First-Hand Knowledge of BC Ocean Change: Oyster Farmers' Experiences of Environmental Change and Oyster Die-Off Events

by

Evie Morin

BA Geography (Honors), Trinity Western University, 2017

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management

in the
School of Resource & Environmental Management
Faculty of Environment

SIMON FRASER UNIVERSITY
Summer 2020

Approval

Name:	**Evie Morin**
Degree:	**Master of Resource Management**
Project number:	
Title:	**First-Hand Knowledge of BC Ocean Change: Oyster Farmers' Experiences of Environmental Change and Oyster Die-Off Events**
Examining Committee:	**Chair:** Eleanor Simpson Doctor of Resource Management Candidate
	Karen Kohfeld Senior Supervisor Professor
	Debby Ianson Supervisor Adjunct Assistant Professor
	Jennifer Silver Supervisor Associate Professor
Date Defended/Approved:	July 27, 2020

Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

or has conducted the research

c. as a co-investigator, collaborator, or research assistant in a research project approved in advance.

A copy of the approval letter has been filed with the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Simon Fraser University Library
Burnaby, British Columbia, Canada

Update Spring 2016

Abstract

Recent studies call for transdisciplinary research to address the consequences of anthropogenic change on human-environment systems, like the impact of ocean acidification (OA) on oyster aquaculture. I surveyed oyster farmers in coastal British Columbia, Canada, about their first-hand experiences of ocean change. Farmers reported that oyster mortality (die-off events) is one of many challenges they face and is likely related to several interacting environmental factors, including water temperature and oyster food, particularly in 2016. I examined temperature, productivity, and carbonate chemistry conditions from 2013 to 2017 using available observations and the Salish Sea model, to understand poor oyster growing conditions in 2016. While temperatures were relatively high and chlorophyll relatively low during the 2016 spring bloom, carbonate conditions were relatively good, suggesting OA was not a key driver of difficult oyster growing conditions. This work provides a novel example of using local knowledge to better inform scientific investigation and adaptation to environmental change.

Keywords: Oyster aquaculture; ocean change; local knowledge; oceanographic hindcast; transdisciplinary research

Table of Contents

List of Tables

List of Figures

1. Introduction

Recent academic literature calls for transdisciplinary research – studies led by academic and non-academic actors across multiple disciplines and expertise – to address challenges in human-environmental systems (E. Allen, Kruger, Leung, & Stephens, 2013; Carmen Lemos, Kirchhoff, & Ramprasad, 2012; DeLorme, Kidwell, Hagen, & Stephens, 2016; Phillipson, Lowe, Proctor, & Ruto, 2012). Coastal communities are human-environmental systems that are especially vulnerable to environmental changes and need to adapt to multiple stressors augmented by climate change (Wong et al., 2015). The prioritization of those stressors depends on the industry and location.

Multiple environmental factors are changing globally as a result of anthropogenic carbon emissions and is likely to amplify in the future (Gruber, 2011; IPCC, 2018). As atmospheric CO_2 concentrations rise, global average temperatures also increase, and studies project that many regions will face more extreme weather events in the future (Kharin et al., 2018; Li et al., 2019; Trenberth, Fasullo, & Shepherd, 2015). As the ocean absorbs CO_2 from the atmosphere and other localized coastal carbon sources, ocean acidification (OA) is expected to increase, a process that lowers the ocean's pH and saturation of minerals shell-forming organisms use to build their shells (Haigh, Ianson, Holt, Neate, & Edwards, 2015; Moore-Maley, Allen, & Ianson, 2016; Raven et al., 2005; Waldbusser & Salisbury, 2013). Moreover, marine heatwaves (MHW), coherent areas of extreme warm sea surface temperature (SST) persisting for days to months, are expected to become more common (Frölicher, Fischer, & Gruber, 2018; Frölicher & Laufkötter, 2018). These environmental changes have profound implications for marine ecosystems, including altering phytoplankton species composition and abundance (Haigh et al., 2015), increasing the frequency and severity of harmful algal blooms (Hallegraeff, 2010), and heightening species' vulnerability to bacteria, phytoplankton, and viruses (Fuhrmann, Richard, Quéré, Petton, & Pernet, 2019; Green et al., 2019; Hershberger, 2020). These fundamental changes have far-reaching implications for other environmental factors, which, though currently poorly understood, will affect human-environmental systems, such as oyster aquaculture industries.

This particular case study focuses on British Columbia's (BC) oyster industry and the challenges they are facing in the context of global environmental changes. Throughout history and around the globe, oysters have provided a culturally significant food (Botta, Asche, Borsum, & Camp, 2020; Fedje, Mackie, Wigen, Mackie, & Lake, 2005; Silver, 2014), as well as other non-market-services (Cooley, Lucey, Kite-Powell, & Doney, 2012). Oyster aquaculture, or farming, has developed into an important industry for many coastal communities and has been rapidly increasing on a global scale through the 1900's (Botta et al., 2020). Today, as global food demand increases and fisheries are pushed beyond capacity, oyster aquaculture has been noted as an economically and environmentally viable means to address food insecurity (Holden et al., 2019). However, recent declines in oysters suggest a threat to the industry worldwide (Botta et al., 2020).

In BC, despite favorable biophysical conditions, the wholesale value of the oyster aquaculture industry has reached only a fraction of its estimated potential (Holden et al., 2019). Local media suggests industry-threatening oyster die-off events, short time periods over which a large proportion of a farm's oysters die, linked to OA have occurred since the early 2000's and are at the root of this challenge (Hume, 2014; Luymes, 2015; Owsianik, 2012). Laboratory experiments and previous case studies in Washington have also shown that oysters are sensitive to OA (Barton, Hales, Waldbusser, Langdon, & Feely, 2012; Haigh et al., 2015; Waldbusser & Salisbury, 2013). However, OA as a key driver of recent oyster die-off events in BC has yet to be confirmed by research, and by assuming that OA is causing oyster mortality in BC, research may have overlooked other factors that may contribute to die-off events.

As transdisciplinary research calls for engagement of non-academic experts at the start of the project to inform research questions, this project represents a novel case study of using local knowledge (via survey) to inform investigations into how ocean change is impacting the regionally important oyster industry on the Pacific Coast of Canada. In this study, I examine a known problem within the scientific community, learn from industry stakeholders' local knowledge to further define the problem, and use their experience to develop questions and understand the mechanisms behind the problem. Local knowledge is a unique source of information because many oyster farmers have a history of interaction with the environment surrounding their tenures and may therefore have a deep understanding of surrounding ecological systems and direct experiences with regional changes and oyster mortality (Reyes-García et al., 2016). Local knowledge can incorporate direct and secondary impacts of change, integrating climate change with social and environmental consequences (Savo et al., 2016). Thus, attached to place, oyster farmers' local knowledge may help distinguish what environmental factors are related to oyster die-off events in BC.

The objective of this transdisciplinary research is to provide insight into BC's oyster aquaculture industry and the challenges farmers face. This study is part of a broader project, the MEOPAR Integration Coastal Acidification Program, which aimed to combine industry stakeholders and expertise in physical, chemical, and biological sciences. The project was originally designed to address the problems of OA, and this particular survey was designed to place the problem of OA within the context of the broader challenges faced by BC's oyster industry. I aim to better understand all challenges faced by BC's oyster industry by surveying oyster farmers about their first-hand experience of oyster aquaculture. I then document environmental changes observed by farmers and how important oyster farmers felt these changes were to their industry. Finally, I use this understanding of industry challenges to develop questions about what environmental factors may be related to poor oyster growing conditions and test these questions by querying a high resolution local model, SalishSeaCast oceanographic hindcast (https://salishsea.eos.ubc.ca/nemo/; Soontiens and Allen, 2017; Jarníková, Ianson, Allen, Shao, & Olson, 2020 in prep; Olson, Allen, Do, Dunphy, & Ianson, 2020 in press).

1.1. Study Area

This research focuses on the Pacific coast of Canada in BC (Appendix B). BC is thought to be biophysically ideal for oyster growth with nutrient rich, cold, and clean waters, abundant coves, and thousands of kilometers of coastline (Holden et al., 2019; Silver, 2014). Not only is BC Canada's largest producer of oysters, growing approximately 60 percent of Canada's annual average of 25,800 tonnes of oysters over the last five years, but also Canada's only producer of the highly demanded *C. gigas* (Government of Canada, 2017). *C. gigas*, however, was newly introduced to the Pacific coast of Canada in the early 1900's. Cool ocean temperatures relative to the species' breeding range limit natural reproduction, so the industry is dependent on obtaining oyster "seed," or larvae, from local and international hatcheries (Banas, Hickey, Newton, & Ruesink, 2007; Barton et al., 2012; Holden et al., 2019). Farmers purchase seed at various sizes and outplant the larvae in trays and bags on deep water longlines or rafts, or grow their product directly on the beach to feed on wild phytoplankton (Holden et al., 2019; Lavaud, La Peyre, Casas, Bacher, & La Peyre, 2017); thus changes in physical, chemical and biological conditions are directly relevant to oyster growers.

1.2. Physical ocean conditions from 2013 to 2017

The Pacific coast of BC is a complex coastal system characterized by acidic conditions. With 27,000 km of coastline, BC has an outer coast exposed to the North Pacific Ocean on the west coast of Vancouver Island, the Queen Charlotte Sound, and the west coast of Haida Gwaii, and an inner coast between the islands (Vancouver Island and Haida Gwaii) and the mainland (Figure 1). Organic matter naturally accumulates and remineralizes into carbon in North Pacific subsurface waters, which upwell seasonally and lead to low pH conditions on BC's outer coast (Haigh et al., 2015; Moore-Maley et al., 2016). Channeled through the Juan de Fuca Strait, these acidified waters enter the Strait of Georgia (SoG), a complex coastal system that is notably acidic and experiences strong seasonality due to Fraser River freshet-driven circulation and large-scale wind patterns (Ianson, Allen, Moore-Maley, Johannessen, & Macdonald, 2016). Bound by physically restrictive channels and sills between islands in the north and south with intense mixing, upwelled "acidified" water has long residence times in the SoG, leading to even more carbon enriched conditions than the outer coast (ibid.).

My analysis largely focuses on ocean conditions between 2013 and 2017, which represented the five full growing seasons directly preceding the survey of oyster farmers. Several changes in physical ocean conditions of BC's outer coast and the SoG are recorded over this 5-year period. During this 5-year period, the region experienced a MHW, colloquially known as a the "Blob," a 100-meter-deep pool of exceptionally warm, low nutrient water that reached coastal BC in 2014 (Bond, Cronin, Freeland, & Mantua, 2015; Chandler, King, & Perry, 2015). By 2015, temperatures associated with the heat anomaly rose to record levels in the SoG and persisted into 2016, when the Blob dissipated substantially to near normal temperature levels (Bond et al., 2015; Chandler, King, & Boldt, 2017; Freeland & Ross, 2019). Simultaneously, El Niño conditions began in 2015, further contributing to warm ocean temperatures into 2016, which transitioned to La Niña conditions by the latter half of the year (Chandler, King, & Perry, 2016). Physical ocean conditions normalized in 2017 (Chandler, King, & Boldt, 2018).

Phytoplankton compositions were influenced by these temperature dynamics. Increased heat amplified stratification, which consequentially reduced nutrient vertical transport and renewal in the winter (Chandler et al., 2016). In 2015, the spring bloom occurred early in the year, which increased pH and aragonite saturation (Ω_{Ar}) (Mahara, Pakhomov, Jackson, & Hunt, 2019). By 2016, phytoplankton compositions returned to a more normal distribution (Chandler et al., 2017). However, on the outer coast there were unusual abundances of gelatinous plankton species, including *Pyrosoma atlanticum*, a pelagic

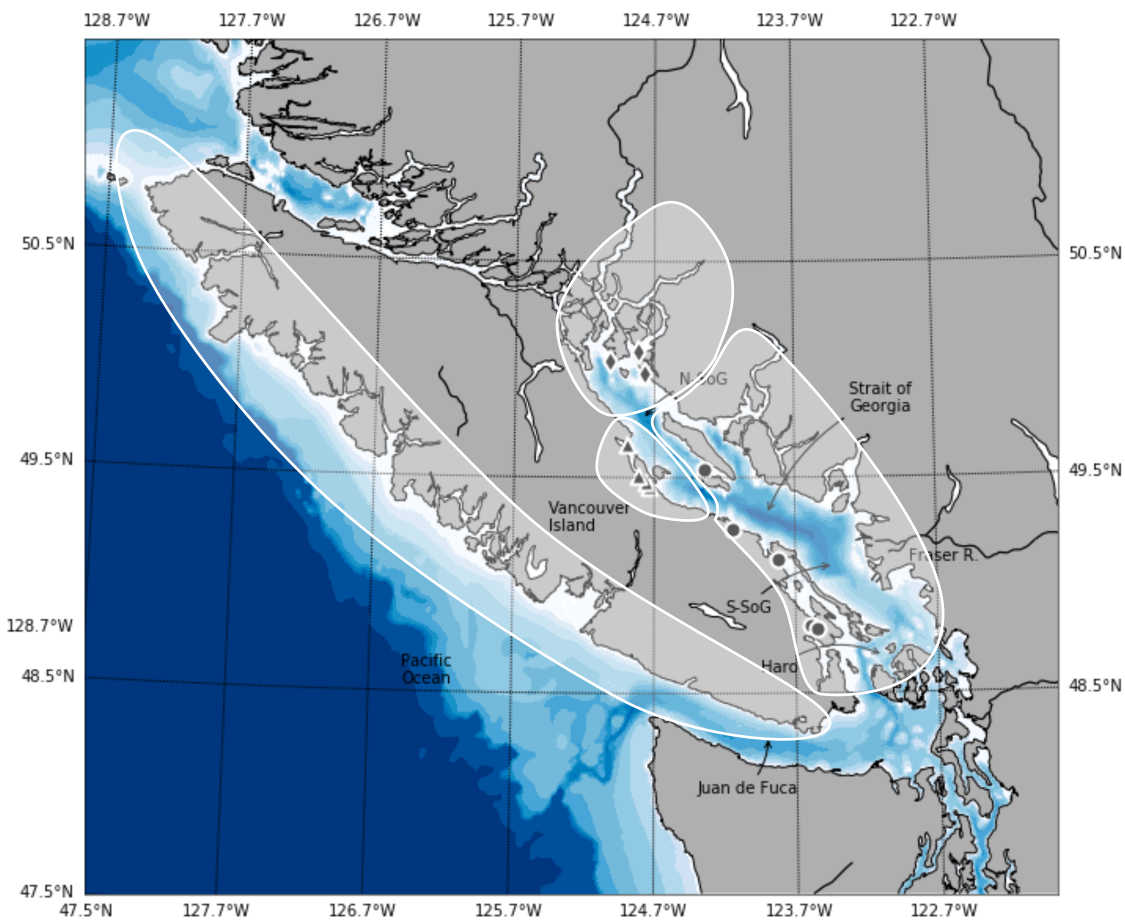


Figure 1. Study area.

The 4 sub-regions are outlined in white within the study region: coastal British Columbia. The points indicate where data from the SalishSeaCast was extracted (Diamond = the Discovery Islands, triangle = Baynes Sound, and circle = the Southern SoG).

tunicate common in warm open ocean waters in the tropics (Brodeur et al., 2018). In the SoG there were unusual coccolithophorid blooms (Chandler et al., 2017). In 2017, the spring bloom was short in duration and moderate in magnitude relative to historical records (Chandler et al., 2017).

1.3. Chemical and physical properties of the study regions

To examine coastal BC in more detail, I divided the study area into four regions based on chemical and physical properties outlined above (Figure 1).

The Southern SoG: the Gulf Islands and Fraser River estuary. The Southern SoG is highly stratified, characterized by freshwater inputs from the Fraser River plume (Ianson, 2013; LeBlond, 1983; Moore-Maley et al., 2016). The surface pH and saturation state are highly variable and have strong seasonal cycles, with higher pH during summer resulting from phytoplankton growth and low pH in winter when light limits phytoplankton growth and increased wind and decreased river flow allows strong mixing (Moore-Maley et al., 2016).

Baynes Sound: a narrow trough between Vancouver Island and Denman Island. Baynes Sound experiences regular high tidal flushing due to freshwater inputs from the Comox Estuary in the north and long residence time deep-water currents running southward (Olson et al., 2020 in pres). This region typically has high nutrients, high pH, and shallow intertidal zones with salt marshes and mud flats (Bourdon, 2015).

The Discovery Islands: Archipelago between north-central Vancouver Island and mainland BC. Overall the Discovery Islands region is characterized by freshwater inputs from numerous fjords, nearly uniformly distributed with seawater due to strong currents and turbulent mixing (Foreman et al., 2012). As a result of this mixing, surface nutrients and pH experience less temporal variability (e.g. Jarníková et al., 2020 in prep; Olson et al., 2020 in pres). However, in the nearshore and connected fjords where mixing is reduced, surface seasonal cycles are stronger (ibid.).

The Outer Coast: West coast of Vancouver Island and the Juan de Fuca Strait. The Outer Coast also experiences a large temporal range of pH especially during summer coastal upwelling, which brings sub-surface, nutrient-rich, low pH, waters to the surface (Haigh et al., 2015). In contrast to the SoG, the lowest surface pH occurs during summer in the Juan de Fuca Strait. (Ianson et al., 2016) and on the outer coast during brief periods immediately following upwelling events (Engida, 2016). Winter downwelling brings offshore, nutrient-depleted, moderate pH surface water onshore and into the deep Juan de Fuca Strait (Masson 2006, Ianson et al., 2016).

2. Methods

My analysis consisted of two steps. First, I administered a survey questionnaire to understand the broad challenges faced by the oyster aquaculture industry and oyster farmers' firsthand experience of ocean changes and oyster die-off events. After learning from oyster farmers, I constructed a dataset that consisted of observations of ocean changes and self-reported oyster die-off events and used descriptive statistics to visualize the regional characteristics, changes, and events. Second, based on farmers' survey responses, I identified certain environmental factors that are likely to contribute to poor oyster growing conditions. To develop a holistic picture of ocean changes in BC and investigate these questions, I examined both in-situ chlorophyll measurements from the SoG as well as outputs of these environmental properties from a three dimensional high-resolution oceanographic hindcast model designed to simulate conditions in the SoG, between 2013 and 2017. This multi-strategy approach, using both quantitative and qualitative data, was important to triangulating key environmental factors affecting oysters, explaining instances of high oyster mortality, and establishing a complete picture of the challenges oyster farmers face and the conditions that influence oyster cultivation.

2.1. Survey Design

The survey structure was designed to consult local knowledge holders and gather qualitative data about their first-hand experiences of climate changes (Byg & Salick, 2009; Glover, Zanotti, & Sepez, 2010; Pietkiewicz & Smith, 2014). The survey questions were part of a broader survey about challenges faced by BC's shellfish industry in general and how these challenges are reported in the media (Drope, 2019). My portion of the survey contained 40 questions covering demographics, environmental changes, and oyster die-off events (Appendix A):

> *Demographics*: Survey respondents indicated how long they worked on a specific farm, the farm's age, and species farmed.
>
> *Environmental changes*: From a list, survey respondents selected environmental factors in which they observed a change. Next, they detailed for each observed change the magnitude (amount of change) or direction (if the change increased or

decreased) of the change, when they observed the change (the period during which the change was observed), and the impact (how the change affected oyster production on the farm).

Die-off Events: An oyster die-off event is a short time period in which a significant proportion of spat, juvenile, and/or adult oysters die. Respondents indicated if they had experienced a die-off event, challenging periods generally, indicators of a die-off event, and what factors they thought are related to die-off events.

As shellfish aquaculture tenures are widely dispersed along coastal BC and shellfish farmers often work in remote locations (Appendix B), I recruited survey respondents using snowball sampling. Initially, informed by a DFO spreadsheet of shellfish aquaculture licence holders (Fisheries and Oceans Canada, 2018), I completed desk research of BC oyster farmers. I also attended the 2018 BC Seafood Expo (https://bcseafoodexpo.com/2018-bc-seafood-expo/) to connect with oyster farmers. After oyster farmers completed the survey, I asked if they could recommend others who would be willing to participate in the survey.

I administered the survey questionnaire using Qualtrics Survey Software (Qualtrics, Provo, UT), which can be completed via an online link for remote respondents. However, to generate a higher response rate, I administered the survey in person on a tablet as much as possible. All responses were anonymous. There are currently no available data on the number of actively farmed tenures or shellfish farmers employed in the industry; thus, I limited responses to one per tenure for accurate representation, which allowed multiple responses from large companies with multiple tenures in different oceanographic regions and one response from small companies with one tenure. Qualtrics Survey Software generated descriptive statistics.

I also analyzed participants' responses to open-ended questions in an inductive manner using NVivo software (NVivio [version 12], 2019). Each response was tagged based on subject matter, resulting in 20 subthemes (Appendix C). These subthemes were then grouped into four overarching themes. The tagging identified key themes in the qualitative data that could be used to corroborate quantitative data (e.g. Bryman, 2006), help explain findings, and contribute to a comprehensive understanding of shellfish farming and ocean changes. The four overarching themes included:

Environmental Conditions: Factors that shape the natural conditions in which the oysters are grown (e.g. algal blooms, animals, and heat and warm periods).

