# NUTRIENT LOADING EFFECTS OF INTEGRATED MULTITROPHIC AQUACULTURE SYSTEMS

By

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# ABSTRACT

Nutrient Loading Effects of Integrated Multitrophic Aquaculture Systems

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Integrated multitrophic aquaculture systems are systems in which organisms of multiple trophic levels are cultivated simultaneously. Here, we analyze the nutrient loading effect of an integrated multitrophic system in which sablefish are cultivated alongside blue mussels to determine environmental impacts associated with nitrogen and phosphorus loading due to addition of fish feed to the system. Under conservative scenarios where the feed conversion ratio of sablefish is higher than expected and growth rate of nutrient-extracting mussels lower than expected, we find that cultivated mussels can totally mitigate nutrient loading of sablefish, in an IMTA system. These findings are consistent with other literature on the bio extractive properties of shellfish and may be valuable to policymakers in determining nutrient-loading impact of IMTA operations in coastal or offshore waters.

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# Acknowledgments

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## Introduction: Sea Proteins and the Growing Human Population

The human species is growing in population at an impressive rate. The World Bank estimates that population will reach well over 10 billion people by 2050 (World Bank 2019), different people process the growth of our species in different ways. It may induce alarm in individuals who are sensitive to the state of the environment and cognizant of the number of resources people, especially those in the developed world, use. For economists, a steadily growing population is often associated with a strong economy (National Bureau of Economic Research, 2016), and there can be concern for the economies of nations with aging populations structures. Nationalists and the military minded might argue that a nation's manpower is ultimately determined by the population of that nation, along with their will to fight. Individuals may celebrate the expansion of their species on philosophical or religious grounds, even to the detriment of individual health (Schenker, 2000). Futurists, such as Isaac Arthur (Isaac Arthur 2020), take an approach of extreme optimism, discussing the near future technologies and socioecological systems which could lay the groundwork for an Earth capable of sustaining a population of hundreds or thousands of billions of humans.

Fears about the capacity of earth to support human life can also lead to genocidal and xenophobic ideologies, discussed by Christopher Parenti (2012) as the 'Politics of the Armed Lifeboat', in which nationalists of rich nations must defend their productive lands from migration with increasingly militarized borders. In this ideology a rich nation is an armed lifeboat, and nationalists conceptualize themselves as the armed oarsman, tasked with slaying the drowning around them to prevent them from climbing aboard and capsizing the boat.

At the core of the discussion on population growth are questions of scarcity and environmental sustainability. Can we provide for our growing population? And can we do so without degrading our environment to a point that we find unbearable or incompatible with life? The United Nations 2022 State of World Fisheries and Aquaculture goes some way towards answering these questions, and echoes many of the points of previous World Fisheries UN reports. Human consumption of seafood has more than doubled since the sixties, and continues to rise, with growing productivity of aquaculture meeting much of this growing demand (United Nations, 2022). The UN extolls the success in aquacultural expansion and productivity, while warning that such growth must be sustainable, stating that "Sustainable aquacultural development remains critical to supply the growing demand for aquatic foods".

This literature review presents a collection of literature on sustainable aquaculture, taking specific interest in integrated multitrophic aquacultural (IMTA) systems. Aquaculture produced roughly 49% of the 195 million tons of captured and grown non-algae seafoods in 2020. With over a third of wild fisheries overharvested beyond biological capacity (UN 2022, page 18/266), aquaculture offers an immensely productive and potentially sustainable way of alleviating pressures on wild fisheries.

# Literature Review

## Considerations for Conduction Shellfish Aquaculture – A Roadmap of the Topic

About 71% of the surface of the earth is covered in water (USGS.GOV, 2019). The topic of aquaculture is similarly massive. Aquacultural operations can take place in rivers, along coasts, in the open ocean; even on land in tanks or pools (Ferreira et al., 2018). Aquacultural operations grow kelp, shellfish, crabs, mammals, alligators, finfish, algae, or any profitable combination of organisms to support the growing needs and desires of the human species.

This literature review explores the topics of profitability and environmental sustainability with equal vigor. A private operation cannot exist if it is not profitable (though government assistance can alter the profitability of operations), and it cannot continue to meet the needs of the human species into the future if it is not sustainable. Often, there is a trade-off between profitability and environmental sustainability, however, there are happy coincidences in which a more sustainable design can be more profitable.

One such coincidence is Integrated Multitrophic Aquaculture (IMTA) Systems. These systems leverage complementary species to form intentional closed loop ecologies which generate multiple profitable species which are routinely harvested to perpetuate the operation. Shumway (2011) speaks highly of them throughout her excellent publication Shellfish Aquaculture and the Environment, Klinger and Naylor (2012) note their potential for reducing marine nutrient loading, and we will cover IMTA systems in more depth in the coming section.

While this thesis will not directly assess the profitability of an IMTA operation, we will more briefly explore literature pertaining to the profitability of aquacultural operations, making particular use of the United States Department of Commerce's excellent 2008 compilation

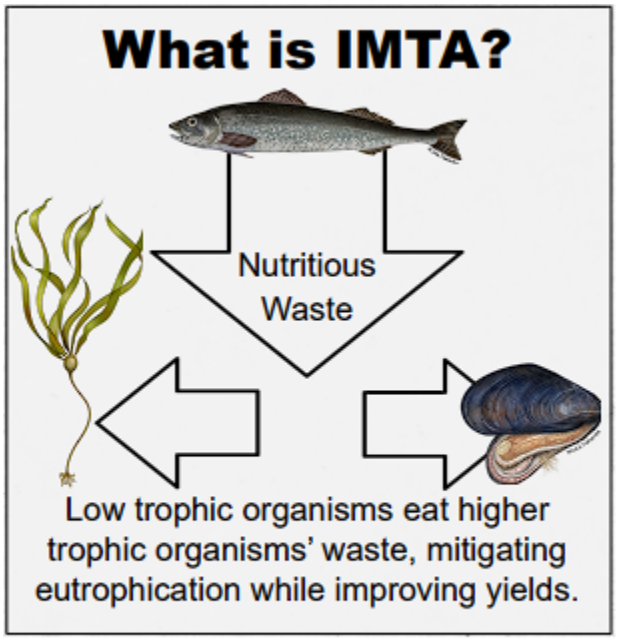
Offshore Aquaculture in the United States: Economic Considerations, Implications, and Opportunities, produced by Anderson and peer researchers and edited by Michael Rubino.

**Integrated Multitrophic Aquaculture**

Integrated multitrophic aquaculture (IMTA) systems cultivate economically valuable species at multiple trophic levels in one aquaculture operation, lower trophic species, such as bivalve filter feeders or kelp, convert the wastes generated by high trophic species into profitable biomass (Troell et al., 2009, Shumway 2011, Klinger & Naylor 2012).

**Figure 1**.

*What is IMTA?*




*Note*. Lower trophic organisms eat higher trophic organisms' waste, mitigating eutrophication while improving yield. Images of sablefish and pacific blue mussel taken from NOAA (2018).

Eutrophication is the term for the depletion of oxygen from water, usually caused by algae and bacteria in response to nutrient loading which increases the carrying capacity of these species. Without oxygen fish, bivalves, and sometimes even primary producers suffocate, damaging local ecologies and eliminating the usefulness of the waters for aquaculture without remediation (National Ocean and Atmospheric Association, 2022). By turning the waste stream of finfish into productive biomass, farmers may increase their economic returns on investments in fish food while mitigating or eliminating the potentially eutrophying and water-quality degrading effects of finfish-waste nutrient loading. Helfman and peer researchers note that finfish absorb only one tenth to half (depending on species and conditions) of the nitrogen and phosphorous in fish feed (Helfman et al., 2009). The surplus nitrogen and phosphorous being lost to the surrounding waters as pollution. Shellfish, and seaweeds, meanwhile, can be grown to capture this fish waste. Shellfish remove phytoplankton and detritus from water, which can reduce the turbidity of water and allow light to penetrate greater depths, additionally, by eating organic matter there is less opportunity for bacteria to metabolize floating organic detritus, which can help prevent the emergence of eutrophication and hypoxic conditions.

**Figure 2.**

*Diagram of an IMTA Operation*

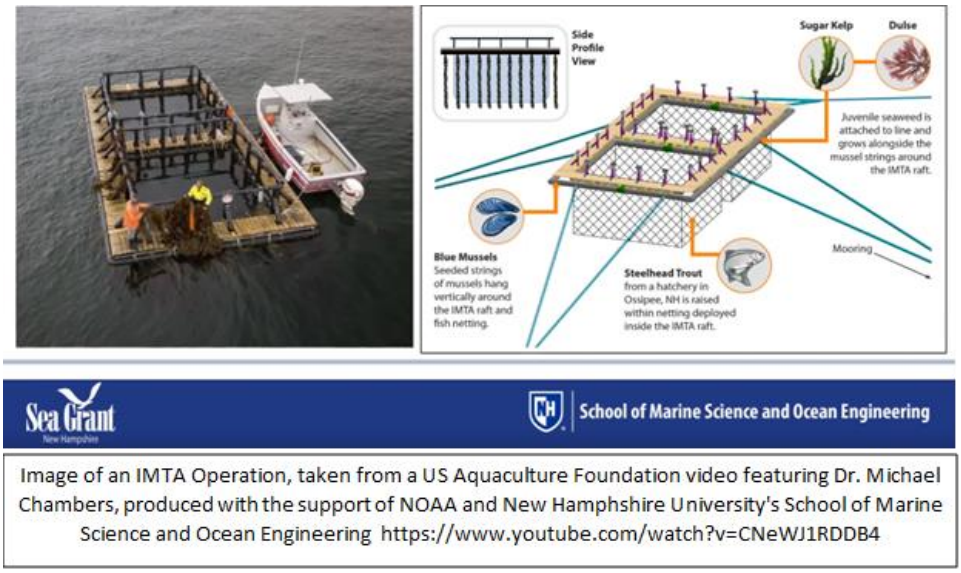



Image of an IMTA Operation, taken from a US Aquaculture Foundation video featuring Dr. Michael Chambers, produced with the support of NOAA and New Hamphshire University's School of Marine Science and Ocean Engineering https://www.youtube.com/watch?v=CNeWJ1RDDB4

*Note*. Image of an IMTA operation, taken from a US Aquaculture Foundation Video (Chambers et al., 2023), produced with the support of NOAA and New Hamphsire University's School of Marine Science and Ocean Engineering.

