Assessing the Profitability of Integrated Multi-Trophic Aquaculture in Canada With and Without a Deposit Feeder Component

by

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Abstract

Integrated Multi-Trophic Aquaculture (IMTA) has been proposed as a sustainable aquaculture technology that can help offset some of the environmental impacts of fed finfish aquaculture. My study builds on a previous financial analysis of salmon monoculture and IMTA in Canada by using a discounted cash-flow analysis (DCF) to examine the financial implications for investors considering investing in either (i) Atlantic salmon (*Salmo salar*) monoculture, (ii) Atlantic salmon, blue mussel (*Mytilus edulis*), and kelp (*Saccharina latissima*) three-species IMTA, or (iii) Atlantic salmon, blue mussel, kelp, and green sea urchin (*Strongylocentrotus droebachiensis*) four-species IMTA.

I found that three-species IMTA is more profitable than both Atlantic salmon monoculture and four-species IMTA, but that four-species IMTA has a lower net present value (NPV) than salmon monoculture if there is no price premium applied to IMTA salmon and mussels. Including a 10% price premium on IMTA salmon and mussels results in substantially higher NPVs for three-species and four-species IMTA compared to salmon monoculture. However, despite the positive indications of my study's DCF and other IMTA-related financial analyses, ongoing uncertainty related to IMTA's financial and environmental performance, and technological and managerial complexity, may be overriding barriers to IMTA adoption in Canada.

Keywords: Integrated Multi-Trophic Aquaculture; green sea urchin; echinoculture; investment appraisal; financial; monoculture

Dedication

This is for Nicholas Carras, a good man who always picked me up.

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I want to thank my partner, Marine Chéné, for her love and support throughout my graduate studies. Thank you to my parents, sisters, brother, aunts, uncles, cousins, nephews, and the whole French contingent who helped get me to where I am today. Also, a big thanks to my many wonderful friends and colleagues. You know who you are, and there are too many to name.

Finally, I want to thank Apollo for guiding my eardrums.

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List of Acronyms

CCA	Closed containment aquaculture
DCF	Discounted cash-flow analysis
HOG	Head-on-gutted
IMTA	Integrated Multi-Trophic Aquaculture
IRR	Internal rate of return
Kwh	Kilowatt hour
Nofima	Norwegian Institute of Food, Fisheries, and Aquaculture
NPV	Net present value
POM	Particulate organic matter
RAS	Recirculating aquaculture system
ROA	Real options analysis
µm	Micron

Chapter 1.

Introduction & Literature Review

1.1. Problem Statement

Aquaculture's growing contribution to global food production and nutrition has been accompanied by concerns over the industry's environmental impacts (Neori et al., 2007; FAO, 2008, 2009, 2016). Environmental concerns related to intensive fed finfish aquaculture include the eutrophication of local marine systems, disease outbreaks and disease transfers to wild populations, loss of biodiversity, health of global marine ecosystems, and food safety (Chopin et al., 2001, 2007; Deutsch et al., 2007; Shi et al., 2013). Integrated Multi-Trophic Aquaculture (IMTA) has been proposed as a sustainable form of aquaculture production that can help mitigate some of the nutrient loading associated with intensive fed finfish aquaculture production, and which may improve aquaculture producers' financial performance and social acceptance (Ridler et al., 2007b; FAO, 2008; Shi et al., 2013).

Research has demonstrated IMTA's potential to reduce local environmental pollution, but there remains uncertainty regarding the financial impacts to private aquaculture producers considering IMTA. This study will help to address this knowledge gap by conducting an updated discounted cash flow analysis that incorporates some financial and managerial considerations that are not widely discussed in the current IMTA economic literature, such as managerial complexity and concomitant cost increases. This study's discounted cash flow analysis will also investigate the financial impact of incorporating a benthic species into IMTA operations, an element increasingly viewed as a key to realizing IMTA's biomitigative potential (Reid et al., 2013; Cranford et al., 2013; Crampton, 2016; Cubillo et al., 2016; Figueira et al., 2017).

1.2. Literature Review

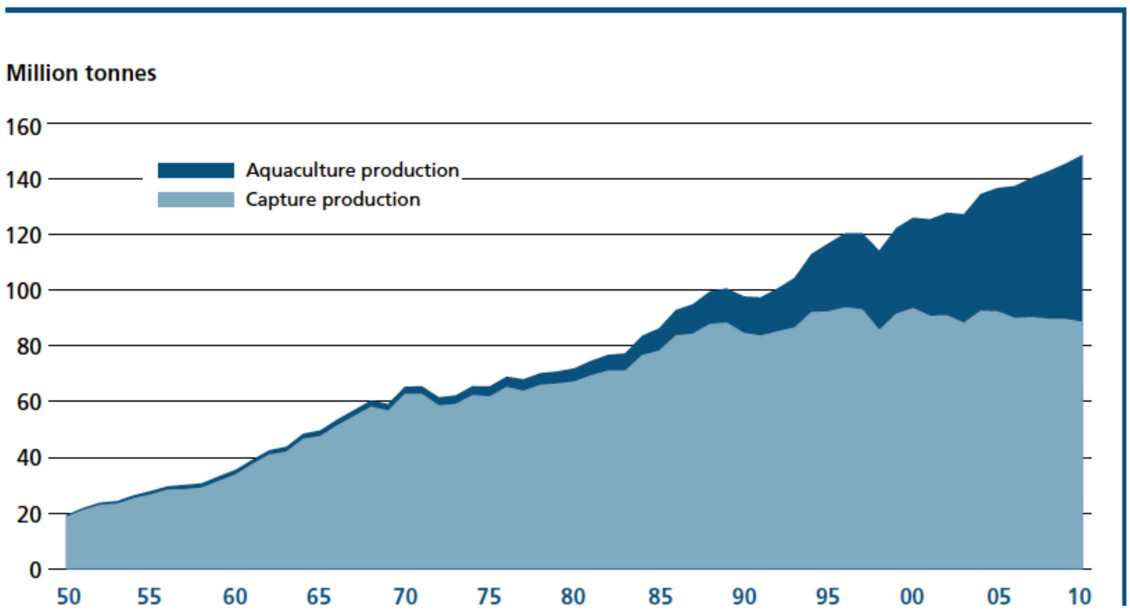
1.2.1. The Case for Sustainable Aquaculture

The aquaculture industry is the world's fastest growing food production sector, with food-fish production having grown at an average annual rate of 6.2% in recent years (Subasinghe et al., 2009; FAO, 2014a). Although the industry's rate of growth has slowed from high rates observed in the 1980s and 1990s, it is projected to remain the main global driver of increased fish production, a position it has held since global capture fisheries production levelled off in the mid-1990s (Figure 1). However, while the world's per-capita food fish supply nearly doubled between the 1960s and 2009, reports indicate that aquaculture food-fish production must increase to approximately 50 megatonnes (Mt) by 2050 to meet projected demand (Troell et al., 2003; FAO 2012, 2014a). The FAO has indicated that the sustainable future growth of aquaculture production will be contingent on new research, improved management practices, stakeholder engagement and benefit distribution, and aquaculture policies (Soto et al., 2008a; Subasinghe et al., 2009).

Researchers often define sustainability in aquaculture along the lines of the Brundtland Commission (1987), as requiring economic, environmental, and social sustainability that can meet the needs of people today without compromising the ability of future generations to meet their own needs. Aquaculture literature also details financial resources, specific environmental concerns, and social license to operate as important factors of consideration for the future sustainable growth of the industry (Troell et al., 2003; Soto et al., 2008a; Sunasinghe et al., 2009; FAO, 2012).

Social concerns of global aquaculture include labour conditions (particularly for aquaculture workers in the Global South), the equitable distribution of benefits to aquaculturists and local communities, aquaculture's impacts on local aesthetics, and water-use conflicts (e.g., between aquaculture operations and commercial fishermen) (Soto et al., 2008b; Bush et al., 2013). Environmental concerns of aquaculture include the degradation of marine ecosystems from eutrophication and chemicals used in disease treatments, escapees, disease outbreaks, increasing demands on wild fish stocks from farmed fish feed manufacturing, increased use of non-marine based aquaculture ingredients for aquaculture feed, and the climate impacts of fossil fuels used in aquaculture inputs and final product transportation (Soto et al., 2008b; Ayer and Tyedmers, 2009; Subasinghe et al., 2009). One body of research into aquaculture sustainability has focused on improving the performance of intensive finfish aquaculture, such as trout or salmon farming.

Figure 1: World capture fisheries and aquaculture production (FAO, 2014a)



While the global aquaculture industry's rate of expansion has declined over the years, farmed Atlantic salmon (*Salmo salar*) production remains high. The farmed salmon industry grew at an annual average of 9.5% from 1990 to 2010, and global demand for farmed salmon has been increasing annually (FAO, 2012). However, environmental concerns associated with intensive finfish aquaculture mirror broader concerns with aquaculture and include the eutrophication of local marine systems, disease outbreaks, loss of biodiversity, health of global marine ecosystems, and food safety (Chopin et al., 2001, 2007; Deutsch et al., 2007; Shi et al., 2013). Associated social concerns include access to employment opportunities, labour conditions, and aesthetic objections to fish farms (Bush et al., 2008; Barrington et al., 2010). Nevertheless, global competitive pressures, alongside public demand for improved social and environmental practices, are helping to drive sustainable innovations in the aquaculture industry (Ridler et al., 2007b; Tacon & Metian, 2008; Barrington et al., 2010; DFO, 2012).

Total aquaculture value in Canada increased over 20% from 2009 to 2013 and directly contributed CDN $962 million to Canada's economy in 2013. Farmed salmon is the primary contributor to Canada's aquaculture industry and comprised over 72% of aquaculture production value and 62% of production tonnage from 2009 to 2013 (DFO, 2015). While Canada is the world's fourth largest producer of farmed Atlantic salmon, it accounts for only 5.7% of global farmed Atlantic salmon production (FAO, 2014b). However, the environmental impacts of extensive salmon monoculture operations in Canada have been a pointed source of public criticism, with Atlantic salmon farming receiving the lion's share of attention. Additionally, Canada's small share of the global farmed salmon market makes it vulnerable to global market conditions, such as price shocks and cheaper labour costs in developing countries, as well as natural perturbations such as disease outbreak (Ridler et al., 2007b; Library of Parliament, 2013; Oglend, 2013). The Canadian aquaculture industry and policy-makers face ongoing pressure to develop and implement more sustainable aquaculture practices and regulations (Ridler et al., 2007b; Boulet et al., 2010; Ridler & Ridler, 2011; Library of Parliament, 2013). Though studies have shown that some rural communities in Canada receive economic benefits from aquaculture and view the industry favourably, a balance between the socio-economic benefits and environmental considerations will be important to the future of aquaculture in Canada (Robinson et al., 2006; Ridler et al., 2007b; Library of Parliament, 2013). Ecosystem-based management approaches to aquaculture and integrated aquaculture systems have been proposed to address some of the sustainability and management challenges facing the global aquaculture industry today and in the future (Soto et al., 2008a; Bostock et al., 2010; FAO, 2012; Chopin et al., 2013).

Closed Containment Aquaculture (CCA) is often seen as the front-runner in the realm of sustainable aquaculture technologies, and is thought by some to be a technically and economically viable form of sustainable aquaculture (Ayers & Tyedmers, 2009; Wright & Arianpoo, 2010; Crampton, 2016). Examples of CCA's popularity can be found in the substantial press coverage received by the development and launch of the

‘Namgis First Nation’s Atlantic salmon CCA farm in Port McNeill, British Columbia; the advocacy of CCA by prominent environmental non-governmental organizations; and studies and reports examining the potential of CCA that have been funded and published by the Government of Canada, project proponents, and consulting groups (Boulet et al., 2010; Wright & Arianpoo, 2010; Weston, 2013; Gardner Pinfold, 2014). In CCA, a cultured aquaculture species is separated from the natural environment using some form of containment structure so as to reduce environmental impacts. There are multiple CCA technologies that separate the cultured species from the natural environment to different degrees, however only land-based recirculating aquaculture systems (RAS) have been demonstrated to be financially viable in the literature (Boulet et al., 2010; Wright & Arianpoo, 2010). Advantages of RAS include increased biosecurity (low probability of escapees, eutrophication of marine environment, disease transfer to and/or amplification in wild marine stocks, disease transfer and/or amplification from wild marine stocks), increased accessibility, and more control over the fish husbandry process due to the technological nature of RAS. Disadvantages include high capital and energy costs, and the possibility of increased vulnerability to market forces. The CCA project being operated by the `Namgis First Nation is an example of an RAS (Martell et al., 2013).

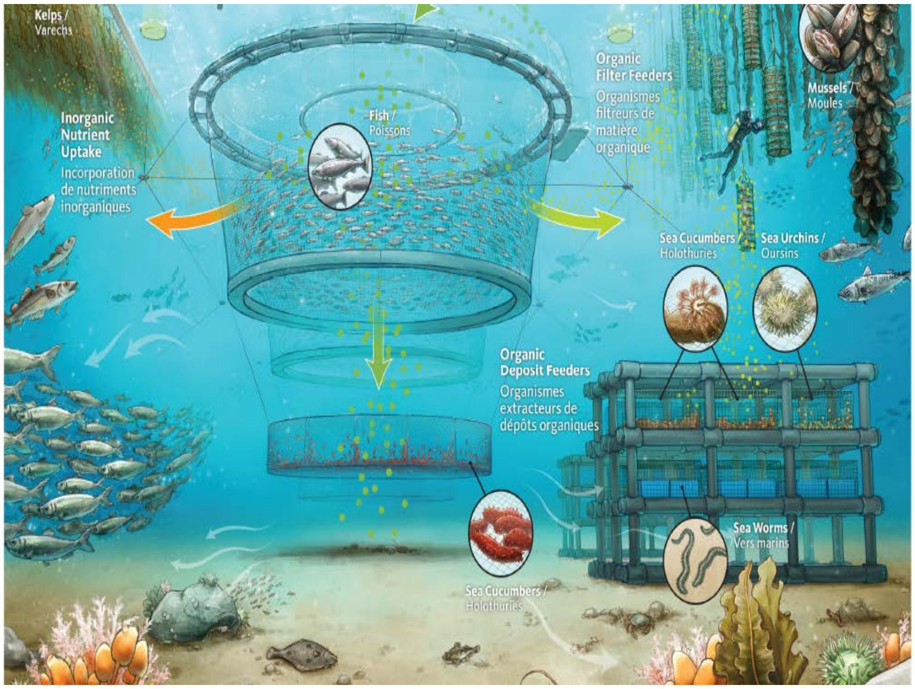
Boulet et al.’s (2010) study uses a discounted cash flow analysis (DCF) to examine the financial outcomes of nine different aquaculture technologies producing Atlantic salmon. The authors included conventional net-pen aquaculture and RAS technologies in the study and found that traditional net-pen intensive aquaculture operations are more financially attractive and resilient from an investor’s perspective. Though RAS systems also produced a positive net income, they also require significantly higher upfront capital investments. No other CCA technologies were found to be financially viable. The authors also noted that future economies of scale and technological innovations in RAS could improve the technology’s financial performance.

Wright and Arianpoo (2010) used a DCF to evaluate the economic implications of investing in an Atlantic salmon RAS in a British Columbia context. The study used a scalable 100-tonne farm module to estimate costs for a 1000-tonne land-based operation. The authors conducted a technology, land, water, and financial assessment and found that, for a RAS operation as analyzed in their study, there are no technological, land access, water access, or financial barriers to investors. Despite higher upfront capital costs, Wright and Arianpoo (2010) cite shorter production cycles, potential price premiums, and the decreased ecological risk of RAS compared to conventional net-pen salmon farming in rural British Columbia as important points of consideration for communities, investors, and policy-makers. A more recent report by Gardner Pinfold (2014) examined RAS prospects in Nova Scotia, Canada. The report concluded that there are still technical and financial uncertainties to overcome in the deployment of RAS at commercial scales, but that land-based closed containment systems could help alleviate social license issues facing the aquaculture industry. Key considerations for potential RAS investors listed in the report were reaching economies of scale and market potential.

1.2.2. Integrated Multi-Trophic Aquaculture (IMTA)

IMTA has been practiced informally for centuries and has been proposed as an aquaculture method that can help mitigate some of the environmental concerns associated with intensive fed finfish aquaculture (Chopin et al., 2001; Deutsch et al., 2007; Ridler et al., 2007b; Subasinghe et al., 2009; Troell et al., 2009; Bostock et al., 2010; FAO, 2012; Shi et al., 2013). In IMTA, the nutrient wastes from higher trophic level species – such as excess fish feed and faeces – are used as nutritional inputs by co-cultured species at lower trophic levels, helping to simulate natural nutrient flows and reduce organic accumulation concerns in the local marine environment (see Figure 2) (Chopin et al., 2001; MacDonald et al., 2011). IMTA systems can involve a wide range of finfish, bivalve, algae, and benthic invertebrate species, but frequent core elements include a fed aquaculture species (e.g., shrimp or salmon) and organic and inorganic extractive aquaculture species (e.g., shellfish and seaweeds, respectively) (Angel, 2004; Chopin & Robinson, 2004; Neori et al., 2007). IMTA can be practiced on land or in ocean-based aquaculture systems (Chopin & Sawhney, 2009).

Figure 2: **Conceptual model for an IMTA system (DFO, 2013)**



Technical, biological, and economic IMTA research to date has indicated that IMTA can improve environmental performance and social acceptability, diversify operating risks from market and natural forces, and lead to higher economic returns (Chopin et al., 2001; Deutsch et al., 2007; Ridler et al., 2007b; Subasinghe et al., 2009; Troell et al., 2009; Bostock et al., 2010; FAO, 2012; Shi et al., 2013). Recent studies have examined the claims of IMTA's improved environmental performance and the nutrient-removal efficiency of IMTA components, lending a deeper understanding to the complexities involved in establishing a fully optimized IMTA operation (Troell et al., 2009; Bostock et al., 2010; Cranford et al., 2013; Filgueira et al., 2017). These study results have indicated that shellfish may not contribute to a net reduction in nutrient loading around fed finfish farms and further emphasized the need for additional research examining the biological and economic roles of benthic-feeding species in IMTA operations (Cranford et al., 2013; Lander et al., 2013; Reid et al., 2013).

IMTA researchers on Canada's east coast have thus far been focusing on IMTA systems that include Atlantic salmon, blue mussels (*Mytilus edulis*), seaweeds (*Saccharina latissima* and *Alaria esculenta*), and the orange-footed sea cucumber

(*Cucumaria frondosa*) (Chopin et al., 2001; Lander et al., 2004; Ridler et al., 2007b; Barrington et al., 2010; Nelson et al., 2012; Chopin et al., 2013). IMTA researchers on the west coast have been focusing on sablefish (*Anoplopoma fimbria*), California sea cucumbers (*Parastichopus californicus*), green sea urchins (*Strongylocentrotus* droebachiensis), Pacific scallops (unconfirmed hybrid: *Mizuhopecten yessoensis* x *Patinopectin caurinus*), mussels (*Mytilus edulis* and *Mytilus galloprovincialis*), Pacific oysters (*Cassostrea gigas*), and kelp (*Saccharina latissima*) (Chopin et al., 2013; Hannah et al., 2013; Webb et al., 2013; Azad et al., 2014; Orr et al., 2014).

1.2.3. Financial and Economic Analysis of Integrated Multi-Trophic Aquaculture (IMTA)

1.2.3.1. Market Analysis

The improved environmental sustainability of IMTA is expected to enable the sale of IMTA-produced Atlantic salmon, oysters, and mussels for a price premium in North American markets (Shuve et al., 2009; Kitchen, 2011; AMB Marine and Coastal Research, 2012; Yip et al., 2017). Studies of consumer preference and willingness-to-pay for IMTA products in northwest North America have found that consumers would be willing to pay a 9.8% premium for IMTA-produced salmon and a 24% premium for IMTA-produced oysters (Kitchen, 2011; Yip et al., 2017). A survey of urban and rural communities in New Brunswick, Canada, showed that 33% of rural residents and over 50% of urban residents would purchase IMTA salmon at a 10% premium based on its improved environmental performance (Ridler & Ridler, 2011). A study of New York consumers of fresh mussels indicated that approximately 25% of respondents would pay a 10% price premium for eco-certified fresh mussels, with another 25% who would consider paying a 10% premium. However, limited distribution channels for IMTA mussels in New York would hamper market penetration (Shuve et al., 2009).

Asian markets are the primary destination for seaweeds and benthic-feeding species, such as sea urchins and sea cucumbers, which could be included in IMTA operations. However, Asian markets exclusively value quality. Seaweeds and kelps may find niche market positions in cosmetics or as an organic food source, and thereby command a price premium, but their largest destination markets place little comparative value on environmental performance (AMB Marine and Coastal Research, 2012). As such, price premiums based on perceived environmental benefits of IMTA may not be relevant for IMTA operations co-cultivating seaweeds and benthic-feeding species.

Some research has looked at the use of prepared feeds in green sea urchin aquaculture and the impact of these formulated feeds on green sea urchins' marketable characteristics (taste, texture, and size of the sea urchin roe) (Pearce et al., 2002; 2004; Eddy et al., 2012 James et al., 2017).[1] Pearce et al.'s (2002; 2004) findings suggest that green sea urchin gonads can achieve a desirable size and colouring when fed prepared feeds compared with kelp-fed or wild urchins. These findings are echoed by Eddy et al.'s (2012) analysis of juvenile green sea urchin growth on a prepared abalone feed versus a macroalgal diet. Pearce et al.'s (2002; 2004) results also highlighted the varying and largely poor-tasting gonads obtained from urchins fed various prepared diets compared with kelp-fed urchins or wild controls. These results suggest that some kind of finishing diet would likely be required for green sea urchins cultured under finfish cages to achieve a desirable taste. Otherwise, IMTA-cultured urchins' primary diet would largely consist of waste fish feed and fish faeces, which is not certain to yield a high-quality tasting urchin roe.[2] James et al.'s (2017) results indicate positive green sea urchin market characteristics for adult urchins fed a specially developed feed designed by the Norwegian Institute of Food, Fisheries, and Aquaculture (Nofima) for sea urchin roe enhancement.

[1] The sea urchin roe, or uni as it is commonly known in the culinary world, is actually the sea urchin gonad. The urchin roe is the edible part of sea urchins for which urchins are typically cultured and harvested (Pearce, 2006).

[2] Green sea urchins generally prefer fleshy microalgae species as food sources, but will eat a range of other food sources, such as benthic detritus and various mobile invertebrate species (Orr et al., 2014); at an intuitive level and based on Pearce et al. (2002; 2004), one can imagine that a diet solely comprised of waste fish-feed and salmon faeces would produce sea urchin gonads with a less than desirable taste. Because the quality of the roe is of primary import for the target market for benthic species (Asia) (AMB Marine and Coastal Research, 2012), even if the size of IMTA-cultured urchin gonads is greater than wild sea urchins, a finishing diet should be considered as part of green sea urchin's integration with fed finfish operations (Eddy et al., 2012; Christopher Pearce, Fisheries and Oceans Canada, personal commentary).

1.2.3.2. Socio-Economic Impacts of IMTA

Aquaculture is known for its positive impacts on income, employment, and food security in communities around the world, and these benefits are particularly pronounced in rural communities (Nobre et al., 2010). A survey of rural communities in NB, Canada, with economic ties to aquaculture, showed that residents hold largely positive views of current monoculture practices, but respondents also felt that IMTA could lead to improved perceptions of the aquaculture industry (Ridler et al., 2007b). However, to achieve improved public perception and a sustainable customer base for IMTA products, further education will be required (Ridler et al., 2006; Shuve et al., 2009; Ridler & Ridler, 2011; AMB Marine and Coastal Research, 2012; Hishamunda et al., 2013; Alexander et al., 2016a). Additionally, when the externalities of nutrient pollution are included in economic analyses, IMTA and other forms of integrated aquaculture have been shown to enhance socio-economic benefits through the improvement of aquaculture sites' environmental performance, as well as the financial performance of aquaculture farms (Chopin et al., 2001; Whitmarsh et al., 2006; Ridler et al., 2007b; Nobre et al., 2010). For example, salmon farms subject to farm-based effluent taxes (e.g., phosphorus, nitrogen) could reduce their compliance costs by 68.2% by integrating seaweeds [e.g., *Gracilaria chilensis* (Chopin et al., 2001)].

1.2.3.3. Economic and Financial Impacts of IMTA

Studies focused exclusively on the financial impacts of IMTA adoption for private actors in the aquaculture industry are less numerous than those addressing social and environmental costs, and there continues to be a call for research to bolster the body of study on the financial impacts for investors considering IMTA (Troell et al., 2003; Ridler et al., 2007a; Nobre et al., 2010; Reid, 2013; Alexander et al., 2016b).

Studies using DCF have shown IMTA to be profitable in both 2-species and 3-species integrated farm designs. Whitmarsh et al. (2006) found that an IMTA[3] mussel and salmon farm had a higher net present value (NPV) than the combined NPVs of salmon

[3] Referred to as *polyculture* in the publication.

and mussel monocultures over a 20-year project period. The authors held prices constant over the project cycle and included enhanced growth of 20% for IMTA-cultured mussels, cost-sharing, and marketing and sales costs. Their sensitivity analysis revealed that IMTA's NPV is more sensitive to fluctuations in salmon prices than mussel prices, and would be negative if salmon prices dropped at 2% per annum.

Ridler et al. (2007a,b) compared the NPV of a salmon, mussel, and seaweed IMTA operation to a monoculture salmon farm using data from Bay of Fundy operations in NB, Canada. Their results showed that IMTA had a higher NPV than salmon monoculture in all tested scenarios. In the reference scenario, IMTA's NPV was 24% higher than salmon monoculture. The study also examined the impact on IMTA and salmon monoculture farm profitability of a 12% drop in the market price of salmon, held constant over the 10-year project period, and large salmon mortality events. The IMTA operation had a higher NPV in all sensitivity scenarios and helped insulate salmon farmers from both market (price drop) and environmental (mortality event) risks. Ridler et al. (2007b) concluded that there is insufficient data to definitively assess the economic impact of IMTA, but that initial assessments of IMTA's financial viability, risk abatement potential, and associated improved social perceptions of the aquaculture industry are encouraging.

Another study by Shi et al. (2013), based in Sanggou Bay, China, measured NPV by area (km^2), and showed that scallop and kelp IMTA had a higher NPV per km^2 than either scallop or kelp monoculture. IMTA's NPV was only 13% lower than the combined NPV per km^2 of scallop and kelp monocultures. The study also applied an emergy analysis, to obtain an environmental sustainability index, and found that IMTA had higher environmental benefits than either monoculture operation.[4] The authors concluded

[4] Emergy analysis uses the principles of thermodynamics, system theory, and system ecology to assess the value of nature and human economies, using solar energy units to examine the energy, materials and currency of a given project/study unit's flow. The use of an emergy analysis helps to overcome the limitations of incorporating different resources measured in different units within the same study, though its use in marine ecosystem-based analysis is not strongly established (Shi et al., 2013).

that IMTA could be potentially applied successfully to open-water Chinese aquaculture operations.

Bunting and Shpigel (2009) used a bioeconomic model to examine the financial impacts of horizontally integrated aquaculture over a 10-year period in a temperate fish, microalgae, and shellfish operation off the coast of France, and a warm-water sea urchin, shrimp, and seaweed operation in Israel. The temperate French operation failed to generate a positive internal rate of return (IRR) when all costs were included. However, the temperate operation obtained a positive IRR when land, labour, and opportunity costs were omitted and aquaculture products were given a 20% price premium. The warm-water Israel model assumed annual production of 1 million sea urchins from year 3 onward and attained an IRR of 18%. The IRR increased to 29.4% when sea urchin mortality rates were reduced from 15% to 9% annually. The IRR increased to 133.4% when seaweed production was increased from to 33 kg m^{-2} y^{-1} from 2.25 kg m^{-2} y^{-1}.

These financial investigations of IMTA illustrate the possible financial benefits for IMTA investors using both models and empirical examples. However, the literature has continued to call for further investigation into the financial impacts of IMTA, looking at the impact of additional IMTA-candidate species, such as benthic-feeding species, and incorporating the trade-offs that would have to be considered by IMTA-adopting aquaculture companies (Troell et al., 2003; Ridler et al., 2007b; Reid et al., 2013; Hughes & Black, 2016). The continued call for a larger body of IMTA-focused economic research led to the present study.

1.3. Research Questions

The Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) has been actively researching the scientific, economic, and social impacts of IMTA production in Canada. As a CIMTAN-funded research student, I will anchor my economic analysis in a Canadian context. I will examine two specific questions in my research to help address the call for improved economic certainty for IMTA adopters:

Research Question #1: How does an updated assessment of the financial performance of a 3-species (Atlantic salmon, blue mussel, and seaweed) IMTA farm compare to the financial performance of an Atlantic salmon monoculture farm? Do these results differ significantly from those of Ridler et al. (2007)?

