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An Analysis of Future Sustainable Aquatic Farming

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Table of Contents

Abstract

As a result of the world population growth in the next 100 years, it will be necessary to find more viable methods of food production. This report examines the prospect of using a sustainable oceanic farm to feed future populations. Advances in genetic engineering to develop salt-tolerant rice will allow rice to be grown alongside algae to feed the growing population. Future strides in robotics will be an enabling technology to manage and to make the farm viable. Economic models were constructed to determine if halophytic farming is viable as well as what factors affect our findings. Results of this modeling have shown that certain factors can be optimized in the future to make oceanic farming viable.

Executive Summary

Every day, the world population increases. Because of the growing number of people in the world, the demand for energy and food increases. Petroleum reserves are limited, and humans cannot expand the amount of farming land much past what is currently available. Although there are various alternatives such as vertical farming and conservation of current arable land to solve the need for higher food production, the caveats that come with these alternatives prevent them from being sustainable in the long term. Unlike those ideas, algae and plant mariculture can solve the need for more food while being sustainable in the long run as well.

Halophytic farming, or farming of saltwater plants, is an option that few have considered. However, other maritime projects such as the farming of fish and mollusks have shown the potential of ocean farming. Furthermore, the ocean is well suited to grow plants. Seawater contains substantial amounts of the nutrients and elements found in sea water that plants require for growth. There are caveats that come with sustainable aquatic farming, however. Plants are easily affected by adverse environmental factors. Most land plants cannot handle to large amount of sodium present in the ocean. Others thrive only in a narrow pH range. There is also the potential of sea-borne plant diseases and predators that arise due to this new food production method. However, research is currently underway to develop more robust and salt-resistant plants via genetic engineering. In the future, it is very possible to see food crops that can grow in a salinized environment.

The ocean is also a viable place for energy production. With the large amount of wave motion and currents, a large amount of energy can be harvested simply through the motion of water. Buoys and other devices are already currently being developed to harness the large amount of kinetic energy present. Thermal energy can also be obtained by using the gradient between warm surface water and cold deep water to turn turbines. Biodiesel, which can be used as an excellent petroleum alternative, can also be made by growing algae in a halophytic farm.

There are certain considerations that must be factored in before developing an oceanic farm. Piracy of goods or equipment is a possibility, especially with the growing need for more food and energy production. Farms must be built to withstand the harshest and strongest of storms, such as hurricanes. These farms must also be built to resist oxidation and corrosion of materials being used. Runoff from farms and decomposing plants that acidify the ocean are also a possibility and could cause imbalances in populations in the ocean, so care must be done to prevent upsetting the present ecosystem.

Legally, there are few precedents for cultivating algae and plants in enclosed areas of the oceans. Precedents that can be followed concerning the sea tend to involve the usage of the ocean for safe travel. The United Nations Conferences on the Law of the Sea (UNCLOS) were held in response to resources such as oil and other minerals being found in the ocean. It was during these conferences that the Law of the Sea Treaty (LOTST) was drafted. The LOTST grants coastal nations certain rights to govern the ocean extending from their coastline out to 200 nautical miles. For installations built beyond this zone, the rights of other nations must be considered while building the installation so that one nation does not control all the space of interest in the ocean. Also, there is a significant tax on any profit made from any project. Of interest to this project is that, although it generally abides by the policies within the treaty, the United States has yet to ratify the Law of the Sea Treaty.

In terms of technology available for people to use for oceanic use, marine-grade equipment tends to be more expensive due to the more demanding environment. Current costs involved in transport are tankers or cargo ships that consume high amounts of fuel per trip. In addition, personnel must be paid to operate and maintain such vessels. Current robotic technologies such as Autonomous Underwater Vehicles have made great strides in exploring the ocean and withstanding the environment but at great cost. Future technology will be capable of standing the demanding ocean environment while being automated to reduce costs.

Despite the current obstacles and costs, there is evidence that halophytic farming is a sustainable method to procure food and energy in the future. Therefore, this project looked at determining when halophytic farming will be viable and what technologies will make it viable. Data and expert opinions from forward thinkers were gathered to determine what technologies will be available in the future as well as how various factors such as the cost of technologies will move. This data was then be used to build an interaction diagram of factors to consider as to when sustainable mariculture will be viable. Models were built in Mathematica to determine when it will be possible to create a sustainable aquatic farm. It was expected that this project would determine some of the robotics technologies to be used to automate this farm.

The results for this project were the necessary information to farm rice and algae, the design of the farm, the robotic technology that would help with the management of the farm, as well as a model which analyzed the profitability of the farm. In terms of crop information, it was determined that algae is extremely well suited for growth near the ocean surface. Rice was also determined to have advantages in being grown out on offshore farms. When genetically engineered salt-tolerant rice strains have been developed, bringing the rice away from mainland will dramatically reduce the number of pests that can plague rice. Because of rice's position as a staple crop for many cultures and countries, halophytic rice is of great interest to a sustainable oceanic farm. Off-shore farming also has numerous advantages, such as less destruction of crops due to storms versus coastal farming. Another advantage presented by offshore farming is reduction of the effect of waste brought out to the coast by rivers and streams.

After looking at various designs for the farm, several design requirements were determined. Considerations necessary for the farm would be the depth of plant growth as well as whether the farm would be stationary or free floating. Although seaweed is less susceptible to destruction, rice would need to be protected, and this can be done either by moving the farm away from the path of the storm or shielding the crop. A free floating farm would be able to move away from a storm whereas a stationary farm would need to shield any rice crop. The position of the farm would ideally be in a location where storms tend to occur less frequently. Environmental waste from the station must also be taken into account when building the station, as plant waste due to processing is possible. This was found to be remedied by using any excess as fertilizer or biodiesel.

Robotics could be a key enabling technology for the development of ocean farming. it was determined that robots would be an enabling factor in the harvesting of crops, sensors to protect the investment, long-term reduction of expenses, and would potentially help with transportation of crop from farm to shore. In addition to automated underwater vehicles (AUVs), other technologies useful at an oceanic farm include robots that help with the process of farming. Currently, the constraint on the usage of robotics in such a venture is the cost due to the lack of investment in this area. However, with proper investment in the market, oceanic robotics will play an important role in cultivating crops in the ocean.

When analyzing the profitability of a halophytic offshore farm, numerous factors were considered. Crop yield and earnings from the crop were considered the income generated from this farm, while operational costs such as personnel and processing were considered expenses that reduced the viability of an oceanic farm due to generating a loss on the farm. Currently, there are certain, specific expenses that heavily outweigh the income generated by the farm. For seaweed, this is the processing cost involved in drying, whereas rice faces certain limiting factors in its processing that reduce overall crop yield. Both crops will benefit in advancements in farming technology that make the process more efficient with fewer errors. This results in the farms being viable, possible, and capable of feeding the ever growing world population.

1. Introduction

Every day, the world population increases. As a result, more resources are consumed in the form of energy and food. All fossil fuels used to power the technology people create are available in limited quantities. For example, the amount of petroleum available to humanity is quickly being used up. As a result, there is an apparent necessity to develop an efficient method of obtaining energy. The amount of fertile land available to farm crops to feed people is limited to what is already being used today. There is an ever present need for alternative methods to produce sufficient amounts of food to feed the growing world population.

Although numerous methods are being explored to solve these problems, sustainable aquatic farming has the potential to solve both problems. Sustainable aquatic farming in the ocean can provide both food as well as energy in the form of biodiesel. Through the harvesting of halophytic or salt-tolerant plants and the automation of such farming with the use of robots, mariculture is an extremely viable method of solving the problem of limited resources with an ever growing population.

Currently, the use of mariculture to harvest the necessary food and power comes with several caveats. Technology used to do such farming must be capable of withstanding the harsh environment of the ocean. The plants grown for the purpose of sustenance must be viable products for humans to consume on a large scale. Furthermore, the costs for technology allowing people to farm the oceans and automating the farming process currently are extremely high. In addition, there is little precedence currently governing the use of the ocean for farming. As such, the legality of considerations such as the operation and defense of an oceanic farm in international waters has yet to be established.

Nevertheless, despite the high costs and considerations, sustainable aquatic farming is capable of addressing the need for more energy and food. It is possible for such technology to develop in the future to the point that it will be capable of providing an alternative method to provide for world needs.

Therefore, this project attempts to address the two following points: when will it be viable to use sustainable aquatic farming, and what technologies will make it possible?

The following paper presents an overview of halophytic farming. Section 2 discusses the background information regarding the need for halophytic farms, factors which could affect the farm, laws which could affect aquaculture, and monetary considerations. In section 3 we outline the data compiled from our research, and the assumptions made in order to build the model. The cost and production analysis is presented in section 4. Finally, section 5 discusses the conclusions which were drawn from the analysis and future work that could be undertaken to further explore this topic.

2. Background Information

2.1 Need

According to the United Nations, the world population is expected to climb to ten billion in approximately 90 years.[1] Although current population numbers show low fertility countries having higher populations, high fertility countries will overtake low fertility countries in population numbers. In addition to population increases in high fertility countries based on procreation assurance, life span is expected to increase among all countries regardless of fertility, adding an additional factor to the world population increase.[2]

Future projections of food and energy consumption are also expected to rise along with population. In addition to population, various drivers such as income, urbanization, and corporate franchises influence food consumption.[3] Food production in the next ten years is expected to level off while the value of trade for food products is expected to increase by 30 billion dollars, resulting in a 50% increase in value from 2010.[4] Current food production requires a large input of fossil fuels, such as preservation of out-of-season foods, inefficient usage of raw material in preparing foods, and changes in consumer demand for certain foods.[5] Demand for petroleum and petroleum based products is expected to rise, with all oil products (gasoline and petroleum based products) expected to rise steadily in China.[6] Arable land capable of providing the nutrients necessary to grow plants is also a limited commodity.

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[1] United Nations. Department of Economic and Social Affairs. *World Population to Reach 10 Billion by 2100 If Fertility in All Countries Converges to Replacement Level*. *World Population Prospects*. United Nations, 3 May 2011. Web. 10 Sept. 2011. <http://http://esa.un.org/unpd/wpp/Other-Information/Press_Release_WPP2010.pdf>

[2] ibid

[3] Kearney, John. "Food Consumption Trends and Drivers." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365.1554 (2010): 2793-807. Print.

[4] United States Department of Agriculture. Interagency Agricultural Projections Committee. *USDA Agricultural Projections to 2020*. *USDA Agricultural Projections to 2020*. United States Department of Agriculture, Feb. 2011. Web. 11 Sept. 2011. <http://www.ers.usda.gov/publications/oce111/>.

[5] Dutilh, Chris E., and Klaas J. Kramer. "Energy Consumption in the Food Chain." *AMBIO: A Journal of the Human Environment* 29.2 (2000): 98-101. Print.

[6] Dargay, Joyce M., and Dermot Gately. "World Oil Demand’s Shift toward Faster Growing and Less Price-responsive Products and Regions." *Energy Policy* 38.10 (2010): 6261-277. Print.

Fertile land is shrinking quickly in an urbanizing China[7] while British arable land is neither decreasing nor increasing.[8] Increased food demand is met with a decreasing and limited amount of arable land that can be used to farm.

Various methods have been proposed to compensate for the increased need for food and energy production. Vertical farming, in which plants are grown in tall buildings under specially controlled conditions, has been proposed to compensate for the decreasing amount of arable land.[9] Such a controlled environment is flawed due to the amount of light lost by stacking layers of farms on top of each other, resulting in an insufficient amount of light to grow plants. Other considerations that would make vertical farming difficult to implement include proper climate control in an artificial environment and providing such an environment without using too much energy. Other researchers are looking into preserving arable land by analyzing whether using certain farming methods (organic or processed) play a role in maintaining fertile soil.[10] (Comis, p. 4) Although this research looks into preserving what arable land we have at the moment, it does not solve the need for more food.

2.2 Maritime Considerations

2.2.1 Existing Mariculture

Mariculture refers to the cultivation of marine organisms for food and other products in the open ocean. Mariculture is currently practiced to grow different species of algae, shellfish, and finfish.

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[7] Qian, Wang. "Arable Land Shrinking Fast." *Business Daily Update* 29 June 2009. Print.

[8] Horne, Suzie. "Arable Land Holds Steady." *Farmers Weekly* 1 Oct. 2010: 74. *ABI/INFORM*. Web. 17 Sept. 2011. <http://search.proquest.com/docview/759233401/fulltext/131E95C64473BB9F2A5/1?accountid=29120>.

[9] Cox, Stan, and David Van Tassel. ""Vertical Farming" Doesn't Stack Up." *Synthesis/Regeneration* 22 Mar. 2010: 4-7. Print.

[10] Comis, Don. "Which Is Better: Alternative vs. Conventional Farming." *Agricultural Research* 37.10 (1989): 4-7. Print.

Cultivation includes several different methods for containment and harvesting.[11] The existence of mariculture could help to jumpstart halophytic farming with tried and tested methods and technology for the cultivation of sea life.

There are several primary species which are cultivated popularly. Species of fish include salmon, sea bass, tuna, cobia, snapper, and pomano. Fish are grown as a food source for humans as well as other animals. Three different color types of seaweed are grown, notably kelp. Algae are used for food as well as for alginate production.[12] Alginate is a cell wall constituent of algae, and is used in a variety of things from toothpaste to tires.[13] Several different species of shellfish are also reared, primarily for food, but also because there are several mollusks which can help to clean the water they grow in. Shellfish raised for mariculture include prawns, crabs, lobsters, mussels, oysters, and abalone.[14] The experience gained from rearing these different species could provide crucial insight to the management of halophytic farms, as well as handling the introduction of a foreign species to a new environment.

Several methods of mariculture are practiced throughout the industry. These range from open ocean herding, which takes advantage of migratory paths of certain fish and crustaceans, to methods which utilize physical structure to control the location of the organisms being reared, to simple beds which are ‘seeded’ with immature mollusks and simply left until harvest time. These various methods of mariculture have allowed it to become a significant source of seafood production.[15] Annual seafood

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[11] "Mariculture." *Wikipedia, the Free Encyclopedia*. Wikipedia Foundation, 5 Sept. 2011. Web. 08 Oct. 2011. <http://en.wikipedia.org/wiki/Mariculture>. Mariculture is used to grow algae, shellfish, and finfish. Various methods of cultivation include caged and open variations.