Shumway speaks positively about the profitability of IMTA systems, and her affirmations are echoed by Amir et al. 2008, Troell et al., 2009, Klinger & Naylor 2012; and Rubino et al., in passing. She notes that fish, shellfish, and seaweed are all marketable, and that the fish waste nourishes the shellfish, increasing their biomass. table 1 shows the dramatically increased profitability of an IMTA operation, compared to an aquaculture operation which exclusively produces shellfish.

**Table 1.**

*Oyster Monoculture and IMTA Scenarios in Sanggou Bay*

Table 1.4 Oyster monoculture and IMTA scenarios in Sanggou Bay.

| | Scenario A | Scenario B |
|---|---|---|
| Description | Oysters in monoculture all sections | Oyster and fish IMTA all sections |
| People | | |
| TPP (t TFW) | 7.5 | 219.7 |
| APP | 0.22 | 6.54 |
| Planet | | |
| Chlorophyll *a* ($P_{90}$) | 9.4→6.2 | 9.4→5.9 |
| N removal (kg year$^{-1}$) | 356 | 2468 |
| Population equivalents (PEQ) | 108 | 748 |
| Organic detritus removal (kg C year$^{-1}$) | 7816 | 39,973 |
| ASSETS | 4 → 4 | 4 → 4 |
| Profit | | |
| Income (shellfish; k€ year$^{-1}$) | 22.9 | 668.4 |
| Gross profit (aquaculture; k€) | 4.0 | 1065 + 15[†] = 1080 |

[†]Income due to finfish culture.

*Note.* Table taken from page 17 of Sandra E. Shumway's Shellfish Aquaculture and the Environment (2011).

**The Scope of This Thesis**

This thesis' scope is to create a farm scale model (FSM) of an integrated multitrophic aquaculture operation in the Strait of Juan De Fuca. The farm scale model will consist of interrelated models for each species cultivated in the operation. All species will be marketable and palatable organisms native to the Strait of Juan de Fuca. Nutrient inflow-and-outflows will be modelled for each organism in the interest of assessing hypothetical water quality impacts of the cultivated species. To build these bioenergetic models, remote sensing, buoy, and other data will be collected to create physical and chemical site parameters for a hypothetical site for the operation. The models, which chart the weight of organisms within each species' population, will be used to estimate the marketable yields of cultivated organisms, providing a base from which a simple profitability model could be built based on a range of estimated and reasonable costs and market prices for the cultivated organisms. It is important to note that the market rate of seafood commodities is highly variable, and local species (such as sablefish, bull kelp, or pacific blue mussel) aren't necessarily widely marketed, making cash flow models for large difficult to construct and heavily impacted by the operational model and local conditions. As such, this thesis will focus exclusively on the nutrient loading and extraction of cultivated species, with an eye to providing data valuable to future analyses focused on assessing the profitability of such operations.

The work of Hartley et al., (2020) in their 2020 NOAA Technical Memorandum, which developed a cash-flow simulation model to compare the profitability of sablefish aquaculture operations which reared mixed-sex fish and those which exclusively reared the larger females, produced from breeding stocks of sexually dimorphic (female to male) neo male fish is leveraged

in this thesis to help quantify the growth curve of sablefish of various sexes, their feed conversion rates, and their expected nutrient loading impact.

An important step in completing any model is the adjustment, refinement, and validation of a model against real-world observed conditions. Unfortunately, raising at least two species of aquatic organisms in an IMTA aquacultural operation is an undertaking beyond the scope of this thesis, I have neither the capital to cultivate and observe these organisms in the numbers required to validate a model, nor the time to rear these organisms and tend to them as they mature and can be harvested. Because of these capital and time constraints, this thesis will thoroughly explore a hypothetical IMTA operation, and build models for the cultivated species within it while attempting to quantify nutrient loading and extraction from the IMTA operation but will stop short of validating the models through lab-based assessment of cultivated organisms. It will present a plausible hypothetical farm-scale IMTA operation model, ready to be adjusted and validated against real-world results if the capital and time necessary for such an undertaking become available.

**The Profitability of Aquacultural Operations and the Benefits of IMTA Operations**

The profitability of aquacultural operations is discussed in depth in the United States Department of Commerce's 'Offshore Aquaculture Operations in the United States, Economic Considerations, Implications, and Opportunities' edited volume, by Rubino et al. (2008), While this literature collection emphasizes offshore aquacultural operations, the conceptual frameworks it describes for profitability are applicable to riverine and coastal operations.

Knapp. (Rubino et al., 2008, Chapter 2, p. 15), in the same collection of literature, writes that as sites move offshore, costs of increase production along with exposure, and that costs

continue to increase as aquacultural operation sites move from low exposure to high exposure sites. Knapp explains that most offshore siting locations are highly exposed, with comparatively small areas of moderate and low exposure locations, and that together offshore siting locations vastly outnumber coastal and riverine siting locations. Knapp argues that a conceptual framework for the profitability of aquacultural operations has the following premises:

1. An aquacultural operation is profitable so long as the marketable cohort of produced sea resources can be sold at sufficient prices to exceed operating costs.
2. The existence of lower cost operations doesn't preclude the possibility of a higher cost operation being profitable, so long as there is sufficient demand leftover for the market to purchase produced product at a price necessary to ensure operational profitability.
3. Higher cost offshore farms can be profitable and exist alongside lower cost coastal, riverine, or less exposed offshore farms so long as there is sufficient demand for the produce of higher cost farms to be sold at a profitable price.

Knapp's conclusions are valuable from the perspective of US aquaculturists, who must compete in a global market against domestic operations as well as enterprises operating in foreign nations where operational costs may be substantially lower. The rising demand for sea proteins, the existence of niche markets which are attracted to high quality domestic product, the skilled labor force of the USA, the US's massive Economic Exclusion Zone (EEZ) and the USA's technological advancement are all tailwinds propelling US aquaculturists forwards (Rubino et al., 2008, Chapter 2, p. 15). However, lethargic and obtuse regulatory frameworks and competing stakeholder demands for coastal, riverine, and offshore use all substantially impede the growth of the domestic aquaculture industry (Rubino et al, 2008, Chapter 2, p. 15).

Integral to analyzing an operation's profitability is modelling the harvestable product produced through various operational inputs. Shumway discuss a very general equation used to find the marketable cohort of shellfish:

$$M = f(V,F,D)$$

where M is marketable cohort (those shellfish of sufficient size and quality to sell to the public or other enterprise) V is the velocity of water currents, F is the amount of available food on those currents, and D is the stocking density of the shellfish (Shumway, 2011).

Increasing the stocking density of shellfish (D) is done by increasing seeding density, however it yields diminishing returns which Shumway (2011) states are represented by a 'standard Malthusian curve'.

Shumway continues to discuss the vulnerability of the profitability of shellfish aquaculture imposed by red tide events, which can be external and unrelated to nutrient loading from land surfaces, and instead result from offshore sources such as 'upwelling relaxation'. Monitoring for red tide events is limited, and often only provides days of warning, and can seriously impact the health of humans who consume exposed shellfish. Therefore, it presents a serious and unpredictable threat to the profitability of a shellfish aquaculture operation.

Shumway references the work of Jolly and Clonts (1993) and the Cobb-Douglas production algorithm when discussing profitability models, where functions related to stocking density and marine parameters of interest are used to estimate total harvestable biomass. Increased stocking densities reduce the average physical product (APP) while increasing the Total Physical Product (TPP) up until the Malthusian curve of diminishing returns results in a reduction of Total Physical Product.

The cost of shellfish seed is an important variable, though Shumway notes that it is often inexpensive and that its low cost encourages farmers to have densely stocked aquacultural systems. It is worth considering the relation between stocking density and disease, but the literature on disease, stocking, and risk quantification is beyond the scope of this section of the review.

Producing multiple types of aquatic species might be a way to mitigate some of the risks associated with red tide or disease events, which may destroy the profitability of some cultivated beings, but not others, leading to a diversified and risk-resilient set of income streams for an IMTA operation.

Shumway notes that the increased nutrient availability resulting from fish poop allows farmers to stock shellfish populations more heavily, resulting in a potential increase not only in the size of shellfish, but in the number of shellfish of marketable size. To these revenues the revenues of finfish and seaweed sale must be added. Additionally, there may be subsidies available (or penalties to avoid) for utilizing filter feeding shellfish to reduce or eliminate water quality damages finfish aquaculture alone can induce.

The profitability and sustainability of IMTA operations is grounded in peer-reviewed literature beyond the excellent scholarship of Shumway, including the 2004 work of Neori et al., who emphasize the increasing demand for sea proteins, and the modularity and massive productivity of integrated multitrophic aquaculture operations. Neori et al., glowingly note: "Through plant biofilters, integrated aquaculture recycles nutrients into profitable products, while restoring water quality. Fish–phytoplankton–shellfish systems convert the fish waste into bivalves, which have a large global market." While Neori's work is promising, it is largely focused on land-based aquaculture operations.