Farming Operations: Factors related to farm practices and administration (e.g. costs, husbandry, closures, and infrastructure).

Oyster Biology: Factors related to oysters' growth and resilience (e.g. genetic strain, disease and viruses).

Unsure/Unknown/Mix: Respondents list multiple possible factors, acknowledge the interaction of factors, or cannot distinguish factors.

2.2. Ocean Model - SalishSeaCast

I used output from an oceanographic model to quantitatively examine qualitative observations from the survey results. Ancillary regional temperature, primary productivity, pH (total scale), and Ω_{Ar} data were obtained from the SalishSeaCast (SSC), a three dimensional high-resolution oceanographic hindcast model of the region (https://salishsea.eos.ubc.ca/nemo/; Soontiens and Allen 2017; Jarníková et al., 2020 in prep; Olson et al., 2020 in pres). The SSC accurately simulates conditions in the Salish Sea, covering three of the four sub-regions, with high model-skill (Jarníková et al., 2020 in prep; Olson et al., 2020 in pres) as far back as 2013. The model predicts pH, temperature, salinity, and primary productivity using wind, tides and freshwater flow data. Because the SSC is highly resolved, I was able to extract relevant data from 12 nearshore sites within each sub-region where oyster operations occur (Figure 1, Appendix D). Chlorophyll observations from ferry-tracks between Nanaimo and Tsawwassen (Olson et al., 2020 in pres) from 2013 to 2019 were also used in my analysis.

2.3. Local Knowledge-informed investigation of poor oyster growth conditions

Based on farmers' and scientific knowledge, I derived three hypotheses linking environmental change to first-hand experiences; specifically, that (1) ocean water temperature, (2) primary productivity, and (3) OA were key triggers of oyster mortality in

2016. I extracted temperature, primary productivity (small phytoplankton, diatoms, and *M. Rubrum*), and carbonate conditions (pH and Ω_{Ar}) from the model for the years 2013 to 2017 at 12 locations within the model's domain (Figure 1*)*. Since oysters live for years and do not need to feed every day (Lavaud et al., 2017), these data were examined at a daily resolution. I averaged the data over the top 5-m of the water column since oysters are typically grown within this depth range and experience environmental signals due to the ~4m tidal range (LeBlond, 1983).

The spring bloom is associated with large increases in phytoplankton concentrations (Harrison 1983), exerts a significant influence over the local ecology (Beamish et al. 2004; El-Sabaawi et al. 2009), and provides critical food for oysters. The spring bloom occurs during the time period from year day 60 to 130, or March to May (S. E. Allen & Wolfe, 2013; Chandler et al., 2017). Thus, I calculated annual averages as well as spring-bloom averages of modelled and observed quantities. I investigated both model-derived productivity at each location and an observed chlorophyll time-series adjacent to the Baynes Sound (Figure 1, Olsen et al. in press) to understand the quantity of food available for oysters during this period. While primary production is the amount of biomass produced by plankton, the standing stock of chlorophyll can be used to represent the amount of biomass present at a given location during sampling (i.e. the total biomass produced minus the biomass lost to grazing, mortality, and physical transport).

2.4. Thresholds

Throughout the analysis of model outputs, I examined important thresholds and ranges of water temperature, chlorophyll, Ω_{Ar} to visualize interannual differences and understand the possible impact on oysters. Though self-sustaining *C. gigas* populations have been documented to survive temperatures as low as -2°C in the coldest month of the year, during the warmer months, 14° to 29°C is a key physiologically optimal temperature range, above which wild populations do not prosper (e.g. Carrasco & Barón, 2010). The study region does reach 29°C, so I impose a threshold of 19°C that most years exceed in the warmest months, but do not sustain for extended periods. In the SoG, the mean annual chlorophyll concentration is around 2 μg/L, while in the spring, the mean concentration is greater, around 4.5 μg/L (Masson & Peña, 2009). I impose a threshold above this mean, 8 μg/L, that is exceeded most years during peak spring bloom times in the SoG. A pH range of approximately 7.8 to 8.3 is considered standard conditions for *C. gigas*, while pH concentrations below 7.4 have been documented as stressful for bivalves (Venkataraman, Spencer, & Roberts, 2019; Waldbusser et al., 2015). For Ω_{Ar} (the saturation state of aragonite which plays an important role in the early stages of larval oysters), I used a physiologically relevant threshold of 1.5, which has been identified as a minimum threshold for early development and commercial production-to-settlement competency for *C. gigas* (Barton et al., 2012; Gimenez, Waldbusser, & Hales, 2018).

3. Survey Findings

3.1. Demographics

In total, 55 shellfish farmers participated in the survey from May to September 2018, 46 of whom grew oysters. The proportion of farmers who grew oysters ranged from 70 percent in Southern SoG to 89 percent in the Baynes Sound and the Discovery Islands. In BC, 40 to 60 people typically participate annually in commercial shellfish aquaculture (Ried, 2020) and similar research done on the significantly larger U.S. west coast shellfish aquaculture industry (encompassing the three states of Washington, Oregon, and California) had 86 respondents (Mabardy, Waldbusser, Conway, & Olsen, 2015), emphasizing a high response rate to my survey questionnaire in comparison. Since responses were limited to one per tenure, this high response rate is likely representative of the distribution of BC oyster farming activities in 2018. Of the total responses, 35% came from the Baynes Sound, 37% came from the Discovery Islands, 15% came from the Southern SoG, and 13% came from the Outer Coast.

Overall, most farmers have over a decade of experience and knowledge of a location, with 59% having worked at their current farm for more than 11 years. The Discovery Islands had the most farmers employed for the longest time period, with 41 percent working on their farm for more than 21 years. In the Southern SoG and the Baynes Sound, more than 43 percent of respondents have worked on their current farm for more than 11 years. The Outer Coast has the greatest percentage of respondents who have worked on the farm at which they are currently employed for five years or less (67 percent), followed by the Baynes Sound (33 percent).

3.2. Farm Operations

The majority of farms in the Outer Coast, Discovery Islands, and Southern SoG are small (83, 76, and 73 percent, respectively), meaning they have one to three employees or produce approximately 25,000 dozen shellfish per year. In contrast, Baynes Sound holds the largest farms: 47 percent of farms are medium-sized (four to eight employees or producing approximately 50,000 dozens of shellfish per year), and 47 percent are large and extra-large farms (eight or more employees or producing 175,000 dozens or more of shellfish per year).

In all regions, more than 80 percent of the farms have been in operation for 11 or more years. The oldest farms are in the Discovery Islands; all have been in operation for 11 or more years, with 35 percent in operation for more than 30 years. The Outer Coast has the youngest farms with 17 percent in operation for less than 11 years.

3.3. Environmental Changes

Environmental changes observed by BC oyster farmers were diverse (Table 1). Only environmental factors in which ten percent or more of respondents in two or more regions are further analyzed regionally. The six environmental factors in which most farmers observed a change include water temperature, oyster food availability, other existing and new species on the lease, weather patterns and extreme events.

> *Water temperature*: More than 50 percent of farmers in all regions regularly monitor water temperature. In general, oyster farmers reported that ocean water has become warmer, particularly over the past five years, and that this change has negatively impacted production on their farm. All farmers who observed a change in water temperature in the Baynes Sound said it was warmer and 44 percent of these respondents said water was much warmer. The Outer Coast was the only region in which the majority of respondents reported cooler water. Half of the respondents from the Southern SoG reported experiencing the change earlier than other regions, over the last ten to 20 years. Additionally, the Southern SoG was the only region in which no respondents perceived the increased water temperature as negative.

Oyster food availability: Water clarity can give a sense of oyster food availability (Fleming-Lehtinen & Laamanen, 2012) and was monitored by more than 50 percent of respondents on the Outer Coast. Several farmers experienced a change in oyster food availability over the last 5 years but were regionally divided about the direction and impact of this change. Change in food availability was perceived as positive in the Discovery Islands and the Southern SoG where an increase in food available for oysters was reported. In contrast, respondents reported that decreased food availability negatively impacted production on farms in the Baynes Sound and the Outer Coast.

Species-related changes: In all regions, more than 50 percent of respondents monitor other species and predation. Several farmers described an increase in crabs (Baynes Sound), jellyfish (Baynes Sound), and barnacles (all except the Outer Coast). Farmers in the Southern SoG, the Discovery Island, and the Baynes Sound reported a decrease in sea stars. Tunicates and squirts are the most observed new species in all regions, except in the Southern SoG, and were reported to have impacted more than half of respondents' production negatively. Respondents generally noted experiencing a medium to large amount of change other species starting five to ten years ago.

Weather-related changes: More than half of farmers in all regions except the Southern SoG indicated that they regularly monitored weather in some way. Farmers in the Baynes Sound and Discovery Islands also reported monitoring wind direction and rainfall. Farmers generally reported a medium amount of change in weather patterns over the past five years, which had particularly negative impacts on farms in Baynes Sound and on the Outer Coast. Reported changes in weather patterns include warmer temperatures and increased wind and storms. More extreme weather events during this time negatively impacted several respondents from all regions. All regions reported an increase in extreme storms and wind. Respondents in the Baynes Sound also described heavier rainfall and periods of extreme temperatures.

Table 1. Most commonly observed environmental changes.

Responses listed include all environmental changes in which ten percent or more of respondents in two or more regions reported observing a change. Environmental changes that were choices in the survey but did not meet the above criteria include water salinity, water quality (e.g. oxygen, pH), changes in food timing, harmful algal blooms, coastal landforms, and other. Numbers shown in bold are the number of respondents who observed a change with percent of all survey respondents in brackets. Below, are the most commonly reported details of the change shown as a count (and percentage in brackets) of respondents to the question.

Data shown are from all responses. Since the majority of survey respondents worked on their farm for more than ten years, I examined how removing responses from those employed for ten years or less would affect results. This analysis did not noticeably change the overall results.

All details of the change (i.e. direction/amount, timing, or impact of change) equal 100 percent. For warmer, the percent not shown is colder. For negative impact, the percentage not shown is neutral and/or positive.

Response	Overall *N = 46*	By Region Southern SoG *N = 7*	Baynes Sound *N = 16*	Discovery Islands *N = 17*	Outer Coast *N = 6*
	Count (%)	Count (%)	Count (%)	Count (%)	Count (%)
Water temperature	**24 (52)**	**4 (57)**	**9 (56)**	**7 (41)**	**3 (50)**
Warmer	19 (79)	4 (100)	9 (100)	5 (71)	1 (33)
Over the last 5 years	18 (75)	2 (50)	8 (89)	5 (71)	3 (100)
Negative Impact	11 (46)	0 (0)	5 (56)	4 (57)	2 (67)
Other existing species	**20 (43)**	**2 (29)**	**7 (44)**	**9 (53)**	**2 (33)**
Medium/Large	15 (75)	1 (50)	7 (100)	5 (56)	2 (100)
Over the last 5 years	10 (50)	2 (100)	3 (43)	4 (44)	1 (50)
Negative Impact	9 (45)	1 (50)	3 (43)	4 (44)	1 (50)
New species	**14 (30)**	**3 (43)**	**3 (19)**	**6 (35)**	**2 (33)**
Medium	8 (57)	0 (0)	3 (100)	3 (50)	1 (50)
Over the last 5-10 years	11 (79)	3 (100)	2 (67)	4 (67)	2 (100)
Negative Impact	9 (64)	2 (67)	1 (33)	4 (67)	2 (100)
Oyster food availability	**9 (20)**	**2 (29)**	**3 (19)**	**2 (12)**	**2 (33)**
Somewhat more	4 (44)	1 (50)	0 (0)	2 (100)	1 (50)
Over the last 5 years	7 (78)	2 (100)	2 (67)	1 (50)	2 (100)
Negative Impact	4 (44)	0 (0)	2 (67)	0 (0)	2 (100)
Weather patterns	**14 (30)**	**0 (0)**	**4 (25)**	**7 (41)**	**3 (50)**
Medium	4 (29)	0 (0)	0 (0)	2 (12)	2 (67)
Over the last 5 years	7 (50)	0 (0)	3 (75)	2 (12)	2 (67)
Negative Impact	5 (36)	0 (0)	2 (50)	1 (6)	2 (67)
Extreme weather	**13 (28)**	**1 (14)**	**6 (38)**	**5 (29)**	**1 (17)**
Somewhat more	9 (69)	1 (7)	3 (50)	4 (24)	1 (100)
Over the last 5 years	8 (62)	1 (7)	5 (83)	2 (12)	0 (0)
Negative Impact	11 (85)	1 (7)	5 (83)	4 (24)	1 (100)

3.4. Die-off Events

Prior to asking farmers about oyster die-off events, I asked respondents to elaborate on their biggest challenges about oyster farming, which could be related to ocean conditions, or not. Twenty-nine farmers responded to this open-ended question, referencing a total of 44 challenges that were coded into 12 subthemes and then three overarching themes (Figure 2a): farming operations (66 percent), environmental conditions (20 percent), and oyster biology (16 percent). Factors related to farming operations were a prominent difficulty faced by farmers in all regions, with the cost of operations and oyster handling accounting for 23 and 18 percent of responses, respectively.

However, when looking at subthemes (Figure 2b), oyster survival emerges as a significant challenge (16 percent) in all regions except the Outer Coast. Overall, 62 percent of respondents said the farm on which they work had experienced a die-off event (Figure 3a). In all regions, the majority confirmed experiencing a die-off event, except in the Discovery Islands, where 63 percent of respondents reported having never experienced a die-off event. This region also had the greatest proportion of famers with over two decades of employment on their farm during which they could have experienced an oyster die-off event, but did not, suggesting oyster die-off events may have been less historically prevalent in the Discovery Islands.

I also asked respondents to compare whether oyster mortality in 2017 was greater, generally the same, or less than five, ten, 20, and more than 30 years ago. Overall, the majority of respondents felt oyster mortality was the same in 2017 as in the past, though 25 to 35 percent felt oyster mortality was greater (Figure 3c). Less than ten percent experienced less oyster mortality than the past. All regions follow this pattern with around 30 percent experiencing greater oyster mortality in 2017 than in the past, except the Outer Coast where 60 percent of respondents reported greater mortality in 2017 (Figure 3d). This result may be misleading as there are few farmers from the Outer Coast. It is important to note that I chose 2017 because it was the most recent complete production year and that, according to respondents, 2017 is not an archetype for notably good or bad oyster growing conditions.

Thus, though many oyster farmers' most pressing obstacles are related to farming operations, oyster survival has long been a significant challenge of oyster farming. For most, oyster die-off events are not becoming less problematic and several farmers have experienced more oyster mortality in recent years.

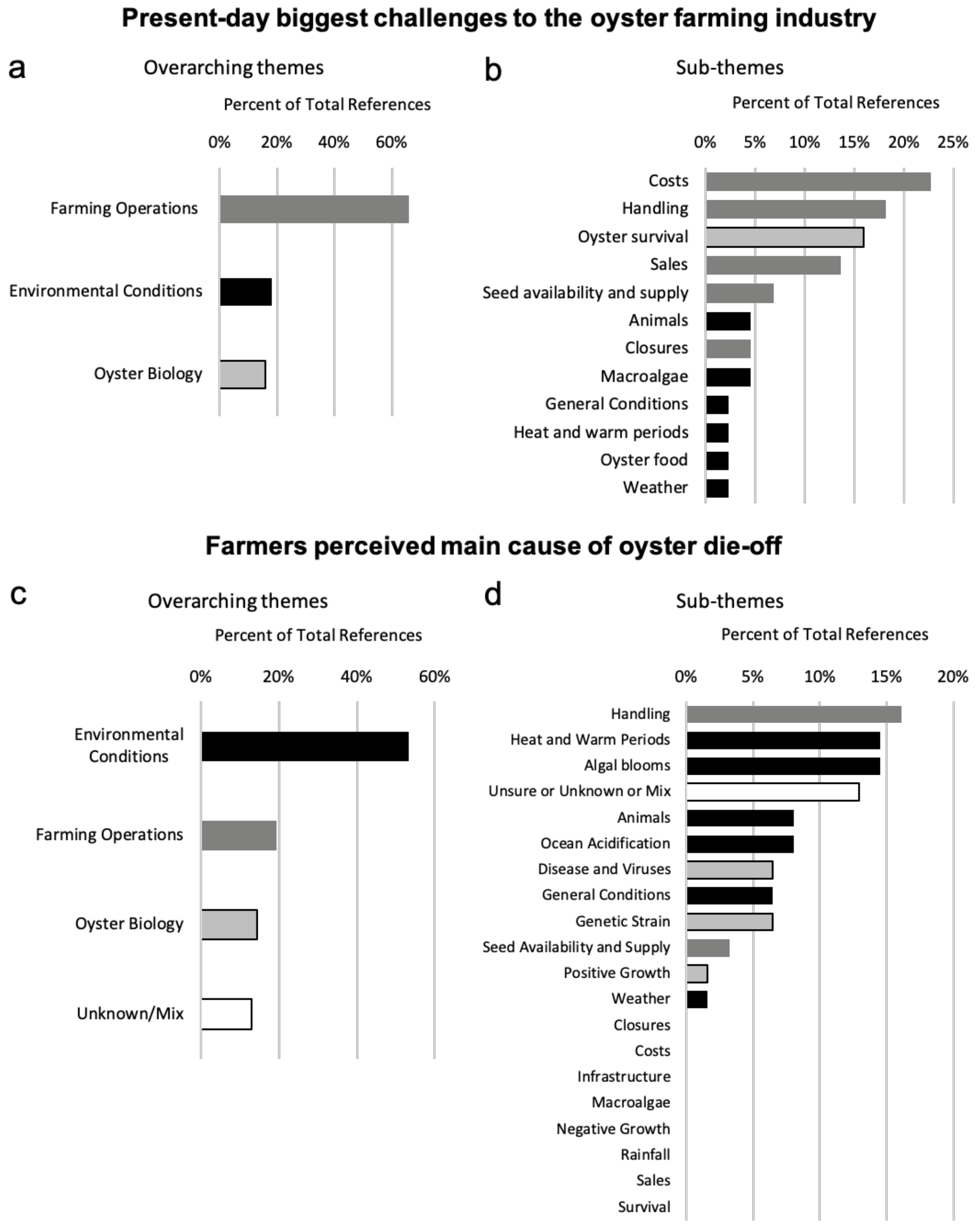


Figure 2. Oyster farmers' biggest challenges and perception of oyster die-off cause.

Comparison of farmers' main challenges in the industry and farmers' perceived main cause of oyster die-off. Themes and subthemes from famers' responses to open-ended questions were coded and counted on NVivo 12 (Section 2.1). a) The percent of references related main challenges sorted into overarching themes, which are b) divided into a hierarchy of subthemes and color-coded based on overarching themes. c) and d) show the same, but for farmers' perception of the main causes of oyster die-off events.