[12] "Mariculture - Seawater, Sea, Important, Salt, Types, System, Plants, Marine, Human." *Water: Science and Issues*. Advameg. Web. 09 Oct. 2011. <http://www.waterencyclopedia.com/La-Mi/Mariculture.html>. Article about an overview of worldwide mariculture.

[13] "Seaweed.ie :: Alginates." *The Seaweed Site*. Nui Galway. Web. 09 Oct. 2011. <http://www.seaweed.ie/uses_general/alginates.html>. Describes what alginate is, how it is produced, and has statistics on the production of alginate.

[14] Ibid 12

[15] Ibid 12

production reached 143.6 million metric tons in 2006, at that time aquaculture accounted for 47% of that production.

2.2.2 Growing Conditions in the Ocean

The ocean is a very different environment than land for growing plant life. The ocean may not appear to be equitable to growing commercial crops. However there are many factors to consider when evaluating growing environments. The successful cultivation of plant life considers several factors such as the pH of the growing medium, the presence of nutrients, and the absence of toxins.

One important factor in growing crops is the acidity or alkalinity of the growing medium. The preferred pH of a large number of crops falls between 6 and 7 (some plants prefer a lower pH)[16]. The pH of the ocean ranges from slightly basic (8.2) to about neutral (7.2). The pH of the ocean surface varies geographically, and the area with the lowest pH selection (≈7.8) occurs in a band between the tropic lines[17]. This band of ocean would be the most promising to begin mariculture in.

Nutrients dissolved in ocean water are also a very important factor in aquaculture. Plants require three elements in significant quantities: phosphorous, potassium, and nitrogen. Plants also require a number of other elements, but in much smaller quantities[18][19]. Potassium and nitrogen are both very plentiful in sea water. Phosphorous is available as well, albeit to a much lesser extent[20]. This simply means that there may be a need to fertilize oceanic farms. However, they would still not need to

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[16] Heiniger, Ronnie W. "How Soil PH Affects Wheat and Corn Yields." *North Carolina Cooperative Extension: Home*. NC State University, 13 Mar. 2001. Web. 20 Sept. 2011. <http://www.ces.ncsu.edu/plymouth/cropsci/docs/how_soil_pH_affects_yields.html>

[17] Anthoni, J. F. "Composition of Seawater." *Seafriends*. Seafriends, 2000. Web. 15 Sept. 2011. <http://www.seafriends.org.nz/oceano/seawater.htm>

[18] "ROLES OF THE 16 ESSENTIAL NUTRIENTS IN." *EL Dorado Chemical Company*. Eldorado Chemical. Web. 13 Sept. 2011. <http://www.eldoradochemical.com/fertiliz1.htm>.

[19] "Plant Nutrients." *North Carolina Department of Agriculture & Consumer Services*. NCAGR. Web. 17 Sept. 2011. <http://www.ncagr.gov/cyber/kidswrld/plant/nutrient.htm>.

[20] Anthoni, J. F. "Composition of Seawater." *Seafriends*. Seafriends, 2000. Web. 15 Sept. 2011. <http://www.seafriends.org.nz/oceano/seawater.htm>.

be fertilized as much as land based farms. The other miscellaneous nutrients also appear readily dissolved in sea water. A significant advantage oceanic farms would have over land based farms is that the oceanic farms would not face soil depletion like land based farms would. Soil depletion occurs when one type of plant is grown repeatedly in the same soil and the soil is depleted of its nutrients. However, sea water is constantly circulating due to ocean currents and upwelling[21], as such no two crops would ever be grown in the same water. Another advantage oceanic farming has is the form in which nutrients are available in the ocean. Plants can only take up nutrients which are in an inorganic[22], or ionic form, any nutrients dissolved in seawater must be in an ionic form. The reason for this is because plants absorb nutrients by releasing hydrogen atoms from their roots which negatively charges the roots attracting the positively charged ionic nutrients.[23]

There are still serious obstacles to overcome in order to farm the ocean, just as there are in land based farming. One difficulty with hydroponics is maintaining stasis of the growing medium. Because there is no soil buffer plants are very quickly affected by adverse growing conditions such as incorrect pH, or the presence of toxins.[24] This would demand either very carefully maintained oceanic farms or much more robust plants than what are currently available. The salt content of sea water is also a very serious problem. Sodium is the next most available element in seawater next to water. Most plant life is

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[21] Feldman, Gene C. "Ocean Planet:Ocean Currents." *OceanColor Web - SeaWiFS - JASON - Ocean Planet - In Search of Giant Squid*. NASA. Web. 20 Sept. 2011. <http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/oceanography_currents_1.html>.

[22] "Crop Plants Take Up (Absorb) Nutrients in Inorganic Form." *International Plant Nutrition Institute - (IPNI)*. International Plant Nutrition Institute. Web. 13 Sept. 2011. <http://www.ipni.net/ppiweb/ppibase.nsf/$webindex/article=304E9A7948256C5400523EBE0AB5D73C>.

[23] Kehdi, Noucetta. "Plant Food, You Say? Part Four: Organic or Mineral Nutrients?" *Eurohydro*. Web. 3 Oct. 2011. <http://www.eurohydro.com/pdf/articles/gb_plant-food4.pdf>. Article explaining nutrient uptake by plants.

[24] Winterborne, Jeffrey. *Hydroponics: Indoor Horticulture*. Pukka, 2005. Web. 20 Sept. 2011.

unable to handle this much salt[25]. However, following in the wake of a recent tsunami, Japan has begun to develop a salt tolerant strain of rice because the tsunami saturated the soil with salt.[26] There is also a sister effort being made in Australia to engineer salt tolerant cereal crops.[27]

There are other considerations as well which we are unable to give definite answers to at this point. These are factors such as sea-borne plant diseases and unknown predators which we cannot predict because of the novelty of oceanic farming. We can however say this: given the precedence of what has followed from introducing foreign organisms to a new ecosystem, it is very likely that both new predators and new diseases will surface.

2.2.3 Sustainable Energy Production

The ocean contains a significant amount of energy in the motion of waves and the sub-surface currents. It has been estimated that the ocean contains over 2 terawatts of harvestable power.[28] In addition to this energy, the ocean is also an excellent platform for other renewable power sources such as thermal energy and biofuel.

Hydroelectric energy is well known and commonly used in dams across the world, and harvesting hydro energy from the ocean is a promising field. There are two ways to turn the kinetic energy of the ocean into electric energy: by harvesting the periodic motion of waves or by harvesting

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[25] Pence, Garrison. "How Does Salt Act As a Weed Killer? | Garden Guides." *Garden Guides, Your Guide to Everything Gardening*. Garden Guides. Web. 20 Sept. 2011. <http://www.gardenguides.com/75633-salt-act-weed-killer.html>.

[26] Shetty, Priya. "Tsunami-hit Farmers to Grow Salt-tolerant Rice - SciDev.Net." *News & Information on Science & Technology for Development - SciDev.Net*. SciDev Net, 2 Feb. 2005. Web. 20 Sept. 2011. <http://www.scidev.net/en/news/tsunamihit-farmers-to-grow-salttolerant-rice.html>.

[27] "Scientists Closer To Developing Salt-Tolerant Crops." *Seed Daily - Land Seed Water Food*. Seed Daily, 14 July 2009. Web. 20 Sept. 2011. <http://www.seeddaily.com/reports/Scientists_Closer_To_Developing_Salt_Tolerant_Crops_999.html>.

[28] Gunnar, M., S. Barstow, and D. Mollison. *Green Energy and Technology, Ocean Wave Energy*. By J. Cruz. Springer Science+Business Media. 93. Print.

the subsurface ocean currents. Research is currently underway investigating the use of piezoelectrics to generate electricity from the bobbing motion of a buoy. Piezoelectrics, or piezoelectric materials, are substances which produce an electric charge when deformed.[29] Researchers from SRI international have built an electricity generating buoy on this principle. The device is predicted to produce up to a kilowatt of electricity per square meter.[30] There is also a very promising Scottish company which has successfully built and tested a wave harvesting ‘oyster’ (a name derived from the shape of its design), which can generate 315-kilowatts.[31] The device is essentially a giant hinge which sits on shallow seabed and has one flap of the hinge floating. The motion of waves pushes the hinge open and closed driving hydraulic pistons which feed pressurized water back to a power station which uses the water pressure to generate electricity. Finally, there is the method of generating power by harvesting ocean currents. This is done by submersing turbines well beneath the surface of the ocean, the subsurface currents then turn the impellers which in turn drive dynamos, which generate electricity.

Ocean thermal energy is another field which has had promising results. Ocean thermal energy production works off of the temperature differential between surface sea water and deeper water. Warm surface ocean water is used to turn turbines before being cooled by deeper cold ocean water. There has already been a significant amount of research into ocean thermal energy, and engineering firms currently have the capability to build thermal energy capturing stations. A Hawaii based company called OTEC has successfully built two power stations on repurposed boats, and it has designed a 3

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[29] "The Piezoelectric Effect." *Aurelien*. Web. 3 Oct. 2011. <http://www.aurelienr.com/electronique/piezo/piezo.pdf>. Document describing the piezoelectric effect.

[30] Bullis, Kevin. "Harvesting Power from the Ocean - Technology Review." *Technology Review: The Authority on the Future of Technology*. MIT, 23 Aug. 2007. Web. 13 Sept. 2011. <http://www.technologyreview.com/Energy/19295/>

[31] Fairley, Peter. "Wave Energy Scales Up Off Scotland - Technology Review." *Technology Review: The Authority on the Future of Technology*. MIT, 25 Mar. 2010. Web. 13 Sept. 2011. <http://www.technologyreview.com/energy/24865/?mod=related>.

megawatt station.[32] Unfortunately, the second of the power stations was destroyed in a storm and the 3 megawatt station was never constructed because it was too costly, however, the first station built on a small boat generated enough power to supply all of the boat's systems.

Biofuel has a two-fold benefit. Algae differs from most other plants in that it consumes waste products, like sewage, and then produces lipid filled cells. These cells can be processed and used as biofuel because the oil content is so high. Algae are currently grown inland for biofuel. Seawater is pumped into depressions in waste land, and then algae are grown in the large ponds, or algae are grown in bioreactors on sewage.[33] Growing algae for biofuel is readily adaptable to aquaculture and has the added benefit of cleaning the sea as well as recapturing any excess fertilizer used on the crops, since nitrogen is a necessary nutrient for algae. Some types of algae can produce up to 2,000 gallons of oil per acre per year, compared to palms, another source of biofuel, which produce 600 gallons of oil per acre per year.[34]

There is also the possibility of employing the energy of the ocean directly. Research is currently underway on an underwater robotic glider with a transcontinental course, and shorter term gliders are already in use for research purposes. These so called underwater gliders are able to manipulate their buoyancy in order to ascend or descend under water. As they ascend and descend, the gliders travel forward because of the hydrofoils mounted on the sides of the robots. This method of travel is

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[32] "Energy Savers: Ocean Thermal Energy Conversion." *EERE: Energy Savers Home Page*. U.S. Deparment of Energy, 9 Jan. 2011. Web. 24 Sept. 2011. <http://www.energysavers.gov/renewable_energy/ocean/index.cfm/mytopic=50010>.

[33] Marlaire, Ruth D. "NASA - NASA Envisions "Clean Energy" From Algae Grown in Waste Water." *NASA - Home*. NASA, 22 Apr. 2009. Web. 24 Sept. 2011. <http://www.nasa.gov/centers/ames/news/features/2009/clean_energy_042209.html>.

[34] Ibid

extremely energy efficient because it takes very little energy to change the robot's buoyancy.[35] Larger versions of the robot gliders currently in use with storage compartments could transport produce from the ocean farms back to land where it would be offloaded to retailers.

Finally, wind and solar are two well established energy sources. Both of these require plentiful space to harvest significant quantities of power. With all three sources of energy (sunlight, wind, and space plentiful at sea), both of these resources could be easily harvested. Solar powered electricity generation would most likely be implemented using solar concentration. This utilizes mirrors to concentrate sunlight to heat a liquid which is then used to turn a dynamo and generate electricity.[36] Wind would be harvested in the same way as on land. Large propellers mounted on poles would be spun by wind, and use the spinning motion to generate electricity.

2.2.4 Maritime Hazards

Humans have been operating sea worthy vessels for at least 6 millennia now. As such, there are very few exigencies that the sea can produce which mankind has not overcome, and those few that man has not overcome it has at least met.

Storms are a very serious concern to any nautical enterprise. Hurricanes can reach winds speeds up to 155 mph, which is strong enough to buckle iron pilings.[37] Hurricanes frequent coasts worldwide. Beginning out at sea and working their way inland, they are strongest while out at sea.[38] In recent years, nautical construction has improved considerably and is now at a point where structures can be built

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[35] "Robots Powered By The Ocean Itself." *Science Daily: News & Articles in Science, Health, Environment & Technology*. Science Daily. Web. 24 Sept. 2011. <http://www.sciencedaily.com/releases/2002/10/021003075710.htm>.

[36] "Offshore Solar Energy." *OCS Alternative Energy and Alternate Use Programmatic EIS Information Center*. Bureau of Ocean Energy Management. Web. 08 Oct. 2011. <http://ocsenergy.anl.gov/guide/solar/index.cfm>.

[37] "What Causes Hurricanes?" *Weather Questions and Answers*. WeatherStreet.com, 25 Apr. 2011. Web. 12 Sept. 2011. <http://www.weatherquestions.com/What_causes_hurricanes.htm>.

[38] Ibid.

with a very high rate of survivability. Evidence of this can be seen in the fall out of recent storms. In 2004-2005 there were 113 platforms in the gulf which failed in the hurricanes of that year. However, most of these platforms were built prior to 1988, meaning that the platforms were destroyed over a decade and a half after they were built. Modern oil rigs, or rigs built after 1988, are built to withstand category 5 storms, the most powerful classification of storms to date. These oil rigs have more stringent requirements and are better engineered overall.[39] However, while manmade constructions are very capable of withstanding storms, hurricanes would be devastating to vegetation on the open ocean. Any maritime farming enterprise would necessitate either heartier plants or some way to protect the plants from storm winds.