Research Question #2: How does the addition of a fourth species – a benthic element (green sea urchin) – to a 3-species IMTA farm (Atlantic salmon, blue mussel, and seaweed) affect the financial performance of IMTA?

1.4. Study Approach

Popular studies oft-cited in the sustainable aquaculture literature examining the profitability of IMTA or CCA operations compared with traditional monoculture aquaculture operations have taken a capital budgeting approach, using a DCF and NPV decision rule with differing results (Whitmarsh et al., 2006; Liu & Sumaila, 2007; Ridler et al., 2007b; Boulet et al., 2010; Wright & Arianpoo, 2010; Shi et al., 2013; Hughes & Black, 2016). I use the same analytical approach in this study.

My DCF models required the identification of production, financial, technical, and biological data by relevant species, shared costs expected in IMTA production, expected production rates and feed conversion ratios, increased management costs, and overhead costs. I found some of this information in existing capital budgeting models and spreadsheets used by Fisheries and Oceans Canada (DFO), Ridler et al. (2007b), and one kelp (*S. latissima* and *A. esculenta*) and one mussel (*M. edulis*) model provided by CIMTAN's Adrian Hamer. In an effort to make my DCF analyses more realistic than the previous Canada-based IMTA NPV analysis conducted by Ridler et al. (2007b), I examined these models' assumptions and individual data points, in consultation with a literature review, to determine which assumptions can be safely incorporated into my analysis and which assumptions should be modified or discarded. This information was supplemented by conversations with aquaculture industry professionals, researchers, and academics. Finally, the capital budgeting models will assume that the hypothetical aquaculture farms are start-up operations with identical project lifespans. The costs and revenues accruing to each specific farm and capital budgeting model will then be estimated for each year of the project’s lifespan and discounted at an appropriate private discount rate.

1.5. Organization of the Study

This study is divided into four chapters. Chapter 1 includes a basic literature review and provides a high-level description of my study approach and methods. Chapter 2 and Chapter 3 of this report are written as stand-alone research papers and address, respectively, this study’s two research questions listed above with more detailed literature reviews and methodology overviews. Chapter 4 serves as the study’s conclusion and includes a discussion of the implications of my results, IMTA and Canadian aquaculture policy, financial implications and considerations for potential IMTA investors, and areas for further research.

Chapter 2.

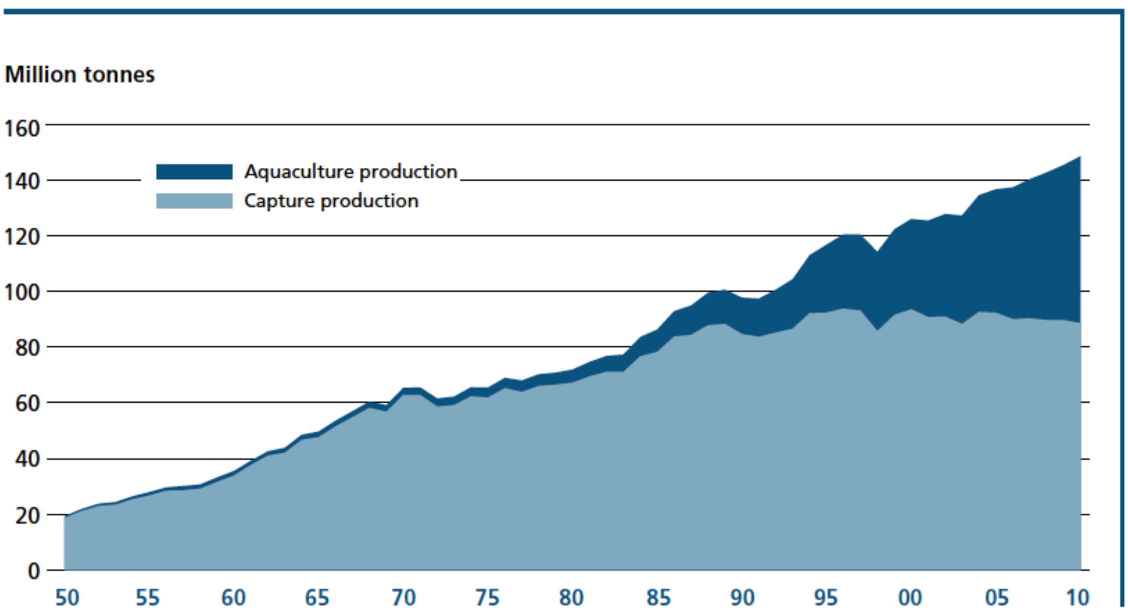
Comparing a Monoculture Salmon Farm and a Three-species IMTA Farm: a Discounted Cash-Flow Analysis of East Coast Canadian Aquaculture Operations

2.1. Introduction

Aquaculture is the world's fastest growing food production sector and has seen rapid expansion in the past three decades (see Figure 3), steadily increasing its contribution as a protein and nutrient source for a growing global population (Ridler et al., 2006; FAO, 2012). Aquaculture is also seen as an important economic activity for developing economies and rural communities, including rural east and west coast Canadian communities (Ridler et al., 2006; FAO, 2012; Nguyen & Williams, 2013; FAO, 2014a). However, the industry is facing calls to improve its social, environmental, and economic performance to ensure sustainable future growth and social license (Soto et al., 2008a; FAO 2012, 2016). Innovations and research in ecosystem-based management and integrated aquaculture systems have been proposed as possible solutions to address some of the sustainability and management challenges facing the aquaculture industry today and in the future (Soto et al., 2008a; Bostock et al., 2010; FAO, 2012, 2014a; Chopin et al., 2013).

Canada's farmed Atlantic salmon (*Salmo salar*) industry contributed over 70% of Canada's aquaculture production by value and 60% by volume from 2009 to 2013 but faces opposition from existing and expanding non-governmental organizations and community stakeholders calling for more sustainable aquaculture practices (DFO, 2015). One approach to sustainable aquaculture that has been investigated in Canada is integrated multi-trophic aquaculture (IMTA). IMTA is an aquaculture farming technique that mimics natural ecosystems by co-culturing multiple species from different trophic levels on the same farm site. In an IMTA farm configuration the organic and inorganic wastes of one cultured species serve as nutritional inputs for another, helping to diversify aquaculture producers' product lines, insulate against market and environmental risks, and reduce nutrient loading (Chopin et al., 2001, 2007; Chopin & Robinson, 2004; Troell et al., 2009). IMTA research on Canada's east coast has typically examined a three-species IMTA farm configuration that includes Atlantic salmon (*S. salar*), blue mussels (*Mytilus edulis*), and kelp (*Saccharina latissima* and *Alaria esculenta*) (Ridler et al., 2007b; Nguyen & Williams, 2013).

Figure 3: World capture fisheries and aquaculture production (FAO, 2014a)



IMTA has been shown to reduce benthic ecological impacts in proximity to Atlantic salmon farms, improve social perceptions of aquaculture, and have potential financial benefits for aquaculture producers through product diversification, faster production cycles, and price premiums for IMTA products (Chopin et al., 2001; Whitmarsh et al., 2006; Ridler et al., 2007b; Chopin & Sawhney, 2009; Barrington et al., 2010; Ridler & Ridler, 2011; Shi et al., 2013; Alexander et al., 2016a). Cooke Aquaculture, the dominant salmon farming company on Canada's east coast, has been experimenting with IMTA on some of its sites (Ridler & Ridler, 2011). However, researchers continue to cite a dearth of financial analyses of IMTA operations examining the viability of IMTA for potential investors (Ridler et al., 2007b; Ridler & Ridler, 2011; Alexander et al., 2016a; Crampton, 2016).

2.2. Background

In one of the definitive economic analyses of IMTA to date, Ridler et al. (2007b) used a discounted cash-flow analysis (DCF) to examine IMTA versus salmon monoculture farm profitability in the Bay of Fundy, New Brunswick, Canada. The study's results showed that an IMTA operation with Atlantic salmon (*S. salar*), blue mussels (*M. edulis*), and kelp (*S. latissima* and *A. esculenta*) resulted in a higher net present value (NPV) and profit margin than salmon monoculture at discount rates of both 5% and 10%. Ridler et al.'s (2007b) sensitivity analysis showed that IMTA farms can enhance resiliency and provide superior financial returns in the face of a sustained market price decrease for salmon and the loss of salmon harvests due to common environmental perturbations (Ridler et al., 2007b). However, though Ridler et al. (2007b) is widely cited in the IMTA literature, a lack of data precluded their definitive assessment of IMTA's economic potential. Another DCF study based in Scotland compared a salmon monoculture and a blue mussel monoculture operation with a salmon and blue mussel IMTA operation (Whitmarsh et al., 2006).[5] The authors found that the NPV and internal rate of return (IRR) of salmon and mussel IMTA outperformed salmon and mussel monocultures at a discount rate of 8%, whether the monoculture profits were considered individually or in combination. However, they found that IMTA's NPV turned negative when salmon prices were subjected to a sustained drop of 2% per annum (Whitmarsh et al., 2006). Another study, comparing real-world kelp monoculture and scallop monoculture with a kelp and scallop IMTA operation in Sanggou Bay, China, showed that IMTA had a higher NPV and benefit cost ratio (BCR) than either the kelp or scallop monoculture operation (Shi et al., 2013). Despite these largely encouraging results concerning IMTA profitability, researchers and industry stakeholders continue to note

[5] Whitmarsh et al. (2006) labeled their combined salmon and mussel farm a polyculture operation, which is technically correct, but also falls within the definition of IMTA (Chopin et al., 2001).

that profitability and economic analyses can be improved and uncertainty reduced with higher quality data and more detailed analyses (Ridler et al., 2007b; Ridler & Ridler, 2011; Alexander et al., 2016b; Crampton, 2016).

IMTA is only justifiable for investors if there is additional profitability (Ridler & Ridler, 2011), and the Whitmarsh et al. (2006), Ridler et al. (2007b), and Shi et al. (2013) results suggest that higher profitability is possible with IMTA than with monoculture aquaculture farms. These studies ascribe IMTA's financial performance to varied combinations of higher growth rates of co-cultured extractive IMTA species, IMTA's cost-sharing possibilities (e.g., marketing and sales costs, salaries and wages, utilities), and access to additional income streams. Whitmarsh et al. (2006), Ridler et al. (2007b), and Shi et al. (2013) also acknowledged that IMTA investors would face higher upfront capital requirements and added operational complexity than traditional monoculture operators, but did not attempt to explicitly address these issues. However, ongoing uncertainty around IMTA's technical feasibility, profitability, and increased complexity are suggested to be factors limiting IMTA adoption in Canada (Crampton, 2016). To help address this uncertainty in the IMTA literature, this study attempts to incorporate additional elements of IMTA's operational complexity into financial models and conduct a DCF and NPV analysis to provide a more detailed exploration of IMTA's costs and benefits for potential investors based on updated research and data. This study's operating hypothesis is that the inclusion of more accurate financial data will result in a higher cost profile for salmon, mussel, and kelp IMTA adoption on Canada's east coast compared to Ridler et al.'s (2007b) study.

2.3. Materials and Methods

I used a capital budget and investment appraisal approach to compare the financial performance of two hypothetical aquaculture projects located in the Bay of Fundy, New Brunswick, Canada:

(i) An open net-pen salmon monoculture operation, and

(ii) A salmon, mussel, and kelp IMTA operation.

All models created and used for this study were developed in Microsoft Excel. The biological, technical, economic, and financial data, figures, and assumptions used in this study are anchored in academic, industry, and government reports and studies, statistical databases, and conversations with industry operators and researchers. Capital budgeting models were developed in consultation with the DCF models employed by Boulet et al. (2010) and Ridler et al. (2007b) and incorporate outputs of unpublished kelp and mussel models developed by Adrian Hamer at the University of New Brunswick as a part of the IMTA project funded by the Atlantic Coastal Opportunity Agency Atlantic Innovation Fund. Costs that were not included in the mussel and kelp models (e.g., mooring system) have been included in the present IMTA model. This study prioritizes and incorporates data from Canadian aquaculture industry proponents where available. For example, regulatory costs are based on the costs of doing business in the province of New Brunswick, but Atlantic salmon prices are linked to global commodity markets, necessitating the incorporation of international data. Data obtained through dialogue with representatives of Cooke Aquaculture has been provided here at an aggregate level to preserve the integrity of any proprietary information.

Like Ridler et al. (2007b), I used a DCF and NPV analysis to examine the profitability of different investment opportunities, and to compare the NPV of investment options i and ii.[6] DCF and NPV analysis allows potential investors to examine the net monetary return of a project over its estimated useful life in present day dollars. NPV analysis assumes the project(s) under investigation are mutually exclusive, “now-or-never” decisions (Pearce & Nash, 1981; Bierman Jr. & Smidt, 1993; Dixit & Pindyck, 1994).

The NPV calculation (equation 1) uses a polynomial function and yields the present day value of the net returns (or losses) of a given project by estimating a project’s cash flows over the project’s expected useful life (Bierman Jr. & Smidt, 1993). In

[6] Other examples of DCF in the sustainable aquaculture literature are Whitmarsh et al. (2006), Liu and Sumaila (2007), and Boulet et al. (2010).

equation 1, where *n* represents the useful life of the project and *r* represents the discount rate, a project's costs are subtracted from its benefits (revenues) for each t^{th} year of a project's operation and then discounted to yield a net present value for the investment at time t=1.[7] The present value of benefits minus costs in years 1 through 10 are summed to give the investment's gross net present value. The decision rule for a NPV analysis says that if the gross NPV is positive, then the investment opportunity is worthwhile and should be pursued (Hawkins & Pearce, 1971; Pearce, 1971; Pearce & Nash, 1981; Bierman Jr. & Smidt, 1993).

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t} \quad (1)$$

The discount rate used in a DCF is effectively the chosen opportunity cost of capital selected for the purposes of this analysis, and represents the rate of return that could have been earned on the proposed capital investment if that money was invested in the next best investment opportunity. In my study, I set the discount rate to the borrowing rate (marginal cost of financing) for a firm (Bierman Jr. & Smidt, 1993).

I also attempted to calculate the internal rate of return (IRR), alternatively known as the return on investment (ROI), alongside a NPV for this study. The IRR of a project is calculated as the discount rate at which NPV equals zero (Bierman Jr. & Smidt, 1993). However, due to the timing of cash flows from projects i and ii, and the NPV equation above being a polynomial, I encountered the multiple-root problem detailed by Hawkins and Pearce (1971).[8] I attempted an extended IRR calculation to address this issue but continued to encounter difficulties. Due to the multiple-root problem, and in conjunction with recommended best practices in the capital budgeting literature, I abandoned the IRR

[7] *r* is equal to the discount rate. However, the denominator from equation (1), $(1+r)^t$, is called the discount factor.

[8] Because an IRR calculation requires solving a polynomial equation, multiple changes in the sign of cash flows (i.e., positive and negative cash flow returns) over the course of a project's life can result in multiple-solutions for r^* (where r^* is the IRR). See Hawkins and Pearce (1971, pp. 29-35) and Hawkins and Nash (1981, pp. 48-50) for more detail.

calculation and employed the NPV analysis as this study's investment appraisal method of choice (Bierman Jr. & Smidt, 1993).

2.3.1. Technical and Biological Assumptions

Projects i and ii are both located on a hypothetical 30-hectare coastal ocean plot in the Bay of Fundy area in New Brunswick on Canada's east coast, with a uniform site depth of 30 m and a useful project life of ten years.[9] Mussels (*M. edulis*) and kelp (*S. latissima*) are assumed to be harvested annually starting in year one, with salmon harvested bi-annually starting in year two. All species are harvested at the end of the calendar year. Salmon are grown on an 88-week (approximately 20-month) grow-out cycle (Boulet et al., 2010), leaving time for the mandatory 4-month fallowing period required by the New Brunswick Department of Agriculture, Aquaculture and Fisheries (Gail Smith, NBDAAF, personal communication). The weight of an individual fish at week t of the model is represented by:

$$W_t = W_{t-1} + \left[\left(\frac{F_t}{N_t}\right) * \left(\frac{1}{FCR}\right)\right] \qquad (2)$$

where FCR represents the feed conversion ratio, W_t is the average individual fish weight at week t, F_t is the total weight of salmon feed used at week t, and N_t is the number of fish at week t. This equation was used to overlay real-world growth data from an 800,000 smolt salmon monoculture operation on Canada's east coast into my model, and factors into salmon feed costs of the hypothetical aquaculture operations.

I assume that the IMTA site is optimally designed in order to attain the maximal productive benefits of IMTA for mussels and kelp assumed in A. Hamer's unpublished

[9] Ten years is the maximum lease length granted to shellfish farmers in New Brunswick (Gail Smith, NBDAAF, personal communication).

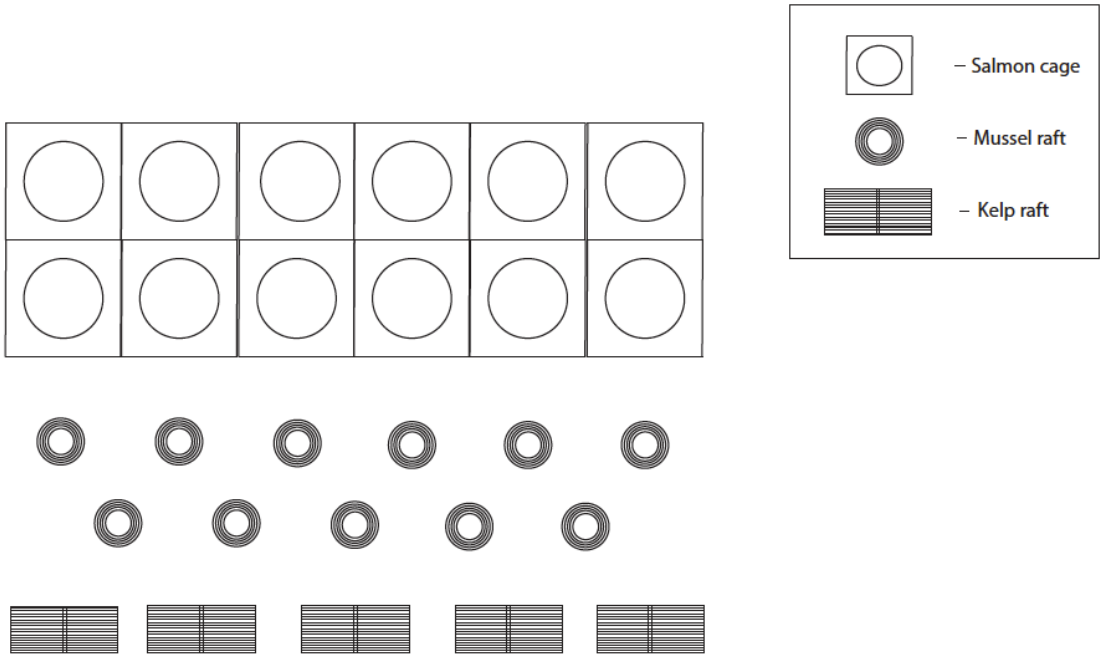
kelp and mussel models (Chopin et al., 2007).[10] The mussel model incorporated into this study used mussel growth data from Lander et al. (2004), which showed that mussels cultured in an IMTA setting with salmon can increase their biomass production by up to 50%, thereby enabling more frequent harvests and revenues. The kelp model incorporated into this study used data collected by Dr. Thierry Chopin’s lab at the University of New Brunswick during field studies on Canada’s east coast over a six-year period (Adrian Hamer, University of New Brunswick, personal communication). I also calculated and incorporated capital costs for mooring and anchoring the kelp and mussel rafts, which were not included in the original models. Any possible co-benefits of mussel and kelp co-culture were not incorporated in this study.

I initially wanted to examine the impact of reducing salmon production to accommodate additional species in the ocean lease site. However, discussions with industry professionals and researchers highlighted that salmon farmers on Canada’s east coast would not be willing to reduce their total salmon production to accommodate IMTA because salmon is too valuable for existing operators (FAO, 2016; Gregor Reid, University of New Brunswick, personal communication; Ted Weaire, Cooke Aquaculture, personal communication). Accordingly, this study’s hypothetical aquaculture operations are assumed to be configured so that the total amount of salmon produced on site is not reduced with the addition of kelp or mussels, and the salmon cage configuration, mooring system, and costs are unchanged in projects i and ii.

Key technical and biological data and assumptions employed in this study are detailed in Table 1. An overhead view of the IMTA site layout is provided in Figure 4.

[10] Adrian Hamer, with Dr. Thierry Chopin at the University of New Brunswick, developed two separate economic models examining the profitability of (i) mussel and (ii) kelp in IMTA operations as part of work funded through the Atlantic Canada Opportunities Agency Atlantic Innovation Fund’s Economic Module looking at the commercialization of IMTA.

Figure 4: Overhead view of salmon, mussel, and kelp IMTA farm design.[11]



2.3.2. Economic and Financial Assumptions

All costs are presented in 2016 US dollars. Where required, Canadian cost data was converted to 2016 dollars using the Bank of Canada's online inflation calculator. In keeping with recommended capital budgeting best practice, no financial costs (e.g., depreciation, interest charges on working capital) were included in this DCF (Bierman Jr. & Smidt, 1993). Capital costs are all assumed to be incurred in Year 1 and to have no salvage value at the end of the project period. No replacement capital is expected over the project life cycle. All harvested species are sold at farm-gate prices. I assumed discount rates of both 5% and 10% for the study, based on the discount rates used by Ridler et al., (2007b). According to rules for the treatment of operating losses in Canada, any negative cash flows in year *t-1* are carried forward to year *t* to reduce total taxable income at year *t* (Canada Revenue Agency, 2017).

[11] The salmon monoculture site would have the same salmon cage grid as the IMTA site, but would not include the mussel and kelp cages shown in Figure 3.

Managerial costs for IMTA were estimated to be higher than salmon monoculture due to IMTA's greater technological complexity (Whitmarsh et al., 2006; Ridler et al., 2007b; Shi et al., 2013). However, due to the experimental and pilot-project nature of existing IMTA efforts, real-world costing data was lacking (Ridler et al., 2007b). The cost of this managerial and operational uncertainty of IMTA was accounted for by increasing the capital contingency requirement in the model from 10% for salmon monoculture to 15% for IMTA.[12] This is the same approach taken by Boulet et al. (2010) in their examination of a land-based recirculating aquaculture system (RAS) versus a salmon monoculture operation, where a higher capital contingency requirement was applied to their RAS model to account for increased complexity. Mooring line lengths used to inform mooring system costs were calculated based on a combination of DFO (2011) depth data for St. Mary's Bay, Nova Scotia, and proprietary mooring information for aquaculture farms in the same location. I took a ratio of the "short" side to the "long" side using a simple Pythagorean theorem calculation for three different farm sites to inform the calculation.[13] Costing information obtained from Cooke Aquaculture was based on internal pricing and augmented 25% in my model to account for the cost-savings realized vis-à-vis their vertically integrated business structure (Ted Weaire, Cooke Aquaculture, personal communication).

Regulatory costs are based on New Brunswick Department of Agriculture, Aquaculture and Fisheries' estimated application costs (Gail Smith, NBDAAF, personal communication). Labour rates are reflective of wages employed by Cooke Aquaculture. The salmon and IMTA operation assumes that on-the-water farm activities require six labourers over the project life cycle and one site manager. The site manager earns an annual salary, and hourly wages are paid out at 37.5 hours per week and 45 weeks per year per labourer. Wages are assumed the same for salmon monoculture and IMTA. Additional labour associated with IMTA from kelp and mussel raft building, deployment,

[12] Boulet et al. (2010) assumed a 20% capital contingency for RAS compared with 10% for salmon monoculture. IMTA has less technical complexity than RAS, so a mid-point between these two Boulet et al. (2010) assumptions was taken for this study.

[13] Where "A" is the short side of the triangle (depth) and "C" is the long side of the triangle (mooring line length to ocean floor).

and harvesting activities were built into the figures from Hamer’s mussel and kelp models that were incorporated into the IMTA capital budgeting model. Tables 2 through 5 summarize key capital cost and variable cost information for this study. Variable costs not included in Table 3 but included in the capital budgeting models are harvesting costs, chemical and vaccination costs, and diving costs, which are assessed on a head-on-gutted (HOG) pound per harvest basis (Steve Smith, Cooke Aquaculture, personal communication), as well as regulatory compliance costs and fuel costs. Total salmon feed costs were dependent on the salmon production model developed using the technical and biological parameters above.

Table 1: Technical and biological capital budgeting parameters for salmon, mussels, and kelp.

Item	Unit	Quantity	Description	Source
Salmon				
Number of salmon cages	-	12	6 x 2 - 160 m circumference salmon cage and 250' grid array	-
Starting # of smolt	-	800,000	Number of fish at beginning of production cycle	-
Starting weight per smolt	kg	0.075	-	Boulet et al., 2010
Feed Conversion Ratio	-	1.25	Amount of feed ingested and converted into biomass (e.g., 1.25 pounds of feed required for 1 pound of flesh)	Ridler et al., 2007b
Mortality rate, salmon	-	10%	Fish mortalities over harvest period as percentage of initial number of smolt	Marine Harvest, 2015
Live weight to head-on-gutted	%	83%	Quantity of fish for sale after gutting (as % of live weight)	Marine Harvest, 2012
Live weight per fish at harvest	kg	5.85	Weight of fish prior to head-on-gutted (HOG) processing	-
Mussels				
# of mussel rafts	-	11	Quantity of 32 m diameter mussel rafts on IMTA farm site	-
IMTA production enhancement	%	20%	Percentage of production increase (harvestable mass) over un-integrated mussel farm operations	Hamer, unpublished data, 2012
In-sock mortality rate per month	%	1.39%	Percentage of monthly mortalities of socked mussels	Hamer, unpublished data, 2012
Processing loss/waste	%	10%	Percentage of total live weight at harvest lost during harvest activities	Hamer, unpublished data, 2012
# mussels per metre of socking	-	500	-	Hamer, unpublished data, 2012

Mussels per metre of sock at harvest	kg	5.875	Total kg mussels per metre of sock at time of harvest, annual cycle	Hamer, unpublished data, 2012
Size of mussel at harvest	g	11.75	Size of 55mm mussels at harvest	Hamer, unpublished data, 2012
Kelp				
# of kelp rafts	-	5	Quantity of 70m x 30m kelp rafts (occupying .21 hectares/raft)	Hamer, unpublished data, 2012
# of ropes per kelp raft	-	18	-	Hamer, unpublished data, 2012
Kg of freshweight per rope	kg	15	Used to calculate *S. latissima* dry weight and revenues	Hamer, unpublished data, 2012
Drying factor	-	10	Conversion of fresh weight (wet weight) to dry weight	Hamer, unpublished data, 2012

Table 2: Salmon monoculture and IMTA key economic and financial parameters.

Item	Unit	Quantity	Description	Source
Price per smolt	$/smolt	$2.43	Price per 75g smolt	Ridler et al., 2007b
Atlantic salmon selling price	$/kg	$5.03	Price of salmon, farmgate (HOG)	IndexMundi.com, 2016
Mussel selling price	$/kg	$1.10		
Kelp (*S. latissima*) selling price	$/kg	$26.43	Selling price is per kg of kelp, dry weight	
Federal Tax Rate	%	15%	-	CRA, 2016
New Brunswick Provincial Tax Rate	%	14%	-	CRA, 2016
2016 USD:CAN Exchange Rate	-	0.755107	Average 2016 value of 1 dollar CAD in US dollars	www.canadianforex.ca

Table 3: Key variable cost indicators for salmon monoculture and IMTA.

Item	Unit	Quantity	Description	Source
Farm-site Manager	$	$47,572	Annual salary, based on $63,000 CAD/annum	Cooke Aquaculture
Farmhand (labourer)	$	12.8	Hourly wage, based on $17.00 CAD/hour	Cooke Aquaculture
Net Cleaning and Maintenance	$/annum	$108, 953	Net cleanings occur monthly and costs incorporate an hourly barge rental and two labourers	Cooke Aquaculture
Cost of salmon feed	$/tonne	1,006	-	Boulet et al., 2010

Table 4: Salmon monoculture capital cost summary.

Item	**Unit**	**Quantity**	**Description**	**Source**
Net Pen Cage System	$	$453,064	6x2 salmon grid and 160 m circumference cage system	Cooke Aquaculture
Service and Crew Boat	$	$113,153	Jackson Craft	Boulet et al., 2010
Fork Lift	$	$19,822		Hamer, unpublished data, 2012
Feed Barge	$	$1,887,768		AKVA
Feed Monitoring System	$	$101,939		AKVA
Misc. Fish Culture Equipment	$	$247,059	Graders, fish pumps, feeding equipment etc.	Boulet et al., 2010
Nets	$	$1,016,676	Holding and predator nets	Cooke Aquaculture

Mooring System	$	$395,152	Compensator buoys, lift lines, mooring lines and chains, etc.	Cooke Aquaculture
Capital Contingency (10%)		$423,463		
Total Capital Costs		$4,658,096		

Table 5: IMTA capital cost summary.