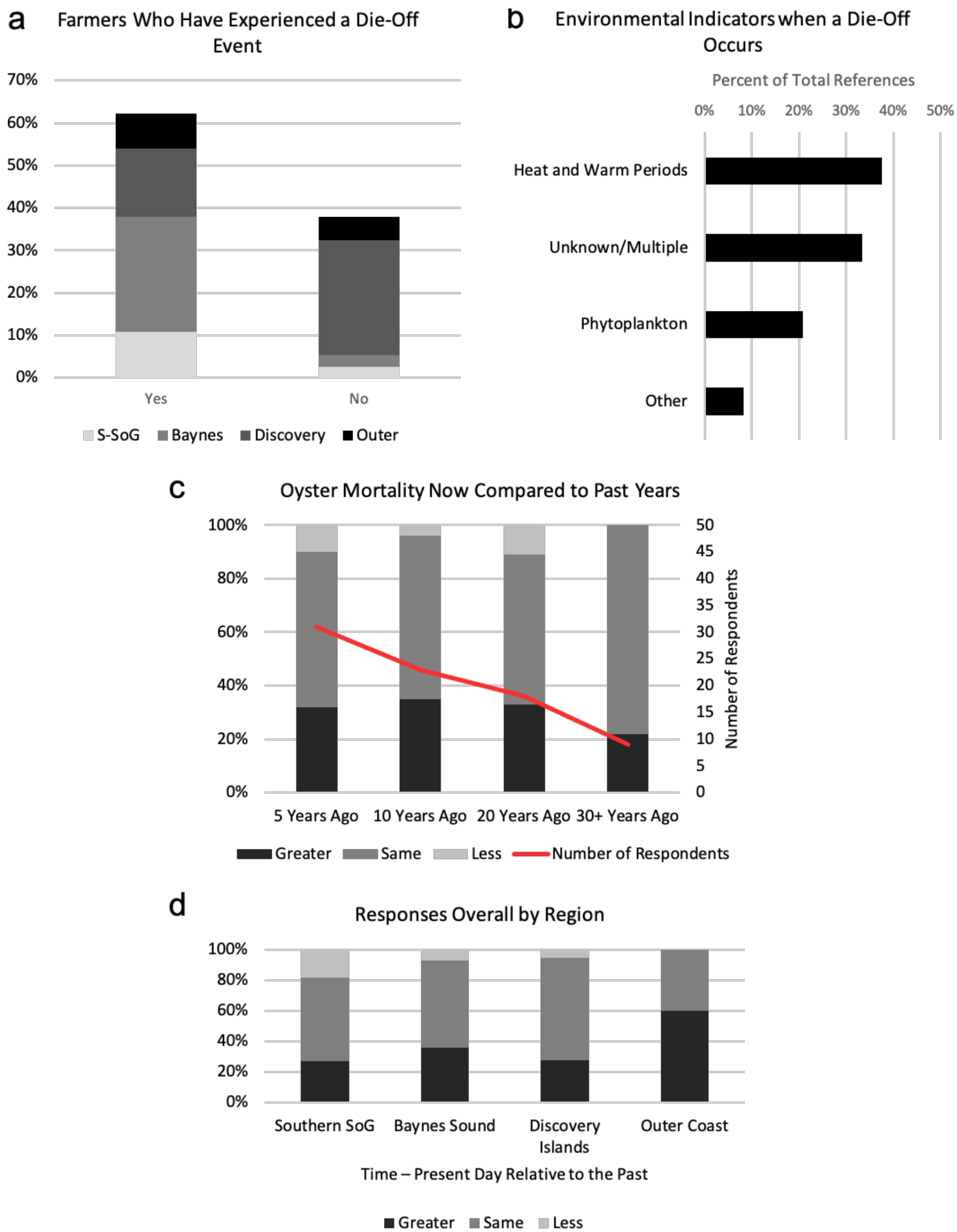


Figure 3. Farmers' experience of oyster mortality.

a) The percent of respondents in each region who have experienced an oyster die-off event compared to those who have not. b) Environmental indicators observed before a die-off event sorted on NVivo 12 (section 2.1) by percentage of total indicators mentioned. c) The percent of farmers who experienced more, less, or the same amount of oyster mortality at the time of the survey compared to 5, 10, 20, and more than 30 years ago. The red line shows the number of respondents to each question, which decreases as the total number of farmers employed in the past decreases. d) The proportion of respondents experiencing more, less or the same oyster mortality as in the past is similar in all regions.

3.5. Difficult Conditions for Oyster Farming

To better understand how environmental conditions may relate to oyster mortality, I asked respondents about their first-hand knowledge of oyster die-off events and difficult cultivation conditions. Questions were open-ended. Throughout, oyster farmers highlighted heat, phytoplankton species composition and abundance, and an unknown/mixture of factors may be related to oyster die-off events.

I asked respondents if they observed any environmental indicators when a die-off occurred. Answers provided by 20 respondents were focused, composing only four subthemes (Figure 3b): heat and warm periods (38 percent) in all regions except the Southern SoG, multiple or unknown reasons (33 percent), phytoplankton species composition and abundance (21 percent), or other (8 percent). Several responses describe challenging growing conditions during the spring and summer months and when water temperatures are high. In the Baynes Sound, respondents observed a lack of oyster food, while other regions reported the presence what seemed to be harmful algal blooms. Some farmers specifically mentioned *Heterosigma*, a harmful alga that typically turns the water brown or reddish (Mudie, Rochon, & Levac, 2002; Taylor & Haigh, 1993); others pointed to a red or orange alga. Many respondents also said there were a number of environmental factors, or that they were unsure of the factors that led to a die-off event. Example responses include:

> *"Usually poor seed survival occurs when a spring bloom does not last into early summer (lack of rainfall causing nutrient deficiency possibly) and summer water temperature is high."*
>
> *"This is a very complex issue, and I don't believe it can be tied to any individual event or variable."*

I also asked farmers if there was a period of time over the past five years when farmers were particularly concerned about their stock due to environmental conditions. With one or more response from each region, totaling 20% of all respondents, 2016 stands out as a challenging year for oyster farming due to environmental conditions (Figure 4a). Overall, 25 percent of respondents specified that poor growing conditions affected oyster seed and 13 percent specified these conditions negatively impacted juvenile and adult oysters. Twenty-four respondents offered a wide range of challenging environmental conditions (Figure 4b). Heat and warm periods in all regions (24 percent) and algal blooms in the

Discovery Islands and the Outer Coast (15 percent) were noted as key experiences that caused concern. Weather was particularly concerning in the Baynes Sound (9 percent). Some responses addressed factors beyond direct environmental conditions (Figure 4b). Twenty-one percent expressed concern due to oysters contracting diseases and viruses, while another 18 percent focused on limited seed availability and supply. Some farmers mentioned the interconnection of direct and indirect environmental phenomena, as well as the connection of observable and non-observable factors, for example:

> *"In the recent years it has been a lot hotter than normal and it kills lots of oysters and causes virus. Also in the winter a large amount of rainfall."*
>
> *"Yes, was worried that the oyster seed was weirdly shaped due to acidification but had no way to tell if this was happening or not."*

Finally, I asked farmers what they perceived was the main cause of oyster die-off in BC's shellfish industry. Thirty-three respondents answered with a total of 47 references to possible environmental and non-environmental causes of oyster die-off events based on both respondents' first-hand experience and other sources of information (Figure 2c). Over half of the references (53 percent) described environmental conditions including heat and warm periods, algal blooms, ocean acidification and other animals (Figure 2d). The majority of these responses were from the Baynes Sound, though some respondents from the Discovery Islands perceived that other animals cause die-off events on their farms. Respondents from all regions except the Southern SoG perceived OA as a possible factor related to die-off events. In addition, 28 percent referenced farming operations, particularly handling, and 15 percent referenced factors related to oyster biology including diseases and seed genetics (Figure 2d). Finally, 13 percent of the references emphasized that the issue is complex and cannot be narrowed to a single factor:

> *"I think warmer water (and potential algae community shifts) combined with high density farming practices are the root cause of mortality events. additional stressors present (low pH, viruses, bacteria) add to the cumulative stress and maybe tip the balance between survival and mortality but are not the root cause....in my opinion."*
>
> *"Many potential and important factors. Genetics, family selection at hatchery, environmental conditions, phytoplankton blends, timing of natural events, husbandry practices, . . . My suspicion is mortality events are the result of a cocktail or combination of stressors happening in either specific or broadly based geographic areas that impact specific oyster families to varying degrees at different times, environmental conditions and stages of life. This is a very complex issue."*

The environmental factors that farmers observed and perceived were related to challenging oyster growing conditions and die-off events highlight the complexity and multiplicity of environmental properties contributing to conditions as a whole. For each open-ended question, temperature and algal blooms stood out as main environmental conditions that may be related to oyster die-off. However, several comments also discussed the interconnectivity of environmental properties and emphasized uncertainty and complication in distinguishing individual factors that trigger oyster die-off events. References to perceived causes of oyster die-off are broader than farmers' observations and experiences of related governmental conditions, suggesting famers understand that the interaction of many obvious and imperceptible factors contribute to the conditions in which oysters are grown. Moreover, farmers may gather information about die-offs from sources other than their own observations. For instance, while some respondents emphasized that OA is not directly observable and detecting the impact of OA on oysters in ambient conditions is poorly understood, fifteen percent still reported OA may be a factor related to oyster mortality.

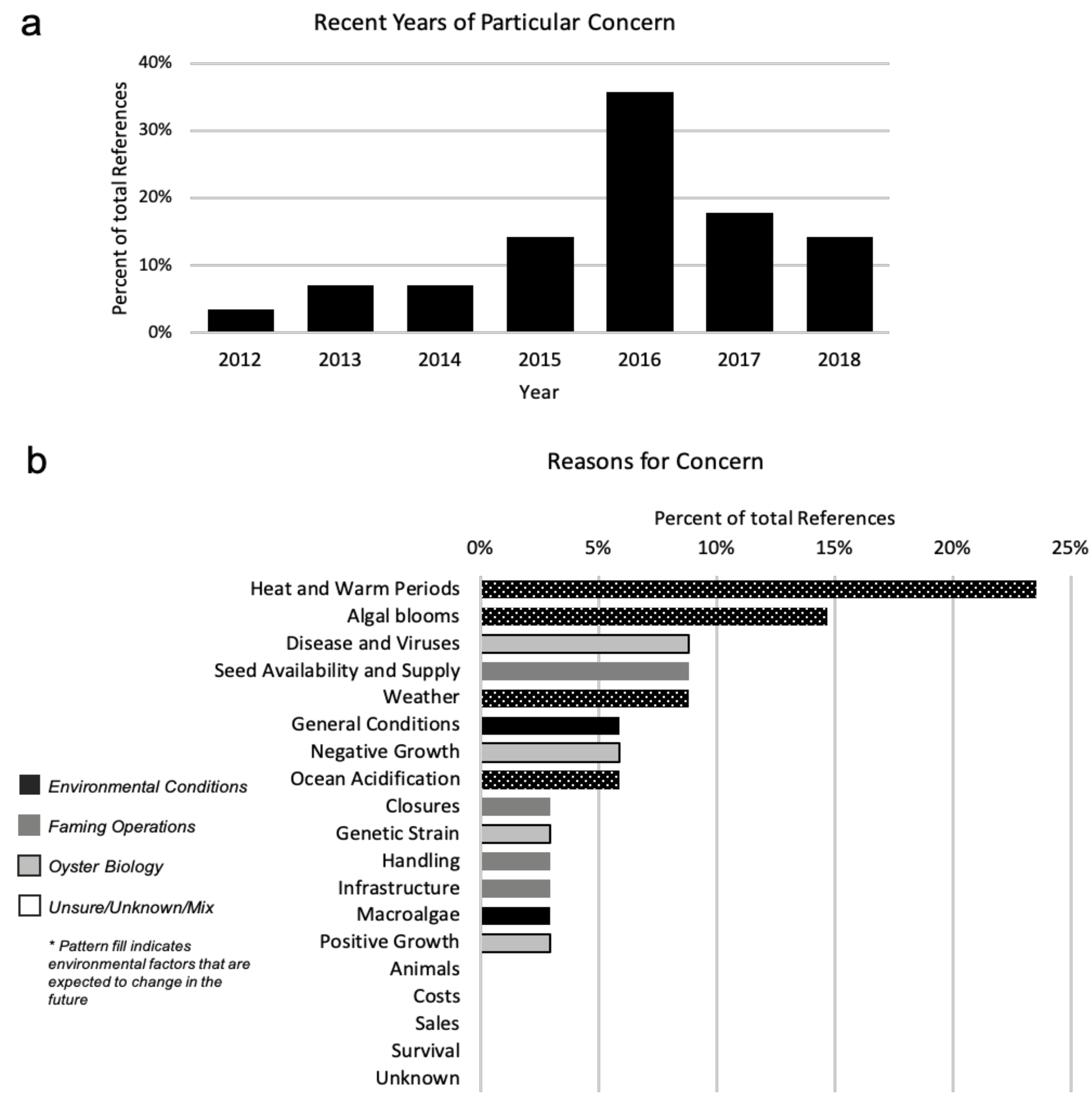


Figure 4. Years of concern.

a) Recent years in which respondents reported feeling particularly concerned for their stock due to environmental conditions. Two thirds of respondents who described recent years of particular concern have worked on their farm for more than ten years. 29 percent of respondents did not mention a year that they were particularly concerned. b) References to specific concerns during these years were sorted on NVivo 12 (Section 2.1). Bars with a pattern fill indicate conditions that are expected to change in the future.

3.6. Future Research Areas Informed by Oyster Farmers' Local Knowledge

Results from the survey of oyster farmers' experiences emphasize the breadth of challenges faced by the industry and the complexity of ocean conditions, while highlighting possible key environmental conditions that lead to more difficult oyster growing seasons. Oyster mortality has been a problem for the industry over decades and is generally not improving, and several respondents pointed to heat and phytoplankton species and composition as possible environmental factors related to oyster die-off events. Oyster farmers also reported a range of environmental changes at their tenures, many of which, particularly warmer water temperatures, lack of oyster food, other species, and changing weather, contributed to difficult oyster growing conditions and negatively impacted their product in recent years. Several also acknowledged that a single environmental factor may not be the root cause of oyster die-off events; rather, environmental conditions are complex and expose oysters to multiple stressors.

In addition to these environmental challenges, respondents communicated that they faced other challenges related to farming operations that felt more pressing than environmental changes. Further in-depth study of these environmental factors and the industry's broader challenges may contribute to greater understanding of the systems in which oysters are grown and help the industry be more resilient to difficult cultivation years. While OA has been a recent focus of research related to the oyster industry, farmers' experiences help inform research areas beyond OA that involves cooperative work from multiple backgrounds and disciplines, and highlights research that is most actionable for BC's oyster industry.

Table 2. Future research areas.

Oyster farmers' survey responses highlight several important directions for future oyster aquaculture-related research to take. Topics are sorted into research areas below, which are accompanied by sample questions based on knowledge shared by the oyster farmers.

Research Area	Example research questions and directions to pursue
Environmental properties.	- What has driven variation in environmental factors identified by farmers as key contributors to difficult oyster cultivation periods in recent years. - What were the dynamics of other environmental factors that are not directly observable (such as pH and oxygen content) in recent years? - How are observable factors (temperature and primary productivity) and unobservable conditions (pH and oxygen content) correlated? - How might the correlation of perceptible and imperceptible environmental factors manifest and impact oyster aquaculture?
Weather events.	- What are the physical and biophysical impacts of wind, rain and extreme weather on oysters and farming operations? - What research and technologies can help the industry prepare for and withstand these physical impacts?
Species interactions.	- How do other species including crabs, jellyfish, sea stars and barnacles interact with oysters? - How are other species that impact oysters changing? - How are non-native tunicates introduced to the Pacific coast of Canada? - How can oyster farmers manage tunicates and other pests?
Future environmental changes (Figure 4b).	- How will an increase in the frequency, duration, intensity, and spatial extent MHWs, extreme weather, OA impact oysters. - What other future environmental changes may impact oyster aquaculture and how? - How can farmers prepare and adapt to coming changes?
Oyster resiliency.	- Are bred oysters resilient to a wide variety of factors including heat, low primary productivity, high OA, and Ω_{Ar} (de Melo, Divilov, Schoolfield, & Langdon, 2019; de Melo, Durland, & Langdon, 2016)? - Are bred oysters resilient to changes in environmental conditions from year-to-year? - Is local oyster seed more resilient? - How can farmers have greater access to local hatcheries and seed?

4. SalishSeaCast

To exemplify how oyster farmers' observations and experiences of ocean changes can focus research questions, I further investigate environmental properties (Table 2) by using the SSC to examine how water temperature, oyster food availability, and carbonate chemistry (Section 2.3) may have contributed to the poor oyster growing conditions experienced by farmers in 2016. Overall, conditions during this 5-year period were dynamic, and included passage of the severe marine heat-wave 'the Blob' through the Salish Sea (Bond et al., 2015). Results from the SSC also show that 2016, the end of this heatwave, differed from other years; specifically, during early spring and summer average temperature was higher and primary productivity was lower than preceding and subsequent years.

4.1. Temperature

Heat was the most common environmental factor that oyster farmers encountered and associated with difficult cultivation periods (Figure 4b). Heat was also the most commonly reported environmental change respondents both observed before a die-off event and felt threatened oyster production, except in the Southern SoG (Figure 2b). I found that model results confirmed the farmer's experiences. Ocean temperatures in the SoG document the progression of the "Blob" MHW, which rose in 2014, peaked in 2015, and dissipated in 2016 (see Figure 5a). 2015 had the highest daily average temperature across the whole year relative to other years. However, 2016 had the highest daily average temperature during the spring bloom, which coincided with El Niño conditions that peaked in early 2016 (Chandler et al., 2016).

While the annual mean daily average ocean temperatures varied slightly between years, reaching its highest point in 2015 (12.19°C), 2016 had notably higher mean daily average temperatures relative to other years during the spring bloom period (days 60 to 130, Section 2.3). The spring bloom period provides a major food source for the Salish Sea and is therefore an important time for oysters and the surrounding ecology (Collins, Allen, & Pawlowicz, 2009). During this time, the mean daily average in 2016 was 7% (0.67°C) greater than the mean daily average temperature averaged over the years 2013 to 2015 and 14% (1.41°C) warmer than 2017.

Though research suggests periods of high temperatures above 29°C may be stressful for oysters due to increased proliferation of pathogens, bacterial growth and anerobic metabolic activity, model results suggest high surface water temperatures were not likely to have been the sole environmental challenge in 2016 (Carrasco & Barón, 2010; Lavaud et al., 2017). Over the five-year period, temperatures did not exceed 24°C (Appendix F.1), which is well below the upper optimal temperature threshold for oysters of 29°C (Carrasco & Barón, 2010). Additionally, while periods of highest daily average temperatures typically occur in the summer (Appendix E), 2016 did not have extended or extreme summer warm periods relative to other years. Thus, higher spring and summer temperatures are likely not the sole cause of challenging oyster growing conditions in BC; rather, high temperatures may co-occur with other conditions (Section 4.4) which are stressful for the oysters and as such, temperature may serve as an indirect indicator. It is possible that the marine heat wave and associated environmental changes may have also contributed to concerning oyster cultivation conditions.

4.2. Primary Productivity and Chlorophyll

Changes in phytoplankton species and composition represented another common environmental factor that oyster farmers encountered and associated with difficult cultivation periods. Baynes Sound (Figure 1) in particular reported a lack of oyster food, while other regions observed the presence of new algae species (Mudie et al., 2002; Taylor & Haigh, 1993). All farmers who experienced reduced food availability for their oysters felt that it negatively impacted their product, though it was harmful algal blooms that were noted as problematic in 2016.

As described above (Section 1.2), several researchers have documented changes in the phytoplankton composition – including increased bloom size, altered bloom timing, and new species – within the study region during the Blob's tenure along the coast (Brodeur et al., 2018; Chandler et al., 2017; Mahara et al., 2019). My research focuses on the possibility of its effects on oyster food availability. Examining primary productivity and chlorophyll concentrations provides an understanding of the phytoplankton growth and biomass in the area where oysters are grown. Modelled primary productivity varied little year-to-year (Figure 5b) and suggest 2017 had low spring primary productivity relative to other years. In contrast, chlorophyll measurements from a mooring representative of conditions outside of Baynes Sound (Figure 1; Olson et al., 2020 in press) from 2013 to 2019 (Figure 5e) show that food availability was low during 2016. In fact, 2016 was the only year in which chlorophyll concentrations did not exceed 8 μg/L during the spring bloom. Thus, while the model appears to illustrate that 2016 had typical food availability, observations actually suggest that low food availability in 2016 may have been one of the multiple factors that contributed to the difficult growing season that year.

4.3. Carbonate Chemistry

Since carbonate chemistry is difficult to observe (Brewer, 2013; Byrne, 2014), oyster farmers could not confirm in survey responses that they faced low pH and Ω_{Ar} during challenging oyster cultivation periods, though some respondents emphasized that OA could harm oysters. Rather, local media reports have targeted OA as the fundamental property driving oyster die-off events (Hume, 2014; Luymes, 2015; Owsianik, 2012). However, model results show that in 2016, surface pH and Ω_{Ar} were typically the same or greater than the average of all five years (Figure 5c and 5d), which I would expect to alleviate OA stress for oysters.