Piracy, another danger in the open ocean, has been around almost since mankind began exploring the sea. Dating back to the advent of sea commerce, piracy is simply thievery on the open ocean. Modern piracy typically does not involve thievery anymore. Instead pirates will take sea farers and their vessels hostage and then demand a ransom for their return.[40] [41] It is difficult to assess how piracy will affect ocean-based farms because there is really no precedence for the situation. However, consider the land locked counterparts. The thievery of farms is rarely if ever heard of because the return is much less than that of something more profitable, such as a bank. Therefore, it would be reasonable to assume the same about the piracy of oceanic farms.

Corrosion also must be taken into account, especially in the ocean. Corrosion occurs when metals become oxidized; all metals are subject to this effect. For many metals oxidation causes them to

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[39] "Hurricanes and the Offshore Oil and Natural Gas Industry." *NOIA*. National Ocean Industries Association. Web. 7 Sept. 2011. <http://www.noia.org/website/download.asp?id=326>.

[40] Associated Press. "Piracy at Sea." *The New York Times*. *New York Times*. 24 Feb. 2011. Web. 12 Sept. 2011. <http://topics.nytimes.com/top/reference/timestopics/subjects/p/piracy_at_sea/index.html>.

[41] Black, Ian. "Kenya Attack: Danger from Many Sides | World News | The Guardian." *Latest News, Comment and Reviews from the Guardian | Guardian.co.uk*. The Guardian, 11 Sept. 2011. Web. 13 Sept. 2011. <http://www.guardian.co.uk/world/2011/sep/11/kenya-shooting-pirates-terrorists-somalia>.

weaken over time and can eventually completely erode the metal. Oxidation is an electrochemical process which is enhanced by sea water because sodium chloride is an electrolyte.[42] Iron and steel are two metals which are very susceptible to oxidation. Both of these metals are also used for many nautical applications because of their strength and availability. Because these metals are so popular in nautical applications, methods to control corrosion became necessary long ago. As such Solutions include water proofing metal with paint or other materials, and using metals which don't oxidize easily such as aluminum where constructs come into contact with water.

2.2.5 Pollution

Pollution due to aquatic farming is something which will have to be mitigated. The ocean is part of the water cycle as well as a significant source of food stuffs for humans, meaning that any toxins that end up in the sea can potentially end up in our water and food. There are several possible ways in which oceanic farming could contribute to pollution. Some of these pollution sources will likely be fairly negligible. Others may be more damaging, and will require the attention of the sea farms in order to preserve the ocean ecosystem.

Corrosion from nautical structures could damage the ecosystem by leaching metal into it. However, iron occurs naturally in the ocean and is in fact used by many organisms. In very large quantities iron can be damaging to aquatic ecosystems.[43]However, the amount of iron that could be put into the sea by corrosion is negligible compared to what occurs naturally.[44]

Runoff from farms and lawns is currently a serious problem in regard to ocean conservation. Excess pesticides, herbicides, and fertilizer are washed away by rainwater and end up in the ocean.

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[42] Asato, Robert. "Corrosion." Reading. *Internet Chemistry; Oxidation/Reduction*. Leeward Community College. Web. 6 Sept. 2011. <http://library.kcc.hawaii.edu/external/chemistry/everyday_corrosion.html>.

[43] "Iron (Fe) and Water." *Water Treatment and Purification - Lenntech*. Lenntech B.V, 1998. Web. 12 Sept. 2011. <http://www.lenntech.com/periodic/water/iron/iron-and-water.htm>.

[44] Ibid

These chemicals have a variety of negative effects on the ocean's environment ranging from killing aquatic life to causing imbalances in populations and destabilizing the ecosystem.[45] Ideally, if the farms are located far enough off shore, the plants will be inaccessible to common pests and animals which eat land based crops. Consequently there would be no need to spray the plants with chemicals to deter the land based pests, resulting in not only a healthier end product but also far less land and water pollution. However, the independence of oceanic farms from these chemicals is contingent upon there being no new pests in the ocean.

Dead plants and biomass left over from harvesting may very well prove to be a significant threat to ocean inhabitants. Decomposing plants acidify the area surrounding them. This acidification can result in a decrease of dissolved iron in the water, a nutrient which is vital to microscopic organisms called phytoplankton.[46] The diminishment of such an important organism could have many negative consequences. Phytoplankton are primary producers in the food chain, which means that they are crucial to the food supplies of almost every organism above them in the food chain. Phytoplankton also contributes 90% of the earth's supply of oxygen to the oceans and atmosphere.[47]

The combination of dead biomass and excess fertilizer also has the potential to create 'dead zones' in the ocean. A dead zone occurs when a limiting nutrient is suddenly available in extremely large quantities. A limiting nutrient is a nutrient that is necessary to one or more organisms in an ecosystem that is available only in limited amounts. This means that organism populations in an ecosystem are capped by how much of a limiting nutrient is available. When a limiting nutrient suddenly becomes

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[45] "Ocean Pollution." *Thinkquest*. Oracle. Web. 8 Oct. 2011.
<http://library.thinkquest.org/CR0215471/ocean_pollution.htm>.

[46] Marshall, Jessica. "Rising Ocean Acidity May Deplete Vital Phytoplankton : Discovery News." *Discovery News: Earth, Space, Tech, Animals, History, Adventure, Human, Autos*. Discovery, 14 Jan. 2010. Web. 19 Sept. 2011.
<http://news.discovery.com/earth/phytoplankton-iron-ocean-acidity.html>.

[47] "Phytoplankton ID Homepage." *CIMT Home*. Center for Integrated Marine Technology, 2007. Web. 08 Oct. 2011.
<http://cimt.ucsc.edu/habid/habhome.html>.

available in very large amounts, organism populations (usually algae, or other microorganisms) bloom and end up depleting nutrients, such as oxygen, which are important to other sea life. The sudden depletion of these nutrients eventually starves the organisms in the ecosystem, including the organisms responsible for the depletion of nutrients creating a ‘dead zone’ where very little life is present.[48] However, so long as fertilizer is used in moderation, and plant waste is disposed of properly, halophytic farms should be able to prevent dead zones.

2.3 Law

The high seas are a complex legal topic. Therefore, the legal ramifications of halophytic farming need to be considered. Until the mid-1900’s the seas were ruled by the freedom-of-seas doctrine, which stated that all nations could use the seas for safe transport. While safe transport governance has precedence, the usage of natural resources on the high seas lacks definition. As oil and valuable minerals were discovered offshore, the question of ownership became a serious concern. Further complicating the matter was the timing; these resources were discovered during the Cold War. Many nations feared the oceans would be ravaged by the warring superpowers in their bids for dominance.[49] In response to these fears, the United Nations held several international meetings called the United Nations Conferences on the Law of the Sea (UNCLOS). The most impactful of these, UNCLOS III, took place from 1973 to 1982 and had 162 nations in attendance. During this time, the nations at the third conference drafted the Law of the Sea Treaty.[50] This treaty is still in effect today and is the primary law of the high seas.

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[48] Gulick, Amy. "No Oxygen, No Life." Web. 15 Sept. 2011. <http://www.dtmag.com/Stories/Ocean%20Science/12-03-ecoseas.htm>.

[49] "The United Nations Convention on the Law of the Sea (A historical perspective)." *Oceans and Law of the Sea*. United Nations, n.d. Web. 19 Sep 2011. <http://www.un.org/depts/los/convention_agreements/convention_historical_perspective.htm>.

[50] ibid

UNCLOS states that nations have a specific set of rights to the oceans just outside their borders. This zone, called the Exclusive Economic Zone (or EEZ), extends 200 nautical miles from the nation's baseline. [51] The baseline is defined in Article 5 as "the low-water line along the coast as marked on large-scale charts officially recognized by the coastal State."[52] In Appendix A, Chart A demonstrates the geography of this baseline in the case of small islands and deformations in the coastline. Within a nation's own EEZ, they have the right to the exploitation and preservation of any and all natural resources. This includes living resources such as fish and nonliving resources such as oil, energy, and minerals on the seabed. They also have the right, as laid out in Article 60, to construct artificial islands and other "installations and structures" for economic gain, marine research, and other purposes brought forth in Article 56 of UNCLOS. [53]With this in mind, these installations must be placed so as to not interfere with "recognized sea lanes essential to international navigation." (Article 60) Additionally, any installations built are under the full sovereignty of the coastal State, the nation owning the Economic Exclusion Zone (EEZ).[54] In practical terms, if an installation was built in the United States' EEZ, then United States law would govern the installation and they would have the right to protect the site.

For halophytic farming, these laws have a strong bearing on the results. Building aquatic farming facilities within an EEZ greatly simplifies any legal matters. For all intents and purposes, building it within an EEZ would be the same as building it on national soil. The owners would have the rights to the area's resources, and would also have the right to protect their facility from scavengers and pirates, all without any specialized permits or processes beyond those used to build the facility.

However, for this project, installations within such a relatively limited area (as compared to the entire ocean) may not be sufficient. For this reason it is necessary to examine UNCLOS' stance on the

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[51] United Nations. *United Nations Convention on the Law of the Sea*. 1982. Web. <http://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm>.
[52] ibid
[53] ibid
[54] ibid

ocean outside of any EEZ. In Article 87 it says that states have the “freedom to construct artificial islands and other installations permitted under international law, subject to [previous sections of this treaty regarding artificial islands]” on the high seas.[55] There are some key differences between building such an installation on the high seas as opposed to in an EEZ. First, any installations constructed must be built with other nations of the treaty in mind.[56] In practical terms, this means that the space available for such projects would likely be limited by the U.N. to ensure that one nation doesn’t control all of the farmable ocean area. Second, there would be a significant tax on any profit made from the farming installation. After five years of operation, the U.N. would require a one percent tax on the facility’s profit. This tax would increase by one percent each year, capping at a seven percent tax in the thirteenth year.[57] Third, and perhaps most importantly, no state would have sovereignty.[58] No single state would be able to claim authority on the installation, making any legal matters concerning the structure significantly more difficult to resolve. These are all important risks to consider in this project and will need to be factored into the viability of facilities constructed on international waters.

There is one final legal consideration that will likely have a bearing on this project: The United States, at the time of this writing, has yet to ratify the Law of the Sea Treaty. The reasons for this are many but can be summarized in a few main points. First, submitting to an international authority and accepting a loss of sovereignty has been distasteful to some policymakers.[59] Second, due to Article 144, the United States would be forced to share the technology they use for seabed mining operations.[60] This also has been a source of contention with policymakers.[61] On top of those reasons, the U.S. already

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[55] United Nations. *United Nations Convention on the Law of the Sea*. 1982. Web. <http://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm>.

[56] ibid

[57] ibid

[58] ibid

[59] Becker, Michael A. "International Law of the Sea." The International Lawyer 43.2 (2009): 915. Print.

[60] United Nations. *United Nations Convention on the Law of the Sea*. 1982. Web. <http://www.un.org/depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm>.

[61] Becker, Michael A. "International Law of the Sea." The International Lawyer 43.2 (2009): 915. Print.

follows most of the provisions laid out in the treaty.[62] With little pressing need to sign it and several legal hurdles in its way, it is no surprise that the treaty remains a low-key topic. There have been encouraging signs in recent years though. In 2007, the Senate Foreign Relations Committee voted in favor of ratifying the treaty, although a vote has yet to be scheduled in Congress.[63] Former president George W. Bush and current president Barack Obama have expressed a strong desire to see the treaty signed.[64] However, the United States' current non-ratification of the treaty must be considered in the legal ramifications of this project.

2.4 Current Costs

A successful economic understanding of potential oceanic systems requires a strong background in the monetary costs and trends of current marine technologies. Marine-grade equipment tends to be more expensive than other equipment due to the fact that the ocean environment is generally more demanding. Between strong short-term stresses (e.g. storms, accidents) and long-term consequences of the marine environment (e.g. cyclic loading due to waves, bio-growth, accelerated corrosion), marine technologies have both significant upfront costs and large maintenance and operating costs. Compiling the monetary costs of existing marine technologies which are relevant to ocean operations and halophytic farming is a key step towards making grounded economic extrapolations. The marine technology areas identified as potential economic model inputs are commercial transport, automation, and structures. An overview is presented below.

For a project that intends to explore the economic feasibility of creating ocean goods to be delivered to shore, a good background in the economic workings of commercial maritime transport is important. For a typical cargo or oil tanker ship, the cost per mile is related primarily to fuel prices,

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[62] ibid

[63] ibid

[64] ibid

vessel speed, and the given ship's Twenty-foot equivalent unit or TEU (measure of cargo capacity).[65] Specific cost varies widely depending on the ship and trip. However, an estimate of costs per mile can be approximated (for a 100 thousand horsepower ship) to 120 gallons per mile,[66] and with crude oil estimated at $2.8 per gallon[67] the average mile of transport costs about $350. Cargo ships often have relatively few hands on deck for such large vessels and operators are generally paid from $40,000 - $70,000 per year[68]. Risks associated with cargo and tanker ships include loss of cargo, spills at sea, and piracy. Although the probability of such events happening is low, the impact of such events is high both economically (loss of valued cargo), politically, and potentially environmentally.

Automation will be a significant enabling technology with marine applications because it reduces operation costs and can act as a 'force multiplier' for tasks that require human effort. Notably, recent years have seen the increased use and reliability of Autonomous Underwater Vehicles (AUVs) in various aquatic industries: scientific, oil, and military for example. The Institute of Engineering and Technology states, "The Autonomous Underwater Vehicle (AUV) market is estimated to be worth $2.3bn over the next decade and it is forecast that around 1,400 new AUVs will be built."[69] The aforementioned trend is reflective of a rapid growth in that sector which will ultimately make the technology more available economically. Furthermore, units built to perform specific tasks tend to be cheaper than 'general use' vehicles. Units expected to perform in less demanding environments (typically a factor of depth) also tend to be cheaper. A large, deep-ocean cruiser AUV can have an expected price tag of $1 to 5 million. Smaller shallow-dive (~100m) AUV can have an expected price tag of $50 to 250 thousand in

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[65] "How Much Fuel Does a Container Ship Burn." *Wiki Answers*. Web. 19 Sept. 2011. <http://wiki.answers.com/Q/How_much_fuel_does_a_container_ship_burn>.