Salmon				
Item	**Unit**	**Quantity**	**Description**	**Source**
Net Pen Cage System		$453,064	6x2 salmon grid and 160 m circumference cage system	Cooke Aquaculture
Service and Crew Boat		$113,153	Jackson Craft	Boulet et al., 2010
Fork Lift	$	$19,822		Hamer, unpublished data, 2012
Feed Barge	$	$1,887,768		AKVA
Feed Monitoring System	$	$101,939		AKVA
Misc. Fish Culture Equipment	$	$247,059	Graders, fish pumps, feeding equipment etc.	Boulet et al., 2010
Nets	$	$1,016,676	Holding and predator nets	Cooke Aquaculture
Mooring System	$	$395,152	Compensator buoys, lift lines,	Cooke Aquaculture

			mooring lines and chains, etc.	
Mussels				
Mussel Raft Mooring System		$130,975		Hamer, unpublished data, 2012
Mussel and Spat Rafts		$433,622		Hamer, unpublished data, 2012
Socking and Grading Equipment		$33,300		Hamer, unpublished data, 2012
Predator Net		$71,060		Hamer, unpublished data, 2012
Labour associated with initial capital outlay/raft construction		$33,496		Hamer, unpublished data, 2012
Kelp (*S. latissima*)				
Kelp Raft Mooring System		$61,001		Hamer, unpublished data, 2012
Truck		$20,000		Hamer, unpublished data, 2012
Bonar Ice Chests		$12,000		Hamer, unpublished data, 2012
Raft Piping		$20,670		Hamer, unpublished data, 2012
Tobacco Dryer		$30,800		Hamer, unpublished data, 2012
Refrigerated Room		$6,980		Hamer, unpublished data, 2012

Labour & Vessel Costs Associated w/Initial Capital Outlay/setup		$7,270		Hamer, unpublished data, 2012
Lab Culture System		$26,583		Hamer, unpublished data, 2012
Capital Contingency (15%)		$768,359		Hamer, unpublished data, 2012
Total Capital Costs		$5,890,749		

2.3.3. Investment Appraisal and Sensitivity Analyses

The base-case scenario uses the biological, technical, and financial assumptions articulated above to forecast costs and revenues over a 10-year time horizon for salmon monoculture and IMTA. In the base-case production scenario, adult salmon reach a live-weight of 5.85 kg salmon^{-1} at harvest, with a single production cycle yielding 4.21 tonnes of salmon and revenues of $23,282,896 every two years, including a four month fallow period. The IMTA base case includes the same salmon costs and revenues, as well as annual harvests and sales of, respectively, 9,450 tonnes dry weight of *S. latissima* worth $249,752, and 530 tonnes of mussels worth $583,664.

The impact of salmon price on IMTA operations has been explored by Ridler et al. (2007b) and Whitmarsh et al. (2006) and shown to be an important consideration for the overall profitability of integrated aquaculture systems.[14] Though farmed salmon prices continue to remain at high levels and show an overall upward trend over time, farmed salmon is still an agricultural commodity and is susceptible to rapid price spikes or declines (see Table 6). I conducted two sensitivity analyses to examine (i) an immediate and sustained 10% drop in the price of salmon over a 10-year period, as well as (ii) a 2% drop per annum in the price of salmon over a 10-year period.

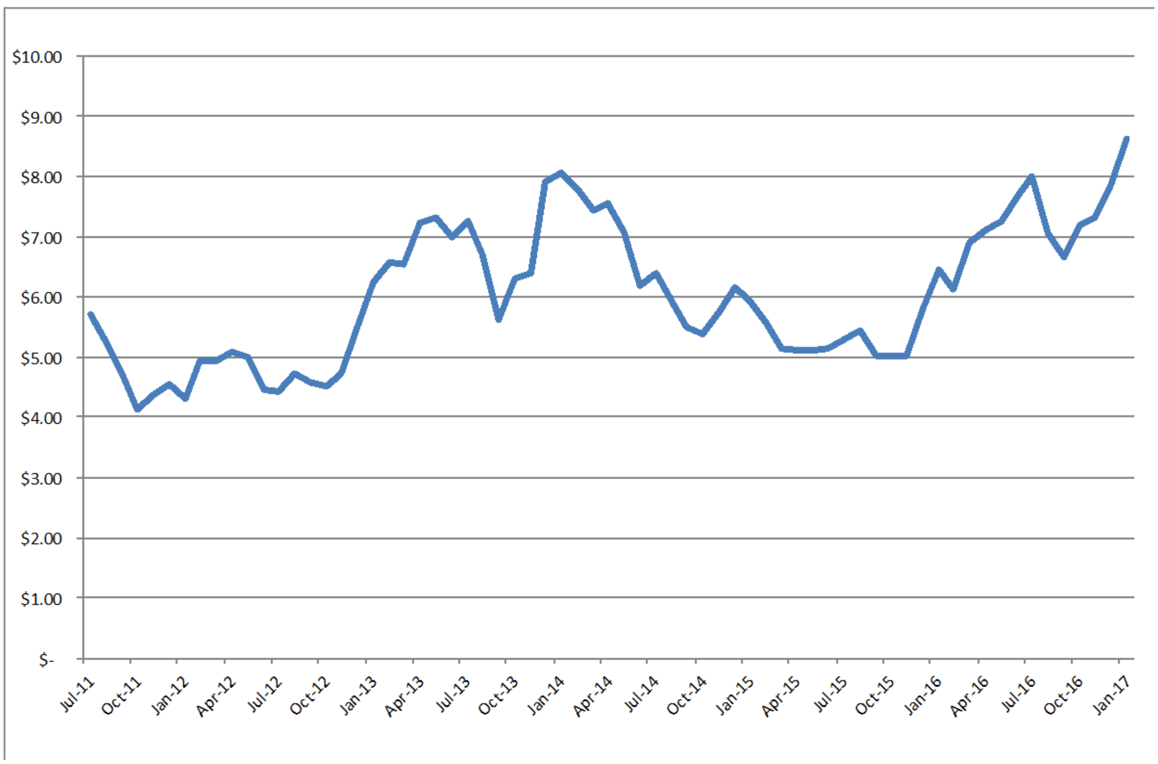
IMTA price premiums were not incorporated into Ridler et al. (2007b), Whitmarsh et al. (2006), or Shi et al. (2013), but market studies and consumer preference and attitudinal surveys conducted in communities in Canada, the United States, and Europe indicate consumers' willingness to pay more for IMTA products compared to their conventionally produced counterparts, ranging from 10% for salmon and mussels to 24% to 36% for oysters (Bunting, 2008; Shuve et al., 2009; Kitchen, 2011; Ridler &

[14] Ridler et al. (2007b) found a 12% decline in the price of salmon held over a 10-year project period would result in overall higher returns for IMTA over net-pen salmon monoculture, helping demonstrate IMTA's potential to help offset lost revenue from a sudden and sustained drop in the selling price of salmon for New Brunswick aquaculture farmers. However, Whitmarsh et al.'s (2006) polyculture study showed that a 2% per annum decline in the price of salmon over a 20-year production cycle would result in net project losses that could not be offset through the polyculture of mussels, even with productivity enhancements of mussels increasing to 30%.

Ridler, 2011; Whitmarsh & Palmieri, 2011; AMB Marine and Coastal Research, 2012; Yip et al., 2017). This willingness to pay more for IMTA products is expected to apply to North American and European consumers, where there is a demand for sustainable seafood (Ridler et al., 2007b; AMB Marine and Coastal Research, 2012; Organic Monitor, 2014). A sensitivity analysis has been included in the present study to examine the impact on IMTA operations of a 10% price premium applied to IMTA salmon and mussels.

I also examined the impact of losing one harvest of salmon due to disease or other natural disturbances (e.g., storm event) on NPV in scenarios with and without price premiums on IMTA salmon and mussels. The harvest was assumed to be lost in the sixth year of the project.

Table 6: Price of farmed salmon in US dollars per kilogram (July 2011 – January 2017).*



* Export price of Norwegian farm-bred Atlantic salmon (IndexMundi, accessed: April 15, 2017).

A direct comparison with Ridler et al.'s (2007b) results was complicated due to the paucity of explanatory variables listed in their study, as well as an inability to align the results of Ridler et al.'s (2007b) study with the capital budgeting model provided to me by one of the lead authors (M. Wowchuk). Therefore, where possible, efforts were made to compare this study's results with Boulet et al.'s (2010) DCF study of ocean net-pen Atlantic salmon monoculture versus a land-based closed containment Atlantic salmon farm. Even though Boulet et al. (2010) based their study on Canada's west coast, they were able to provide a much more detailed accounting of their assumptions than Ridler et al. (2007b), making for easier comparisons.

2.4. Results

The base-case scenario presented in Table 7(a) compared salmon monoculture against an IMTA with no IMTA price premiums. The IMTA operation was shown to have an NPV approximately 6% higher than the salmon monoculture farm. When price premiums are included, IMTA has an NPV between 26% and 27% higher than traditional salmon monoculture at discount rates of 5% and 10%, respectively, shown below in Table 7(b). The inclusion of a 10% price premium on IMTA salmon and mussels results in a 19% and 20% increase in NPV over IMTA culture receiving no price premiums at discount rates of 5% and 10%, respectively.

Table 7: Salmon monoculture and IMTA results for NPV (10 years, 2016 US prices).

(a)	Base-case scenario		
	Salmon monoculture	3-IMTA	(Δ) % over monoculture
r=5%	$32,096,556	$33,974,817	5.9%
r=10%	$23,649,913	$24,998,840	6%
(b)	Base-case monoculture and IMTA results, with 10% price premium on salmon and mussels		
	Salmon monoculture	3-IMTA, 10% price premium	(Δ) % over monoculture
r=5%	$32,096,556	$40,538,598	26.3%
r=10%	$23,649,913	$30,106,888	27%
(c)	Loss of salmon harvest in Year 6, with 10% price premium on salmon and mussels		

	Salmon monoculture	3-IMTA	(∆) % over monoculture
r=5%	$19,760,976	$21,639,238	9.5%
r=10%	$14,318,676	$15,667,602	9%
(d)	Loss of salmon harvest in Year 6, with 10% price premium on salmon and mussels		
	Salmon monoculture	3-IMTA, 10% price premium	(∆) % over monoculture
r=5%	$19,760,976	$26,969,461	36.5%
r=10%	$14,318,676	$19,842,526	39%
(e)	Impact of 10% immediate drop in salmon price sustained over 10-year project period on salmon monoculture and IMTA		
	Salmon monoculture	3-IMTA	(∆) % over monoculture
r=5%	$25,869,878	$27,748,140	7.3%
r=10%	$18,813,010	$20,161,937	7%
(f)	Impact of 2% drop in salmon price per annum on salmon monoculture and IMTA		
	Salmon monoculture	3-IMTA	(∆) % over monoculture
r=5%	$25,512,591	$27,390,853	7.4%
r=10%	$18,850,404	$20,199,331	7%

Sensitivity analyses (c) and (d) in Table 7 summarize changes in the NPV of salmon monoculture and IMTA operations when subjected to a mortality event (e.g., storm, disease outbreak). This loss is assumed to occur in year 6 of operations and wipes out an entire salmon harvest. These results show that the IMTA operation has a higher NPV than salmon monoculture at discount rates of 5% and 10% if faced with a mass mortality event.

Sensitivity analyses (e) and (f) in Table 7 show the impact of price declines on salmon monoculture and IMTA.[15] NPVs in both price-drop scenarios for salmon monoculture and IMTA show a clear drop in net revenue due to the salmon price decline. When subjected to an immediate and sustained 10% decline in the market price of salmon

[15] Price premiums were not examined as part of the price decline sensitivity analysis.

at 5% and 10% discount rates, salmon monoculture and IMTA saw their NPVs decline between 19% and 20%, and 32% and 33%, respectively. When salmon sales are subjected to a drop of 2% in their market price per annum and at 5% and 10% discount rates, salmon monoculture and IMTA NPVs declined between 22% and 21%, and 32% and 33%, though IMTA earns a higher NPV than monoculture in both price-drop scenarios.

These results echo those of Ridler et al. (2007b) and suggest that the adoption of IMTA by salmon farmers on Canada's east coast will result in increased NPVs when compared with salmon monoculture. My results also highlight a significant NPV bump associated with IMTA price premiums in both the base-case scenario and even when a crop of salmon is lost.

2.5. Discussion

My results suggest a similar conclusion to that of Ridler et al.'s (2007b) study, namely that the financial gains of salmon, mussel, and kelp IMTA on the east coast of Canada are superior to salmon monoculture when the quantity of salmon produced remains unchanged after IMTA integration. This is a logical conclusion that doesn't necessarily warrant a detailed financial study; if mussels and kelp are added onto an existing salmon monoculture operation to create an IMTA farm, with no changes to the production schedule or size of the salmon harvest, and if the revenues of mussel and kelp sales exceed their costs of production, IMTA will have a higher NPV than salmon monoculture. Therefore, it should not be surprising that profits from IMTA operations in this study increase the financial returns to an investor.

Canada's aquaculture industry now has pilot-scale experience with IMTA and Canadian studies have demonstrated positive financial results and socio-economic attitudes toward IMTA (Ridler et al., 2006, 2007b; Barrington et al., 2010). Similar findings by European researchers (Whitmarsh et al., 2006; and Shi et al., 2013; Alexander et al., 2016a, 2016b), taken together with the results of my study, suggest that a 3-species salmon, mussel, and kelp IMTA financial return can exceed that of salmon monoculture in Canada. But if IMTA research findings are accurate and actors in the Canadian aquaculture industry have experience with IMTA at a pilot-scale, why has IMTA not yet been deployed at a commercial scale to maximize investment returns?

My working hypothesis was that Ridler et al. (2007b) underestimated the costs of IMTA. To test my hypothesis, I attempted to compare my study's updated costs with Ridler et al.'s (2007b) modelling costs. However, the limited technical information provided by Ridler et al. (2007b) precluded this comparison. Overall, the challenges I encountered comparing my costs with similar economic studies in the aquaculture literature suggest the importance of including as much detail on model assumptions and results as possible in future studies. This limitation could be addressed in future studies by hiring an engineering firm to carry out an engineering costing study for the hypothetical aquaculture operations.

To help address the data gap in Ridler et al.'s (2007b) paper, and determine if my salmon aquaculture costing was accurate, I compared my capital cost per tonne of salmon produced with that of Boulet et al. (2010).[16] Boulet et al. (2010) had a capital cost per tonne of salmon produced of $2000 compared to my study's $1,106.[17] This large discrepancy suggests that I may have underestimated requisite capital costs in my salmon model. However, my study's cost estimates reflect detailed cost information provided by industry players, as well as previous academic studies, and I used conservatively high cost estimates where I had an option between different cost profiles. Based on conversations with industry professionals, it is my view that the salmon farm costing presented in this model is accurate. One reason that may help account for this difference between the two studies would be the difference in the Canada-US exchange rate used by Boulet et al. (2010) and my study, which were 1.05:1 and 0.75:1, respectively. Boulet et al. (2010) also presented their study in Canadian dollars, whereas my costs are presented

[16] I considered, and ultimately rejected, additional comparisons of the capital cost per tonne of salmon produced based on Whitmarsh et al. (2006) or Liu and Sumaila (2007) due to a lack of data in the former and a lack of a comparable production cycle in the latter.

[17] Capital cost per tonne of salmon produced was calculated by dividing total capital costs by total tonnes of live salmon produced per harvest cycle. Boulet et al. (2010) assumed a 2,500 tonne bi-annual harvest cycle and total estimated capital costs of CAN $5,000,716 for a 12-cage salmon monoculture operation.

in US dollars.[18] Another possible reason for the difference could be related to quotes received from industry suppliers and price conversions to free-market rates.

Boulet et al.'s (2010) DCF model assumed $4,762,586 in capital costs for Atlantic salmon monoculture compared to $21,545,576 for RAS. They assumed identical 2,500 tonne harvests for both operations and revenues of $9,979,762 per harvest. Additionally, Boulet et al's (2010) net-pen salmon model could harvest salmon every 15 to 20 months compared to RAS's annual harvest cycle. My study assumed capital costs of $4,658,096 for net-pen salmon monoculture and $5,890,749 for three-species IMTA. Both operations harvested 4,212 tonnes of salmon biannually with revenues of $23,282,296. Three-species IMTA included annual mussel and kelp sales of $583,664 and $249,752, respectively. Boulet et al. (2010) found that salmon monoculture was a more desirable investment due to its faster payback period and higher observed return on equity, combined with the increased complexity and significantly higher upfront capital costs of RAS. Comparatively, my study's three-species IMTA labour costs are 16% of Boulet et al.'s (2010) RAS labour costs. Taken together, these IMTA and RAS cost differentials suggest that IMTA may be a more financially attractive sustainable aquaculture investment than RAS for Canadian salmon farming companies at this time.

If we assume that the results of this study and Ridler et al. (2007b) are true, an alternate explanation for the lack of IMTA development in Canada is warranted. Insights from Crampton's (2016) interviews with stakeholders from Canada's aquaculture industry, government, and environmental non-governmental organizations suggest that qualitative considerations related to uncertainty may be limiting IMTA adoption in Canada. Crampton's (2016) results suggest that Canadian stakeholder doubts related to IMTA's profitability, ecological viability and benefit, technical viability, and additional operational complexity are limiting factors. Overall, Crampton (2016) observed that technical uncertainty and insufficient organizational and managerial IMTA expertise were the key barriers to IMTA adoption for his interviewees. Viewed in tandem,

[18] Boulet et al.'s (2010) presents their costs in Canadian dollars. I have converted their figures into US dollars for this study.

Crampton's (2016) results and research indicating the possibility for higher profits from IMTA over salmon monoculture suggest that the increased complexity of IMTA compared with salmon monoculture is inhibiting the adoption of IMTA.

The real-options analysis (ROA) investment appraisal technique provides an alternate framework that may help explain the divergence between available financial analyses of IMTA and the qualitative concerns identified by Crampton (2016). ROA is an alternative investment appraisal technique that highlights three interacting aspects of investments that influence investor decisions that are not included in neoclassical investment theory, including NPV analysis (Dixit & Pindyck, 1994). The first aspect is that investments are either partially or totally irreversible, and therefore investment costs are at least partially lost; the second is that the future cash flows of an investment are uncertain; and the third is that investors can choose when they want to invest based on any given number of factors (e.g., foreign exchange rates, interest rates, waiting for further information to improve certainty, etc.). The ROA critique of NPV highlights unstated assumptions implicit in NPV calculations; namely that investments are either reversible, or that if they are irreversible, the decision is "now or never".[19] Dixit and Pindyck (1994) argue that the act of investing is effectively exercising an investor's option to invest and eliminates the possibility and potential value of waiting for further information to assess the investment opportunity; once capital has been expended, the investment is not easily reversed, if it is reversible at all. According to these authors, NPV can underestimate the impact of uncertainty of future cash flows, government policies, and shifting economic conditions on investor behaviour, and does not account for the value to investors of waiting for more information, a different investment climate, etc.

To address uncertainty, investors often use a hurdle rate, or required rate of return on investment (i.e., IRR or ROI), which investment opportunities must meet in order to

[19] Here, the implicit assumption of reversibility refers to an investor's ability to easily withdraw investment capital from a recent investment and immediately deploy it to another investment opportunity. The implicit "now or never" assumption implies that the investor is precluded from waiting and learning more about a given investment opportunity before making their investment decision.

be pursued (Dixit & Pindyck, 1994). Summers (1989) observed that investment 'hurdle rates', i.e., the mandatory ROI requirements for investors operating under uncertainty, have been shown to range from 8% to 30%, with a median of 17%. Anderson and Newell's (2002) results indicate required hurdle rates of 50% to 100% for manufacturing plants to invest in energy efficiency projects, with uncertainty over the performance and staffing requirements of new technology as possible investment-deterring factors. Unfortunately, a hurdle-rate analysis was not possible due to an unsuccessful attempt to calculate an IRR. Nonetheless, the uncertainty of IMTA profits, technological viability, and regulatory frameworks identified by Crampton (2016) appear to fit within the ROA framework as important investor considerations that are not captured by traditional NPV analysis.

Suppliers and merchants throughout North America have indicated an interest in selling IMTA species (AMB Marine and Coastal Research, 2012; Alexander et al., 2016b). However, consumers need to be educated on IMTA to help to ensure IMTA products are seen as socially acceptable, sustainable, and safe, and therefore induce the potentially lucrative IMTA premium and reduce investor risk (Ridler et al., 2007b; Shuve et al., 2009; AMB Marine and Coastal Research, 2012; Alexander et al., 2016b). Without this education, businesses will be less likely to sell IMTA products (AMB Marine and Coastal Research, 2012). IMTA's relative novelty, the increasing importance of sustainable seafood to consumers, and the desire of vendors to obtain an IMTA price premium suggest the necessity of a well-known eco-certification and an educational communication and outreach program for seafood vendors and consumers (Kitchen, 2011; AMB Marine and Coastal Research, 2012; Yip et al., 2017). Packaging IMTA products in this way has been shown to be necessary, though not necessarily sufficient, to create and increase demand for more sustainable aquaculture products (Nguyen & Williams, 2013). However, the results of my sensitivity analysis highlight that benefits of \$6.4 to \$8.4 million can accrue to a salmon, mussel, and kelp three-species IMTA investor over a salmon monoculture investor in the base-case scenario. In the event of a mortality event wiping out an entire salmon harvest, my results show that a salmon, mussel, and kelp three-species IMTA operation can result in benefits of \$5.5 to \$7.2

million over a salmon monoculture operation. Taken with Ridler et al. (2007b), these results may be sufficient to incent IMTA investment. However, salmon farmers in Canada may see greater benefit delaying investment to wait for better regulatory or economic conditions, meanwhile continuing to sell farmed salmon as a commodity product grown out in an open net-pen salmon-cage monoculture.

Nobre et al. (2010) note that IMTA production is suggested to result in greater benefits for the public at large than for the bottom line of aquaculture operators. However, an enabling institutional environment, including the internalization of the environmental costs of aquaculture, is critical to facilitating the development of integrated aquaculture initiatives (Bunting & Shpigel, 2009).[20] The financial benefits that Ridler et al. (2007b) and my study suggest would accrue to eastern Canadian salmon farmers who adopt IMTA, Crampton's (2016) qualitative examination of factors influencing IMTA adoption in Canada's salmon aquaculture industry, and the lack of private IMTA investment by Canadian salmon farmers, suggest that a more enabling policy framework could help encourage Canadian IMTA investment in Canada. According to Crampton's (2016) interviews with Canadian aquaculture industry professionals, factors that could induce industry adoption of IMTA, by order of importance, are (1) IMTA-only site leases, (2) technical and knowledge transfer, (3) corporate tax credits, (4) nutrient taxes on salmon feed with lower tax rates for IMTA operators, and (5) subsidies.

2.6. Conclusions

Based on the uncertainty of IMTA adoption for Canadian aquaculture investors, the ROA approach to assess IMTA suggests that IMTA must generate significantly more profits than net-pen salmon monoculture operations in order to stimulate investment (Crampton, 2016). The results of this study suggest that only scenarios where price premiums can be attained for IMTA products would yield a significant increase in profits

[20] Fisheries and Oceans Canada (2014) recently embarked on a revision of aquaculture regulations in Canada. These revised regulations were not examined as a part of this discussion.

over salmon monoculture. A quantitative analysis using ROA to incorporate the effect of uncertainty on IMTA investments may provide a more accurate assessment of profitability.

Chapter 3.

Three-species Integrated Multi-Trophic Aquaculture (IMTA) vs. Four-species IMTA: a Comparative Financial Analysis

3.1. Introduction

Though aquaculture has and likely will continue to play an important role in meeting the global food needs in the future, the industry is facing calls to improve its social, environmental, and economic sustainability to ensure sustainable future growth and performance (Troell et al., 2003; Subasinghe et al., 2009; Barrington et al., 2010; Alexander et al., 2016a; Filgueira et al., 2017). One potential alternative to current monoculture practices employed by salmon farmers, often criticized by the broader public for their environmental impact, is integrated multi-trophic aquaculture (IMTA) (Chopin et al., 2001; Ridler et al., 2007b; Barrington et al., 2010; Alexander et al., 2016a). IMTA can help address benthic loading under finfish farms by co-culturing species from different trophic levels on the same site. A properly designed IMTA site can simulate a natural ecosystem where organic and inorganic nutritional wastes of one species are recycled and serve as productive inputs for another, and has been shown to have both environmental and economic benefits (Chopin et al., 2001; Ridler et al., 2007b)

Canadian IMTA research to date has focused primarily on a three-species configuration using fed finfish, kelp (inorganic extractive species), and shellfish (organic extractive component), although more recent research has examined the inclusion of benthic feeding invertebrates into IMTA (Chopin et al., 2012; Hannah et al., 2013; Orr et al., 2014). Recent modelling work done by Cranford et al. (2013), Cubillo et al. (2016), and Filgueira et al. (2017) suggests that the role shellfish can play in mitigating organic waste from fish farms through IMTA is limited. These results reinforce researchers' calls for investigations into the role of benthic-feeding invertebrate species, such as sea urchins and sea cucumbers, in IMTA to mitigate benthic loading below fed finfish cages (Cranford et al., 2013; Reid et al., 2013; Cubillo et al., 2016; Filgueira et al., 2017). Since IMTA is not feasible if it is not profitable for investors, the financial impact of integrating benthic feeders into IMTA systems is an important element for consideration in the overall assessment of IMTA (Ridler & Ridler, 2011). However, researchers have continued to note a paucity of quantitative economic IMTA analysis and data to support investment decisions in IMTA (Ridler et al., 2007b; Alexander et al., 2016b).

One of the most comprehensive studies of the financial implications of IMTA investment to date was based on a hypothetical IMTA site in the Bay of Fundy, New Brunswick, Canada that examined an Atlantic salmon (*Salmo samar*), mussel (*Mytilus edulis*), and kelp (*Saccharina latissima*) IMTA farm versus a standard monoculture salmon farming operation (Ridler et al., 2007b). Ridler et al.'s (2007b) results suggested that IMTA was more profitable than monoculture using a net present value (NPV) and sensitivity analysis. This present study aims to build on the results of Chapter 2's updated three-species IMTA versus monoculture salmon farm operation and examine the impacts on IMTA profitability by incorporating a benthic-feeder element into an Atlantic salmon, mussel, and kelp IMTA operation and contrasting that with a three-species salmon, mussel, and kelp operation.

3.2. Background

3.2.1. Benthic Species in IMTA

Filgueira et al.'s (2017) modeling simulation of a hypothetical IMTA operation under typical hydrological conditions in the Bay of Fundy in eastern Canada showed that salmon faeces' high settling velocity limits the efficacy of mussels (*M. edulis*) in reducing benthic nutrient loading from salmon farms.[21] Filgueira et al. (2017) concluded by supporting IMTA researchers' calls for the deployment of benthic-feeding species on the seabed directly below fed finfish cages to reduce benthic loading (Cubillo et al., 2016).

Benthic-feeding invertebrate species native to Canadian waters that have been investigated for their suitability as co-cultured species in IMTA include the orange-footed sea cucumber (*Cucumaria frondosa*), California sea cucumber (*Parastichopus californicus*), and green sea urchin (*Strongylocentrotus droebachiensis*) (Ahlgren, 1998; Paltzat et al., 2008; Nelson et al., 2012; Hannah et al., 2013; Azad et al., 2014; Orr et al., 2014; Cubillo et al., 2016). *Cucumaria frondosa* and *P. californicus* are native to the east and west coasts of Canada, respectively (Cameron & Fankboner, 1986, 1989; Therkildsen & Petersen, 2006; Nelson et al., 2012), while *S. droebachiensis* is found on both coasts (Himmelman, 1978). *Parastichopus californicus* currently shows the most promise of the two sea cucumber species for inclusion in IMTA, but a review of the *C. frondosa* and *P. californicus* literature, along with other species of sea cucumbers, such as *Australostichopus mollis*, highlights that there remain economic factors and existing gaps in knowledge that currently limit sea cucumbers' attractiveness as IMTA candidate-species (Hamel & Mercier, 1998; Paltzat et al., 2008; So et al., 2010; Nelson et al., 2012; Hannah et al., 2013; Purcell et al., 2013; Azad et al., 2014). However, *S. droebachiensis*, and sea urchins in general, appear to have a stronger base of research and in terms of biology, required culture techniques, dietary requirements, and commercial markets (Pearce et al., 2002, 2004; Robinson et al., 2002; Pearce, 2006; Siikavuopio, 2008; Daggett et al., 2010; Pearce & Robinson, 2010; Orr et al., 2014). For example, Orr et al. (2014) have demonstrated that green sea urchins are capable of eating and absorbing waste from sablefish, and James et al. (2017) showed that gonad enhancement trials of urchins held in SeaNest cages improved the market characteristics of green sea urchin

[21] Filgueira et al. (2017) did not consider fish feed waste because mussels are not able to filter this larger organic particulate matter. Additionally, waste feed levels from open-net pen salmon farms have dropped significantly, from estimates of 20% in the 1980s to between 3% and 5% today (Reid, 2007).

roe. The extensive *S. droebachiensis* research base and their natural distribution on Canada's east and west coasts motivated the selection of *S. droebachiensis* for this study.