At the sample locations, the mean daily average surface pH stayed within 1% of the mean daily average of all five years, which was 8.04 across the whole year (Figure 5c). Similarly, the mean daily average surface Ω_{Ar} varied little between years and stayed within 1% of the mean at most locations, except in 2017 where the annual mean daily average Ω_{Ar} was between 1 and 2% below the mean of all locations (Figure 5d). The average annual Ω_{Ar} for 2013-2017 was 1.60 across the whole year. During the spring bloom, the mean daily averages of pH and Ω_{Ar} are slightly higher at 8.16 and 1.67, respectively (Figure 5c and 5d), as a result of rapid carbon uptake by phytoplankton (Figure 6b and 6d) (Ianson et al., 2016). There was also more variation between the mean daily average of each year during the spring. However, with the exception of spring 2017 with a mean daily average Ω_{Ar} of 1.47 (just below or the same as the literature threshold, Section 2.4), none of these pH and Ω_{Ar} averages are typically considered harmful for shellfish (Gimenez et al., 2018; Waldbusser et al., 2015). In fact, mean daily Ω_{Ar} was highest of all five years in spring 2016 at 1.75 and was not particularly variable. These high pH and Ω_{Ar} values suggest that carbonate chemistry was not a prime contributor to the worse conditions experienced in 2016. Moreover, if OA was the sole cause of oyster die-off events, I would expect to see that 2016 was a good year for oyster growth and 2017 was challenging, but I did not.

a

	End of Year (Day 250 to 365)					Spring Bloom (Day 60 to 130)					Whole Year (Day 1 to 365)				
Daily Average Temperature (°C)	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Deep Bay	10.56	10.95	10.88	10.79	10.50	9.32	9.09	9.68	9.94	8.67	11.46	11.90	12.31	11.99	11.48
Southern Baynes	10.55	10.92	10.86	10.74	10.44	9.25	9.08	9.66	9.84	8.64	11.32	11.71	12.07	11.75	11.26
Northern Baynes	10.62	10.96	10.77	10.66	10.42	9.18	9.17	9.68	9.75	8.60	11.31	11.68	11.83	11.53	11.17
Fanny Bay	10.71	11.15	11.00	10.85	10.61	9.38	9.27	9.82	10.01	8.69	11.65	12.11	12.45	12.09	11.60
Maple Bay	11.14	11.32	11.56	11.10	11.11	9.29	9.02	9.99	10.39	8.75	11.60	11.97	12.62	12.27	11.72
Salt Spring	11.18	11.33	11.55	11.08	11.10	9.16	8.86	9.93	10.27	8.63	11.55	11.92	12.52	12.19	11.67
Nanoose Bay	10.94	11.22	11.01	10.88	10.70	9.36	9.25	9.95	10.17	8.82	11.81	12.34	12.39	12.18	11.88
Lasqueti Island	11.14	11.75	11.15	11.02	10.77	9.46	9.36	10.01	10.20	8.71	12.08	12.29	12.25	12.08	11.77
Main SoG	10.89	11.31	11.29	10.67	10.90	9.18	9.04	10.04	10.25	8.83	11.68	12.15	12.39	12.00	11.73
Cortes/Marina	10.71	11.43	10.83	10.77	10.30	9.24	9.25	9.78	10.09	8.73	11.50	11.56	11.68	11.63	11.33
Lund/Desolation Sound	10.74	11.56	10.84	10.73	10.26	9.27	9.31	9.81	10.03	8.66	11.57	11.66	11.58	11.41	11.12
Mouth of Okeover	10.84	11.71	11.05	10.85	10.35	9.44	9.42	9.98	10.45	8.69	11.93	12.16	12.22	11.97	11.50

> Mean
Mean temperature (*white*)
< Mean

b

	Spring Bloom (Day 60 to 130)					Whole Year (Day 1 to 365)				
Daily Average Primary Productivity (N/m3/day)	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Deep Bay	3.35	2.73	3.47	3.09	2.35	1.64	1.61	1.61	1.61	1.58
Southern Baynes	3.20	2.62	3.33	2.84	2.37	1.54	1.52	1.56	1.52	1.54
Northern Baynes	3.66	3.14	3.68	3.49	2.76	1.84	1.97	1.89	1.91	1.81
Fanny Bay	3.13	2.93	3.48	3.02	2.38	1.59	1.54	1.58	1.52	1.41
Maple Bay	2.44	2.36	2.35	2.20	2.14	1.37	1.38	1.32	1.27	1.32
Salt Spring	2.46	1.98	2.33	2.13	2.00	1.36	1.31	1.31	1.25	1.29
Nanoose Bay	2.50	2.28	2.46	2.29	1.74	1.13	1.05	1.15	1.07	0.92
Lasqueti Island	2.07	1.86	2.14	2.12	1.75	1.06	1.14	1.41	1.21	0.98
Main SoG	2.33	2.28	2.57	2.19	1.73	1.22	1.19	1.32	1.17	1.01
Cortes/Marina	3.12	2.12	2.50	2.68	1.65	1.58	1.84	1.59	1.59	1.16
Lund/Desolation Sound	2.63	2.27	2.35	2.38	1.47	1.36	1.46	1.51	1.44	1.04
Mouth of Okeover	2.06	2.06	2.10	1.51	1.35	1.06	1.17	1.04	0.98	0.79

20% > the mean
10% > the mean
10% < the mean
20% < the mean

c

Daily Average pH	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Deep Bay	8.09	8.05	8.10	8.10	8.01	8.01	8.02	8.01	8.03	8.02
Southern Baynes	8.07	8.03	8.07	8.07	8.00	8.00	8.01	8.00	8.02	8.01
Northern Baynes	8.07	8.06	8.08	8.09	8.02	8.00	8.02	8.01	8.02	8.01
Fanny Bay	8.13	8.10	8.14	8.12	8.05	8.03	8.04	8.03	8.04	8.04
Maple Bay	8.10	8.08	8.14	8.11	8.04	8.03	8.03	8.03	8.04	8.04
Salt Spring	8.07	8.04	8.11	8.09	8.02	8.01	8.02	8.02	8.02	8.03
Nanoose Bay	8.10	8.08	8.13	8.11	8.04	8.03	8.05	8.04	8.05	8.05
Lasqueti Island	8.12	8.11	8.18	8.13	8.08	8.06	8.07	8.06	8.07	8.07
Main SoG	8.09	8.07	8.17	8.10	8.04	8.04	8.05	8.05	8.05	8.06
Cortes/Marina	8.08	8.07	8.10	8.11	8.05	8.04	8.06	8.04	8.06	8.06
Lund/Desolation Sound	8.11	8.12	8.16	8.13	8.09	8.06	8.08	8.05	8.07	8.08
Mouth of Okeover	8.17	8.16	8.20	8.18	8.10	8.09	8.11	8.09	8.10	8.10

10% > the mean
1% > the mean
1% < the mean
10% < the mean

d

Daily Average Ωar	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Deep Bay	1.65	1.55	1.64	1.65	1.40	1.54	1.61	1.61	1.64	1.60
Southern Baynes	1.63	1.52	1.60	1.63	1.37	1.53	1.60	1.59	1.62	1.57
Northern Baynes	1.65	1.58	1.63	1.68	1.40	1.54	1.61	1.60	1.62	1.56
Fanny Bay	1.79	1.71	1.79	1.78	1.50	1.62	1.69	1.68	1.71	1.66
Maple Bay	1.72	1.67	1.78	1.79	1.52	1.58	1.64	1.65	1.68	1.65
Salt Spring	1.64	1.55	1.71	1.73	1.46	1.54	1.60	1.61	0.64	1.61
Nanoose Bay	1.70	1.63	1.72	1.74	1.45	1.61	1.68	1.66	1.69	1.66
Lasqueti Island	1.82	1.75	1.89	1.84	1.57	1.72	1.77	1.74	1.76	1.74
Main SoG	1.66	1.57	1.74	1.72	1.39	1.54	1.59	0.63	0.61	1.58
Cortes/Marina	1.73	1.65	1.73	1.79	1.53	1.67	1.74	1.69	1.75	1.72
Lund/Desolation Sound	1.76	1.70	1.80	1.76	1.54	1.63	1.68	1.64	1.66	1.67
Mouth of Okeover	1.92	1.80	1.91	1.93	1.55	1.71	1.78	1.75	1.77	1.71

2% > the mean
1% > the mean
1% < the mean
2% < the mean

e

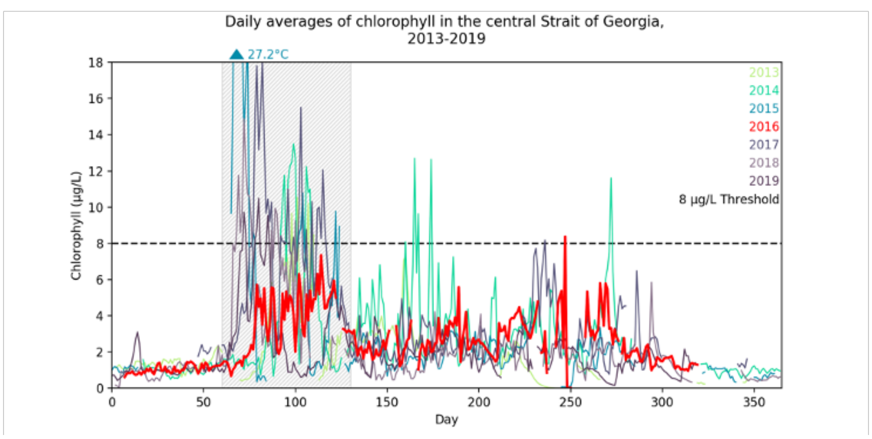


Figure 5. Comparison of environmental factors' mean daily averages.

Tables comparing the mean daily averages of a) temperature, b) primary productivity, c) pH, and d) ΩAr between 2013 and 2017 over the whole year and during the spring bloom. e) shows a chlorophyll timeseries from 2013 to 2019 with 2016 highlighted in red. The spring bloom period is shaded in grey.

4.4. Seasonal covariance of environmental variables

Many survey participants pointed out that environmental factors are interrelated (Section 3.5). Model results confirm these observations, illustrating strong relationships between surface temperature, primary productivity, pH, and Ω_{Ar} (Figure 6). These relationships are governed by a balance of biophysical controls that shift through the seasons (Moore-Maley et al., 2016).

In winter, surface ocean temperatures are cold, between 4 and 11°C (Figure 6b and 6d) and light limits primary productivity (Figure 6a), which keeps pH and Ω_{Ar} low as well (Figure 6b and 6d) (Moore-Maley et al., 2016). Around day 60, the spring bloom period begins, when biological dynamics begin to drive the carbon cycle. During this time, as temperature reaches around 7 to 10°C, primary productivity, pH, and Ω_{Ar} increase rapidly, peaking around day 90 (Figure 6c, 6b and 6d) (Ibid.). Through the summer, temperatures continue to rise, with maximum daily averages between days 180 to 210 (Figure 6a, 6b and 6c) (Ibid.). Once surface nutrients are depleted, primary productivity decreases rapidly (Figure 6a), but pH and Ω_{Ar} remain quite high (Figure 6a, 6b and 6c) (Ibid.). In the fall, as temperatures begin to fall, with increased cloud cover and mixing, primary productivity continues to decrease (Figure 6a and 6c), and pH and Ω_{Ar} decrease rapidly (Figure 6b, 6c and 6d) (Ibid.). These relationships did not differ significantly between years (Appendix F.3).

Though water temperature is one of many factors contributing to the conditions in which oysters are grown, it is the most easily observable and is monitored by farmers from all regions; thus, water temperature can provide valuable information about other key environmental factors such as productivity (amount of food) or Ω_{Ar} and pH. In the spring and summer, when SST is between approximately 10 and 15°C, periods of high primary productivity (above 8 mmol N/m^3/day) often occur (Figure 6a). Similarly, when spring and summer SST is between approximately 8 and 15°C, Ω_{Ar} is typically above a threshold of 1.5 (Figure 6d). As temperatures approach 7°C in the beginning of the year or decrease from approximately 15°C at the end of the year, periods of low primary productivity (less than 1 mmol N/m^3/day) and low Ω_{Ar} (below 1.5) tend to occur (Figure 6a and 6d).

Thus, based on farmers' experiences and perceptions of ideal oyster growing conditions in terms of water temperature, oyster food, and carbonate conditions, in the Salish Sea, I would expect the best conditions to occur when temperatures are between 8 and 15°C. These conditions occur broadly during the spring and summer are correlated with high primary productivity, pH, and Ω_{Ar}. However, other factors, like occurrence of disease (Green et al., 2019), and harmful algal blooms (Haigh et al., 2015) that are not examined in my study, may also influence conditions.

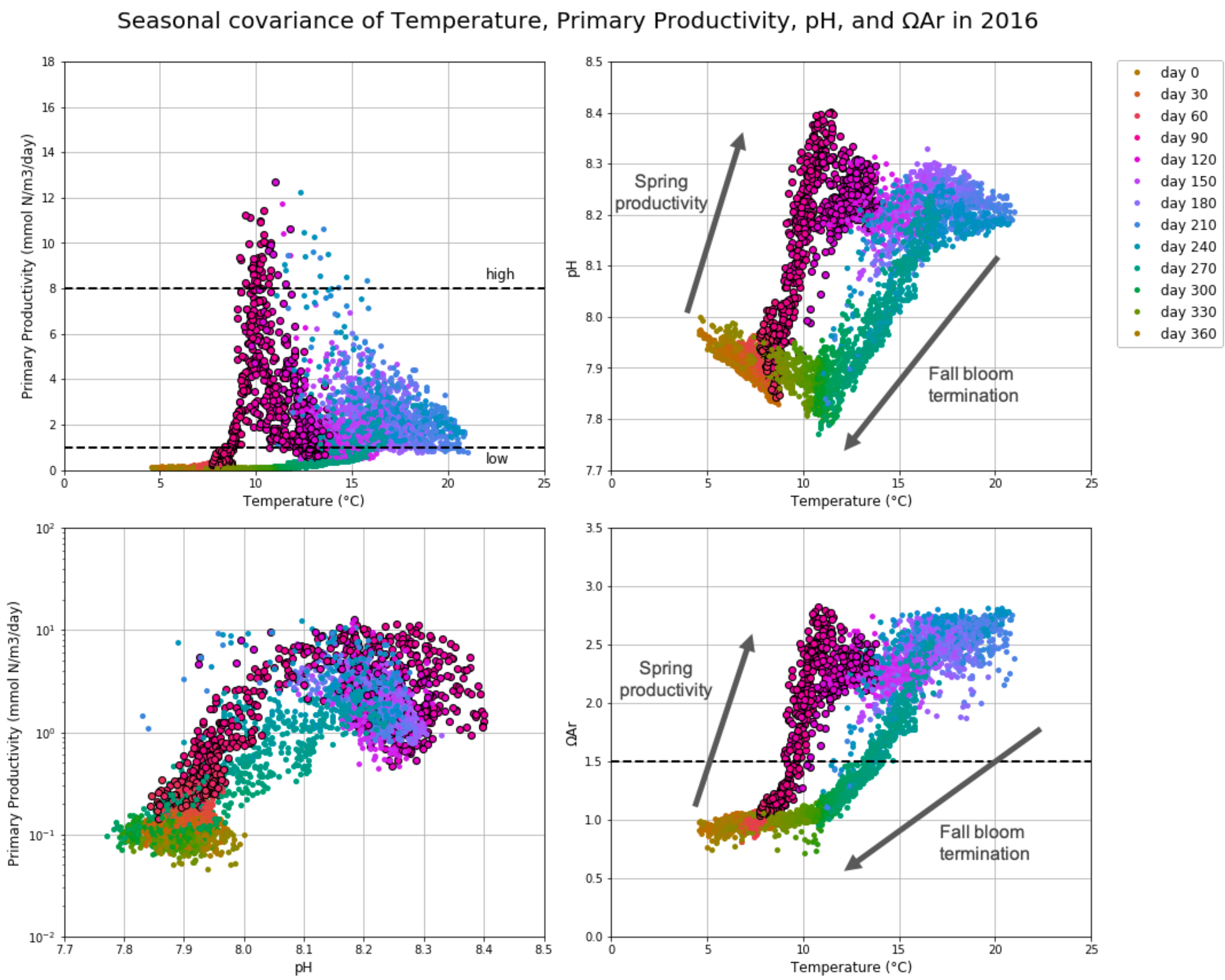


Figure 6. Seasonal covariance of environmental properties.

Plots showing the seasonal covariance of a) primary productivity and temperature, b) pH and temperature, c) primary productivity and pH, and d) Ω_{Ar} and temperature for all locations. The color indicates the year-day of each point, with spring bloom points (days 60 to 130) outlined in black. 2016 is used a typical example, as these relationships remain consistent from 2013 to 2017 (Appendix F.3).

5. Comparing Local and Scientific Knowledge

5.1. Stress predisposes oysters to more die-off

Comparing survey responses to model outputs and other observations further emphasizes the complexity and multiplicity of environmental factors driving oyster die-off events. Neither oyster farmers nor other data examined attributed the difficult growing conditions in 2016 to a single factor. Over the five years examined, carbonate conditions were most ideal in years of high reported oyster mortality (e.g. 2016), suggesting OA is not likely the sole cause of die-off events. Moreover, if the cause of die-off events were driven by the yearly annual temperature alone, I would have expected 2015 to be the worst of the years investigated for growing oysters, but it was not. Similarly, the observed yearly annual chlorophyll was not low in 2016 relative to other years. Rather, like many farmers reported, it appeared that a “cocktail” of stressors that lead to increased oyster mortality. During the spring bloom of 2016, high temperature and unusual algal blooms may have been two of the key ingredients that lead farmers to be concerned for their product.

Over the 5-year period, the most difficult time for many oyster farmers was in the spring bloom of 2016, when above average temperatures and low biomass converged. These conditions combined may be stressful for oysters, predisposing them to greater mortality due to other environmental properties. For instance, loss of biomass and increased oxygen consumption in oysters have previously been correlated with warmer growing conditions (Lavaud et al., 2017). In light of climate change, some stressors may get worse (Abeysirigunawardena, Gilleland, Bronaugh, & Wong, 2009; Frölicher et al., 2018; Frölicher & Laufkötter, 2018; Haigh et al., 2015; Kharin et al., 2018).

5.2. Local Knowledge informs and focusses research questions

The complexity of natural systems is further complicated by human-environment interactions. To tackle these issues, recent literature emphasizes the need for transdisciplinary research to both integrate knowledge of broad, interacting factors, and develop implementable climate change-related knowledge (DeLorme et al., 2016; Savo et al., 2016). Local and scientific knowledge both have strengths that complement each other, leading to comprehensive, actionable understanding of and response to phenomena (Appeaning Addo & Appeaning Addo, 2016). However, though local perspectives could be essential for climate change preparedness strategies, local knowledge often plays a minimal role in the ecological research that informs this adaptation (Firn, Ladouceur, & Dorrough, 2018). This study emphasizes multiple ways in which local knowledge is an important aspect of developing and focusing climate change-related research and how oyster farmers were one of the fundamental experts in a transdisciplinary project.

First, local knowledge can help ground-truth academic research and model findings. In this study, the alignment of oyster farmers' observations with model results, particularly regarding the warm ocean temperatures during the spring bloom of 2016 supports the modeled temperature patterns from the SSC. While patterns in modelled primary productivity broadly agree with observations, subtleties in spring bloom dynamics (e.g. during 2016) are not always accurately reproduced (Olsen et al. in press). The correspondence of farmers' experience of low oyster food quantities and chlorophyll data collected from BC ferries provide information for model development.

Transdisciplinary research may also result in new interpretations of data, alternative explanations of findings, and innovative products (DeLorme et al., 2016; Phillipson et al., 2012). Oyster farmers' expertise offers a new lens through which to query the SSC, helping prioritize time periods and environmental variables to examine in depth. Moreover, farmers' local knowledge can contribute to alternative, or more developed, explanations of oyster mortality, emphasizing that mortality not simply the impact of increasing ocean acidity on oyster physiology. As a result, more effective management strategies and approaches may be developed.

Considering both local and scientific knowledge contributes to a more complete picture of events and phenomena. Local and scientific knowledge complement each other by providing both specific and broad context, as well as qualitative and quantitative information about a situation (Appeaning Addo & Appeaning Addo, 2016). Local knowledge holders often observe the consequences of environmental change, and those consequences often integrate multiple stressors (Savo et al., 2016). Accordingly, I found that farmers could provide detailed information about observable environmental changes surrounding their tenures, while model results could provide information about the imperceptible mechanisms behind these observations. Moreover, oyster farmers know how environmental changes impact their production and product, while instrumental data quantify the amount of change that has occurred. As a result, this study provides greater understanding of the connection between oyster die-off events and environmental conditions.

Basing research on local knowledge also uncovers research questions and directions that may have otherwise been overlooked (Carmen Lemos et al., 2012). Scientifically testing questions developed based on local knowledge may be effective for both offering explanations for farmers' experiences and revealing environmental dynamics and phenomena that need to be further corroborated scientifically (Firn et al., 2018). Farmers' knowledge shared in this study suggests that high water temperature and low oyster food are likely two of several factors that stressed oysters, leaving them more susceptible to die-off during the spring bloom period of 2016. The knowledge oyster farmers shared also helps inform future research areas regarding environmental conditions, oyster biology, and farming operations (Table 2).

A final, but significant, strength I found of pairing local and scientific knowledge was that local knowledge can caution scientists from directing research towards one factor at the exclusion of other factors when investigating human-environment interactions and the manifestation of environmental change. Through oyster farmers' contributions, this study found that OA was not the sole driver of the challenges faced by BC's oyster farming industry like the media portrays the situation. Rather, farmers emphasized that there are multiple complex environmental factors that contribute to oyster die-off events in coastal BC. Thus, designing climate change adaptation strategies for BC's oyster industry in response to only one factor (e.g. OA) would be narrow and likely ineffective.

There are possible sources of bias in self-reported data, particularly regarding sensitive topics. Sensitive topics include issues that may be associated with social stigma, are controversial in nature, and have negative consequences for respondents if disclosed (Floress et al., 2018; Yan & Cantor, 2019). Oyster die-off events may be a sensitive topic for oyster farmers because product mortality may be stigmatised, questions may seem intrusive, and dissemination of this information could harm an oyster farm's reputation if misinterpreted as an individual's poor husbandry rather than the consequence of global anthropogenic (or other) change. While completing this survey, at least some respondents may have consciously or subconsciously weighed the benefits and risks of answering truthfully based on factors including social desirability, affinity towards the project, and anonymity (Preisendörfer & Wolter, 2014). Different groups may have unique benefits and risks, such as farmers on small versus large farms (Ibid.). Thus, it is possible that some respondents felt incentivized to underreport die-off events and the amount of oyster mortality compared to the past to protect their reputation Figure 3c). However, some farmers have also benefited from sharing this information by using the momentum of hyperbolized media reports to advocate for a broader range of supports for the sector (Drope, 2019).