[66] "An Estimate of Operating Costs for Bulk, Ro-ro and Container Ships." *Bureau of Transport Economics*. Australian Bureau of Infrastructure, Transport and Regional Economics, 10 Jan. 1983. Web. 19 Sept. 2011. <http://www.bitre.gov.au/publications/06/Files/IP004.pdf>.

[67] "Crude Oil and Commodity Prices." *CRUDE OIL PRICE*. Web. 19 Sept. 2011. <http://oil-price.net/>.

[68] DOL. "Water Transportation Occupations." *U.S. Bureau of Labor Statistics*. U.S. Dept. of Labor, 17 Dec. 2009. Web. 24 Sept. 2011. <http://www.bls.gov/oco/ocos247.htm>.

[69] Ibid.

addition to smaller logistical and deployment costs.[70] Considering the design space if oceanic farming in the case of this project is limited to shallow waters (<100m), a number of smaller cheaper AUVs is acceptable and preferable. A significant cost of an AUV is its sophisticated on-board navigation system, which sometimes comprises up to half the vehicle cost.[71] Complex navigation is necessary when an AUV operates at depth and in isolation however, considering how for the scope of this project an autonomous vehicle would be expected to stay near the farm-site, the issue of expensive complex navigation equipment can be marginalized by using cheaper sensors which rely on station-based bearings. Although the initial investment in AUVs is high compared to a skilled diver hired for a task, their operation and logistical costs and benefits are significantly better. A professional commercial-enterprise diver is expected to make between $40,000 - $100,000 a year which over several years is significantly more expensive than a smaller AUV.[72] Additionally, an AUV can operate longer, deeper, farther than a human counterpart, doesn't require rest, and can operate on relatively cheap amounts of energy. Ten years ago, operation costs were about $2 per kilometer[73], and between-mission maintenance costs were about $1000[74]. A particular class of AUV, ocean gliders, have such little energy requirements that they can travel great distances. For example, the 2009 Scarlet Knight, a glider from Rutgers University, crossed the Atlantic on a single battery charge.[75] There are even market incentives to bring automation to offshore oil platforms, where "the main contributor costs [to operational

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[70] Ibid.

[71] Caffaz, Andrea, Andrea Caiti, Giuseppe Casalina, and Alessio Turetta. "The Hybrid AUV Folaga." *IEEE Explore*. IEEE Robotics & Automation Magazine, Mar. 2010. Web. 16 Sept. 2011. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5430396&tag=1>.

[72] Singh, Aakash. "Scuba Diving Jobs." *Buzzle.com*. 18 Aug. 2010. Web. 9 Sept. 2011. <http://www.buzzle.com/articles/scuba-diving-jobs.html>.

[73] Eriksen, Charles C. "Autonomous Underwater Gliders." Geo-Prose.com. University of Washington, Mar.-Apr. 2003. Web. 23 Sept. 2011. <http://www.geo-prose.com/ALPS/white_papers/eriksen.pdf>.

[74] Davis, Russ E., Charles C. Eriksen, and Clayton P. Jones. "Autonomous Buoyancy-Driven Underwater Gliders." UCSD.edu. Univ. of California San Diego, 3 Aug. 2002. Web. 20 Sept. 2011. <http://www-pord.ucsd.edu/~rdavis/publications/4Gliders.pdf>.

[75] NOAA IOOS, Rutgers University, and Teledyne Webb Research. "First Unmanned, Underwater Robot Crosses the Ocean." *IOOS.gov*. U.S. Dept. of Commerce, June 2010. Web. 16 Sept. 2011. <http://www.ioos.gov/library/cross_ocean_glider_onepager.pdf>.

expenditures] are site personnel"[76]. Automation will be a significant factor in reducing persistent offshore operations.

Oceanic platforms, structures, and the costs associated with them will likely be another significant and expensive portion of any open ocean harvesting project. Offshore oil rigs and wind-farm are examples of the costs involved with ocean platforms. Purchasing an operational offshore oil rig costs between $100 - 400 million. Renting for a day is about a thousandth of that price. They can take $50 million a year simply to maintain and operate. Part of that expense goes to riggers who get paid between $50 - 100 thousand a year.[77] Furthermore, each rigger position has on average 2.5 people working that position in shifts. Automation of high-shift positions could significantly reduce personnel costs. Retrofitting otherwise unusable or decommission-ready oil platforms for mariculture can have an expected capital cost of $10 million.[78] Another modern ocean-structure model to examine is oceanic windfarms. The cost distribution of a wind-farm's expected life cycle (assuming ~60m depth) is as follows: 10% logistics and installation, 13% support structure/platform material costs, 20% operation & maintenance, paperwork 5%, (the rest is wind farm specific like turbine, power transmission, and misc. costs).[79] Research funds for offshore wind farms are well documented.[80] For example, the American Reinvestment and Recovery Act of 2009 (ARRA) supported floating turbine platform research with

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[76] Pinosofa, and Yermagaliyeva. "Unmanned Offshore Platforms: Automation Kit." OnePetro. June-July 2010. Society of Petroleum Engineers. 20 Sept. 2011 <http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-132289-MS&soc=SPE>.

[77] "Salary Information for Offshore Oil Rig Personnel." Offshore Oil Industry Jobs. Halderman, 2011. Web. 20 Sept. 2011. <http://www.oil-industry-jobs.com/salaries.html>.

[78] Kaiser, Mark J., Biran Snyder, and Yunke Yu. "Ocean & Coastal Management : A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico." Science Direct. Oct. 2011. Elsevier. 25 Sept. 2011 <http://www.sciencedirect.com/science/article/pii/S0964569111001050>

[79] U.S. Dept. of Energy, U.S. Dept. of Interior, Knauss Sea Grant Fellow, SRA Intl., New West Technologies, and Energetics Incorporated. "A National Offshore Wind Strategy: Creating an Offshore Wind Energy Industry in the United States." Energy Efficiency & Renewable Energy. 7 Feb. 2011. U.S. Dept. of Energy. 18 Sept. 2011 <http://www1.eere.energy.gov/windandhydro/pdfs/national_offshore_wind_strategy.pdf>.

[80] DOE. "41 Offshore Wind Power R&D Projects Receive Energy Department Funding." Energy.gov. 7 Sept. 2011. Dept. of Energy. 23 Sept. 2011 <http://energy.gov/articles/41-offshore-wind-power-rd-projects-receive-energy-department-funding-0>.

approximately $8 million.[81] In “A National Offshore Wind Strategy” a general formula is presented to quantify the net dollar cost per energy unit for a given long-term high capital cost energy project. Whether that energy is measured in Mega-Joules or food Calories depends on the input parameters such as the annual amount of energy (e.g. food) produced, insurance and equipment warrantee fees, discount rate factors, maintenance costs and installation costs[82]. Furthermore, the document describes an expected 30% decrease in the installation capital cost and a 60% decrease in the cost per energy sector over a 20 year period[83] which reflects a maturing of large, economically important, ocean projects.

In order to solve this problem, we planned to thoroughly examine all the factors of aquatic farming to discover what kept it from being profitable. If we could pinpoint the limiting factors, then we could look at how said factors changed over time to figure out when aquatic farming would be viable. To do this, we planned two methods of information gathering. First, we would use what research resources we had available to us to build a strong knowledge base on various topics. Second, we would contact experts and forward-thinkers in the fields of robotics, biology, and genetics to see what directions their fields were going in. In this way, we could find detailed information we may not be able to find elsewhere. Combined, these should have given us sufficient information to appropriately answer our focus question.

As the project continued, we were forced to change our approach. Our first method was a great success, yielding us mountains of data and information. Unfortunately, as we explored aquatic farming further, we soon discovered that it was far more complex and involved so many unexplored fields that it

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[81] DOE. "41 Offshore Wind Power R&D Projects Receive Energy Department Funding." Energy.gov. 7 Sept. 2011. Dept. of Energy. 23 Sept. 2011 <http://energy.gov/articles/41-offshore-wind-power-rd-projects-receive-energy-department-funding-0>.

[82] Ibid.

[83] Ibid.

took our project far out of the planned scope. Our second method was less successful. We had hoped to communicate with the majority of the expert contacts listed in Appendix B but we seldom received tangible replies. To account for these, we altered our approach. Many assumptions were made regarding the hypothetical aquatic farm. Only operation costs would be counted, only two types of crops would be considered, rice and algae. The more complex elements of aquatic farms would merely be discussed and then left for future project groups. Since we were unable to obtain accurate information concerning the future of the robotics industry concerning oceanic robots, it was not possible to discern when enabling technologies would be available to a halophytic farming venture. The information gathered reflects elements that the farm comprises, as well as the features that we conjecture will be available in the future to enable a sustainable aquatic farm.

3. Results

3.1 Population

There are many complicated factors that affect population growth and decline. The simplest factors are fertility and mortality. However, there are many more aspects of society which affect birth and death rates. These aspects also affect the land available for farming produce and grain. For example, wars and disease increase death rates and decrease birth rates, and war can decimate arable land. More developed countries experience lower death rates, but also lower birth rates. Additionally, the more developed countries become the more arable land is given up to residential development, because arable land is generally considered a pleasant living climate. Population projections and societal trends will put a serious strain on the land available for both residential requirements and farming requirements.

There are two possible solutions to the land requirements for the growing population: either living in more compact quarters or finding alternatives to our current farming practices. The earth's population is increasing quickly and is projected to reach ten trillion by 2100.[84] The projection used to predict the population makes the assumption that, by 2100, most countries will have become significantly more developed. This means that the population will increase by approximately 42% and the demand for food will correspondingly increase. Additionally the population will have a higher standard of living and expect more attractive living spaces which will infringe on the available farm land. Approximately 29% of the earth's surface is land, and only 12.37% of the earth's surface is available for agriculture.[85] It would be exceedingly difficult for that land to provide food for the population as well as equitable living space for said population, even if humans were to find more efficient farming practices. Instead, it would be much wiser to farm the ocean which covers almost 71% of the earth.

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[84] "World Population Prospects, the 2010 Revision." *United Nations, Department of Social and Economic Affairs; Population Division, Population Estimates and Projections Section*. United Nations, Department of Social and Economic Affairs, 20 Oct. 2011. Web. 29 Nov. 2011. <http://esa.un.org/unpd/wpp/index.htm>.

[85] "Geographic Overview: World." *The World Factbook 2009*. Central Intelligence Agency, 19 Feb. 2012. Web. 24 Feb. 2012. <https://www.cia.gov/library/publications/the-world-factbook/docs/contributor_copyright.html>.

3.2 The Crop

The crop being cultivated will be a major factor contributing to the success or failure of aquatic farming on a large scale. The major advantage of farming at sea is the near limitless real-estate and water available to grow plants with. The major drawbacks of farming in the ocean are the relative lack of nutrients in extra-coastal waters and the salinity of ocean water. The best crop to optimize these conditions would have several qualities. It would be a staple crop or other plant that is required in large quantities so that the crop presents a worthwhile investment to potential farmers. It would be a plant that grows abundantly in order to take advantage of the large space. Lastly, the crop would require comparatively little care so that the farms would not require a large number of workers. Two crops were chosen as potential candidates for an aquatic farming operation, rice and seaweed.

Rice is an extremely common and well known grain. Originating in Asia, it has since become a staple crop in many cultures. With a little over a Calorie per gram, rice is very energy dense and is also nutritious.[86] For this reason rice was chosen to be analyzed for its effectiveness as an oceanic crop. Another reason is because rice is currently the best suited non-native crop to be introduced to the ocean. Rice paddies are flooded during growing season, an environment akin to a substrate floating just under the surface of the ocean. For more detail on a floating substrate infrastructure please see section 3.3. Rice has also been successfully engineered to grow in salt levels which would kill many other crops[87], making it a prime candidate to be adapted for in-ocean growth. However, rice is not a perfect candidate because it is typically seeded and grown into seedlings before being transplanted to a flooded

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[86] *Self Nutrition Data*. Self Magazine. Web. <http://nutritiondata.self.com/facts/vegetables-and-vegetable-products/>.

[87] "Salt-tolerant Rice 'could Aid Japan's Tsunami Farmers'" *BBC News*. BBC, 24 Jan. 2012. Web. 02 Feb. 2012. <http://www.bbc.co.uk/news/uk-england-norfolk-16699426>.

field.[88] This makes rice a more work intensive crop, and also makes the logistical aspect of growing rice in the ocean more complicated.

Seaweed is another choice candidate for oceanic cultivation. The major advantage of seaweed is obviously that it is native to the ocean. Seaweed, although not very high in energy, is extremely high in nutrients making it a valuable contribution to any diet.[89] Additionally, carrageenan, a product of refined seaweed, is used in a wide variety of products ranging from toothpaste to ice cream. This broad spectrum of uses makes it a fairly stable product on the market. However as with rice, seaweed is not a perfect candidate. Seaweed lacks the same demand as rice, global production of seaweed is approximately 6 million metric tons whereas global rice production is just under 700 million metric tons.[90]

3.2.1 Production Factors

The crop component of aquatic farms can be further broken down into factors that positively and negatively affect the productivity of the plants. Influences like storms, pests, and nutrient availability must be taken into account when examining the plausibility of an aquatic farm because if there are too many negative influences then the crops will not produce enough to support the operation. It is also important to consider these factors when discussing the actual structure of the farm because methods to compensate for negative influences can be built into the farms. The five main factors that will influence crop production are pests and diseases, storms, environmental conditions, the hydroponic effect, and the harvesting and processing of the plants.

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[88] Akaogi, Takeshi, and Linda Akaogi. "Rice Growing Manual for the Northeast USA." USDA Sustainable Agriculture Research and Education, 6 Mar. 2009. Web. 17 Nov. 2011. <http://nofavt.org/assets/files/pdf/factsheetsforfarmer/ricegrowingmanual.pdf>.

