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INTEGRATING DUCKWEED INTO AN AQUAPONICS SYSTEM

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ABSTRACT OF THE THESIS

Integrating Duckweed into an Aquaponics System

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Aquaponics, the combination of aquaculture and hydroponics, can lead to sustainable food production. This study shows how duckweed can add value to an aquaponics system. It builds off of a previous case study that explored the addition of hydroponic grown buttercrunch lettuce to a barramundi fish production system. That case study concluded that the benefits of the integrated system include the reduction in barramundi effluent disposal costs, and saving of water and nutrient costs of the lettuce system. We build off that analysis by adding duckweed to the integrated system, and compare the variable costs and revenue of a production system of barramundi and lettuce, to that of barramundi, lettuce, and duckweed. Duckweed serve as fish feed and a biological filter. The addition of duckweed results in a decrease in feed cost and effluent disposal cost, as well as significantly reduced the area needed to build the integrated system.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

The global population is expected to grow by another 2 billion people by 2050 (FAO 2014). That will put the worldwide population at a total of 9.6 billion people. With this expected population growth, our planet faces a detrimental challenge of feedings its people while maintaining its natural resources for future generations. Therefore, it is critical that new approaches of feeding this growing population continue to be explored. One promising approach is aquaponics. Aquaponics is the method of growing fish and plants simultaneously in a symbiotic polyculture system. The waste products of the fish are used as nutrients for the plants. The plants will then clean the water as they grow. This approach improves on normal fish culture by saving water, yielding multiple marketable products, reducing harmful discharges into the environment, and decreasing land space. To be successful intensive management and close attention need to be stressed in order to achieve optimal harvests. One successful approach is using highly effective biological filters to keep the water clean and reduce harmful discharges into the environment.

One aquatic plant has stands from the rest in filtering harmful effluent. Duckweed can be found in almost every environment. These plants have been used in wastewater treatment plants in many countries. Duckweed has the ability to grow faster than any other plant and can double their mass in only a few days. They distinguish themselves from other efficient wastewater treatment methods by accumulating a valuable, protein-rich biomass as a byproduct. These plants make a great addition to an aquaponics system by increasing the uptake of nitrogen and phosphorous found in fish effluent, while being able to fully feed the fish.

While the addition of duckweed appears to be ideal in theory, it is not economically sustainable unless it increases the profits of the farmers who use aquaponics. The objective of this paper is to assess the economic impact of adding duckweed to an aquaponics system. The impact assessment is broken down into the following components: changes in variable costs, changes in revenue, changes in profit, and changes in some capital requirements in the form of space needed to grow components of the aquaponics system.

The thesis is organized as follows: The first section explores the need for aquaculture as a means of feeding a world facing an increasing population growth. Next section examines the different aquaculture practices and how recirculating aquaculture production systems can decrease water usage. We then explain the production systems of hydroponics and aquaponics. After that we look into the aquatic plants of duckweed and how they can add value to aquaponic systems. Then to understand what practices need to be adopted for an effective aquaponics system, we analyze four case studies that shed light on successful and unsuccessful practices in aquaponic operations. We further elaborate one of those case studies and compare their aquaponics system to the same system with the integration of duckweed. We analyze the differences of revenue and variable costs that incur in one batch of production.

Chapter 2: Food Insecurity & the Importance of Aquaponics

Currently there are more than 800 million people who suffer from chronic malnourishment. The Food and Agricultural Organization of The United Nations (FAO) warns that protein-energy malnutrition (lack of calories and protein) in young children is currently the most important problem in most countries in Asia, Latin America, the Near East, and Africa (Latham 1997). The critical need to feed the population pushes for new sources of food and nutrients to be explored and utilized.

With 71% of the earth's surface made up of water, it's no surprise that fish have become a popular avenue of utilization (USGS 2016). Fish is used in many developing countries as a primary source of protein. 2010 estimates show that fish accounted for 17% of animal protein intake and 6.5% of all global protein consumed (HLPE 2014). The fish food supply has been increasing at an average annual rate of 3.2% over the last 50 years, outpacing world population growth during that time by 1.6%. This growth is due to a combination of population growth, rising incomes and urbanization, and is facilitated by the strong expansion of fish production and more efficient distribution channels (FAO 2014).

It is estimated that more than 158 million people in the world depend directly on fish-related activities (fishing, fish farming, processing, and trading) and more than 90% of them run small scale operations in developing countries (HLPE 2014). Further FAO research undertaken in "The State of World Fisheries and Aquaculture" found that fish consumption per capita in developing regions has surged from 5.2 kg in 1961 to 17.8 kg in 2010. This is still well behind the consumption by developed regions, although the gap is narrowing. Stemming from local and seasonally available products, supply used to drive the fish chain in developing countries. However, rising domestic income and wealth, are allowing consumers in emerging economies to experience a diversification of the types of fish available, owing to an increase in fishery imports. The proportion of assessed marine fish stocks fished within biologically sustainable levels declined from 90% in 1974 to 71.2% in 2011, when 28.8% of all fish stocks were overfished. There is no more room for expansion in catch, and effective management practices and/or substitutions need to be implemented to appease demand for future generations (FAO 2014).

Fish play an important role in food security due to the fact that it is easily available, accessible, and nutrient dense. Fish is a particularly nutritious food, rich in numerous micronutrients that are often missing in diets. Fish contains essential nutrients such as iodine, vitamin B12 and D, the long-chain fatty acids (LC-PUFA), eicosapentaenoic (EPA) and docosahexaenoic (DHA) omega-3 fatty acids, and high quality protein. Fish is also very rich in calcium, iron, zinc, and Vitamin A (HLPE 2014). When it comes to economic growth and malnutrition the advent of “aquaculture”, could be used to improve desolate conditions. Aquaculture simply means, “The cultivation of aquatic organisms (as fish or shellfish) especially for food” (Merriam-Webster 2016). Increasing the production of fish can be used as a tool to feed families all over the globe.

Chapter 3: Aquaculture

Aquaculture ranges in intensity from simple weeding of natural stands of algae to complete husbandry of domesticated fish like trout and carp. Aquaculture could allow most countries to meet their population's protein needs without depleting the earth's wild stock of fish. Usually only one species of fish is raised in typical aquaculture productions, although a few to several compatible species may be cultivated simultaneously (Bardach 1968). Early examination in "Aquaculture", John Bardach stated to be productive for husbandry, aquatic animals should have the following characteristics:

i) "They should reproduce in captivity or semi-confinement to make selective breeding possible".

ii) "Their eggs or larvae, or both, should be fairly hardy and capable of being hatched or reared under controlled conditions".

iii) "The larvae or young should have food habits that can be satisfied by operations to increase their natural foods, or they should be able to take extraneous feeds from their early stages".

iv) "They should gain weight fast and nourish themselves entirely or in part from abundantly available food that can be supplied cheaply, or that can be readily produced or increased in the area where the cultured species live" (1098).

Few aquatic organisms have all these attributes. In addition to economic constraints, success depends in part on how biological and engineering innovation can make the missing characteristics less crucial (Bardach 1968).

Most products of aquaculture could be considered luxury foods, seen as indulgences rather than necessities (Dictionary 2016), capable of bringing a good return to the producer. In this sense it might appear unrealistic to expect aquaculture to help alleviate the world protein deficiency, but this may not necessarily be the case. Luxury foods stop being a luxury when they can be mass produced, a case well documented by the broiler chicken industry in the United States. Upgrading the culture methods could reduce yields per unit of effort per unit of weight leading to more yield with less work. Under ideal conditions, production of animal flesh from a unit volume of water far exceeds that attained from a unit of surface of ground (Bardach 1968). Population growth has created an increase in competition from other users of land, water, and other resources. Developing sustainable management and production practices is becoming a necessity.

Aquaculture is nothing new. Early estimates date the beginning of this form of farming to 2000-1000 B.C. on the continent of China, where a strong carp husbandry and culture is maintained to this day (Rabanal 1988). Over the last decade fish aquaculture has grown globally at an annual rate of 6.2%, outpacing all other food-producing industries (FAO 2014). In “Aquaculture Systems and Practices: A Selected Review”, Baluyet identified that aquaculture practices are used world-wide in three types of environments (freshwater, brackish water, and marine) for a wide array of culture organisms. "Freshwater aquaculture can be carried out in fish ponds, fish pens, fish cages, or on a limited scale, in rice paddies" (3). Aquaculture found in brackish water is usually carried out in fish ponds located in coastal areas. "Marine culture uses fish cages or substrates for mollusks and seaweeds such as stakes, ropes, and rafts" (3). Baluyet continues to explain that these culture systems range from extensive to intensive depending on stocking density of the culture organisms, the level of inputs, and degree of management. Extensive systems use low stocking densities (e.g. 5,000-10,000 shrimp post larvae (PL)/ha/crop) and no supplemental feeding. Some fertilization may be used to stimulate the growth and production of natural food in the water, and water is let in using tides. Semi-intensive systems use higher stocking densities than extensive systems (e.g. 50,000-100,000 shrimp PL/ha/crop) and use supplemental feeding. Intensive cultures use very high stocking densities (e.g. 200,000-300,000 shrimp PL/ha/crop), and is exclusively dependent on artificial, formulated feeds. Each system uses small pond compartments of up to one ha (2.47 acres) in size for ease of management. Additional management of applying inputs (feeds, fertilizers, lime, and pesticides) and manipulation of the environment, primarily through water management using pumps and aerator, can help achieve added productivity (Baluyut 1989).

Drawbacks from aquaculture's environmental impacts on land, water, and biodiversity, have led to the exploration of new types of production systems. Resource conservation of water and land, plus growing environmental concerns of effluent discharges, has sparked interest in intensive, recirculating aquaculture production systems (RAS). Recirculation aquaculture is a technology for farming aquatic organisms, usually indoors, which reuses the water in production by utilizing mechanical or biological filters (Bregnballe 2015). Although recirculation system technology has been used for over 30 years, it is still at a relatively early stage of development when it comes to large-scale commercial operations (Murray 2014). These recirculating systems provide several advantages over the more traditional pond production practices.

(i) *Recirculating systems allow for a high degree of control over key physical and chemical parameters of the culture environment*.

All-important water quality parameters (temperature, dissolved oxygen, ammonia, and pH) can be controlled for optimal growth and feed conversion (Ebelling 2000). Traditional fish farming is dependent on external conditions such as water temperature of the river, cleanliness of water, oxygen levels, or weed and leaves drifting and blocking inlet screens, etc. Controlling these parameters creates stable and optimal conditions for fish, which causes less stress and promotes better growth (Bregnballe 2015).

(ii) *Recirculating systems require only a fraction of the water that is required by pond production systems* (Ebelling 2000).

Intensive farming systems installed inside a closed insulated building can use as little as 300 liters of new water, and sometimes less, per kilo of fish produced per year. That is a significant decrease compared to traditional flow-through systems for trout that typically use $30m^3$ (30,000 liters) per kilo of fish produced per year. Systems of traditional outdoor farms rebuilt into recirculated systems showed a drastic reduction, using only $3m^3$ (3,000 liters) of new water per kilo of fish produced per year (Bregnballe 2015).

(iii) *Indoor tank-based systems can be sited anywhere and make year round production possible* (Ebelling 2000).

