change on shellfish biology, namely growth rate (20) and distribution (26), would be encapsulated by EAA by linking climate change drivers to ecological impacts. This is particularly relevant for concerns relating to ocean acidification and spat survival (37), and shellfish mortality rates (11). EAA would also address the possibility that farmers and researchers raised about opening farms in new areas (13), and closing currently operating farms (23), due to warming ocean temperatures. In 2009, DFO referenced ecosystem-based management and integrated management of aquaculture as two of the defining principles of aquaculture management in Canada (DFO, 2009). Despite this, climate change is not mentioned explicitly as a part of either of these management approaches.

Insurance, or purchasing financial compensation to prepare for potential loss, has long been used as a way to manage risk. Recently, it has been suggested as a mechanism by which risks incurred by aquaculturists can be mitigated (DeSilva and Soto, 2009). The risk for damage to/loss of property may become intensified in the future, in association with increased storm frequency and intensity predicted as a result of climate change (Lemmen et al., 2016). Interviewed stakeholders acknowledge the possibility of storms becoming more frequent and intense (1, 7), however these statements were not ranked above a +2 for any perspective. Several stakeholders mentioned during the interview that insurance often was not available for shellfish farming. Interestingly, the majority of stakeholders (Perspectives 1 and 3), ranked the statement about how climate change will impact insurance costs for shellfish farming (17) at zero, indicating they did not know how it would be impacted, or that it was not an important consideration. Currently in PEI and NS, insurance is not mandatory, or often available for shellfish farmers (Tremblay, pers. comm.). In the past, severe storms such as the category 2 hurricane that made landfall in NS in 2003 have caused serious setbacks for shellfish farmers (Purdy, pers. comm). With the prediction that these kind of storms may become more frequent (Lemmen et al., 2016), and that prediction being supported by stakeholders (1, 7), insurance could protect small scale farmers from incurring the burden of loss. This adaptive response to climate change would limit bankruptcies in the aquaculture industry, and help to minimize impacts to livelihoods (De Silva and Soto, 2009).

Adaptive management is a tool applied to the management of natural resources which uses cyclical decision making in the face of uncertainty, to effectively improve management techniques over time (Holling, 1978). Adaptive management is particularly well suited to deal with natural systems impacted by climate change (Peterson et al., 1997), as the changes experienced by these systems have the potential to impact natural variability (Shelton, 2014). An iterative process, adaptive management is also able to address both short- and long-term considerations. This research identified a temporal divide between how stakeholders consider the impacts of climate change. Generally, people agreed that impacts would occur, but differences between perspectives reflected that some stakeholders were more concerned with more immediate effects, and others on the long-term. As discussed, Perspective 2 placed emphasis on observable impacts to shellfish farming such as tunicate abundance (30) and harmful algal blooms (2), whereas Perspective 1 showed greater concern for the future impacts of temperature change on shellfish growth (20). The concern for impacts of climate change to shellfish farming over a variable timescale indicates the usefulness for adaptive management. This temporal mismatch is often observed at the science-policy interface (Jones et al., 1999), and further explains the divide between resource managers and resource users (e.g. the farmer-manager divide observed in this study).

Adaptive management, and in particular monitoring, could help to prepare the industry to face climate change (Shelton, 2014). As climate change will have impacts previously unexperienced by both resources users, and affected species, monitoring will assist with recording when and what those effects are (Shelton, 2014). Information from monitoring programs, observations from farmers, and knowledge generated by researchers could inform adaptive management and ultimately policy decisions that benefit industry. For example, increased mortality rates of mussels have been observed by farmers in PEI in occurrence with prolonged high water temperatures, researchers are currently exploring the effect of temperature on bivalve performance (Myrand et al., 2000) and stakeholders in this study identified this relationship as a concern (11). Anticipating summer heatwaves and effectively mobilizing this knowledge into an adaptive management framework is key to bridging the science-policy gap towards effective regulations. Potentially, impacts from summer heatwaves could be mitigated by 1. Growing mussels and cooler water (23) or 2. Amending leases so farmers can cultivate more thermally tolerant species in their lease area. DFO makes reference to adaptive management as a tool that should guide the development of Canada’s aquaculture development (DFO, 2009) however makes no mention of how this framework should be specifically applied, or how its particular relevance of climate change. To address this, an adaptive policy framework specific to aquaculture, which acknowledges the unique uncertainties generated by climate change should be created.

