Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in British Columbia

An Exploration of Barriers and Future Directions for the Industry

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Signature Page

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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List of Acronyms

BC   British Columbia

BCSGA   British Columbia Shellfish Growers Association

DFO   Department of Fisheries and Oceans Canada

PSP   Paralytic Shellfish Poisoning

SDI   Shellfish Development Initiative

SIWI   Scoot Integrated Welfare Index

TFW   Total Fresh Weight

VOI   Value of Information

Project Overview | Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in B.C.

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1. Project Overview

1.1 Significance

Shellfish aquaculture has a key role to play in the future of British Columbia's (B.C.) seafood industry and has the potential to further contribute to the economic and cultural sovereignty of coastal First Nations. This ancient cultivation practice has provided seafood-dependent communities sustenance for millennia and has gained increasing attention for its potential to meet the growing global demand for low carbon protein. At higher intensities, shellfish cultivation provides income via sale of shellfish or payments for nutrient removal from waterways. In B.C., the shellfish aquaculture industry has transitioned to higher intensification over the last century and needs greater support to offset the limited growth potential of traditional sectors supporting coastal communities such as mining, forestry, and fisheries.

A substantial effort by the B.C. provincial government to support the shellfish aquaculture industry's growth began in 1998 with the initiation of the Shellfish Development Initiative (SDI). The SDI's primary goal was to increase the total area under private tenure for shellfish aquaculture from 2,300 ha to 4,230 ha and achieve a $100 million wholesale sector in one decade.[1] Government representatives and sector advocates saw shellfish aquaculture as an efficient and uncomplicated fix to declining fish stocks, unemployment in rural coastline communities, and a seamless path for First Nations to preserve shellfish harvesting traditions while creating new economic opportunities for their communities. By 2017, almost 20 years later, the wholesale value of the shellfish aquaculture sector had reached only $61.9 million driven primarily by rising wholesale shellfish prices rather than increased harvest.

This stymied growth has run in contrast to more rapid expansion of shellfish cultivation in other countries and is due in part to four categories of barriers: (1) environmental, (2) logistic & economic, (3) social & cultural, and (4) regulatory & political. Key among environmental bar-

riers is uncertainty of future environmental conditions, which makes investing in new farms difficult with many uncertain environmental variables affecting farm management decisions and ultimately profits. To reduce risk from environmental uncertainty, shellfish aquaculture industries around the world are investing in environmental monitoring and forecasting tools. In contrast to this growing trend, B.C. farmers have made minimal investment in the acquisition of environmental information of future conditions through environmental monitoring and forecasting.

Scoot Science (Scoot) has extensive experience managing ocean risk in aquaculture through data management, oceanographic analysis, and modeling. Their work with salmon farmers in B.C. has demonstrated the potential for environmental monitoring and forecasting to optimize farm management, ultimately reducing investment risk and uncertainty. Scoot's tools have shown that acquiring environmental information has substantial value for the salmon industry when mitigating mass mortality from superchill events or improving fish health by tracking fish welfare using the Scoot Integrated Welfare Index (SIWI). Scoot believes its environmental monitoring and forecasting tools can be adapted to provide value to B.C.'s shellfish aquaculture industry and has the potential to enable growth and investability in the coming decades.

While environmental information has been shown to have high value in salmon aquaculture, no study has examined the value of information in shellfish aquaculture. Our key research questions are:

1. What is the **value of environmental information** to shellfish farmers?

2. What **non-environmental barriers** have inhibited B.C.'s growth?

1.2 Project Objectives

(1) Develop a quantitative, replicable model to calculate the value of environmental information in shellfish aquaculture farm management. This model will allow us to answer the following questions:

a) Is environmental information valuable?

b) What parameters or conditions render environmental information the most valuable?

c) What kinds of environmental information are more or less valuable for shellfish farms?

(2) Identify and perform a comprehensive review of non-environmental barriers for shellfish farmers in British Columbia and provide practical solutions.

1.3 Study Area

The cool, productive waters of B.C. are well-suited for shellfish production and are home to many native and non-native shellfish species with commercial, cultural, and ecosystem value.[3] Many studies have concluded that the region has biophysical conditions well suited to support the growth of a wide range of bivalve species.[3] A multitude of native species can be found along the coast of B.C., commonly harvested species include the Pacific littleneck clam (*Leukoma staminea*), butter clam (*Saxidomus gigantea*), Nuttall's cockle (*Clinocardium nuttallii*), horse clam (*Tresus capax, T. nuttallii*), and various mussels (*Mytilus californianus, M. edulis/trossulus/galloprovincialis* species complex).[3,4]

This project's scope focuses on Vancouver Island, B.C., where the majority of farming tenures in the province are located. In particular, the concentration of farms is greatest in Baynes Sound on the eastern side of Vancouver Island. There are 450 shellfish aquaculture tenures in B.C., with 129 located in Baynes Sound.[5]

Farmers have been intensively cultivating shellfish in B.C. for over 100 years.[5] While there are many native shellfish species that grow throughout the province, it was the introduction of the Pacific oyster (*Crassostrea gigas*) from Japan in the early 1900s and the accidental introduction of the Manila clam in the 1930s to Baynes Sound that spurred the development of the industry.[3,5]

B.C. shellfish farmers use a wide variety of cultivation methods ranging from highly mechanized technology to practices that have not changed for generations. A literature review and discussions with our clients and industry members focused the project's scope on Vancouver Island to identify and catalog barriers to the industry's development.

From late-August to early-September 2021, our research team traveled to B.C. to visit tenure locations in an effort to better understand the current state of the shellfish industry landscape. Focused on building relationships with client's existing connections, we spent much of our time in Baynes Sound region. In addition to farms in the area, we visited the Vancouver Island University (VIU) Deep Bay Marine Field Station and learned about their current research efforts aimed at supporting the shellfish industry in B.C. We were also able to view historic lease sites in Nootka Sound that were previously used by the Mowachaht/Muchalaht First Nation. Site visits and discussions with industry members, shell-

fish farmers, researchers, and members of First Nation communities provided valuable context to assessing the value of environmental information for shellfish farmers and categorizing non-environmental barriers.
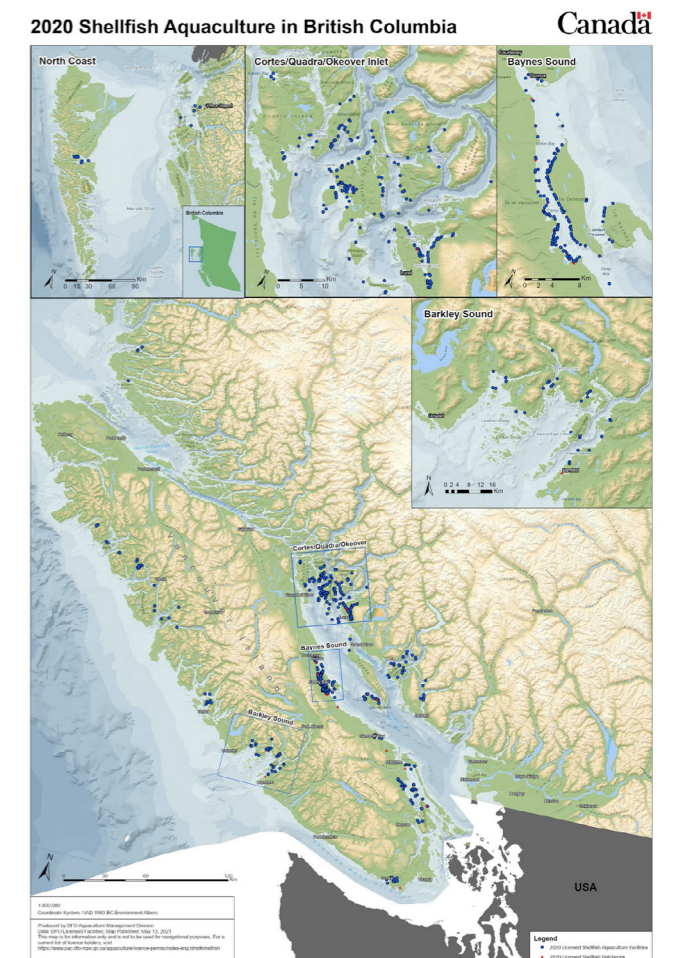
Figure 2. *Locations of shellfish facilities in 2020. Upper right inset is Baynes Sound.*[6]

Change in the BC Shellfish Industry's Landings, Landed Value, and Wholesale Value (1997-2017)
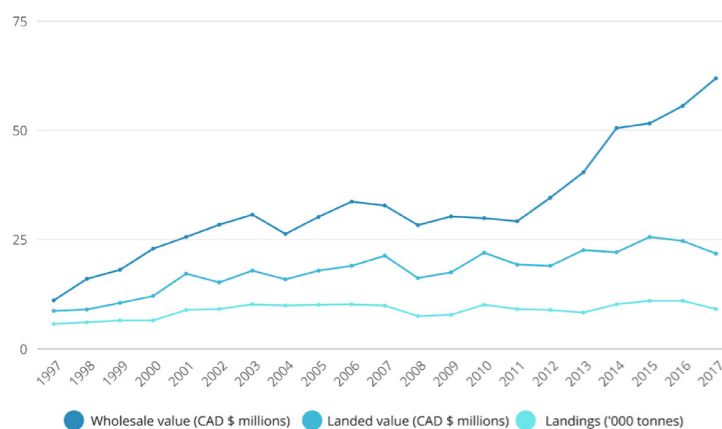

Figure 1. *B.C. shellfish landings, landed value, and wholesale value from 1997 - 2017.*

Key note: *After 20 years, the B.C. shellfish industry has still not reached its aspiration goal of $100 million wholesale value. It remains unclear if the significant spike in wholesale value will hold up through the future or is being driven more by changes in global market prices.*[2]

Figure 3. *Lease and license tenures in Baynes Sound, B.C..*

2. Background

2.1 A Brief History of Shellfish Aquaculture in British Columbia

2.1.1 Early First Nations Farming Practices

The roots of shellfish aquaculture by coastal First Nations extend back at least 10,000 years.[7] Throughout the coastal region, communities carried out practices of thinning, transplanting, selective harvesting, and habitat enhancement for sustainable and increased harvest of bivalves.[4] The cultivation of clam gardens for native shellfish has a long history of providing stable sustenance and a means for intergenerational connection to community and place.[4,8] The management practice of constructing stone walls to form intertidal terraces at specific tidal heights dates back at least 3,500 years.[9] The construction and tending to of clam gardens allows for an increase in productivity, efficiency of harvest, and habitat for clam populations.[10] For butter clam (*Saxidomus gigantea*) and littleneck (*Protothaca staminea*) the effect of the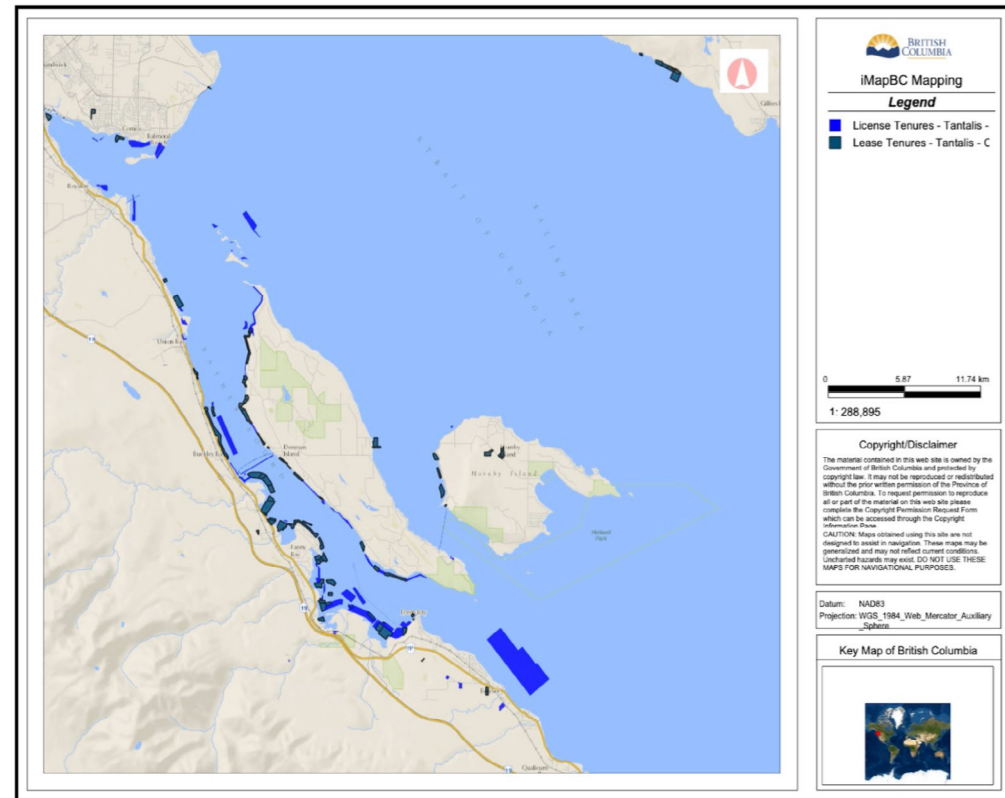 improved and increased habitat persists today where clam garden areas can support 2-4 times more production than in non-walled beaches.[10,11] This practice of traditional mariculture is tied to Indigenous sovereignty, food security, and the identity of coastal First Nations.[9]

Nuu-chah-nulth management practice, for example, designates one person or group of people as "beach-keepers".[12] Beach-keepers were responsible for managing the shoreline, intertidal space, and all the resources therein, including salmon and shellfish.[12] They were also in charge of sharing knowledge of the beach with community members and evaluating outsiders that arrived by boat.[12] Shellfish, specifically, were a versatile Nuu-chah-nulth resource, used not only for sustenance but also for jewelry, carving tools, and decoration.[12] The sociological importance of shellfish, communal harvest techniques, and their application is not unique to Nuu-chah-nulth territory but is shared by communities along the B.C. coast.[13] With the introduction of non-native species like the Manila clam and Pacific oyster and subsequent influx of non-Indigenous growers over the last century, shellfish cultivation has grown more intensive and mechanized, reducing the practice of clam gardens and traditional harvesting techniques as the primary form of cultivation.