This can provide a degree of biosecurity through measures to isolate the stock from the external environment (Murray 2014). The impact of pathogens is lowered considerably because invasive diseases from the outside environment are minimized through the limited use of water. Traditional fish farms take water from a river, lake, or sea, which naturally increases the risk of dragging in diseases. These stable conditions result in a steady and foreseeable growth pattern that enables the farmer to precisely predict when the fish will reach a certain stage or size. A precise production plan can then be drawn up to predict the exact time the fish will be ready for sale, favoring overall management of the farm and strengthening the ability to retail the fish in a competitive way. The controlled structure can also make the systems easier to study and forecast future results (Bregnballe 2015). Knowing the production schedule allows farmers to take a market base approach, trying to match seasonal supply and demand. This precise control allows aquatic species to be cultured out of their normal climatic range, allowing producers to prioritize production goals linked to the optimal criteria of market, regulatory, or resource availability (Murray 2014).

The limited amount of water used in recirculation is beneficial since water has become a limited resource in many regions. It also makes it much easier and less expensive to remove the nutrients excreted from the fish as the volume of discharged water is much lower than that discharged from a traditional fish farm. This discharged wastewater, which contains nitrogen, can then be used to fertilize agricultural farmland, although this nitrogen waste product could pose a potential challenge if accumulated at high levels. The couplet of increased production and decreased water use makes recirculation agriculture one of the most environmentally conscious ways of producing fish at a commercially viable level (Bregnballe 2015). The main disadvantages of intensive recirculating systems are high operating expenses of energy cost and management, large capital investments, and risk of total crop loss (Ebelling 2000). RAS are highly dependent on electricity or other power sources. Pumps must be used in order to maintain the constant flow of water, and this water likely needs be heated or cooled in order to maintain ideal temperatures. A less expensive and environmentally friendly option would be to take advantage of alternative energy and heating sources (White 2004). Although recirculating systems use less water, and the controlled environment allows for flexibility in time and location of operations. This increased control comes at a cost, recirculating systems need to be managed efficiently in order to be successful operations.

Chapter 4: Hydroponics

A factor to keep in mind is that biological filters are required in systems with high levels of water recirculation. The level of water renewal in recirculating systems depends on the bio-filter's ability to efficiently remove toxic metabolites resulting from metabolism, as well as the amount of water lost when removing the accumulated waste products from the bio-filters. The addition of "hydroponic" units to biological filters in recirculating systems has the potential to increase the bio-filter efficiency plus provide a complimentary income from the plants being produced (Malone 1993). Hydroponics is the production of plants in a soilless medium whereby all of the nutrients supplied to the crop are dissolved in water. The major advantages of hydroponics are that plants can be grown where suitable soil is not available for cultivation, and weeds and soil pathogens are usually not a major problem in these systems (Philipsen 1985). There are three main hydroponic techniques: media bed units, nutrient film technique (NFT), and deep water culture (DWC).

(i) Media bed units, also known as particulate beds, grow plants in a substrate (e.g., gravel).

(ii) In the nutrient film technique, also known as vertical systems, plants grow with their roots in wide pipes supplied with a trickle of culture water.

(iii) Deep water culture, also known as floating bed systems, suspends plants above a tank of water using a floating raft.

Each method has its advantages and disadvantages, all with different component styles to suit the needs of each method (Somerville 2014). For example, sand/gravel systems (media beds) may remove the need for a separate bio-filter because the substrate will also act as a solids-filtering medium, replacing the need for a conventional bio-filter. On the other hand, the sand/gravel substrate can clog easy, leading to water channeling, inefficient bio-filtration, and inefficient delivery of nutrients to plants. NFT tend to be easier to construct and are much lighter than other systems, but have not yet received much research attention in aquaponic systems (Lennard 2006).

Chapter 5: Aquaponics

The combination of Aquaculture and Hydroponic systems has led to a technique known as "Aquaponics." Aquaponics is a bio-integrated system that links recirculating aquaculture with hydroponic vegetable, flower, and/or herb production (Diver 2010). Recirculating systems are designed to raise large quantities of fish in small volumes of water by treating the water to remove toxic waste products. As the water is reused many times over the non-toxic nutrients and organic matter accumulate. These metabolic by-products can be utilized by channeling them into secondary crops. If these secondary crops are aquatic or terrestrial plants grown in conjunction with fish, this integrated system is an aquaponics system. This integrated system allows for a reduction of discharge to the environment and the extension of water use (Rakocy 2005). Improvement in water efficiency gives these systems the potential to be more environmentally sustainable. Integrating production systems and reducing the use of chemicals can reduce ecological impact while increasing productivity. Merging two disciplines, wastewater treatment and crop production, can maximize the recycling rates of phosphorous and nitrogen resulting in increased plant biomass and effluent water (Graber 2009). In RAS systems removal efficiencies were between 85% and 98% for organic matter and suspended solids, and between 65% and 96% for phosphorous. Aquaponics are recirculating systems which act as small scale ecosystems where no waste is released into the environment. This closed-loop system mimics a natural system that provides an eco-friendly and sustainable system for the agriculture sector (Blidariu 2011).

The concept of using fecal waste from fish to fertilize plants is nothing new. Early civilizations in both Asia and South America have used this method for millennia. Aquaponic systems did not receive much attention until pioneering work from the New Alchemy Institute and other North American and European academic institutions revitalized this age old practice in the late 1970's. Fueled by further research in the following decades, the basic form of aquaponics evolved into the modern food production systems of today (Somerville 2014). Aquaponic systems are now being practiced on every continent and in at least 43 countries around the world (Love 2014). These systems can serve as models of sustainable food production for several reasons:

i) The waste products of one biological system (fish) serve as nutrients for a second biological system (plants).

ii) The integration of fish and plants results in a polyculture that increases diversity and yields multiple products.

iii) Water is re-used through biological filtration and recirculation.

iv) Lastly, the production of local food in this system can provide access to nutrient rich foods and enhance the local economy (Diver 2010).

Fish effluent contains significant levels of ammonia, nitrate, nitrite, phosphorous, potassium, and other secondary and micronutrients to produce hydroponic plants and kick start the whole system (Diver 2010). In "Aquaponics: Community and Economic Development", Elisha Goodman believes it is understood among scientists that the nitrogen cycle, which provides fertility to the plants and cleans the water for the fish, is the biochemical engine that drives the aquaponics system. “The nitrogen cycle occurs as water flows from fish tanks, to biological filters containing bacteria, to plants, and back again. The major input into the nitrogen cycle is the fish feed that is thrown into the fish tanks” (9). This fish feed can be either commercial or aquatic plants.” Aquatic plants can be grown in the system itself or elsewhere on site” (9). Uneaten fish food and fish effluent will break down into ammonia (NH3). Typically this wastewater then flows into a biological filter. The biological filter use Nitrosomonas bacteria to convert the ammonia into nitrite, and then a second type of bacteria, Nitrobacter bacteria, to convert the nitrite into nitrate (NO3). The nitrate then flows through the pipes into the hydroponics portion of the system where it serves as fertilizer for the plants. In this hydroponic component, the plants function as a filter as they absorb the nitrate, which allows the plants to thrive, and improves system efficiency as a whole. This process purifies the water, which circulates back to the fish tanks and provides clean, fresh water in which the fish thrive (Goodman 2011).

Modern aquaponic systems can be highly successful, but they require intensive management and have special considerations. “Aquaponics-Integration of ATTRA Hydroponics with Aquaculture” by Steve Diver finds that the selection of plant species adapted to hydroponic culture is related to the stocking density of fish tanks and subsequent nutrient concentrations of aquacultural effluent. “Lettuce, herbs, and specialty greens (spinach, chives, basil, and watercress) have low to medium nutritional requirements and are well adapted to aquaponic systems” (2). Plants yielding fruit (tomatoes, bell peppers, and cucumbers) have a higher nutritional demand. These plants grow better in heavily stocked, well established aquaponic systems. Tilapia is the most common species of fish grown in commercial aquaponic systems in North America. This is due to the fish's tolerance for fluctuating water conditions such as pH, temperature, oxygen, and dissolved solids. Barramundi and Murray cod fish species are the most commonly grown species in Australia. However other warm water and cold water fish species of trout, perch, Arctic char, and bass are well adapted to recirculating aquaculture systems as well (Diver 2010).

The stocking density and growth rate of fish, feeding rate and volume, and related environmental fluctuations can elicit rapid changes in water quality, so attentive water quality monitoring is essential. Aquaponic systems are made of a fish and plant component. Matching the volume of fish tank water to the volume of hydroponic media is known as component ratio. Early component ratios used were 1:1 meaning the fish tank volume equally matched the hydroponic plant component. Now 1:2 is common and some as high as 1:4 are used. The variation in range depends on the type of hydroponic system, fish species, fish density, feeding rate, plant species and other characteristics of the system (Diver 2010). The average fish will pass through the life stages of egg, larvae, fry, fingerling, juvenile, grow-out (adult fish), and finally sexual maturity (spawning adult). Fish require the correct balance of proteins, carbohydrates, fats, vitamins and minerals to grow healthy and reach maturity (Somerville 2014).

Commercially available fish feed pellets are highly recommended for small-scale aquaponics, especially at the beginning (Somerville 2014). Fish feeds simplify feed management, but typically significantly increase operating costs because they cost more than fertilizer, manures, or compost. Fish feeds are usually blended from a variety of vegetable and animal products in order to provide the necessary nutrients for fish to grow. Fish grow best on a balanced diet with a balanced amino acid profile (Skillicorn 1993). Protein is the most important component for building mass. In “Small-scale aquaponic food production”, Christopher Somerville describes that Younger fish (fry and fingerlings) require diets richer in protein than fish in the grow-out stage. At the fry and fingerling stage fish eat about 10% of their body weight per day. As the fish continue to grow, the percentage body weight of food per day decreases. The grow-out stage is the stage aquaponics typically focus on because it is when the fish are eating, growing, and excreting wastes for the plants. Most fish are harvested during the grow-out stage. After this stage they reach sexual maturity and their physical growth slows down as they devote more energy into the development of sex organs (Somerville 2014).

The three major physical inputs in the aquaponic systems are water, energy, and fish feed. A 2013 international survey of over 809 respondents practicing aquaponics highlighted the diversity of these inputs used in different operations. The survey found that 90% of the respondents used traditional drinking water sources (e.g. community-piped water or well water) and 39% of them supplemented it with rainwater capture. Only 8% of respondents used surface water (e.g. streams, lakes, springs, or reservoirs) to supplement water supply when they had no access to drinking water. Surface water isn’t recommended in aquaponic systems because it may contain fish and human microbial pathogens as well as other organisms. The vast majority (95%) of respondents used electricity from the power grid to run their systems. About 5% of respondents used propane or natural gas to supplement electricity, but many more (57%) used forms of renewable energy, the most popular being sunlight, to supplement electricity from the grid. To feed their fish 94% of respondents used feed pellets, which are usually sold commercially as a complete feed. Some respondents supplemented the use of feed pellets with alternative sources such as aquatic plants (33%), live feed (e.g. black soldier flies and earthworms) (30%), or human food scraps (13%) (Love 2014).

The most common animals raised in aquaponic systems were tilapia (55%) and ornamental fish (e.g. koi, goldfish, and tropical fish) (48%), followed by catfish, perch, bluegill, trout, and then bass. The average respondent grew 8 (+/- 5) crops in aquaponic systems and the most common crops were basil (70%), tomatoes (69%), and salad greens (64%). The largest commercial system was built on 1.9 hectares (4.6 acres) of land, but the average system was housed on the respondents' property (indoors or in a greenhouse) and contained 500 gallons of water and took up $15m^2$ of space. Most of the respondents practiced aquaponics as a hobby, but they were knowledgeable about how to maintain their system's infrastructure (fish and crops), and their main reasons for this engagement was to grow their own food, improve personal health, and advance environmental sustainability (Love 2014). With an integrated model for best practices aquaponic systems can provide economic benefits as well. Research should continue to examine the best combination of management, fish, plants, and food to optimize results.