The primary metric of aquatic farm profitability is the harvested marketable cohort, and the amount that marketable cohort can be sold for. Charting the growth of individual organisms using established models, calibrated to the species and locations of an operation alongside population scale metrics of mortality is an effective way in predicting the number of organisms within a marketable cohort, and extensive literature and practically applicable software exists with which to conduct this task (Shumway 2011, Rubino et al., 2008, Chapter 2, p. 15). Software tools such as ShellSim, AquaModel, and models produced by researchers like those presented and used by João et al. (2018) have demonstrated reasonably accurate predictions of marketable cohort productions and carrying capacities for harvest. The producers of ShellSim note that their model has reliably predicted the production of marketable cohorts in environments and for species it is not calibrated for within 20% of the **actual** amount of marketable cohort, and reliably has less than 5% deviation between modelled and actual marketable shellfish cohort production for those populations and sites that the model has been calibrated for.

**Siting Aquaculture - Riverine, Coastal, and Offshore Aquacultural Operations**

Siting aquacultural operations requires utilization of weather exposure data to inform operational costs (Rubino et al., 2008, Chapter 3, p. 51), financial costs associated with purchasing or leasing land (Troell et al., 2009, Rubino et al., 2008, Chapter 2, p. 15, Klinger & Naylor 2012), and perhaps more holistic models, such as those proposed by Buck and peer researchers in 2004 and reintroduced by Shumway in 2011, which encourage marine spatial planning to identify competing stakeholders and aquatic carrying capacities.

Offshore aquacultural operations have distinct benefits and disadvantages, in comparison to aquacultural operations with coastal and riverine siting. These costs and benefits are detailed in tabular format as follows:

**Table 2.**

*Advantages and Disadvantages of Offshore Aquaculture*

| **Advantages** | **Disadvantages** |
|---|---|
| Land is expensive, and coastal waters are often in exceptionally high demand. Moving a shellfish operation offshore utilizes space which is less in demand, reducing costs. (Shumway 2011). | Although offshore operations may utilize space which is less in-demand than terrestrial or coastal lands, there is an immensely complicated regulatory framework surrounding operations in the US economic exclusion zone. Additionally, there are conflicting demands for IEE seaspace by conservationists, fishers, military stakeholders, wind farms, etc. (Mann, 2021) |
| Universities and commercial stakeholders have run numerous offshore shellfish operations to assist in determining the profitability of such operations, providing a substantial base of practical literature and information for aspiring offshore aquaculturists. (Klinger and Dane, 2012) | Strong currents can present substantial and potentially lethal forces to filter feeders, and likewise challenge the structural integrity of offshore infrastructure (Max et al., 2009). Some organisms fare better in deep or shallow open ocean waters than others. |
| In personal conversation with thesis-reader Pauline Yu, Yu noted that in some cases existing offshore infrastructure from defunct oil exploitation operations could | Offshore shellfish operations are capital intensive. Moving operations away from the shore increases the transportation costs associated with moving labor and resources |

| | |
|---|---|
| hypothetically serve as a platform for launching IMTA operations. Out of the box thinking, such as the cost saving proposition proposed by Yu, could reveal unexpected opportunities to minimize costs or increase revenues. | for laborers, as well as the rigidity of infrastructure and the maintenance costs incurred, as offshore locations become exposed to powerful ocean storms and immense wind and wave pressures. (Klinger and Dane, 2012, Rubino et al., 2008, Chapter 3, p. 51) |
| Offshore shellfish aquaculture operations will not be directly affected by terrestrial pollutants on the same magnitude as operations near coasts or in rivers would be, and likewise will have less of an impact on coastal and riverine ecological communities. (Klinger and Dane, 2012). | |

*Note*. Explores the costs opportunities and disadvantages of offshore aquaculture.

**Environmental Impacts and Sustainability of Integrated Multitrophic Aquaculture Systems**

IMTAs can be immensely effective at preventing eutrophication by mitigating the nutrient loading effects of finfish cultivation (Troell et al., 2009, Shumway 2011, Klinger & Naylor 2012). However, modelling the input/output steams of nutrients and feces (from fish,

shellfish, or other cultivated species) is essential to correctly quantify the impacts of any given IMTA operation. Shumway discusses the employment of the Assessment of Estuarine Trophic Status (ASSETS) model, stating that it is what researchers should use as a first step in planning aquacultural operations. According to Shumway (2011), the ASSETS model has three parts:

1. Influencing factors, such as human deposition of nutrients into the area of interest
2. Eutrophic condition, evaluated through the following 'symptoms'
    2.1.Toxic and nuisance algae blooms
    2.2.Loss of submerged vegetation
    2.3.Chlorophyll a macroalgae
    2.4.Dissolved oxygen
    2.5.Nutrient related water quality problems
3. Future outlook
    3.1. Pending human response
    3.2. Likely future ecological conditions stemming from current and past conditions

Shumway discusses the FARM (Farm Aquaculture Resource Management) model, also discussed by Ferreira and peer researchers in 2007. This model considers water flow, resources and contaminants, and biodeposition, as well as the growth of cultivated species. FARM is a modified version of the ASSETS framework. It tracks water properties such as dissolved ammonia and oxygen, suspended particulates, detritus and phytoplankton.

These models can be coupled with species specific growth models, models of water dynamics appropriate to the siting location, and fiscal feasibility models to identify operations which can be both profitable and environmentally sustainable in terms of chemical dynamics. Interestingly, the scholarship of Rensel and peers 2009 shows the potentially overlooked impact

that conventional (limited to finfish, rather than deliberately integrating multiple trophic levels) fish pen operations can have in sustaining micro ecologies of native organisms. This scholarship emphasizes the impact chemical dynamics and physical structures for species colonization can have on natural ecology.

In addition to the chemical impacts of aquaculture, aquaculture may disturb or alter benthic structure, with associated impacts on local ecology (Klinger & Naylor 2012). Additionally, the genetic impacts of aquacultural operations should be considered (Shumway 2011). For kelp and shellfish, genetic escape of cultivated species into the surroundings is nearly inevitable (shellfish, for example, reproduce through spat), posing potential risks of harmful alteration of indigenous populations, alongside opportunities for ecological engineering. A balanced composition of multiple wild-type genetic lineages chosen with characteristics favorable to commercial operation under increasingly warm and acidic conditions could reinforce existing diversity and ecological resilience, for example.

Escape of captive fish poses risks to wild fish in terms of genetic contamination, disease transfer, and negative ecological interactions, although genetic risk has been studied most heavily in the literature (Washington State Department of Fish and Wildlife 2022). Maintaining the structural integrity of nets or other fish containment systems and implementing best practices to avoid accidental escapes are two general methods of escape prevention. The risk presented by escape may be mitigated by cultivating native species which don’t present an ecological interaction risk to the environment in the event of their escape, by vaccinating fish to improve their resistance to disease, thus reducing the risk of disease transfer, and by taking other disease control measures such as leaving pens fallow for an extensive period of time between batches of

fish (NOAA 2022). Additionally, farmed fish tend to demonstrate lower foraging and survival skills than wild fish, making their survival probability comparatively low (NOAA 2022).

**Regulatory History & Modern State of Fin Fish Aquaculture Regulatory Feasibility in WA State**

While this thesis is not intended to serve as a comprehensive analysis of the regulatory conditions of the state of Washington with regards to integrated multitrophic aquaculture, it would be remiss to avoid discussing the current regulatory status of IMTA in Washington state, as current and pending policy has substantial implications on the practical feasibility of aquaculture in the State, and on the likelihood of acquiring capital to conduct such operations.

Net pen aquaculture in Washington occurred throughout the 1980s up until the present, with regulatory policy remaining essentially unchanged since 1990 up until Cooke Aquaculture suffered a catastrophic net pen failure which resulted in over 300,000 non-native salmon escaping into the surrounding environment in 2017 (State guidance for net pens - Washington State Department of Ecology). The Washington State Department of Natural Resources, local environmental advocacy organizations, and tribes dependent on native salmon species were horrified by the release, shortly after, Washington State House Bill 2957 phased out non-native fish farming in Washington State. Cooke Aquaculture responded by pivoting their operation, securing a permit from Washington Department of Fish and Wildlife to begin growing native and sterile steelhead (National Marine Fisheries Service West Coast Region, 2022). However, the Wild Fish Conservancy appealed to the King County Superior Court, alleging that an environmental impact statement was required and that the Washington Department of Fish and Wildlife violated the State Environmental Policy Act. The Washington State Supreme Court ultimately ruled in favor of Cooke Aquaculture and the Washington Department of Fish and Wildlife. It is helpful to examine this case: Wild Fish Conservancy v. Department of Fish and Wildlife, no. 99263-1, to understand the reasoning and motivations behind the appellants,

respondents, and Supreme Court and to contextualize the regulatory landscape for aquaculture in the State of Washington today. The Wild Fish Conservancy alleged that Washington Department of Fish and Wildlife's analysis of the adverse effects of genetic and disease transfer between captive and wild fishes was insufficient. Washington Department of Fish and Wildlife, meanwhile, released a document justifying their permits (2020), which the Supreme Court of the State of Washington found was "more than sufficient". The report includes a summary of the ecological effects of net pen operations, as well as 29 provisions which Cooke Aquaculture was required to follow as a condition of its permits. We will not discuss all these provisions here, but relevant provisions are cited under the 'Best Practices for Profitable and Environmentally Sustainable IMT Aquaculture" section.