For First Nations, coastal systems remain intimately linked to food harvesting practices. Through living in close relation to the local land and seascape, Indigenous peoples monitor social and ecological conditions for resources and the broader environment. Communities continue to live by relational values and monitor the landscape through species abundance, weather patterns, water quality parameters and countless other indicators. The intergenerational monitoring framework allows for rich data to be collected and passed on in ways that are lost or nonexistent in Western science-based practices.[14] A major theme of Traditional Ecological Knowledge and Wisdom (TEKW) is a focus on practices and approaches for sustainable use of resources.[15]

2.1.2 Approaching Commercialization

Although the wild harvesting of clams had long been predominantly carried out for ceremonial and subsistence purposes by First Nations, the arrival of colonial settlers influenced the treatment of natural resource extraction and management for the province. Throughout the late 19th century and into the early 20th century the native clam and oyster species were harvested by settlers without regard for sustainable practices.[16]

Oysters were imported into Victoria and other large cities to feed growing populations in the late 1800s. It was believed that the native shellfish could support employment opportunities for the communities as well as provide economic growth if markets could be enlarged.[17] In 1862, an excerpt from the British Colonist, a newspaper out of Victoria, B.C. read "OYSTER TRADE -- [...] Bringing it down simply to the supply of our little market, it might be enlarged into quite an extensive and profitable business. Oyster eating cities find employment for oyster diggers, oyster growers, oyster-boats, oyster-sloops."[17] The wild harvest of native Olympia oyster beds by settler communities intensified and it appears that overharvesting was already occurring by 1887 when the Fisheries Inspector for B.C., Thomas Mowat, reported the condition of the oyster beds on Vancouver Island: "We have a number of defined beds on this coast, but for want of proper care and attention they have deteriorated and are now almost worthless."[17]

Non-native species of shellfish were not introduced to B.C. until 1913, when farmers on Vancouver Island imported Pacific Oysters from Japan in hopes they could be transplanted on Western shores.[18] Over the next two decades, Pacific oyster seed was scattered around the Island, while more seed from Asia continued to be imported before the start of World War II.[18] Manila clams and several other non-native species were also introduced around this time.[16] Some literature suggests that several large spawning events between 1940 and 1960, triggered most likely by a combination of optimal environmental conditions, prompted an explosion of shellfish populations.[19] Following these mass-spawnings, Pacific oyster populations grew and eventually began to outcompete native species.[19] Subtidal harvest techniques emerged in the mid-1970's, making it possible to grow more shellfish with less space.[16] By the 1990's, technological advancements and increases in private and government investment allowed B.C. to consistently produce enough shellfish to be able to compete in international markets.

By the mid-1900's, B.C.'s provincial government had employed a simple tenure system for shellfish farming, where growers could lease defined areas of the coast to seed and grow oysters.[16] In the following decades, this process underwent a series of changes but has more or less retained the same basic regulatory structure, with the significant addition of a license to operate issued by the Department of Fisheries and Oceans (DFO), a branch of Canada's federal government.[20] In this case, "operate" pertains to carrying out husbandry practices from the seeding stage to grow-out, implementing new equipment or infrastructure, and transporting product to be tested or sold. Today, an aspiring grower must apply for a shellfish aquaculture license from the DFO and obtain a tenure from the Province.

After the Province established the SDI in the late 1990's, industry focus shifted to siting new tenures and expanding existing ones.[21] In an effort to meet SDI goals on a local scale, the Comox Valley Shellfish Steering Committee was created in 2002 and was made up of First Nations representatives, Provincial and regional agencies, as well as local stakeholders.[21] The goal of the CVSSC was to identify optimal locations for farming operations in the Baynes Sound area of Vancouver Island.[21]

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Though it was disbanded several months after being formed, the committee, at its core, exemplifies an inclusive approach to aquaculture expansion.

Supporting the B.C. shellfish aquaculture industry in reaching the SDI targets will require continued effort from governments, academic institutions, community leadership, and private companies. Central to this effort will be coastal First Nations who have shut down or negotiated agreements with many existing salmon farming operations in their traditional territories over the last few decades. To date, 78% of all salmon farmed in the province is under a beneficial partnership with a First Nation and about 20% of salmon farming jobs are held by people of First Nations' heritage.[22]

2.1.3 Current Landscape of Shellfish Aquaculture

Despite biophysical analyses indicating favorable conditions for shellfish aquaculture development in B.C., difficulty accessing capital and the unclear future for land treaty negotiations and resource rights compound perceived risk in this market.[23] Additionally, a lack of sociocultural and political consensus within some First Nations has led to resistance to the development of shellfish aquaculture in coastal communities.[23]

Though the market for farmed shellfish in B.C. accounts for a small proportion of overall seafood production, there has been some growth in the industry's output since the early 2000s. The wholesale value of B.C.'s shellfish aquaculture production in 2017 was an estimated $61.9 million, at 9,100 tonnes of total product, still significantly lower than the $100 million goal set out by the SDI for 2010.[24]

2.2 Shellfish Farming 101

Most shellfish in B.C. take between 1 ½ to 3 years to reach marketable size depending on species and growing conditions. Geoducks are a widely cultivated exception which grow for around 7 years before reaching market size. The most common commercially cultivated species are Pacific oyster (*Crassostrea gigas*), Manila clam (*Venerupis philippinarum*), Purple varnish clam (*Nuttallia obscurata*), native Butter clam (*Saxidomus gigantea*) and Littleneck clam (*Protothaca staminea*), Japanese scallop (*Patinopecten yessoensis*) and Japanese/weathervane scallop (*Patinopecten yessoensis x caurinus*), Blue mussel (*Mytilus edulis*), Mediterranean mussel/Gallo mussel (*Mytilus galloprovincialis*) and to a lesser extent, the geoduck (*Panopea generosa*).

Shellfish farmers procure "seed", or small bivalves ranging from 2-6 mm in size that are then raised in nursery gear until they are large enough to be placed in the gear for grow-out.[3] Hatcheries breed adult broodstock shellfish and often raise hundreds of millions of larvae that set and develop into shellfish "seed". Nurseries can consist of floating upwellers, land based raceways, nursery floating bags or trays, or other upweller designs. In B.C. "seed" are purchased from the few hatcheries located within the province, Washington state, Hawaii, or more commonly Chile, which typically offers the lowest seed prices.[3] The grow-out phase ranges in techniques from the original method of planting small shellfish in intertidal beach zones where they are left until the time of harvest to off-bottom culture methods which can reduce the grow-out period as the shellfish are constantly suspended in the water column.[3] More equipment is needed for subtidal, or deep-water planting and harvesting as floating farm layouts can require rafts, longlines, cages, floating bags, trays, and nets, among other equipment.

Common Shellfish in B.C.

Clams — Clams are often cultivated and wild-harvested from mud-gravel beaches. Oftentimes a mesh or cloth protection netting is laid atop the beach site to prevent predation from birds, crabs, and other marine organisms. After 2-4 years clams can be harvested on low tides by long-tined rakes and scrapers. Most clams are exported to markets in the United States, followed by Japan, China, and Hong Kong.[3,25]

Oysters — Much of the industry cultivates oysters in deep-water leases with the utilization of floating gear where the shellfish are suspended in the water column on strings, tubes, or in bags or cages hung from longlines and rafts. In B.C., intertidal beach zones are often used for the grow-out of oysters or the finishing or "hardening" of oysters grown in suspended cultures before reaching market size.[3]

Scallops — Scallop seed is often started in spat bags before being transferred to pearl nets, being ear-hung on down-line or suspended in lantern nets for the grow-out period, which can take between 1 to 3 years to reach market size.[3,25]

Mussels — Commonly grown in "socks", mussels are farmed in off-bottom suspension from rafts or longline systems.[3,26]

Shellfish aquaculture is typically positioned somewhere between wild harvesting of shellfish and the more intensive finfish aquaculture that has an established, yet historically contentious, place in B.C.'s waters. While farmed fish aid in filling the growing demand for seafood products as wild fisheries struggle under overharvesting and other climatic and anthropogenic stressors, current practices still require many inputs and the footprint, or "fishprint" is substantial. The "shellfishprint" on the other hand has a significantly lower environmental impact. The farming of these lower trophic-level species offer up a more sustainable means of producing sources of protein, both environmentally and often socially.

While the land based hatchery phase can be energy intensive, the grow-out phase for shellfish requires no input of feed, freshwater, antibiotics, or additions to the ecosystem of any kind. This is a contrast to land-based agriculture which typically is the most intensive followed by finfish aquaculture which is typically less nutrient intensive than land-based agriculture, but still requires inputs. Shellfish aquaculture's lower impact positions itself well for future growth as the global demand for animal protein continues to increase and people become more aware of the variability of impact across different food cultivation methods.

2.3 Exploring the Potential Benefit of Environmental Monitoring and Forecasting Through the Lens of Other Shellfish Inititiatives

Reducing uncertainty in farm management through environmental monitoring and forecasting tools has the potential to improve farm management decisions for B.C. farmers and be a catalyst for the industry. In this section we walk through two examples of new technologies developed for the shellfish industry which generate actionable environmental information for shellfish farmers. These examples demonstrate how technology could harness new environmental information for B.C. farmers in the future and provide context to what more advanced methods of environmental information generation can look like.

A team of mechanical engineering researchers at University of Maryland recently initiated efforts to improve shellfish farming decision-making with "smart" technology. Sponsored by the National Institute of Food and Agriculture, their "Smart Sustainable Shellfish Aquaculture Management (S3AM)" framework aims to amplify nationwide production and increase the economic viability of shellfish farming. One of the main objectives of this S3AM framework is to assist farmers in gaining in-depth knowledge of their farm conditions by developing highly efficient monitoring (S3AM monitoring) and harvesting tools (S3AM harvesting).

S3AM monitoring uses AI-enabled environmental sensing and imaging tools with an underwater drone to map water quality and bottom substrate conditions. This information can aid farmers in precision planting which helps reduce seed mortality and economic losses while also increasing farm productivity. Throughout the grow-out period, this tool will be used to conduct inventory monitoring to create precise

inventory maps that will help future farm productivity and profitability. The S3AM harvesting tool follows the monitoring tool to create an optimized path for a dredging vessel to conduct efficient and precise harvesting. The engineering team at Maryland believes that these technologies will contribute to long term sustainable shellfish production as well as promote economic development of coastal communities and stakeholders worldwide. They state that "[The] shellfish industry currently faces significant production bottlenecks due to outdated technology and tools…in light of today's advances in sensing and control, robotics, and artificial intelligence, which have led to transformative development in terrestrial agriculture, great opportunities have arisen to revolutionize shellfish aquaculture".[27]
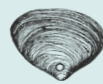
Another example demonstrating the potential of new technologies is ShellEye, a UK initiative developing satellite Earth Observations and modeling tools for environmental monitoring and forecasting of water quality for shellfish aquaculture.[28] The ShellEye project combines work across four project partners from 2015-2019: Plymouth Marine Laboratory, University of Exeter, Scottish Association for Marine Science (SAMS) and the Center for Environment, Fisheries and Aquaculture Science (CEFAS). Their objective was to further promote the development of the UK's shellfish industry by helping shellfish farmers make more informed harvesting, stock control, and risk management decisions when facing uncertain water quality.