3.2.2. *Strongylocentrotus droebachiensis* in aquaculture

Green sea urchins are attractive for aquaculture because they can reach market size in two years or less under the right culture conditions, can handle relatively high culture densities, have an established market, and have been shown to grow effectively on prepared diets (Pearce, 2006). The vast majority of Canadian sea urchin exports go to Japan, the world's largest sea urchin market (AMB Marine and Coastal Research, 2012).

Like all sea urchins, green sea urchins are sold for their gonads, also known as roe or 'uni'. Sea urchin growth is also particularly sensitive to the quality and quantity of food available (de Jong-Westman et al., 1995). For *S. droebachiensis* to attain its maximum value, the gonads should be bright yellow or orange in colour with a smooth and firm texture (Pearce, 2006). Larger gonads absent other important quality characteristics for *S. droebachiensis* are less likely to fetch any price premium (Siikavuopio, 2009; AMB Marine and Coastal Research, 2012). Research has shown that green sea urchins can grow effectively on prepared diets, but can have a lower quality taste and colour. These findings and market research suggest that a finishing diet for IMTA-cultured green sea urchins will be required to ensure marketable green sea urchin roe from IMTA operations (Pearce et al., 2002, 2004; AMB Marine and Coastal Research, 2012). Considering that this study's IMTA-cultured green sea urchins are assumed to ingest a significant amount of faecal waste and feed from salmon cages to support their growth further reinforces the necessity of a finishing diet for urchins; it is unlikely that the taste profile for green sea urchins eating salmon farming waste would exhibit higher market characteristics than urchins fed an artificial feed for growth or roe-enhancement purposes.

Recent work by James et al. (2017) has shown that wild green sea urchins fed a prepared feed designed for sea urchin roe enhancement attained a mid-range selling price on the Japanese import market and exhibited good colour after 39 hours of live transport, but lacked a strong and sweet sea urchin flavour and were a bit soft. The Japanese processor consulted by the authors stated that the roe-enhanced urchins were of much better quality than green sea urchins imported from the east coast of North America. This indicates that there may be an opportunity to improve the value of eastern Canada's green sea urchin harvests through feed enhancement trials at a commercial scale. Because sea urchin value in the Asian market is wholly dependent on roe quality and urchin species, IMTA-grown green sea urchins need to exhibit high gonad quality to optimize production value (AMB Marine and Coastal Research, 2012; James et al., 2017).

3.3. Materials and Methods

I used a capital budget and investment appraisal approach to compare the financial performance of two hypothetical IMTA farms: (i) an Atlantic salmon, blue mussel, and kelp IMTA operation (three-species IMTA farm), and (ii) an Atlantic salmon, blue mussel, kelp, and green sea urchin operation (four-species IMTA farm). This investment appraisal approach is known as a discounted cash flow analysis (DCF) and is commonly employed in aquaculture economic literature.[22] DCF uses the same principles as cost benefit analysis (CBA), but CBA is a regulatory analysis tool typically used by governments to evaluate public projects and policies, while DCF is used to examine potential investments from a private perspective and is focused on the financial implications of potential investment opportunities (Hawkins & Pearce, 1971; Pearce, 1971; Pearce & Nash, 1981; Bierman Jr. & Smidt, 1993).[23]

A capital budget model was developed using forecasts of the estimated costs and revenues for each of the two hypothetical IMTA farms over the course of their expected useful life. These cash flow estimates were then converted into present day dollars to

[22] See Whitmarsh et al., 2006; Ridler et al., 2007b; Liu and Sumaila, 2007; Boulet et al., 2010.

[23] For a selection of studies examining the economics of IMTA from a social perspective, see Chopin et al. (2001), Nobre et al. (2010), Shi et al. (2013), and Martinez-Espiñeira et al. (2016).

account for the time value of money (Bierman Jr. & Smidt, 1993).[24] Cost estimates were taken from academic literature; industry and research reports; existing Atlantic salmon, shellfish, and kelp farming biological and economic models; and informal interviews and information exchanges with researchers and aquaculture industry professionals (see Appendix B for a list of the key researchers and industry professionals consulted). I compared the financial performance of the two hypothetical investments using a net present value (NPV) decision criterion. In NPV analysis, a project's present value cash inflows (revenues) and cash outflows (costs) are added together to give the project's estimated net return to the investor in monetary units. The NPV decision rule says that if the NPV is positive, the investment is deemed worthwhile, as shown in equation 3.

$$NPV = \sum_{t=1}^{n} \frac{(B_t - C_t)}{(1+r)^t} \tag{3}$$

where n represents the useful life of the project and r represents the discount rate, a project's costs are subtracted from its benefits (revenues) for each t^{th} year of a project's operation.

Another common investment appraisal indicator is the internal rate of return (IRR). The IRR is also known as the return on investment (ROI) of a project and can be used to compare the rate of return of investment opportunities at different scales of operation. It can also evaluate a project against an investor's chosen hurdle rate (Bierman Jr. & Smidt, 1993; Dixit & Pindyck, 1994).[25] The IRR calculation is based on equation 3 and is found by solving for the discount rate (r) that results in a NPV of zero. The IRR of a project can be used to evaluate risk by comparing its value against a required ROI determined by investors and evaluating the margin of difference between possible projects and the required ROI (Bierman Jr. & Smidt, 1993). I attempted to calculate the

[24] The time value of money is an accepted business and economic concept used in DCF and CBA that presumes a dollar today is worth more than a dollar received at some point in the future. See Bierman Jr. and Smidt (1993) and Hanley and Barbier (2009) for further reading.

[25] Hurdle rates are defined as the minimum ROI required by investors to make any given investment; higher uncertainty can lead to higher hurdle rates (Dixit, 1994).

IRR of the two IMTA farms under investigation here, but due to technical issues I used the NPV criterion instead.[26] NPV is seen as a simpler, safer, and more commonly employed and endorsed analytical tool according to CBA and capital budgeting literature (Hawkins & Pearce, 1971; Pearce, 1971; Pearce & Nash, 1981; Bierman Jr. & Smidt, 1993).

3.3.1. Technical and Biological Assumptions

This study assumes a 30-hectare ocean lease in the Bay of Fundy in New Brunswick, Canada with a uniform site depth of 30 m for both three-species and four-species IMTA farms. In the base case, mussels and kelp are harvested annually, salmon every two years beginning in year two, and green sea urchins every two years beginning in year four. The lag in sea urchin sales is due to hatchery construction and employee training, and the time required to rear *S. droebachiensis* from seed through to an early juvenile with a 7-mm test diameter.[27] All green sea urchin hatchery and grow-out operation assumptions in terms of scale and equipment stem from an assumed final culturing density of 10 kg urchins per SeaNest cage and this study's calculated ending somatic body weight per urchin (Brian Tsuyoshi, Urchinomics, personal communication).[28,29] Ultimately, all hatchery space requirements will vary based on the species being cultured, associated culture equipment, targeted production levels, space requirements, and choice of design (Helm & Bourne, 2004). The study assumes one year for construction and design of the urchin hatchery facility and associated infrastructure.

[26] Because the NPV equation is polynomial and there are multiple sign changes in net cash flows over the estimated ten-year useful life of the hypothetical IMTA operations, I encountered the multiple roots problem (Hawkins & Pearce, 1971; Pearce & Nash, 1981). I unsuccessfully attempted to address this issue with an extended IRR calculation as detailed by Pearce and Nash (1981) and subsequently abandoned the IRR calculation to focus on the NPV analysis.

[27] Test diameter refers to the maximum diameter of the sea urchin shell (Pearce, 2006).

[28] 10 kg urchins per SeaNest is equal to approximately 8.2 kg m^{-2} according to the technical specifications of the SeaNest cage. This is calculated based on SeaNest technical specifications and green sea urchins being able to inhabit the bottom and all four sides of the cages, but not the top.

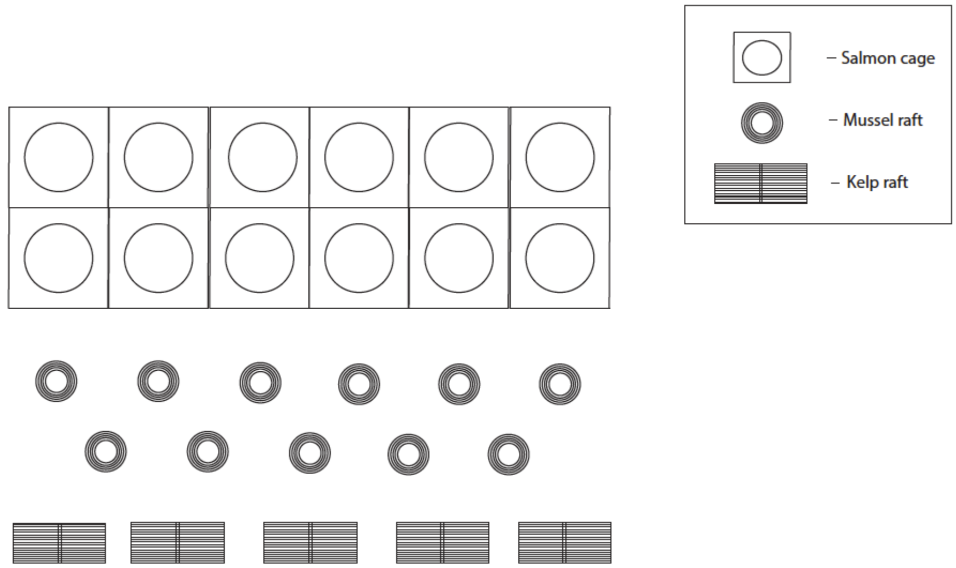
[29] SeaNest cages were designed in Norway by Vidar Mortensen (Principal, SeaNest system) for the specific purpose of green sea urchin aquaculture.

The hatchery property is assumed to include requisite access roads, utilities, and boat-launch facilities at purchase.

There is a dearth of data on sea urchin aquaculture systems and key factors for consideration in the design and evaluation of land-based grow-out systems (James & Siikavuopio, 2015). Therefore, I created a feasible urchin production system and design, including a hatchery for rearing green sea urchin larvae and early juveniles. My green sea urchin model is based on academic and grey literature, Service New Brunswick's Property Assessment Online and GeoNB mapping and land registry tools, and extensive consultations with government, academic, and industry professionals with expertise in sea urchins (green sea urchins in particular). I assumed there are no operational complications related to the interaction of mooring systems for mussel, kelp, urchin, and salmon containment and mooring equipment. Prices for the model were taken from the Pentair Aquatic Eco-systems ® 39th Edition Master Catalogue, online industry resources, and conversations with industry professionals from AKVA Group, Cooke Aquaculture, and Urchinomics. Costs provided by industry are considered proprietary and cannot be presented in this study. For full technical, biological, and costing details of green sea urchin production, including hatchery design, consult Appendix A. See Figure 5 for an overhead representation of the three-species and four-species IMTA farm configurations.

SeaNest cages were chosen for the green sea urchin grow-out containment system because they have been specifically developed for sea urchin aquaculture; are currently employed at a commercial or research scale in Europe, Asia, and North America; have known costs, culture densities, and labour requirements; and are proven containment systems (Brian Tsuyoshi, Urchinomics, personal communication). Sea ranching was also considered as an option for sea urchin grow-out culture. In sea ranching, hatchery seed would be released on the bottom of aquaculture lease sites to roam and eat at will for several years prior to being harvested. However, industry stakeholders have shied away from sea ranching of urchins due to doubts that ranched sea urchin seed would survive or stay within the boundaries of the aquaculture lease-site (Brown et al., 2013).

Figure 5: Overhead view of three-species and four-species IMTA farm design.[30]



In a four-species configuration, there are six sea urchin long-lines strung underneath the 6 x 2 array of salmon cages (aligned vertically to the 6 x 2 cage array displayed in this image). SeaNests are not represented in the legend, but are assumed to float directly underneath the salmon cages.

The urchin hatchery is designed as a flow-through system, where water passes through two sand-bed filters before being cartridge-filtered to 50 µm as it flows into the assorted green sea urchin culture tanks (James & Siikavuopio, 2015).[31] All hatchery seawater flows at a rate of 3 L min^{-1}, which has been shown to be in the optimal range for larval and juvenile rearing of green sea urchins (James & Siikavuopio, 2015).[32] Aeration of urchin holding tanks is assumed to occur naturally vis-à-vis the seawater inflow pipe's natural disturbance of water in the holding tanks (Supan, 2014). The seawater is first pumped into a separately constructed pump house through a 5 cm diameter HDPE pipe before entering the hatchery facility (there is a second backup pipe). There is enough

[30] An overhead representation of the four-species IMTA farm configuration as assumed to have the same layout as the three-species design, because the SeaNests are strung directly below the salmon cage system, and no other alterations to the IMTA site configuration are made.

[31] There is no banjo filter on incoming seawater in the diatom culture tank to allow for a natural microbial film to collect on the diatom settlement racks.

[32] The required flow-through rate will depend on the size of the rearing container. A flow-through rate of 3 L min^{-1} in a 100 L container will be different than 3 L min^{-1} in a 1000 L container.

seawater storage on-site to supply two days' worth of hatchery seawater requirements. There is a Mitsubishi Kato generator to supply backup power.

3.3.1.1. Green Sea Urchin Hatchery Production

The hatchery production consists of a broodstock conditioning and spawning phase, a larval rearing phase, and an early juvenile rearing phase. Both the broodstock and the diatom cultures are held in seawater at ambient temperature. Larvae and early juveniles are cultured at 9–13˚C (Pearce et al., 2002, 2006).[33] Broodstock are held in a separate broodstock room and cultured at an ambient photoperiod (Daggett et al., 2006). All other culture tanks are located on the main floor of the hatchery on a 10:14 light/dark photoperiod (de Jong-Westman et al., 1995; Daggett et al., 2005).

A licensed commercial diver collects 20 wild adult green sea urchins as broodstock. Each broodstock animal is assumed to weigh 90 g, have a 50-mm test diameter at collection, and maintain a uniform weight throughout the 10-year project period (Pearce et al., 2002; Daggett et al., 2006). The broodstock are held in two 600-L tanks at a culture density of 6 kg m^{-2} and eat 3% of their weight day^{-1} in *S. latissima* (Hagen & Siikavuopio, 2010; Pearce & Robinson, 2010; Siikavuopio & James, 2011; James & Siikavuopio, 2015). I assume 100% survival of broodstock under these conditions. The broodstock are induced to spawn after 10 weeks with an injection of 1 ml potassium chloride (KCl) per animal while they are held inverted over a container. Male and female gametes are collected and mixed manually for fertilization (Hagen, 1996). I assume 2 million fertilized eggs per urchin pairing and 10 broodstock pairings (Teralynn Lander, Fisheries and Oceans Canada, personal communication). Fertilized eggs are held in a fridge for a 24-hour period prior to being released into larval holding containers for larval development, metamorphosis, and settlement (Hagen, 1996; McBride, 2005).

[33] Diatom culture water temperature was provided by Christopher Pearce (Fisheries and Oceans Canada, personal communication).

Larval culture lasts 21 days prior to settlement (McEdward & Miner, 2001; McBride, 2005). The larvae are held in a 1,703-L tank filled with 966 L of filtered seawater (James & Siikavuopio, 2015). Larvae are cultured at 1000 individuals ml^{-1} and fed phytoplankton *Chaetoceros neogracile* (*C. gracilis*) at an average rate of 14,444 algal cells ml^{-1} day^{-1}. This figure is based on a phytoplankton feed rate of 5000 cells ml^{-1} for days 1–14 of larval culture and 33,333 cells ml^{-1} for days 15–21 (Hagen, 1996; Pearce, 2006; Pearce & Robinson, 2010). Phytoplankton is cultured using an Industrial Plankton™ 1000-L Algae Bioreactor (bioreactor), with relevant cost outputs sourced through a proprietary Industrial Plankton™ Microsoft Excel spreadsheet model that was provided to me for research purposes. The bioreactor cultures algae at a density of 82 million cells ml^{-1} and operating costs were based on the phytoplankton requirements for larvae culture. This was calculated by inputting the number of algal cells required L^{-1} of larvae culture, larvae rearing tank water volume (L), and daily water exchange rate based on the assumed hatchery seawater flow-through rate of 3 L min^{-1} (Helm & Bourne, 2004; Suppan, 2014). Using this approach, and because of the bioreactor's efficiency, total *C. gracilis* drawdown from the bioreactor culture amounts to 19.55 L over the 21-day culture period.

The larvae are induced to settle using diatom settlement racks made of CPVC piping and corrugated PVC sheeting. The settlement racks are placed in two 908.5 L troughs of sand-filtered seawater for three weeks to collect a natural microbial film of diatoms (Christopher Pearce, Fisheries and Oceans Canada, personal communication). The racks are then moved into early juvenile nursery troughs where the larvae are transferred for settlement (McBride, 2005). I assume a survival rate of 10% from viable larvae to settled early juveniles (Teralynn Lander, Fisheries and Oceans Canada, personal communication). This is higher than Brown et al.'s (2013) larval to early juvenile survival rate of 5%, but lower than the 60% and 70% survival rates observed by some Japanese researchers as noted by Brown et al. (2013). Larvae reach an average test diameter of 0.9 mm at the time of transfer to the settlement tanks (Christopher Pearce, Fisheries and Oceans Cnadaa, personal communication). I calculated the weight of the 0.9-mm larvae using a logarithmic equation employed by Meidel and Scheibling (1999) to estimate the relationship between test diameter (mm) and weight (g) in juvenile green sea urchins with a 13–17 mm test diameter (equation 4). No alternate equation was found to represent this relationship for younger urchins.

$$ln(W) = -7.164 + 2.859 * ln(D) \quad (4)$$

3.3.1.2. Green Sea Urchin Grow-out

Early juveniles are fed 2% of their body weight per day with IMTA-cultured *S. latissima* at a culture density of 0.25 kg m^{-2} (Pearce, 2006; Siikuvuopio & James, 2011). After a nursery period of 49 weeks, the juveniles reach an average test diameter of 0.7 mm and weight of 0.21 g and are transferred into SeaNest cages and held in the ocean for the IMTA culture and finishing diet.

SeaNests filled with the 7-mm juvenile green sea urchins are hung by long-line running directly underneath the site's salmon cages for a 92-week grow-out cycle in the base-case scenario and 144-week grow-out cycle in the alternate 3-year production cycle scenario. Six long-lines of urchin cages are strung individually underneath each length of 2 salmon cages, with salmon cages arranged in a 6 x 2 array (see Figures 5, 6, and 7).[34] While it would be ideal to understand the dynamics of organic matter interception and ingestion rates of green sea urchins cultured in cages suspended by long-line under salmon cages, a noted paucity of such data precluded such an investigation (James & Siikavuopio, 2015). Accordingly, assumptions of the survival rate and the final test diameter and weight of IMTA-cultured green sea urchins were required for this analysis. I assume 90% of IMTA-cultured green sea urchins survive to the finishing diet culture period. The urchins have an average somatic body weight of 43.5 g, 40-mm test diameter, and a gonad index of 10% at the end of both 2-year and 3-year production cycle scenarios, prior to the finishing diet culture period (Christopher Pearce, Fisheries and

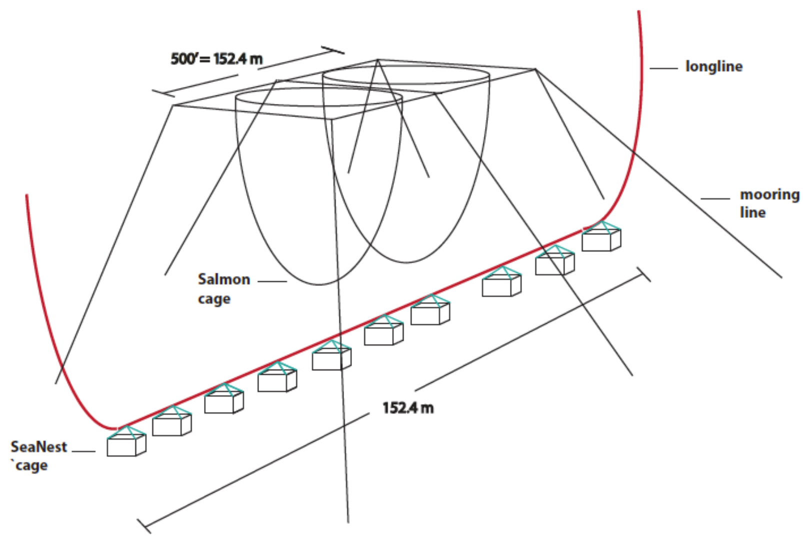
[34] This hypothetical long-line IMTA culture design was reviewed by Christopher Pearce (Fisheries and Oceans Canada, personal communication) and Brian Tsuyoshi (Urchinomics, personal communciation).

Oceans Canada, personal communication).[35,36] This size falls into Pearce et al.'s (2004) optimal range for green sea urchin gonad enhancement.

3.3.1.3. Green Sea Urchin Finishing Diet

After 92 weeks, the urchin cages are moved to another long-line on the perimeter of the farm site for a 12-week finishing diet of Urchinomics prepared urchin feed. This feed, developed at the Norwegian Institute of Fisheries and Aquaculture Research Ltd., has been shown to enhance the marketable properties of the green sea urchin gonads and gonad index in research and commercial applications (James et al., 2017; Brian Tsuyoshi, Urchinomics, personal communication). Adult urchins are fed once a week at a rate equivalent to 0.5% of their body weight. They are assumed to increase in weight 1% per week to reach a final weight of 49.1 g and a 22% gonad index at harvest. The 1% weight gain per week is assumed to go directly to the gonad. With a survival rate of 90% in the

Figure 6: SeaNest ™ cage long-line integration with salmon cage grid system.

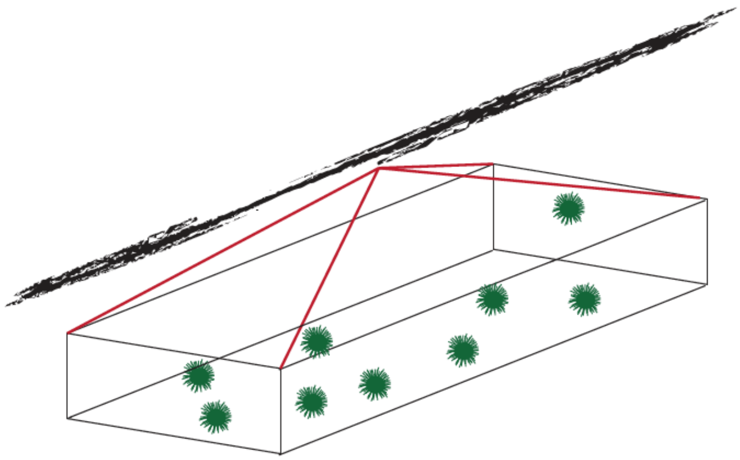


There are six long-lines strung underneath the 6 x 2 array of salmon cages. Not to scale.

[35] Gonad index is calculated as [(wet gonad weight/weight of whole urchin) x 100] (McBride, 2015).

[36] 43.5 g is the mid-point between Brown et al.'s (2013) observed weight range of 28–61 g in 'large' *S. droebachiensis*.

Figure 7: SeaNest ™ cage attached to long-line



finishing diet culture period, there are 74,308 urchins with a total live weight of 3,645 kg at the end of the 12-week finishing period (Brian Tsuyoshi, Urchinomics, personal communication).

3.3.2. Economic and Financial Assumptions

All costs are presented in 2016 US dollars for the purpose of this analysis unless noted otherwise. Canadian dollar values, where required, were converted to 2016 dollars using the Bank of Canada's online inflation calculator. Keeping with best practice in DCF, no financial costs (e.g., depreciation, interest expenses) were included in the study (Bierman Jr. & Smidt, 1993).[37] All capital costs are assumed to occur in Year 1, with no salvage value for capital equipment and no replacement capital expenditures required during the project life cycle. Energy costs were calculated for the hatchery based on total kwh of assumed hatchery equipment and electricity rates taken from the NB Power website in April 2017.

The hypothetical green sea urchin hatchery used in this study was designed as a pilot-sized hatchery to meet assumed green sea urchin production levels. Accordingly,

[37] The cost of capital is assumed to be equal to the chosen discount rate (r).

this study's hypothetical hatchery operation is too small to achieve commercial economies of scale.[38] To help account for this gap between my hatchery design and a real-world commercial sea urchin hatchery, I calculated the hatchery's capital costs per unit of green sea urchin seed to inform future studies and cost comparisons between hatchery operations. My calculated capital cost per unit of urchin seed produced comes out to $1.25 in the base-case pricing scenario. This capital cost per unit of urchin seed produced is likely to be substantially higher than the cost per seed of a commercial scale hatchery operation and should be considered an upper-bound estimate.[39] To help ensure my hatchery costs were accurate, I also consulted with a west coast Canadian commercial hatchery operator, J.P. Hastey of Nova Harvest Ltd. He confirmed that, while my costs are probably high in relation to true commercial scale costs, the cost of my study's hypothetical pilot-scale hatchery is realistic for my assumed green sea urchin production level. Given the high costs associated with my hypothetical hatchery design, I did not modify my costing figures to account for slightly higher capital costs that might be expected with an east coast green sea urchin hatchery.[40] See section 3.3.2.1. for a sensitivity analysis that explores the impact of lower hatchery capital costs on the profitability of four-species IMTA.

All IMTA species are sold at their farm-gate value. Keeping with Chapter 2 of this study and Ridler et al.'s (2007b) DCF of an east coast IMTA operation, I assumed discount rates of 5% and 10%. Negative cash flows incurred in years 1, 3, 5, 7, and 9 are carried forward to the following year to reduce total taxable income (Canada Revenue Agency, 2017). The capital costs for three-species and four-species IMTA are summarized in Tables 8 and 9, and key variable cost assumptions in Table 10. Salmon

[38] The scale of operation can be a limiting factor for hatchery operations (Leask et al., 2008).

[39] The capital cost requirements per seed was calculated using total seed requirements per harvest (965,661 seed) and all capital costs directly associated with the hatchery operation. All capital costs associated with the IMTA grow-out and finishing diet phases of green sea urchin culture were excluded from the capital cost base, as was the estimated capital contingency.

[40] I consulted with J.P. Hastey, President and Founding Member at Nova Harvest Ltd. regarding my study's assumed hatchery costs. J.P. Hastey informed me that my hatchery model might have underestimated seawater pump costs or electrical costs required for water heating by a few thousand dollars. I did not incorporate any such revised cost estimates into my model because of the small cost differentials quoted to me by J.P. Hastey.

harvesting costs, chemical costs, vaccination costs, diving costs, and regulatory compliance costs and fuel costs are not included in Table 10.[41] Total salmon feed and urchin feed costs were dependent on the IMTA production model developed using the technical and biological parameters above. The 3-year cycle reduces total green sea urchin harvests to two, in years 5 and 8 of the project timeline, with reduced total variable costs owing to reduced labour requirements for hatchery operations, and winding down of labour requirements after the final harvest in year 8 of the 3-year production scenario. I based regulatory costs on New Brunswick Department of Agriculture, Aquaculture and Fisheries' estimated aquaculture application costs (Gail Smith, NBDAAF, personal communication).

I assume that both IMTA operations require 6 labourers and one farm manager over the project life cycle for salmon, mussel, and kelp IMTA aquaculture activities. Farm manager and labourer wage rates are reflective of those employed by Cooke Aquaculture (Michael Szemerda, Cooke Aquaculture, personal communication). The farm manager earns an annual salary, and hourly wages are paid out at 37.5 hours per week and 45 weeks per year per labourer. In the four-species IMTA farm, the hatchery employs one full-time lead hatchery technician/manager paid an annual salary, and 1–1.5 hatchery technicians paid hourly based on Canadian industry averages for hatchery employees and 52 weeks $year^{-1}$ (Indeed.ca, 2017). Training and hatchery set-up requirements assume the hatchery manager and 1.5 hatchery technicians work 25% during year one in the two-year and three-year production cycle scenarios. I assume two additional full-time farm labourers from years three through ten on a four-species IMTA farm to account for weekly SeaNest maintenance, SeaNest cage deployment, and green sea urchin harvesting. I assume that all hatchery employees and aquaculture farm labourers practice correct handling procedures when working with the green sea urchins, as handling stress has been linked to lower urchin survival rates (Dale et al., 2005; Daggett et al., 2006; Brown et al., 2013). Wage rates are assumed the same for both

[41] Salmon harvest, chemical and vaccination, and diving costs are assessed on a per pound basis, based on the total salmon harvest converted to its HOG weight (Steve Smith, Cooke Aquaculture, personal communication).

three-species and four-species IMTA. Labour associated with kelp and mussel raft building, raft deployment, and harvesting activities were built into Hamer's (2012) mussel and kelp models that have been incorporated into this study's capital budgeting model.