Five elements of the decision are worth highlighting for the sake of understanding the current environmental justification of net pen aquaculture and the regulatory environment within the state:

1. Washington Department of Fish and Wildlife only requires an environmental impact assessment if an action is expected to have a 'more than moderate adverse effect' after reviewing the scientific literature, analyzing applicable data, and consulting experts. This means that actions resulting in moderate adverse environmental effects may be permitted without environmental impact statements (Washington Department of Fish and Wildlife, 2020). In the event that an environmental impact statement is not required, a Mitigated Determination of Non-Significance may be issued, which allows the activity while seeking to mitigate its adverse effects.
2. When determining if an environmentally adverse action requires an environmental impact statement, or if the issue of a Mitigated Determination of Non-Significance is

appropriate, the Supreme Court abides by case law which states that the Supreme Court is not merely determining if the agency issuing a Mitigated Determination of Non-Significance had substantial evidence supporting their decision, but rather is itself tasked with absorbing the entirety of available evidence to determine if they are "left with the definite and firm conviction that a mistake has been committed". (Washington State Supreme Court Slip Opinion 992630-1, 2022)

3. The Wild Fish Conservancy argued that Washington Department of Fish and Wildlife failed to fully assess the risk associated with "gradual, low-level leakage" of escape fish, arguing that the escape of these fish could result in genetic contamination of wild fish. While fish are sterilized, testing by Washington Department of Fish and Wildlife estimated a rate of non-sterile diploid female fish of roughly 0.2%. Assuming 2 million fin fish raised in captivity, roughly 4,000 fertile fish could exist in captivity. Washington Department of Fish and Wildlife agreed that while low level 'leakage' escape of fish could have a genetic impact on wild fish, it noted that its mitigating provisions included continuous video monitoring of net pens, a load analysis of the mooring and cage system consistent with Norwegian aquacultural standards which has been found to be effective at escape mitigation, and required Cooke Aquaculture to test every lot of fish it received according to Washington Department of Fish and Wildlife procedure, to ensure acceptable rates of sterilization. Washington Department of Fish and Wildlife ultimately concluded that such mitigation measures would preclude more than moderate adverse effects.

4. Washington Department of Fish and Wildlife argued that they reduced the risk of adverse environmental effects relating to disease transfer to a ‘moderate or below moderate’ level by:
    a. Requiring finfish and embryos to be tested for known pathogens at multiple stages of their life cycle. For instance, smolts would be tested prior to deposition in marine net pens.
    b. Using native broodlines for spawning the cultivated fish.
    c. Requiring a swathe of fish vaccinations, including vaccination for multiple strains of infectious hematopoietic necrosis virus.
    d. Mandating 42-day minimum fallow periods for net pens which would be required for cleaning, maintenance, and elimination of existing pathogens.
5. After carefully reviewing the record, Wild Fish Conservancy’s concerns, and Washington Department of Fish and Wildlife’s report justifying their Mitigated Determination of Non-Significance, the Washington State Supreme Court upheld Cooke Aquaculture’s steelhead permit.

These five elements of the *Wild Fish Conservancy v Department of Fish and Wildlife* Supreme Court case help to give us an idea of the environmental standards required for conducting fin fish aquaculture within the State of Washington and may help us infer some financial costs these standards could incur, such as testing costs, underwater CCTV to monitor net pens, vaccination, and purchase of additional pens to allow for mandatory fallow-time between pen replacement and refill.

However, the 2022 Washington State Supreme Court decision is not the end-all and be-all of fish aquaculture regulation in the state. Concurrently a State of the Science report relating

to net pen aquaculture (Hawkins et al., 2022) was released by an inter-agency collaboration involving National Oceanic and Atmospheric Administration, Washington State Department of Ecology, Washington State Department of Fish and Wildlife, Washington Department of Natural Resources, and Washington Department of Agriculture. Meanwhile, the National Oceanic and Atmospheric Administration released an opinion in February (2022), relating to the EPA's acceptance of Washington Department of Ecology's Sediment Management Standards for marine fish farms stating in its conclusion:

> "When analyzed into the future, with variable ocean conditions and climate change stressors, only a small number of fish relative to the affected populations would be killed or injured by the effects that result from net pen structures and operations. Further, despite a degraded baseline and anticipated cumulative effects primarily associated with population growth and development, we do not expect the habitat effects of the net pens to appreciably diminish the conservation value of critical habitat for PS Chinook (Hood Canal salmon run chum), HCSRC, PS/GB yelloweye rockfish or PS/GB bocaccio. After reviewing and analyzing the current status of the listed species and critical habitat, the environmental baseline within the action area, the effects of the proposed action, the effects of other activities caused by the proposed action, and cumulative effects, it is NMFS' opinion that the proposed action is not likely to jeopardize the continued existence of PS Chinook salmon, PS steelhead, HCSRC (Hood Canal salmon run chum), PS/GB yelloweye rockfish or PS/GB bocaccio, or adversely modify their designated critical habitat."

The opinion did note that native threatened fish species would likely be adversely affected because of incidental take, including but not limited to temporary reduction in available forage in the event of a cultivated fish escape (NOAA 2022).

While the rulings of the Washington State Supreme Court, the findings of NOAA and the EPA, and the existing legislative situation all seemed favorable to continuation of well-regulated native finfish aquaculture in the State of Washington as of 2022, with the inter-agency State of the Science report serving as repository of risks, mitigation opportunities, and best practices, the Department of Natural Resources issued an executive order (2022) banning fin fish aquaculture outright. Department of Natural Resources Commissioner Hillary Franz stated:

> "As we've seen too clearly here in Washington, there is no way to safely farm finfish in open sea net pens without jeopardizing our struggling native salmon. Today, I'm announcing an end to the practice. We, as a state, are going to do better by our salmon, by our fishermen, and by our tribes, commercial finfish farming is detrimental to salmon, orcas and marine habitat. I'm proud to stand with the rest of the west coast today by saying our waters are far too important to risk for fish farming profits." (DNR 2022)

Franz's executive order was supported by numerous Tribes and environmental advocacy organizations (DNR 2022) and seemed to signal the end of net pen aquaculture in Washington State, as well as effectively eliminate the possibility of IMTA operations within state waters. However, the Jamestown S'Klallam tribe and industry partners took issue with the ruling, with

Cooke Aquaculture and Jamestown S'Klallam Tribe filing separate appeals relating to the wholesale ban (White 2023). Cooke Aquaculture ultimately dismissed their suit in early 2024, while Jamestown S'Klallam Tribe won a small victory, with Thurston County Superior Court Judge Indu Thomas ruling that the DNR's executive order had "no legal effect" (The Fish Site 2023).

The Jamestown S'Klallam tribe submitted the following statement in 2022:

> "A vast array of scientific studies have repeatedly shown that well-regulated aquaculture is not an ecological threat to the Puget Sound marine environment."

In March 2022, the National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service released an extensively researched biological opinion that studied marine finfish aquaculture in Puget Sound and found little to no negative impact on Puget Sound marine ecosystems, including native species such as endangered salmon, Orcas, or their habitat.

Farmed seafood requires the lowest energy demand of any sourced protein, a fraction of what is required to farm chicken, pork, or beef and produces far less greenhouse gas emissions than land-based agriculture. It seems only natural that Washington would embrace aquaculture as an industry that complements its own natural stock fisheries and allows our State to be a global leader in feeding the planet, and sourcing locally grown seafood in the most climate-friendly way possible.

In addition to refusing to respect the science about marine net-pen aquaculture, this decision was highly undemocratic. Commissioner Franz has mistakenly usurped the authority of

our Washington State Legislature to make public policy decisions, like the bipartisan bill passed in 2018 which allows native species marine net-pen farming in Washington waters.... Food sovereignty, the ability to grow and provide one's own food sources, builds self-reliance, independence, and confidence in our youth and community. That is all in jeopardy now due to Commissioner Franz's announcement to end marine net-pen aquaculture in Puget Sound." (Jamestown S'Klallam Tribe sues DNR of marine net-pen aquaculture ban | The Journal of the San Juan Islands (sanjuanjournal.com)

As of now, the state of the feasibility of IMTA operations in Washington State is anything but clear. A complicated court case involving treaty rights, Departmental authority, and environmental science is just the latest unfolding event in the highly complicated regulatory environment. Investments in aquaculture at scale which require millions of dollars in capital costs will likely be hard to justify in an environment where a wholesale ban and resulting capital loss is possible or even probable. This is doubly true for IMTA operations, which by cultivating multiple species to increase yields and mitigate nutrient pollution are inherently more complicated and may require greater scale to be economical.

## Methods:

Assessing the overall productivity (in harvested kilograms of cultivated organism per year) and nitrogen and phosphorus loading effects (referred to as 'nutrient loading effects' henceforth) of an IMTA operation requires a thorough investigation of the biological characteristics of cultivated organisms, and determination of how best to quantify the nutrient loading effects of fish feed, and the bio extractive effects of seaweeds and shellfish.

### Nutrient Loading Modelling and Model Parameterization:

Islam's model of nitrogen and phosphorus loading from coastal and marine finfish aquaculture provides a valuable blueprint for our models of IMTA operation nutrient loading and extraction in surrounding waters (2005). Islam's model is focused entirely on finfish cage aquaculture and does not consider an IMTA operation. Nitrogen and phosphorous loading per ton of fish is assessed by computing the nitrogen and phosphorus portion of fish feed, multiplying that portion by the quantity of fish feed to supply one ton of harvested fish, calculating the amount of feed lost to the system due to feeding inefficiency and adding the lost feed's nitrogen and phosphorous directly to total nutrient loading figures. Then, feed consumed by fish is multiplied by an 'excretion coefficient' representing the amount of nutrients **not** accumulated in fish tissues. The resulting nitrogen and phosphorus loads are added to the total of feed lost to the system. Remaining nitrogen and phosphorus accumulate in fish tissues, which are removed from the system at harvest.