ShellEye worked with shellfish farmers to develop a monitoring and forecasting bulletin service providing near real-time environmental information. The bulletin provides farmers with environmental information such as sea surface temperature, wind direction, surface current speed, and chlorophyll concentrations to help inform their management decisions. The creation of this bulletin was carried out in conjunction with shellfish farmer input to ensure that the environmental information shared was relevant to farm level needs.

During development, ShellEye hosted a workshop with various shellfish industry stakeholders to elicit input on willingness to pay for the bulletin service to help gauge the value of this environmental information for farmers. After four years of funded research and development and a proven water quality bulletin in supporting the UK's shellfish industry, ShellEye transitioned to a subscription-based service — confirming that the environmental information provided by ShellEye was indeed valuable.

Despite a clear demand for actionable environmental information from shellfish farmers, no study to date has tried to quantitatively examine the value of environmental information with a modeling framework. It's likely that some sources of information contain characteristics that make it inherently more valuable than others, and knowing this information will be crucial in prioritizing the development of new forecasting tools. Our first project objective is to develop a model of the value of information applied to shellfish aquaculture management. The next section demonstrates this approach.

Value of Information Methodology | Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in B.C.

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3. Value of Information Methodology

3.1 Value of Information Theory

Value of information (VOI) analysis is a framework used to assess the expected gain from acquiring information that reduces uncertainty in decision-making.[29] This framework can be useful for a decision-maker who is seeking to:

1. Maximize an outcome (typically profits)
2. By optimizing a decision
3. And the optimal decision is dependent on uncertain external variables

By assessing the expected gain from acquiring information, VOI analysis determines the value of that additional information, which can then be compared against its cost of acquisition. By knowing the value of information, a decision-maker can then assess whether a decision should be made on current information or if it is worth investing in the acquisition of additional information that will reduce uncertainty in their decision-making.

VOI analysis has assisted decision-makers across industries including healthcare, fisheries management, and agriculture. Example questions in these industries include:

- What is the value of El Niño forecasts in the management of salmon?[30]
- What is the value of information in prioritizing healthcare research?[31,32]
- What is the value of El Niño forecasts in the management of crop-production?[33]

To date, there have been no studies applying the value of information methodology in a shellfish aquaculture context.

3.2 Value of Information Applied to Shellfish Aquaculture

We developed and applied the VOI framework to a shellfish aquaculture farm management problem. Achieving accurate estimates for different types of environmental information in the B.C. region is secondary. We take the perspective of a shellfish farmer as the decision-maker to address our first research question: what is the value of environmental information to shellfish farmers?

To find the value of information we calculate the expected profits for a shellfish farmer who has perfect information of future environmental conditions and the expected profits for the same shellfish farmer, all else equal, with uncertain information of future environmental conditions. The difference in profits between the farmer with perfect information and the farmer with uncertain information is the value of information.

We assume the decision-maker is seeking to:

1. Maximize expected farm profits (outcome)
2. By optimizing stocking density (decision)
3. Where the theoretically optimal management decision depends on the uncertain environmental variables water temperature, current speed, particulate organic matter (POM), and chlorophyll *a* (uncertain external variables)

Because there are four uncertain environmental variables in our study, we calculate a separate value of information for each variable. Because we look at the value of perfect information, our estimates can be viewed as an upper bound on the value of information.

3.2.1 Introducing a simplified example of VOI

To understand how the we will calculate the value of information for each variable, we start with a simplified example for calculating the value of information using water temperature as the uncertain environmental variable and stocking density as the management decision the farmer is seeking to optimize to maximize profits.

In section 3.2.2, we will step through how a farmer would make their stocking density decision with perfect information of future environmental conditions. In section 3.2.3, we will step through how the same farmer, all else equal, would make their stocking density decision with uncertain information of future environmental conditions. In section 3.2.4, we will calculate the value of information using the difference in profits between the farmer with perfect information and the farmer with uncertain information.

In this simplified example, we assume:

1. There are 2 possible environmental scenarios in the future (1) low water temperature and (2) high water temperature
2. From previous experience, the farmer knows (1) there is an equal probability of each scenario occurring in the future and (2) the relationship between stocking density and expected profits under the 2 environmental scenarios as represented by Figures 4 and 5.
3. Expected profits are not to scale or representative of real values

3.2.2 Decision-making with perfect information of future environmental conditions

With perfect information of future environmental conditions, the farmer knows at the time of making their stocking density decision

which water temperature scenario will occur in the future; this information is assumed to be acquired through environmental forecasting.

With this knowledge, the farmer would choose either X1 or X2 as their stocking density depending on which scenario was projected to occur. By selecting either one of these points, they would maximize their expected profits under either scenario.

3.2.3 Decision-making with uncertain information of future environmental conditions

With uncertain information of future environmental conditions, the farmer is unsure of what environmental scenario will occur in the future and is reliant solely on past experience. Without knowing which scenario will occur, they would choose a stocking density that would yield the highest expected profit *on average* under previous conditions.

To determine this optimal point, they would calculate the average of the high and low water temperature scenario curves (Figure 5) and select the stocking density that would yield the highest expected profit. This stocking density leads to suboptimal expected profits under either future environmental scenario.

3.2.4 Calculating the value of information

To calculate the value of information, the expected profits under the high and low water temperature scenarios are multiplied by the probability of their occurrence. They are then summed to determine the expected profits for the farmer with perfect information based on their stocking density choice:

$$\pi(Pi) = \pi(X_1, E_l) * p(E_l) + \pi(X_2, E_h) * p(E_h),$$

where $\pi(Pi)$ is the expected profits under perfect information; $\pi(X_1, E_l)$ and $\pi(X_2, E_h)$ are the expected profits from selecting a precise optimal stocking density for the low and high temperature scenario, respectively; and $p(E_l)$ and $p(E_h)$ are the probability of occurrence of the low and high temperature scenario, respectively.

To determine the expected profits for the farmer with uncertain information based on their stocking density choice, the expected profits with the high and low water temperature scenarios are multiplied by the probability of their occurrence and added together:

$$\pi(Ui) = \pi(X^*, E_l) * p(E_l) + \pi(X^*, E_h) * p(E_h),$$

where $\pi(Ui)$ is the expected profits under uncertain information, $\pi(X^*, E_l)$ and $\pi(X^*, E_h)$ are the expected profits from selecting a single optimal aggregate stocking density under uncertainty about temperature, and $p(E_l)$ and $p(E_h)$ are the probability of occurrence of the low and high temperature scenario respectively.

Subtract the expected profit with uncertain information from expected profits for the farmer with perfect information to determine the VOI (see Figure 6 for calculations):

$$VoI = \pi(Pi) - \pi(Ui).$$

3.2.5 Decision-making for all 4 environmental variables

Expanding the 3 steps from section 3.2.2, 3.2.3, and 3.2.4 to the four environmental variables, each with five possible future scenarios of equal probability, the farmer would decide their stocking density following the steps in Figure 7.
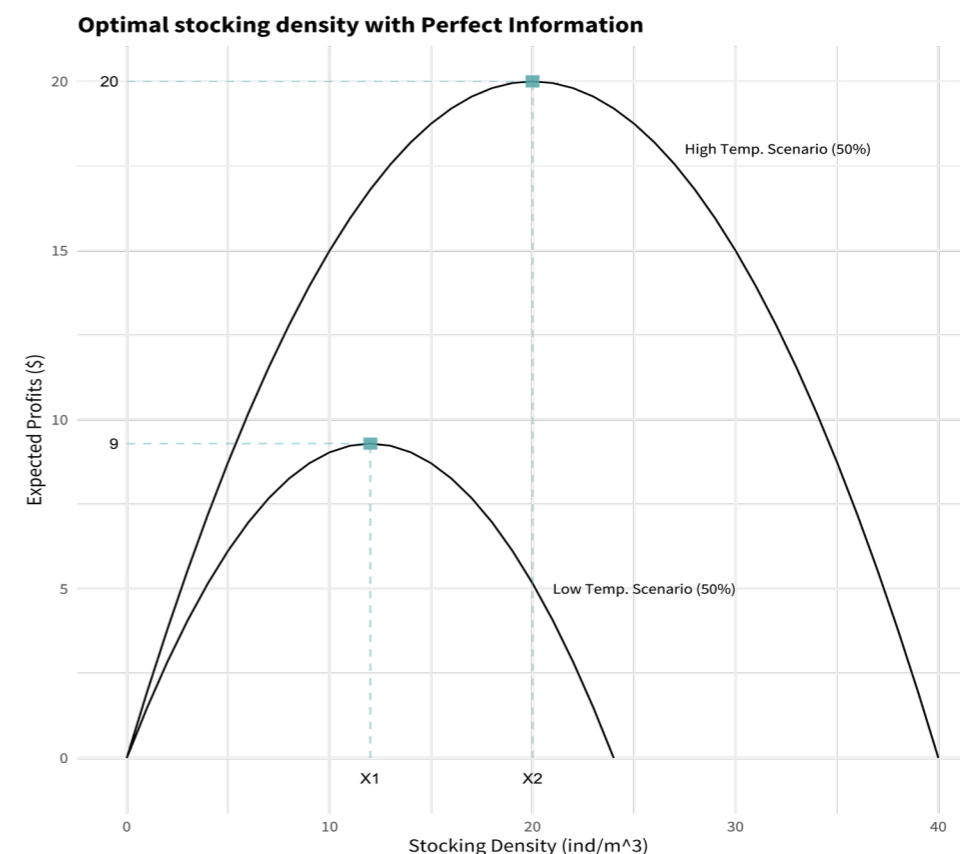

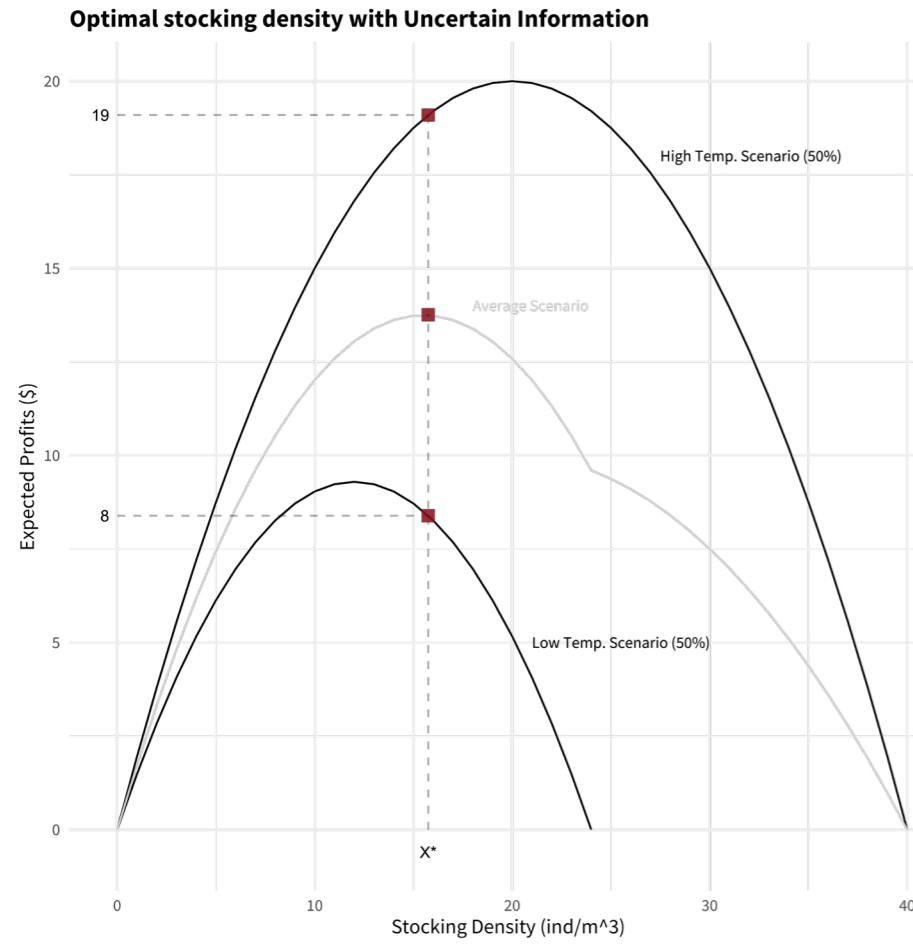**Figure 4.** *Decision-making with perfect information*