Chapter 6: Duckweed

One biological filter and aquatic fish feed crop that has been heavily studied in cleaning effluent water is Lemnaceae, more commonly known as Duckweed. Duckweeds are some of the smallest and simplest flowering plants, consisting of an ovoid frond (leave) a few millimeters in diameter and a short root usually less than 1 cm long. They are monocotyledons belonging in the botanical family Lemnaceae and are classified as higher plants, or macrophytes, although they are often mistaken for algae. The duckweed family consists of four genera, Lemna, Spirodela, Wolffia, and Wolffiella, among which about 40 species have been identified (Skillicorn 1993). Lemna species are intermediate size at 6-8 mm, Spirodela have the largest fronds measuring as much as 20 mm across, while Wolffia are smallest at 2mm or less in diameter (Skillicorn 1993). Differentiation and identification of the genus is difficult and perhaps irrelevant. This is because species that grows on any water is the one with the characteristic requirement of that particular water and the dominant species will change with any variation of water quality, topography, management, and climate (Leng 1999).

Reproduction normally occurs through the budding of mature fronds so a population of duckweed is actually a population of individual fronds that can reproduce and divide to produce daughter fronds. The rate at which this occurs is affected by temperature, availability of nutrients in the medium and light intensity (Cheng 2009). The Lemnacae family is worldwide, but most diverse species appear in subtropical and tropical areas. These readily grow in the summer month in temperate and cold regions and occur in still or slowly moving water and will persist in mud. Luxurious growth occurs in sheltered small ponds, ditches, or swamps where there are rich sources of nutrients (Leng 1999).

The growth behavior of individual species can be studied under controlled conditions (such as those present in a growth chamber), and mathematical relationships derived from this behavior can be applied to the more natural conditions present in a field environment, such as a wastewater treatment plant or aquaculture farm (Cheng 2009). Duckweed species have adapted to a wide variety of geographic and climatic zones. It can be found in every environment except waterless deserts and permanently frozen Polar Regions. To cultivate duckweed a farmer needs to organize and maintain conditions that mimic its natural environmental niche: a sheltered, pond-like culture plot and a constant supply of water and nutrients (Skillicorn 1993). Duckweed is a perfect addition to aquaponic systems due to its durability and ability to grow in water that contains effluent waste.

Duckweed has created a niche by acquiring the ability to clean and thrive off of wastewater in fresh as well as brackish water. As water pollution threatens local ecosystems, where agriculture can be a main source of this pollution, biological mechanisms to clean water need to be more viable. Like all photosynthetic organisms, duckweed grows with only requirements for minerals, utilizing solar energy to synthesize biomass. However, they have the capacity to utilize preformed organic materials and can grow without sunlight when provided with such energy substrates

(Leng 1999). Duckweed, like all plants, need an array of trace elements (nitrogen, phosphorous, potassium), and have well developed mechanisms for concentrating these from dilute sources (Goopy 2003). When nutrients, Nitrogen (N) and Phosphorous (P), are available in wastewater duckweed takes the nutrients from the wastewater to support its growth and to store the nutrients in its tissue. The nutrient reserve in its biomass has been showed as the key to the kinetics of its growth (Landesman 2005). Duckweed's ability to sequester nitrogen and phosphorous has been widely discussed in the literature for thirty years. Duckweed has been used either alone or in combination with other plants to treat effluent in the United States, Middle East, and Indian subcontinent. Studies found that fecal coliforms decreased by 50-90% and Giardia and Cryptosporidium fell by over 80% in eutrophic waters where duckweed was grown (Goopy 2003). Duckweed can remove up to 99% of the nutrients and dissolved solids contained in wastewater. The rapidly growing plants act as a nutrient sink, absorbing primarily nitrogen, phosphorous, calcium, sodium, potassium, magnesium, carbon, and chloride from the wastewater. These ions are then removed permanently from the effluent stream as the plants are harvested, leaving behind purified water (Skillicorn 1993). Duckweed can be a tool used in aquaponic systems to ensure water is filtered and able to be recirculated.

Duckweed systems distinguish themselves from other efficient wastewater treatment mechanisms in that they quickly accumulate a valuable, protein-rich biomass as a byproduct. Duckweed fronds have little fiber, as little as 5% in cultured plants, because they do not need structural tissues to support leaves or stems. As a result nearly all tissue is metabolically active and useful as feed or food product. Harvested duckweed can be used as the sole feed input for fresh-water fish culture, and has been shown to make up 40% of poultry feed (Skillicorn 1993). Fresh duckweed species, such as Lemna minor, can contain about 92-96% water. The composition of duckweed depends on the nutrient content of the water and prevailing climatic conditions. Protein content is higher in duckweed colonies that grow faster (Mwale 2013). Duckweed is unique amongst plants in that its protein content can be manipulated according to the nitrogen content of the water in which it's growing (Chau 1998). Studying duckweed grown on nutrient-poor water in South Whales showed that the plant typically consists of 15-25% protein and 15-30% fiber. The study went on to say that duckweed grown under ideal conditions and harvested regularly will have (in dry matter) 5-15% fiber, 35-43% protein, and a polyunsaturated fat content of about 5% depending on species involved(Leng et al. 1995). In addition to its high protein content, duckweed consists of a wide array of amino acids and a high concentration of pigments and xanthophylls (over 1,000 part per million [Skillicorn 1993]) making it a valuable supplement for livestock (Mwale 2013). Duckweed can be fed fresh or after drying and storage or both dried and fresh together (Leng 1999). Duckweed protein has higher concentrations of the essential amino acids lysine and methionine than most plant proteins such as cottonseed meal, groundnut meal, and soybean meal, and more closely resembles animal protein in that respect. Utilizing duckweed in its fresh, green state as a fish feed minimizes handling and processing costs. The nutritional requirements of fish were observed to be met completely in ponds receiving only fresh duckweed, despite the relatively diluted concentration of nutrients in fresh plants. Having fresh duckweed as a complete nutrient package for polyculture reduces or potentially eliminates fertilizer and other feed inputs and greatly simplifies the nutrition of the polyculture (Skillicorn 1993).

Duckweed is probably the fastest growing of all multicellular plants. Further found in “Duckweed Aquaculture” by Paul Skillicorn. “An individual frond may produce as many as ten generations of progeny over a period of ten days to several weeks before dying. As the frond ages its fiber and mineral content increases and it reproduces at a slower rate” (3). Duckweed plants can double their mass in less than two days (sometimes within 24 hours) under ideal conditions of nutrient availability, sunlight, and temperature. This is faster than almost any other plant. Under experimental conditions their production rate can approach an extrapolated yield of four metric tons/ha/day of fresh plant biomass. This closely resembles the exponential growth of unicellular algae than that of higher plants which represents an unusually high biological potential (Skillicorn 1993). While duckweed’s fast growth rates is a major benefit of the plant, in order to remain this high growth rate the use of labor is required to promote ideal conditions. Once the plant has formed a mat the body of water is covered resulting in the limiting of further growth of the plant. Duckweed must be continuously harvested to maintain an optimal growth rate (Mwale 2013). Duckweed species are well equipped to survive but are fickle when it comes to thriving. The most favorable circumstance is water with decaying organic material to provide duckweed with a steady supply of growth nutrients and trace elements. Duckweed will grow in as little as one centimeter of water, but good practice would require a minimum of 20 cm or more to moderate potential sources of stress and to facilitate harvesting (Skillicorn 1993). Studying Lemna obscura plants, normal growth requires a temperature greater than 15 ° C (59° F) with the optimum temperature around 26 ° C (78.8°F) (Landesman 2005). N and P are very important elements for plant growth. A suitable N/P ratio (4:1-5:1) showed importance for ideal duckweed growth. If nutrients are stable temperature will play the most important role in the growth of duckweed (Xu, 2010 [quoted in Xiao 2013]). Duckweed can survive and recover from extremes in temperature, nutrient loadings, nutrient balance, and pH. Though for duckweed to thrive these four factors need to be balanced and maintained within reasonable limits (Skillicorn 1993).

Chapter 7: Case Studies

7.1 Case Study 1: Aquaponics - Catfish and Tomatoes

The integration of aquaculture and hydroponics has resulted in the manipulation and optimization of many components of aquaponics leading to successful production practices. Fish and plant species, fish feed, temperature, stocking intensity, harvesting rate, tank capacity and plenty of other parameters can be maneuvered to provide different results. Past case studies can shed light on successful and unsuccessful operations. In early 1999 an economic and technical evaluation was conducted to assess an aquaponics system consisting of channel catfish and tomatoes, and compare it to a fish-only system. Channel catfish was chosen because it was well-adapted for intensive recirculation systems, and a market was identified through a local catering company. Tomato was the plant species chosen due to its sustainability in hydroponic systems and its importance to the overall crop production in a region with well-established markets for fresh tomatoes and/or tomato paste. The fish were sold at £4/kg ($2.56/pound) and the tomatoes were sold at £210/tonne ($0.13/pound).

The level of production was chosen as a minimum level for economic efficiency estimated to approximate to a full-time unit for one man, assisted by a contract laborer for harvest period both for fish and tomato production. Fish were stocked at a rate of 40kg of fish/m^3 of system volume. The system was planned to produce 500g of catfish per year in water measuring 23° C. The rate of feeding ranged from 1% to 3% of live weight, with a feed conversion ratio of 2:1.When the aquaponics system was compared to the fish-only system, little difference was seen between the financial performances of the two systems. Examination of the budgeted sales price and direct costs for the tomato production showed an essentially small gross margin. The authors found that the crop production is likely to be the minor element in contributing to the total profit of the aquaponics system. However through the same comparison of aquaponics to fish-only systems, the natural bio-filters of the aquaponics system increased fish rate growth by 1.5%. This is consistent with previous literature and was due to the removal of end products (nitrates, phosphates, and other elements) which normally accumulate in recirculating systems using conventional systems.

The authors also found several environmental advantages. The combination of fish and plant production in a water recirculation unit reduces the total water requirement, both compared to separate intensive systems and alternative flow-through fish cultivation (consistent with previous literature) and plant irrigation systems. The introduction of hydroponics to utilize the waste products reduces dependency on artificial fertilizers. The aquaponics system greatly reduced effluent discharges into watercourses, and reduced land use compared with conventional aquaculture systems. This reduction in water leads to greater flexibility in the siting of these systems. The authors stressed that further study was needed, but pointed out the potential gains in fish production as a result of improved water quality. Even a small increase in the growth rate could turn the economic advantage towards an aquaponics system (Caves 1999).

7.2 Case Study 2: Aquaponics - Barramundi and Lettuce

A second case study explored the economic net benefits of integrating commercial barramundi aquaculture and hydroponic lettuce production based on data from an existing integrated system in northern New South Wales, Australia. The barramundi were produced in an indoor greenhouse under an intensive water recirculation system. The system had facilities to produce 40 tons of barramundi per year, and a hydroponic area of 550m^2 which could hold 22,000 lettuce plants. Several batches of lettuce were produced per annum, using a nutrient film technique where the plants grow in continuous water flow. Lettuce grown on fish effluent usually takes 5-6 weeks to grow to marketable size, making it possible to have 10 harvests per year (220,000 lettuce plants). Barramundi farmers who use recirculation systems usually maintain water temperatures of 26 -28° C. Barramundi feed intake increases linearly with water temperature until 29° C. Temperatures higher than 29° C are detrimental to the fish. Feed cost $1.35/kg when fish weight was greater than 60 grams and $1.15/kg when fish weight was less than 60 grams. The barramundi were priced at $12/kg and the lettuce was priced at $0.60/head.