Shahidul Islam states that 132.5 kilograms of nitrogen and 25 kilograms of phosphorus are loaded into surrounding waters per metric ton of fish harvested, assuming a feed conversion ratio of 2.5, 6.5% nitrogen and 1.4% phosphorus in feed, 3% nitrogen and 1% phosphorus

portions in fish tissue and feeding efficiency of 80% (20% of feed not consumed by fish and immediately lost to surrounding system). Islam's model is valuable conceptually as a model for calculating nutrient loading associated with net-pen aquaculture. It is important to note, however, that the parameters used by Islam are far different than the parameters best suited to modelling sablefish IMTA operation in the Pacific. For one thing, cultured sablefish can be expected to have a feed conversion ratio, conservatively, of 1.5, not 2.5 (Hartley et al., 2020). This would mean fewer kilograms of feed (and therefore, of nutrients) are added to the system per kilogram of produced sablefish. Additionally, the assumed 80% feeding efficiency (percent of feed eaten by fish) is quite low, with older literature suggesting 90% efficiency (Hozniak et al., 1992), and more modern literature suggesting 95% efficiency (Bai et al., 2022). Cameras, sensors, real-time monitoring and analytics, scientific experimentation and artificial intelligence could all be utilized to identify trends in feeding efficiency and optimize feeding to minimize uneaten fish feed from being deposited into the surrounding environment. Finally, figures for fish feed and fish tissue nutrient proportions would have to be adjusted for sablefish operations, but I was not able to find supporting literature with these figures and used Shahidul's figures for these totals as defaults. A stronger model would assess adult sablefish tissue samples cultivated under a range of environmental conditions and feeding regimens to determine expected nitrogen and phosphorus percentages.

Islam's contributions to fish farm nutrient modelling are complemented by three other publications: Park and peer researchers' *Evaluation of nutrient bioextraction by seaweed and shellfish aquaculture in Korea* (Park et al., 2021), Chambers and peer researchers' *Integrated multi-trophic aquaculture of steelhead trout, blue mussel and sugar kelp from a floating ocean platform,* and Buer et al.'s *Nitrogen and phosphorus* content *in blue mussels (Mytlilus spp.)*

*across the Baltic Sea* (Buer et al., 2020). Together, these papers provide us with reasonable estimates of blue mussel nutrient extraction capabilities, allowing us to construct a parameterized model of IMTA nutrient loading.

To determine the capacity of blue mussels to absorb nitrogen and phosphorous from the surrounding waters I referenced existing peer reviewed literature on the nitrogen and phosphorous content of blue mussels. Measurements of nitrogen content tended to vary heavily between studies, which is unsurprising because mussel nutrient content has been found to vary substantially between samples within a given study, depending on their environment. Blue mussels in farms suspended in the water column where they could hypothetically have greater nutrient access were found to be more nutrient rich than wild mussels found in seabeds, or mussels grown in culture bed (Buer et al., 2020). Buer and peer researchers found that mussels cultivated in long lines averaged 9.43% N content and 0.96% phosphorous content in their dry weight, while Chambers and peer researchers (Chambers et al., 2024) measured that their long-line cultivated mussels had 1.9% nitrogen content in tissue and 0.58% nitrogen content in their shells, or 1.32% nitrogen content overall. The disparity between the two papers' figures can be explained by different units of measurement, Buer mainly used dry weights, while Chambers used wet weights. Buer's figures for wet weights nutrient portions are more in line with Chamber's findings, averaging 1.14% nitrogen content and 0.13% phosphorous content. Buer et al.'s note that "Chlorophyll-a and temperature did not significantly correlate with nutrient content, but…season and habitat were the most influential effects on the variation of N and P in DW (dry weight) tissue." Is interesting from the perspective of IMTA farmers, as it implies that the mitigation potential of mussels may increase when cultivated alongside nutrient-rich fish farms. While Buer's comprehensive figures on nitrogen and phosphorous portions in a variety of

blue mussel sampling locations are extremely valuable for assessing hypothetical nutrient mitigation potentials of shellfish, they are only a starting point. Substantial limitations of the studies applicability to native-species IMTA operations in Washington State include:

- Buer and peers studied various blue mussels of the Mytilus genus in the Baltic Sea. The geographic location and environmental factors of the Baltic Sea are different than those of WA State waters.
- While *Mytilus trossulus* (the mussel species native to the Pacific Northwest that aquaculture in WA state would grow) can be found in the Baltic Sea, Buer's study was not limited to this species of mussel. As a result, genetic differences between mussel nutrient proportions may exist as well.
- Buer's study did not include any investigation of mussel nutrient portions in the nutrient-rich waters surrounding an IMTA operation, so it is impossible to assess the impact that synergistic effects between fish and mussel farming may have on overall mussel yields and mitigation.

Interestingly, Buer et al. also found that the portions of nitrogen and phosphorous varied with the size of mussels, with nitrogen portion being significantly inversely correlated with size and phosphorous portion being positively correlated with size. In a real-world IMTA operation, sampling and analysis of mussel nutrient proportions could help expand scientific knowledge about mussels and allow farm operators to better define the overall nutrient loading of an IMTA system.

Figures on annual blue mussel productivity are informed by a NOAA technical memorandum on offshore aquaculture, (Jin, 2008; Kirkley, 2008), while figures on sablefish productivity were included using another NOAA technical memorandum *Sablefish Aquaculture:*

*An Assessment of Recent Developments and Their Potential for Enhancing Profitability* (Hartley et al, 2020). Hartley and peer researchers and other NOAA sources (NOAA 2022) noted that monosex female sablefish grow substantially and significantly faster than mixed sex or monosex-male cohorts, and this model assumes the cultivation of a monosex female stock.

This model focused wholly on the production of sablefish and blue mussel, but the work could be expanded by incorporating the cultivation of other lower-trophic organisms such as sea cucumbers and kelp species. The work of Kite-Powell and peer researchers (Kite-Powell et al., 2022) could be incorporated into preliminary models of an IMTA operation to expand the analysis to include seaweed cultivation. With Kite-Powell's figures, researchers and entrepreneurs could model potential growth rates, operational costs, and bioextraction totals of incorporating seafood production in their operation. This modelling would be extremely valuable in further refining forecasts of profitability and nutrient loading impact, particularly if the model presented by Kite-Powell and peers was re-parameterized for native seaweed species of interest.

Additional considerations include the biophysical characteristics of the site selected, such as its expected temperature ranges, pH, and circulation. ESRI's Ecological Marine Unit layer can help facilitate this analysis by presenting a host of biophysical data (2024). Additionally, the impact of site selection on cost profile should not be ignored, with costs increasing with distance from a shore station due to greater fuel and time costs and increasing along with site depth as anchored line installation costs increase (Rubino et al., 2008, Chapter 6, p. 117; Kirkley, 2008).

IMTA operations models such as the one proposed by Ren and peer researchers in *An ecosystem model for optimizing production in integrated multitrophic aquaculture systems* (Ren et al., 2012) use complex and heavily parameterized applications of Dynamic Energy Budget (DEB) theory to predict how slight changes in PH, temperature, or water circulation could effect

the growth of cultivated organisms, overall yields, and nutrient loading effects. While such models are very appealing, they are highly complex and rely heavily on species-specific parameters which can only be determined through in-depth experimentation and observation of cultured organisms and are beyond the scope of this thesis. Nonetheless, future research leveraging DEB theory alongside species-specific parameters based in scientific observation of cultivated species could be an exceedingly powerful tool in optimizing the profitability and nutrient loading/extracting effects of IMTA operations.

**Model Construction:**

Finfish and shellfish growth were each assessed independently, with overall nutrient loading and mitigation. All model scripts were created in R, utilizing the tidyverse, readxl, gsubfun, and zoo packages.

*Finfish Model:*

The finfish model was adapted from Di Jin's *Economic Models of Potential U.S. Offshore Aquaculture Operations* found in Rubino's 2008 Offshore Aquaculture technical memorandum (2008, Chapter 6, p. 117), re-parameterized using NOAA's 2020 technical memorandum on Sablefish Aquaculture written by Hartley et al., to assess offshore sablefish production rather than offshore Atlantic cod production. Our model assumed that every thirty days, one new fish pen would be added to the system by operators, and stocked with 1000 75-gram fingerlings, up until 26 total cohorts were established in the operation. Fish would be harvested 780 days after a cohort was established, with cohorts replaced during the harvest month. This timeline would allow consistent production of fish and avoid unnecessarily avoiding overburdening crews with excessive harvests in any given month, as there would be at most one fish cohort to harvest, process, and replace each month. It is assumed that replacement cohorts

are stored in brand new net pens, with the old net pen being removed to lie fallow for 42 days in accordance with best practices in disease control. Sablefish feed was assumed to contain 6.5% nitrogen, 1.4% phosphorus, in line with Islam's figures for fish feed nutrient portions (Islam, 2005). Fish tissue nutrient proportion parameters were set to 3.5% nitrogen, 0.4% phosphorus, also in-line with Islam's figures. In future work, feed and fish tissue parameters should be adjusted to be in-line with those of actual sablefish feeds and tissue parameters, but lacking those figures this model utilized Islam's figures as default parameters.

Feed conversion rate was set to 1.5, in line with Hartley and peer researchers' figures (Hartley et al., 2020). Feed efficiency was set to 0.95, in line with the most recent figures (Bai et al., 2022), implying 5% of fish food was never consumed by fish at all and lost to the surrounding waters. Fish mortality was given a high baseline value of 1% per thirty-day interval, to provide conservative assumptions about overall yield, due to both natural death and cannibalization of fish.