Optimal stocking density with Uncertain Information

Figure 5: *Decision-making with uncertain information*
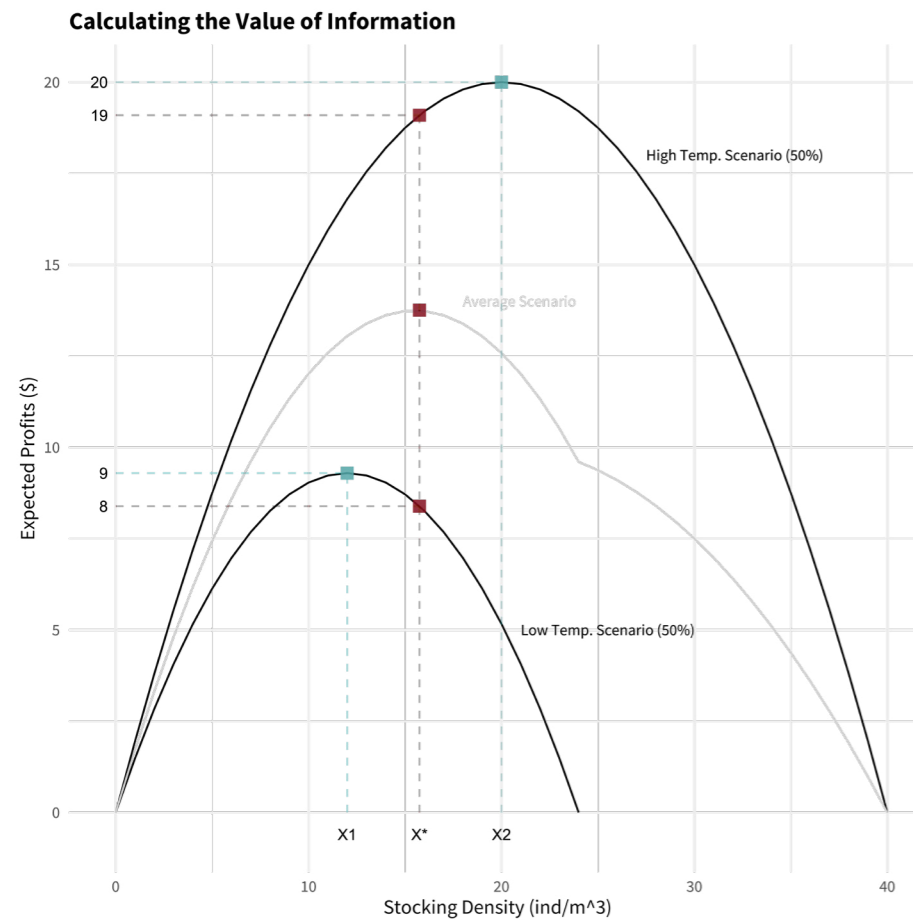
Calculating the Value of Information

Figure 6. *Calculating the value of information*

Expected Profit with Perfect Information:

$9*(0.5) + $20*(0.5) = $14.50

Expected Profit with Perfect Information:

$8*(0.5) + $19*(0.5) = $13.50

Value of Information:
$14.50 - $13.50 = $1

Perfect Information

Optimal stocking density for each scenario

Current Speed

Chl. a.

P.O.M.

Temp.

Optimal Profits

Optimal Growth Rate

Chl. a.
Current Speed
P.O.M.
Temp.

Known environmental conditions

Uncertain Information

Optimal stocking density on average

Current Speed

Chl. a.

P.O.M.

Temp.

Suboptimal Profits

Suboptimal Growth Rate

Chl. a.
Current Speed
P.O.M.
Temp.

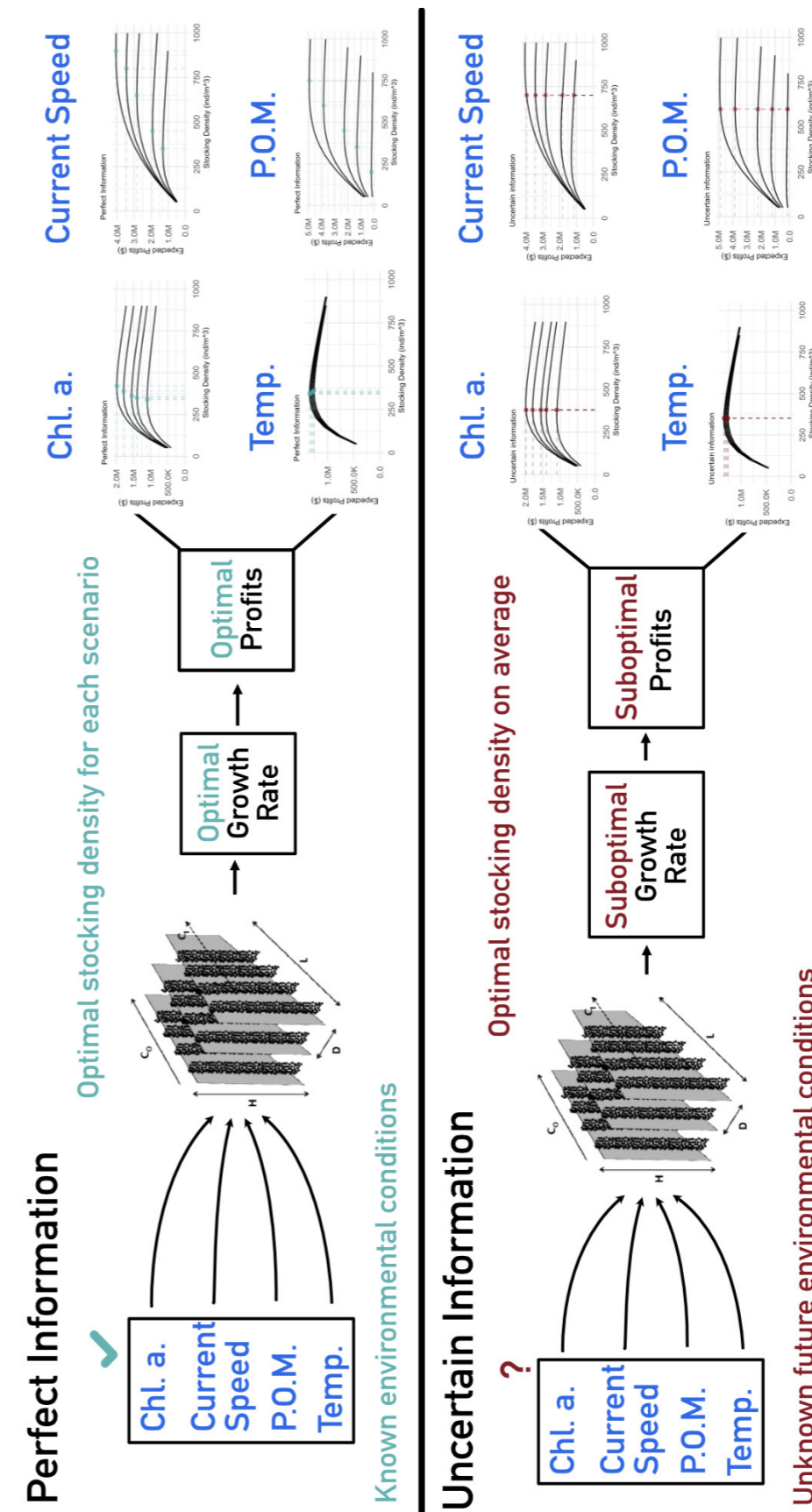**Unknown future environmental conditions**

Figure 7. *Farmer decision-making with perfect and uncertain future environmental information for all four environmental variables, each with five possible scenarios with equal probability of occurring in the future. The farmer with perfect information would choose optimal stocking densities under each of the five possible scenarios for each environmental variable while the farmer with uncertain information would choose the stocking density that yielded the highest expected profit on average.*

Value of Information Methodology | Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in B.C.

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3.3 Methodology for Calculating the Value of Environmental Information For Four Environmental Variables Using FARM Model Data

3.3.1 Data Source and Extraction

To calculate the value of information for each of the four environmental variables, data were collected from the Farm Aquaculture Resource Management (FARM) model.[34] This model is used to assess the "productivity, environmental effects and profitability of shellfish aquaculture" by calculating anticipated shellfish growth under the following modifiable parameters:

- Environmental conditions
- Stocking density
- Farm size and the number of sections
- Species
- Grow-out period

The FARM model was chosen for its widespread use in the aquaculture industry, comprehensive consideration of management decisions, and flexible data acquisition interface, farmscale.org.[35]

Empirical data sources and analysis of the relationship between stocking density and shellfish growth rate under varied stocking densities are sparse and disjointed, typically only assessed under lab conditions for larval growth.

The dataset was collected using the following process:

1. Each of the four environmental variables was assigned five possible levels, which we refer to as "scenarios". The range of scenarios was selected to prioritize methodological clarity over exact accurate representation of conditions in B.C., but represent a reasonable range of values for these variables.

2. The model was run for each of the five environmental variable scenarios while adjusting stocking density in increments of 50 ind/m^3 ranging from 50-999 ind/m^3. After each iteration of the model, we extracted Total harvest (T.P.P.).

Note: When running the model for a single environmental variable across five scenarios, all other environmental variables were held constant at baseline values. There was also a set of fixed variables that were kept constant under each iteration of the model running as detailed in Table 1.

3. After extraction, we converted Total harvest (tons) to expected profits assuming an average $8.50CAD/lb conversion for mussels, generating four datasets. Figure 9 is an example of the full chlorophyll *a* dataset converted into expected profits.

Parameter assumptions for each dataset extracted are detailed in Table 1 and 2.

3.3.2 Calculating Results

We evaluated the four environmental variables (water temperature, current speed, particulate organic matter, and chlorophyll *a*) following the steps developed in sections 3.2.2, 3.2.3, and 3.2.4. We estimated optimal stocking density and expected profits with perfect and uncertain

future information for the four environmental variables, each with five possible scenarios with equal probability of occurrence. For both perfect and uncertain future information, we calculated expected profits by multiplying the expected profits of each environmental scenario by its probability of occurrence (20%):

$$\pi(Pi) = \pi(X_1, E_1) * p(E_1) + \pi(X_2, E_2) * p(E_2) + \pi(X_3, E_3) * p(E_3) + \pi(X_4, E_4) * p(E_4) + \pi(X_5, E_5) * p(E_5)$$

$$\pi(Ui) = \pi(X^*, E_1) * p(E_1) + \pi(X^*, E_2) * p(E_2) + \pi(X^*, E_3) * p(E_3) + \pi(X^*, E_4) * p(E_4) + \pi(X^*, E_5) * p(E_5),$$

where $\pi(Pi)$ is the expected profits under perfect information; $\pi(Ui)$ is the expected profits for uncertain information; $\pi(X_{1-5}, E_{1-5})$ are the expected profits from selecting a precise optimal stocking density for each environmental scenario; $\pi(X^*, E_{1-5})$ are the expected profits from selecting a single optimal aggregate stocking density based solely on previous information for all environmental scenario; and $p(E_{1-5})$ are the probability of occurrence of each environmental scenario.