6. Conclusion

In recent years, amongst other challenges, oyster farmers have experienced periods of poor oyster growing conditions, which media dramatically reported was due to OA. However, these results suggest that, from 2013 to 2017, OA was not overwhelmingly and independently driving oyster mortality; rather, this period was particularly dynamic and included an intense MHW. BC's Pacific coast and farmers' observations emphasized the complexity and multiplicity of factors that stress oysters, predisposing them to die-off events. During this period, many farmers observed warmer water temperatures, a change in oyster food availability, shifts in other species' populations, and evolving weather patterns including warmer temperatures and increased wind and storms. Based on first-hand experience, several farmers associated these changes, particularly high SST and low oyster food availability, with difficult oyster cultivation conditions, which were evident in all regions in 2016.

By taking a transdisciplinary approach, this case study helped ground-truth model outputs, offered new interpretations of model data and other observations, developed a more complete picture of the problem, uncovered overlooked questions, and helped broaden the focus of future research when it comes to addressing real-world, present-day human-environment problems related to oyster farming and environmental change. With data from the SSC and chlorophyll observations, I had the tools to begin investigating one of several uncovered research questions: whether key environmental factors identified by farmers, scientists, and the media – water temperatures, oyster food availability, and OA – were at the root of difficult oyster growing conditions in 2016. Querying model and observational data, informed by farmers' experience, I found that in 2016, relatively high temperatures and low oyster food availability during the spring bloom may have contributed to poor oyster growing conditions, but carbonate conditions were actually better relative to other years. Starting research from the first-hand environmental knowledge and experience of oyster farmers begins to form a clearer and more complete picture of the multiple interacting environmental factors that drive oyster mortality, not solely OA. Thus, oyster farmer's local knowledge is essential for understanding the consequences of global anthropogenic change on oysters and broader industry challenges and for preparing the industry to adapt and be resilient to future changes.

This case study provided insight into challenges faced by BC's oyster aquaculture industry and environmental factors that may contribute to these issues, gathering a qualitative dataset of oyster farmers' first-hand experiences of changes surrounding their tenures as a starting point for future industry research. As uncovered by this project, there are several research areas – other environmental properties, weather, species interactions, future environmental changes, and oyster resiliency – through which future transdisciplinary research can build on this study. Oyster farmers communicated that environmental conditions beyond OA in 2016 were poor for the industry, which was supported by the SSC results, emphasizing that future oyster aquaculture research and adaptation strategies needs to combine local knowledge and academia and be based on a multi-stressor approach.

References

Abeysirigunawardena, D. S., Gilleland, E., Bronaugh, D., & Wong, P. (2009). Extreme wind regime responses to climate variability and change in the inner south coast of British Columbia, Canada. *Atmosphere - Ocean*, *47*(1), 41–62. https://doi.org/10.3137/AO1003.2009

Allen, E., Kruger, C., Leung, F. Y., & Stephens, J. C. (2013). Diverse perceptions of stakeholder engagement within an environmental modeling research team. *Journal of Environmental Studies and Sciences*, *3*(3), 343–356. https://doi.org/10.1007/s13412-013-0136-x

Allen, S. E., & Wolfe, M. A. (2013). Hindcast of the timing of the spring phytoplankton bloom in the strait of Georgia, 1968-2010. *Progress in Oceanography*, *115*, 6–13. https://doi.org/10.1016/j.pocean.2013.05.026

Appeaning Addo, K., & Appeaning Addo, I. (2016). Coastal erosion management in Accra: Combining local knowledge and empirical research. *Jàmbá: Journal of Disaster Risk Studies*, *8*(1), 1–10. https://doi.org/10.4102/jamba.v8i1.274

Banas, N., Hickey, B., Newton, J., & Ruesink, J. (2007). Tidal exchange, bivalve grazing, and patterns of primary production in Willapa Bay, Washington, USA. *Marine Ecology Progress Series*, *341*, 123–139. https://doi.org/10.3354/meps341123

Barton, A., Hales, B., Waldbusser, G. G., Langdon, C., & Feely, R. A. (2012). The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography*, *57*(3), 698–710. https://doi.org/10.4319/lo.2012.57.3.0698

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, *42*(9), 3414–3420. https://doi.org/10.1002/2015GL063306

Botta, R., Asche, F., Borsum, J. S., & Camp, E. V. (2020). A review of global oyster aquaculture production and consumption. *Marine Policy*, *117*, 103952. https://doi.org/10.1016/j.marpol.2020.103952

Bourdon, R. (2015). *Interactions between fish communities and shellfish aquaculture in Baynes Sound, British Columbia*.

Brewer, P. G. (2013). A short history of ocean acidification science in the 20th century: a chemist's view. *Biogeosciences Discuss*, *10*, 8715–8748. https://doi.org/10.5194/bgd-10-8715-2013

Brodeur, R., Perry, I., Boldt, J., Flostrand, L., Galbraith, M., King, J., … Thompson, A. (2018). *An unusual gelatinous plankton event in the NE Pacific: The Great Pyrosome Bloom of 2017*. Retrieved from https://www.researchgate.net/publication/322665037

Byg, A., & Salick, J. (2009). Local perspectives on a global phenomenon-Climate change in Eastern Tibetan villages. *Global Environmental Change*, *19*(2), 156–166. https://doi.org/10.1016/j.gloenvcha.2009.01.010

Byrne, R. H. (2014). Measuring ocean acidification: New technology for a new era of ocean chemistry. *Environmental Science and Technology*, *48*(10), 5352–5360. https://doi.org/10.1021/es405819p

Carmen Lemos, M., Kirchhoff, C. J., & Ramprasad, V. (2012). Narrowing the climate information usability gap. https://doi.org/10.1038/NCLIMATE1614

Carrasco, M. F., & Barón, P. J. (2010). Analysis of the potential geographic range of the Pacific oyster Crassostrea gigas (Thunberg, 1793) based on surface seawater temperature satellite data and climate charts: The coast of South America as a study case. *Biological Invasions*, *12*(8), 2597–2607. https://doi.org/10.1007/s10530-009-9668-0

Chandler, P. C., King, S. A., & Boldt, J. (Eds.). (2017). *State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2016. Canadian Technical Report of Fisheries and Aquatic Sciences* (3225th ed.). Nanaimo. Retrieved from http://waves-vagues.dfo-mpo.gc.ca/Library/40617944.pdf

Chandler, P. C., King, S. A., & Boldt, J. (Eds.). (2018). *State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2017 Canadian Technical Report of Fisheries and Aquatic Sciences* (3266th ed.).

Nanaimo.

Chandler, P. C., King, S. A., & Perry, R. I. (Eds.). (2015). *State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2014 Canadian technical report of fisheries and aquatic sciences* (Vol. 3131). Nanaimo.

Chandler, P. C., King, S. A., & Perry, R. I. (Eds.). (2016). *State of the physical , biological and selected fishery resources of Pacific Canadian marine ecosystems in 2015 Canadian technical report of fisheries and aquatic sciences* (3179th ed.). Nanaimo.

Collins, A. K., Allen, S. E., & Pawlowicz, R. (2009). The role of wind in determining the timing of the spring bloom in the Strait of Georgia. *Canadian Journal of Fisheries and Aquatic Sciences*, *66*(9), 1597–1616. https://doi.org/10.1139/F09-071

Cooley, S. R., Lucey, N., Kite-Powell, H., & Doney, S. C. (2012). Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. *Fish and Fisheries*, *13*(2), 182–215. https://doi.org/10.1111/j.1467-2979.2011.00424.x

de Melo, C. M. R., Divilov, K., Schoolfield, B., & Langdon, C. (2019). Selection of group and individual traits of Pacific oysters (Crassostrea gigas) on the West Coast, US. *Aquaculture*, *512*, 734389. https://doi.org/10.1016/j.aquaculture.2019.734389

de Melo, C. M. R., Durland, E., & Langdon, C. (2016). Improvements in desirable traits of the Pacific oyster, Crassostrea gigas, as a result of five generations of selection on the West Coast, USA. *Aquaculture*, *460*, 105–115. https://doi.org/10.1016/j.aquaculture.2016.04.017

DeLorme, D. E., Kidwell, D., Hagen, S. C., & Stephens, S. H. (2016). Developing and managing transdisciplinary and transformative research on the coastal dynamics of sea level rise: Experiences and lessons learned. *Earth's Future*, *4*(5), 194–209. https://doi.org/10.1002/2015EF000346

Drope, N. (2019). *Media representations and shellfish farmer perceptions of ocean acidification in the British Columbia shellfish aquaculture sector*. University of Guelph.

Engida, Z. (2016). *Remote forcing of subsurface currents and temperatures near the northern limit of the California Current System*. University of Victoria. https://doi.org/10.1002/2016JC011880

Fedje, D. W., Mackie, A. P., Wigen, R. J., Mackie, Q., & Lake, C. (2005). Kilgii Gwaay: An early maritime site in the south of Haida Gwaii. In D. W. Fedje & R. Mathewes (Eds.), *Haida Gwaii: Human history and environment from the time of loon to the time the Iron People* (pp. 187–203). Vancouver: UBC Press.

Firn, J., Ladouceur, E., & Dorrough, J. (2018). Integrating local knowledge and research to refine the management of an invasive non-native grass in critically endangered grassy woodlands. *Journal of Applied Ecology*, *55*(1), 321–330. https://doi.org/10.1111/1365-2664.12928

Fisheries and Oceans Canada. (2018). Shellfish BC aquaculture licence holders (for processors). Fisheries & Oceans Canada. Retrieved from https://open.canada.ca/data/en/dataset/522d1b67-30d8-4a34-9b62-5da99b1035e6

Fleming-Lehtinen, V., & Laamanen, M. (2012). Long-term changes in Secchi depth and the role of phytoplankton in explaining light attenuation in the Baltic Sea. *Estuarine, Coastal and Shelf Science*, *102–103*, 1–10. https://doi.org/10.1016/j.ecss.2012.02.015

Floress, K., Reimer, A., Thompson, A., Burbach, M., Knutson, C., Prokopy, L., … Ulrich-Schad, J. (2018). Measuring farmer conservation behaviors: Challenges and best practices. *Land Use Policy*, *70*, 414–418. https://doi.org/10.1016/j.landusepol.2017.11.030

Foreman, M. G. G., Stucchi, D. J., Garver, K. A., Tuele, D., Isaac, J., Grime, T., … Morrison, J. (2012). A circulation model for the discovery Islands, British Columbia. In *Atmosphere - Ocean*. https://doi.org/10.1080/07055900.2012.686900

Freeland, H., & Ross, T. (2019). 'The Blob' - or, how unusual were ocean temperatures in the Northeast Pacific during 2014-2018? *Deep-Sea Research Part I: Oceanographic Research Papers*, *150*, 103061. https://doi.org/10.1016/j.dsr.2019.06.007

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*(7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

Frölicher, T. L., & Laufkötter, C. (2018). Emerging risks from marine heat waves. *Nature Communications*. Nature Publishing Group. https://doi.org/10.1038/s41467-018-03163-6

Fuhrmann, M., Richard, G., Quéré, C., Petton, B., & Pernet, F. (2019). Low pH reduced survival of the oyster Crassostrea gigas exposed to the Ostreid herpesvirus 1 by altering the metabolic response of the host. *Aquaculture*, *503*, 167–174. https://doi.org/10.1016/j.aquaculture.2018.12.052

Gimenez, I., Waldbusser, G. G., & Hales, B. (2018). Ocean acidification stress index for shellfish (OASIS): Linking Pacific oyster larval survival and exposure to variable carbonate chemistry regimes. *Elementa*, *6*(1). https://doi.org/10.1525/elementa.306

Glover, D., Zanotti, L., & Sepez, J. (2010). Local Communities and Natural Resources: Ethnobiology in Practice. In *Environmental Social Sciences: Methods and Research Design* (pp. 110–131). Retrieved from https://soundideas.pugetsound.edu/faculty_pubs/839/

Government of Canada. (2017). Farmed Oysters. Retrieved from https://www.dfo-mpo.gc.ca/aquaculture/sector-secteur/species-especes/oysters-huitres-eng.htm

Green, T. J., Siboni, N., King, W. L., Labbate, M., Seymour, J. R., & Raftos, D. (2019). Simulated marine heat wave alters abundance and structure of vibrio populations associated with the Pacific oyster resulting in a mass mortality event. *Microbial Ecology*, *77*(3), 736–747. https://doi.org/10.1007/s00248-018-1242-9

Gruber, N. (2011). Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Trans. R. Soc. A*, *369*. https://doi.org/10.1098/rsta.2011.0003

Haigh, R., Ianson, D., Holt, C. A., Neate, H. E., & Edwards, A. M. (2015). Effects of ocean acidification on temperate coastal marine ecosystems and fisheries in the northeast pacific. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0117533

Hallegraeff, G. M. (2010, April 1). Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology*. John Wiley & Sons, Ltd. https://doi.org/10.1111/j.1529-8817.2010.00815.x

Hershberger, P. (2020). Climate change can drive marine diseases. In *Marine Disease Ecology* (pp. 83–94). https://doi.org/10.1093/oso/9780198821632.003.0005

Holden, J. J., Collicutt, B., Covernton, G., Cox, K. D., Lancaster, D., Dudas, S. E., … Jacob, A. L. (2019). Synergies on the coast: Challenges facing shellfish aquaculture development on the central and north coast of British Columbia. *Marine Policy*, *101*, 108–117. https://doi.org/10.1016/j.marpol.2019.01.001

Hume, M. (2014). Mystery surrounds massive die-off of oysters and scallops off B.C. coast. Retrieved June 24, 2020, from https://www.theglobeandmail.com/news/british-columbia/mystery-surrounds-massive-die-off-of-oysters-and-scallops-off-bc-coast/article17156108/

Ianson, D. (2013). The increase in carbon along the Canadian Pacific coast. *Canadian Technical Report of Fisherieis and Aquatic Sciences*, *3032*, xi + 113p.

Ianson, D., Allen, S. E., Moore-Maley, B. L., Johannessen, S. C., & Macdonald, and R. W. (2016). Vulnerability of a semienclosed estuarine sea to ocean acidification in contrast with hypoxia. *Geophysical Research Letters*, *43*(11), 5793–5801. https://doi.org/10.1002/2016GL068996

IPCC. (2018). Global Warming of 1.5 °C. *IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*.

Jarníková, T., Ianson, D., Allen, S. E., Shao, A., & Olson, E. M. (2020). No Modest uptake of CO2 has already shifted some coastal systems to aragonite undersaturationTitle. *Nature-Geosciences*.

Kharin, V. V., Flato, G. M., Zhang, X., Gillett, N. P., Zwiers, F., & Anderson, K. J. (2018). Risks from climate extremes change differently from 1.5°C to 2.0°C depending on rarity. *Earth's Future*, *6*(5), 704–715.

https://doi.org/10.1002/2018EF000813@10.1002/(ISSN)2328-4277.HAZARDS1

Lavaud, R., La Peyre, M. K., Casas, S. M., Bacher, C., & La Peyre, J. F. (2017). Integrating the effects of salinity on the physiology of the eastern oyster, Crassostrea virginica, in the northern Gulf of Mexico through a Dynamic Energy Budget model. *Ecological Modelling*, *363*(November), 221–233. https://doi.org/10.1016/j.ecolmodel.2017.09.003

LeBlond, P. H. (1983). The Strait of Georgia: functional anatomy of a coastal sea. *Canadian Journal of Fisheries and Aquatic Sciences*, *40*(7), 1033–1063. https://doi.org/10.1139/f83-128

Li, C., Zwiers, F., Zhang, X., Chen, G., Lu, J., Li, G., … Liu, M. (2019). Larger increases in more extreme local precipitation events as climate warms. *Geophysical Research Letters*, *46*(12), 6885–6891. https://doi.org/10.1029/2019GL082908

Luymes, G. (2015). Increase in shellfish deaths causes “full-scale panic” for B.C. industry. Retrieved June 24, 2020, from https://www.timescolonist.com/news/b-c/increase-in-shellfish-deaths-causes-full-scale-panic-for-b-c-industry-1.1765167

Mabardy, R. A., Waldbusser, G. G., Conway, F., & Olsen, C. S. (2015). Perception and response of the US west coast shellfish industry to ocean acidification: The voice of the canaries in the coal mine. *Journal of Shellfish Research*, *34*(2), 565–572.

Mahara, N., Pakhomov, E. A., Jackson, J. M., & Hunt, B. P. (2019). Seasonal zooplankton development in a temperate semi-enclosed basin: two years with different spring bloom timing. *Journal of Plankton Research*, *41*(3), 309–328. https://doi.org/10.1093/plankt/fbz016

Masson, D. (2006). Seasonal water mass analysis for the Straits of Juan de Fuca and Georgia. *Atmosphere - Ocean*, *44*(1), 1–15. https://doi.org/10.3137/ao.440101

Masson, D., & Peña, A. (2009). Chlorophyll distribution in a temperate estuary: The Strait of Georgia and Juan de Fuca Strait. *Estuarine, Coastal and Shelf Science*, *82*(1), 19–28. https://doi.org/10.1016/j.ecss.2008.12.022

Millero, F. J. (2010). Carbonate constants for estuarine waters. *Marine and Freshwater*

Research, *61*(2), 139. https://doi.org/10.1071/MF09254

Moore-Maley, B. L., Allen, S. E., & Ianson, D. (2016). Locally driven interannual variability of near-surface pH and Ωa in the Strait of Georgia. *Journal of Geophysical Research: Oceans*. https://doi.org/10.1002/2015JC011118

Mudie, P. J., Rochon, A., & Levac, E. (2002). Palynological records of red tide-producing species in Canada: Past trends and implications for the future. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *180*(1–3), 159–186. https://doi.org/10.1016/S0031-0182(01)00427-8

Olson, E. M., Allen, S. E., Do, V., Dunphy, M., & Ianson, D. (2020). Assessment of nutrient supply by a tidal jet in the northern Strait of Georgia based on a biogeochemical model. *Journal of Geophysical Research: Oceans*. https://doi.org/10.1029/2019JC015766

Owsianik, J. (2012). Could acidic waters ruin B.C.'s shellfish industry? Retrieved June 24, 2020, from https://bc.ctvnews.ca/could-acidic-waters-ruin-b-c-s-shellfish-industry-1.951533/comments-7.324249

Phillipson, J., Lowe, P., Proctor, A., & Ruto, E. (2012). Stakeholder engagement and knowledge exchange in environmental research. *Journal of Environmental Management*, *95*(1), 56–65. https://doi.org/10.1016/j.jenvman.2011.10.005

Pietkiewicz, I., & Smith, J. A. (2014). A practical guide to using interpretative phenomenological analysis. *Psychological Journal*, *20*, 7–14. https://doi.org/10.14691/CPPJ.20.1.7

Preisendörfer, P., & Wolter, F. (2014). Who is telling the truth? A validation study on determinants of response behavior in surveys. *Public Opinion Quarterly*, *78*(1), 126–146. https://doi.org/10.1093/poq/nft079

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., … Watson, A. (2005). *Ocean acidification due to increasing atmospheric carbon dioxide*. Retrieved from www.royalsoc.ac.uk

Reyes-García, V., Fernández-Llamazares, Á., Guèze, M., Garcés, A., Mallo, M., Vila-

Gómez, M., & Vilaseca, M. (2016). Local indicators of climate change: the potential contribution of local knowledge to climate research. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(1), 109–124. https://doi.org/10.1002/wcc.374

Ried, R. (2020). *Integrated Fisheries Management Plan Summary Pacific Oyster (Crassostrea gigas) Pacific Region2020/21*. Vancouver.