The operating costs of phytoplankton production are determined based on a proprietary Industrial Plankton™ Microsoft Excel production model made available to me for this study. I input this study's estimates and calculated the number of algal cells required L^{-1} of larvae culture, larvae rearing tank volume (L), and daily water exchange rate.[42,43] Maintenance costs for the bioreactor are included in the operating cost outputs of the Industrial Plankton™ proprietary model. See Table 11 for a summary of operating costs and phytoplankton production.

Japan makes up 80% of the global sea urchin market, and although Europe is a promising secondary market for uni, this study assumes that all sea urchins are sold live to the Japanese market (Siikavuopio, 2009). The salmon, mussels and kelp IMTA products are all assumed sold at farm-gate prices to North American or European markets. I also ran three sensitivity analyses to examine the impact of sea urchin selling prices on overall IMTA profitability. The base-case and intermediate urchin prices were taken from Fisheries and Oceans Canada's (DFO) green sea urchin fisheries management plan (2016) and their dataset on commercial sea fisheries landings and value for sea urchins in New Brunswick for the year 2014 (DFO, 2017). A third, high urchin price was based on DFO's sea fisheries data for green sea urchins in New Brunswick. I assumed an average gonad yield of 15% per wild harvested green sea urchin in eastern Canada, and calculated a higher market price based on the higher gonad index obtained by IMTA-cultured green sea urchins.[44] However, this high urchin price may be over-estimating potential prices for larger gonads (John Lindsay, Pacific Urchin Harvesters Association,

[42] Ashley Rawlston, Industrial Plankton ™, personal communication.

[43] The daily water exchange rate is based on the total assumed daily flow-through of seawater at a rate of 3 L min^{-1}.

[44] My model's results showed that IMTA green sea urchins' average final gonad yield would be 21.9% at the end of the 12-week finishing diet.

personal communication).[45] Base-case, intermediate, and high urchin prices and the base selling prices for mussels, kelp, and salmon are summarized in Table 12.

An overhead view of the hypothetical green sea urchin hatchery design, approximately to scale, is presented in Figure 8. Table 13 summarizes the estimated square footage requirements of the hatchery and associated costs based on a construction cost of $211 per square foot, including utilities and electrical. The construction cost per square foot is based on a feasibility study for a shellfish hatchery in British Columbia, Canada (Leask et al., 2008). Due to the low number of culture tanks required for the hypothetical urchin hatchery's scale of production, vertical stacking to minimize space was not considered, although this could help lower costs (Leask et al., 2008; Brown et al., 2013). I assume the main open-floor space is used for miscellaneous hatchery tasks, as well as for the transfer of early juvenile green sea urchins from the culture tanks to SeaNest cages for IMTA grow-out.

[45] Green sea urchins with a gonad index of 22% sold for about $3.00 kg^{-1} in the 2016 harvesting season (John Lindsay, Pacific Urchin Harvesters Association, personal communication).

Table 8: Three-species IMTA capital cost summary.

Salmon				
Net Pen Cage System		$453,064	6x2 salmon grid and 160 m circumference cage system	Cooke Aquaculture
Service and Crew Boat		$113,153	Jackson Craft	Boulet et al., 2010
Fork Lift	$	$19,822		Hamer, unpublished data, 2012
Feed Barge	$	$1,887,768		AKVA
Feed Monitoring System	$	$101,939		AKVA
Misc. Fish Culture Equipment	$	$247,059	Graders, fish pumps, feeding equipment etc.	Boulet et al., 2010
Nets	$	$1,016,676	Holding and predator nets	Cooke Aquaculture, 2016
Mooring System	$	$395,152	Compensator buoys, lift lines, mooring lines and chains, etc.	Cooke Aquaculture, 2016
Mussels				
Mussel Raft Mooring System		$130,975		Hamer, unpublished data, 2012
Mussel and Spat Rafts		$433,622		Hamer, unpublished data, 2012

Socking and Grading Equipment		$33,300		Hamer, unpublished data, 2012
Predator Net		$71,060		Hamer, unpublished data, 2012
Labour associated with initial capital outlay/raft construction		$33,496		Hamer, unpublished data, 2012
Kelp (*S. latissima*)				
Kelp Raft Mooring System		$61,001		Hamer, unpublished data, 2012
Truck		$20,000		Hamer, unpublished data, 2012
Bonar Ice Chests		$12,000		Hamer, unpublished data, 2012
Raft Piping		$20,670		Hamer, unpublished data, 2012
Tobacco Dryer		$30,800		Hamer, unpublished data, 2012
Refrigerated Room		$6,980		Hamer, unpublished data, 2012
Labour & Vessel Costs Associated w/Initial Capital Outlay/setup		$7,270		Hamer, unpublished data, 2012
Lab Culture System		$26,583		Hamer, unpublished data, 2012
Capital Contingency (15%)		$768,359		
Total Capital Costs		$5,890,749		

Table 9: Four-species IMTA (with green sea urchins) capital cost summary and revised capital contingency.

Urchins (*S. droebachiensis*)				
Hatchery Construction and Land Costs		$1,089,814		
Hatchery Equipment		$200,383		
Capital Contingency (15%)		$961,888		
Total Capital Costs		$7,374,475		

Capital costs for salmon, mussel, and kelp are assumed to remain the same in the 4-species IMTA operation. The capital contingency of 15% is based on total capital costs for all 4 IMTA-species. Full details on sea urchin hatchery equipment, construction and land costs can be found in Appendix A.

Table 10: Key variable cost parameters for three-species IMTA and four-species IMTA operations.

Farm-site Manager	$	$47,572	Annual salary, based on $63,000 CAD/annum	Cooke Aquaculture, 2016
Farmhand (labourer)	$	$12.80	Hourly wage, based on $17.00 CAD/hour	Cooke Aquaculture, 2016
Lead Hatchery Technician	$	$46,517	Annual salary, based on 61,303 CAD/annum	Indeed.ca (2017)
Hatchery Technician	$	$15.06	Hourly wage, based on $19.95 CAD/hour.	Indeed.ca (2017)
Cost of salmon feed	$/tonne	$1,006	-	Boulet et al., 2010
Cost of Urchinomics Urchin Feed	$/kg	$7.00	-	Brian Tsuyoshi, personal commentary, April 21, 2017

Table 11: Phytoplankton production and operating cost summary.

Item	Quantity	Source
Total number *S. droebachiensis* larvae	965,661	
Feed rate *C. gracilis* cells/ml per day (Days 1-14)	5,000	Hagen, 1996
Feed rate *C. gracilis* cells/ml per day (Days 15-21)	33,333	Hagen, 1996
Average *C. gracilis* cell/L feed rate per day	14,444,000	
Total larval tank water volume (L)	966	Pearce, 2006
Required background phytoplankton cell count on Day 1 of larvae culture	13,952,904,000	Based on volume of tank and algal cell requirements of juvenile *S. droebachiensis*
Daily seawater flowthrough rate (L/min) replacement *C. gracilis* requirements for larval culture	62,398,080,000	Based on James and Siikavuopio's (2015) 3L min-1 seawater flow through rate.
Total est. phytoplankton cells required per day	76,350,984,000	
Industrial Plankton™ Algae Bioreactor phytoplankton production (*C. gracilis* cells/L)	82,000,000,000	Industrial Plankton™, 2017
Required bioreactor volume (L) per day	0.93	
Required bioreactor drawdown (L) per day as % of bioreactor volume	0.00093	
Required bioreactor volume (L) over 21-day culture period	19.55	
Daily Operating Cost	$7.09	Industrial Plankton™, 2017

Table 12: Selling prices and financial parameters for three-species and four-species IMTA.

Item	Unit	Quantity	Description	Source
Price per smolt	$/smolt	$2.43	Price per 75g smolt	Ridler et al., 2007b
Atlantic salmon selling price	$/kg	$5.03	Price of salmon, farm-gate (HOG)	IndexMundi.com, 2016
Mussel selling price	$/kg	$1.10		
Kelp (*S. latissima*) selling price	$/kg	$26.43	Selling price per kg of kelp, dry-weight	
Urchin (*S. droebachiensis*) base-price	$/kg	$2.38		DFO, 2016
Urchin (*S. droebachiensis*) intermediate-price	$/kg	$2.64		DFO, 2017
Urchin (*S. droebachiensis*) high-price	$/kg	$3.84	Assumed an average 15% gonad index for wild east coast green sea urchins. Intermediate price adjusted up 5% to reflect increased gonad yield for IMTA-cultured *S. droebachiensis*	
Federal Tax Rate	%	15%	-	CRA, 2016
New Brunswick Provincial Tax Rate	%	14%	-	CRA, 2016
2016 USD:CAN Exchange Rate	-	0.755107	Average 2016 value of 1 dollar CAD in US dollars	www.canadianforex.ca

Figure 8: Green sea urchin hatchery overhead layout

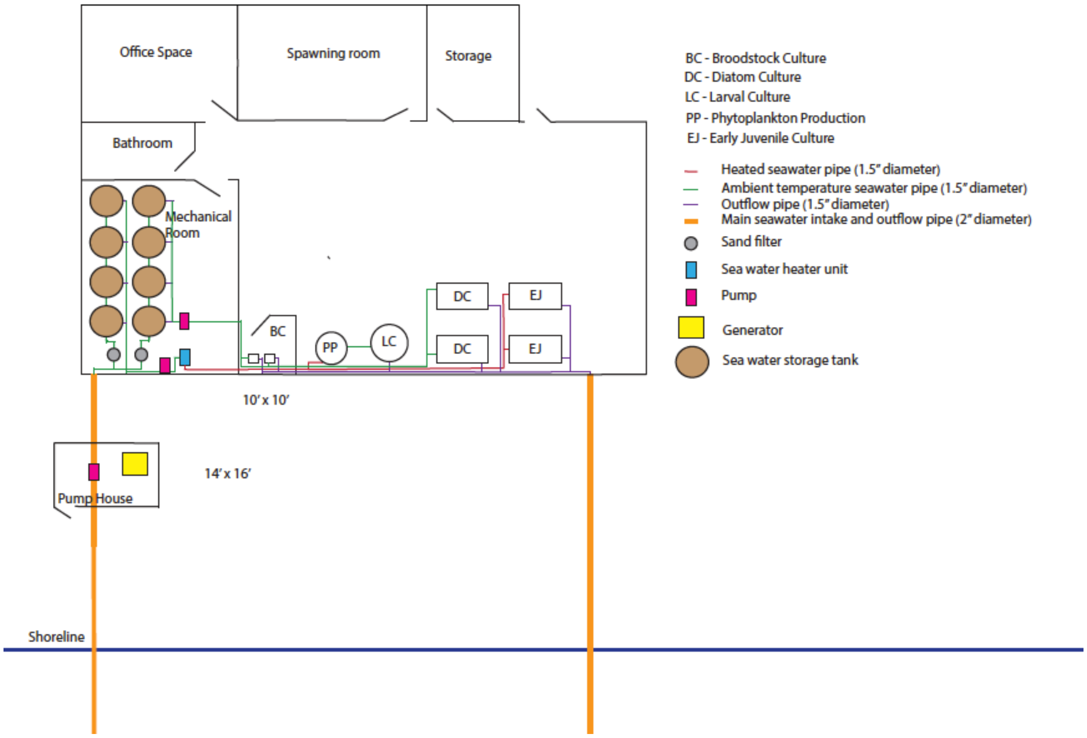


Table 13: Green sea urchin hatchery square footage and capital cost estimates.

Hatchery Facility Construction	Square Feet	Cost
Broodstock Culture Room	100	$21,101
Mechanical Room	750	$158,255
Bathroom	180	$37,981
Office Space	432	$91,155
Spawning Room	540	$113,944
Storage	252	$53,174
Main hatchery floor space	2490	$525,408
Pumphouse	224	$47,266
Total Hatchery Construction:	4968	$1,048,283
Cost of land	7 acres	$41,531
Total Hatchery construction and land costs:		$1,089,814

3.3.2.1 Investment Appraisal and Sensitivity Analyses

This chapter's base-case scenario uses the financial, technical, and biological assumptions described above to forecast costs and revenues over a 10-year time horizon for three-species and four-species IMTA farms. In the three-species IMTA base-case, adult salmon reach a live weight of 5.85 kg salmon^{-1} at harvest, with a single production cycle yielding 4.21 tonnes of salmon and revenues of $23,282,896 every two years, as well as annual harvests of 9,450 tonnes of *S. latissima* (dry weight) with revenues of $249,752, and 530 tonnes of mussels with revenues of $583,664. These amounts remain unchanged in the four-species IMTA scenario, but there are additional revenues and costs from the sale of 3,645 kg of green sea urchins in years 4, 6, 8 and 10. Revenues in the base-case are estimated using the base-case urchin price and total $8,675 per harvest year. These revenues would increase to $9,623 and $13,997, respectively, for intermediate and high urchin prices. In the 3-year green sea urchin production-cycle scenario, green sea urchin revenue occurs only in years 5 and 8 due to a longer IMTA-culture period, but salmon, mussel, and kelp volume and sale quantities are assumed unchanged. Labour costs also change in the 3-year production cycle scenario; a part-time hatchery technician is not required for years 4 and 7, the two urchin-specific farm labourers are not required in years 9 and 10, and the lead hatchery technician/manager is the only remaining hatchery employee in year 10 as hatchery operations are assumed to wind down. Urchinomics urchin feed costs are also reduced due to a decrease in the number of green sea urchin harvests.

Building on Chapter 2 results, I examined what the impact to the NPVs of three-species and four-species IMTA would be if a 10% price premium were included for mussels and salmon in the base-case and 3-year urchin production scenarios. This IMTA premium has been shown to be attainable for IMTA products and can be assumed to apply to North American and European markets. Sea urchins are not assumed to attain an IMTA price premium because the Asian market tends to exclusively value quality over other attributes (Ridler et al., 2007b; Bunting, 2008; Shuve et al., 2009; AMB Marine and Coastal Research, 2012; Organic Monitor, 2014; Yip et al., 2017).

I also examined the difference in the NPV of three-species and four-species IMTA farms when assuming a more complex operating environment for four-species IMTA. To estimate the cost of increased technological complexity, I increased the capital contingency requirement from 15% for four-species IMTA in the base case to 20% in the sensitivity analysis. A 20% capital contingency is the same figure assumed by Boulet et al. (2010) in their DCF analysis of an open net-pen salmon monoculture and a land-based recirculating aquaculture (RAS) salmon production system. This capital contingency sensitivity analysis is based on the assumption of increased technical complexity associated with integrating the green sea urchin with a three-species IMTA operation in the Bay of Fundy and assumes similarities in terms of technological complexity between Boulet et al.'s (2010) RAS study and this paper's hypothetical land-based green sea urchin hatchery operation. This sensitivity analysis was undertaken for both the base-case and 3-year production cycle scenarios.

It is possible that green sea urchin roe from IMTA operations fed a finishing diet designed for roe-enhancement could exhibit improved market characteristics over wild urchins at harvest (e.g., size, colour) (Robinson et al., 2002; James et al., 2017). This improved quality of urchin roe could result in higher prices for IMTA green sea urchins over wild green sea urchins. Accordingly, I employed a sensitivity analysis using a revised urchin price to examine differences in the NPV of the base-case three-species IMTA operation and the base-case four-species IMTA operation. I first used arbitrary price premiums of 50%, 100%, and 200% over the base-case urchin selling price to examine impacts to NPV. I also examined a pricing scenario based on a price of $400 kg urchin roe^{-1}. This price is in the upper-range of possible market prices for sea urchin roe and was used to estimate the revenues that could be realized from IMTA-urchin production that resulting in high-quality green sea urchin gonads (Pearce et al., 2002; Woods et al., 2008).

I also examined the impact of reducing the hypothetical hatchery's capital costs of the hatchery operation by 50% and 75% to test for changes in the NPV of four-species IMTA resulting from decreased costs per seed produced compared to three-species

IMTA.[46] These sensitivity analyses are intended to account for the small-scale nature of my hypothetical hatchery design and potential cost efficiencies of a commercial hatchery. However, the 50% and 75% hatchery capital cost reduction figures used here are guesses at the potential improvements in capital costs per unit of seed produced that might be realized in a commercial scale hatchery operation integrated with IMTA.

3.4. Results

Table 14, scenarios (a) and (b) show the results of three-species and four-species IMTA operations in the base-case scenario with and without a 10% price premium on IMTA salmon and mussels at discount rates of 5% and 10%. The three-species IMTA farm examined in this study is a more profitable investment opportunity with or without a price premium. The four-species IMTA operation is at least 5.6% less profitable than three-species IMTA when a price premium is included, and up to 8% less profitable than three-species IMTA with no price premium in the base-case production scenario. Scenario (c) and (d) in Table 14 replicate the (a) and (b) scenarios, but for the three-year green sea urchin production-cycle scenario. Table 14(c) shows that the NPV of four-species IMTA is 5.3% lower than the NPV of the three-species IMTA farm in a best-case scenario at a 5% discount rate with a 10% price premium on IMTA mussels and salmon. Scenario (d) shows that four-species IMTA has a NPV 7.7% lower than that of a three-species IMTA farm at a 10% discount rate with no price premiums applied to IMTA mussels and salmon. The results of scenarios (c) and (d) show that the four-species IMTA farm's NPV is higher than those observed in the base-case 2-year green sea urchin production-cycle scenario, but that four-species IMTA is remains less profitable than three-species IMTA.

The result of higher costs from increased operational complexity of four-species IMTA is shown in Table 14(e) and (f) for the base-case and 3-year production cycle scenarios.

[46] I calculated the capital costs per unit of urchin seed as \$0.62 unit^{-1} and \$0.31 unit^{-1} with hatchery capital costs reduced by 50% and 75%, respectively.

Table 14: Three-species IMTA and four-species IMTA results for NPV (10 years, 2016 US prices).

(a)	Base-case, three-species IMTA and four-species IMTA results.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$33,974,817	$31,838,227	-6.3%
r=10%	$24,998,840	$22,991,638	-8%
(b)	Base-case, three-species IMTA and four-species IMTA results, 10% price premium on salmon and mussels.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$40,538,598	$38,402,007	5.3%
r=10%	$30,106,888	$28,178,883	6.4%
(c)	3-year green sea urchin production cycle, three-species IMTA and four-species IMTA results.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$33,974,817	$31,829,702	-6.4%
r=10%	$24,998,840	$23,064,743	-7.7%
(d)	3-year green sea urchin production cycle, three-species IMTA and four-species IMTA results, with 10% price premium on IMTA salmon and mussels.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$40,538,598	$38,393,482	-5.3%
r=10%	$30,106,888	$28,172,791	-6.4%
(e)	Base-case, 20% capital contingency with four-species IMTA.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$33,974,817	$31,532,865	-7.2%
r=10%	$24,998,840	$22,779,354	-8.9%
(f)	3-year production scenario with 20% capital contingency and four-species IMTA.		
	3-IMTA	4-IMTA	4-**species (Δ) %** over 3-species
r=5%	$33,974,817	$31,524,341	-7.2%
r=10%	$24,998,840	$22,773,262	-8.9%

(g)	Base-case comparison of four-species IMTA with a more complex four-species IMTA.		
	4-IMTA, 15% capital contingency	4-IMTA, 20% capital contingency	**(∆) %, 20% Capital** Contingency over 15%
r=5%	$31,838,227	$31,532,865	-0.59%
r=10%	$23,070,835	$22,779,354	-0.92%
(h)	3-year production scenario comparison of four-species IMTA with a more complex four-species IMTA.		
	4-IMTA, 15% capital contingency	4-IMTA, 20% capital contingency	**(∆) %, 20% Capital** Contingency over 15%
r=5%	$31,829,702	$31,524,341	-0.96%
r=10%	$23,064,743	$22,773,262	-1.3%

Table 14(e) examines the difference in NPV between a four-species IMTA operation (base-case scenario with a 15% capital contingency) against a four-species IMTA operation with increased operational complexity. Table 14(f) shows the results of the same analysis for the four-species IMTA operation in the alternate 3-year production scenario. These results highlight that additional complexity increases the NPV differential between three-species and four-species IMTA in both the base-case and 3-year production cycle scenarios. The smallest NPV differential between four-species IMTA and three-species IMTA in the base-case increased from -6.6% to -7.2% at a discount rate of 5%, and from -8.0% to -8.9% at a 10% discount rate. The alternate 3-year scenario had NPV differentials increase from -6.4% to -7.2% at a 5% discount rate and from -7.7% to -8.9% at a 10% discount rate. Scenarios (g) and (h) in Table 14 respectively examine the NPV differentials between four-species IMTA operations in the base-case and 3-year production-cycle scenarios when additional technological complexity is introduced. These results demonstrate that increased technological complexity of four-species IMTA reduces NPV by approximately 1% in both base-case and three-year production-cycle scenarios.

The results of the sensitivity analyses in Table 14 show that the three-species IMTA farm is more profitable than the four-species IMTA farm in every tested scenario. A simple examination of the anticipated cash flows of full life-cycle green sea urchin IMTA culture as configured in this study shows that green sea urchin sales per harvest of $8,675 (base-case urchin price), $9,623 (intermediate urchin price) or $13,997 (high urchin price), regardless of the production scenario, cannot offset the $1,290,197 capital investment required for green sea urchin culture, nor additional variable costs required for green sea urchin IMTA integration. Following this finding, I calculated the required number of green sea urchins to break even with the capital costs of equipment and construction required for the green sea urchin hatchery, IMTA culture, and finishing diet at base-case production levels. I also calculated the number of SeaNest cages required to expand on possible spatial scale requirements required for profitability. The capital costs for green sea urchin culture are divided by the price of urchins kg^{-1} using the three urchin prices from this study to give the total required number of urchins. I then divided the total required number of urchins by 203, which is the total possible number of adult urchins at a harvest weight of 0.0491 kg that would fit into a SeaNest cage at a culture density of 10 kg $cage^{-1}$. These results are presented in Table 15.

Table 15: Required number of green sea urchins per harvest (base-case) to break even with existing green sea urchin capital costs.

	Price ($/kg)	Urchin price ($/unit)	Required Adult Urchins (No.)	Required SeaNests (No.)	Current scale of operation as % of Required # SeaNests
Base-case	2.38	0.12	74,308	450	-
Base-case urchin price	$2.38	$0.12	11,040,723	13,597	3.3%
Intermediate urchin price	$2.64	$0.13	9,953,379	12,258	3.7%
High urchin price	$3.84	$0.19	6,842,948	8,428	5.3%

The results from Table 15 demonstrate that in the high urchin price scenario, the number of SeaNests used for green sea urchin IMTA is 5.3% of the break-even SeaNest cage requirements, and 3.3% in the worst-case price scenario.[47] One hectare can accommodate 11,215 SeaNest cages side by side, with no room for additional mooring equipment.[48]

Scenarios (i) through (l) in Table 16 present a series green sea urchin hatchery cost and pricing scenarios to examine the effect on NPV differentials between the base-case three-species IMTA operation with the base-case four-species IMTA operation of alternate scenarios. Table 16(i) and (j) scenarios show the effect of lower hatchery costs on four-species IMTA profitability to help shed light on how a commercial-scale hatchery operation, versus this assumed study's hypothetical pilot-scale hatchery, could impact the NPV differential between four-species IMTA and the base-case three-species IMTA operation examined in Table 14. These results show that, with hatchery capital costs reduced by 50%, four-species IMTA has an NPV 4.4% less profitable than three-species IMTA at a 5% discount rate and 5.2% less profitable at a 10% discount rate. When hatchery capital costs are reduced by 75%, four-species IMTA is shown to have a NPV that is, respectively, 3.4% and 3.9% less profitable than three-species IMTA at discount rates of 5% and 10%. The hatchery's capital costs per unit of green sea urchin seed produced decreases from the base-case four-species IMTA's value of \$1.25 seed^{-1} to \$0.62 seed^{-1} and \$0.31 seed^{-1} with hatchery capital costs reduced by 50% and 75%, respectively.

Scenarios (k) through (o) in Table 16 examine the effect on NPV of the base-case four-species IMTA scenario with the inclusion of various price premiums for IMTA green sea urchins compared with the base-case three-species IMTA operation. The price premium scenarios presented in Table 16 are assumed to be possible based on possible

[47] This study's green sea urchin production design uses 450 SeaNest cages.

[48] SeaNest dimensions are: 1.164 L x 0.766 W x 0.244 H. I used L x W to calculate the area of the bottom of the cage, which comes to 0.89 m^2.

Table 16: Three-species IMTA and four-species IMTA results for NPV with reduced hatchery capital costs and assorted green sea urchin price premiums (10 years, 2016 US prices).

(i)	Base-case, three-species IMTA and four-species IMTA, with hatchery capital costs reduced 50%		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	\$33,974,817	\$32,496,861	-4.4%
r=10%	\$24,998,840	\$23,699,531	-5.2%
(j)	Base-case, three-species IMTA and four-species IMTA, with hatchery capital costs reduced 75%		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	\$33,974,817	\$32,826,178	-3.4%
r=10%	\$24,998,840	\$24,013,879	-3.9%
(k)	Base-case, three-species IMTA and four-species IMTA, with 50% price premium on base-case urchin price		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	\$33,974,817	\$31,847,034	-6.3%
r=10%	\$24,998,840	\$23,077,301	-7.7%
(l)	Base-case, three-species IMTA and four-species IMTA, with 100% price premium on base-case urchin price		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	\$33,974,817	\$31,855,841	-6.2%
r=10%	\$24,998,840	\$23,083,767	-7.7%
(m)	Base-case, three-species IMTA and four-species IMTA, with 200% price premium on base-case urchin price		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	\$33,974,817	\$31,873,454	-6.2%
r=10%	\$24,998,840	\$23,096,699	-7.6%
(n)	Base-case, three-species IMTA and four-species IMTA, assuming \$400 kg^{-1} IMTA urchin roe		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species

r=5%	$33,974,817	$32,873,454	-4.4%
r=10%	$24,998,840	$23,533,878	-5.9%
(o)	Base-case, three-species IMTA and four-species IMTA, assuming \$400 kg^{-1} IMTA urchin roe and 50% reduced hatchery costs		
	3-IMTA	4-IMTA	4-**species (∆) %** over 3-species
r=5%	$33,974,817	$33,127,547	-2.5%
r=10%	$24,998,840	$24,162,574	-3.3%

See section 3.3.2 for details on green sea urchin price scenarios.

quality enhancements of IMTA green sea urchin roe through the use of a finishing diet (Urchinomics urchin feed).

The results of scenarios (k) through (m) in Table 16, with price premiums of 50%, 100%, and 200% over the base-case urchin price of \$2.38, demonstrate that there is no substantial difference in the NPV differential between four-species IMTA and three-species IMTA compared with the base-case scenario examined in Table 14(a). Table 14(a) highlighted that the NPV of four-species IMTA was 6.3% and 8% lower than three-species IMTA in the base-case analysis at discount rates of 5% and 10%, respectively. Scenarios (k) through (m) show the NPV of four-species IMTA to be between 6.2% and 6.3% lower than three-species IMTA at a 5% discount rate, and between 7.6% and 7.7% at a 10% discount rate.

The Table 16(n) and (o) sensitivity analyses looked at changes in the NPV of four-species IMTA compared with three-species IMTA based on a market price of \$400 kg^{-1} green sea urchin roe. Table 16(n) shows that a four-species IMTA has a NPV 4.4% and 5.9% lower than the base-case three-species IMTA operation. Scenario 16(o) in Table 16 uses the same price point and also includes a 50% reduction in hatchery capital costs. The NPV of four-species IMTA at \$400 kg^{-1} green sea urchin roe and 50% reduced hatchery capital costs resulted in NPVs that were, respectively, 2.5% and 3.3% lower than three-species IMTA at 5% and 10% discount rates. These price differentials are smaller than those observed in Table 14(a), where the NPV of four-species IMTA was 6.3% and 8% lower than three-species at discount rates of 5% and 10%, respectively.

Taken together, the results of scenarios 16(i), (j) and (o) suggest that lower green sea urchin hatchery costs are a key factor in the NPV of four-species IMTA operations.

3.5. Discussion

Under all tested scenarios comparing the NPVs of three-species IMTA and four-species IMTA farms, three-species IMTA resulted in higher profits for potential IMTA investors. Even with the range of potential price premiums for green sea urchin roes investigated in this study, three-species IMTA maintained a higher NPV than four-species IMTA. This result shows that the relatively low revenues of green sea urchin sales are not enough to offset the capital costs of integrating full life-cycle green sea urchin culture into this study's assumed four-species IMTA operation. However, the results of Table 16 showed that reducing the capital costs of the green sea urchin hatchery improves the NPV of the four-species IMTA operation examined in this study and decreases the negative differential between four-species IMTA and three-species IMTA more effectively than potential sea urchin price premiums. My results suggest that green sea urchin hatchery capital costs need to be substantially reduced in order for investors to realize higher NPVs with four-species IMTA over three-species IMTA as configured in this study. A commercial-sized hatchery facility could help bring down the capital cost per unit of urchin seed produced and improve the profitability of four-species IMTA.[49]

Another possibility to realize higher profits from green sea urchin sales is to consider processing the live urchins and selling the roe to buyers in Japan. This approach has proven lucrative in the past and can yield prices of up to \$400 kg uni $^{-1}$ (Pearce et al., 2002; Woods et al., 2008). However, an urchin-processing operation would also increase the technological complexity and therefore the costs of green sea urchin rearing (Pearce,

[49] J.P. Hastey (Nova Harvest, personal communication) was unable to provide an estimate of the break-even capital cost per unit of urchin seed produced in a commercial-scale hatchery, and no comparable figure was found in the sea urchin literature. A reliable industry source for an estimated break-even capital cost per unit of urchin seed produced would be of benefit to future studies examining the financial impact of incorporating a benthic-feeding species with a hatchery component into an IMTA operation.