[89] Ibid. 86

[90] "World Production of Seaweed." *Seaweed.ie*. ISRG. Web. 02 Mar. 2012. <http://www.seaweed.ie/aquaculture/WorldProduction.html>.
"Rice." *Wikipedia*. Wikimedia Foundation, 29 Feb. 2012. Web. 05 Feb. 2012. <http://en.wikipedia.org/wiki/Rice>.

3.2.2 Rice (Oryza sativa)

One of the major advantages to growing plants which are native to land at sea is that many pests and diseases become much easier to handle. Many natural pests like the armyworm and tadpole shrimp are eliminated because the rice plants would be too far removed from the pests' habitat.[91] Also, flying pests like the rice seed midge would become much less of a nuisance because the ocean breeze and distance to the farm would discourage insects from reaching the rice crops. Reducing flying pests means the reduction of rice diseases as well, since rice diseases are primarily due to fungi. Without insects as vectors, fungal spores would be much less able to find and attach to rice plants. There is the possibility that rice will develop new predators, however investigating how this would affect crop productivity at this point would be premature. Lastly, parasitic weeds which would compete with the rice crop would be virtually eliminated because the salinity of the ocean water would act as an herbicide.[92]

Storms will be a significant concern for rice crops at sea. Rice is a fragile crop because of its structure. It is a type of grass that has wide bladed leaves and a long thin stalk with seed-heavy tassels. Therefore, it is not well suited to withstand the force of strong winds. In fact, wind speeds of 45 miles per hour can cause up to a 25% yield loss if the rice is exposed to winds while flowering.[93] This becomes even more problematic in ocean storms with the addition of waves. The plants that are not uprooted by the winds would be bent and damaged by the waves, and any rice left submerged in the water would drown. Without some way to protect the rice plants, or avoid storms, inclement weather would have a significant negative impact on crop yield.

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[91] Godfrey, L. D., and L. A. Espino. "How to Manage Pests." *Rice Pest Management Guidelines--UC IPM*. University of California. Web. 17 Dec. 2011. <http://www.ipm.ucdavis.edu/PMG/selectnewpest.rice.html>.

[92] Pence, Garrison. "How Does Salt Act As a Weed Killer? | Garden Guides." *Garden Guides, Your Guide to Everything Gardening*. Garden Guides. Web. 20 Sept. 2011. <http://www.gardenguides.com/75633-salt-act-weed-killer.html>. Post describing how to use salt as a pesticide and why it works.

[93] Banerjee, Chirantan, and Ernst Berg. "EFFICIENCY OF WIND INDEXED TYPHOON INSURANCE FOR RICE." Institute for Food and Resource Economics, University of Bonn, Germany, 2 Sept. 2011. Web. 21 Jan. 2012. <http://ageconsearch.umn.edu/bitstream/114240/2/Banerjee_Chirantan_13.pdf>.

Rice grows in a variety of climates and can be adapted to many levels of water availability. However, rice productivity is subject to changes in temperature. In a study done in 2004, researchers found that for every 1 degree Celsius increase in the minimum growing season temperature, rice crops produced approximately 10% less grain.[94] Higher temperature should not be a concern at sea because the temperature on the open ocean is much more stable and also much lower than on land. Instead, the lower temperatures may result in lower crop yield. The optimal temperature for the various stages of rice growth sits between 25-29^{o}C. The ocean temperature between the tropics ranges from 20-30^{o}C, which overlaps with rice's optimal growing temperature.[95] This means that farms would have better harvests if the farms were located closer to the equator where the temperature range is warmer.

Using a hydroponic approach to horticulture typically results in higher crop yields. This is due to the high levels of water, oxygen, and nutrients available to roots in hydroponic systems.[96] Close to shore these nutrients would come from runoff from land, however, in extra-coastal waters the ample nutrients would need to be supplied as fertilizer. On an aquatic farm plants suspended in a circulating nutrient solution, this is the basis of hydroponic cultivation. These conditions will likely lead to positive influences on the rice crop yields.

The last factor to be considered is the harvesting and processing of rice at sea. The same processes used on land will be used on halophytic rice. However, it is still worth considering how much of the plant is discarded during processing and also what has to go into preparing rice for shipping. Rice is harvested when the grain has a moisture content of ~25%, then it is threshed. Threshing is the

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[94] Peng, Shaobing, Jianliang Huang, John E. Sheehy, Rebecca C. Laza, Romeo M. Visperas, Xuhua Zhong, Grace S. Centeno, Gurdev S. Khush, and Kenneth G. Cassman. "Rice Yields Decline with Higher Night Temperature from Global Warming." *Proceedings of the National Academy of Sciences*. International Rice Research Institute, 27 May 2004. Web. 29 Dec. 2012. <http://www.pnas.org/content/101/27/9971.abstract>.

[95] Bergman, Jennifer. "Temperature of Ocean Water." *Windows to the Universe*. NESTA, 16 Feb. 2011. Web. 10 Nov. 2011. <http://www.windows2universe.org/earth/Water/temp.html>.

[96] Winterborne, Jeffrey. *Hydroponics: Indoor Horticulture*. Pukka, 2005. Web. 20 Sept. 2011. Comprehensive guide to hydroponics.

separation of the edible grain from the inedible chaff and can be done up to two days after harvesting. After threshing, the rice must be dried until the moisture content is ~20%.[97] This is good because it means that threshing facilities do not need to be maintained on the ocean. Both threshing and harvesting is done primarily by hand in Asian countries where the majority of rice is produced. However, there is growing interest in mechanical harvesting and threshing. This is also good because it means that this part of the process can be automated, which translates into fewer workers needed on the open ocean.

3.2.3 Seaweed (Porphyra tenera)

Seaweed does not gain any inherent benefits from being grown in the sea as far as pests are concerned. However, carefully choosing the location of the seaweed farm can minimize the effect of predators and diseases. Some fish, like the parrot fish, are known to be problematic for seaweed farms because the fish will graze the seaweed and consume much of the harvest. This can be avoided by placing the seaweed farms away from the habitats of the fish which typically graze on seaweed.[98] Seaweed, like many plants, can contract bacterial, fungal, and viral diseases. Diseases which afflict seaweeds are not well understood and are still a topic of great scrutiny. Much of what is known about seaweed diseases comes from studies of the disease “ice-ice”, such as the ones done by Correa, Largo, and Tsukidate. This disease affects eucheuma seaweed. Because of these studies many researchers hold that seaweeds contract diseases due to a number of circumstances. One key condition which makes seaweed disease more likely is slow flowing water in the growing area. A slow current allows infectious agents to attach to the skin of seaweed much easier. This can become a substantial problem because the agents which cause diseases are usually very motile. Due to the slow current, pathogens can transfer

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[97] "Rice Production and Processing." *IRRI.org*. International Rice Research Institute. Web. 20 Dec. 2011. <http://irri.org/about-rice/rice-facts/rice-production-and-processing>.

[98] Foscarini, Roberto, and Jayant Prakash. "HANDBOOK ON EUCHEUMA SEAWEED." *FAO: FAO Home*. MINISTRY OF PRIMARY INDUSTRIES, FISHERIES DIVISION. Web. 03 Dec. 2011. <http://www.fao.org/docrep/field/003/AC287E/AC287E04.htm>.

from seaweed to seaweed very easily and destroy much of a harvest. In the case of “ice-ice”, bacteria begin to metabolize the carrageenan in the cell walls of the seaweed.[99] Unfortunately this completely devalues the seaweed because the seaweed is no longer fit for consumption, and neither can it be processed into carrageen.

The wave action of storms will likely have the greatest impact on the yield of seaweed crops. Close to shore, wave action pulls on the ends of the seaweed fronds which come close to the surface. This periodic tugging can eventually tear parts of the frond off and even dislodge the entire plant.[100] This can be solved by moving the seaweed lower beneath the ocean’s surface, but this is limited by the seaweed’s sunlight needs and by the sea floor. Another solution is to locate the farms further out to sea where the waves are much lower frequency and contain less energy. Even with this method the crops are threatened by storms. During hurricanes and tropical storms, waves up to 100 feet high have been observed. Swells of that magnitude would easily tear the seaweed fronds from their scaffolding, and potentially break the scaffolding. This could be prevented by sinking the scaffolding and seaweed well below the surface of the water for the duration of the storm. The drawback of locating a farm further from shore it would cost more to transport workers, supplies, and crops back and forth between land and the farm.

Suboptimal environmental conditions can increase seaweeds’ susceptibility to infection. In a pristine environment light and salinity fluctuations do not affect seaweed’s growth. However, researchers have observed that seaweed’s resilience to disease is tied to temperature, light, and salt levels. If there is too much or too little sunlight or salt in the permeating the water, or if the temperature

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[99] Largo, D.B. (2002). Recent developments in seaweed diseases. In: A.Q. Hurtado, N.G. Guanzon, Jr., T.R. de Castro-Mallare, & M.R.J. Luhan (Eds.) Proceedings of the National Seaweed Planning Workshop held on August 2-3, 2001, SEAFDEC Aquaculture Department, Tigbauan, Iloilo. (pp. 35-42). Tigbauan, Iloilo : SEAFDEC Aquaculture Department.

[100] Mach, Katharine J., Benjamin B. Hale, Mark W. Denny, and Drew V. Nelson. "The Journal of Experimental Biology." *A Fracture and Fatigue Analysis of Wave-swept Macroalgae*. The Journal of Experimental Biology, 8 Apr. 2007. Web. 13 Dec. 2011. <http://jeb.biologists.org/content/210/13/2231>.

of the water is too high or too low then seaweed becomes predisposed to diseases.[101] Again, careful consideration of where the farm is located will mitigate these conditions. Locating the seaweed further out to sea and closer to the surface will generally solve both of these issues. Again, the disadvantage to having a farm further out to sea is the increase in transportation costs.

Seaweed naturally grows underwater. Consequently, growing seaweed in the ocean does not have the same hydroponic effect as does growing rice in the ocean. Increasing the concentration of nutrients in the water needed by seaweed, such as iron, can increase the growth rate of the algae.[102] However, this is more akin to fertilizing the seaweed than hydroponic horticulture.

The harvesting and processing of seaweed is of particular interest. Seaweed is harvested simply by collecting as much or as little of the plant as desired. Often seaweed is chopped partway down its 'leaf,' then the separated plant is collected while the rest is left to continue growing. The collected seaweed is washed in sea water, and then dried to prevent the growth of mold. The process is essentially 100% efficient in terms of converting plant matter to food matter, as compared to rice where much of the plant is discarded during processing. This is beneficial because the seaweed does not need to be reseeded, it can be harvested at any time, and the only by-product from processing seaweed is water vapor. Unfortunately, most of the volume of seaweed comes from the moisture content; seaweed is usually dried to 10% of its original mass.[103] This drying process presents a potential obstacle. Either very large quantities of energy, or lengthy periods of time would be needed to dry the seaweed. In most small scale seaweed production efforts, which are where a significant amount of seaweed comes from, drying is done by the sun over the course of several days. For a commercial venture, it would be most convenient to industrialize the drying of seaweed because the time and space that sun-drying would

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[101] Ibid. 99

[102] "Agriculture Business Week." *Iron Fertilization Increases Seaweed Yield Â«*. Agriculture Business Week. Web. 02 Nov. 2011. <http://www.agribusinessweek.com/iron-fertilization-increases-seaweed-yield/>.

[103] Ibid. 97

require would be greatly reduced. The energy needed to dry seaweed properly is approximately 21 megajoules per kilogram, this is the energy required to raise 9 kilograms of water to 100^{o}C at 1 atmosphere of pressure assuming that the ambient temperature is 22^{o}C. For reference, 21 MJ is approximately the amount of energy used by one person in an average U.S. household in one day, and this energy would be used to produce a mass of seaweed equivalent to a liter of water. Taking into account the cost of diesel fuel means that it costs approximately 54 cents to produce one kilogram of dried seaweed which is relatively expensive, especially since this does not take into account the cost to wash the seaweed or transport it.[104] It is possible that a hybrid system would work the best. First the seaweed would be sundried to remove a significant amount of moisture, and then it could be heated artificially until it reached the correct moisture content.

3.3 Farm Structure

The structure of the farm will have a great impact on its cost. The growing area for this farm will need protections against the hazards of the ocean. The farm will also require a central facility to hold robots, equipment, a dock, and other supplies. All this will need to be designed with both the monetary and environmental costs in mind. The location of the farm will dictate its design.

3.3.1 Growing Area Design

One possible design of the growing area would be to keep the crops free-floating. Apart from the basic infrastructure to keep the crops at the appropriate depth, the cost would be almost negligible. Unfortunately, this method is also the most hazardous for the crops. Nothing would exist to prevent the crops from receiving hazardous materials through the ocean. There would be no deterrents against pests, and crops would be exposed to rough weather. As mentioned in previous sections, rice would be devastated by open-ocean storms. Unless the yield from the crops was significant enough to outweigh

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[104] "Gasoline and Diesel Fuel Update." *Eia.org*. U.S. Energy Information Administration, 27 Feb. 2012. Web. 29 Feb. 2012. <http://www.eia.gov/petroleum/gasdiesel/>.

the losses, or the station itself was designed to protect the entire facility from storms, then it is unlikely the cost-saving measures of this design would prove fruitful.

An alternative method to the previous, free-floating design would be to keep the crops in a semi-enclosed area. For example, netting could be strung beneath the crops in an upside-down dome to keep out large detritus and unwanted fish. This would lower crop losses to sea-based predators and keep large pollutants from reaching the plants. This strategy has its downsides as well. Netting would add an additional cost for the farm per area, or roughly thirty-six thousand dollars per acre of netting alone[105]. Additionally, given its position in the sea and massive area covered, repairs to such a barrier would prove difficult. This could be alleviated by dividing the barriers using many small nets instead of a few large ones. This way, if a single net were to fail, then only a small portion of the barrier would need to be removed and repaired. This would add additional infrastructure cost for the rigging, but would ultimately be a worthwhile investment if crop losses were a concern. This design still does not intrinsically protect crops from storm damage. A facility located in a low strength and frequency strong area or designed to avoid or prevent storm damage (discussed later) would be ideal for providing a balance between crop safety and cost.