3.4.5 Conclusions

Stakeholders of the bivalve aquaculture industry in Nova Scotia and Prince Edward Island do not feel unanimously about the expected effects of climate change. Three main perspectives were found that defined all stakeholders, and although these perspectives were all defined by more than one stakeholder group, no farmers and managers were found to share similar perspectives, indicating a significant gap between these boundary groups. This disconnect between managers and farmers has the potential to be bridged by researchers, who shared perspectives with both groups of stakeholders. Although stakeholders recognized the link between climate change and biological impacts for shellfish, they were generally less certain (or concerned) with the impacts of climate change on farming costs, planning, and practices. As these uncertainties generate risk, government policy should make use of proposed management frameworks such as the ecosystem approach to aquaculture and adaptive management, to incorporate the predicted impacts of climate change, and how this industry can prepare to respond. The nature of these frameworks demand a higher level of integration between social, ecological, and economic systems, and provide potential to use research as a way to integrate farmers into the management process. This research shows the need for policy to consider the impacts of climate change on shellfish farming, both in the short- and long-term, so that farmers can prepare for these impacts.

Chapter 4: Conclusions and recommendations

The projected and perceived impacts of climate change on bivalve aquaculture in Nova Scotia and Prince Edward Island creates uncertainty about the future viability of this industry. Observable effects of climate change, primarily warming sea surface temperatures, have been recorded over the past several decades, and are expected to continue to do so in coastal areas of Nova Scotia and Prince Edward Island. As these changes are predictable, their impacts could be anticipated and mitigated by adaptive management plans. This study demonstrates the need for both scientific and social research to be integrated into management solutions, to reduce risk and uncertainty generated by climate change, and to create a more resilient industry.

This research shows the potential use of coupled climate-bioenergetic models to assist with site- and species-selection in the coming decades, under climate change conditions. As sea surface temperatures are expected to warm differentially geographically, choosing which species are cultivated where will become increasingly important to maximize benefits and minimize risks posed by climate change. Thermal tolerances of specific bivalve species should be considered as ocean temperature continues to rise, and offshore aquaculture could be considered as a specific mitigation strategy to avoid thermal stress. Recognizing the importance of stakeholder input in management decisions, this research also analyzed the perspectives of farmers, researchers, and managers on the relationship between climate change and bivalve aquaculture. These perspectives indicated the need for a higher level of integration both between stakeholder groups, namely farmers and managers, and management tools and climate change. Increased understanding between farmers and managers could be achieved through the use of researchers as knowledge brokers, collaborating and communicating with both groups. Making use of management tools, such as the ecosystem approach to aquaculture, required insurance, and adaptive management, governmental bodies on both a federal and provincial level can act as channels by which uncertainty generated by climate change can be further reduced.

The results of this study can be used to inform broader management activities such as marine spatial planning (MSP). Coastal spaces in Nova Scotia and Prince Edward Island are increasingly subject to multiple and competing uses, creating a need to spatially plan activities like aquaculture. Exploring the effects of climate change on shellfish farming from various disciplines in spatially explicit ways, this study matches the integrated nature of MSP exercises. Preparing for the longevity of currently operating shellfish farms, as well as the creation of new ones, modelling techniques such as those used in this study, can be used to anticipate changes to cultured species, and stakeholder perceptions can be applied to further adapt to these changes.

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Appendices

Appendix i: Equations used in the Dynamic Energy Budget (DEB) model.