Savo, V., Lepofsky, D., Benner, J. P., Kohfeld, K. E., Bailey, J., & Lertzman, K. (2016). Observations of climate change among subsistence-oriented communities around the world. https://doi.org/10.1038/NCLIMATE2958

Silver, J. J. (2014). Shellfish and coastal change: Pacific oysters and Manila clams in BC waters. *BC Studies: The British Columbian Quarterly*, (181), 83–103. Retrieved from https://search-proquest-com.proxy.lib.sfu.ca/docview/1535632812?rfr_id=info%3Axri%2Fsid%3Aprimo

Taylor, F. J. R., & Haigh, R. (1993). The ecology of fish-killing blooms of the chloromonad flagellate Heterosigma in the Strait of Georgia and adjacent waters. In T. Smayda & Y. Shimuzu (Eds.), *Toxic phytoplankton blooms in the sea* (pp. 705–710). Retrieved from https://ci.nii.ac.jp/naid/10006328178/

Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2015, July 24). Attribution of climate extreme events. *Nature Climate Change*. Nature Publishing Group. https://doi.org/10.1038/nclimate2657

Venkataraman, Y. R., Spencer, L. H., & Roberts, S. B. (2019). Larval response to parental low pH exposure in the Pacific oyster Crassostrea gigas. *Journal of Shellfish Research*, *38*(3), 743. https://doi.org/10.2983/035.038.0325

Waldbusser, G. G., Hales, B., Langdon, C. J., Haley, B. A., Schrader, P., Brunner, E. L., … Hutchinson, G. (2015). Ocean acidification has multiple modes of action on bivalve larvae. https://doi.org/10.1371/journal.pone.0128376

Waldbusser, G. G., & Salisbury, J. E. (2013). Ocean acidification in the coastal zone from an organism’s perspective: Multiple aystem parameters, frequency domains, and habitats. https://doi.org/10.1146/annurev-marine-121211-172238

Weather: La Niña - Canada.ca. (n.d.). Retrieved February 14, 2020, from https://www.canada.ca/en/environment-climate-change/services/la-nina.html

Wong, P. P., Losada, I. J., Gattuso, J. P., Hinkel, J., Khattabi, A., McInnes, K. L., … Amez, S. (2015). Coastal systems and low-lying areas. In *Climate Change 2014 Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects*. https://doi.org/10.1017/CBO9781107415379.010

Yan, T., & Cantor, D. (2019). Asking survey questions about criminal justice involvement. *Public Health Reports*, *134*, 46S-56S. https://doi.org/10.1177/0033354919826566

Appendices

Appendix A. Survey Questions

Ocean Change and Shellfish Farming in British Columbia

1. Please identify the region where the farm you own and/or work on is located.

- 1. Southern Strait of Georgia (1)
- 2. Baynes Sound (2)
- 3. Discovery Island (3)
- 4. Outer Coast/Juan de Fuca Strait (4)
- 5. North Coast (5)

2. How long has the farm been in operation?

- Less than 5 years (1)
- 5 to 10 years (2)
- 11 to 20 years (3)
- 21 to 30 years (4)
- More than 30 years (5)

3. How long have you owned and/or worked at this farm?

- Less than 5 years (1)
- 5 to 10 years (2)
- 11 to 20 years (3)
- 21 to 30 years (4)
- More than 30 years (5)

4. Are you a member of the BC Shellfish Growers Association?

- Yes (1)
- No (2)

5. Please select the farm's size classification.

- Small: 1 to 3 employees, up to 25,000 dozens oysters (or equivalent) per year. (1)
- Medium: up to 8 employees, up to 50,000 dozens per year. (2)
- Large: up to 16 employees, average of 175,000 dozens per year. (3)
- Extra-Large: More than 16 employees, 1,000,000 dozens per year. (4)

6. Please select what kinds of shellfish are grown on the farm (select all that apply):

- ☐ Oysters (1)
- ☐ Clams (2)
- ☐ Scallops (3)
- ☐ Mussels (4)
- ☐ Geoduck (5)
- ☐ Other species (please specify) (6)

7. Does the farm currently do environmental monitoring or take measurements related to the following and do you keep records (please check all that apply):

	Monitored?			Keep Records?		
	Yes (1)	No (2)	Don't know (3)	Yes (1)	No (2)	Don't know (3)
Biotoxins (1)	o	o	o	o	o	o
Predation (2)	o	o	o	o	o	o
Phytoplankton species composition (3)	o	o	o	o	o	o
Water temperature (4)	o	o	o	o	o	o
Dissolved oxygen (5)	o	o	o	o	o	o
Salinity (6)	o	o	o	o	o	o
Oyster genetics (7)	o	o	o	o	o	o
Vibrio (8)	o	o	o	o	o	o
Water clarity (9)	o	o	o	o	o	o
Weather (12)	o	o	o	o	o	o
Wind direction (13)	o	o	o	o	o	o
Rainfall (14)	o	o	o	o	o	o
Other (please specify) (11)	o	o	o	o	o	o

If you have observed any of the following environmental changes while you've been working on the farm, please select all that apply:

- ☐ Water temperature (1)
- ☐ Water salinity (2)
- ☐ Water Quality (e.g. oxygen, pH). (3)
- ☐ Other existing species on the lease, but not farmed (e.g. change in behaviour, population) (4)
- ☐ New species on the lease, but not farmed. (e.g. invasive, introduced) (5)
- ☐ Available food (phytoplankton densities). (6)
- ☐ Changes in food timing (e.g. timing of spring bloom). (7)
- ☐ Harmful algal blooms (12)
- ☐ Weather patterns (9)
- ☐ Extreme weather events (e.g. storms). (10)
- ☐ Coastal landforms (e.g. erosion, landslides) (11)
- ☐ Other (13)

Now that you have told us what changes you have noticed in your surrounding environment, we'd like a bit more information.

For each change, please select:
Direction*: Has the change gone up or down*
How much: *The amount of change observed*
Impact: *How each change affects production on the shellfish farm*
Timing: *Over what period you observed the change*

If you have not observed a change, select "no change." If you are unsure, select "don't know."

8. Water temperature

	Much cooler (1)	Somewhat cooler (2)	Somewhat warmer (3)	Much warmer (4)	No Change (5)	Don't know (6)
Direction (1)	o	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No Change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

9. Water salinity

	Much less salty (1)	Somewhat less salty (2)	Somewhat saltier (3)	Much saltier (4)	No Change (5)	Don't know (6)
How much (1)	o	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

10. Water Quality (e.g. oxygen, pH).
Describe change:

____

____

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

11. Other existing species on the lease, but not farmed (e.g. change in behaviour, population)
Describe change:

____
____

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

12. New species on the lease, but not farmed. (e.g. invasive, introduced)

What species:

____
____

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

13. Available food (phytoplankton densities).

	Much less (1)	Somewhat less (2)	Somewhat more (3)	Much more (4)	No change (5)	Don't know (6)
Direction (1)	o	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

14. Changes in food timing (e.g. timing of spring bloom).

	Much sooner (1)	Somewhat sooner (2)	Somewhat later (3)	Much later (4)	No Change (5)	Don't know (6)
Direction (1)	o	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

15. Harmful algal blooms

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

16. Weather patterns
Describe:

____
____

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

17. Extreme weather events (e.g. storms).
Describe:

____
____

	Much less (1)	Somewhat less (2)	Somewhat more (3)	Much more (4)	No Change (5)	Don't know (6)
Direction (1)	o	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

18. Coastal landforms (e.g. erosion, landslides)

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

19. Other changes you observed in your surrounding environment.
Describe:

____
____

	Small (1)	Medium (2)	Large (3)	No Change (4)	Don't know (5)
How much (1)	o	o	o	o	o

	Highly negative (1)	Somewhat negative (2)	Neutral (3)	Somewhat positive (4)	Highly positive (5)	No change (6)	Don't know (7)
Impact (1)	o	o	o	o	o	o	o

	This year (1)	Last 5 years (2)	Last 10 years (3)	Last 20 years (4)	30+ years (5)	No change (6)	Don't know (7)
Timing (1)	o	o	o	o	o	o	o

27. Was there a period of time in the past 5 years when you were particularly concerned about your stock due to environmental conditions?
Describe:
____
____

*Please answer the questions in this section with only **oysters** in mind.*

28. Do you farm oysters?
- o Yes (1)
- o No (2)

29. What is your biggest challenge about oyster farming?
____
____

30. What size of oysters are currently grown on the farm (please select all that apply)?
- ▢ Cocktail (1)
- ▢ Extra-small (2)
- ▢ Small (3)
- ▢ Medium (4)
- ▢ Large (5)
- ▢ Extra-large (6)

31. What growing method(s) are currently used (please select all that apply)?
- ▢ Beach hardened (1)
- ▢ Intertidal beach (2)
- ▢ Suspended bags (3)
- ▢ Suspended trays (4)
- ▢ Suspended rope lines (5)
- ▢ Other (please specify) (6) ____

32. Where does the farm currently get oyster seed from (please select all that apply)?

- ☐ British Columbia (1)
- ☐ Elsewhere in Canada (2)
- ☐ Washington/Oregon (3)
- ☐ Elsewhere in North America (4)
- ☐ Hawaii (5)
- ☐ Chile (6)
- ☐ Elsewhere in South America (7)
- ☐ Europe (9)
- ☐ Other (please specify) (8) ____

33. Compared to annual oyster mortality on the farm about 5 years ago, what was the typical rate of oyster mortality in 2017:

- o Greater (1)
- o Roughly the same (2)
- o Less (3)
- o Don't know (4)
- o Farm is less than 5 years old (5)

34. Compared to annual oyster mortality on the farm about 10 years ago, what was the typical rate of oyster mortality in 2017:

- o Greater (1)
- o Roughly the same (2)
- o Less (3)
- o Don't know (4)
- o Farm is less than 10 years old (5)

35. Compared to annual oyster mortality on the farm about 20 years ago, what was the typical rate of oyster mortality in 2017:

- o Greater (1)
- o Roughly the same (2)
- o Less (3)
- o Don't know (4)
- o Farm is less than 20 years old (5)

36. Compared to annual oyster mortality on the farm about 30+ years ago, what was the typical rate of oyster mortality in 2017:

- o Greater (1)
- o Roughly the same (2)
- o Less (3)
- o Don't know (4)
- o Farm is less than 30 years old (5)

37. An oyster die-off event is a short time period in which a significant proportion of spat, juvenile, and/or adult oysters die. Has the farm ever had an oyster die-off event?

- o Yes (1)
- o No (2)

38. How long ago did the last oyster die-off event occur?

- o Within the last year (1)
- o 1-2 years ago (6)
- o 3-5 years ago (2)
- o 6-10 years ago (3)
- o 11-20 years ago (4)
- o More than 20 years ago (5)

39. Has the farm changed anything in response to oyster die-offs (please select all that apply)?

- ▢ Oyster depth (1)
- ▢ Where you get your oyster seed (2)
- ▢ Seed size when placed in natural conditions (3)
- ▢ Monitoring (4)
- ▢ Handling (5)
- ▢ Outplanting gear (e.g. tray type) (8)
- ▢ Timing (10)
- ▢ None (6)
- ▢ Other (please specify) (7) ____

40. Are there environmental indicators when a die-off occurs?

____
____

41. What do you think is the main cause of oyster die-off events within the BC Shellfish Farming Sector?

____
____

Appendix B. 2018 Map of Shellfish Licences

Figure B. Fisheries and Oceans Canada's map of 2018 shellfish aquaculture licences obtained from https://www.dfo-mpo.gc.ca/aquaculture/bc-cb/docs/maps-cartes/shell-conch-eng.pdf in the summer of 2018. The four study regions are outline in white.

Appendix C. Table of themes and subthemes

Table C. Explanations of themes (bolded words) and subthemes (italicized words) coded on NVivo 12 (Section 2.1).

Environmental Conditions: Features of oysters' surrounding natural environmental that influence mortality.

Algal blooms	Phytoplankton species and composition, including harmful species and plankton on which oysters feed.
Animals	The presence of other animals influences oyster production (e.g. predation, crowding, clear).
General conditions	Acknowledging that the natural environment influences oyster growth without specifying a single factor (e.g. water quality, multiple factors).
Heat and warm periods	Times when oyster growing conditions are warm (e.g. summer, notably warmer water).
Macroalgae	The presence of new seaweed.
Ocean acidification	Signs that oyster growth is affected by pH.
Weather	Conditions including wind, rain, and freezing.

Farming Operations: The business and procedures of oyster aquaculture.

Closures	Periods when the Department of Fisheries mandates farmers cannot harvest their product, typically due to the presence of bacteria and viruses that are harmful to humans.
Costs	Financial considerations (e.g. maintaining infrastructure, staffing, purchasing seed) and making a profit.
Handling	Adequate, knowledgeable staff.
Infrastructure	Equipment used for oyster aquaculture (e.g. trays, Floating Upweller System).
Sales	Getting oysters to market (e.g. processing plant, market demand).
Seed availability and supply	Farmers' ability to purchase safe, adequate seed.

Oyster Biology: Oyster characteristics that influence mortality.

Disease and viruses	Factors that effect oysters' health.
Genetic strain	Oyster characteristics based on where the seed is from (seed source and family).
Negative growth	Signs of unhealthy growth (size, shell abnormalities)
Positive growth	Natural sets of oysters or signs of healthy growth (growth rate, meat, shell, etc.)
Survival	Oysters are dying (at any life stage).

Unsure or Mix: Respondents either do not know what factors or emphasize that the combination of several factors contribute to the overall effect.

Appendix D. SalishSeaCast Sampling Locations

Region	Point	Latitude	Longitude
Baynes Sound	Deep Bay	49.4606	-124.7392
	Southern Baynes	49.4760	-124.7457
	Northern Baynes	49.6492	-124.8924
	Fanny Bay	49.5086	-124.8227
Southern SoG	Maple Bay	48.8140	-123.5947
	Salt Spring	48.7993	-123.5513
	Nanoose Bay	49.2609	-124.1359
	Lasqueti Island	49.5442	-124.3384
	Main SoG	49.1177	-123.5832
Discovery Islands	Cortes/Marina	50.0418	-125.0194
	Lund/Desolation Sound	49.9804	-124.7666
	Mouth of Okeover	50.0805	-124.8174

Appendix E. Consecutive days over a temperature threshold

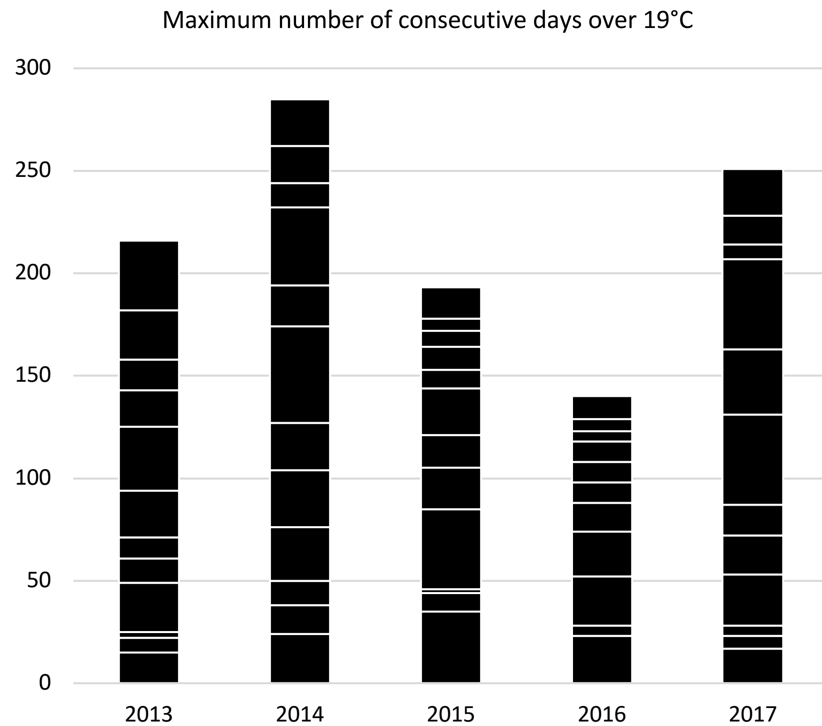
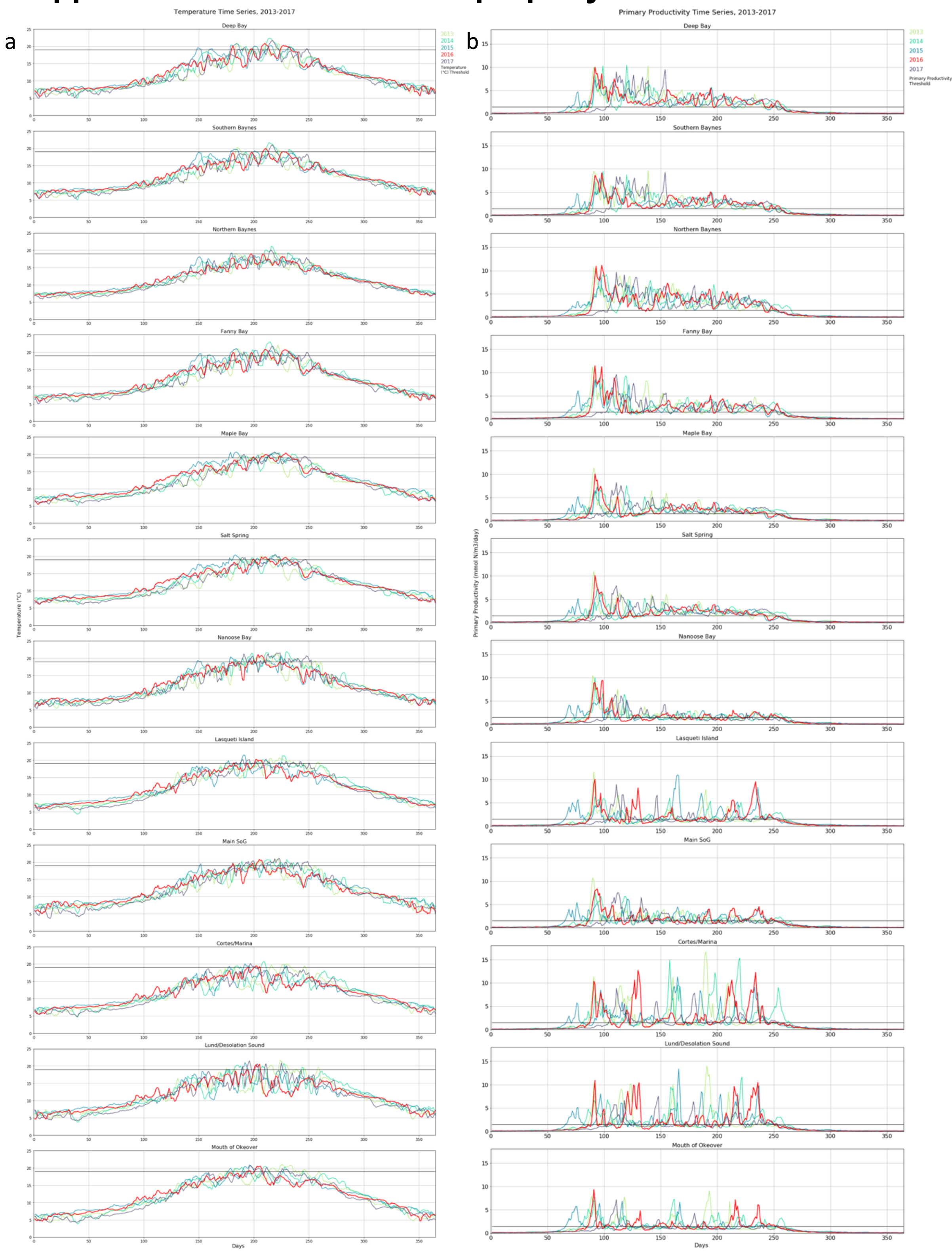


Figure D. Data are from the SSC. The maximum number of consecutive days over a temperature threshold of 19°C by year. Annual traces (Appendix F.1) show that most years exceed, but do not sustain for extended periods temperatures above 19°C in the warmest months, making 19°C a good threshold to visualize differences in yearly warm periods. Each year is composed of the maximum number of consecutive days above the threshold at each of the 12 model sample locations, distinguished by white lines.