Yet another method would completely enclose the crops while grown, either in small pods or a few giant enclosed structures. The bottoms of such structures could be built out of wire mesh and the tops out of a hard, but transparent material, allowing crops to receive both water and sunlight. This is one of the most ideal solutions as far as crop safety is concerned. The plants would be protected from both predators and foul weather, resulting in extremely low crop loss. However, this design would undoubtedly be the most expensive to implement and difficult to use. The pods or structures would

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[105] "Umbrella Nets." Memphis Net and Twine. Memphis Net and Twine. Web. 09 Feb. 2012. <http://www.memphisnet.net/category/nets_unbrella>

need to be both accessible enough to plant and retrieve crops, and durable enough to withstand inclement weather.

The design of the crop growing area will depend largely on the design and location of the farming facility. With the station located in the ocean, all materials needed would need to be shipped to the site. The first method, requiring no real materials, would be the cheapest. The second would be expensive, but not excessively so. The third method would require tons of materials to work, so distance from shore is a real factor. But if the station is at real risk of frequent storms, then the added cost may save the facility money in the long term. Additionally, some crops may not have many ocean-based predators, and other crops may be grown under the ocean's surface, protecting them from storms. The design of the growing area will depend on these kinds of factors. No one method is right or wrong for every type of facility and careful consideration of the risks and rewards of each method will be needed.

3.3.2 Station Design

The station design will greatly impact how the rest of the station functions and operates. In addition to housing a dock, facilities for personnel (if any), storage, and other departments, its design will dictate how storms affect the station. Storms on the ocean will be devastating for crops, as mentioned in the previous section. Crops could potentially be guarded from storms by the growing area, but the equipment and facilities on the station need protection. This section will discuss two options: a solid facility like modern oil rigs, or a free-floating structure capable of evading storms.

The station could be built directly on or otherwise anchored to the sea floor, in the style of modern-day oil rigs. Such a design would have several advantages. Oil rigs are built to withstand category 5 storms, and thus would be safe in most weather[106]. Their close proximity to land would lower transportation costs. New stations could even be made by refurbishing old oil platforms at a lower cost

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[106] "Hurricanes and the Offshore Oil and Natural Gas Industry." *NOIA*. National Ocean Industries Association. Web. 7 Sept. 2011. <http://www.noia.org/website/download.asp?id=326>.

than building new ones[107]. However, such a facility would encounter difficulties. Building new rigs is extremely expensive and the cost only increases the further out into the ocean one goes due to depth. Additionally, while the structure may be safe from storms, it offers no such protection for the crops. Such a design would be worthwhile if storms are a major concern for the equipment on-site, but the crops could be replaced at low cost.

Another option would be to not permanently anchor the station, and instead let it float unattached at the surface. The major advantage of this method is that it allows the facility to evade incoming storms. Depending on the location, this could be a necessary feature to ensure the safety of the crops or equipment. Unfortunately, this would have the disadvantage of leaving the station more susceptible to storms in general. Without a foundation, the station would be at high risk for damage from any storm it had to endure. Additionally, the fuel costs for moving such a station would be astronomical. Large barges, as mentioned previously, typically run costs of $350 per mile. Assuming the station must move 100 miles per month on average, it would cost an estimate of nearly a million dollars a year in fuel. A mobile design such as this would only be worth considering if another, more-cost effective way to move the station could be found or another function could be fulfilled by dynamic station relocation. Additionally, this design would be feasible if fewer trips must be made.

3.4 Environmental Concerns

There are other, more specific concerns related to farming out on the open ocean with regard to environmental cost. Due to aquatic farming's unique locale, little study has been done on many of these issues. As such, many will also be listed in the Additional Problems section.

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[107] Kaiser, Mark J., Biran Snyder, and Yunke Yu. "Ocean & Coastal Management : A review of the feasibility, costs, and benefits of platform-based open ocean aquaculture in the Gulf of Mexico." Science Direct. Oct. 2011. Elsevier. 25 Sept. 2011 <http://www.sciencedirect.com/science/article/pii/S0964569111001050>

One major concern is plant waste left behind after harvesting plants. On land, such leftover biomass would be left behind as fertilizer or compost. On the ocean, that luxury does not exist, and, as mentioned in section 2.2, decaying plant matter damages the environment in many ways. There needs to be some method to control the leftover biomass once the harvest is complete. One technique that could work would be harvesting the entire plant instead of just the fruit or grain. In this way, little plant matter would be left behind. The plants could simply be fully harvested once aboard the facility or on the ship en route to shore. The tradeoff of this method is the increase in expenditures to preserve the additional plant matter and dispose of the extra biomass properly.

Although the ocean is rich in nutrients, the plants grown may require additional nutrients in the form of fertilizer. This presents another problem that land-based farms often face: runoff. But this problem is magnified on the ocean, as any additional fertilizer used will go directly into the ocean. The amount administered to the plants needs to be carefully measured, and even then a system needs to be in place to prevent runoff. For example, if the water leaving the growing area could be filtered somehow, then excess nutrients could be removed from the water. Proper fertilizer distribution will have to be a major part of the station's design, because excess fertilizer can lead to harmful algae blooms. The risks and causes of algae blooms are discussed more thoroughly in section 2.2. To summarize, algae blooms will deplete the oxygen and nutrients from the area and some types of algae even secrete toxic chemicals. Both scenarios would be deadly to the crops. While our crops need nutrients to survive, without a carefully designed method of giving them these nutrients, they will die.

A major concern that will dictate how the facility is run is shipping. As previously mentioned, current costs for shipping using an oil tanker are high at approximately $350 per mile. With the high cost of moving equipment and crops via boat, the station will need to be run in such a way that minimizes the number of trips ships need to make. For instance, the same ships that carry crops back to shore could carry supplies to the station. But this tight constraint on the timing of supply runs introduces further problems. If machines break down before the harvest, then crops may not be harvested fast enough to meet deadlines, and even more money is lost. Stations will need to have enough redundant equipment and parts to stay operational through the harvest. Another shipping concern is the transit time. Many crop plants need to be preserved or processed within a few days of harvest. With the time a boat would take to load the crops and make the journey back to shore (estimate), many crops may be lost to decomposition. One solution would be to use specialized transport ships that house processing facilities as well as transport crops. In this way, crops could be preserved while in transit, instead of waiting to be processed on a land-based facility. These are just a few scenarios, but they illustrate the problems that the long transit times and cost of transport that farming on the ocean entails.

3.5 Robotic Integration

3.5.1 Automation

A significant contribution to the success of large scale farming in general is the ability to scale up human abilities through automation. On land, this is achieved with the automation of irrigation, large harvesting machines, and processing lines. An oceanic farm would need a number of innovative analogous systems, as well as novel automated systems. Some topics such as the potentially mobile farm design, crop processing, and shipping have been mentioned in previous sections and are likely candidates to be robotized. Farm labor furthermore is hard work and marine labor tends to be just as intensive if not more demanding due to the harsher, isolated nature of marine facilities. These considerations highlight the importance of automation of farming processes on the ocean.

Like its land-based counterpart, oceanic farms need systems to administer crop supplements, effective methods of harvest, and effectual processing and shipping procedures. Some of these have been mentioned in the previous section. On land, farms have to supplement their crops with water and fertilizer and they do so at regular, automated intervals. Water is not a limiting agent in the open ocean but nutrients are. A system which automatically samples the nutrient levels in the water and distributes fertilizer in appropriate amounts would ensure consistent growing conditions. Such a controlled system would also be necessary to monitor the environmental impact of the fertilizer beyond the immediate perimeter of the farm for ecological purposes. This is also likely to be the first of these technologies to be applied to a pilot aquafarm project as it is relatively low cost, has few moving parts, and requires little human supervision.

Crop collection on major land-based agricultural plots is performed by large, human operated harvesters and, to some extent, analogously machines for the ocean already exist. As mentioned in previous sections, algae is currently gathered from natural seaweed beds for a variety of purposes. The collection process involves using two or more manned ocean thresher which operates somewhat like a giant lawn mower[108]. Rice on the other hand is traditionally harvested by hand although patty harvesters do exist. Patty harvesters however are currently ill suited to operate on the high seas. The design of a maritime one would have to take into account the specific method and architecture the farm facility intends to implement to cultivate rice. While it is currently only possible to operate these two types of crop collectors manually, it will be preferable to make them autonomous or remotely operated to reduce the human workforce physically present at the ocean farm facility for safety and monetary reasons (more on this will be described in a following subsection).

An oceanic farm may require additional robotics machinery beyond the analogous robotics technologies previously mentioned. On land, it is routine and relatively easy to check a farm's equipment and infrastructure for damage or wear. Due to the partially-submerged nature of ocean facilities it would be difficult to adequately asses the physical integrity and perform maintenance on its components. A human would have to either remove focus of the inspection or maintenance from the

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[108] "Harvesting of Macro Algae." *Oilgae*. Web. 5 Feb. 2012. <http://www.oilgae.com/algae/har/ma/ma.html>.

water or use a SCUBA and dive into the water. If such tasks meant to be routine it results in a lot of equipment downtime and expensive or challenging human labor. A system of robotic agents that regularly traverse the farm and its submerged equipment to check for emergent defects or other issues would be a practical failure-prevention strategy. The oil industry already employs robots to fulfill a similar task: they use them to travel the length of underwater pipelines checking for defects or leaks.

Although the future of robotics and automation is promising, current state of the art technology is not currently available. More challenging tasks, such as the performing maintenance or repairs autonomously, are still experimental or unfulfillable by the current state of technology. Given time and development however it is plausible that most if not all the functionality of an aquatic farm could be robotized. The level of autonomy and human presence on an oceanic farm, discussed below, will likely determine when in the future such a farm will be feasible.

3.5.2 Autonomy

Different levels of autonomy exist for the various automation components mentioned in the previous subsection. The frequency at which human intervention is necessary for a system to function is known as the Man in the Loop (MitL) timescale. Tethered remote controlled submarine-robots known as ROVs, for example, have a MitL at the moment-to moment or real-time timescale. Autonomous Underwater Vehicles (AUVs) today have MitL timescales on the order of 10s of hours or even days and is related to the time they can run on their own batteries[109]. On an oceanic farm, it would be desirable to have the longest MitL timescale possible. This is because the shorter the MitL, the more human intervention necessary to continue the operation, and thus the costlier the operation becomes.

While remote oceanic farms have many logistical disadvantages, these issues can be circumvented via remote operation. Humans are ill suited to withstand the isolation and harsh offshore

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[109] Blidberg, Richard. "The Development of Autonomous Underwater Vehicles." *AUVSI.org*. Autonomous Undersea Systems Institute, 2000. Web. 10 Mar. 2012. <http://ausi.org/publications/ICRA_01paper.pdf>.

environment of an oceanic farming enterprise. To watch the proverbial grass grow day in and day out is dull and working at sea is inherently more dangerous than on land (issues robots do not have qualms about). To expect a human laborer to work offshore and either live at the farm facility or commute is prohibitively expensive and, eventually, unnecessary. Tasks that would need oversight at the farm could be achieved remotely at a shore-side station or anywhere else in the world. Depending on how complete and flexible the robotic automation system is, it would be possible to operate a station with no humans on board at all for months at a time. There are multiple benefits of such a situation. For example, facilities for human necessities, such as sleeping, eating, locomotion, and waste removal, which would otherwise have to be provided, would no longer be needed, therefore reducing infrastructure overhead. Keeping the human facility managers on shore additionally reduces wage expenses meant to compensate for the dangers of working at sea.

The most notable tradeoff to reducing human labor is that an automated farm would have a much higher initial material cost. The technologies necessary for an automated farm, regardless of the efficiencies of the future, will likely still be costly. As of 2011, a single mid-level AUV costs nearly $1 million with reported 5 to 10% yearly upkeep cost[110]. To use such AUVs as the primary workforce of an oceanic farm would not be economically feasible. However, there are several cost effective 'tricks' that can be applied to drop these exorbitant prices. Today's AUVs are designed to act as single, self-reliant systems isolated from direct reference points and external information. Up to half of their cost can be accounted for by their complex onboard navigation and/or task specific equipment[111]. This equipment may not be needed if a farm structure can be used as a practical, permanent reference and instruction

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[110] Email conversation with David Kelly, CEO of BlueFin Robotics, 9/27/11 to 10/28/11

[111] Caffaz, Andrea, Andrea Caiti, Giuseppe Casalina, and Alessio Turetta. "The Hybrid AUV Folaga." *IEEE Explore*. IEEE Robotics & Automation Magazine, Mar. 2010. Web. 16 Sept. 2011. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5430396&tag=1>.

tasking point. As mentioned above, a lot of the automation will also not necessarily take the form of mobile robots.

The AUV business is experiencing steady growth, but could benefit from further investments. In fact, it is estimated to become a $2.3 billion market by the year 2019.[112] There is much room for application and cost improvement, as "the AUV market is still in its early adopter/infancy stage."[4] The greatest barrier to lowering the costs of these technologies is the relatively narrow market. The Military, Oil, and Research sectors are the predominant buyers of Unmanned Underwater Vehicle (UUV) systems. Significant changes in costs will likely only occur when greater demand drives production up and costs down. This push will likely only happen if other sectors, such as mariculture, become involved and invest in UUVs. Therefore, the best way to achieve greater economic feasibility of open ocean farming with robotic technology is to start investing in automated technologies now.

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[112] The World AUV Market Report 2010-2019 pamphlet.

4. Analysis

4.1 Model Construction

To understand the viability of farming the ocean, a mathematical model was constructed in Wolfram Mathematica to assess the earnings possible from offshore aquaculture farms. This model was based off an interaction diagram constructed by our IQP group relating crop yield factors to expenses and factors that would hinder yield, as seen in appendix C. This model reflects profits earned by the farms but does not take into account start-up costs that would be required to start the farms. Three models were made: one for a rice farm, one for an algae farm, and one for a farm producing both rice and algae. To assess earnings, two major functions were formed: income and expenses. The income function was calculated based on the crop yield possible for the crops. However, the percentage of crop yield was reduced due to various factors. These factors are dependent on whether it is algae or rice being grown.