When compared to stand alone operations of fish and lettuce the aquaponics system saved $3,391 each year. The researchers found the integrated aquaponics system removed about 74 kg of nitrogen and 17 kg of phosphorous each year, around 5% of total, compared to stand-alone systems. This reduction saved $1,269 in nutrient removal costs, plus an additional $1,320 from nitrogen and phosphorous nutrient cost in lettuce production. Further, the aquaponics system saved $802 each year in water cost compared to the stand-alone system. The integrated aquaponics system showed an increase of 4.6% in net present value over the stand-alone production. The study points out that the net present value of the aquaponics system is much more sensitive to the price of barramundi than to the price of lettuce. This is because lettuce revenue makes up just 22% of total revenue for base prices, but this could increase with a larger growing area. Sensitivity analysis projected that a 20% fall in barramundi price will decrease the net present value by 123% resulting in a negative net present value (increasing price by 20% increases net present value by 123%) (Rupasinghe 2010).

7.3 Case Study 3: Aquaponics - Perch and Lettuce

Even though the first two case studies appeared to have positive results, profit from aquaponic systems is far from guaranteed. A later case study examining the financial analysis of an aquaponics system in a temperate climate found little profit in small scale operations. The researcher used a 750-gallon aquaponics starter system with a 4'X 8' footprint as his basic unit of analysis. He then compared cash flow projections of one system of tilapia and lettuce to a second operation of yellow perch and lettuce. The author then investigated the potential for economies of scale by projecting cash flows for a system with two 3,750-gallon units with a total footprint of 4'X 40'. The study found a net present value loss of $185,867 over 10 years for the 750 gallon operation of tilapia and lettuce, assuming an estimated 10% per year rise in energy costs. The 750 gallon system of yellow perch and lettuce came much closer to attaining a positive cash flow, but still netted a present value loss of $110,031 over the same 10-year period. The yellow perch system was more successful because the perch's wholesale value was $16/pound compared to $6/pound for tilapia. Yellow perch also thrive in colder water temperatures and therefore reduced the energy costs of heating the water.

When projected the systems to demonstrate economies of scale the tilapia and lettuce system was still not profitable. However the system was profitable at large scale when growing yellow perch and lettuce, revealing a net present value of $106,404 after 10 years. Even though three out of the four aquaponic systems failed to be profitable from fish and vegetable sales alone, changing the business model can change the financial analysis. Adding an aquaponics operation to an existing business would eliminate incorporation cost. If the business was owner-operated the owner could do most of the work to reduce the labor expenses. A cooperative business model could also be explored to reduce startup, operating, and labor costs. This study demonstrates that it is possible to attain profitability from an aquaponics operation, however the endeavor is a risky one (Goodman 2011).

7.4 Case Study 4: Aquaculture - Carp and Duckweed

Further studies show the potential benefits of incorporating different types of fish feed, especially duckweed. The World Bank explored aquaculture using duckweed and conducted a case study using a 1 hectare Bangladesh duckweed-fed carp culture. Carp was used because of its tolerance for wide differences in pond temperature and chemistry. Their ease of management and high growth rate have made them a favorite of fishery development programs worldwide. The farm provided a balanced diet for those carp by feeding the duckweed directly and indirectly. Duckweed was fed to certain carp species and the effluent of the duckweed-fed species was also consumed directly by detritus feeders. Duckweed was later fed indirectly through fertilization or plankton and other food organisms, providing adequate food for bottom and mid-feeding carp varieties. This leads to a cropping strategy of both top and bottom feeder varieties of carp. Biological methods seem more appropriate in most developing countries, where it is easier and cheaper to acquire animals and feeds than laboratory equipment and chemicals, both of which may require foreign exchange (Nguyen 1997).

Early results show the addition of duckweed increases carp polyculture 10-15 metric tons/ha/year in non-aerated ponds. The combination of grass carp/mrigal can produce 1 kg of fish for 10-12 kg of fresh duckweed, or about $0.30-0.40 worth of duckweed consumed. Fish was sold at $1.50 at wholesale price. They further analyzed the costs and returns of a 5-year investment scenario for the duckweed-fed carp culture. The profitability of duckweed-fed fish production is most sensitive to the price of fish, and the cost of investment capital. The duckweed-fed fish operation broke even in 1.8 years and had a net present value of $20,141 (Skillicorn 1993). This early World Bank report sheds light on the advantages of incorporating duckweed into aquaculture and aquaponic systems alike.

Chapter 8: Case Study Analysis

Based on a study by Jagath W. Rupashinghe and John O. S. Kennedy where they analyzed “Economic Benefits of Integrating a Hydroponic-Lettuce System into a Barramundi Fish Production System”, this paper adds duckweed to the aquaponics system and compares the results to the aquaponics system they studied. Rupashinghe’s study was mentioned earlier in this paper and used as the second case study. The objective of their study was to explore the economic benefits of integrating commercial barramundi aquaculture and hydroponic-lettuce production. The authors demonstrated the net benefit as the difference between the sum of the net benefits of the enterprise run in isolation and the net benefits of the integrated enterprise. The data used in their study was obtained from a case study integrated aquaculture/hydroponic farm, which is located near Port Stephens on the central coast of New South Wales with the exception of some data that was changed, and noted accordingly, for convenience of modeling the data. Data not readily available from farm sources were obtained from published sources or from personal communications. The main focus of their modeling was on the control variables of barramundi production, with a more minor focus on lettuce, a subsidiary activity for adding income and reducing the aquaculture effluent costs.

This study uses their economic and biological modeling but includes the use of duckweed to add to the aquaculture system. The added duckweed has its own biological growth parameters and should lead to a severe reduction, possible elimination, of feed and effluent costs. This study will then compare the different systems, barramundi and lettuce (B-L), to barramundi, lettuce, and duckweed (B-L-D). We will analyze only the cost that varies from each system. Under Rupasinghe's (2010) study, the barramundi was produced in an indoor greenhouse under an intensive water recirculation system, which consists of grow-out tanks and other facilities such as filters and pumps. The system has the facilities to produce approximately 40 tons of barramundi per annum with each fish's' final weight aimed for 500 to 600g. The researchers' staggered parallel batches and continuously harvested weekly or biweekly. All the staggered batches were started at 4-week intervals to simplify the analysis. Five staggered batches each with a duration of 20 weeks are modeled to run continuously. The final weight of each individual fish was estimated at 586 g and each batch produced 3,077 kg of final biomass under feeding without restriction.

The nutrient-film technique (NFT) hydroponic crop-production system is used to produce several batches of lettuce per annum. As mentioned earlier, the farm has a hydroponic area of 550m^2, which can hold up to 22,000 lettuce plants. The area is about 14% of the average area of hydroponic farms in New South Wales. Taking 5 to 6 weeks to grow to marketable size, allowed for 10 harvests per year. During the operations of the system fish effluent is gravity fed to the storage tank of the hydroponics system. Effluent in the storage tank of the hydroponic system is diverted through the lettuce plants and discharged to grassland. Water is not returned from the hydroponic farm to the fish farm. Filtered waste water is stored and released to promote hydroponic growth as needed. In this study a third element of duckweed will be introduced into the system. The aquatic plants will grow first until they produce enough biomass to sustainably feed the fish. The biological and economic parameter values shown in this study are found in Table 1 for barramundi, Table 2 for duckweed and Table 3 for lettuce.

Table 1 Barramundi Biological and Economic Parameters

Parameter	Symbol	Value	Eq.	Source
		Biological parameters		
Food conversion ratio	*FCR*		(2)	Rupasinghe (2010) Case study farm
Fish weight ≤ 100 g		0.9		
100 g < fish weight ≤ 200 g		1		
200 g < fish weight ≤ 800 g		1.1		
Daily feed intake determinants				
Feeding frequency/day	*FF*		(3)	Williams and Barlow (c.1996)
Fish weight ≤ 100 g		2		
Fish weight > 100 g		1		
Target water temperature (◦C)	*T*	29	(3)	Based on maximum tank water temperature for Rupasinghe (2010) Case study farm
Number of fingerlings per batch	*N0*	6,074	(6)	Based on mortality rates for Rupasinghe (2010) Case study farm
Fingerling weight (g)	*W0*	7	(1)	Commercial hatchery Pers. Comm.
Weekly mortality rate	*M*		(6)	Based on survival rates for Rupasinghe (2010) Case study farm
Fish weight ≤ 200 g		0.00878		
200 g < fish weight ≤ 400 g		0.00855		
400 g < fish weight ≤ 800 g		0.00168		
Nitrogen and phosphorus flows				
Nitrogen in feed (%)	*NFE*		(9)	Estimated using protein percentages for Rupasinghe (2010) Case study farm
Fish weight ≤ 60 g		7.9		
Fish weight > 60 g		7.4		
Phosphorus in feed (%)	*PFE*		(10)	Skretting Australia (2002)
Fish weight ≤ 60 g		1.35		
Fish weight > 60 g		1.3		
Nitrogen in fish (%)	*NFI*	4.4	(9)	Williams and Barlow (c.1996)
Phosphorus in fish (%)	*PFI*	0.6	(10)	Williams and Barlow (c.1996)
		Economic parameters		
Average price of barramundi ($/kg)	*MPF*	12	(20)	Sydney Live Fish Market (2003)
Optimal age (week)	*ψ*		(21)	Hochman (2016)
Scale of value	*Sc*	0.7	(22)	Hochman (2016)
Feed unit cost ($/kg)	*FUC*		(25)	Skretting Australia (2002)
Fish Weight <= 60g		1.35		
Fish Weight > 60g		1.15		
Nitrogen discharge unit cost ($/kg)	*NDCU*	16	(26)	Based on Muir et al. (1999)
Phosphorus discharge unit cost ($/kg)	*PDCU*	5	(27)	Based on Muir et al. (1999)

Chapter 9: Material and Methods

A spreadsheet-based bioeconomic model of barramundi and lettuce production and barramundi, lettuce, and duckweed production was used to estimate the profit or loss for a batch of production. For simplicity purposes we will call the aquaponics system, of barramundi and lettuce, as "Batch B-L" and the integrated aquaponics system of barramundi, lettuce, and duckweed, will be called "Batch B-L-D". We will analyze at the profit maximizing level (optimal profit) of output to determine which system is superior.