EQUATION	TERMS AND PARAMETERS	
$\frac{dE}{dt} = \dot{p}_A - \dot{p}_C$	E	Reserve (J)
	$\dot{p}_A$	assimilation rate (J d^{-1})
	$\dot{p}_C$	mobilization rate of reserve energy (J d^{-1})
$\dot{p}_A = \left\{\dot{p}_{Am}\right\} T_D f V^{2/3}$	$\left\{\dot{p}_{Am}\right\}$	maximum surface-area-specific assimilation rate (J cm^{-2} d^{-1})
	f	Functional response
	V	structural volume (cm^3)
	T_D	Arrhenius temperature function
$\dot{P}_C = \frac{[E]}{[E_G]+K[E]}\left(\frac{[E_G]\{\dot{P}_{AM}\}\boldsymbol{T_D}V^{2/3}}{[E_M]} + \dot{P}_M\right)$	κ	fraction of utilized energy to somatic maintenance and growth
	$[E_G]$	volume-specific costs for structure (J cm^{-3})
	$[E_m]$	maximum energy density (J cm^{-3})
$\dot{P}_M = [\dot{P}_M] T_D \boldsymbol{V}$	$\dot{p}_M$	maintenance rate (J d^{-1})
	$\left[\dot{p}_M\right]$	volume-specific maintenance costs (J cm^{-3} d^{-1})
$\frac{dV}{dt} = \left(\kappa\ \dot{p}_C - \dot{p}_M\right) / \left[E_G\right]$		
$\frac{dE_R}{dt} = (1-\kappa)\dot{p}_C - \left(\frac{1-\kappa}{\kappa}\right) \cdot V \cdot \left[\dot{p}_M\right]$	E_R	energy allocated to reproduction buffer (J)
$\frac{dE_R}{dt} = \kappa\ \dot{p}_C - \dot{p}_M \mid \kappa\ \dot{p}_C - \dot{p}_M < 0$		reproduction buffer dynamics when energy storage is too low
$\boldsymbol{L} = \frac{\boldsymbol{V^{1/3}}}{\boldsymbol{\delta_M}}$	L	filter-feeder length (cm)
	δ_M	dimensionless shape coefficient

Appendix ii: Standard DEB parameters for *Crassostrea virginica* (From Lavaud et al. 2017) and *Mytilus edulis* (from Rosland et al. 2009[1] and Saraiva et al. 2011[2]).

PARAMETER	**SYMBOL**	**UNIT**	***C. VIRGINICA***	***M. EDULIS***
SHAPE COEFFICIENT	δ_V	-	0.2	0.2[1]
ARRHENIUS TEMPERATURE	T_A	K	6700	5800[1]
REFERENCE TEMPERATURE	T_1	K	293	293
MAX. SURF. AREA-SPECIFIC INGESTION RATE	$\{\dot{p}_{Xm}\}$	J cm^{-2} d^{-1}	249.5	273[1]
ASSIMILATION EFFICIENCY	κ_A	-	0.75	0.75[1]
VOLUME-SPECIFIC COSTS FOR GROWTH	$[E_G]$	J cm^{-3}	5230	5993[2]
MAXIMUM STORAGE DENSITY	$[E_m]$	J cm^{-3}	5420	1438[2]
VOLUME-SPECIFIC MAINTENANCE COSTS	$[\dot{p}_M]$	J cm^{-3} d^{-1}	38	27.8[1]
FRACTION OF P_C TO MAINTENANCE AND GROWTH	κ	-	0.82	0.45[1]
% OF REPRODUCTION BUFFER FIXED IN EGGS	κ_R	-	0.95	0.9[1]
INITIAL PERCENTAGE OF MASS IN E_R	κ_{IM}	-	0.1	0.1
STRUCTURAL DRY WEIGHT : WET WEIGHT	DW:WW	-		0.12

Appendix iii Review of observed growth rates of *Mytilus edulis* and *Crassostrea virginica* used to validate the DEB model output

SPECIES	GROWTH RATE (CM/DAY)	LOCATION	STUDY
MYTILUS EDULIS	0.00481	Bedford Basin (NS)	Freeman and Dickie, 1979
	0.00128	St. Peter's Bay (PEI)	Guyondet et al., 2015
	0.00167	New London Bay (PEI)	Lauzon-Guay et al., 2006
	0.00329	Tracadie Bay (PEI)	Waite et al., 2005
	0.00325	Lunenburg (NS)	Mallet and Carver, 1995
	0.00158	St Peter's Bay (PEI)	Lauzon-Guay 2001 (dissertation)
	0.00265 ± 0.00137	**Average**	
	0.00233 ± 3.65e-05	PEI (Northumberland Strait)	This study
CRASSOSTREA VIRGINICA	0.003	Caraquet (NB)	Sonier et al., 2011
	0.005	Cocagne (NB)	Sonier et al., 2011
	0.003	Ellerslie (PEI	Sonier et al., 2011
	0.004	Wedgeport (NS)	Sonier et al., 2011
	0.00266	Ellerslie (PEI)	Comeau et al., 2008
	0.00274	Malpeque (PEI)	Comeau et al., 2008
	0.00340 ±0.00092	**Average**	
	0.00198 ± 5.11e-05	PEI (Northumberland Strait)	This study