The difference in expected earnings between perfect and uncertain future environmental information represents the value of the information (VOI); that is, how much a farmer should be willing to pay for this information to guide his decision-making:

$$VoI = \pi(Pi) - \pi(Ui).$$

Fixed Variables		
Variable Section	**Variable**	**Assumption**
Farm layout	Farm width	20m
	Farm length	300m
	Farm depth	10m
	N sections	3
Shellfish Cultivation	Species	Mussels
	Cultivation period	180 Days
Environment	TPM	50 mg /L
	Dissolved Oxygen	9.02 mg /L

Table 1. *FARM Model fixed variables. These values were held constant through all iterations of data extraction.*

Adjusted Variables						
Variable Section	**Variable**	**Assumption**				
Shellfish cultivation	Density (first box)	50-999 ind/m^3 (harvestable biomass was calculated at stocking densities under ind/m^3)				
	Density (second box)	50-999 ind/m^3				
	Density (third box)	50-999 ind/m^3				
Environment	Water temperature (C)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		4	8	12	16	20
		Baseline: 10				
	Chlorophyll *a* (µg/L)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		2	7	10	15	20
		Baseline: 5.5				
	Current speed (m/s)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		.05	.07	.10	.12	.14
		Baseline: .10				
	POM (mg/L)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		2	5	7	10	12
		Baseline: 5				

Table 2. *FARM Model adjusted variables. These values were adjust across data extraction iterations.*

Figure 8. *The FARM model's extraction interface, farmscale.org*

Density	Chlorophyll Level: Scenario 1	Expected Profit	Chlorophyll Level: Scenario 2	Expected Profit	Chlorophyll Level: Scenario 3	Expected Profit	Chlorophyll Level: Scenario 4	Expected Profit	Chlorophyll Level: Scenario 5	Expected Profit
50	2	$397,990	7	$479,079	10	$507,625	15	$538,622	20	$558,218
100	2	$687,020	7	$842,559	10	$903,381	15	$972,241	20	$1,016,737
150	2	$880,991	7	$1,095,722	10	$1,188,292	15	$1,298,714	20	$1,372,489
200	2	$999,533	7	$1,255,214	10	$1,374,671	15	$1,525,425	20	$1,630,632
250	2	$1,063,593	7	$1,343,988	10	$1,483,044	15	$1,668,051	20	$1,803,693
300	2	$1,091,523	7	$1,384,771	10	$1,536,230	15	$1,746,674	20	$1,908,689
350	2	$1,097,054	7	$1,395,647	10	$1,553,988	15	$1,781,101	20	$1,963,536
400	2	$1,089,257	7	$1,388,881	10	$1,550,541	15	$1,787,463	20	$1,984,135
450	2	$1,073,614	7	$1,371,910	10	$1,534,831	15	$1,777,031	20	$1,982,812
500	2	$1,053,273	7	$1,348,954	10	$1,512,005	15	$1,756,802	20	$1,968,098
550	2	$1,030,025	7	$1,322,350	10	$1,484,909	15	$1,730,791	20	$1,945,360
600	2	$1,004,903	7	$1,293,411	10	$1,455,122	15	$1,701,234	20	$1,917,756
650	2	$978,534	7	$1,262,896	10	$1,423,541	15	$1,669,390	20	$1,887,079
700	2	$951,310	7	$1,231,260	10	$1,390,687	15	$1,635,986	20	$1,854,367
750	2	$923,495	7	$1,198,792	10	$1,356,873	15	$1,601,449	20	$1,820,236
800	2	$895,279	7	$1,165,688	10	$1,322,296	15	$1,566,025	20	$1,785,062
850	2	$866,813	7	$1,132,098	10	$1,287,092	15	$1,529,858	20	$1,749,073
900	2	$838,228	7	$1,098,155	10	$1,251,377	15	$1,493,035	20	$1,712,397
950	2	NaN	7	NaN	10	NaN	15	NaN	20	NaN
999	2	NaN	7	NaN	10	NaN	15	NaN	20	NaN

Figure 9. *Dataset extracted from FARM for chlorophyll a, the model was not able to generate stocking density values for 950 and 999.*

4. Value of Information Results

4.1 Value of Information for Each Environmental Variable

The results of the calculations detailed in section 3.3.2 for each environmental variable are shown in Figures 10-13. The value of environmental information varied from $122 for temperature to $73,765 for current speed. These results demonstrate the capacity of the VOI framework to estimate the value of forecasting future environmental scenarios and the potential variability across different environmental variables that affect shellfish farmers' decision-making. The wide variance in these values confirms that in fact some environmental variables are more valuable to farmers than others.

Chlorophyll a (µg/L) — Value of Information: $2792

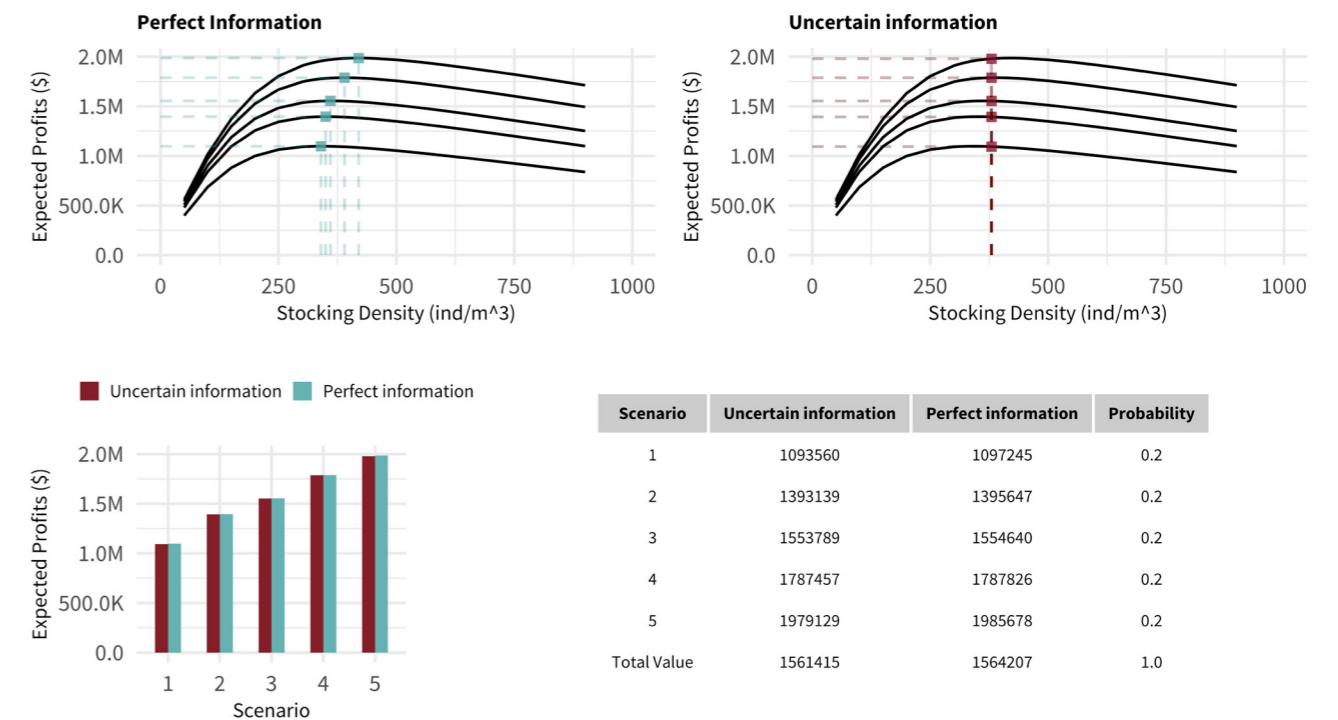| Scenario	Uncertain information	Perfect information	Probability
1	1093560	1097245	0.2
2	1393139	1395647	0.2
3	1553789	1554640	0.2
4	1787457	1787826	0.2
5	1979129	1985678	0.2
Total Value	1561415	1564207	1.0

Figure 10. *Expected profits with perfect and uncertain information for different scenarios and value of information for the environmental variable chlorophyll a.*

Current speed (m/s)

Value of Information: $73765

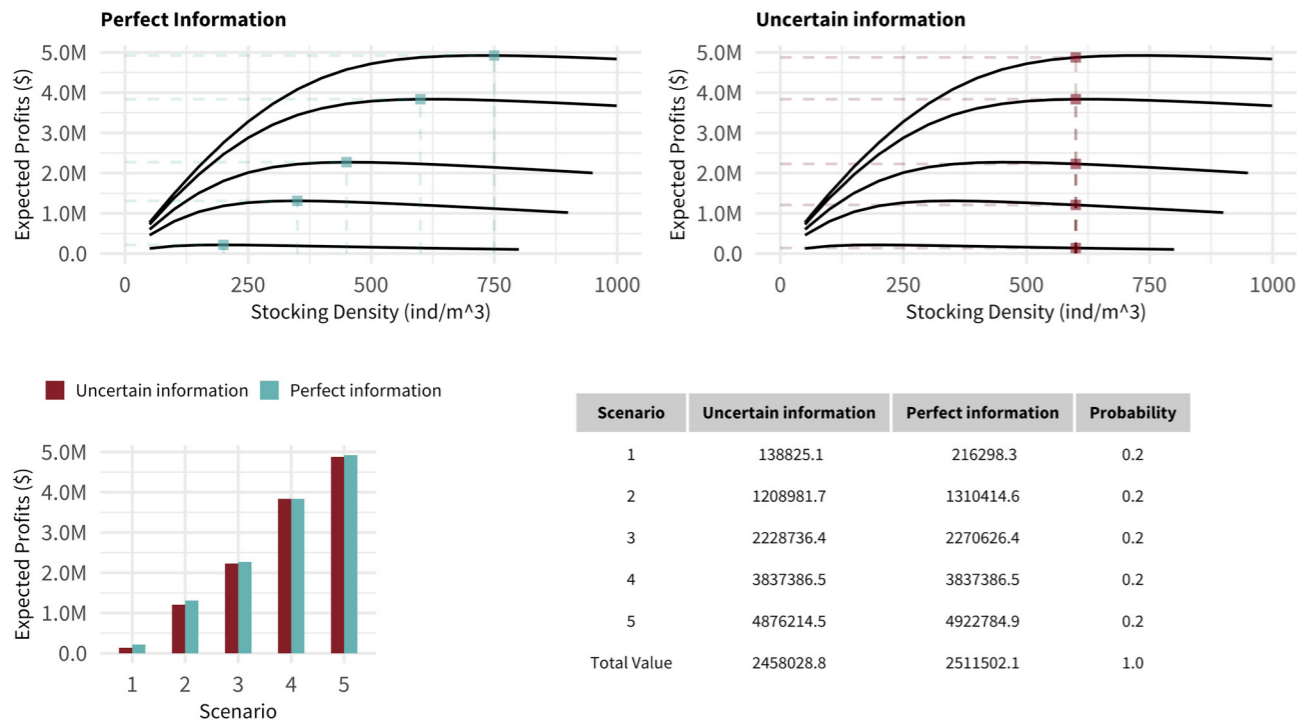| Scenario	Uncertain information	Perfect information	Probability
1	138825.1	216298.3	0.2
2	1208981.7	1310414.6	0.2
3	2228736.4	2270626.4	0.2
4	3837386.5	3837386.5	0.2
5	4876214.5	4922784.9	0.2
Total Value	2458028.8	2511502.1	1.0

Figure 11. *Expected profits with perfect and uncertain information for five different scenarios and value of information for the environmental variable current speed.*

Particulate organic matter (mg/L)