For rice, certain factors were taken into consideration when determining yield loss. These factors were processing, diseases, pests, and storms. Although rice loss due to milling machinery can be averted by using machinery designed past 1985, drying the rice paddy using machinery results in a 30% loss of polished grains.[113] The percentage of crop yield for rice reduced due to pests, diseases, and storms was considered negligible. While it is possible for pests and diseases to decrease crop yield, it is assumed that fungicides would control outbreaks of diseases and that pests would not be capable of attacking crops in the open ocean. For storms, it is assumed that the farm would be placed away from areas where storms normally occur. The destructive capability of storms makes it possible to destroy the crop before a harvest can occur. According to Banerjee, Chiratan, and Ernstberg, percent loss of crop due to storms can be calculated based on wind speed, shown in the equation in Figure 1. A storm with

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[113] "Grain Losses in Rice Processing." *FAO: Food and Agriculture Organization of the United Nations, for a World without Hunger*. Food and Agricultural Organization of the United Nations. Web. 29 Feb. 2012. <http://www.fao.org/docrep/x5427e/x5427e0h.htm>.

wind speeds over 17 km is capable of producing a 100% loss of crop. Therefore, it is assumed that, should the farm be hit by a storm, the farm is capable of protecting the crop from storms by moving itself or shielding the rice. Because of this, storm damage was not factored into the model.

$$\%loss = 7.2 * speed - 19.4$$

Figure 1. Percent loss of rice based on storm wind speed (in km/hr)[114]

For algae, crop loss was based on processing, disease, pests, and storms as well. As previously discussed in the Algae Results section, animals that feed on algae normally are not found outside of coral reefs and are therefore negligible. Diseases also do not affect algae significantly as well. Algae can also take force from storm waves well, as previously discussed. Therefore, storms also do not play a significant role in algae loss. The biggest loss in mass is due to processing the algae. Because only 10% of the mass is retained after proper drying, seaweed loses a substantial amount of mass before and after processing.

For both models, it is necessary to know the amount of crop produced prior to loss. Crop yield for rice is expected to be 3085 kg/acre/harvest.[115] Algae yield was based on agar producing seaweed, or red algae. Yield was calculated by the growth rate of seaweed per day, factoring in the mass increase per increase of frond (or leaf) length. The resultant crop yield without taking consideration to losses is 4080 kg/acre/harvest.

Harvest times for each crop were taken into consideration when developing this model. Rice requires at least three months before the grain can be harvested. (University of Arkansas, p. 39) The number of harvests is therefore limited to a maximum of four per year. However, agar grows at a

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[114] Banerjee, Chirantan, and Ernst Berg. "EFFICIENCY OF WIND INDEXED TYPHOON INSURANCE FOR RICE." Institute for Food and Resource Economics, University of Bonn, Germany, 2 Sept. 2011. Web. 21 Jan. 2012.

[115] Shwetha, M. K., S. B. Mahajanshetti, and N. M. Kerur. "Economics of Paddy Processing." University of Agricultural Sciences, Dharwad, India, Aug. 2010. Web. 19 Feb. 2012.

considerably faster rate. At a rate of 0.6 meters per day, Agar harvests can be done every day of the year if necessary.

The other part of the model, expenses, used a similar format. Both types of farms would require similar expenses, but the values for these expenses are dependent on what crop is being grown. The factors used to determine expenses were the costs for personnel, equipment maintenance, fertilizer, fungicides, seeds, transporting the harvest, processing, and legal taxes. Cost per worker amount to \$75,000-\$100,000 every year. The model was constructed with one person per acre to manage the operations of the farm. Maintenance costs are estimated to be a few hundred thousand dollars a year for every ten acres. For the model, the input value used was \$20,000, or \$200,000 divided over ten acres, for maintenance. Fertilizer is dependent on the type of farm as well as the strain of rice used. Legal taxes are applied only when the farm is placed outside the 200 nautical mile EEZ limit. Transportation of crops was determined by the distance the farm would be placed from the coastline as well as the fuel cost. The model uses a general distance of 150 nautical miles, placing it well within the EEZ boundary. The model also uses fuel prices as of February 15, 2012. The calculation for transportation is shown below in Figure 2.

$$Transportation = Fuel\ Efficiency * 3.85 * Distance\ from\ shore$$

Figure 2. Transportation costs as related by distance (in nautical miles) and fuel efficiency.

To determine viability of a farm assuming all the resources required were available, the model was based on the area of the farm as well as the harvests per year. For a relation of profit versus area of the land in acres, a positive slope for a certain number of harvests indicated profitability, while a negative slope indicated that expenses outweighed the income. The values used to construct the model can be found in Appendices D, E, and F.

The third model analyzes a hybrid farm that grows both algae and rice For this model, a special factor was used to deduct from crop yield per area. Algae was given a certain percentage of farm and rice was given the rest of the area. For a constant number of harvests per year for each crop, the same slope determination was used to determine profitability depending on the percentage of area used to grow seaweed.

4.2 Model results

For the rice model, the number of harvests was limited to a range of one to four. Within this narrow range, the farm does not have the ability to turn a profit. At the maximum number of harvests, each additional acre the results in a loss of $86,605, as seen in Figure 3.

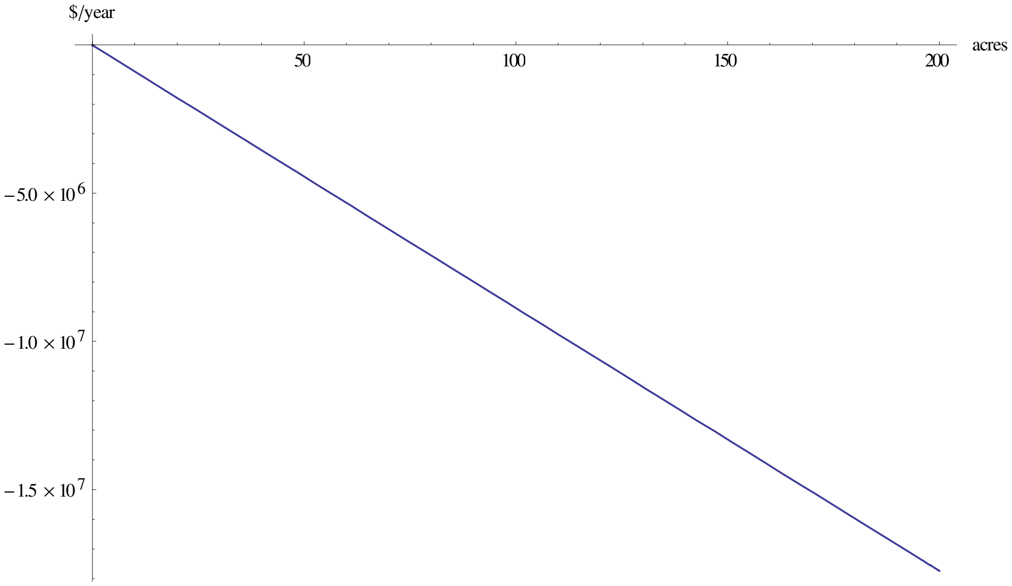

Figure 3. Plot of rice model in $/year vs. acres

In the model for algae, the net income is also negative. For every additional acre of farm, the net loss increased by $2,968,000, as seen in Figure 4. Looking at the difference between the two models, there is a stark contrast in the amount of crop yield lost between the two different crops as well as processing costs.

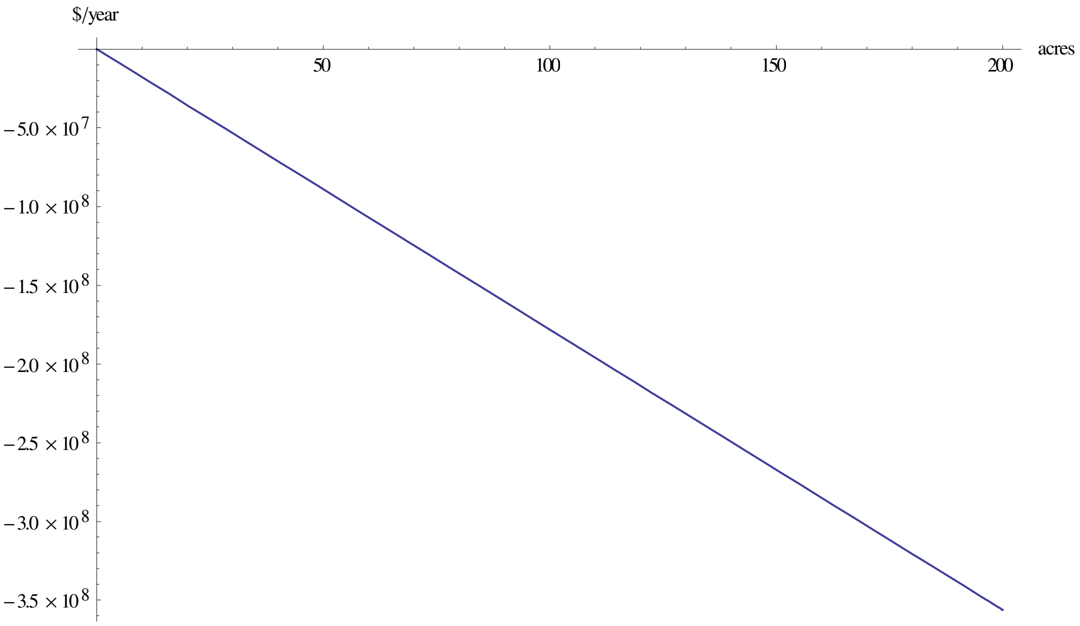

Figure 4. Plot of Seaweed model with $/year vs. acres of farm.

The third model observed the profitability of the farms dependent on the percentage of farm used to cultivate algae. Because of the large net loss caused by algae, an even split between the two does not increase profit, seen below in Figure 5..

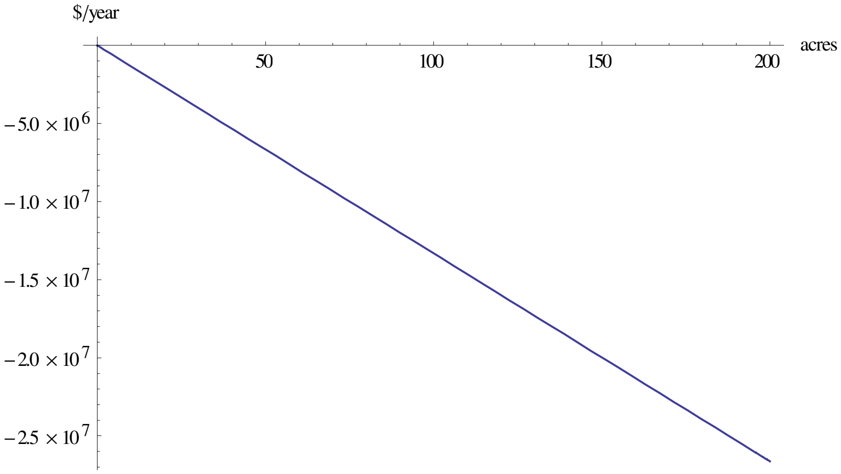

Figure 5. Plot of $/year vs acres of farm for a 35% algae composition farm.

For both crops, personnel and maintenance costs contribute approximately $95,000 per acre in costs. A large factor in the net loss of algae was the processing costs. Eliminating algae processing costs (using a method of open air drying) would cause a net profit in algae, with each additional acre of algae increasing profit by $80,200, as shown in Figure 6. Rice, on the other hand, also requires some amount of fertilizer and fungicides, and removal of processing costs only brings down net loss to $85,544 per acre.

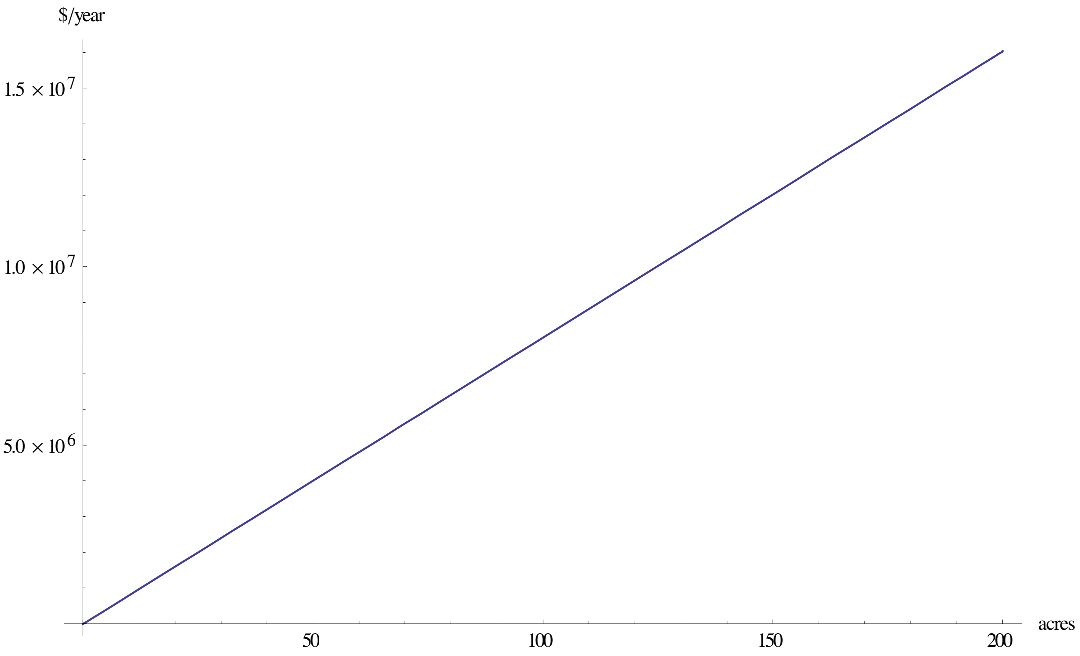

Figure 6. Plot of $/year per acre of farm for seaweed without processing costs

A hybrid plot disregarding processing costs was also generated. The result was that 77% of the farm would need to be algae in order to turn a profit. This would result in 23% of the farm to be used for farming rice, as shown in Figure 7.