An iterative function named 'calculateFish' was used to calculate the following statistics for each fish cohort during each 30-day interval of the simulation:

1) Number of surviving fish at the end of the 30-day interval.
    a. Computed by multiplying the number of fish last recorded in this cohort by the 30-day interval mortality rate. If this cohort is being instantiated (a new pen has been filled with fingerlings) this cohort is set to 1000, if it is being harvested the number is set to 0.
2) Mean mass of surviving fish at the end of the 30-day interval.
    a. Computed using observations of female monosex sablefish mass recorded by Hartley et, al. Missing observations are determined by interpolating the dataset

provided by Hartley et al., with R's na.approx() function. If sablefish are harvested, the mean mass is set to 0.

3) Age of cohort
    a. Computed by adding '30' to the last recorded cohort age unless the cohort is being harvested. In which case, the cohort's age is reset to 0.
4) Feed required over the last 30-day interval.
    a. Computed by multiplying the feed conversion rate by the change in mean fish mass for a cohort between the current time step and the preceding time step, multiplied by 1 over the feed efficiency rate, multiplied by the sum of fish in the current and preceding timestep over two (to account for fish mortality over the course of the timestep).
5) Nitrogen pollution over the last 30-day interval.
    a. Computed by determining the amount of waste feed and excreted feed.
        i. Waste feed N is equal to the amount of feed required during this time step multiplied by the 1 - feed efficiency coefficient multiplied by the feed's nitrogen proportion.
        ii. Excreted feed is determined by multiplying the feed efficiency coefficient (portion of feed actually eaten by fish) by the nitrogen excretion coefficient by the amount of feed required during the timestep.
6) Phosphorus pollution over the last 30-day interval.
    a. Computed by determining the amount of waste feed and excreted feed.

i. Waste feed N is equal to the amount of feed required during this time step multiplied by the 1 - feed efficiency coefficient multiplied by the feed's phosphorus proportion.

ii. Excreted feed is determined by multiplying the feed efficiency coefficient (portion of feed actually eaten by fish) by the phosphorus excretion coefficient by the amount of feed required during the timestep.

7) Mean mass of fish harvested in this cohort in the last 30-day interval.
    a. Calculated by determining the mean mass of fish at harvest time if the fish cohort is being harvested in this time step. Otherwise set to 0.
8) Number of fish harvested during the last 30-day interval.
    a. Calculated by determining the mean number of surviving fish at harvest time if the fish cohort is being harvested in this time step. Otherwise set to zero.

At the end of each 30-day interval a row of data is generated for each cohort and added to a dataframe. This dataframe is returned at the end of the simulation and written to an excel file, where it can be piped into Microsoft's Power Business Intelligence platform for analysis and reporting.

*Shellfish Model:*

The shellfish model has a very similar structure to the finfish model. An iterative calculateShellfish function is used to simulate timesteps and record changes to the number of shellfish long lines, and their overall characteristics, over the course of the simulation. The shellfish model differs from the finfish model in that the interval is not based on 30-day periods, but rather on discrete days. This is helpful as new mussel long lines are installed after a specified number of days, set to 7 by default to align with figures given by Jin (2008). Each long line

represents a large cohort of mussels anchored to the sea bed with 200 additional ‘culture lines’ attached to it. The model assumes a crew of workers installing lines regularly. Also, unlike the finfish model, it contains a completed calculateCosts function, which stores fixed and operational costs which can be utilized in future profitability analyses.

During each day of the simulation the model runs, calculating the following for each installed long-line:

1) Age of cohort
    a. Equal to 1 + the age of that cohort from the preceding timestep, unless the cohort is harvested. If the harvested age is set to 0.
2) Total mass of mussels.
    a. Computed using interpolated figures from Jin 2008.
3) Mussel Nitrogen Absorbed Kg
    a. Computed by multiplying the expected nitrogen proportion of mussel shell and tissue as defined by Chambers et al., (2024) by the total growth of mussels on the line during the last time step.
4) Mussel Phosphorus Absorbed Kg
    a. Computed by multiplying the expected phosphorus proportion of mussel shell and tissue as defined by Bai et al, (2022) by the total growth of mussels on the line during the last time step. Bai and peer researchers’ figures were used instead of Chambers and peers because Chambers et al did not measure mussel phosphorus portions.
5) Mussel Harvested Kg.
    a. Equal to the total mass of mussels at harvest time.

6) Fixed and operational costs

    a. Fixed and operational costs are also calculated in this function, but the methodology for their computation is not included here. Future research could leverage these modelled costs for profitability and feasibility analyses.

The resulting data is returned by the function in a dataframe and exported to Excel for further analysis and reporting in Power BI just as with the fish dataset.

## Results:

Our modeled IMTA operation was conducted under three scenarios, a conservative 'standard' scenario which contained assumed a substantial amount of fish mortality and waste feed, a conservative feed conversion rate of 1.5 kilograms of feed per kilogram of fish, and no synergistic effects between fish nutrient loading and mussel growth, as well as conservative scenario in which $1/5^{th}$ of feed was promptly lost to surrounding waters, mussel growth was substantially below expectations (80% of low-end estimates from the literature), fish mortality was 2% monthly, and an optimistic scenario in which feed conversion rate for sablefish was 1.2, synergistic effects were observed in mussel growth, and feed nitrogen and phosphorus concentrations were relatively low. The results of all scenarios and their parameters are available in Appendix 1.

Our standard scenario produced 1093 metric tons of mussels and 197.97 metric tons of sablefish metric tons of sablefish over 10 years. Mussels absorbed 27.22 metric tons of nitrogen and 1.86 metric tons of phosphorus, while sablefish contributed 14.53 metric tons of nitrogen and 1.79 metric tons of phosphorus.

Under our 'standard' and 'optimistic' scenarios our IMTA operation ultimately reduced nitrogen and phosphorus concentrations in surrounding waters via harvest of animals loaded with these nutrients. Under the 'conservative' scenario nitrogen was removed from the system but roughly one metric ton of phosphorus was contributed.

# Discussion

## Exogenous Opportunities

The standard model takes a conservative approach, assuming there are no synergistic effects between sablefish and blue mussels in terms of the sablefish farm boosting blue mussel yields due to greater availability of growth-limiting nutrients. The model includes a variable called 'IMTAGrowthCoefficient' set to 1 by default, which can be adjusted to assess the nutrient extraction of the blue mussels under baseline or more synergistic scenarios. Changes in mussel biomass are multiplied by the IMTAGrowthCoefficient variable during each time-step of the model.

In a small-scale IMTA experiment in the North Atlantic, Chambers et al., found that a blue mussel, sugar kelp, and steelhead trout farm could operate in coastal New Hampshire while providing nutritional services to the surrounding waters by extracting more nitrogen from the system than was introduced. In total 16.4 kilograms of Nitrogen were extracted from the fish farm to produce 416 kilograms of fish, 3072 kilograms of blue mussel, and 638 kilograms of kelp. Chambers and peers did not study the extraction of other nutrients, such as phosphorus, but they did find that lower trophic organisms cultured in their IMTA operation grew more quickly than might have been expected solely by referencing past literature on the growth of these organisms in monocultures, which is consistent with Shumway's assessment in Shellfish Aquaculture and the Environment. Blue mussels grown in their IMTA experiment had substantially more biomass and density compared to other grow-out experiments in the literature and researchers hypothesized that the accelerated rate of mussel growth and higher density was due to proximity to the fish farm. Mussel biomass was recorded at 7.55 kg per meter of line. Chambers et Al (2024) noted that other researchers' grow-out experiments on blue mussel

monocultures yielded diverse figures ranging from 0.27 kg/m to 5.2kg/m (Guillou et al., 2020). Those differences may be due to differences in seeding densities, chemical concentrations, or physical characteristics of the grow-out locations. Kelp also grew quickly in their study, but overall biomass yields were lower, which Chambers et al. speculated was due to lower seeding densities in their own study.

Chambers et al.'s (2024) research provides further evidence of the potential synergistic effects of IMTA operations, and of the ability of lower trophic organisms to fully mitigate nutrient inputs from depositing fish feed into a water system. Along with the impressive aquacultural and environmental results, Chambers and peers noted potential economic benefits of this study, pointing out that the collapse of Atlantic salmon and cod fisheries had devastated New Hampshire's fishing industry, and that small-scale IMTA farms could allow the expertise of fisherman to be leveraged to facilitate a sustainable rebirth of the fishing industry.

Park et al. (2021) emphasize that nitrogen equivalent to roughly 8.6% of nitrogen discharged by all wastewater treatment plants in Korea are extracted from coastal waters through cultivation of three major kelp and two shellfish species. Their research on tissue nitrogen and carbon portions by various species and environmental conditions implies an opportunity to optimize selection of site and cultivated species, not just for profit, but for environmentally desirable bioextraction capabilities.

**Best Practices for Conducting IMTA Operations**

The Washington Department of Fish and Wildlife's Justification for the Mitigated Determination of Non-Significance (WDFW 2020) is a great starting point for identifying best practices for conducting IMTA aquaculture in coastal or marine waters. These best practices broadly include:

1) Interventions to minimize nutrient loading.
    a. These include implementation of sensors and sampling to determine nutrient loading to surrounding waters.
    b. And sampling of surrounding benthic soils to determine overall nutrient deposition.
    c. IMTA operations can serve to mitigate nutrient loading, as explored by Chambers et al. (2024) and others.
2) Interventions to prevent genetic contamination of wild fish.
    a. These include growing native fish species and should be expanded to include cultivating native shellfish and seaweed species as well.
    b. Cultivating sterile fish, so that in the event of fish escape risks of genetic interchange are reduced.
    c. Monitoring pens with cameras, sensors, and routine maintenance checks, so that issues are rapidly identified, and extents of escape can be quantified.
3) Interventions to minimize disease contamination of wild fish.
    a. These include sampling smolts, embryos, and adult fish at numerous points for pathogen levels, to proactively identify emerging issues related to bacterial or viral loads.
    b. Using a variety of vaccinations, including vaccinations for multiple strains of infectious hematopoietic necrosis virus, to improve fish resilience.
    c. Mandating fallow periods between harvests to thoroughly clean net pens and ensure no viral or bacterial particles are left behind between cohorts.