Value of Information: $53473

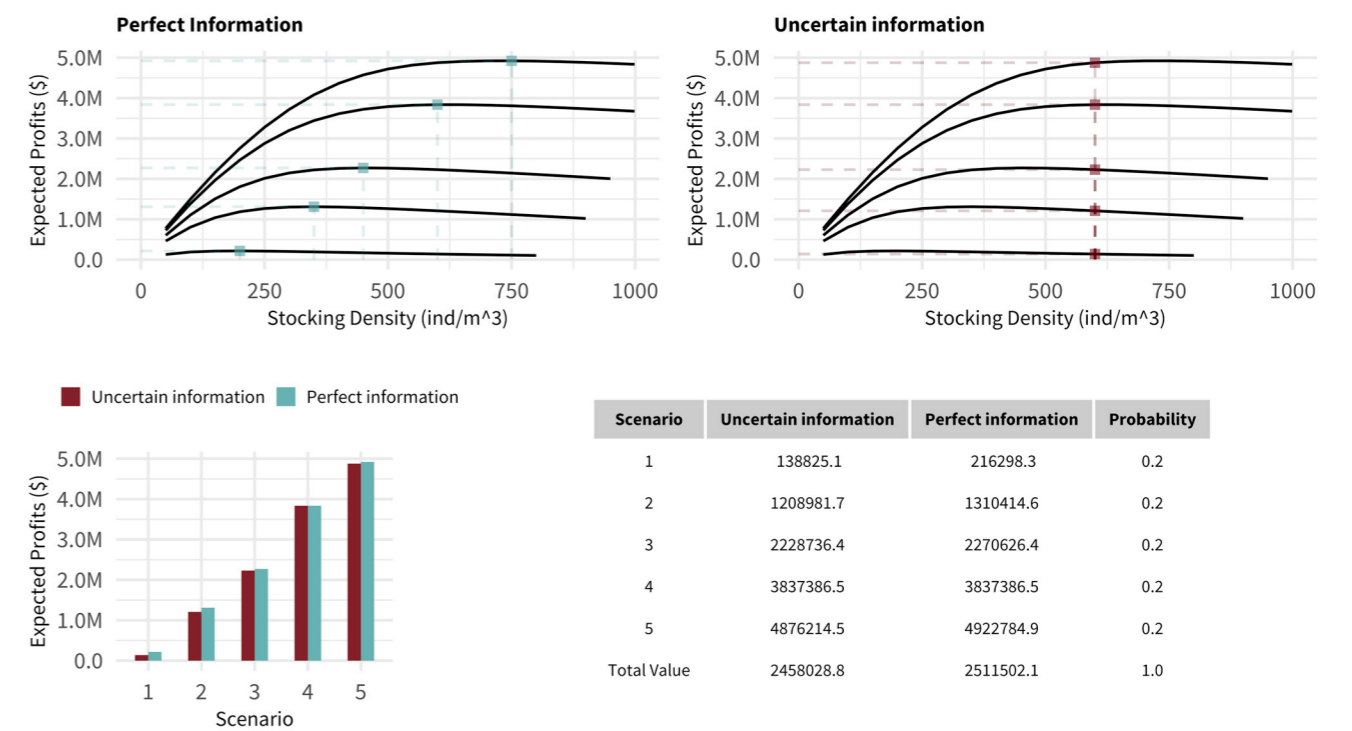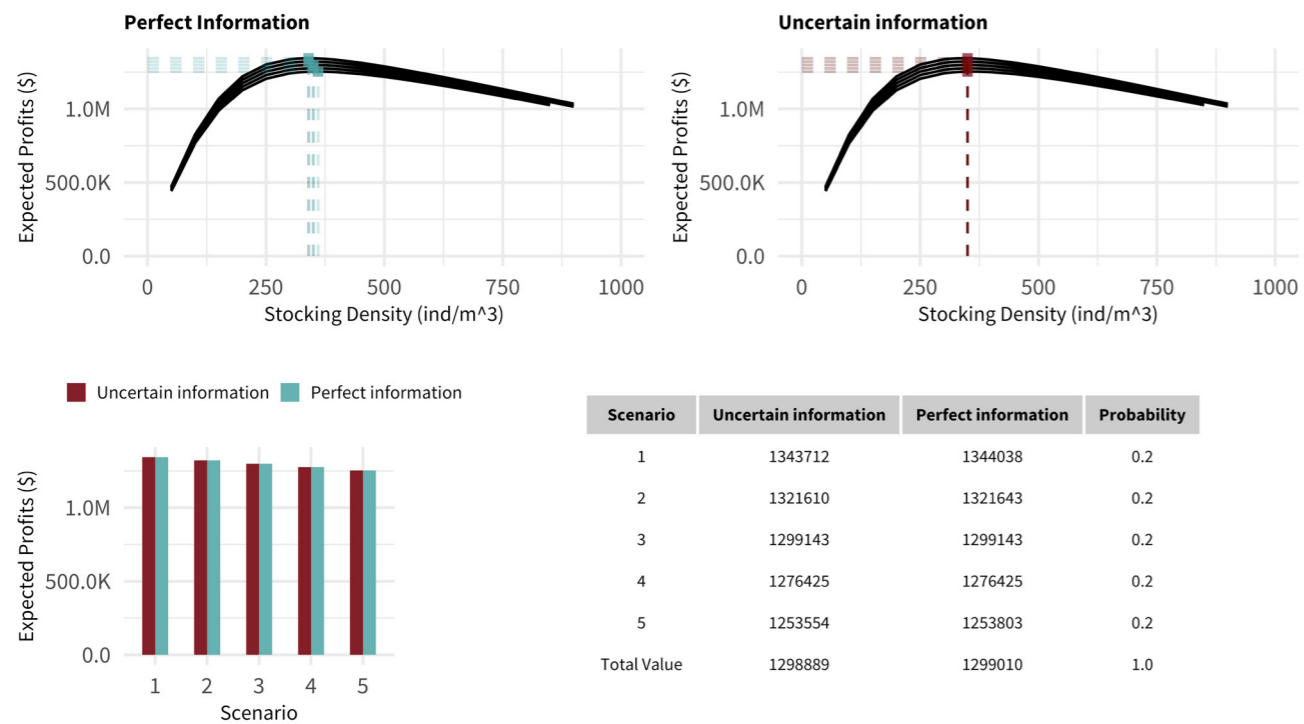| Scenario	Uncertain information	Perfect information	Probability
1	138825.1	216298.3	0.2
2	1208981.7	1310414.6	0.2
3	2228736.4	2270626.4	0.2
4	3837386.5	3837386.5	0.2
5	4876214.5	4922784.9	0.2
Total Value	2458028.8	2511502.1	1.0

Figure 13. *Expected profits with perfect and uncertain information for five different scenarios and value of information for the environmental variable particulate organic matter.*

Temperature (degrees C)

Value of Information: $122

Scenario	Uncertain information	Perfect information	Probability
1	1343712	1344038	0.2
2	1321610	1321643	0.2
3	1299143	1299143	0.2
4	1276425	1276425	0.2
5	1253554	1253803	0.2
Total Value	1298889	1299010	1.0

Figure 12. *Expected profits with perfect and uncertain information for five different scenarios and value of information for the environmental variable temperature.*

4.2 Summary of Results

Using these results, we can develop an intuition for when to expect a high or low value of information for an environmental variable. This intuition enables a rapid assessment of what environmental information has the most value to farmers and the greatest potential impact on their decision-making. Directing resources to provide forecasting services for variables with a higher value environmental information will be more consequential for a shellfish farmer's expected profit, and in tandem an increased willingness to pay for a service providing this information. To develop this intuition, it is helpful to first understand what factors influence the value of an environmental variable.

The first factor is the variability in the distribution of optimal stocking densities across environmental scenarios. Environmental variables with more variability in their optimal stocking densities across the five scenarios have a higher value of information because a farmer's stocking density choice based on previous environmental conditions is less likely to be near the optimal stocking density under future conditions than at a location where the variability between optimal stocking density points is less. This concept is demonstrated by moving left to right on the bottom row of Figure 14. As the variability of optimal stocking densities increases, the value of information increases as well.

The second factor is the variability in the expected profits across environmental scenarios. Environmental variables with more variability in their expected profit across the 5 scenarios are more valuable because choosing a less than optimal stocking density under each scenario leads to a greater reduction in expected profits than with less variability. This is demonstrated by moving from the bottom of Figure 14 to

the top (except on the first column, where the optimal and best guess stocking density are the same).

Applying this intuition to the results from our four environmental variables, we can see that variables with a high value of information exhibit substantial variability between optimal stocking densities and expected profit curves, as exhibited by particulate matter and current speed. Variables with low value have similar expected profit curve shape and optimal stocking density are relatively similar across scenarios; chlorophyll *a* and temperature exemplify this well.

Understanding What Makes Information Valuable
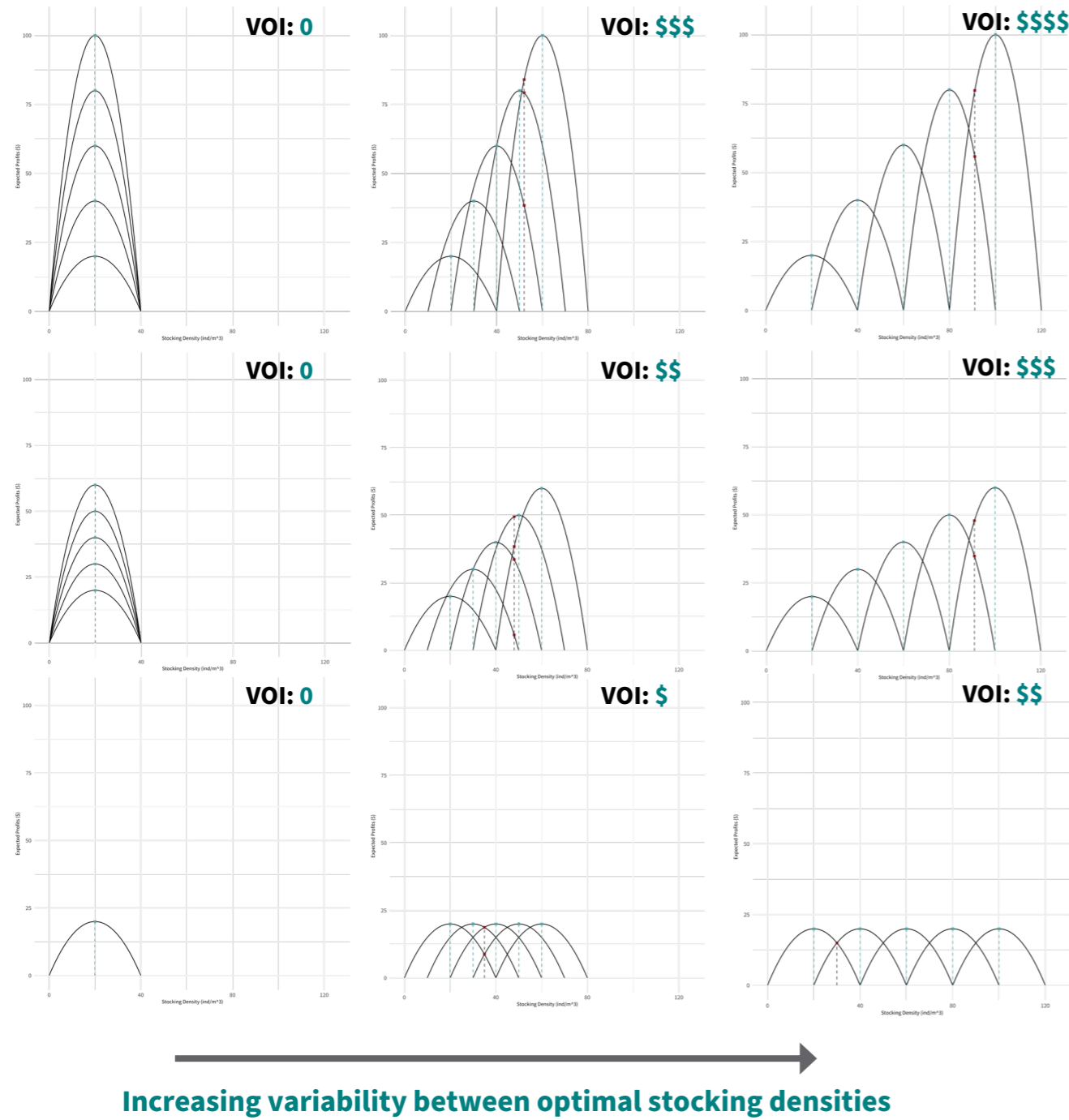

Increasing variability between expected profit

Increasing variability between optimal stocking densities

Figure 14. *The change in VOI as variability between optimal stocking densities and/or expected profits increases.*

5. Non-Environmental Barriers

5.1 Exploring Other Sources of Uncertainty

Using VOI analysis, we found that environmental information may hold value for shellfish farmers. However, environmental uncertainty is not the only barrier that farmers face. We identified three cateogries groups of non-environmental barriers for farmers in B.C., collected from interviews and compiled from our literature review.

We categorized these barriers into the following groups: logistic & economic, social & cultural, and regulatory & political. These categories aim to capture the breadth and complexity of challenges shellfish farmers face, while acknowledging commonality among experiences. Though distinctly categorized, many of these barriers are acutely interconnected. These challenges carry more or less weight depending on the operation or respective community, but they are common across the province and industry. These non-environmental barriers will be described in further detail in the following sections.

From our conversations in B.C., it was apparent that there is potential for inclusive collaboration and cooperation as a way to alleviate these barriers. Many of the large farm operations on Vancouver Island have limited involvement from First Nations, despite tenures being located on their traditional territories. There is a growing interest by some Nations to become involved in the industry, though the extent and capacity of which is highly variable. Amidst the changing sociocultural and political landscape in B.C., this collaboration can take the form of cooperative business partnerships and agreements that highlight First Nations priorities and values while moving towards a more sustainable and productive industry.

Figure 15. *Team members Tom Wheeler and Caitie Reza interview Dr. Tim Green, a researcher at the Deep Bay Marine Field Station in Baynes Sound. Photo: Halley McVeigh*

5.2 Interview Methodology

Interview Limitations

The intent of conducting interviews in B.C. with farmers, researchers, and others connected to the industry was to gain a deeper understanding of the current state of the industry and the communities shellfish farms are operating in. This portion of the project was significantly limited by COVID-19 policies restricting access to B.C. through the beginning of the summer of 2021 and reduced our time in B.C. from two months to two weeks. COVID-19's effect on the shellfish farming communities we visited also reduced potential interviewees' willingness to participate in interviews and the overall capacity of communities that were contacted. Furthermore, efforts to include First Nations perspectives and knowledge in informing project scope and development did not fully align with our limited project timeline and their community practices.