2006; Pisces Consulting Limited, 2014).[50] Investors could also consider focusing on North American and European markets, where price premiums for IMTA products are more likely to be realized (Ridler et al., 2007b; AMB Marine and Coastal Research, 2012; Organic Monitor, 2014; James et al., 2017). Nonetheless, my results suggest that capital costs have a greater impact on the NPV of IMTA operations incorporating a green sea urchin and hatchery component than price premiums. These trade-offs should to be weighed carefully by potential investors and are good directions for future research.

Cranford et al. (2013) found that the scale of mussel culture required to reduce benthic loading at salmon farms would decrease oxygen in the water column by reducing water flow. Canadian aquaculture stakeholders have also noted concerns related to the scale of kelp culture that may be required to reduce inorganic nutrient loading from salmon farms (Crampton, 2016). My study examined the scale of operation required to make a profit, not to affect the meaningful environmental performance of *S. droebachiensis* in an IMTA setting. I found that the scale of urchin culture required to break even with assumed capital costs for green sea urchin culture is 19 times larger than my assumed scale of green sea urchin culture in the best-case pricing scenario, and 30 times larger in the worst-case price scenario (see Table 15). This break-even calculation ignores the increased capital costs that would be required to reach a production scale 19 to 30 times larger than my assumed production levels, as well as increases in green sea urchin operating costs. Including the requisite additional capital and variable costs associated with break-even production levels would necessarily increase the scale of production required to break even with green sea urchin culture under this study's assumed operational design. My research indicates that the required scale of operation to make a profit may be an inhibitor to green sea urchin integration with IMTA from a cost and operational perspective. Given recent work by Cubillo et al. (2016) highlighting the economic and biomitigative potential of *P. californicus* cultured beneath finfish and

[50] This potential price premium for IMTA urchins was examined in Table 16(n) and (o). However, additional costs involved in sea urchin processing were not included in the Table 16(n) and (o) sensitivity analyses.

shellfish farms, as well as recurring calls for deposit-feeder species integration with fed finfish IMTA operations, the economic factors at play in this capital budgeting exercise warrant careful consideration when evaluating the financial potential of benthic species in IMTA operations (Reid et al., 2013; Cranford et al., 2013; Filgueira et al., 2017). Consideration of where the stock of juvenile deposit-feeder animals would come from, as well as suitable holding systems, are important factors that can impact financial performance and may have important implications for IMTA capital costs and the profitability of deposit feeders. The required biomass of deposit feeders will also need to be considered within the context of oxygen availability in the water column to avoid potential harmful impacts to salmonids (Reid et al., 2013).

Green sea urchins are a generalist species, able to ingest fish waste as a food source, and have a propensity to eat the best food available to them in a given habitat (Scheibling & Hatcher, 2001; Orr et al., 2014). The urchins were therefore assumed to intercept sufficient quantity and quality of food sources (waste feed, salmon detritus, and ambient organic matter in the water column) to reach a weight of 43.5 g and a test diameter of 45 mm at the end of the IMTA co-culture period using one hypothetical approach to sea urchin IMTA integration. However, there is a dearth of research into appropriate sea urchin system designs and critical factors for consideration in such systems (James & Siikavuopio, 2015). Researchers also note that data from literature on faecal properties should be used with caution in IMTA models, and that green sea urchin somatic and gonadal growth appear to be influenced by environmental factors that can vary between adjacent geographic populations (Reid et al., 2009; Kling, 2009; Siikavuopio, 2009). Additionally, no research was found to confirm that green sea urchins would be able to successfully intercept, ingest, and convert the organic waste from salmon farms while suspended by long-line in SeaNest cages as this study assumes.[51] Accordingly, readers should note that there is considerable uncertainty associated with my hypothetical hatchery, IMTA grow-out, and finishing diet production cycle approach to green sea urchin IMTA-integration. These elements of uncertainty at the biological and technical level warrant further research. Determining a suitable system for urchin echinoculture that maximizes survival, feed exposure, and water quality, facilitates waste removal, is commercially scalable, and provides an environment conducive to high-quality gonad development remain challenges for the integration of *S. droebachiensis* into Canadian IMTA operations (Daggett et al., 2006; James & Siikavuopio, 2015).

Sea ranching, where juvenile urchin seed is released on the ocean floor to roam and eat at will, is another possible grow-out method for IMTA-produced urchins (McBride, 2005; Brown et al., 2013; James et al., 2017). However, investors have shied away from ranching sea urchins because of technological uncertainty and doubts that the sea urchin seed would survive and stay within the confines of the designated aquaculture lease-site (Brown et al., 2013; James et al., 2017). Additionally, co-cultured sea urchins have been known to actively move away from sea urchins that have died and are decomposing in SeaNest cages during roe-enhancement aquaculture activities (Brian Tsuyoshi, Urchinomics, personal commentary). It is plausible that green sea urchins could demonstrate some of the same aversion to voluntarily remaining beneath salmon cages, where salmon faeces and waste feed flows tend to concentrate (Lander et al., 2013; Filgueira et al, 2017).

Real options analysis (ROA) is an alternative investment appraisal technique that differs from the DCF and NPV approach by observing that uncertainty is an important factor impacting investor decision-making that is not always expounded or factored into

[51] SeaNests were originally designed to be stacked for manual feeding with a prepared feed, and were assumed modified for this study by swapping out their standard solid top with mesh netting. I also assumed mesh netting was placed inside the SeaNest cage to contain early juvenile urchins that were too small to be contained by the standard SeaNest cage dimensions. This mesh netting, necessary for containment, could possibly inhibit organic particulate matter from entering the cage. SeaNests have a 10-mm slot height, from which early juveniles of 7–10-mm test diameter could escape.

traditional DCF analyses (Dixit & Pindyck, 1994). In ROA, an investor's choice to invest is viewed as similar to a financial call option; once an investment has been made, the option to invest has been exercised and is difficult to reverse. This option has value for investors. For example, Dixit and Pindyck (1994) note that in the face of uncertainty, whether political, economic, technological or otherwise, there is often value to investors in waiting for more information and delaying their investment decision.

The impact of uncertainty was recently investigated by Crampton's (2016) assessment of barriers and incentives to IMTA adoption in the Canadian salmon aquaculture industry. Crampton (2016) interviewed Canadian aquaculture stakeholders from industry, government, and environmental non-governmental organizations to identify potential barriers and incentives to IMTA adoption. Stakeholder uncertainty and doubts related to IMTA's profitability, ecological viability and benefits, and technical viability and complexity in Canada were viewed as important factors limiting IMTA adoption. Crampton's (2016) study also quoted one industry participant saying that the successful integration of benthic species into IMTA is likely critical to IMTA's adoption in the Canadian salmon farming industry. This quote helps to demonstrate the Canadian salmon farming industry's understanding of benthic loading associated with open net-pen salmon farming.

Overall, this study's DCF results highlight the costs that could be involved in a full-scale hatchery operation developed for the purposes of integrating benthic feeders into IMTA systems and the impact of those costs on overall IMTA profitability. Following this study's results and the qualitative concerns raised by Crampton (2016) related to IMTA generally and deposit-feeder IMTA-integration specifically, future research is recommended into alternative business models and echinoculture IMTA production systems that could help reduce the financial requirements of a suitable benthic species for IMTA integration in Canada.

3.6. Conclusion

The high vertical flux and localized distribution of particulate matter coming from fed finfish farms suggests that benthic-feeder integration into IMTA farms with a fed finfish component is a key factor for the technology's successful adoption in Canada (Crampton, 2016; Filgueira et al., 2017). My study aimed to examine the possibility of including *S. droebachiensis*, an echinoid found on the east and west coasts of Canada, in a three-species kelp, mussel and salmon IMTA farm. I made a series of assumptions based on existing literature and also made simplifying technological, biological, and operational assumptions for modelling purposes due to a dearth of related literature (James & Siikavuopio, 2015).

My results showed that three-species IMTA outperformed salmon monoculture in every scenario, and that four-species IMTA is less profitable than salmon monoculture if no IMTA-price premiums are obtained. I also found that three-species IMTA outperformed four-species IMTA in all tested scenarios. However, even if my results had demonstrated positive impacts on profitability for a four-species IMTA farm vis-à-vis NPV analysis, the requisite technological and biological modelling assumptions and the uncertainty associated with those assumptions could inhibit the adoption of four-species IMTA, just as it has been hypothesized to negatively impact three-species IMTA adoption in Canada (Dixit & Pindyck, 1994; Crampton, 2016).

Ultimately, IMTA must be profitable to be a viable alternative to traditional aquaculture practices. My study's findings suggest that the integration of green sea urchins with a hatchery component into three-species IMTA farms in Canada is not financially viable. My results suggest that IMTA researchers and potential investors looking at benthic-feeder integration with IMTA should be aware of the associated capital requirements, break-even production levels, requisite scale of operation, additional complexity, and ultimate revenue generating possibilities of benthic-feeder culture. Canada's federal and provincial regulators interested in promoting the adoption of IMTA for its biomitigative potential may benefit from ensuring enabling regulatory frameworks exist and considering the spatial scale of production required for organic and inorganic extractive species. Government officials may also want to consider subsidies to encourage IMTA-adoption, or taxing the environmental externalities associated with the benthic loading from fish farming operations.

Chapter 4.

Discussion and Policy Recommendations

4.1. Sustainable Aquaculture

Global aquaculture production has increased markedly over the past three decades and plays an important role in the provision of food and nutrients to a growing global population in a world of finite resources (FAO, 2012). Marine-based aquaculture has faced particular public scrutiny due to various potential environmental impacts of cage aquaculture in an open marine environment. These impacts include the overloading local marine ecosystems' carrying capacities; benthic loading; eutrophication; escapees, and disease and parasite transfer to wild stocks (Ridler et al., 2006; Ridler & Ridler, 2011; Alexander et al., 2016b). Canadian public criticism of ocean-based net-pen aquaculture, which is particularly focused on salmon farming, has been associated with concerns over the environmental impacts of net-pen aquaculture and the potential effect of these impacts to traditional industries and ways of life (Ridler et al., 2006; Liu & Sumaila, 2007; Weston, 2013). The adoption of more sustainable aquaculture methods is seen as an important step for the sustainable future growth of the global aquaculture industry. Sustainable aquaculture methodologies have also been shown to reduce opposition to aquaculture activities in Canada and improve perceptions of the industry (Ridler et al., 2006; Ridler et al., 2007a; Shuve et al., 2009; Troell et al., 2009). CCA and IMTA are two alternative approaches to aquaculture that are designed to address issues of ecological sustainability. The former employs an approach that separating aquaculture activities from the marine environment through various containment systems, and the latter employs an ecosystem-based approach to aquaculture (Chopin et al., 2001; Liu & Sumaila, 2007; Soto et al., 2008b; Boulet et al., 2010).

Researchers have used DCF to compare the financial performance of various CCA systems and monoculture salmon farms (Liu & Sumaila, 2007; Boulet et al., 2010; Wright & Arianpoo, 2010). Liu and Sumaila's (2007) comparison of an enclosed sea-bag CCA system and a net-pen salmon farm found that CCA was only profitable when CCA-produced salmon attained a price premium. Open net-pen salmon farms were found to be more profitable under the same operating conditions as sea-bag systems if environmental costs were not considered. Wright and Arianpoo (2010) found that a land-based recirculating aquaculture system (RAS) in British Columbia producing 100 and 1000 tonnes of Atlantic salmon could yield returns of CAD $335,275 and CAD $5,082,754, respectively, for capital investments of approximately CAD $1.8 million and CAD $11.8 million. Researchers at DFO also investigated the potential profitability of different CCA systems versus open net-pen salmon farming and determined that RAS was the only CCA technology likely to demonstrate positive financial results. After conducting a more detailed DCF analysis of RAS and salmon monoculture, the DFO authors suggest that net pens have a significant advantage in terms of capital costs (approximately CAD $5 million to RAS's estimated costs of $22.6 million) at a production volume of 2,500 tonnes per harvest. The financial performance of the RAS system was also seen as likely to be considerably more susceptible to market forces (Boulet et al., 2010). The discrepancies between Boulet et al.'s (2010) and Wright and Arianpoo's (2010) capital costs, taking into account the studies' scale of production, suggests there is uncertainty related to the total capital expenditure requirements and returns possible for RAS.

Alternatively, IMTA is intended to address nutrient loading from aquaculture operations and create synergies between co-cultured species, thereby improving the environmental and economic performance of aquaculture (Chopin et al., 2001; Ridler et al., 2007b). IMTA has also been shown to yield price premiums for shellfish and salmon in North American and European markets and improve public perceptions of aquaculture (Ridler et al., 2007a; Bunting, 2008; Shuve et al., 2009; AMB Marine and Coastal Research, 2012; Yip et al., 2017). Consumer attitudes toward IMTA in Europe and North America have also been shown to be generally positive (Ridler et al., 2007b; Alexander et al., 2016a). Additionally, various DCFs have shown that the NPV of IMTA investments can surpass those of traditional monocultures (Whitmarsh et al., 2006; Ridler et al., 2007b; Shi et al., 2013).[52] However, the authors of IMTA DCF studies have not put forth substantial discussion of the additional complexity inherent in an IMTA operation that would maximize ecosystem benefits, nor the impact of this increased complexity on investor decision-making and commercial-scale IMTA adoption (Chopin et al., 2001; Troell et al., 2009; Cranford et al., 2013; Reid et al., 2013; Crampton, 2016).

4.2. Comparing the financial performance of three-species IMTA, four-species IMTA, and salmon monoculture in Canada

Ridler et al.'s (2007b) NPV analysis of a hypothetical salmon, mussel, and kelp IMTA farm and a salmon monoculture farm was based in the Bay of Fundy, Canada, and is a seminal financial analysis of IMTA that is referenced throughout the body of IMTA literature. Ridler et al.'s (2007b) results showed that IMTA's NPV was 23.7% higher than salmon monoculture at a discount rate of 5% and a production scale ranging from approximately 3,270 to 4,900 tonnes.[53] Ridler et al. (2007b) also found that IMTA could help insulate Canadian salmon farmers from mass salmon mortality events and downturns in the market price of salmon. My study expanded on Ridler et al.'s (2007b) research by taking into account additional costs of technological complexity entailed in a three-species salmon, mussel, and kelp farm. I also provided greater detail on my assumptions and incorporated more real-world data into my analysis than Ridler et al. (2007b). In this way, my study attempts to help address the paucity of real-world data available in the existing base of IMTA investment appraisal literature (Ridler & Ridler, 2011).

[52] Whitmarsh et al. (2006) observed that a sustained price decline in the market price of salmon of 2% per annum would result in a negative NPV for IMTA, highlighting the sensitivity of profits to salmon prices.

[53] Ridler et al. (2007b) estimate a harvest weight of 8-12 pounds salmon^{-1}, corresponding to harvest weights of 7,200,000 to 10,800,000 pounds. Their study assumed an initial stocking of 1,000,000 Atlantic salmon smolt and an assumed survival rate of 90% at harvest.

My study showed that a three-species salmon, mussel, and kelp IMTA farm has a higher NPV than a standard monoculture operation using the same discount rates as Ridler et al. (2007b). I found that the NPV of three-species IMTA with the inclusion of a 10% IMTA price premium on salmon and mussels is greater than salmon monoculture by $1.9 million at a 5% discount rate and $1.3 million at a 10% discount rate, and $8.4 million and $6.5 million greater at 5% and 10% discount rates. My sensitivity analyses examining a mass salmon mortality event also showed a higher NPV for three-species IMTA over salmon monoculture. The inclusion of a 10% IMTA price premium in the salmon mortality scenario resulted in three-species IMTA having an NPV 36.5% and 39% higher than salmon monoculture at 5% and 10% discount rates, respectively. My results suggest that IMTA operations incorporating salmon, mussels, and kelp on Canada's east coast are more profitable than traditional monoculture approaches to salmon farming, and considerably more profitable with a 10% IMTA-price premium on salmon and mussels.

More recent research into the nutrient plumes of fed finfish (e.g., Atlantic salmon) operations indicates that the distribution of particulate organic matter (POM) from fish farms is characterized by a high vertical flux and limited spatial distribution of large POM, which may limit the potential biomitigative role of filter-feeding shellfish in IMTA (Cranford et al., 2013; Lander et al., 2013; Cubillo et al., 2016; Filgueira et al., 2017). These recent studies reinforce the importance of investigating the potential role and financial implications of benthic feeders in an IMTA system (Chopin et al., 2012). However, there is a paucity of literature examining the financial implications of integrating benthic feeders into IMTA. To help address this research gap, my study took the revised three-species IMTA model from Chapter 2 and compared it with a hypothetical four-species salmon, mussel, kelp, and green sea urchin IMTA in Chapter 3 using the same DCF approach. The hypothetical four-species IMTA operation examined in Chapter 3 includes requisite capital and operational expenditures for the hypothetical green sea urchin hatchery, IMTA grow-out, and finishing diet culture phases, and necessarily entails a substantial degree of uncertainty due to the paucity of data and research related to commercial echinoid systems (James & Siikavuopio, 2015). I examined the NPV differentials between three-species and four-species IMTA under 2-year and 3-year green sea urchin production-cycle scenarios, both with and without a 10% price premium on IMTA salmon and mussels. I also conducted sensitivity analyses to examine the impact of increased complexity inherent in the four-species IMTA operation and associated break-even production levels.

My results showed that the NPV for four-species IMTA was lower than that of three-species IMTA in all tested scenarios, with three-species IMTA having an NPV ranging from $1.9 million to $2.45 million higher than four-species IMTA. The reduced NPV of my hypothetical four-species IMTA farm in eastern Canada is largely the result of small incremental revenues from green sea urchin production compared with the substantial capital costs involved in constructing an urchin hatchery and integrating the urchins into an IMTA system. I also found that the scale of green sea urchin culture required to break-even with the estimated capital costs of my study's base-case four-species IMTA hatchery (assuming capital costs remain unchanged with an increasing scale of operation) is 19 times greater than my study's assumed scale of operation in the base-case urchin price scenario and 30 times greater in the high urchin price scenario. These DCF results and subsequent sensitivity analyses suggest that the integration of green sea urchins into IMTA systems may entail a substantial capital investment and, absent sufficient revenue generation and/or scale of operation, green sea urchin IMTA-integration is unlikely to be pursued by investors at this time.

I only came across one financial analysis of IMTA that incorporated a sea urchin component (Bunting & Shpigel, 2009). This study used bioeconomic modelling to examine the broader implications of land-based horizontal marine aquaculture in temperate and warm-water settings. Their warm-water model examined the implications of integrating sea urchin (*Paracentrotus lividus*), shrimp (*Paeneus semisulcatus*), and seaweed (*Salicornia* spp.) culture with a constructed wetland near Eilat, Israel. This warm-water IMTA bioeconomic model was informed by industry data provided by small and medium enterprises, similar to my study.

Bunting & Shpigel's (2009) warm-water IMTA prototype model assumed annual harvests of 1,000,000 sea urchins stocked at 350 urchins m^{-2} with a survival rate of 85%. Sea urchins were assumed to reach a harvest weight of 44 g $urchin^{-1}$, amounting to a 50 tonne total annual sea urchin harvest with revenues of €1,037,550. Comparatively, my study assumed bi-annual harvests of 74,308 urchins at a total harvest weight of 3,645 tonnes and an average weight of 49.1 g $urchin^{-1}$, with revenues of €7,374 in the base-case four-species IMTA scenario. Bunting & Shpigel's (2009) base-line scenario assumed total capital costs of €1.95 million for the warm-water land-based IMTA operation compared to my study's assumed green sea urchin IMTA capital costs of €1.26 million, but with a substantially higher volume of sea urchin production.[54] Unfortunately, Bunting & Shpigel (2009) did not include a cost per urchin seed produced in their study, which prevented a more direct comparison of their commercial-scale prototype IMTA model with my own. Bunting & Shpigel's (2009) base-line scenario also assumed operating costs of €900,720, including labour costs of €82,500, feed costs of €243,500, and electricity costs of €163,400. These operating costs are substantially higher than my study's sea urchin operation, which assumed average annual labour costs of €110,098, feed costs of €60, and electricity costs of €3,572.

Overall, Bunting & Shpigel's (2009) land-based warm-water three-species IMTA operation earned an NPV of €949,879 at a 5% discount rate and €459,090 at a 10% discount rate compared with my study's NPV of €27 million and €19.5 million at 5% and 10% discount rates. My study's base-case NPV is substantially higher than Bunting & Shpigel's (2009) land-based IMTA operation and reflects the high value of farmed Atlantic salmon included in my IMTA-operation. Additionally, my study found that the integration of green sea urchins into a four-species salmon, mussel, kelp, and urchin IMTA operation resulted in a lower NPV than a comparable three-species salmon, mussel and kelp IMTA operation. Taken alongside my study's results, this brief comparative analysis suggests that the commercial scale of Bunting & Shpigel's (2009) urchin,

[54] For comparison purposes, I used Google's currency conversion tool to adjust my study's costs into euros using a July 28, 2017 exchange rate of 1 euro to 0.85 US dollars.

shrimp, and seaweed IMTA operation resulted in economies of scale for sea urchin production and a positive NPV using discount rates of 5% and 10%. Identifying the break-even green sea urchin production level required to improve the NPV of four-species IMTA as presented in this study remains a challenge for future research.

Taken together, the results of Chapters 2 and 3 indicate that investors could benefit from higher net returns if they invest in a three-species salmon, mussel, and kelp IMTA farm, but the integration of a green sea urchin component with the three-species farm should be avoided based on negative impacts to NPV.[55] Academic research has also highlighted the possibility of attaining a price premium for IMTA mussels and salmon, which my study has shown can substantially increase the NPV for a three-species salmon, mussel, and kelp farm investment, and that IMTA can improve public perceptions of aquaculture. However, there continues to be a lack of commercial investment in IMTA in Canada that warrants investigation.

Crampton (2016) interviewed Canadian aquaculture industry stakeholders in the private, public, and academic realm and identified continued technological, ecological, and financial uncertainty as important considerations for potential IMTA investors. Crampton's (2016) results align with my study's stated uncertainty in the assumptions used to model a hypothetical integration of green sea urchins into an existing IMTA operation. However, setting aside that uncertainty, the financial results of my three-species and four-species comparative DCF alone are enough to dampen investor appetite. But what about the positive net returns demonstrated by my results from Chapter 2, as well as in other pieces of academic literature? Why, as Crampton (2016) asked, does there continue to be a lack of IMTA adoption? An alternate investment appraisal technique known as real options analysis (ROA) provides some possible clues.

[55] One potential option to help reduce green sea urchin culture costs could be to ranch the juvenile urchins instead of suspending them in SeaNest cages by long-line. However, additional research into sea ranching is likely required given investor doubts related to the viability of ranching sea urchins (Brown et al., 2013; James et al., 2017).

ROA posits that investors are wary of uncertainty, and observes that investors may find substantial value in waiting for additional information, a change in economic, political, or social circumstances, etc., prior to making an investment decision. This is because once an investor has exercised their option to invest, that capital is expended and the investment may be difficult to undo, whether in whole or in part. Essentially, the investor loses a future opportunity to invest based on more information (Dixit & Pindyck, 1994). A traditional DCF and NPV analysis, such as those employed in this study and by Ridler et al. (2007b), does not account for this uncertainty. Because NPV analyses implicitly assume that decisions are either wholly reversible or they are a “now-or-never” investment decision, traditional investment appraisal techniques may overestimate the financial benefits for potential IMTA investors. Crampton’s (2016) qualitative research highlighted some of the uncertainty of Canadian IMTA stakeholders regarding the commercial viability of IMTA operations. Given the multiple NPV analyses suggesting that IMTA is more profitable than monoculture operations, it is possible that uncertainty associated with IMTA’s technical, ecological, and financial feasibility may outweigh the positive results of NPV analyses presented by academics over the past decade in the minds of potential investors (Whitmarsh et al., 2006; Ridler et al., 2007b; Shi et al., 2013).

Beyond uncertainty, however, there may be other business considerations at play. First, consider that farmed Atlantic salmon is a standard commodity with an existing market (Marine Harvest, 2012). Canada’s monoculture salmon operators can sell their product and be relatively sure of their returns. Second, Canada’s salmon farmers have likely already acquired the necessary capital and technical know-how required to operate a successful aquaculture operation. Although three-species salmon, mussel, and kelp IMTA farms have been shown to increase the NPV of aquaculture investments in Canada when compared with salmon monoculture, research also tells us that obtaining an IMTA price premium – a key component to substantially increased net profits according to this study’s results – will possibly require eco-certification and likely require a focused marketing and education campaign for consumers, buyers, and farmers (Bunting, 2008; Shuve et al., 2009; AMB Marine and Coastal Research, 2012; Crampton, 2016). The increased costs and complexity associated with this marketing effort, potential costs involved in opening up and reaching new markets, as well as additional training for staff, present a series of unknowns and additional costs for existing salmon farmers who already earn a healthy return on their salmon monoculture investments. Considering that salmon sales account for 93% of total IMTA revenues in both three-species and four-species IMTA operations examined in this study, an investor with existing expertise in salmon farming may not see the value in pursuing IMTA when the bulk of IMTA profits will come from salmon sales. Similar arguments could also be made regarding CCA adoption by aquaculture investors, although it is possible that a higher public awareness of CCA and CCA's ability to address more environmental concerns than IMTA (Yip et al., 2017), may be factors that have influenced current levels of CCA investment in Canada, even though capital cost requirements for CCA are higher than both IMTA and conventional net-pen salmon farms and government and industry stakeholders view IMTA as a more profitable sustainable aquaculture technology.

Keeping with the findings of Crampton (2016), I suggest that governments that wanting to incent IMTA adoption consider policies that encourage investment by reducing uncertainty. For example, nutrient taxes have been suggested as a possible policy lever by industry stakeholders and academic researchers and may warrant closer examination (Nobre et al., 2010; Crampton, 2016). Such a policy could have the dual benefit of applying to agricultural runoff, which is another contributing factor to the eutrophication of marine ecosystems (Neori et al., 2004). Future studies looking at the financial benefits of IMTA should also consider the spatial scale required to achieve ecosystem-wide environmental benefits (Soto et al., 2008b). The IMTA configuration used for this study is not optimized for maximal biomitigative effects due to tensions between the practical scale of IMTA required to achieve maximum biomitigative benefits of IMTA at a site-level for both kelp and mussels (Reid et al., 2013; Cranford et al., 2013). Therefore, if policymakers want to leverage IMTA to improve the environmental performance of aquaculture operations, ecosystem and bay-management approaches to aquaculture regulation should be considered.

This study also entails significant uncertainty related to the capital and operational expenditures and requirements of green sea urchin culture. Given the purported negative impact of investor uncertainty on IMTA adoption, future research should aim to reduce the uncertainty associated with benthic feeder integration into IMTA systems. Future research is required to determine financially and operationally viable benthic-feeder culture systems and related engineering and operational requirements for successful benthic-feeder IMTA integration. Research is also required to understand the effectiveness of various benthic feeders at reducing benthic loading below fed finfish cages in a commercial, real-world operating environment, which was a noted limitation of this study; hypothetical assumptions regarding the ability of benthic feeders to intercept, ingest, and convert waste POM into marketable biomass is likely insufficient to stimulate commercial investment, particularly in the context of my study's NPV analysis of four-species IMTA. This research may be even more important in the Canadian context given the high percentage of total IMTA revenues found to come from salmon sales versus the complementary IMTA organisms included in this study and recent study results that suggest the filter-feeding shellfish component of IMTA is unlikely to significantly reduce benthic loading (Cranford et al., 2013; Cubillo et al., 2016; Filgueira et al., 2017).

Overall, my study's results, comprehensive literature review of academic, industry, government, and private studies, and conversations with industry professionals from government, industry, and academia, indicate that potential IMTA investors in Canada will not invest in the integration of green sea urchins into an IMTA operation of salmon, mussels, and kelp. This conclusion is derived from this study's observed lower NPV associated with four-species IMTA culture compared with three-species IMTA, as well as the uncertainty associated with my hypothetical green sea urchin hatchery, IMTA grow-out, and finishing culture operation. Further, an analysis of ROA theory and Crampton's (2016) recent interviews with Canadian aquaculture stakeholders suggests that three-species IMTA as described in this study has seen limited investment in Canada because of real or perceived technological, ecological, and financial uncertainty associated with IMTA production.