Appendix F.1. Environmental property annual traces



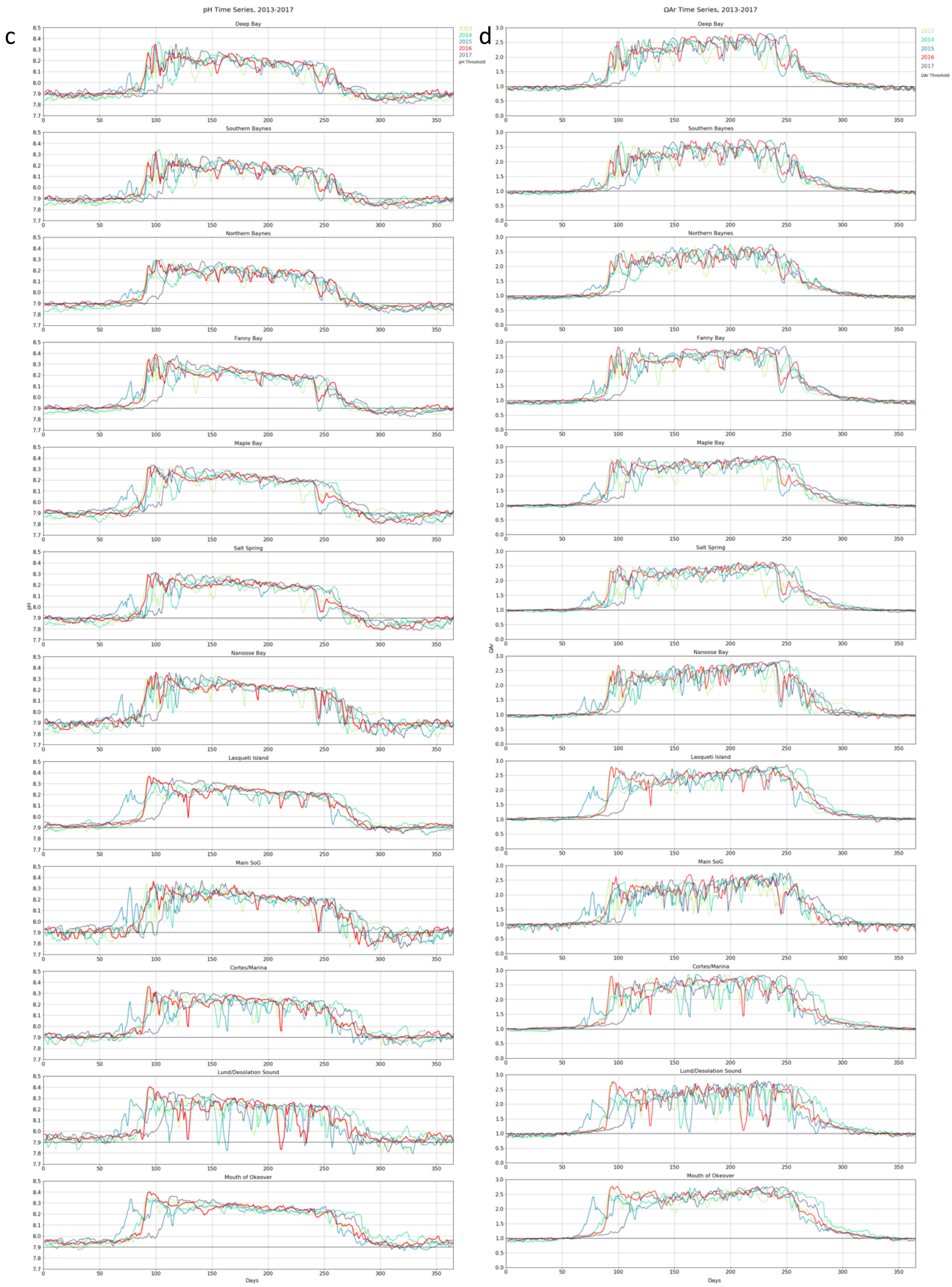
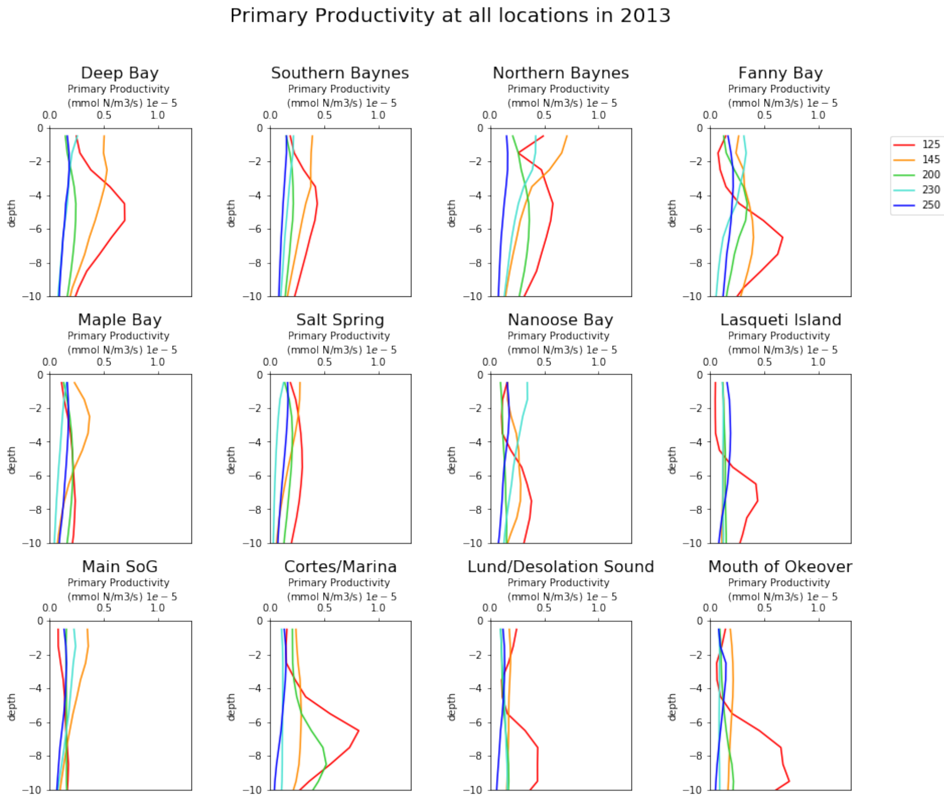


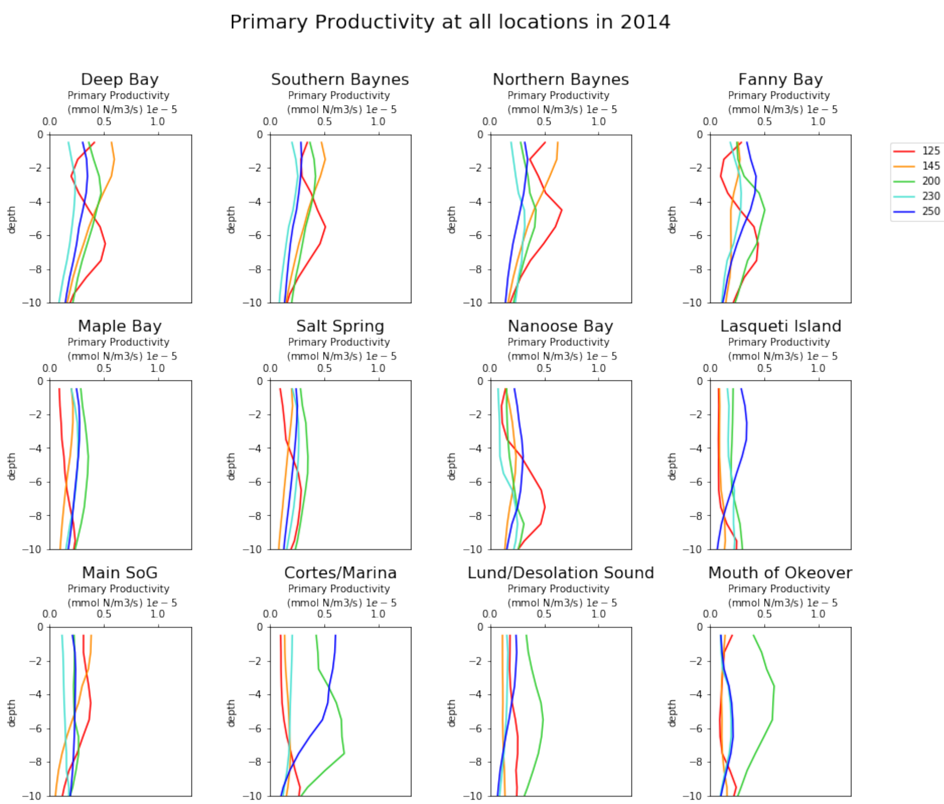
Figure E.1. Annual traces of a) temperature, b) primary productivity, c) pH, and d) Ω_{Ar} data from the SSC. The year 2016 is highlighted in red.

Appendix F.2. Primary productivity profiles

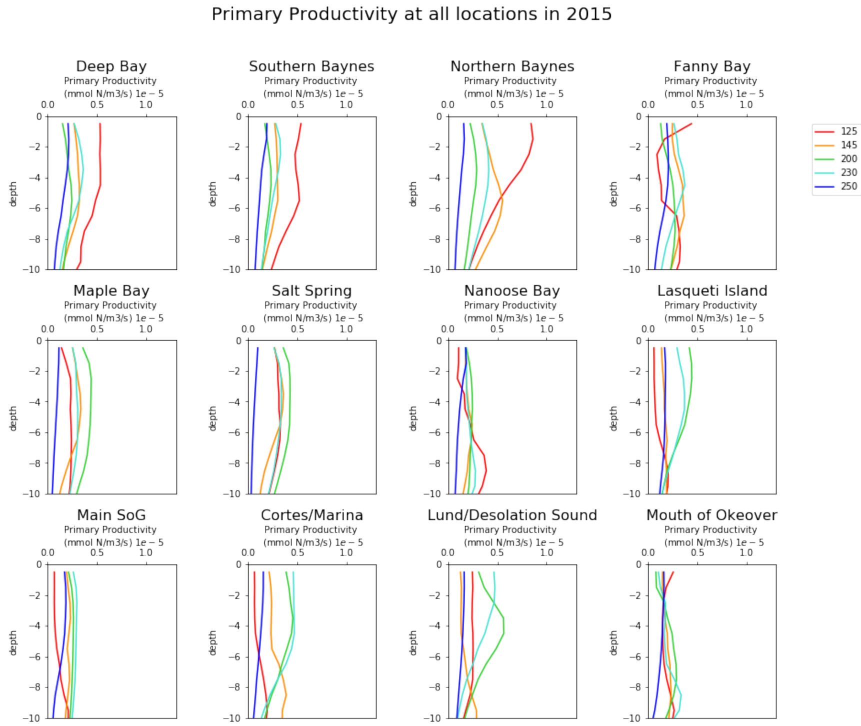
a



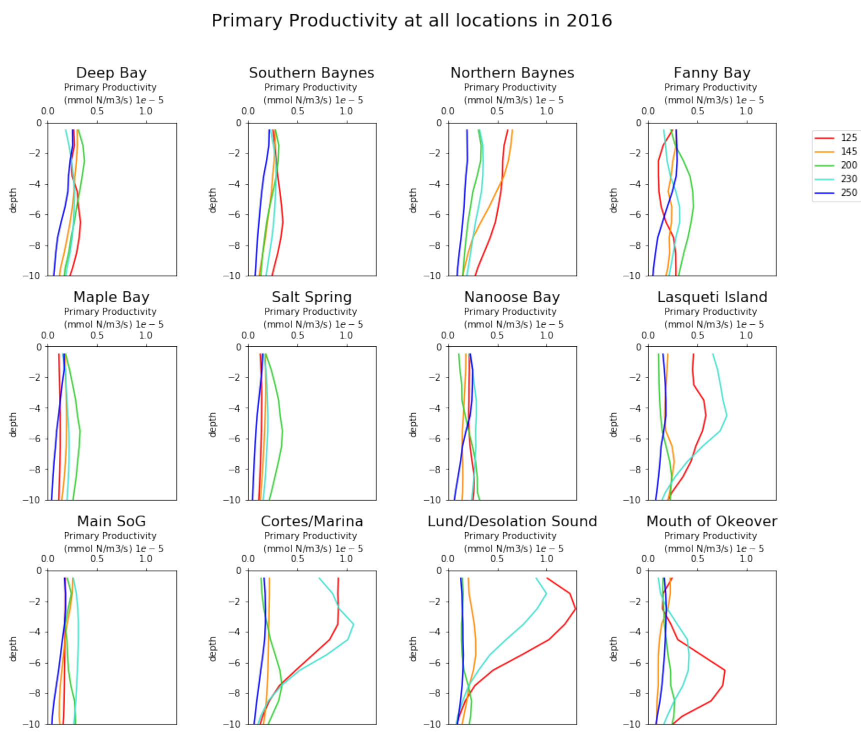
b



c


Primary Productivity at all locations in 2015
Deep Bay
Southern Baynes
Northern Baynes
Fanny Bay
Maple Bay
Salt Spring
Nanoose Bay
Lasqueti Island
Main SoG
Cortes/Marina
Lund/Desolation Sound
Mouth of Okeover
Primary Productivity (mmol N/m3/s) 1e − 5
depth
125
145
200
230
250

d


Primary Productivity at all locations in 2016
Deep Bay
Southern Baynes
Northern Baynes
Fanny Bay
Maple Bay
Salt Spring
Nanoose Bay
Lasqueti Island
Main SoG
Cortes/Marina
Lund/Desolation Sound
Mouth of Okeover
Primary Productivity (mmol N/m3/s) 1e − 5
depth
125
145
200
230
250

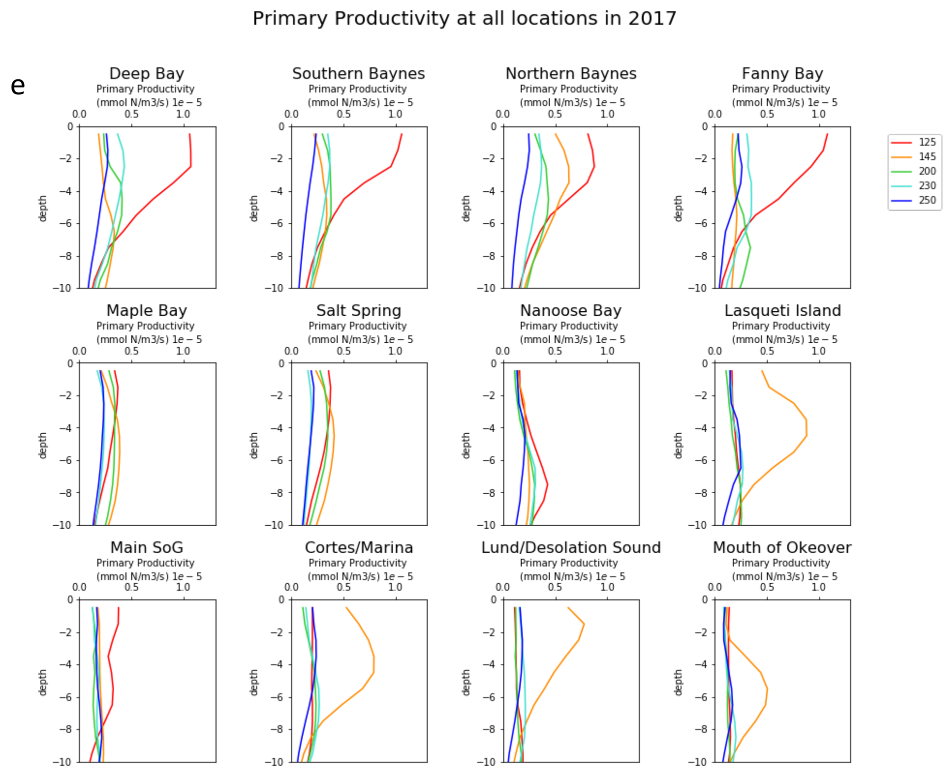


Figure E.2. Primary productivity profiles at all 12 locations in a) 2013, b) 2014, c) 2015, d) 2016, and e) 2017. Data are from the SSC.

Appendix F.3. All seasonal covariance plots

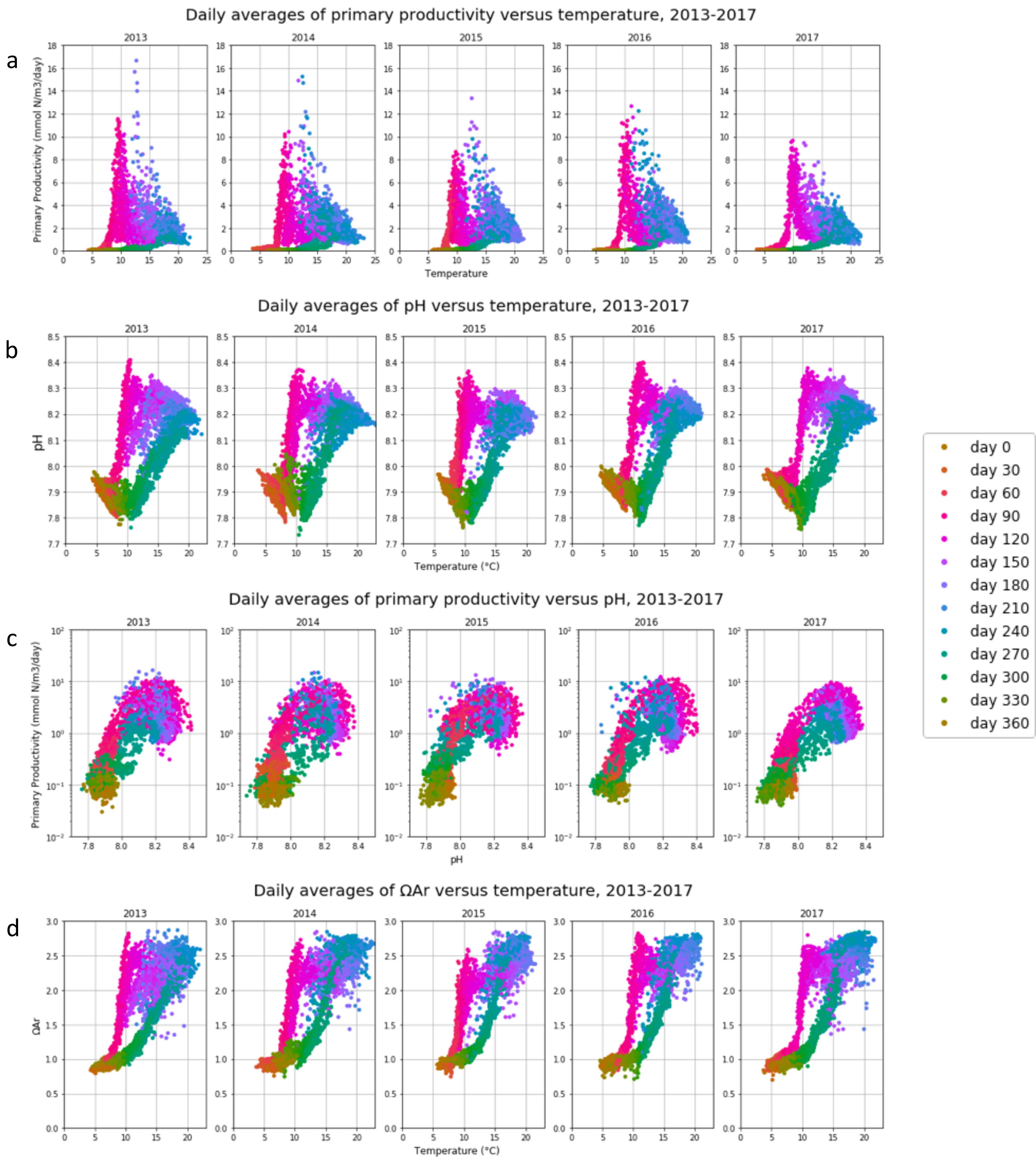


Figure E.3. Seasonal covariance of a) primary productivity and temperature, b) pH and temperature, c) primary productivity and pH, and d) Ω_{Ar} and temperature from 2013 to 2017. Relationships of environmental properties remain consistent across years. Data are from the SSC.

Appendix F.4. Chlorophyll plots

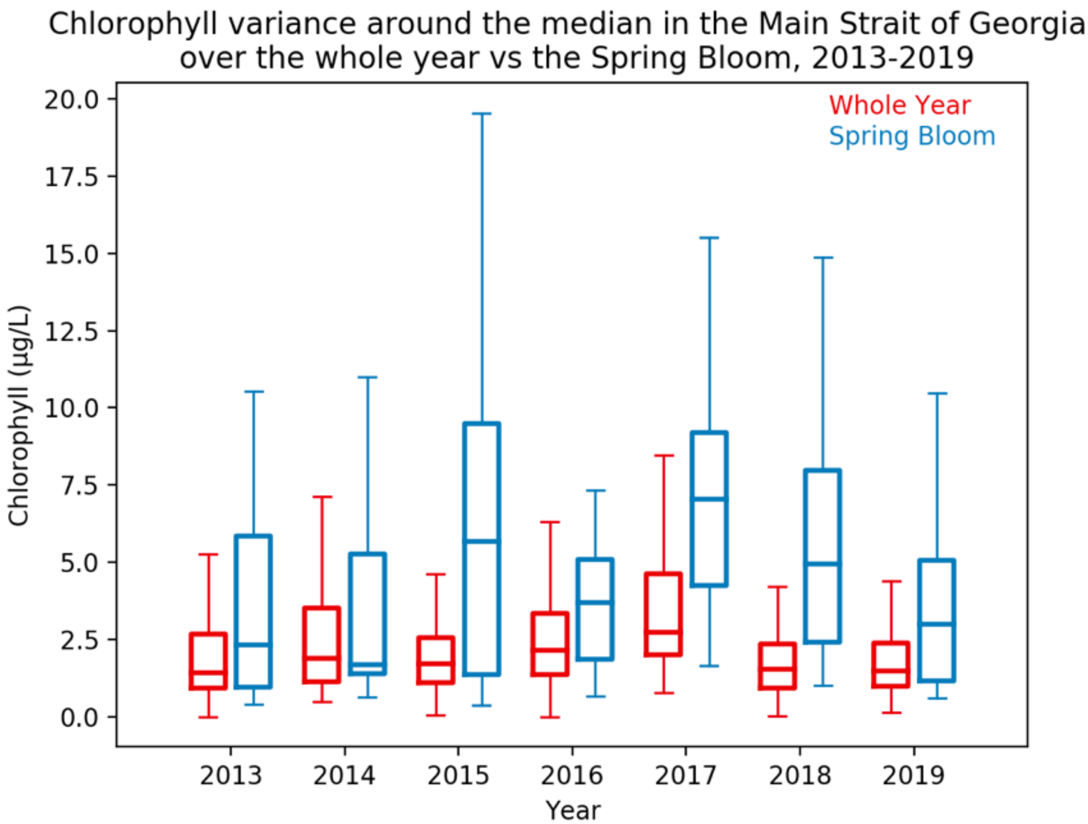


Figure E.4. Variance around the median chlorophyll concentration over the whole year (red) and during the spring bloom (blue). Data are from chlorophyll observations from ferry-tracks within the Salish Sea.