Approach

Interviews were largely opportunistic in nature and semi-directive in format.[36] While we aimed to solicit a varied range of opinions and perceptions, contacts were greatly influenced by client directive and their prior outreach. The bulk of this portion of the study took place during the summer months of 2021. We conducted five in-person interviews in the Vancouver Island area of B.C., while additional interviews were conducted via Zoom throughout the summer and early fall months. Farmers that were included in this portion represented large-scale operations and small, multi-generational farms. Additionally, we spoke with longtime industry members and applied shellfish researchers. All participants acted voluntarily and were not compensated for their time. This research project was certified by the UCSB Human Subjects Committee Office of Research under Category 2 Exempt status.

5.3 Key Takeaways

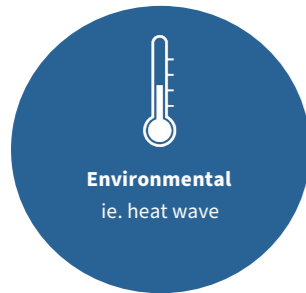### 5.3.1 Categories of Non-Environmental Barriers

Logistic & Economic

Many shellfish farmers in B.C. operate in remote locations with limited access to infrastructure and business resources needed to participate in markets. These barriers can be cost prohibitive for an operation's growth ambitions and limit suitable locations for establishing new farms. Logistic and economic barriers often materialize in the period between grow-out and distribution phases of the production process.

Input costs for first-time shellfish growers are high; farming equipment and vessels are substantial investments and farmers do not receive a payout for at least 1.5 to 3 years, when most B.C. shellfish species reach marketable size. Shellfish seed needs to be purchased annually and in large quantities. The price of seed, is highly variable based on the

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Science & Management

Environmental
ie. heat wave

Logistic and Economic
ie. transportation costs

Social and Cultural
ie. lack of collabo-ration

Regulatory and Political
ie. testing standards

source, season, and availability. Additionally, the B.C. shellfish industry has suffered a consistent shortage of labor. On one hand, rising housing prices and increased costs of living necessitate employees being paid higher wages on-site. On the other, physical demand and seasonality of the job has led to high turnover rates and an overall lack of retention of employees.

Before shellfish are able to be distributed, they must be a) harvested, b) transported from the farm to a processing facility, c) cleaned and graded, and d) packaged for shipping. Samples for oyster shipments must also be externally tested in a lab for Paralytic Shellfish Poisoning (PSP), Vibriosis, and other biotoxins. Transporting products to be sold off of Vancouver Island often involves multiple trucks and at least one ferry, with high fuel costs compounded by long travel times and the need for constant refrigeration. Access and proximity to processing facilities are also considerable obstacles for small-scale farms in B.C., especially those in more remote or semi-rural locations. In addition to high transportation and labor costs, the time and effort needed for harvesting, grading, sorting, and testing shellfish greatly impedes the ability of smaller growers to expand operations.

Insurance

Tools to manage financial risk in the B.C. shellfish industry are limited. Across all farm scales, lack of affordable insurance reduces sources of capital willing to invest in new operations or expansion as the perceived risk of investing in a shellfish farm is high. Difficulty quantifying the risk associated with a shellfish farming operation has created a gap in the market for insurance services to farmers.

In contrast to land-based farmers, B.C. shellfish growers are unable to receive compensation for their expenses associated with loss of product. A blueberry farmer in Vancouver, for example, is covered for any lost or damaged inventory due to an unavoidable natural event, like a storm or drought, under B.C.'s Agricultural Production Insurance program. An oyster grower, on the other hand, might lose 60% of the year's stock to a heatwave and receive no support.

While growers might have insurance on physical assets like processing facilities, boats, and gear, the shellfish themselves are not considered insurable crops. By legal definition, shellfish growers are "fishermen" rather than "farmers" and cannot claim damages.

Several types of coverage programs from B.C. land-based agriculture and the US shellfish industry could theoretically be applied to B.C. shellfish aquaculture. In addition to standard production insurance, growers could enroll in parametric insurance, where payouts occur once environmental conditions reach certain thresholds that are considered extreme or known to negatively affect the health of oysters. In addition to extreme weather events, many crop insurance programs cover land-based farmers for loss or damages inflicted by wildlife. In the same way that grain might be damaged by elk on land, an oyster

grower could be covered for damages from gear fouling and predation by urchins, sea stars, and crabs – even when the best prevention measures are taken.

Potential Shellfish Aquaculture Insurance

1. **Production Insurance**: covers any loss of inventory due to an unavoidable natural event (heat wave, storm, etc)

2. **Parametric Insurance**: automatically triggered at or above specific environmental thresholds

3. **Wildlife Damages**: replaces product lost to gear fouling and predation

Socio-Cultural

Many social and cultural challenges faced by shellfish farmers in B.C. are tied to conflicting priorities towards natural resource management, and shellfish aquaculture more specifically, across intergenerational, inter-community, and intergovernmental divides. These conflicting priorities feed into a lack of collaboration between communities, and are exacerbated by the individuality of operations.

Administratively, First Nations have the capacity to approve or deny proposed tenures, beach permits, and changes in management techniques proposed by new or existing operations. As First Nations gain more sovereignty over their traditional lands, the process of territory designation has been transitioning away from "strength of claims", whereby a collection of evidence concerning the rights of a Nation to a geographic region is reviewed and analyzed by the Province, and towards land claims. Land claims are collaborative agreements and achieved through extensive negotiation between multiple Nations and, oftentime, government agencies. Land claims of multiple Nations often overlap with each other, and, in some instances, up to 14 First Nations might share the same traditional territory. Subsequently, a full consensus on a potential tenure site, for example, is hard to reach, and projects often stall or do not move forward.

Regulatory & Political

Many of the logistic and social barriers are amplified by regulatory and political barriers across the B.C. shellfish industry. Regulatory authority is divided between Canada's Department of Fisheries and Oceans (DFO) and the Province of B.C..

Licenses, for example, are issued by the DFO, while the provincial government issues tenures for all marine and freshwater sites. All farming activities are required to be cataloged in a "Management Plan", a document that is submitted to the DFO as part of the license application. The authorization of any changes to a farm's Management Plan, including

Feature Story:
Small-Scale Cooperative Farm in Baynes Sound

Our feature story highlights a small-scale oyster farm owned by a family on the Eastern coast of Vancouver Island. Late in the summer of 2021, we met with a small-scale shellfish grower in Baynes Sound who was eager to tell his family's story. His father, an immigrant from Vietnam, began working in the commercial halibut and salmon fisheries before transitioning to shellfish aquaculture in the 1990's. In 1997, along with 6 other local families, he obtained a 50-year provincial lease from the K'omoks Nation in the Union Bay area. The purchase included 40 rafts and several, 400 square-foot sections of beach previously leased by the K'omoks Nation. Our interviewee's family acquired and operates 10 of the 40 rafts, with the remaining 30 run by other families. The farm functions as a cooperative where all oysters produced within the lease are sold together as a single order to a large-scale seafood company, who processes them for distribution.

Currently, they grow Pacific oysters and primarily employ manual harvesting techniques that have changed little since operations began. Tracking inventory and recordkeeping, as a whole, is almost exclusively conducted using handwritten notes. Important management decisions, such as deciding when to harvest and identifying racks affected by disease, are largely based on anecdotal information, a common practice for smaller operations.

Challenges

This farm and many other smaller, family-run farms on Vancouver Island face a multitude of challenges when attempting to expand their operation. A language barrier still exists for many first-generation Vietnamese Canadian farmers that hinders communication with other farmers, impedes collaboration with the wider community, and affects business and management decisions, such as price negotiation with buyers. The B.C. Shellfish Growers Association (BCSGA), an organization which provides benefits for shellfish farmers in B.C., including technical training, business advising, and marketing events. Though the family are members of the BCSGA, many other farmers in their community do not pursue membership. This is possibly due, at least in part, to the language barrier.

Our interviewee's farm, face a multitude of environmental challenges that collectively contribute to high annual mortality rates and mass die-off events. Predation by starfish, sea urchins, and red rock crabs, as well as equipment fouling by seaweed and barnacles, are common issues facing most farmers. Though mitigation strategies designed to combat gear fouling, predation, and tidal desiccation do exist, warming events and pathogenic outbreaks are much more difficult to predict and prevent. Harmful algal blooms and heat-induced mortality can trigger massive market "close-offs", due to the risk of PSP.

Many family-run operations also face challenges securing consistent labor, sources of seed, and access to biotoxin testing. Throughout B.C., seasonal shifts and market variability impede a steady shellfish aquaculture workforce. Securing long-term employees is a challenge for their farm, which relies heavily on our interviewee and his sibling as sole laborers. Increased price and decreased availability of oyster seed has also been a limiting factor to many smaller operations in Baynes Sound, who generally purchase wholesale seed from larger farmers like Fanny Bay Oysters or import from Chile.

Towards a Better Future

Looking forward, our interviewee hopes to adopt a vertical business model by forging a direct path from grow-out to distribution. Consolidation of the distribution process will likely involve the construction of an on-site processing facility, which will require funding for purchasing land and a processing permit from the DFO. Many of his goals mirror the Community Supported Fishery (CSF) model, a seafood marketing and distribution process focused on connecting small-scale fishermen directly to consumers. In other regions where CSFs have taken hold, oyster farmers can raise their selling prices in response to consumers' increased willingness to pay for locally-sourced, high quality seafood. CSF's also have the potential to indirectly raise the wholesale price of oysters, which has remained fixed at around 32 cents per oyster since the late 1990's; potentially due in part to the limited number of wholesale distribution channels for farmers in B.C..

Ultimately, our interviewee hopes to empower other local growers, especially those from first- and second-generation immigrant families or otherwise underrepresented groups. He also hopes to enhance the branding of his family's oysters to increase visibility in the grocery store market, garner a broader audience, and share the story of immigrant-run oyster farms in B.C..
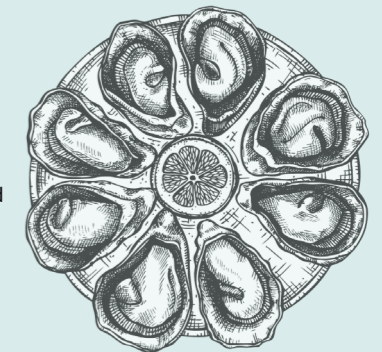
minor gear changes or management techniques, requires extensive consultation with First Nations in the area. Subsequently, this process can prove particularly challenging in regions with many overlapping land claims. Additionally, it can take years for a plan to garner approval from the DFO, forcing some farmers to make undocumented changes to their farm.

The DFO requires that each batch of shellfish be tested for waterborne pathogens like Vibriosis and Pseudo-nitzschia before being sold to buyers. The frequency of testing depends on weather conditions and regional water-monitoring status, among other factors, and can occur as often as once a day. Coupled by the need to outsource testing, keeping up with monitoring is inherently challenging for many farmers across B.C.. Inspection fees and transportation, have an outsized impact on rural, small-scale operations.

5.4 Partnerships & Future Directions

The following information on future directions of the shellfish aquaculture industry and First Nations involvement is compiled from literature reviews and biweekly discussions with with our external advisor, Kadin Snook, a member of the Mowachaht/Muchalaht Nation and an employed resource manager of the Five Nations on the West Coast.[42]

First Nations Perceptions of Shellfish Aquaculture

First Nation perceptions of shellfish aquaculture in B.C. range from highly positive to highly negative, or at the very least skeptical. Variables influencing opinions include environmental impacts, economic risks and benefits, and sociocultural impacts of shellfish aquaculture development. Some First Nations see shellfish aquaculture development potentially conflicting with wild beach harvesting, other land and water use conflicts, and take issue with the privatization of coastal waters more broadly.[5]

Historically, the region of what is now known as B.C. was a common property landscape for wild fisheries and other natural resources.[23] The development of the tenure and licensing system has led rise to issues with First Nations cultural and territorial sovereignty. Of the three types of habitats that leases occupy, nearshore and deepwater tend to conflict less with cultural and subsistence practices whereas foreshore leases may conflict with the more accessible natural shellfish beach habitat. Denman Island Marine Stewards highlight threats imposed to sensitive beach habitats such as leftover plastic debris and anti-predator netting, vehicle traffic, and the alteration of natural shoreline structure.