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Appendix A
Green Sea Urchin Echinoculture Model

This appendix reviews the technical and financial assumptions used to create this study's hypothetical green sea urchin hatchery and IMTA operation. Technical and biological production parameters are outlined first, followed by human resources assumptions, and capital costs and equipment listings.

This study's hatchery design is based on the Japanese echinoid rearing method detailed by Hagen (1996). Some echinoculture assumptions, methods, and hatchery technologies were revised based on an evolving echinoculture and sea urchin research base. I also informed my sea urchin hatchery design by reviewing shellfish hatchery design and construction, which is similar to that which would be used in a sea urchin hatchery (Dr. Christopher Pearce, personal communication, April 12, 2017).[56] The hatchery design and echinoculture methodology was additionally informed through conversations with aquaculture researchers and industry professionals.

James and Siikavuopio (2015) noted that there is a dearth of literature related to optimal land-based containment and grow-out systems for juvenile green sea urchins. Accordingly, where academic or grey literature was found lacking, this study made use of personal commentaries from industry and research professionals with experience in sea urchin culture aquaculture.

Broodstock and Spawning

A licensed commercial diver will collect 20 adult green sea urchins from the wild as broodstock for the hatchery. The required amount of broodstock and green sea urchin seed are based on the maximum culture density of SeaNest cages (SeaNests), the total number of SeaNests able to be cultured in this hypothetical IMTA operation (see IMTA Grow-out section), the estimated size per urchin at harvest (49g), urchin mortality rates at each stage of green sea urchin culture, and estimated viable settled larvae per fertilized egg. Seed requirement parameters are summarized in Table A1 and broodstock and spawning production parameters are summarized in Table A2.

Each broodstock animal is assumed to weigh 90g, have a 50 mm test diameter (TD) at collection, and maintain a uniform weight throughout the 10-year project period (Pearce et al., 2002; Daggett et al., 2006). Male and female broodstock are held in 600 litre tanks at 6 kg urchin m^{-2} culture density with seawater filtered to 50 µm at a 3 L min-1 (Hagen and Siikavuopio, 2010; Siikavuopio and James, 2011; James and Siikavuopio, 2015; Terralynn Lander and Shawn Robinson, personal commentary, April 28, 2017). The broodstock are assumed to remain healthy over the course of the study period, with no

[56] Consult References section for the detailed list of the echinoculture and shellfish hatchery literature used to inform this study.

new broodstock required. The broodstock consume 3% of their body weight per day in *S. latissima* that is harvested by a farm labourer from the IMTA cultured kelp.

I assumed all broodstock to be held in the same tank for this study. However, separating and individually storing the broodstock urchins would be useful in the future to inform the selective breeding of urchins with the most desirable market characteristics (Shawn Robinson, personal commentary, April 28, 2017).

Broodstock can be conditioned for spawning within 8 to 10 weeks of collection (Pearce and Robinson, 2010). To induce spawning, male and female urchins are selected and individually injected with 1 ml of potassium chloride (KCl) per animal while inverted over a container. The KCl injection induces male and female gametes to be released by the urchins into the containers from. Gametes are then manually mixed for fertilization by a hatchery technician (Hagen, 1996). Because a single spawning can yield up to 2 or 3 million eggs, the hatchery technician will divide the fertilized eggs into two separate 1-litre containers filled with seawater filtered to 1 μm at a concentration of 1 per ml (Terralynn Lander, personal commentary, April 28, 2017). This study assumes 2 million fertilized eggs per urchin pairing and 10 broodstock pairings. The fertilized eggs are held in a fridge for a 24-hour period prior to being released into larval holding containers for the metamorphosis and settling period (Hagen, 1996; McBride, 2005; Terralynn Lander, personal communication, April 28, 2017).

Table A1: Seed Requirements

Item	Quantity	Source	Notes
Harvest weight of finished urchin (kg)	0.049		Based on 1% of body weight growth per day on Urchinomics feed fed at 5% bodyweight day-1
SeaNest Culture Density per Cage (kg)	10	B. Tsuyoshi, pers. comm., April 21, 2017	
Total Number of Urchin Cages	450		
Urchin Mortality (in gonad enhancement stage)	0.1	B. Tsuyoshi, pers. comm., April 21, 2017	

Item	Quantity	Source	Notes
Target number of urchins at harvest	91738		
Total required viable early juveniles	96566	Brown et al., 2013	95% survival of early juveniles to IMTA Grow-out stage. Transfer of juvenile urchins to IMTA Grow-out occurs at 7mm.
Total required seed	965661	Terralynn Lander, personal commentary, April 28, 2017	The denominator is based on a series of data points provided by Dr. Lander. See Appendix 1 in 'Appendices' for further detail. Chosen as a low survival point, but higher than that observed by Brown et al. (2012). Still less than the high 60-70% survival quoted by some Japanese researchers.

Table A2: Broodstock and Spawning Culture Parameters

Broodstock & Spawning	Quantity	Source (if required)	Notes
No. of urchins	20.00	S. Robinson, pers. comm., April 28, 2017)	Shawn Robinson said 20-30 would be more than enough for my initially assumed seed requirement of 7,500,000. The model was further refined and urchin seed requirements were lowered to 965,661. 20 broodstock, based on Dr. Robinson's personal commentary should be more than sufficient. I assume equal amounts of male and female urchins are harvested from the wild for the purposes of this model, however the sex of urchins is not truly known until spawning. I was unsuccessful in finding an average number of eggs produced per female *S. droebachiensis* in the literature.
Starting Weight (g)	90.00	Pearce et al., 2002	90.3g mean weight, rounded down to 90g.
Ending Weight (g)	90.00		I assume constant broodstock weight throughout *S. droebachiensis* culture
Daily Feed Req't per broodstock (g)	2.70	Pearce et al., 2002	Assuming between 2.6% and 3.5% of bodyweight is consumed per day per broodstock. I selected 3.0% as a middle of the road estimate.

Total daily feed requirements (g)	54		*S. latissima* harvested from the IMTA site.
Total annual feed requirements (g)	19710		*S. latissima* harvested from the IMTA site. 19.71 kg *S. latissima* required per year.
Max culture Density (kg/m^2)	6	Siikavuopio and James, 2011	
Total Possible Broodstock per m^2	66.67		Feeds into tank system & cost
Water temperature (˚C)	Ambient temperature	Pearce et al., 2002; 2005	
Water filtration (µm)	50	James and Siikavuopio, 2015	Feeds into the cost of water filters. McBride (2015) and Kirchoff et al. (2010) suggest 35 um filters for incoming seawater to urchin hatchery facility. I chose 50 µm to align with the requirements of the other stages of green sea urchin hatchery culture.
Water aeration/flow rate (L min-1)	3	James and Siikavuopio, 2015	The flow rate is based on early juvenile grow-out requirements
Lighting requirements	Ambient photoperiod	Daggett et al., 2006	
Survival Rate	100%		I assume culture conditions and technician oversight allow for 100% survival of broodstock.

Larvae Culture and Settlement

The fertilized eggs are held in filtered seawater held at a constant temperature of 9-13˚C and a stocking density of approximately 1000 larvae L^{-1}. Stocking density decreases to approximately 800 larvae L^{-1} due to natural larvae mortality toward the end of the larval rearing period (Hagen, 1996; Pearce, 2006; Chris Pearce, personal commentary, June 9, 2017). Larvae are cultured in one 1,703 L tank filled with 966 L of 50 µm-filtered seawater (Siikavuopio and James, 2011) flowing through at a rate of 3 L min^{-1} (James and Siikavuopio, 2015). Larvae are fed phytoplankton *Chaetoceros neogracile* (*C. gracilis*) at an average rate of 14,444 algal cells ml^{-1} per day (Hagen, 1996; Pearce, 2006; Pearce and Robinson, 2010). For more details on larvae feed, see the phytoplankton production section of this appendix. For a summary table of larval production parameters, see Table A4.

McEdward and Miner (2001) observe that planktonic feeding urchin larvae such as *S. droebachiensis* are on the order of 3.8 times greater in diameter at the outset of the juvenile stage than their initial egg size, with a relatively wide range of variability between species and organisms. This figure corresponds with the 250 μm to 900 μm size estimate for end-stage *S. droebachiensis* larvae provided by Dr. Christopher Pearce (personal commentary, May 8, 2017), as well as ranges noted by McBride (2005) and de Jong-Westman et al. (1995). Where, de Jong-Westman et al. (1995) confirmed that adult diet and conditioning impacts *S. droebachiensis* larval size and development, and due to the controlled nature of hatchery operations and the growing knowledge base of sea urchin and *S. droebachiensis* ecology, biology and market-oriented research, I assume that *S. droebachiensis* larvae reach an average 900 μm in size at time of larval transfer to early juvenile settlement and nursery culture.

Settlement is assumed to occur after 21 days of larval culture (McEdward and Miner, 2001; McBride, 2005). This assumption falls within the middle of Hagen's (1996) reported 16 to 30 day range for settlement due to the water temperature. 10% of the initial viable larvae are assumed to successfully settle and move onto the early-juvenile culture stage (see Table A3). This survival rate is lower than the 60-70% observed by some Japanese researchers, but slightly higher than the 5% survival rate observed by Brown et al. (2013).

Table A3: Average viable settled larvae per fertilized egg

		Fertilized Eggs		Notes:
		7000	8000	Teralynn Lander (personal commentary, April 28, 2017) quoted an average of 500 or 1000 viable settled larvae per 7000-8000 fertilized eggs in cultured containers.
Viable Larvae	500	7.14%	6.25%	
	1000	14.29%	12.50%	
Average viable settled larvae per fertilized egg:			10%	

Table A4: Larval Culture Parameters

Larval Rearing	Quantity	Source (if required)	Notes
Amount of viable larvae seed settled from broodstock spawning	965,661		See Table A1

Larval Rearing	Quantity	Source (if required)	Notes
Ending Test Diameter Size (mm)	0.90	C. Pearce, personal commentary, May 8, 2017	Competent larvae can range 250-900 microns.
Daily Larval Feed Req't in phytoplankton cells ml-1	5000	Hagen, 1996	See Table A5 for more detail
Total daily feed requirements (g)	0.93		See Table A5 for more detail
Total annual feed requirements (g)	19.55		See Table A5 for more detail
Total amount (L) Bioreactor phytoplankton drawn day-1	0.93		See Table A5 for more detail
Initial culture density at spawning (larvae/ml)	1.00	Siikavuopio & James, 2011	Optimal for larval *S. droebachiensis* culture
Total ml in 1 L	1000		Feeds into tank system & cost (see 'Echinoculture Equipment List')
Water temperature (˚C)	9 - 13	Pearce et al., 2005	
Water filtration rate (µm)	50	James & Siikavuopio, 2015	Feeds into water filters. # of Tanks/holding containers dictates # of filters. SABS uses no extra filtration for Broodstock at their facility, but seawater already filtered to 20 um for full facility.
Water aeration/flow rate (L min-1)	3	James & Siikavuopio, 2015	
Photoperiod	10:14	de Jong-Westman et al., 1995	Light:Dark
Survival Rate	0.10		See Table B3

Phytoplankton Production

The hatchery uses a 1000 L Industrial Plankton Automated Bioreactor™ (bioreactor) to reduce uncertainty associated with some forms of microalgae production and to reduce labour costs associated with phytoplankton production (Leask et al, 2008; Terralynn Lander & Shawn Robinson, personal communication, April 28, 2017).[57] This study made use of a proprietary costing spreadsheet provided by Industrial Plankton™ to calculate the cost and quantity of phytoplankton required for the hatchery operation, along with study estimates of algal cells required L^{-1} of larvae culture, larvae rearing tank volume (L), and daily water exchange rate based on an assumed flow-through rate measured in L min^{-1} (Helm & Bourne, 2004; Suppan, 2014). Maintenance costs for the bioreactor are included within the bioreactor's operating costs.

Chaetoceros neogracile (*C. gracilis*) is a favourable phytoplankton species for *S. droebachiensis* culture and was selected as the phytoplankton species of choice for this study (Hagen, 1996; Pearce, 2006; Pearce & Robinson, 2010). *S. droebachiensis* larvae are cultured at a density of approximately 1000 larvae L^{-1}, which is assumed to decrease to 800 larvae L^{-1} due to naturally occurring mortality amongst initial larvae seed (Pearce, 2006; Christopher Pearce, personal commentary, May 8, 2017). Total water volume in the larval rearing tank is 966 L, based on an initial density of approximately 1 larvae ml^{-1}, and an estimated 966,369 larvae required for a successful hatchery and urchin grow-out operation. The total number of larvae required for the hatchery is based on Brown et al.'s (2013) observed survival rates of competent larvae from their land-based culture operation of *S. droebachiensis*, where survival from competent larvae to juvenile urchin ready for was 4.9%,[58] the estimated size of adult urchins at harvest (49 g), and a culture density of 10 kg urchins per SeaNest (Brian Tsuyoshi, personal communication, April 21, 2017).[59]

S. droebachiensis larvae are estimated to require 5000 cells ml^{-1} in the early stages of larval culture, increasing to 33,333 cells ml^{-1} toward the end of the larval culture period (Hagen, 1996). Assuming a 21-day larval rearing period (McEdward & Miner, 2001), the model assumes *S. droebachiensis* larvae require 5000 cells ml^{-1} from days 1 to 14, and 33,333 cells ml^{-1} days 15 to 21, for an average algal density of 14,444 cells ml^{-1}. The initial background algal cells for the larval rearing tank was calculated using the average algal density converted to litres and the 966 L volume of the culture tank, divided by 21 to provide a daily average for the initial bioreactor drawdown. This estimate was added to the estimated algal cell replacement requirements for the larval rearing tank. The estimated daily algal cell replacement requirement for algal culture is based on a water

[57] This section is based on information provided by Ashley Roulston, Co-owner and Director of Sales and Operations, Industrial Plankton. Technical information on the Industrial Planton Automated Bioreactor™ can be obtained by contacting Industrial Plankton at www.IndustrialPlankton.com.

[58] Rounded up to 5% for simplification purposes.

[59] 10 kg per sea urchin cage is equal to 8.2 kg/m^{-2}. This conversion is based on the internal dimensions of the floor and four sides of the SeaNests.

flow rate of 3 L min^{-1} (4320 L day^{-1}). The average daily initial background algal cell requirement was added to the estimated daily algal cell replacement requirement for the larval rearing culture's total estimated daily phytoplankton requirement.

The bioreactor is capable of generating 82 billion cells of *C. gracilis* L^{-1} and holds a total volume of 1000 L of algal culture. Dividing the total estimated daily phytoplankton requirements of *S. droebachiensis* larval culture by the total *C. gracilis* cell count L^{-1} results in the total daily drawdown (L) of the bioreactor. These calculations equated to a total drawdown of 19.55 L of *C. gracilis* from the bioreactor per larval rearing period. A summary of phytoplankton production can be found in Table A5.

Table A5: Phytoplankton production summary

Initial Assumptions	
Total days of larval culture (w/phytoplankton)	21
Total number larvae	966,369
Feed rate algae cells/ml per day (Days 1-14)	5,000
Feed rate algae cells/ml per day (Days 15-21)	33,333
Average algal cell/ml feed rate per day	14,444
Total ml in larval culture tank	966,000
Initial algal cell Count required for larval rearing tank	
Volume (L) of tank	966
Algal cell density L^{-1}	14,444,000
Starting background algal cell requirement for volume of tank	13,952,904,000
Starting background algal cell requirement for volume of tank (average day^{-1})	664,424,000
Daily estimated replacement algal cell count required for larval rearing	
L $minute^{-1}$ flow-through	3
L $hour^{-1}$ flow-through	180
L day^{-1} flow-through exchange of larval rearing tank	4320
Daily required 'replacement' algal cells	62,398,080,000
Roll-up Estimates	
Total estimated phytoplankton cells required per day	76,350,984,000
C. gracilis algal cells produced L^{-1} by Industrial Plankton ™ Bioreactor	82,000,000,000
Required bioreactor volume (L) per day	0.93
Required bioreactor volume (L) per day as % of Bioreactor volume (L)	0.0009
Required bioreactor volume (L) over 21-day culture period	19.55

Total kg *C. gracilis* required per larvae rearing culture phase	0.06905183

The bioreactor requires CO_2, nutrients, and starter cultures of algae (a.k.a. master cultures) and an incoming and outgoing line for seawater. Assumed nutrient costs of USD \$27 kg algae^{-1}, CO_2 costs of USD \$1 kg^{-1} (Industrial Plankton, 2017), and electricity costs of USD \$0.039 kwh^{-1} result in bioreactor operating expenses of \$7.09 day^{-1} for larval rearing. Capital cost information can be found in the capital costs section of this appendix.

Early Juvenile Culture

Viable larvae are transferred to the nursery culture for settlement and metamorphosis at an average TD of 0.9 mm (Christopher Pearce, personal commentary, May 8, 2017).

Siikuvuopio and James (2011) examined the effect of stocking density on juvenile sea urchins and found that stocking densities of 0.25 and 0.5 kg urchin m^{-2} resulted in 100% survival rates at constant light (LD 24:0) and temperature (8.8˚C), whereas a stocking density of 1 kg urchin m^{-2} under the same conditions resulted in a mortality rate of 32.5%. This study conservatively assumes that early juveniles are cultured at 0.25 kg urchin m^{-2}, a constant photoperiod of 10:14 light/dark (Daggett et al., 2005), and observes Brown et al's (2013) 95% survival rate from early juvenile to nursery-stage juvenile urchins. See Table A7 for a full summary of early juvenile production parameters.

Juvenile urchins are cultured in two 908.5 L fibreglass troughs, with each trough holding 28 diatom settlement racks (see diatom culture section below). Seawater is filtered to 50 µm and has a flow rate of 3 L min-1 (James and Siikavuopio, 2015). Juvenile urchins are cultured and fed 2% of their body weight per day in *S. latissima* harvested from the IMTA site.

I use the logarithmic equation employed by Meidel and Scheibling (1999) to estimate the starting weight of 0.9 TD larvae (see Table A6).[60] The 0.9 mm TD juvenile urchins are assumed to weigh 0.00057 g urchin^{-1} at the start of nursery culture. Juveniles are transferred out at a mean TD of 0.7 mm and weigh 0.21 g. The early juveniles' ending weight is slightly higher than the 0.20 g that the Meidel and Scheibling equation would yield. This assumption was made to enable a clean 49-week early juvenile hatchery culture period.

[60] Meidel and Scheibling's (1999) equation was used to estimate the TD (mm) to weight (g) relationship in juvenile green sea urchins measuring 13 mm to 17 mm. I did not find an equation to represent the TD to weight relationship for juvenile urchins smaller than this size, which is a limitation of the study.

Table A6: Test Diameter to Weight Equation

ln(W) = -7.164 + 2.859*ln(D)	(W,g) (D,mm)
TD = mm	W = g
TD = 0.9mm	0.00057266
TD = 7mm	0.201766764
Meidel and Scheibling (1999)	

The equation in Table A6 was used to determine the week in which early juvenile urchins reach a 7 mm TD in the juvenile sea urchin growth and feed requirements calculation employed in the green sea urchin culture model.

95% of early juvenile urchins are assumed to survive and be transferred to Urchinomics urchin cages to be cultured by suspended long-line. Early juvenile mortalities were calculated at an average of 97 mortalities per week.

Table A7: Early Juvenile Culture Parameters

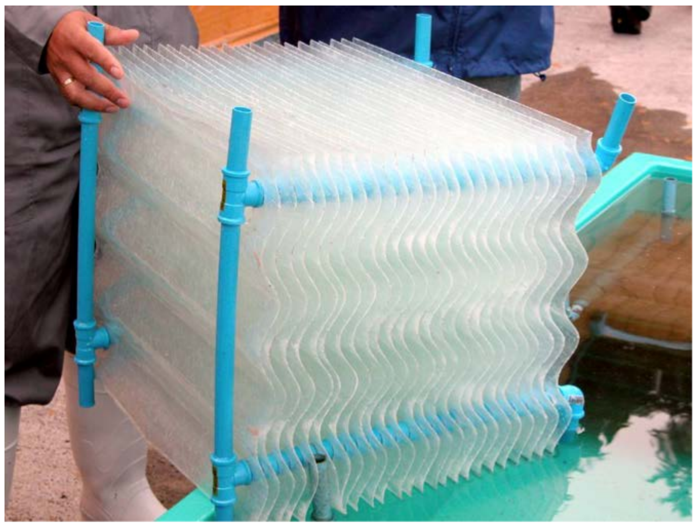
Early Juvenile Culture	Quantity	Source (if required)	Notes
No. of starting EJ	96,566	Brown et al., 2013	Viable settled larvae from larval rearing phase.
Starting TD (mm)	0.90	C. Pearce, personal commentary, May 8, 2017	
Starting weight (g)	0.0005727	Meidel & Scheibling, 1999	See Table B6
Ending TD (mm)	7.00		7mm chosen as a size large enough that urchins should not escape through initial 5mm mesh on the SeaNest cages
Ending Weight (g)	0.20	Meidel & Scheibling, 1999	Based on logarithmic equation in this paper: ln(W) = -7.164 + 2.859LN(D)

Early Juvenile Culture	Quantity	Source (if required)	Notes
Daily Feed Req't per nursery juvenile (% of bodyweight)	0.02	Pearce, 2006; Eddy et al., 2012	Juveniles are fed at 2% of body weight of *S. latissima* per day. No cost adjustments are made to the model to account for the first 8-12 days where larvae are assumed to subsist on larval reserves. *S. latissima* is assumed to be harvested from the IMTA operation at no additional cost, as labourers will be venturing out in the water to conduct regular maintenance and feeding at the IMTA site.
Max culture Density (kg/m^2)	0.25	Siikavuopio & James, 2011	
Total Possible Early Juvenile per m^2	1,239		Feeds into tank system & cost (see capital costs below)
Total required m^2 of req'd surface area	77.94		Informs requisite tank size and diatom collection.
Water temperature (˚C)	9 - 13	Pearce et al., 2005	
Water filtration rate (μm)	50	James & Siikavuopio, 2015	
Water aeration/flow rate (L min-1)	3	James & Siikavuopio, 2015	
Photoperiod	10:14	Dagget et al. 2005	10 light : 14 dark
Survival Rate	95%	Brown et al., 2013	

Diatom Culture

Diatoms are cultured using settlement racks constructed of 12" x 10" translucent corrugated PVC sheeting, assumed to be flat for the purposes of calculating surface area, which is cut from larger pieces of PVC sheeting (see Figure A1 for a visual approximation of diatom culture racks used in this study). These corrugated sheets are cut from 12' by 26" PVC sheeting. 24 'settlement sheets' obtained from one 12' by 26" sheet. The 12" x 10" sheets have 1/2" diameter holes drilled through each of their 4 corners. CPVC piping (1/2" diameter) is cut into 12" pieces, with 1 x 12" length inserted through the each of the corners of the 12" x 10" PVC sheets. This is repeated, sliding on more PVC sheets to the same 12" lengths of CPVC piping, leaving the sheets 1" apart to allow for the growth of early juveniles to their targeted 7mm size prior to the grow-out under salmon cage IMTA phase, with 10 pieces of 12" x 10" PVC sheeting per 1" x 12" CPVC length(s). This will give 120"^2 x 20 sides of PVC sheeting per 12" x 10" x 12" settlement rack. Keeping to a 12"^3 for ease of handling. Because the water level in the trough is assumed kept 10 inches below the top-lip, the surface area is equivalent to 10" x 12", or 120 square inches.

Figure A1: Sample of diatom culture settlement rack



Photograph courtesy of Christopher Pearce, Fisheries and Oceans Canada (2017)

The settlement racks are placed in sand filtered seawater in two 908.5 L troughs for three weeks where they collect a microbial film of diatoms. The racks are then moved into the early juvenile nursery trough where the larvae will settle on the settlement racks with the diatom film. I assume the trough holds 4 length-wise rows of 7 settlement racks. This corresponds with up to 56 settlement racks for diatom culture in the two troughs used for the early juvenile culture phase, which provides more than the requisite surface area for settlement. See the capital costs section of this appendix for a summary of diatom culture material requirements.

IMTA Grow-out

Hatchery employees induce juvenile urchins to release from the settlement racks by spraying the sides of the settlement racks when they reach 7 mm TD using the same KCl solution employed to induce broodstock spawning in spray bottles (Terralynn Lander and Shawn Robinson, April 28, 2017). The KCl solution causes the urchins to release, where upon they are collected and transferred to SeaNests. SeaNest specifications, courtesy of Vidar Mortensen (personal communication, August 2015), are provided in Table A8. Labour requirements are listed in the human resources section below.

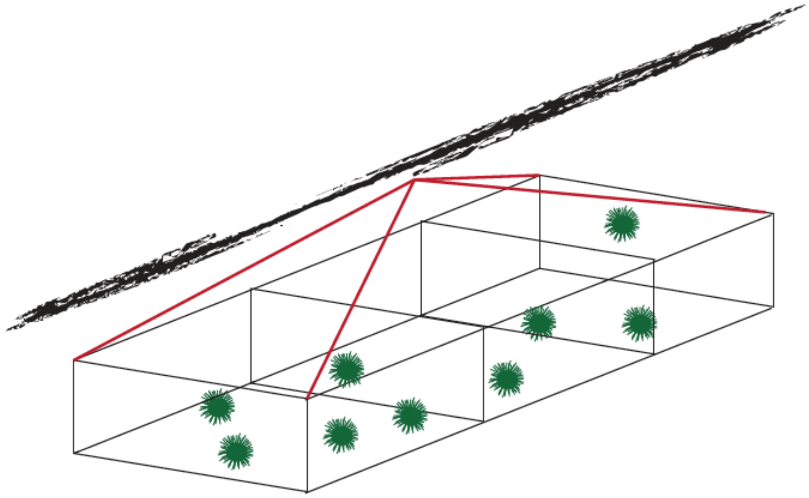
My study's hypothetical IMTA operation on Canada's east coast assumes that SeaNests are attached to a long-line by two Y-cables that connect each corner of the rectangular SeaNest cage to a center point above each cage.[61] The long-line is moored so that it runs directly below the salmon cages above. See Figures A2 and A3 for illustrative representations of this hypothetical integrated aquaculture design. The standard solid tops of SeaNest cages are exchanged for appropriately sized mesh netting that provides sea urchins access to the particulate organic matter (waste feed, salmon faeces, and naturally occurring seston) falling through the water column without escaping the enclosure (Vidar Mortensen, personal communication, August 22, 2015). Netting also surrounds the sides and bottom of the Urchinomics cages to prevent juvenile urchins from escaping at the earlier stages of IMTA culture. The netting is changed out at two separate points in the urchin production cycle to correspond with the urchins' somatic growth, enabling the urchins' to access larger POM as a feed source. The initial mesh size is 5mm, and is changed out to 12.7 mm part way through the grow-out phase.

Table A8: Urchinomics cage dimensions and netting requirements

Item	Quantity	Notes:
Inside Urchinomics Cage Dimension		
L*W (m^2)	0.7597	Arrange in single-chain
W*H (m^2)	0.1278	
H*L (m^2)	0.1926	
Total (m^2)	1.0801	
Total * 2 (reflecting 2 of each side)	2.1602	
Total estimated netting (square metres per cage)	2.2	
Total estimated netting (square feet per cage)	7.217848	

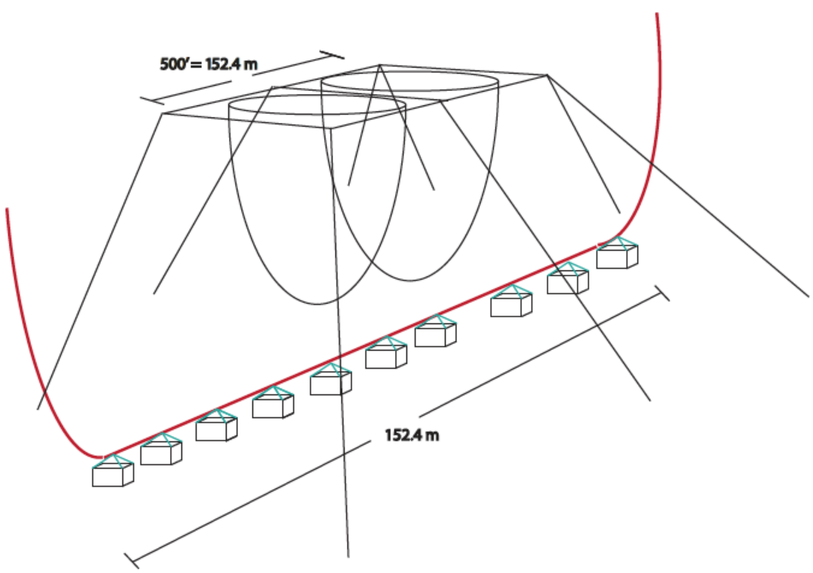
[61] Brian Tsuyoshi (personal commentary, April 21, 2017) noted that Japanese urchin farmers currently use stacks of five SeaNests stacked together to make their operation more efficient. I hypothesize that a stack of cages would inhibit IMTA-cultured urchins held in SeaNests lower in the stack (further away from the salmon cages) from intercepting sufficient POM from the water column, and hence limit urchin growth. I have therefore assumed a single row of cages by long-line, and not stacks of SeaNests as currently operated by Japanese urchin farmers.