Table 2 Duckweed Biological Parameters

Parameter	Symbol	Value	Eq.	Source
Duckweed growth rate (%)	*DGR*	7	(4)	Leng et al. (1995)
Dry weight conversion (%)	*DWC*	10.3	(4)	Xu (2011)
Duckweed nitrogen uptake (%)	*NDU*	50	(11)	Leng (1999)
Duckweed phosphorus uptake (%)	*PDU*	48.44	(12)	Leng (1999)

Table 3 Lettuce Biological and Economic Parameters

Parameter	Symbol	Value	Eq.	Source
	Biological parameters			
Wet nitrogen content (g)	*WNC*	2.02	(13)	Zweig (1986)
Wet phosphorus content (g)	*WPC*	0.45	(14)	Zweig (1986)
	Economic parameters			
Market price lettuce ($/head)	*MPL*	0.6	(24)	Rupasinghe (2010) Case study farm
Seed Price ($/head)	*SP*	0.10	(28)	& Pers. Comm. from a hydroponic famer
Packing and freight unit Cost ($/head)	*PFUC*	0.14	(29)	RIRDC (2001)
Nutrient Unit Cost ($/head)	*NUC*	0.006	(30)	RIRDC (2001) and Rupasinghe (2010) Case study farm

9.1 Biological Modeling

Time starts for a Batch B-L at stocking of the barramundi at t=0. Fish weight will grow in daily increments as shown in Eq. (1). The growth rate (2) is determined by daily feed intake and food conversion ratio (3). Weekly feed intake will then be calculated by summing up the previous seven days of *DFI*.

$$W_t+1=W_t+\Delta W_t \quad (1)$$

$$\Delta W_t = DFI_t / FCR_t \quad (2)$$

Where:

W_t = Weight at time t (g),

ΔW_t = Weight gain over period t to *t*+1 (g),

DFI_t = Daily Feed Intake (g),

FI_t= Feed intake over period t to *t*+1 (g) = $DFI_{t1} + DFI_{t2} \ldots DFI_{t7}$,

FCR_t = Food conversion ratio over period *t* to *t*+1.

The FCR values assumed for barramundi on the basis of fish weight interval are presented in Table 1. The unrestricted daily feed intake by a barramundi fish is a function of fish weight, feeding frequency and water temperature (Williams & Barlow, c. 1996 [quoted in Rupasinghe 2004]):

$$Ln\ DFI = -3.543 + 0.486 * ln\ W + 0.074 * FF + 0.083 * T \quad (3)$$

Where:

W = Weight per fish (g),

FF = Feeding frequency per day,

T = Water temperature = 29 (°C).

The feeding frequency explored by barramundi farmers in Australia of feeding small fish more frequently than large fish was verified with technical studies conducted in Williams and Barlow1996 study (quoted in Rupasinghe 2004). The model incorporated the recommendation that fish less than 100g in weight should be fed twice a day, otherwise once a day, as shown in FF. Barramundi farmers who use water recirculation systems in Australia usually maintain water temperatures in the range of 26-28°C. Barramundi feed intake increases linearly with water temperature until 29 °C. Rupasinghe's 2004 study found that income increases from higher temperatures outweigh the increased cost temperature control and feed supply. 29 °C is taken as the water temperature in the study since anything higher can be detrimental to the fish.

Time starts for Batch B-L-D at stocking of duckweed at t=0. Duckweed then grows daily at a rate of 7% (*DGR*) per day (Leng et al., 1995, and references there in [Leng, R. A., Stambolie, J. H., & Bell, R. (1995)]).The daily increment in duckweed biomass (WD_t), measured in meter square (m^2), is determined by field experiments provided by Professor Eric Lam. This daily biomass growth is then divided by 10.3% (Xu 2011) to represent the conversion to fresh weight (*DWC*), defined in Eq.(4) below. The weekly duckweed growth sums up the previous seven days of daily duckweed growth (5). Time starts for barramundi stocking when the aggregate duckweed growth (ADG*t*) equals the minimum fish food required (MFFR) of 8.14 grams. The minimum fish food required of 8.14 g was found as the feed intake needed for week 1 in Rupashinghe and Kennedy's study and in Batch B-L. It should be noted that duckweed growth must meet this daily feed intake in order to meet the dietary needs of the fish. The fish will then grow at the rate shown in equations (1) and (2).

$$WD_{t+1} = W_t + W_t * DGR / DWC \quad (4)$$

$$WWD_t = WD_{t1} + WD_{t2} \ldots WD_{t7} \quad (5)$$

Where:

WD_t = Duckweed weight at time t (m^2),

DGR = Duckweed growth rate = 7%,

DWC = Dry weight conversion = 10.3%,

WWD_t = Weekly duckweed weight over period t to t+1 (m^2).

The biomass of the fish at time t >1 (Bt) is the product of the weight of the individual fish and number of fish surviving to time t from stocking, as given in equations (6) and (7) below. The number of fish at time t+1 after natural mortality is calculated progressively starting with initial stock numbers using:

$$N_{t+1} = N_{te}^{-Mt} \quad (6)$$

Where:

N_0 = Number of fish in a batch at time of stocking,

N_t = Number of fish at time $t > 0$,

M_t = Mortality rate over period t to t+1.

The biomass of fish (g) at time t is:

$$B_t = W_t * N_t \tag{7}$$

Where:

B_t = Biomass of fish over period t to t+1 (g).

Biomass of fish (g) will then be converted into kilograms to show total batch weight (kg):

$$TB_t = B_t/1000 \tag{8}$$

Where:

TB_t = Total batch weight of fish over period t to t+1 (kg).

Sourced from Ingram's 1998 study (quoted in Rupasinghe 2004) , the nitrogen and phosphorus levels in discharged water (effluent) for the barramundi stand-alone system were estimated using the nutrient mass balance method below. The nitrogen percentage in fish and feed vary depending on the weight of the fish. If the fish are less than or equal to 60 g the nitrogen in feed is 7.9% (NFE) and phosphorous in feed is 1.35% (PFE). If the fish are greater than 60 g the NFE will be 7.4% and PFE will be 1.30%.

$$NDW_t = NFE * FI_t - NFI * \Delta W_t/1000 \quad (9)$$

$$PDW_t = PFE * FI_t - PFI * \Delta W_t/1000 \quad (10)$$

Where:

NDW_t = Nitrogen in discharged water over period t to $t + 1$ (kg),

PDW_t = Phosphorus in discharged water over period t to $t + 1$ (kg),

NFE = Percentage of nitrogen in feeds,

NFI = Percentage of nitrogen in fish flesh = 4.4%,

PFE = Percentage of phosphorus in feeds,

PFI = Percentage of phosphorus in fish flesh = .6%.

Since this study replaces feed with duckweed in Batch B-L-D the NFE and PFE do not fully represent the nitrogen and phosphorus discharged in the water. This equation will just be an estimate and needs to be addressed in future studies. Levels of nitrogen and phosphorous discharged as effluent from the integrated system are the levels of barramundi production less the uptake of nitrogen and phosphorous as nutrients in the lettuce and duckweed production.

FAO studies found that Lemna species of duckweed absorbs 50% of the nitrogen and 48.44% of the phosphorous in the effluent water, shown in Table 2 (Leng 1999). For this reason, Batch B-L-D will show additional nitrogen and phosphorus absorption. For Batch B-L-D the effluent uptake by duckweed is shown in equations (11) and (12) below.

$$NRDW_t = NDW_t * NDU \tag{11}$$

$$PRDW_t = PDW_t * PDU \tag{12}$$

Where:

$NRDW_t$ = Excess nitrogen removed by duckweed over period t to t+1 (kg),

$PRDW_t$ = Excess phosphorus removed by duckweed over period t to t+1 (kg),

NDU = Duckweed nitrogen uptake = 50%,

PDU = Duckweed phosphorus uptake = 48.44%.

Previous literature has shown that at market size, the harvest including leaves, roots, and captured detritus is about 90% water, weighs around 450 g, and is made up of 2.02 g of nitrogen (Zweig 1986), as shown in Table 3. On a dry weight basis for hydroponically grown buttercrunch lettuce, the organic matter removed contains 4.5% nitrogen (Zweig 1986), and 1% phosphorus (Seawright et al., c. 1998 [quoted in Rupasinghe 2010]). Converting phosphorus to wet weight estimates to the lettuce plant consisting of .45 g (450 g * .01 *[1-.9]) of phosphorous. For Batch B-L the nitrogen and phosphorous in effluent is absorbed by the lettuce only. The equations (13) and (14) below show the amount of lettuce that will need to be grown in order to absorb all the phosphorus and nitrogen in the effluent waste.

$$QLN_t = (NDW_t * 1000) / \text{WNC} \tag{13}$$

$$QLP_t = (PDW_t * 1000) / \text{WPC} \tag{14}$$

Where:

QLN_t = Quantity of lettuce needed to absorb nitrogen over period t to t+1 (heads),

QLP_t = Quantity of lettuce needed to absorb phosphorous over period t to t+1 (heads),

WNC = Wet nitrogen content = 2.02 (g),

WPC = Wet phosphorus content = .45 (g).

For Batch B-L-D the amount of lettuce that will need to be grown in order to absorb all the phosphorus and nitrogen in the effluent waste is shown in equation (15) and (16) below.

$$QLN_t = ([NDW_t - NRDW_t] * 1000) / \text{WNC} \tag{15}$$

$$QLP_t = ([PDW_t - PRDW_t] * 1000) / \text{WPC} \tag{16}$$

After the effluent uptake by lettuce and duckweed the remainder of nitrogen and phosphorus discharge remains in the water. This excess discharge will have to then be removed at a cost to the producer and the environment. The excess discharge for each batch is calculated below (17) and (18). If the results yield a number 0 or below, then there will be no excess discharge remaining.

$$ENDW_t = ([QLNt - P_t]*WNC)/1000 \quad (17)$$

$$EPDW_t = ([QLP_t - P_t]*WPC)/1000 \quad (18)$$

Where:

$ENDW_t$ = Excess nitrogen in discharged water over period t to $t + 1$ (kg),

Pt = Plants grown (heads),

$EPDW_t$ = Excess phosphorus in discharged water over period t to $t + 1$ (kg).

If the results of equations (17) and (18) are negative then the lettuce grown are not getting enough nutrients from the effluent waste to grow at an adequate level. If this is the case then additional nutrients will need to be added into the system to promote lettuce growth. Excess lettuce plants that need nutrients are calculated in the Eq. (19) below. If the results yield a number 0 or below, then there will be no excess nutrients needed, the plants will grow at adequate levels with the effluent wastewater provided.

$$ELN_t = P_t - PN_t \quad (19)$$

Where:

ELN_t = Excess lettuce that need nutrients over period t to $t + 1$ (heads),

PN_t = Plants needed is the higher value of QLN_t and QLP_t over period t to $t + 1$ (heads).

9.2 Economic Modeling

The economic model in Rupasinghe's (2010) study describes the costs and revenues associated with farming. The model was constructed to show a yearly production schedule. Capital costs included buildings, vehicles, tanks, machinery and other equipment for the fish, and troughs, aerators, tables and pumps for the hydroponic system. Operational expenses are divided between variable and fixed costs. Fixed costs consist of aquaculture license fees, property taxes and insurance premiums for investment, and cost of land for lettuce. Variable costs consist of water, fingerlings, feeds, effluent disposal, labor, electricity, fuel and insurance, lettuce seed, packing and freight, pest and disease control, and hydroponic nutrients.

For this analysis we decided to show the cost of an individual batch of barramundi and lettuce and only focus on costs that vary from system to system. This includes feed, effluent disposal, lettuce seed, packing and freight, and nitrogen and phosphorous cost. We believe the addition of duckweed has the capabilities to remove feed cost and reduce effluent disposal cost. Revenue in each system consists of income from barramundi and lettuce.

$$IFS_t = TB_t * MPF \qquad (20)$$

Where:

IFS_t = Income from fish sale over period t to $t + 1$ (\$),

MPF = Market price barramundi fish = 12 ($/KG).

In Rupasinghe's (2010) case study the farm aimed for a final weight of barramundi between 500 to 600 g. If the barramundi fall out of that weight range the ability to sell the fish at market value should decline. Used in a study of Tilapia, Hochman et al.represented this fall in value by using a quality function which is shown in Eq. (21) (Hochman et al. 2016). Since barramundi is a function of age, the quality function depends on time. Used was distribution function that is similar to the gamma function, a function with a maximum at 1 and minimum at 0. The parameter Ψ is used as the maximum value. So at Ψ the barramundi weight is optimal.

$$QFN_t = (t^* \text{ e } (1\text{-}t/ \Psi))/ \Psi \qquad (21)$$

Where:

QFN_t = Quality function for fish weight over period t to $t + 1$,

Ψ = Optimal age (week).