Researchers who explore the perceptions of shellfish aquaculture in B.C. have found that, in addition to tensions surrounding the tenuring process and impacts to cultural ways of life, uncertainty over risks and benefits of shellfish operations was a major concern for some communities.[23] Other individuals see potential benefits of shellfish aquaculture development due to increased employment opportunities and economic development for their communities in addition to increased food sovereignty and security.

First Nations Partnerships and Co-operative Business Models

As the industry moves away from consultation and accommodation toward relationships of consent and partnerships, there is more opportunity for mutually beneficial cross-cultural and cross-community col-

laboration. Within many First Nations there has been a lack of sufficient internal capacity to devote adequate resources and time to shellfish aquaculture development. This encompasses technical capacity as well as general community capacity. Skills training and education programs can aid in providing the necessary technical competency to increase successful involvement in the industry.

As for management and community capacity, there is often insufficient personnel and financial resources to plan for, and manage long-term developments. Oftentimes, it is the lands and economic development manager who is responsible for business development projects and is unable to devote ample time to other issues. It was emphasized that a role specifically devoted to partnership development would bolster community's involvement while ensuring continuity throughout the development stages of a project or business.

Wihin the scope of an aquaculture business there is opportunity for collaboration throughout the development process. From initial business planning and site selection to procurement of input materials and seed, farm logistics and management, processing, transportation, regulatory services, and environmental monitoring there is expertise required at each point.

The smaller size of many operations coupled with limited access to a market network often results in the sale of products for low prices. This theme was discussed with Nations members as well as with immigrant and first-generation farmers. To address this issue the implementation of cooperative style markets was suggested as a possible and partial solution.

Additionally, a direct-marketing channel strategy, as in many Community Supported Fishery models, can allow for higher prices for farmers due to reduced costs for intermediaries in addition to a reduction in the marketing onus for farmers.

First Nations Sovereignty

Many treaty negotiations and rights and title cases are still unresolved for First Nations and the path towards territorial sovereignty is ongoing in the region. First Nations continue to experience both political and economic marginality which influences how risks are perceived. Political ecologists have studied how groups view policies that impact them with a higher degree of risk if they perceive vulnerability or inequity, as is the case with many Nations.[23]

Potential Benefits for First Nations

Increased accessibility to stable and long term capital was expressed as the leading benefit of participating in partnerships with non-First Nations operations. Additionally, access to greater and farther-reaching networks provides incentive to enter into agreements. These networks span material provisions, maintenance, transport services, processing facilities, and markets.

While coastal First Nations have a long history of tending to the coastlines and harvesting shellfish for subsistence purposes, there is limited expertise in the intensified process of current cultivation within communities. It was expressed that opportunities for education and training were important for communities to further their technical skills in the field to develop internal capacity. In addition to farm management, communities can learn from established companies about product development, marketing and the potential to gain support in business plan development.

An additional potential benefit for First Nations is to enter into partnerships or to pursue business opportunities that are not tied directly to their governing body to insulate the venture from political interference.

Potential Benefits for Existing Operations

Access to labor is a mutual benefit and can allow established companies to continue to operate in remote locations while providing economic benefits to communities.

For existing farm operations that are conducting business in a shifting sociopolitical climate in B.C., partnerships can increase long term stability. Strong relationships with Nations have the potential to reduce NIMBY-ism while increasing social license of operations and their locations. Beginning with the mining industries in the early 1900s, the idea of social license has since been a critical component in forestry, oil and gas, and finfish aquaculture endeavors.[37] It has increasingly become apparent in the shellfish aquaculture industry that local communities and rights and title holders have influence over the longevity of operations on their traditional territories.

By partnering with Nations there is potential to increase access to funding opportunities that are directed at Aboriginal communities. While it varies from Nation to Nation, some communities are more willing to incorporate their culture and Nation into branding for products which is potentially beneficial to already established businesses or those that wish to expand their market base or image.

Important Considerations

While each community and Nation will have different priorities and values that are critical in considering any project or partnership there

are some common underlying themes. On the West Coast of Vancouver Island we heard of a particular interest in ensuring community benefits and a focus on continued progress towards self determination and maintaining self-governance. A key element in view of new ventures is that they not inhibit existing businesses or practices.

> **Nuu-chah-nulth values of iisaak (respect) and hiish-uk-ish-tsawalk (everything is interconnected) are grounding principles for most of the 14 Nations of Nuu-chah-nulth and are key concepts in their Indigenous food sovereignty and foodways.[38]**

In consideration of best management practices of fisheries and resources in the province, government-to-government relations can be strengthened by including First Nations, DFO, and the Province in planning efforts and decision making. Long-term management of shellfish fisheries as well as the sustainable development of shellfish aquaculture is anticipated to be improved by incorporating Indigenous rights and values in community-led practices.[3] The 2014 Pacific Region Shellfish Integrated Management of Aquaculture Plan by DFO highlighted the importance of First Nations engagement with shellfish aquaculture.[3]

Types of Partnership Agreements

Benefit-sharing and Impact Benefit Agreements

Not considered a partnership, rather an agreement that is proposed by a business and involves payments to communities in exchange for the business to continue operations. Historically it was a means for businesses to conduct extractive activities and were not collaborative in structure. The community rarely has influence over the decision-making processes and likely do not hold a sense of ownership or responsibility of the business's actions. Traditionally, there is little to no flexibility in the percentage or extent of capital or opportunity agreements in an agreement. There is a reduction in risk for the community in benefit-sharing agreements over an ownership model.

Cooperatives

Survey research suggests that many industry members see the success of aquaculture businesses hinge on the development of cooperatives or other vertically integrated structures.[23] Cooperative models allow for processing, transport, and marketing to be streamlined and more transparent.[23] Small-scale farms can jointly move and sell shellfish and leverage their products to take advantage of economies of scale. Many farms are burdened with prohibitive costs, demanding processing, and competitive marketing that can be eased in successful cooperatives.

Business-ownership

Unlike low risk, benefit-sharing scenarios, business-ownership approaches have a higher risk to reward trade-off. The community will likely have greater decision-making power and can better advocate for community needs. There are many forms of business-ownership and differ in the proportions of how ownership is distributed.

- Non-majority equity stake in partnership
- 50/50 partnership
- Majority equity stake in partnership
- 100% Nation owned business with relationships with other businesses

Recommendations and Next Steps | Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in B.C.

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6. Recommendations and Next Steps

6.1 Next Steps for Improving the Model

This section aims to provide a roadmap for researchers seeking to improve the accuracy of the VOI model. These recommendations were not incorporated into the model due to the limited project timeline and data limitations.

6.1.1 Accounting for Varying Environmental Probabilities

While our model assumes an equal probability between five possible scenarios, we can imagine a situation with low variability where the median scenario has the highest probability of occurring and the distribution of probabilities varies little and is roughly normal in shape. This could be the case for many environmental variables which often display a normal distribution in their probability of occurring through time. Gaining a better understanding of how conditions vary through time in B.C. would be an important next step for understanding the variability of environmental probabilities across scenarios.

6.1.2 Incorporating Mortality Induced by External Stressors

Harvestable biomass values output by the FARM model for Blue mussels are generated using the ShellSIM growth model developed by the Plymouth Marine Laboratory team.[39] The FARM model draws from ShellSIM and seeks to scale its projections to the farm level. The outputs generated by ShellSIM are limited in how they account for mortality induced by environmental stressors. While ShellSIM can account for mortality by allowing a user to input a "Mortality Fraction" (see Figure 18), this is presumably a best guess based on previous conditions. Due to its limited accounting for mortality, the FARM model may be underestimating the impact greater stocking densities have on susceptibility to disease and resilience to environmental stress when many shellfish are competing for nutrients in a constrained environment during the grow out period.

6.1.3 Accounting for Time

The FARM model default of 180 days was used to calculate the value of information in section 4. We used this time frame as a simplified, one-time management decision, but in the real world there are many decisions that need to be made throughout the grow out period. If a management decision can only be made once over a full grow-out timeline, one would likely want to choose a time period that reflects the full length of time between when the management decision is made and when it needs to be made again. If the management decision can be made multiple times during a grow-out period, as is the case with stocking density, we could consider when it is worth changing stocking density again during a grow out cycle if it could lead to a faster growth rate during an upcoming period of time (such as a changing season leading to a different probability distribution of environmental scenarios). In evaluating this question we would need to weigh the cost of making that stocking density change relative to the impact it would have on shellfish growth.

6.1.4 Accounting for Less than Perfect Accuracy of Environmental Forecasting

Our model calculates the value of perfect information. Under real world conditions, updating the VOI model to allow for less-than-perfect accuracy would be an important next step. This will reduce the value of information.

6.1.5 Accounting for Uncertainty Between all Variables

When calculating the value of information for each environmental variable individually, the demonstrated model assumes all other variables are at a fixed, baseline level. A more realistic approach would account for all variables being uncertain under all scenarios.

6.2 Next Steps for Understanding Non-Environmental Barriers

Information gleaned from conversations regarding future directions for the industry emphasized the successful inclusion of all interested parties. It is important that the perspectives and experiences of underrepresented groups in shellfish aquaculture are elevated to build more inclusive and effective solutions. There are many cases exemplifying the variability in perceptions and preferences of First Nations communities towards shellfish aquaculture. Additionally, lessons learned from other industries in B.C. could provide valuable guidance for the shellfish industry going forward.

Figure 16. *Shell Sim Demo - Tab 1*

Figure 17. *Shell Sim Demo - Tab 2*

Figure 18. *Shell Sim Demo - Tab 3*

Conclusion | Assessing the Value of Environmental Information for Shellfish Aquaculture Farmers in B.C.

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Conclusion

Literature Cited

Shellfish aquaculture will continue to play a growing role in meeting global demand for low carbon protein. Regions that have experienced stymied growth in their shellfish aquaculture industries, such as B.C., have a unique opportunity to capture a substantial share of this growth, but must invest in technical and community-driven solutions to overcome development barriers. A key barrier is environmental uncertainty, which impedes optimal farm management and increases the investment risk of shellfish farms.

To reduce environmental uncertainty, shellfish industries around the world are investing in environmental monitoring and forecasting technologies which provide environmental information to shellfish farmers. We believe these investments signal that shellfish farmers place value on environmental information, but no efforts have been made to develop a model to quantify this value.

We developed a model to quantify the value of environmental information for shellfish farmers. Using this model, we found that perfect knowledge of future average temperature, chlorophyll *a* concentration, current speed, and particulate organic matter concentration has value for shellfish aquaculture farmers seeking to optimize their stocking density to maximize expected profit. Further, we found the value of this environmental information is not uniform across these four variables; current speed exhibited the highest value of information and sea surface temperature the lowest. The change of the value of information across the four variables was dependent on both the variability of optimal stocking densities and the variability in expected profits across the five model environmental scenarios.

To assess the impact of non-environmental barriers on B.C. shellfish farmers, we conducted a literature review and interviews with shellfish farmers, researchers, First Nations members, and industry affiliates, many of which took place in B.C. over the summer of 2021. From this research we assessed experiences with three categories of non-environmental barriers and used feature stories to provide grounded examples of farmer experiences. We found that potential solutions to overcoming non-environmental barriers include a shift toward cooperatives style business models, investing in First Nation capacity to support new ventures, and forging partnerships to enable community ownership and support.

While this project focuses on Western quantitative approaches to data collection and environmental monitoring, it is imperative to understand the value of TEKW and work with, and alongside, those involved in different ways of knowing.[40,41] The immense value that comes from the continuity of traditional data collection and relational processes in TEKW can be paired with standardized technologies and science-based knowledge to best inform management of resources and practices of food cultivation. Many Indigenous communities have partnered with

scientists and researchers to leverage scientific approaches for monitoring efforts that are informed by Indigenous values and pre-existing methodologies.[14]

Looking forward, both environmental and non-environmental barriers will need to be overcome to foster growth and expanded First Nation leadership in the B.C. shellfish industry. Our model is a tool environmental forecasting service providers seeking to reduce environmental uncertainty can use to assess what information is most valuable for shellfish farmers. Most importantly, this tool provides insight into what factors make information valuable, enabling a more rapid assessment of what environmental information has the greatest potential to impact farmer decision-making. Insights from our assessment of non-environmental barriers contribute to a deeper understanding of the B.C. industry landscape and provide a framework for understanding the challenges and experiences of shellfish farmers. To overcome all industry barriers, a combination of new technologies, investments, partnerships, leadership, and understanding will be needed to unlock the B.C. shellfish industry's potential.

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