Appendix G. Research Report

The following is a report co-written by Natalie Drope (Drope, 2019) to report back survey findings to survey participants who expressed interest in follow up.

Ocean Change and Shellfish Farming in British Columbia

Survey Results Report

Evie Morin
evie_morin@sfu.ca
Karen Kohfeld (SFU)

Debby Ianson (DFO)

Natalie Drope
ndrope@uoguelph.ca
Jennifer Silver (UoG)

SFU

University of Guelph

MEOPAR

Fisheries and Oceans Canada
Pêches et Océans Canada

Table of Contents

A Message from the Research Team:

It's a pleasure to present you with a summary of findings from our survey: Ocean Change and Shellfish Farming in British Columbia. This project was developed through collaboration between researchers from Simon Fraser University, the University of Guelph, and the Department of Fisheries and Oceans.

Shellfish farming is an important cultural and economic activity in BC, and shellfish farmers know a great deal about ocean conditions and the health of their stocks. In conducting this research, we were fortunate to travel around coastal BC and speak with many shellfish farmers and engaged stakeholders about their experiences working within the BC shellfish aquaculture sector. We were surprised how interested shellfish farmers were to share their insights and experiences, especially concerning their knowledge about their stocks and ocean health.

Many shellfish farmers have first-hand experiences with ocean change, and we are grateful to present some of these observations in this report. Our hope is that they can support the industry as it continues to provide tasty and nutritious shellfish to consumers around the world.

To those we connected with throughout this project – Thank you. The information and insights you provided are highly valued. If you have any further questions or comments about this research, please don't hesitate to get in touch.

Sincerely,

Evie Morin *Natalie Drope*

Demographics Highlights:

A total of 55 shellfish farmers completed the survey from all 5 farming regions in BC (see map). Similar research done on the U.S. west coast shellfish aquaculture industry (which encompasses Washington, Oregon, and California) had 86 respondents.[1]

The number of respondents from each farming region in BC is illustrated in *Figure 1*. The colors of each bar correspond with the colored regions on the map. The majority of respondents were from the Discovery Islands and Baynes Sound Regions, where the majority of shellfish aquaculture takes place in BC.

As seen in *Figure 2*, Survey respondents farmed a wide variety of shellfish products, with many respondents indicating they farm multiple species at a time. 83% of respondents farmed oysters.

Figure 3 shows that over three quarters of respondents indicated that their farm had been in operation for at least 11 years. Around half of farmers had worked on their farm for less than 10 years and around half had worked there for more than 10 years.

In addition, there were respondents from small, medium, large, and extra-large farms, with the most common responses (25) from small farms with 1-3 employees or up to 25 dozens of oysters (or equivalent) per year.

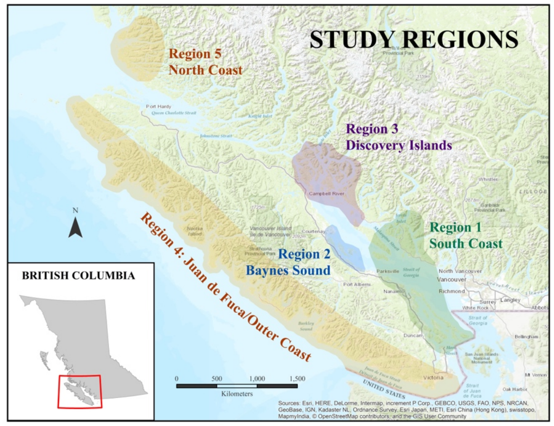


Figure 1: 55 Respondents By Region

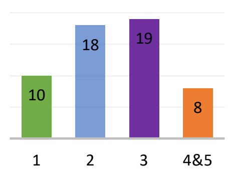


Figure 2: Species of Shellfish Farmed

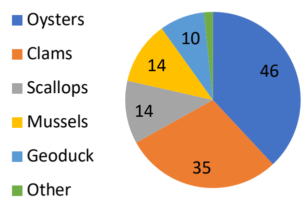
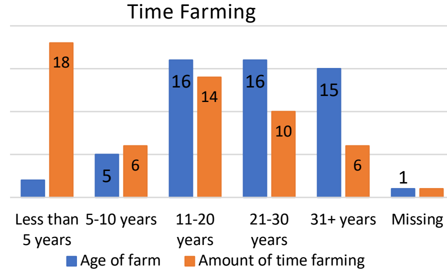


FIgure 3: Age of Farm & Amount of Time Farming



[1] Mabardy, R. A., Waldbusser, G. G., Conway, F., & Olsen, C. S. (2015). Perception and Response of the U.S. West Coast Shellfish Industry to Ocean Acidification: The Voice of the Canaries in the Coal Mine. *Journal of Shellfish Research*, *34*(2), 565–572.

Environmental Change Highlights:

The following are results only from respondents who grew oysters. Respondents were asked to select environmental factors from a list in which they observed a change. Then, they were asked to elaborate on the **DIRECTION** (*Has the change gone up or down?*), **AMOUNT** (*How much change was observed?*), **TIMING** (*Period of time during which the change was observed*), and **IMPACT** (*How each change affects production on the shellfish farm*) of the change.

Choices:
Water temperature
Water salinity
Water Quality
Other existing species on the lease
New species on the lease
Available food
Changes in food timing
Harmful algal blooms
Weather patterns
Extreme weather events
Coastal landforms
Other

More than 10% of respondents in two or more of the regions observed a change in:

		Direction/Amount of change	Timing	Impact
Water Temperature	▶	Somewhat warmer	Over the last 5 years	52% Negative
Other Existing Species on the Lease (Not Farmed) *Figure 4.*	▶	Medium/Large	Over the last 5 years	50% Negative
New Species on the Lease (Not Farmed) *Figure 4.*	▶	Medium	Over the last 5 to 10 years	75% Negative
Food Availability	▶	Somewhat more	Over the last 5 years	57% Negative, 43% Positive
Weather Patterns *Figure 5.*	▶	Small/medium	Over the last 5 years	45% Negative
Extreme Weather *Figure 5.*	▶	Somewhat more	Over the last 5 years	100% Negative

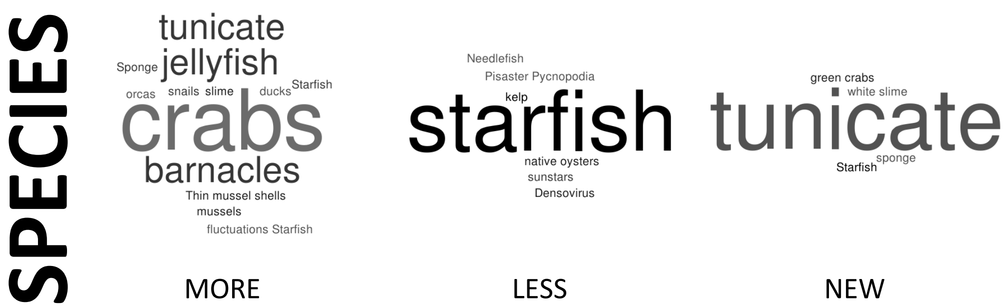


Figure 4: Animals described as more, less, or new are described in the word clouds above. The more a word was mentioned, the larger and darker it appears.

Figure 5: Weather patterns and extreme events are described in the above word clouds. The more a word was mentioned, the larger and darker it appears.

Community Change Highlights:

The following are results only from respondents who grew oysters. Respondents were asked to select community factors from a list in which they observed a change. Then, they were asked to elaborate on the **DIRECTION** (*Has the change gone up or down?*), **AMOUNT** (*How much change was observed?*), **TIMING** (*Period of time during which the change was observed*), and **IMPACT** (*How each change affects production on the shellfish farm*) of the change.

Choices:
Population
Amount of motorized vehicle use
Building and development
Land use
Waste water treatment
Pollution
Other

More than 10% of respondents in two or more of the regions observed a change in:

	Direction/Amount of change	Timing	Impact
Population ►	Small/Medium	Over the last 5 to 10 years	50% Negative
Amount of Motorized Vehicle Use ►	Much more	Over the last 5 years	68% Negative
Building and Development ►	Medium/Large	Over the last 5 to 10 years	50% Negative
Land Use ►	Medium	Over the last 5 to 10 years	55% Negative
Pollution ►	Medium	Over the last 5 years	84% Negative

Oyster Die-Off Events:

Respondents were asked if there was a particular time over the past 5 years when they were particularly concerned about their product *(Figure 6)* and whether they had experienced an oyster die-off event (*Figure 7).* An oyster die-off event is a short time period in which a significant proportion of spat, juvenile, and/or adult oysters die.

Figure 6: **Recent Years of Particular Concern**

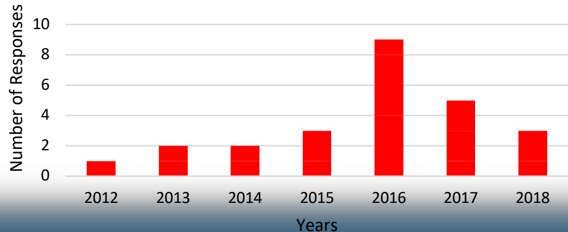


***Figure 7*: Farmers Who Experienced Oyster Die-Off**

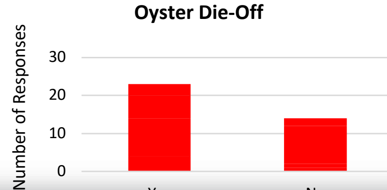


Figure 8 shows the percent of oyster farmers who felt oyster mortality in 2017 was greater, roughly the same, or less than 5, 10, 20, and more than 30 years ago. Most respondents found morality in 2017 was the same as the past, though a larger proportion experienced greater mortality than less mortality.

***Figure 8*: Oyster Mortality in 2017 Compared to Past Years**

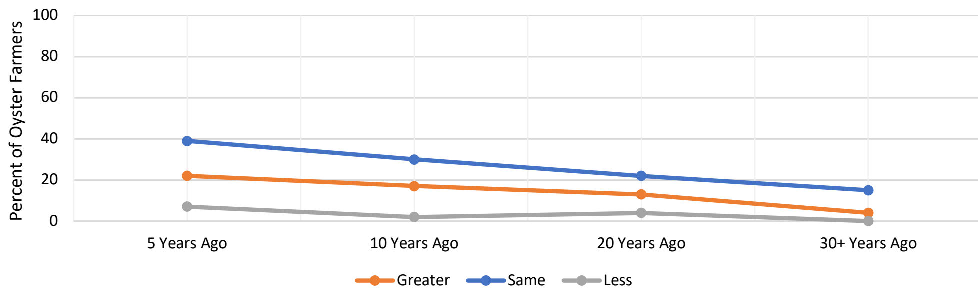
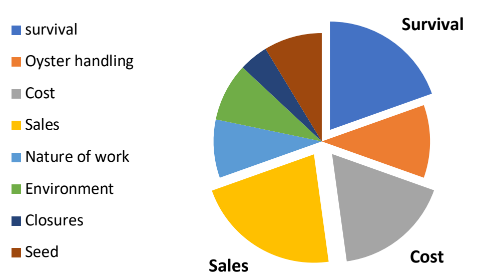
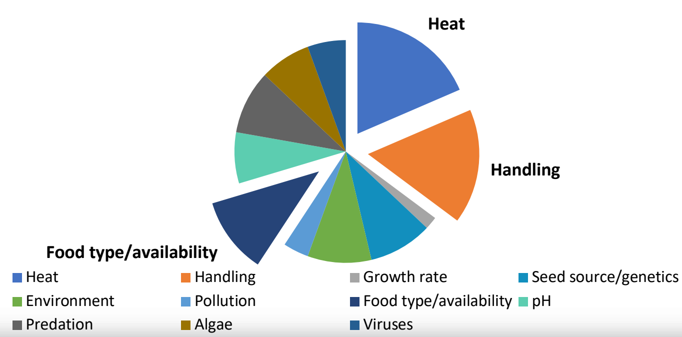


***Figure 9:* Biggest Challenges of Oyster Farming**



Respondents described eight primary challenges of working in BC's oyster industry, shown in *Figure 9.* The three main factors mentioned by several respondents are: **oyster survival, cost of production, and getting the product to sale**. In addition, respondents identified five main indicators preceding an oyster die-off event: **heat, algae, a lack of food, human activity, or an unknown cocktail of factors** (not shown). *Figure 10* below shows eleven factors that respondents think cause oyster die-off events. The three main factors mentioned by several respondents are: **heat, handling, and food type/availability.**

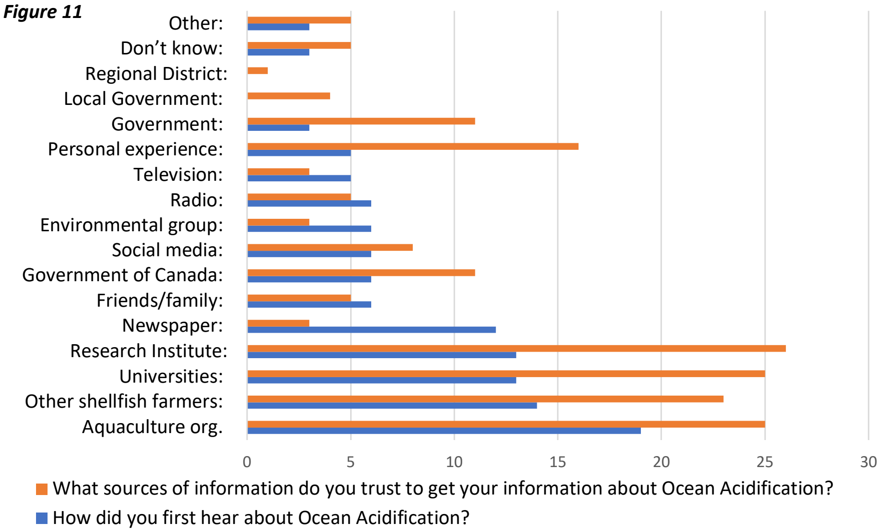
***Figure 10*: Perceived Cause of Oyster Die-Off Events**



Ocean Acidification (OA) Highlights:

Figure 11 illustrates how respondents first heard about OA (blue) and what they consider to be trusted sources of information (orange). The most commonly selected options for both questions relate to sources internal to the industry and directly from scientists. It's also interesting to note that Newspapers were a fairly common source of first contact but are less considered to be a trusted source of information.

Figure 11



The following graphs show how informed farmers feel about OA (*Figure 12)* and to what extent they think OA is a threat to the BC shellfish aquaculture industry (*Figure 13).* The trendlines show that responses lean more towards 'not at all' for how informed farmers feel, and 'a great deal' for how threatened farmers feel.

***Figure 12*: How informed do you feel you are about OA?**

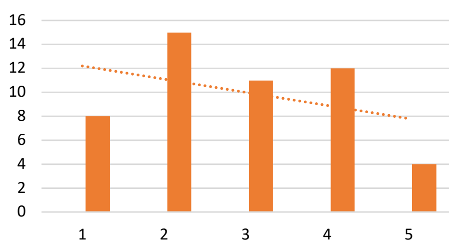
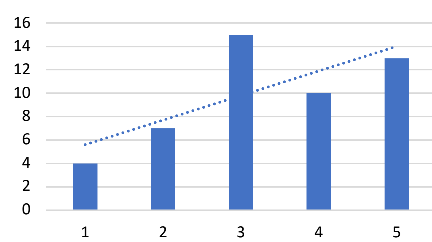


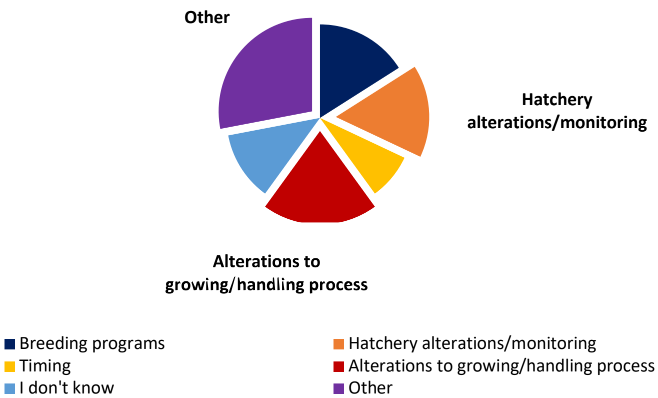
***Figure 13:* To what extent do you think OA is a threat to the industry?**



1 = Not at all 5 = A great deal

Adaptation Highlights:

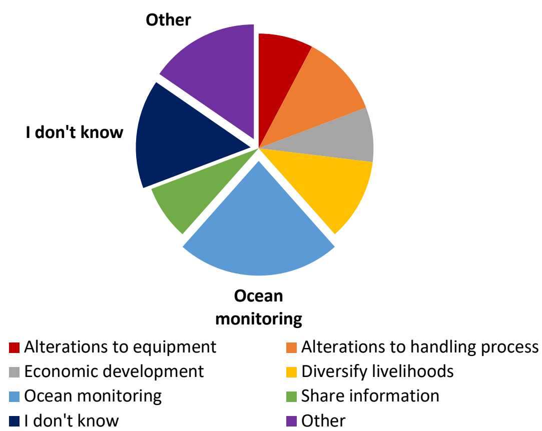
Strategies suggested in response to OA



- "I would suggest supporting a **well-developed breeding program"**
- "**Carbonate replenishment** – Returning shells to the marine source"
- "Experiment to find out what works for their **location**"
- "**decrease culture density** (which we have significant control over) to **reduce baseline stress of cultured animals** allowing the oysters to deal with the additional stress of changing oceans (which we have no control over)"
- "The growing of certain species of **kelp**"
- "Keep animals at a **shallower depth**"
- "Take advantage of the natural adaptive ability of **wild shellfish**. Restock as many beaches as possible to improve the chances of adaptation   Significantly **reduce fees and counterproductive practices**"

Strategies suggested in response to changing ocean conditions more broadly

- "Use **protective netting** to stop crab predation"
- "Plan on **other income sources**. Seriously consider shifting back to a **wild fishery**. Get a handle on **water quality** and other testing right on site in real time for farms and sport fishers. Allow **farm gate sales** and **mobile/floating processing plants**."
- "Try to be more responsible about **keeping the ocean clean**. Social media - people are impacted by seeing the garbage"
- "**Learn more** about food quality and quantity for the size of product feeding. **Don't handle product in the heat**. Less stress as possible on animals."
- "Batten down the hatches"
- "**Share information and strategies** with one another"



10

Project Updates:

To develop a holistic picture of ocean changes in BC, Evie is partnering with the University of British Columbia's SalishSeaCast group to compare observations by BC's aquaculture industry and model results. SalishSeaCast is a three-dimensional oceanographic model domain, shown in *Figure 14*, that accurately simulates conditions in the Strait of Georgia and Salish Sea as far back as 2014. The model predicts pH, temperature, salinity, and primary productivity using wind, tides and freshwater flow data. The SalishSeaCast group will be querying the model in response to shellfish farmers' sharing their firsthand experience of ocean changes. Since 2016 emerged as a particularly challenging year for oyster farmers, the SalishSeaCast group will compare primary productivity, temperature, storm surges and the Fraser River freshet in 2014 with 2016 to highlight anomalies. Guided by oyster farmers' experiences and concerns, this coupling of observational data and model results will show common environmental themes related to difficult growing conditions.

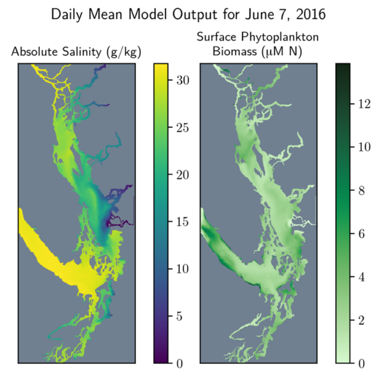


Figure 14: Salinity and Phytoplankton data output by the SalishSeaCast Model on June 7, 2016.

During a meeting with the SalishSeaCast group in January, we discussed how the model may be useful for shellfish farmers. In addition to depicting past conditions, SalishSeaCast also forecasts ocean conditions up to two days in advance. In particular, the model is effective at forecasting temperature and storm surges. We would like to know:

- ► Is ocean condition forecasting two days in advance helpful for shellfish farmers?

If so, and you or anyone you know is interested in partnering with the SalishSeaCast to help make short-term forecasting more easily available to farmers, please contact Susan Allen, lead researcher of SalishSeaCast, at sallen@eas.ubc.ca.

Natalie is researching the relationship between media representations and shellfish farmer perceptions of ocean acidification in the BC shellfish aquaculture sector. The media tends to focus on crisis stories that sensationalize an issue, and most people, including policy makers, learn what they know about environmental issues and science through the media. Natalie has paired the survey results with an analysis of newspaper articles to explore how OA and shellfish farmers are discussed in the media.