After the barramundi reach a certain age the value should begin to decline at a greater rate. We added an additional parameter to show this additional decrease in value after the barramundi reach the age of Ψ. Eq. (22) represents this increase in the decline of value. More research needs to be undertaken regarding the actual age and rate that barramundi will begin to decline. For the sake of this analysis we included an arbitrary value of .7 to show the increasing fall in market price. The income including the quality function is shown in Eq. (23) below.

$$QFN\,\Psi_t = (t^* \, e\,(1\text{-}t/\,\Psi)/Sc)/\,\Psi \tag{22}$$

$$QIFS_t = QFNt * IFS_t \tag{23}$$

Where:

$QFN\ \Psi_t$ = Quality function after optimal age for fish weight over period t to t + 1,

Sc = Scale of value = .7,

$QIFS_t$ = Quality income function from fish sale over period t to t + 1 ($).

Revenue from lettuce is determined by how much lettuce is grown. An optimal amount of lettuce is estimated to be grown each week which will return income and help assimilate effluent waste.

$$ILS_t = P_t * MPL \tag{24}$$

Where:

ILS_t = Income from lettuce sale over period t to t + 1 ($),

MPL = Market price lettuce = 0.6 ($/head).

The barramundi production consists of its own fixed costs. Under Rupasinghe's (2010) study the yearly fixed costs consist of an aquaculture permit of $1,500, property tax of $3,000, and an insurance cost on capital of $11,629.50. The sub-system had its share of variable costs including water, fingerlings, feed, effluent disposal, labor cost, fuel and insurance cost. For this analysis we will only evaluate the cost that varies from the barramundi and lettuce system to barramundi, lettuce, and duckweed system. For the barramundi sub-system these costs include feed and effluent disposal. When the barramundi weigh less than 60 g the feed cost 1.35 ($/kg) and when they weigh more than 60 g the feed cost 1.15 ($/kg), represented by the Eq. below (25).

$$FC_t = ([FI_t * N_t]/1000) * FUC \tag{25}$$

Where:

FC_t = Feed cost over period t to $t + 1$ ($),

FUC= Feed unit cost ($/kg).

A major benefit of adding lettuce to the barramundi production is the decrease in effluent cost. This happens when nitrogen and phosphorous is ingested in the production of lettuce, and consequently duckweed as well. Rupasinghe's (2010) study showed that disposal cost was reduced by 5% when lettuce was added to the barramundi system. This was the effect of growing lettuce in an area of 550m^2. The authors noted that it would take an area of 10,810m^2 to eliminate the barramundi effluent cost all together. This study hopes to save significant amount of space by incorporating the growth of duckweed in a culture to help further reduce effluent cost. The effluent disposal cost is shown in the following equations (26) and (27).

$$NDC_t = ENDW_t * NDUC \tag{26}$$

$$PDC_t = EPDW_t * PDUC \tag{27}$$

Where:

NDC_t = Cost of discharging nitrogen over period t to $t + 1$ ($),

NDCU= Nitrogen discharge unit cost = 16 ($/kg),

PDC_t = Cost of discharging phosphorous over period t to $t + 1$ ($),

PDCU= Phosphorus discharge unit cost = 5 ($/kg).

Lettuce production will have its own set of costs. In Rupasinghe's (2010) analysis the fixed costs are made up of an insurance cost on capital of $2,400. Further the variable costs include labor, electricity, insurance, lettuce seed, packing and freight, pest and disease control, nitrogen and phosphorus (nutrient cost) and other feeding cost. For this study we will focus on only the lettuce seed cost, packing and freight cost, and nutrient (nitrogen and phosphorus) cost, since they will vary from system to system. Seed cost is based off amount of lettuce heads that are expected to be grown, assuming that 11% do not germinate.

$$SC = (P_t * 1.11) * SP \qquad (28)$$

$$PFC = P_t * \text{PFUC} \qquad (29)$$

$$NC = ELN_t * NUC \qquad (30)$$

Where:

SC = Seed cost ($),

SP = Seed price = $.10 ($/head),

PFC = Packing and freight cost ($),

PFUC = Packing and freight unit cost = 0.14 ($/head),

NC = Nutrient costs ($),

NUC = Nutrient unit cost = 0.006 ($/head).

Chapter 10: Results

We will now use parameters described in the biological and economic model above to estimate the production of one batch in an aquaponics system. These aquaponic systems consist of barramundi and lettuce, labeled Batch B-L, and barramundi, lettuce, and duckweed, labeled Batch B-L-D. Equations (1) and (2) are used to determine the growth of barramundi in grams then multiplied by the number of fish (7) to determine the weekly output of the total batch weight in kilograms shown in Eq. (8). The data is run unrestricted for 52 weeks where the fish will grow from 7 grams all the way to 3104 grams if not harvested. We assume a weekly output of 1600 lettuce plants. Each week this lettuce will be sold and shipped at market value and absorb a certain percentage of nitrogen and phosphorous discharged into the water. Duckweed will be introduced for Batch B-L-D at the start of the batch and grow incrementally as shown in Eq. (4). Shown in equation (11) and (12) duckweed will absorb additional nitrogen and phosphorous discharged into the water. The three variables will influence the production of each batch with the results shown below.

10.1 Optimal Harvest

Shown in Eq. (23) revenue from barramundi varies week by week and is determined by weight and number of fish. The expenses that go along with fish production will also vary week by week. The feed cost, shown in Eq. (25) and nitrogen and phosphorus effluent disposal costs, shown in equation (26) and (27) are all impacted by the amount of fish at the time. Lettuce growth is held fixed so revenue shown in Eq. (24) will be the same each week. The lettuce expenses of seed cost, shown in Eq. (26), and packing and freight cost, shown in Eq. (29), will also be the same each week. The last expense, nutrient cost, will vary each week depending on the amount of effluent in the water, represented by Eq. (30).

When choosing the highest quality weight to market the fish, we found that Batch B-L had the highest quality weight of 575.93 g found in week 20, and Batch B-L-D had the highest quality weight of 589.77 g found in week 21. Thus we decipher that the maximum price per kg of barramundi is achieved at Ψ = 20 for Batch B-L, and Ψ = 21 for Batch B-L-D, which is represented by Eq. (21). Figure 1 and 2 below, plots the weekly marginal and average profit from their respective batch. Fluctuations in the marginal profit slope occur when different parameters are triggered. To use Figure 1 as an example, the weight of fish grows to over 100 g in week 7 causing the Feed Conversion Ratio to shift from .9 to 1 leading to a change in the slope of the marginal profit. Additionally, after the highest quality weight is reached the quality function of Eq. (23) takes affect and you can clearly see the marginal profit start to decrease dramatically. This happens because the marketable price of the barramundi will begin to decline as the fish grow to undesirable levels. This decrease in revenue leads to the marginal gain becoming smaller than the marginal costs, so it is no longer worth continuing production at that level of output. Operating where marginal profit equals average profit is reached in week 23 for Batch B-L and week 25 for Batch B-L-D. Batch B-L had a final fish weight of 729.25 g and Batch B-L-D had a final fish weight of 800.35 g.

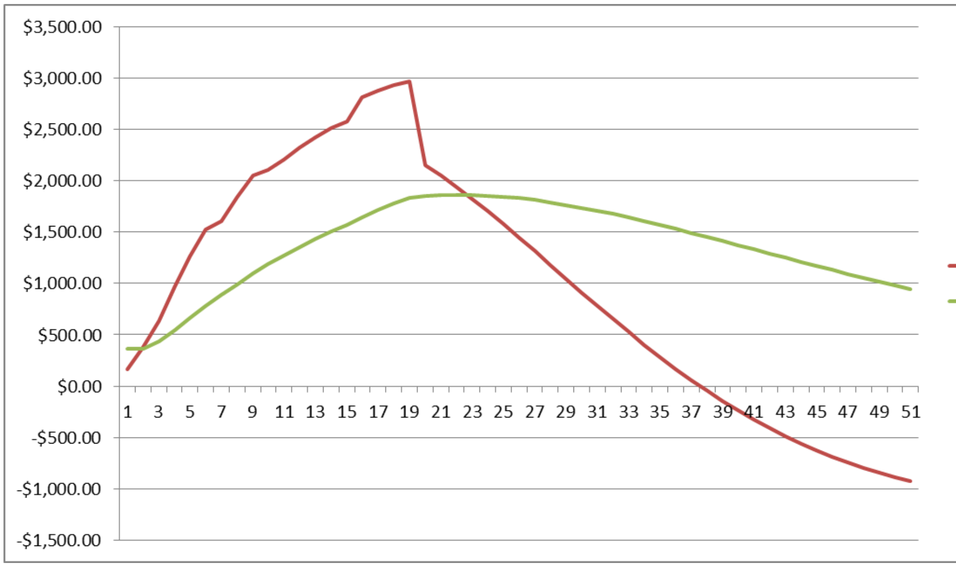


Figure 1. Marginal Profit and Average Profit from Batch B-L operation.

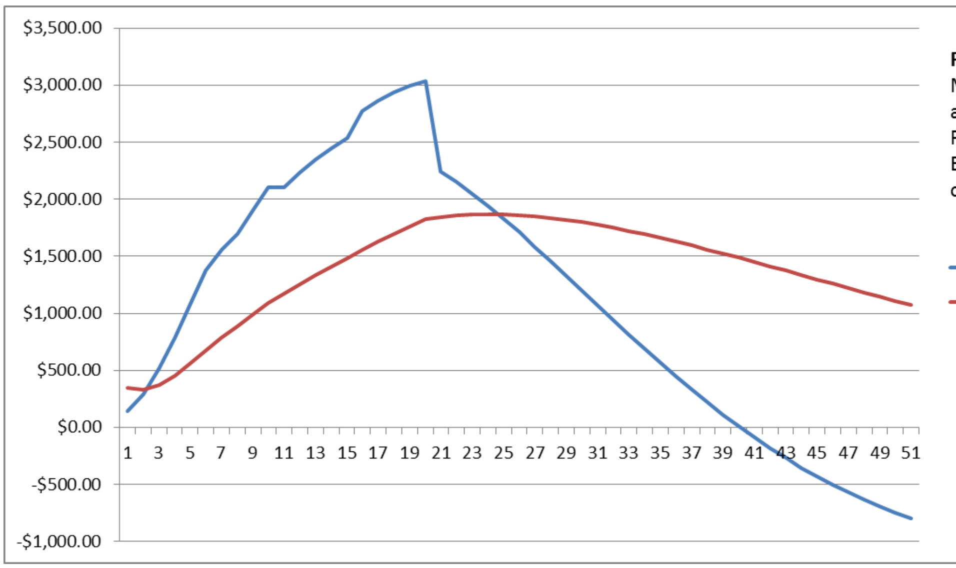


Figure 2. Marginal profit and Average Profit from Batch B-L-D operation.