Figure A2: Urchinomics urchin cage long-line Y-cable design



Not to scale.

Figure A3: Urchinomics urchin cage long-line integration with salmon cage grid-system



There are six long-lines strung underneath the 6 x 2 array of salmon cages. Not to scale.

IMTA urchins are co-cultured underneath the salmon cages for a period of 92 weeks over a 2-year production cycle in the base-case scenario, and 144 weeks over a 3-year production cycle in the alternate production scenario. I assume IMTA cultured green sea urchins reach a 40 mm TD and grow to an average somatic body weight of 43.5 g per urchin and a gonad index of 10% at the end of both 2-year and 3-year production scenarios grow-out period.[62,63] This size falls into the optimal range for green sea urchin gonad enhancement found by Pearce et al. (2004).

A detailed study of potential growth rates and concomitant end-weight and size estimate of green sea urchins in a salmon, mussel and kelp IMTA operation is beyond the scope of this study. However, due to the experimental and hypothetical nature of this study and the proposed IMTA system design, there was no available research to enable an accurate estimate of IMTA urchin grow-out rates or corresponding ending urchin TD or weight at this time. The observed paucity of such data is in keeping with James and Siikavuopio's (2015) noted dearth of literature on optimal land-based containment and grow-out systems for juvenile green sea urchins. Nonetheless, final TD and weight assumptions are necessary to inform the gonad enhancement grow-out calculation and ultimate value of the harvestable sea urchins.[64]

Table A9: IMTA Grow-out Culture Parameters

IMTA Grow-out	Quantity	Source (if required)	Notes
No. of urchins	91,738		
Starting Weight (g)	0.21		This starting weight is slightly higher than Meidel and Scheibling's (1999) logarithmic equation would suggest for a 7 mm urchin and reflects a 49-week juvenile nursery stage.
Ending Weight (g)	43.50		This is the mid-point in the 'large' sized urchin distribution observed by Brown et al. (2013). Assumed as attainable for IMTA-cultured *S. droebachiensis* over its base case grow-out cycle when cultured directly beneath salmon cages.
Daily Feed Req't per urchin (g)	-		Assuming *S. droebachiensis* is able to convert salmon feces and waste feed at a sufficient rate to reach 43.5 g urchin^{-1} at end of co-culture period.

[62] Gonad Weight/Somatic Body Weight = Gonad Index

[63] 43.5 g is the mid point between Brown et al.'s (2013) observed weight range of 28-61 g in 'large' *S. droebachiensis*.

[64] Christopher Pearce verified the ending TD and weight assumptions of IMTA grow-out green sea urchins on June 9, 2017.

IMTA Grow-out	Quantity	Source (if required)	Notes
IMTA Grow-out mortality (%)	0.10	Christopher Pearce, personal communication, June 9, 2017	
Total no. of urchins at end of Grow-out phase	82,564		Total # of urchins going into Finishing Diet (see 'Growth and Feed Consumption')
Max Culture Density (kg/m^2)	10.00	Siikavuopio & James, 2011	Optimal for adult *S. droebachiensis* culture
Total Possible urchins per m^2	48,651		Calculated using weight of juvenile urchins at start of IMTA grow-out culture phase. Urchins will be later separated into different cages and appropriate densities at weekly cleanings.
Survival Rate	0.90	Christopher Pearce, personal communication, June 9, 2017	

Labour associated with the IMTA Grow-out phase is detailed in the human resources section below.

Gonad Enhancement

Roe enhancement refers to increasing the marketable qualities of the sea urchin gonad (e.g., colour, taste, size, texture) (James et al., 2017). A finishing diet for roe (gonad) enhancement is necessary to bring the sea urchin roe to desirable colour, texture and taste for market (Hooper, 2001; Pearce et al., 2002, 2004).

For this phase, the green sea urchins in the Urchinomics urchin cages and long-line are moved away from the 2 x 6 salmon cage grid and are fed a finishing diet of Urchinomics Urchin Feed for a period of 12-weeks at the end of the IMTA Grow-out period.

Green sea urchins can be cultured at a density of 10 kg per sea nest cage (B. Tsuyoshi, Pers. Comm., April 21, 2017). This works out to a density of 8.2 kg/m^2, which is higher than some researcher recommendations (6 kg/m^2) but lower than the 16.3 kg/m^2 observed by Brown et al. (2013).[65] The estimated final weight of adult urchins at the end of the

[65] Assuming the 4 sides and bottom of the SeaNest cage are available to sea urchin culture.

gonad enhancement phase was used along with the stocking density of 10 kg urchins per SeaNest to estimated the total possible harvestable quantity of urchins and seed requirements (see Table A1).

Adult green sea urchins beginning the gonad enhancement culture phase at 43.5 g $urchin^{-1}$ are fed the Urchinomics (Nofima) sea urchin feed at a rate of 0.5% of bodyweight per day. Urchinomics Urchin Feed is specially designed for roe-enhancement and has been used extensively by researchers but seen relatively few commercial applications to date (James et al., 2017). Commercial and research activity using the Urchinomics Urchin Feed, originally formulated at Nofima, is currently being undertaken by Urchinomics, with research and commercial activity ongoing in Canada, Norway, and Japan (B. Tsuyoshi, personal commentary, April 21, 2017).

The gonad index is calculated as [(wet gonad weight/weight of whole urchin) x 100] (McBride, 2015). Urchins grow from an initial weight of 43.5 g and gonad index of 10% to a final weight of 49.1 g and 22% gonad index at harvest. A full list of gonad enhancement culture parameters can be seen in Table A10.

Table A10: Gonad Enhancement Culture Phase

Gonad Enhancement	Quantity	Source (if required)	Notes
No. of urchins	82,564		
Urchins per cage (kg)	10.00	B. Tsuyoshi, pers. comm., April 21, 2017	Based on Urchinomics SeaNest system measurements, this equates to 8.2kg urchins/m^2.
Starting Weight (g)	43.50	Brown et al., 2013	43.5 g is the mid-point in the size distribution of 'large' adult sea urchins sampled by Brown et al. (2013).
Ending Weight (g)	49.05		See 'Growth and Feed Consumption'
Daily Feed Req't per urchin (% of body weight)	0.05	B. Tsuyoshi, pers. comm., April 21, 2017; Christopher Pearce, pers. comm., May 8, 2017	Urchins consume between 0.5 and 1% of bodyweight consumer per day. I selected 0.5%.

Gonad Enhancement	Quantity	Source (if required)	Notes
Total feed requirements per harvest (kg)	1,518.55		
Starting Gonad Index	0.10		
Starting gonad weight (g)	4.35		
Ending Gonad Index	0.22		
Ending Gonad Weight	10.72		
Total live weight of *S. droebachiensis* at harvest	3645		

Human Resources

A hatchery manager is responsible for the overall management and production of the hatchery and supervises the hatchery technicians during the course of daily hatchery operations. The hatchery manager also acts as lead hatchery technician. Hatchery maintenance and culture husbandry are assumed to be included in the regular tasks of hatchery employees.

Requisite hatchery employee hiring and training, as well as hatchery organization and set-up, is assumed to take place during the first year of this study's 10-year project life cycle during facility construction. Training and hatchery setup assumes the hatchery manager and 1.5 hatchery technicians are employed for 25% of the first year of the 10-year project's operation in both two-year and three-year production cycle scenarios. Hatchery operations require one full-time hatchery manager and one full-time and one half-time hatchery technicians from years two through nine in the two-year production cycle scenario. Hatchery labour requirements are the same for the three-year production cycle scenario except for years four and seven, where the half-time hatchery technician is not required due to a longer wait time separating sea urchin harvests, and year ten, when only the lead hatchery technician maintains employment at the hatchery.

This study's hypothetical green sea urchin model assumes two additional full-time farm labourers working from years three through ten. Their tasks include deploying, maintaining, and harvesting green sea urchins. Hatchery employee and farm labourer salaries are listed in Table A11, adjusted from 2016 Canadian dollars. Lead hatchery technician and hatchery technician salaries were derived from most reported salary levels for Canadian hatchery employees on Indeed.com. Farm labourer salaries are based on east coast salmon farm labour rates (Michael Szemerda, personal commentary, January 16, 2016). Hatchery technicians and farm labourer wages were quoted in hourly wages and calculated on an hourly basis, with full-time work calculated as 37.5 hours of work, 5 days per week, 52 weeks a year. The hatchery manager is paid an annual salary.

I assume that all hatchery employees and aquaculture farm labourers practice correct handling procedures when working with the green sea urchins, as handling stress has been linked to lower urchin survival rates (Dale et al., 2005; Daggett et al., 2006; Brown et al., 2013).

Table A11: Salary and hourly wage listing

Position	Salary/Hourly Wage Rate
Hatchery Manager	$46,517
Hatchery Technician	$15
Farm Labourer	$12.80

Hatchery Facility Design and Construction

The study assumes one year for construction and design of hatchery facility and associated infrastructure and that the property is serviced with requisite access roads, utilities, and boat-launch facilities. All green sea urchin hatchery and grow-out operation assumptions in terms of scale and equipment flow from an assumed final culturing density of 10 kg urchins per SeaNest cage, or 8.2 kg/m^2 (Brian Tsuyoshi, personal communication, April 21, 2017).[66] Because this is a developing area of research and practice, future research and real-world experimentation should be able to augment future sea urchin hatchery design and production parameters. A full hatchery equipment listing and price schedule is included in the capital and operating costs section below.

Hatchery land costs are based on a purchased piece of shoreline property identified through a combination of Service New Brunswick's Property Assessment Online and GeoNB mapping and land registry tools. Three serviced shoreline properties of a suitable size in New Brunswick's Bay of Fundy area were identified as potential sites for the hypothetical aquaculture operation; one property in each of Back Bay, Letang, and Saint George. The site locations were selected based on their proximity to existing aquaculture lease sites, relative isolation from other properties, and the industrial characteristics of the sites themselves. After discussions with Service New Brunswick mapping professionals, the Saint George location was deemed to be too small for hatchery purposes. The Letang location was 6.9 hectares and had a 2016 assessed value of CAN $54,300. The Back Bay location had an assessed size of 7 acres and 2016 assessed value of CAN $52,700. These listed prices reflect the selling price of the pieces of property at their time of property

[66] Equal to approximately 8.2 kg m^{-2} according to the technical specifications of the SeaNest cage.

registration. Based on these land values, I assumed a conservative land value estimate of CAD $55,000 converted to 2016 USD. Hatchery land costs are independent of marine-based aquaculture lease site costs required for ocean-based farming in New Brunswick.

The hatchery is designed as a flow-through seawater system. Flow-through seawater systems have been shown to help increase larval production with smaller tanks and less floor space in oyster hatcheries (Supan, 2014). Hatchery space requirements will vary based on the species being cultured, associated equipment and workspace requirements, and choice of design (Helm and Bourne, 2004). For example, vertically stacking early juvenile culture tanks could reduce space requirements and associated construction and heating and cooling costs. However, this study did not assume stacked culture tanks due to the relatively small scale of the hatchery. Figure A4 provides an overhead layout of this study's hypothetical hatchery design, and Table A12 provides a list of the different sections of the hatchery with associated square footage estimates.

Figure A4: Green Sea Urchin Hatchery Overhead Layout

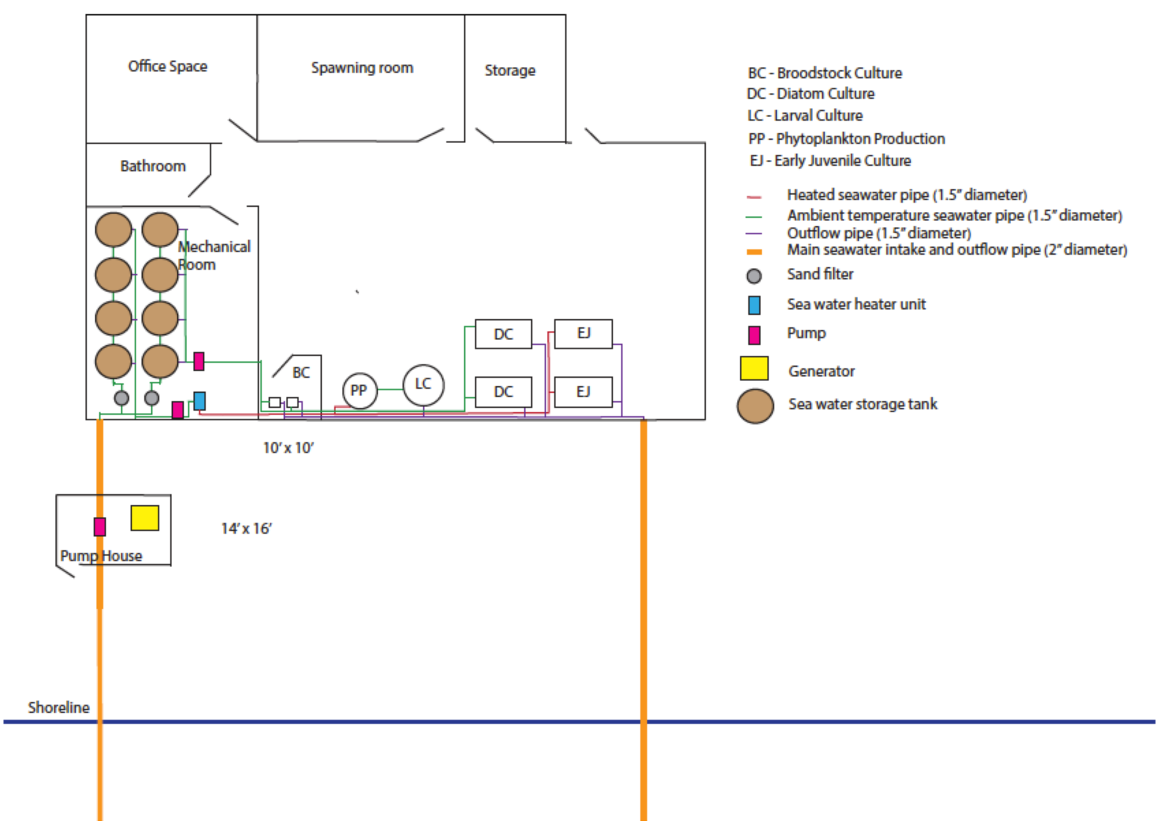


Table A12: Hatchery square footage estimates

Hatchery Facility Construction	Square Feet
Broodstock Culture Room	100
Mechanical Room	750
Bathroom	180
Office Space	432
Spawning Room	540
Storage	252
Main hatchery floor space	2,490
Pumphouse	224
Total:	4,968

Because green sea urchin broodstock rearing requires a different photoperiod than larvae or early juvenile culture, the hatchery requires a separate broodstock room (de Jong-Westman et al., 1995; Daggett et al., 2005; Daggett et al., 2006). Broodstock spawning activities are undertaken in a separate spawning room. Office space is used for hatchery and overall IMTA office and administrative tasks. The mechanical room holds important electrical and mechanical controls for the hatchery, such as seawater pumps, a diesel generator, and a seawater heater. Seawater storage tanks were included in the mechanical room as a simplifying assumption for this study, but a separate facility may be required to isolate seawater tanks for safety purposes (Helm and Bourne, 2004). This modification would likely increase construction costs. Hatchery storage space and the large main hatchery floor space is assumed sufficiently large to account for the activity that will take place inside the hatchery to prepare and transfer early juvenile urchins into Urchinomics urchin cages for the final IMTA grow-out and gonad enhancement culture phases.

There is a separate pump house from the main hatchery facility outfitted with a generator and two 146’ seawater intake lines to protect seawater supply in the event that one intake line malfunctions (Christopher Pearce, personal commentary, June 9, 2017). One 50’ seawater outflow pipe carries seawater out of the hatchery to the high water mark (Christopher Pearce, personal commentary, June 9, 2017). Both the main seawater intake and outflow lines are in 2” diameter HDPE pipe lengths (Helm and Bourne, 2004). Incoming seawater runs through the seawater storage tanks, is heated or maintained at ambient temperature, depending on the phase of hatchery culture, and flows into and out of broodstock, larval, diatom, and early juvenile culture tanks via 1.5” diameter HDPE piping (Helm and Bourne, 2004).

Seawater is pumped through two sand filters and into the hatchery’s seawater storage tanks, reducing most detritus greater than 20 to 40 μm (Helm and Bourne, 2004). Seawater storage requirements are based on two days worth of the hatchery’s total seawater requirements and summarized in Table B13. Prior to entering any urchin or larval holding or culture units, sand-filtered seawater is run through 50 µm banjo filters attached to incoming seawater pipes (James and Siikavuopio, 2015). Aeration of urchin holding tanks is assumed to occur vis-à-vis the seawater in-flow pipe's natural disturbance of the different tanks used throughout the culture process (Supan, 2014).

Table A13: Seawater storage requirements

Seawater Storage Requirements	Flow rate (L min-1)	Flow rate (L hour-1)	Flow rate (gallons hour-1)
Broodstock Culture	3	180	48
Larval Culture	3	180	48
Early Juvenile Culture	3	180	48
Diatom Culture	3	180	48
Maximum water flow through rate	12	720	190
Total Daily Requirements	-	17,280	4,565
Total Storage Requirements (Required # 1,200 gallon storage tanks)		8	8

Capital and Operating Expenses

All capital and operating costs are in 2016 real US dollars and rounded to the nearest dollar. Where costs were received from Canadian suppliers or literature sources, costs were first converted into 2016 Canadian dollars using the Bank of Canada's online inflation calculator tool and then converted into US dollars.[67]

I add a 15% capital contingency to the final value of land, hatchery construction, and hatchery equipment costs to account for unexpected capital requirements, as well as smaller items, such as the KCl solution used for spawning, which would have been too cumbersome to individually cost out for this particular study. This is based off of capital contingency assumptions that Boulet et al. (2010) used for the RAS system examined in their NPV analysis comparing a land-based RAS and a net-pen Atlantic salmon operation. This assumed capital contingency value is higher than the 10% capital contingency applied to the hypothetical net-pen Atlantic salmon farm, but lower than the 20% applied to the RAS operation by Boulet et al. (2010); the higher capital contingency requirement for RAS reflected the system's increased operational complexity. I took the

[67] Leask et al.'s (2008) construction costs were converted into 2016 Canadian dollars using Statistics Canada's (2017) price indexes of non-residential building construction, by class of structure, rather than a standard inflation calculation.

midpoint between these two capital contingency values to reflect the more technical operational requirements of a sea urchin hatchery, which are expected to be higher than net-pen salmon monoculture but lower than a RAS.

Construction costs of $211 per square foot were based on the construction cost per square foot used by Leask et al. (2008) in their discussion paper examining the feasibility of a shared shellfish hatchery in British Columbia. Construction and land costs are summarized in Table A14.

Table A14: Hatchery construction and land costs

Hatchery Facility Construction	Square Feet	Cost
Broodstock Culture Room	100	$21,101
Mechanical Room	750	$158,255
Bathroom	180	$37,981
Office Space	432	$91,155
Spawning Room	540	$113,944
Storage	252	$53,174
Main hatchery floor space	2490	$525,408
Pumphouse	224	$47,266
Total Hatchery Construction:	4968	$1,048,283
Cost of land	7 acres	$41,531
Total Hatchery construction and land:		$1,089,814

The hatchery equipment used in the model is listed in Table A15. Where possible, prices were sourced from a digital copy of the PentAir Aquatic Ecosystems® 39th Edition Master Catalogue (2017), retrieved online at no cost. If required pieces of equipment (e.g., HDPE piping) were not available in the PAES catalogue, I searched through online stores and contacted suppliers to obtain quotes. Any hatchery equipment not listed in the hatchery equipment and cost table (Table A16) that is necessary for a successful hatchery operation is assumed covered by the 15% capital contingency.

Due to the proprietary data sources used to cost out cage mooring systems, mooring equipment costs are not broken out by piece of equipment (i.e., number of shackles, long-line cost per foot), and are instead provided as a single mooring system cost.

Table A16: Hatchery equipment capital cost list

	Model	Price	Quantity	Total Price	Source
Broodstock and Spawning					
Culture Tanks	RT16-B	$86	2	$171	Pentair AES Master Catalogue 2017
Seawater filter (intake and outtake pipes)	Banjo filter	$224	1	$224	McBride, S., 2015; Price retrieved from http://advancees.com /pricing/sediment-and-sub-micron-filters on April 28, 2017
1 litre beakers	GLB 1000	$12	50	$585	Pentair AES Master Catalogue 2017
Total Broodstock and Spawning Equipment Costs:				$980	
Larval Rearing					
Culture Tank (circular cone tank)	TCB450	$587	1	$587	Pentair AES Master Catalogue 2017
Larvae tank stand	STAND FOR TCB450	$1,364	1	$1,364	Pentair AES Master Catalogue 2017
Seawater filter (in/out)	Banjo filter	$224	1	$224	Price retrieved from http://advancees.com /pricing/sediment-and-sub-micron-filters on April 28, 2017
Industrial Plankton ™ Bioreactor	1000 L	$33,600	1	$33,600	Pentair AES Master Catalogue 2017
Total Larval Rearing Equipment Costs:				$35,775	
Diatom Culture					
Translucent corrugated PVC	Suntuf ® - Cor. Pc12 Feed.	$58	24	$1,392	Home Depot, 2017 retrieved from:

	Model	Price	Quantity	Total Price	Source
sheeting	Clear				https://www.homedepot.ca/en/home/p.cor-pc12--feet--clear.1000412014.html
PVC Tee (1/2")	Xirtec white PVC SCH40 1/2 in. socket x socket x socket tee	$2	448	$712	Rona, 2017 retrieved from: https://www.rona.ca/en/pvc-tee
CPVC piping (1/2" diameter x 10' length)	Bow Pumping Group: CPVC Pipe - 1/2 Inch x 10 Feet	$5	45	$231	Home Depot, 2017 retrieved from: https://www.homedepot.ca/en/home/p.cpvc-pipe---12-inch-x-10-feet.1000120793.html
Culture Tank (trough)	FT240L2	$625	2	$1,250	Pentair AES Master Catalogue 2017
Total Diatom Culture Costs:				$3,585	
Early Juvenile Culture					
Culture Tank (trough)	FT240L2	$625	2	$1,250	Pentair AES Master Catalogue 2017, Pg. 186
Seawater filter (in/out)	Banjo filter	$224	1	$224	Price retrieved from http://advancees.com/pricing/sediment-and-sub-micron-filters on April 28, 2017; 60 um from Supan, 2014
Total Early Juvenile Culture Equipment Costs:				$1,474	
IMTA Grow-out					

	Model	Price	Quantity	Total Price	Source
Urchinomics Urchin Cage	Urchinomics ™ Sea Urchin Cage	$125	450	$56,250	Brian Tsuyoshi, Personal Commentary, April 21
Long-line and mooring system	-	-	-	$15,195	Cooke Aquaculture, 2016
Cage netting	XN4700	$405	7	$2,836	Industrial Netting, retrieved from: http://www.industrialnetting.com/xn4700.html
Cage netting	XB1132	$1,119	2	$2,238	Industrial Netting, retrieved from: http://www.industrialnetting.com/xb1132.html
Total IMTA Grow-out Equipment Costs:				$76,518	
Finishing Diet					
Long-line and mooring system				$10,956	Cooke Aquaculture, 2016
Total Finishing Diet Equipment Costs:				$10,956	
Other Capital Requirements					
Seawater storage tank(s)	1,200 gallon polypro plastic water storage tank	$722	8	$5,780	Granite Environmental Store retrieved May 8, 2017 from: http://www.graniteenvironmentalstore.com/1200-Gallon-Polypro-Plastic-Water-Storage-Tank_p_1659.html
Seawater pumps	Sweetwater High-Efficiency	$677.29	3	$2,032	Pentair AES Master Catalogue 2017

	Model	Price	Quantity	Total Price	Source
	Pumps - SHE 2.9				
Seawater sand filter	Arias ™ 4000 sand filter (A-4000-80 AQ	$361.39	2	$723	Pentair AES Master Catalogue 2017
Generator system (back-up)	Mitsubishi Kato	$38,304	1	$38,304	Boulet et al., 2010
Water heat pump	Aqualogic DSHP-5	$2,329	1	$2,329	Pentair AES Master Catalogue 2017
Main seawater intake and outtake piping	2" nsf 125 psi PE pipe, cut to length	$1.39	342	$475	Keith Specialty Store, Retrieved May 6, 2017 from: https://keithspecialty.com/water.line.pe.htm; Christopher Pearce, personal commentary, June 9, 2017
Indoor hatchery piping	1 1/2" nsf 125 psi PE pipe, cut to length	$0.85	484	$411	Keith Specialty Store, Retrieved May 6, 2017 from: https://keithspecialty.com/water.line.pe.htm
Overhead Industrial Lighting	Lithonia Flush-Mount Ceiling White LED Wraparound Light	$113	187	$21,040	Home Depot, Retrieved on June 1, 2017 from https://www.homedepot.ca/en/home/p.48-inch-led-wraparound.1000721879.html
Total Other Capital Equipment Requirements:				$71,094	
Total Capital Equipment Expenditure				$200,383	

	Model	Price	Quantity	Total Price	Source
Requirements:					

Operating costs accounted for in the urchin hatchery model are (i) hatchery employee and farm labour (detailed above), (ii) Urchinomics Urchin Feed, and (iii) electricity. Administrative costs, including items such as accounting services, marketing, janitorial expenses and management fees are incorporated into the 4-species IMTA model outlined in Chapter 3 of this report. Administrative costs are assessed at a cost of CAD $0.21 per kg live weight salmon harvested. I assume that administrative costs are shared across all IMTA species in the hypothetical farm, leading to cost sharing of administrative costs across four aquaculture products.

Electricity costs were calculated using New Brunswick Power's (2016) usage rate for large industrial service companies of CAD 5.2 cents kwh^{-1}, converted to US dollars. This rate was multiplied by total estimated electricity requirements per piece of energy-consuming equipment to provide an annual cost of electricity for the hatchery. Annual electricity costs were calculated at $4,201 and are assumed unchanged in all production scenarios and sensitivity analyses.

Urchinomics urchin feed, assuming North American feed production costs are similar to Japan's, costs $7 kg^{-1}. Urchinomics feed costs are only incurred in years that urchins are harvested. This is years 4, 6, 8 and 10 in the two-year production cycle, and years 4 and 7 in the three-year production cycle. Phytoplankton costs are incurred with each new larval culture and are derived from the Industrial Plankton ™ Bioreactor proprietary model, detailed above.

Fuel costs for the aquaculture farm labourers attending to the IMTA Grow-out and Finishing Diet operations were not included in the operational costs for the urchin model.

Appendix B

List of Consulted Aquaculture Researchers and Professionals

Name	Title	Affiliation
Dr. Christopher Pearce	Research Scientist	Fisheries and Oceans Canada
Dr. Shawn Robinson	Research Scientist	Fisheries and Oceans Canada
Dr. Gregor Reid	Senior Research Scientist	Fisheries and Oceans Canada
Teralynn Lander	Aquatic Science Biologist	Fisheries and Oceans Canada
Steven Neil	Technician	Fisheries and Oceans Canada
Michael Szemerda	Vice President, Saltwater Operations	Cooke Aquaculture
Steve Smith	Business/Projects Manager	Cooke Aquaculture
Ted Weaire	Vice President, Marine Services	Cooke Aquaculture
Dr. Thierry Chopin	Professor	University of New Brunswick
Adrian Hamer	Network Manager	Canadian Integrated Multi-Trohpic Aquaculture Network, University of New Brunswick
Dr. Bruce MacDonald	Professor	University of New Brunswick
Brian Tsuyoshi	Owner and Principal	Urchinomics
Dr. Stephen Cross	Director / Associate Professor	Coastal Aquaculture Research and Training Network, University of Victoria
Ashley Roulston	Co-owner	Industrial Plankton
J.P. Hastey	President and Founding Member	Nova Harvest Ltd.
Dr. Anne Salomon	Associate Professor and Hakai Professor	Simon Fraser University
Gail Smith	Leasing and Licensing Officer	New Brunswick Department of Agriculture, Aquaculture and Fisheries

Janelle Arsenault	Biologist	SIMCorp
Vidar Mortensen	Principal	SeaNest System
Michael Wowchuk	MA Economics, BSc	
Keith Richford	Sales and Marketing Manager	AKVA group North America
Dr. Stephen Eddy	Director, Centre for Cooperative Aquaculture Research	University of Maine
Rob Saunders	Chairman, CEO and president	Island Scallops
Steve Backman	President	Magellan Aqua Farms Inc.