**Limitations:**

As mentioned previously, by focusing exclusively on the nutrient loading effects of IMTA aquaculture, this thesis fails to cover many other forms of environmental impact, including but not limited to: predation of protected species due to cultured fish escape or intrusion of young individuals of protected species into the pen system where they are predated upon, bacterial and/or viral transfer from cultured organisms to wild species, antibiotic escape caused by medicated fish feed or unmetabolized fish metabolites escaping the pen system (NOAA 2022), debris from pen and/or line structures dislodged during storm event impact local habitat, genetic transfer between escaped cultivated fish which were missed by sterilization treatment and wild fish, and changes in chemical concentrations of waters surrounding net pens for nutrients other than those analyzed in the thesis. Additionally, while the model was calibrated using parameters taken from the literature (Chambers et al., 2024, NOAA 2020) that are applicable to native species cultivated in the operation, nitrogen and phosphorus concentrations in animal tissue can be highly variable even within species due to variations in genetics and physical, chemical, and/or hydrological environmental conditions. Utilization of a model concretely grounded in spatially specific observations of mussel and sablefish growth would be preferable to the current model. Finally, observations on the growth curve of sablefish were interpolated from only one study, and the growth rate of mussels was abstracted within the simulation to yield a realistic product without necessarily charting a realistic growth curve for those organisms at all stages of mussel growth. Additionally, the current iteration of the model linearly interpolates expected mussel growth for simplicity, a more robust model would do away with this abstraction and simulate mussel growth curves grounded in experimentation and observation, such as those proposed by Millstein and O'Clair (2001). Dynamic Energy Budget

models, like those pursued by Ren and peer researchers (Ren et al, 2012) could provide a valuable framework for more sophisticated and spatially specific IMTA operations.

## Conclusion:

Offshore integrated multitrophic aquaculture systems are an appealing and significant topic of research because they dangle the possibility of procuring large amounts of sea proteins for human consumption in an environmentally sustainable manner. They can operate outside of coastal and riverine waters, ensuring that these valuable (and often expensive) environments can be preserved while proteins are produced for terrestrial populations. Shellfish and seaweed operations which have improved water quality have been covered extensively in the literature, cultivating fish might take pressure off wild fisheries, and cultivating indigenous species in these operations might serve to bulwark indigenous wild populations. With the United States of America running a substantial seafood production deficit, importing large amounts of seafood from abroad, it may be valuable to consider the economic, social, and environmental benefits of conducting IMTA operations domestically. This thesis is just a starting point in examining one aspect of IMTA operations involving mussel and sablefish, but hopefully will arouse some interest in this promising form of food production in readers.

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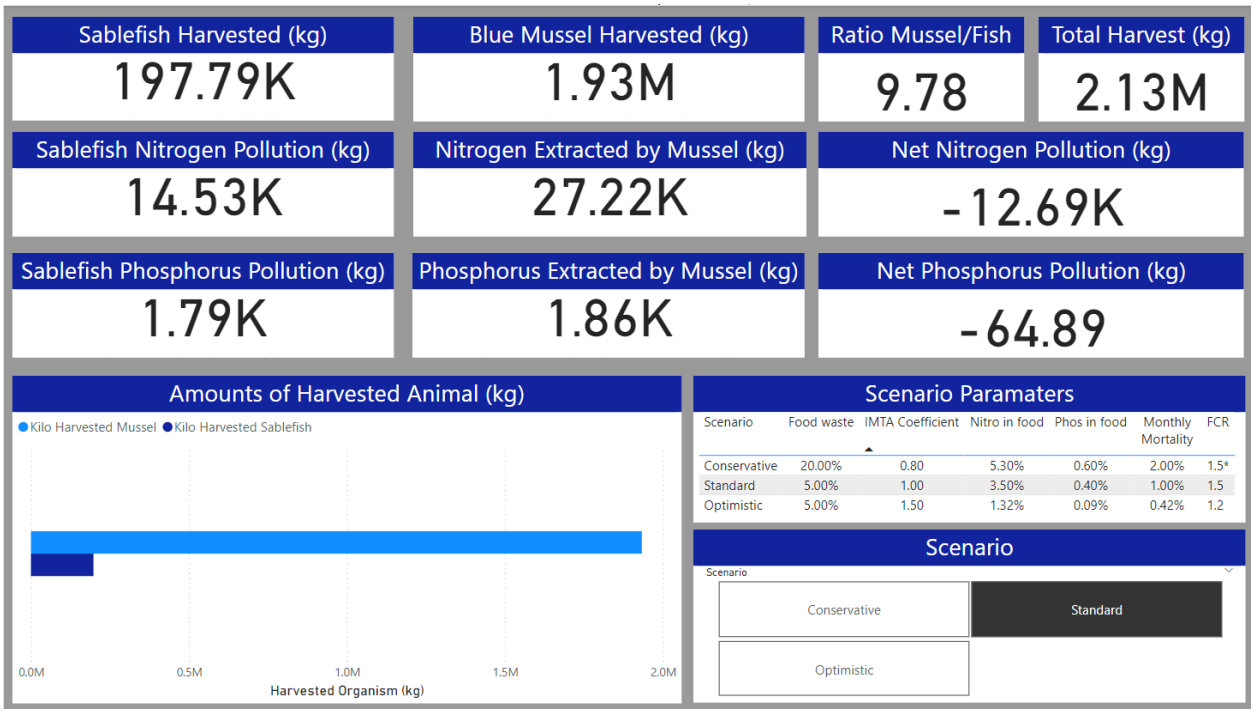
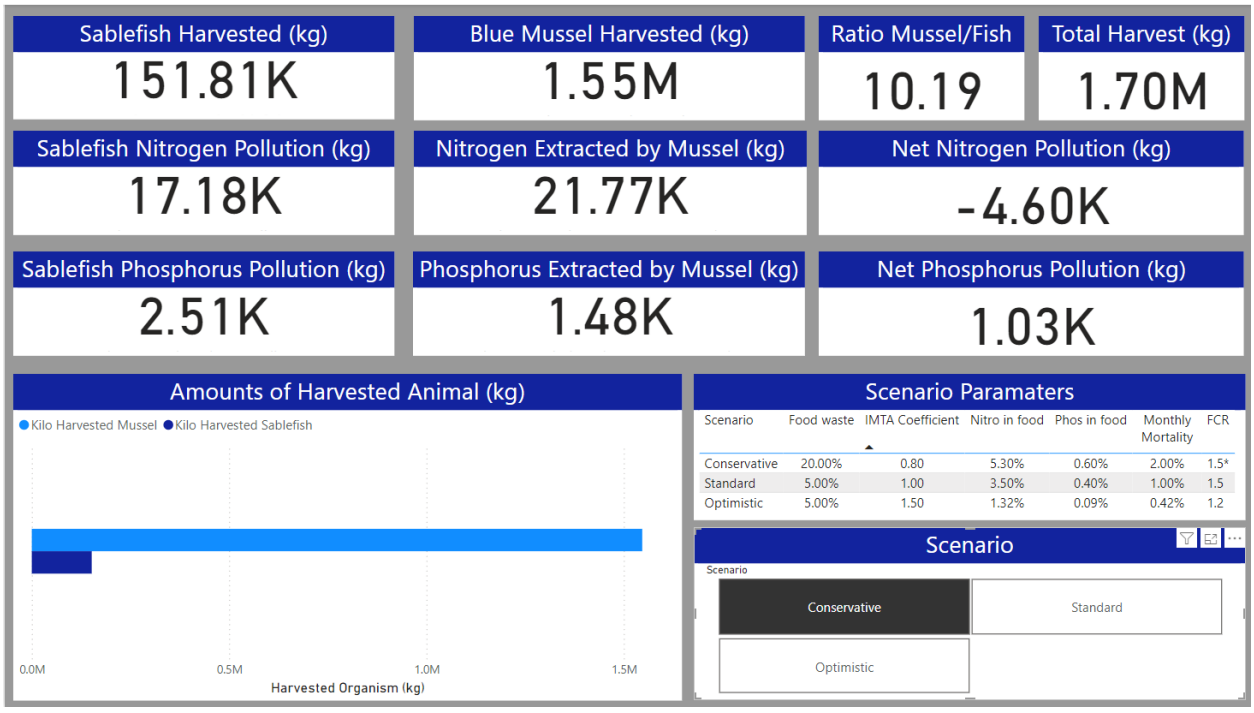
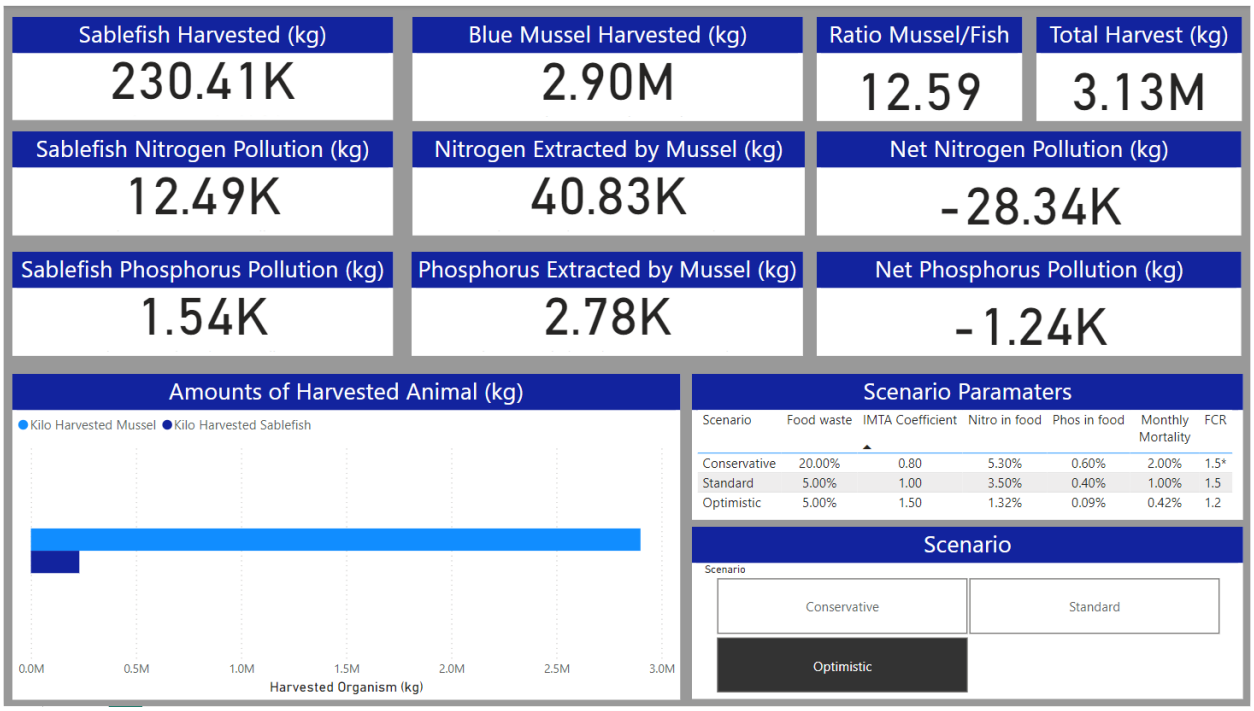
# Appendix 1 – Results of Model Scenarios:

Power Business Intelligence presentations for standard, conservative, and optimistic scenarios respectively:




Sablefish Harvested (kg)
230.41K
Blue Mussel Harvested (kg)
2.90M
Ratio Mussel/Fish
12.59
Total Harvest (kg)
3.13M
Sablefish Nitrogen Pollution (kg)
12.49K
Nitrogen Extracted by Mussel (kg)
40.83K
Net Nitrogen Pollution (kg)
-28.34K
Sablefish Phosphorus Pollution (kg)
1.54K
Phosphorus Extracted by Mussel (kg)
2.78K
Net Phosphorus Pollution (kg)
-1.24K
Amounts of Harvested Animal (kg)
Kilo Harvested Mussel
Kilo Harvested Sablefish
0.0M
0.5M
1.0M
1.5M
2.0M
2.5M
3.0M
Harvested Organism (kg)
Scenario Paramaters
Scenario
Food waste
IMTA Coefficient
Nitro in food
Phos in food
Monthly Mortality
FCR
Conservative 20.00% 0.80 5.30% 0.60% 2.00% 1.5*
Standard 5.00% 1.00 3.50% 0.40% 1.00% 1.5
Optimistic 5.00% 1.50 1.32% 0.09% 0.42% 1.2
Scenario
Scenario
Conservative
Standard
Optimistic

## Appendix 2 - R Code:

FishCalc.R:

```
library(tidyverse)
library(readxl)
library(zoo)
fishDF <- data.frame(read_excel("<READ LOCATION>, sheet = 1, col_names=TRUE))
fishSizeDF <- data.frame(read_excel(<READ LOCATION>, sheet = "FishSize",
col_names=TRUE))
fishSizeDF <- data.frame(na.approx(fishSizeDF))

#Nitrogen and phosphorus loading estimates from:
#Islam, M. S. (2005). Nitrogen and phosphorus budget in coastal and marine cage
#aquaculture and impacts of effluent loading on ecosystem: Review and analysis
#towards model development. Marine Pollution Bulletin, 50(1), 48–61.
#https://doi.org/10.1016/j.marpolbul.2004.08.008
#Ratios given in kg of nutrient / kg of fish feed
nitrRatio = 0.065
phosRatio = 0.014
nitrRatioPostAss = 0.035
phosRatioPostAss = 0.004
harvestMonth <- 26;
#Conservative FCR is 1.5
feedConversionRate <- 1.5;
#Portion of food actually consumed by fish
feedEfficiency <- .8;
#Conservative is 1% mortality per month,
fishMortalityMonthly <- 0.02;

calculateNumber <- function(currentMonth, fishDF, appendDF, fishMortalityMonthly){
```

```
  previousDF <- fishDF %>% filter(Month==currentMonth-1)
  #for each row of appendDF passed to calculate number, check previous moth of
  #the fishDF dataframe for that row's cohort. If that cohort did not exist
  #or was harvested initialize a new cohort otherwise, run the appropriate
  #calculate new values using fishMortalityMonthly.
    appendDF <- appendDF %>%
      left_join(previousDF, by = "FishCohort") %>%
      mutate(
        new_row = ifelse(is.na(NumberFish), TRUE, FALSE),
        NumberFish = ifelse(NumberFish == 0 | is.na(NumberFish), 1000, (1 -
fishMortalityMonthly) * NumberFish),
      ) %>% select(Month.x, FishCohort, NumberFish) %>%
      rename_all(~gsub(".x", "", .))
    return(appendDF)
};
ageFish <- function(currentMonth, fishDF, appendDF, fishSizeDF){
  #If new cohort (did not exist last month), age is 0.
  #Otherwise add 30 days to age
  previousDF <- fishDF %>% filter(Month==currentMonth-1);
  appendDF <- appendDF %>%
    left_join(previousDF, by = "FishCohort") %>%
    mutate(
      CohortAge = ifelse(is.na(NumberFish.y) | NumberFish.y == 0, 0, 30 + CohortAge)
    ) %>% select(Month.x, FishCohort, NumberFish.x, CohortAge) %>%
    rename_all(~gsub(".x", "", .));
  return(appendDF)
}
calculateMass <- function(appendDF, fishSizeDF){
  #Interpolate mass from observations.
  appendDF <- appendDF %>%
```

```
    left_join(fishSizeDF, by = "CohortAge") %>%
    select(Month, FishCohort, NumberFish, CohortAge, MonosexWeight) %>%
    rename_all(~gsub(".x", "", .))
  return(appendDF)
};
calculateHarvest <- function(appendDF, harvestDate){
  #Interpolate mass from observations.
  #print(colnames(appendDF))
  appendDFNoHarvest <- appendDF %>%
    filter(harvestDate!=CohortAge/30) %>%
    mutate(MeanHarvestedFishMass = 0, NumHarvestedFish = 0)
  appendDFHarvest <- appendDF %>%
    filter(harvestDate==CohortAge/30) %>%
    mutate(MeanHarvestedFishMass = MonosWeight, NumHarvestedFish = NumberFish,
           MonosWeight=0, CohortAge=0, NumberFish=0)
    appendDF <- rbind(appendDFHarvest, appendDFNoHarvest)
  return(appendDF)
};
calculateFeed <- function(currentMonth, fishDF, appendDF, fcr, feedEfficiency){
  previousDF <- fishDF %>% filter(Month==currentMonth-1)

  appendDF <- appendDF %>%
    left_join(previousDF, by = "FishCohort") %>%
    mutate(
      FeedRequired = (MonosWeight - MeanFishMass) * fcr * (1 / feedEfficiency) *
        (NumberFish.x + NumberFish.y) / 2)  %>%
    select(Month.x, FishCohort, NumberFish.x, CohortAge.x, MonosWeight,
           FeedRequired) %>%
    rename_all(~gsub(".x", "", .))
  return(appendDF)
```

```
};
calculateNitrogen <- function(appendDF, nitrRatio, nitrRatioPostAss, feedEfficiency){
  appendDF <- appendDF %>%
    mutate(NitrogenPollution =  FeedRequired * feedEfficiency * nitrRatioPostAss +
             FeedRequired * (1 - feedEfficiency) * nitrRatio)
  return(appendDF)
}
calculatePhosphorus <- function(appendDF, phosRatio, phosRatioPostAss, feedEfficiency){
  appendDF <- appendDF %>%
    mutate(PhosphorusPollution =  FeedRequired * feedEfficiency *
             phosRatioPostAss +
             FeedRequired * (1 - feedEfficiency) * phosRatio)
  return(appendDF)
}
#calculateHarvest <- function(appendDF){}

nitrRatio = 0.065
phosRatio = 0.014
#And these ratios are after fish assimilation is accounted for
#(fish hold nutrients, reducing total pollution upon fish harvest)
nitrRatioPostAss = 0.035
phosRatioPostAss = 0.004



calculateFish <- function(monthDuration, numberCohorts, fishDF,fishSizeDF,
                          harvestMonth, fcr, feedEfficiency, nitrRatio,
                          nitrRatioPostAss, phosRatio, phosRatioPostAss,
                          fishMortalityMonthly){
  #cohort Iterator
  ci <- 1;
```

```
#month iterator
mi <- 1;
fishDFVar <- fishDF;
while(mi <= monthDuration){
  #establish one row for each cohort, adding a cohort each month up to max cohorts
  monthFrame <- c(1)
```