Displayed in Table 4 below, Batch B-L produced $42,802.12 of revenue from barramundi and $22,080 from lettuce. Batch B-L-D produced $46,145.51 of revenue from barramundi and $24,000 of revenue from lettuce. In Batch B-L-D, the additional 7.8% of revenue from selling fish is accounted by harvesting the fish at a weight that is 13.84 grams heavier than in Batch B-L. Similarly to the fish, the additional revenue from lettuce shown in Batch B-L-D is explained by the one week lag the system undergoes in order to grow duckweed to an optimal level to feed the fish. The difference is $1920 ([1600*.6]*2) which is 2 weeks revenue from the sale of lettuce.

Table 4 Optimal Profit Production of Batch B-L and Batch B-L-D

	Batch B-L:		Batch B-L-D:			
	Fish	**Lettuce**	**Fish**	**Lettuce**	**Gains from Duckweed**	**% Change**
Week	**23**		**25**			
Expenses:						
Feed	5,305.97	-	-	-	5,305.97	100%
Effluent Disposal	1,541.60	-	371.99	-	1,169.61	76%
Lettuce Seed	-	4,088.88	-	4,444.44	(355.55)	-9%
Packing and Freight	-	5,152.00	-	5,600.00	(448.00)	-9%
Nutrient Cost	-	3.57	-	37.15	(33.58)	-941%
Total Expenses	6,847.57	9,244.45	371.99	10,081.58	5,638.45	35%
Revenue	42,802.12	22,080.00	46,145.51	24,000.00	5,263.38	8%
Profit	35,954.56	12,835.55	45,773.52	13,918.42	10,901.83	22%

In order to determine the value of duckweed it is important to look at the cost of each system. For Batch B-L, the fish production has a total expense of $6,847.57 consisting of $5,305.97 from feed and $1,541.60 from effluent disposal. As you can see in Figure 3 below, feed makes up nearly 33% of total expenses in the production of Batch B-L and effluent disposal makes up 9.58% of total costs. The addition of duckweed to Batch B-L-D completely eliminates the feed cost and reduces the effluent disposal cost to $371.99, only 3.56% of total expenses for that batch, as shown in figure 4 below. Duckweed will cost virtually nothing to grow and is able to adequately feed the fish, in turn eliminating feed cost. Duckweed will also act as a biological filter which helps reduce the effluent disposal cost by 76%. This leads to a total gain in fish production of $9,818.96 when adding duckweed to the system. Despite the cost savings for fish production, there is a tradeoff from the addition of duckweed found in the cost of lettuce production.

Figure 3: Batch B-L Expenses

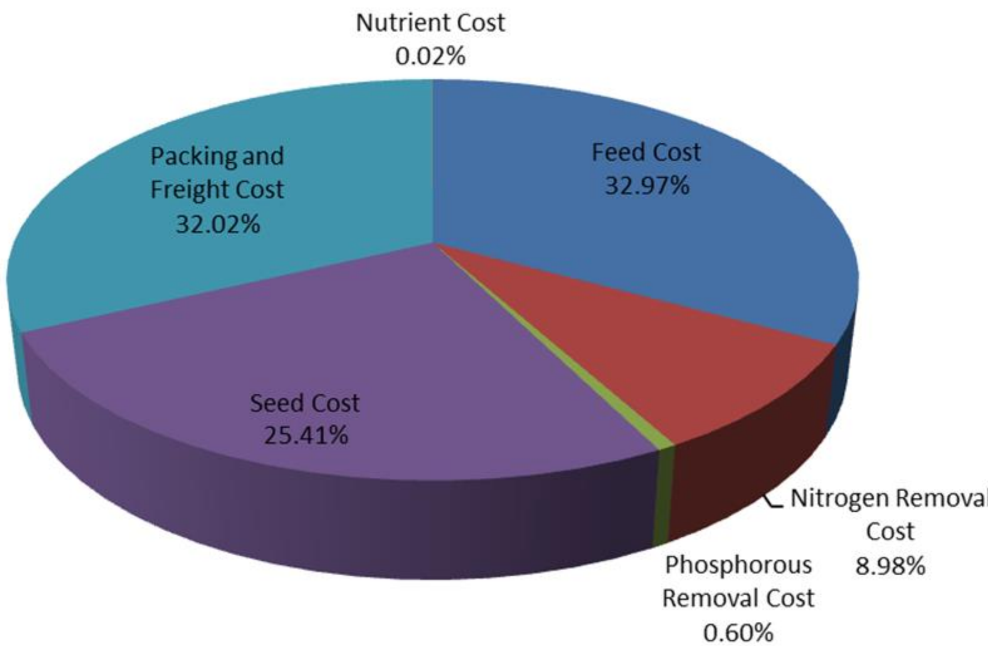
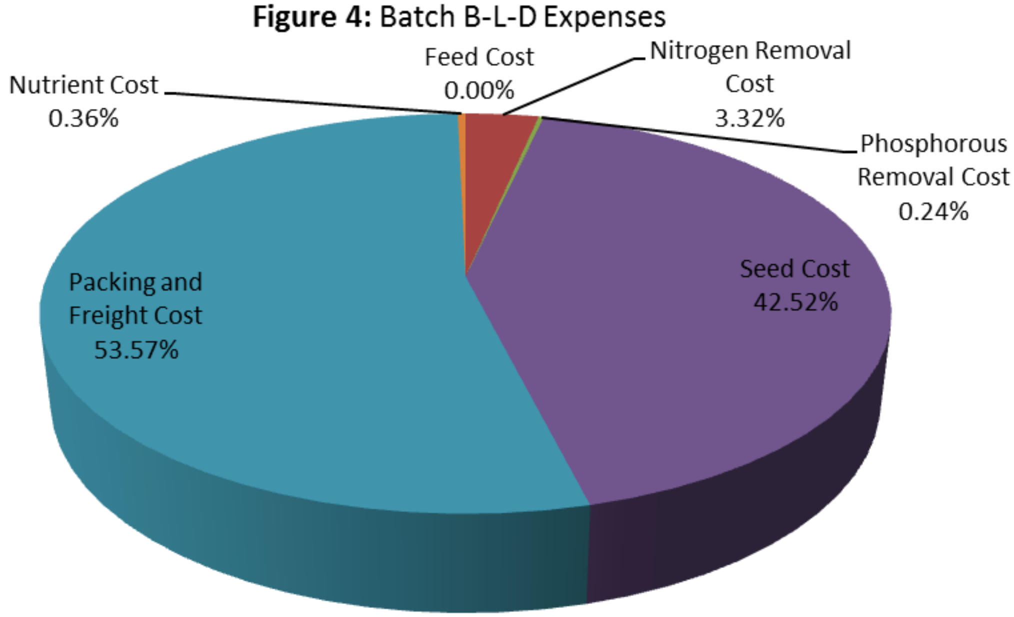
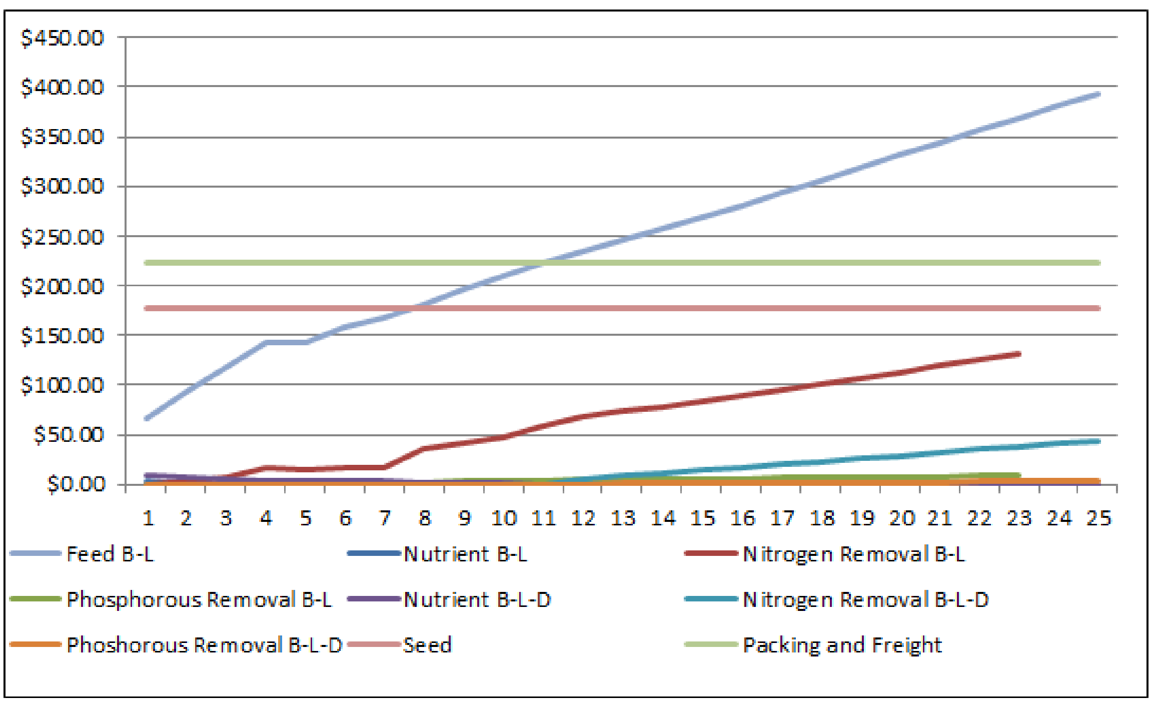


Figure 4: Batch B-L-D Expenses



The cost of fertilizing plants with nitrogen and phosphorous, or nutrient cost, is found to be higher in Batch B-L-D than Batch B-L. Batch B-L only has $3.57 of nutrient cost while Batch B-L-D shows a cost of $37.15 leading to a net loss of $33.58 from the addition of duckweed. This expense is due to the fish not being introduced into the system until week 2, plus the additional absorption of nitrogen and phosphorus duckweed consume as they grow. This is only a concern in the beginning of the batch and once the fish biomass have grown to a certain level the nutrient cost will soon be replaced by a much higher effluent disposal cost. Figure 4 above shows that nutrient cost only makes up a meager .36% of total expenses in Batch B-L-D. As you can see in Figure 5, this small expense is offset quickly by the reduction of feed and effluent disposal cost.

Figure 5: Weekly Expenses for Batch B-L and Batch B-L-D



The two additional losses of adding duckweed comes from packing and freight and lettuce seed cost. Batch B-L-D shows $355.55 more for lettuce seed cost and an additional $448 of packing and freight cost. This again is due to the two additional weeks of production and is offset by the additional $1,920 in revenue gained from the sale of lettuce. For both batches the revenue from the barramundi made up almost 66% of the total revenue with lettuce making up the remaining 34%. Despite making up only 34% of the total revenue, the lettuce production makes up 57.43% of all of Batch B-L's variable expenses, and 96.09% of Batch B-L-D's expenses. This shows that the addition of duckweed can severely reduce the expenses of producing barramundi in an aquaponics system. When comparing the two systems, Batch B-L shows a profit of $35,954.56 from fish, and $12,835.55 from lettuce. Batch B-L-D shows a profit of $45,773.52 from fish and $13,918.42 from lettuce. When harvesting at the optimal profit, the introduction of duckweed to an aquaponics system leads to an increase of 22%, or $10,901.83, in profit compared to a system with fish and lettuce only.

Chapter 11: Discussion

As mentioned in the case study analysis earlier, the highest quality weight to market the barramundi fish was between 500 to 600 grams, with Rupasinghe (2010) ultimately selling the fish at 586 g. To decipher highest profits we decided to analyze the profits of each batch when harvesting at the highest quality weight. For Batch B-L, namely, the barramundi and lettuce system, the highest quality weight of 575.93 g was achieved in week 20. For Batch B-L-D, namely, barramundi, lettuce, and duckweed, the highest quality weight of 589.77 g was achieved in week 21. The one week delay was due to the fact that duckweed will have to grow beforehand in order to feed the fish once they are introduced into the system. The results of the two systems harvesting at the highest quality barramundi weight are shown below in Table 5.

11.1 Highest Quality Weight Harvest

Table 5 Highest Quality Weight Production of Batch B-L and Batch B-L-D

	Batch B-L:		Batch B-L-D:			
	Fish	Lettuce	Fish	Lettuce	Gains from Duckweed	% Change
Week	20		21			
Expenses:						
Feed	4,237.49	-	-	-	4,237.49	100%
Effluent Disposal	1,141.45	-	202.58	-	938.87	82%
Lettuce Seed	-	3,555.55	-	3,733.33	(177.78)	-5%
Packing and Freight	-	4,480.00	-	4,704.00	(224.00)	-5%
Nutrient Cost	-	3.57	-	37.15	(33.58)	-941%
Total Expenses	5,378.94	8,039.12	202.58	8,474.47	4,741.01	35%
Revenue	36,602.49	19,200.00	37,749.31	20,160.00	2,106.81	4%
Profit	31,223.55	11,160.88	37,546.73	11,685.53	6,847.82	16%

When analyzing the highest quality weight production path you can see that it follows the same trend as the optimal profit production batches. The difference in revenue from lettuce, plus lettuce seed and packing and freight cost, is due to the one week lag of introducing the duckweed. Batch B-L shows a profit of $31,223.55 for fish and $11,160.88 from lettuce. Batch B-L-D shows a profit of $37,546.73 from fish and $11,685.53 from lettuce. At the highest quality weight $6,847.82 or an additional 16%, of profit is gained from adding duckweed. At the optimal production $10,901.83, or an additional 22%, of profit is gained from adding duckweed. When comparing the two results, passing the highest quality weight leads to an increase in profits.

11.2 Effluent Consumption

If the main concern is effluent disposal, duckweed has the ability to save space. Mentioned in the literature review in this paper, the average size of most people's aquaponic systems are 15m^2 (Love 2014). In Rupasinghe's (2010) case study, the farm needed 550m^2 to produce 220,000 heads of lettuce. That is roughly .0025m^2 per head. Consistent to that logic, Batch B-L harvesting at highest quality weight needs 80m^2 of space to grow the 32,000 heads of lettuce produced. It is not necessary to analyze harvesting at optimal profit, because this would change the profit of the whole system so a new optimal profit would have to then be calculated. Batch B-L-D harvesting at highest quality weight needs 84m^2 to grow the 33,600 heads of lettuce produced. If you were trying to eliminate all effluent disposal, referring to Eq. (13) and (14), Batch B-L would need to grow 64,634 heads of lettuce in 161.58m^2 of space to harvest at highest quality weight. Without duckweed, Batch B-L-D would need to grow 66,030 heads of lettuce in 165.08m^2 of space to harvest at highest quality weight. With duckweed, Batch B-L-D would only need to grow 33,372 heads of lettuce in 83m^2 of space to eliminate all effluent disposal cost. This is nearly half the space needed to eliminate effluent disposal with plants only. When trying to scale operations up this space could play a vital role in deciding how much fish to produce.

This analysis doesn't include the area needed to grow duckweed. If we want to grow the duckweed in a separate culture, additional space must be added. When harvesting at week 21 for Batch B-L-D, 674.60 grams of feed is needed per fish. At week 21 it is estimated there will be 5,334 fish grown. This leads to a total of 3,598.21 kg of fresh weight of duckweed that needs space to grow. Yields show that a hectare of duckweed can produce between 39.1-105.90 tons of dry weight a year (Xu 2012). Converting the duckweed biomass to dry weight, and assuming duckweed can produce 60 tons in a hectare of space a year, we conclude that an additional 61.77m^2 will be needed to grow duckweed. This additional area leads to an estimated 144.77m^2 (61.77m^2 +83m^2) of total space needed to grow the lettuce and duckweed. This leads to 20.31m^2 of saved space. This shows a conservative estimate, and different techniques of growing duckweed can have different results. Field experiments provided by Professor Eric Lam show that a vertical farming strategy can be implemented. Under a best case scenario using existing data and technology can increase the biomass production rate per unit area by a factor of 3. This would allow the duckweed to grow in only 20.59m^2, saving a total of 61.49m^2 of space compared to lettuce only system. Not only can duckweed save money from eliminating feed cost, and effluent disposal cost, it can save space too, which is a cost saving all in itself. When comparing the two systems, duckweed is shown to help save money for the production of an aquaponics system.

11.3 Sensitivity Analysis

Table 6 Sensitivity Analysis: Change in parameter values

Parameters:	-15%	-10%	-5%	Baseline	5%	10%	15%
				Deviation			
Barramundi Price	$10.20	$10.80	$11.40	$12.00	$12.60	$13.20	$13.80
Lettuce Price	$0.51	$0.54	$0.57	$0.60	$0.63	$0.66	$0.69
Feed Price							
Fish Weight <= 60g	$1.15	$1.22	$1.28	$1.35	$1.42	$1.49	$1.55
Fish Weight > 60g	$0.98	$1.04	$1.09	$1.15	$1.21	$1.27	$1.32
Duckweed Nutrient Uptake							
N Removal (% of total mass)	42.50%	45.00%	47.50%	50.00%	52.50%	55.00%	57.50%
P Removal (% of total mass)	41.17%	43.59%	46.02%	48.44%	50.86%	53.28%	55.70%
Lettuce Nutrient Uptake							
Wet N content (g)	1.72	1.82	1.92	2.03	2.13	2.23	2.33
Wet P content (g)	0.38	0.41	0.43	0.45	0.47	0.50	0.52

Since results of this study were based on a set of economic and biological parameters, we will test the sensitivity analysis of barramundi price, lettuce price, feed price, duckweed nitrogen and phosphorous removal, lettuce nitrogen and phosphorus removal. These parameters are listed in Table 6 above. We will analyze how a decrease and increase of 5%, 10%, and 15% of each parameter will affect the profit of each batch. The sensitivity to profit for each harvest at optimal profit is shown in Table 7 for Batch B-L and Table 8 for Batch B-L-D.

Table 7 Sensitivity Analysis: Optimal Profit Production of Batch B-L

Parameters:	-15%		-10%		-5%		Baseline	5%		10%		15%	
	Profit	% Δ	Profit	% Δ	Profit	% Δ	Profit	Profit	% Δ	Profit	% Δ	Profit	% Δ
Barramundi Price	42,369.79	-13.16%	44,509.89	-8.77%	46,650.00	-4.39%	48,790.11	50,930.21	4.39%	53,070.32	8.77%	55,210.42	13.16%
Lettuce Price	45,478.11	-6.79%	46,582.11	-4.53%	47,686.11	-2.26%	48,790.11	49,894.11	2.26%	50,998.11	4.53%	52,102.11	6.79%
Feed Price	49,586.00	1.63%	49,320.70	1.09%	49,055.40	0.54%	48,790.11	48,524.81	-0.54%	48,259.51	-1.09%	47,994.21	-1.63%
Lettuce Nutrient Uptake	48,608.52	-0.37%	48,669.11	-0.25%	48,729.62	-0.12%	48,790.11	48,850.60	0.12%	48,908.93	0.24%	48,966.32	0.36%

Table 8 Sensitivity Analysis: Optimal Profit Production of Batch B-L-D

Parameters:	-15%		-10%		-5%		Baseline	5%		10%		15%	
	Profit	% Δ	Profit	% Δ	Profit	% Δ	Profit	Profit	% Δ	Profit	% Δ	Profit	% Δ
Barramundi Price	52,770.11	-11.60%	55,077.39	-7.73%	57,384.66	-3.87%	59,691.94	61,999.21	3.87%	64,306.49	7.73%	66,613.76	11.60%
Lettuce Price	56,091.94	-6.03%	57,291.94	-4.02%	58,491.94	-2.01%	59,691.94	60,891.94	2.01%	62,091.94	4.02%	63,291.94	6.03%
Duckweed Nutrient Uptake	59,518.95	-0.29%	59,579.01	-0.19%	59,636.86	-0.09%	59,691.94	59,745.84	0.09%	59,799.74	0.18%	59,850.52	0.27%
Lettuce Nutrient Uptake	59,573.70	-0.20%	59,615.79	-0.13%	59,655.39	-0.06%	59,691.94	59,727.49	0.06%	59,763.33	0.12%	59,797.50	0.18%

Since market prices are subject to change it is important to interpret how the change in price of barramundi and lettuce will affect the profit. As you can see from the tables above, each operation is most sensitive to the change in barramundi price followed by lettuce price, feed price for Batch B-L, duckweed nutrient uptake for Batch B-L-D, then lettuce nutrient uptake for both systems. For Batch B-L a +/- 15% change in barramundi price leads a 13.16% change in profit harvesting at optimal profit. For Batch B-L-D a +/- 15% change in barramundi price leads to an 11.60% change in profit. Change in lettuce price will change profit almost half as much as a change in barramundi price. For Batch B-L a +/- 15% change in lettuce price leads to a 6.79% change in profit. For Batch B-L-D a +/- 15% change in lettuce price leads to a 6.03% change in profit. This makes sense since the revenue from the barramundi made up almost 66% of the total revenue with lettuce making up the remaining 34% of both systems. Batch B-L is more sensitive than Batch B-L-D for all parameter changes. The price of fish is shown to have the biggest effect on the system, so careful review of market price of fish should be undertaken before choosing a species of fish to sell and conducting an aquaponics operation.

Chapter 12: Conclusions

Acting as a biological filter, the addition of lettuce to fish farming has shown to decrease levels of phosphorous and nitrogen found in wastewater created from fish effluent. Further adding duckweed can significantly reduce these nutrient levels in the wastewater. The main variable costs of fish farming comes from labor, fingerlings, fish feed, and effluent disposal. The addition of duckweed can help reduce the cost of feed and effluent disposal greatly, plus lead to a cost saving measure of saving space. This changes the profit function of the aquaponics system and allows for greater revenue and profits to be achieved. Duckweed has the ability to grow fast and immense, can feed fish, and assimilates nitrogen and phosphorous found in waste water. This study shows that duckweed can help save costs in an aquaponics system, and will provide environmental benefits as well. The cost saving is made up of reduction of feed cost, effluent disposal cost, and decrease in land space. The environmental benefits come from water efficiency by reducing the levels of nitrogen and phosphorous found in waste water that will then have to be disposed of. Plus it can lead to more space available not being taken up by farming.

This study represented a theoretical analysis of adding duckweed to an aquaponics system. Duckweed will be used as a biological filter and fish feed. The aquaponics system consisted of barramundi fish and buttercrunch lettuce and was previously analyzed using a case study (Rupasinghe 2010). While the results of adding duckweed to this system were promising, a study needs to be undertaken to fully explore the full effect of this addition in practice. This study only explored the variable costs that varied from the aquaponics system of barramundi and lettuce, to the aquaponics system of barramundi, lettuce, and duckweed. We decided to add no cost for duckweed in this paper. Although it should be small, further research is needed to show the true cost of purchasing duckweed. The variable costs examined were fish feed, effluent disposal, lettuce seed, packing and freight, and nutrient cost. In this study duckweed was valued by the reduction of feed and effluent disposal cost. In order to fully represent the value of duckweed, further studies need to be undertaken to explore the full spectrum of costs that incur during an aquaponics system where duckweed is used.

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