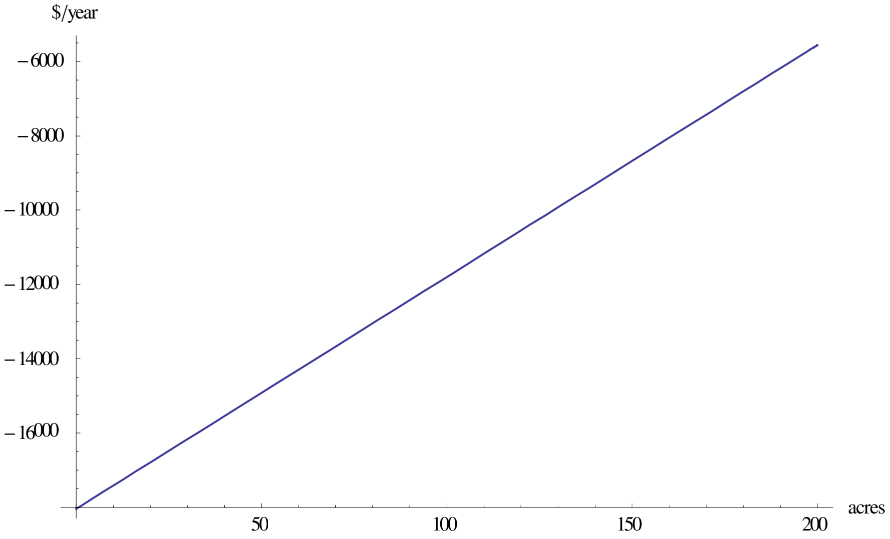

Figure 7. Plot of $/year vs acres of farm for a 77% seaweed farm.

Even with the combination of farms, it is evident that certain expenses must be cut to maximize any sort of gain on the farms. Bar graphs were constructed which showed the differences in the degree of expenses incurred by a 100 acre farm, as shown in Figures 8 and 9 for algae and rice, respectively.

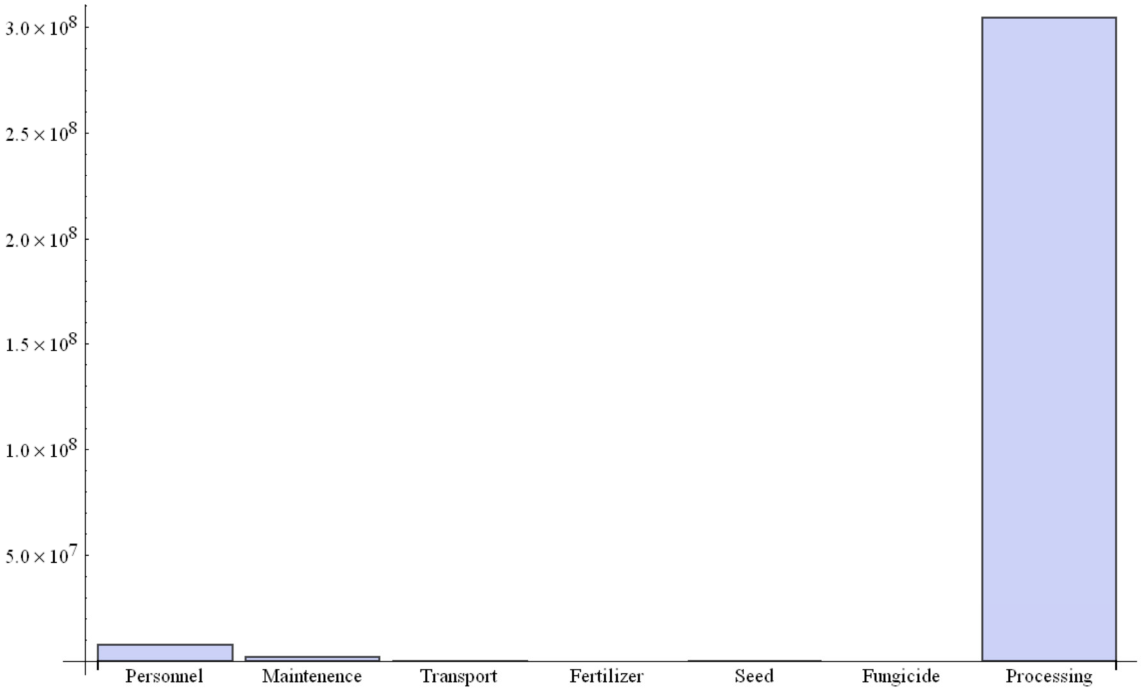

Figure 8. Bar Chart of Oceanic Seaweed Farm expenses

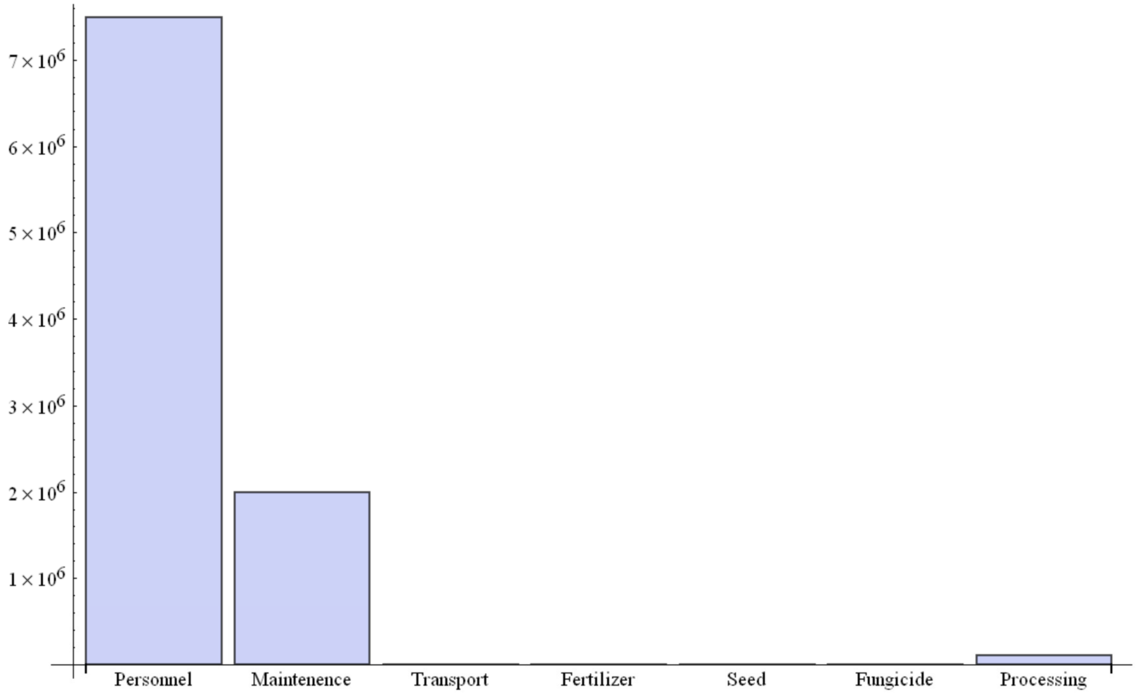

Figure 9. Bar Chart of oceanic rice farm expenses.

These charts outline the heavy expenses that make these farms currently unviable. Each of these farms has a particular expense that heavily outweighs the rest of the expenses. For seaweed, processing costs heavily outweigh any other expense at 500 million dollars. While personnel and maintenance can be optimized with robotics, processing is an expense that must be minimized by using more efficient methods of drying seaweed, such as less fuel burned to dry the seaweed. It is possible to use any waste generated by the plants as biodiesel, driving down the costs. For rice, personnel heavily outweigh any other factor, more than tripling the next highest expense, maintenance, at seven million dollars. Any factor for rice besides personnel and maintenance appears to fall well below costs of one million dollars. These two factors are ones that can be heavily optimized with the use of aquatic robotics to manage the farms, which will make farming this staple crop highly viable.

5. Conclusions

When comparing the two models of rice and algae farms, it is evident that an algae farm is more capable of turning a profit compared to a rice farm. Despite the 90% decrease in algae mass after processing, algae is more accustomed to growing in the ocean than rice. It is unaffected by predators and diseases and grows at an extremely quick rate. Although its caloric value is less than that of rice, it is an extremely nutritious food that requires little maintenance. Rice requires fungicides to assure that crop is not lost to disease, and rice is also easily devastated by storms. The requirement for algae to be profitable is that it is dried in open ocean air as opposed to being heated in a furnace via fossil fuels. This comes with a caveat of taking up a certain portion of farm space. To dry 6000 kg of wet algae, 5/8 of an acre would be required to dry the algae. A combination of heating the algae and ocean drying is possible to dry the algae quickly.

The hybrid farm was done with consideration to the fact that rice is a staple crop and consumed on a daily basis more regularly than algae. With 23% of the farm used to grow rice, the amount of rice produced is limited to production of 2800 kg/acre/year. With a 200 acre farm, the farm produces 560,000 kg/year, which is sufficient to feed 2800 people a year. [116] A current unknown is how diseases will affect rice on water. Although the model accounts for rice fungicides, diseases may not be able to tolerate the salinity. The diseases were included in the model in case the damage is possible, but it is possible that, if rice is capable of being genetically engineered to increase salt tolerance that certain disease resistant strains are selected. This would reduce the amount of fungicide necessary and lower costs overall. Costs for transport could potentially also be lowered by using the algae as biodiesel.

In terms of maintenance and labor costs, personnel and maintenance make up only $100,000 of the overall expenses. In contrast, the algae processing costs amounted to $3,048,480. Thus, personnel and maintenance makes up a very small part of the expenses. Even so, the cost for personnel can be

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[116] "The Asia Rice Foundation: Let's Eat." *Let's Eat Rice*. The Asia Rice Foundation. Web. 29 Feb. 2012.

reduced with the help of robotic automation. The assumption for personnel was that one person would manage one acre of farm. With the use of automated systems and tele-communications, robotics will play an important role in the management of these oceanic farms and will make the farm highly viable.

With the decrease in expenses driving the ability for oceanic farms to be built, these farms will be able to drive a new way of cultivating crops to feed the ever increasing population. The prospect of using robotic technology as an enabler towards this endeavor is highly promising. Oceanic farming will be a method to provide food in the future in a sustainable manner.

5.1 Future Work

Because of the size and nature of this topic, there is more to do that lies beyond the scope of the project. This work is intended to be continued by future IQP groups. A great deal of this work lies in making predictions about the future of economics, population, and technology. In order to encourage farms to shift towards oceanic aquaculture it is important to know what the limitations of certain technologies are, and how increased supply of different crops will affect the world economy. Other key topics that still have a great deal of depth to explore are renewable sources of energy at sea, how oceanic farms could affect world hunger, and the educational value of a halophytic farm regardless of profitability.

For a commercial enterprise like farming, financial matters are critical to analyze and comprehend, because a successful enterprise must generate revenue. Some financial aspects of a halophytic farm that could be furthered explored are:

- The economic backlash of a sudden increase in the supply of crops.
- Financial models for crops other than rice and seaweed.
- The startup costs of an oceanic farm and the response of investors to such an enterprise.
- What would be the most cost effective technologies to use on an aquatic farm?

Closely related to the financial aspects of halophytic farming is the demand for food. An IQP which focused on this could attempt to answer questions such as:

- What will the specific land demands be as the world population grows?
- How could halophytic farming help to alleviate world hunger?

Regardless of the exact structure of a halophytic farm, macroscopic ocean aquaculture promises to be a technologically advanced venture. Areas of technology that could be further studied in detail are:

- The progress of AUV technologies, and how an oceanic farm would drive that progress.
- How will artificially intelligent farm hands impact the robotic field?
- How is genetic engineering progressing, what will we be capable of genetically designing in the future?

Another major aspect of the farm is the ecological impact it will have on the ocean. Important areas that should be better understood before starting an oceanic farm are:

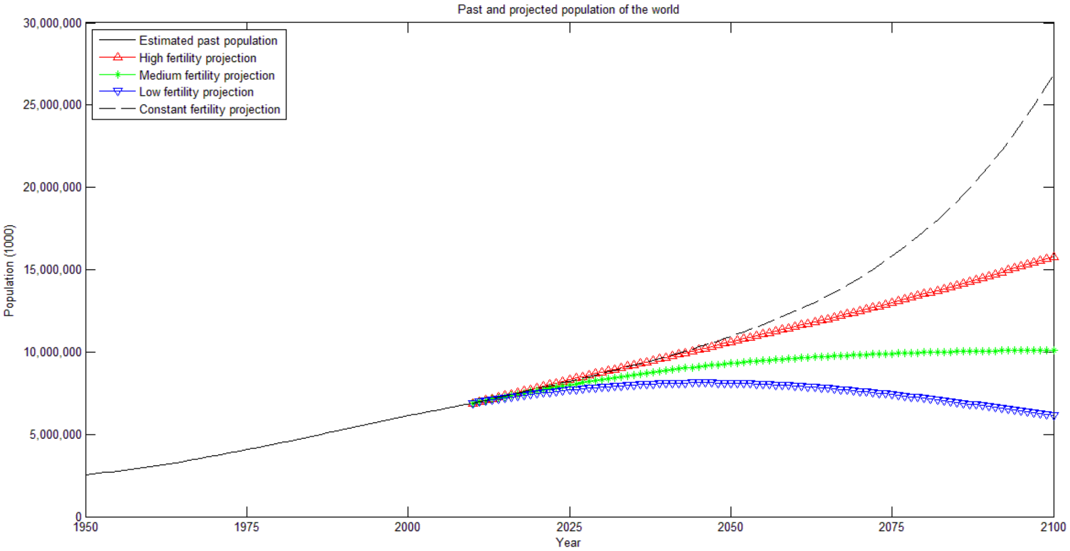
- The impact that nutrient sapping plants have on the ocean ecosystem.
- How will plant waste alter the ecology of the deep sea as it trickles down through the different levels of water?
- What kinds of effects could the regular use of fertilizer on the open ocean have?

Lastly, exploring the intellectual opportunity of sea based farms could be worth the venture in and of itself. There are many areas of research applicable to oceanic farms, and also many areas of research that could be advanced by the farms. Some of these areas are:

- The advances in renewable ocean energy that could be made by building a farm dependant on renewable sources.
- A better understanding of hydroponics, especially in a high salinity environment, and of the ecosystem of the ocean.
- The education of society in regards to the versatility of autonomous robots. An idea similar to the moon base IQP.

Appendices

Appendix A. Population Trends



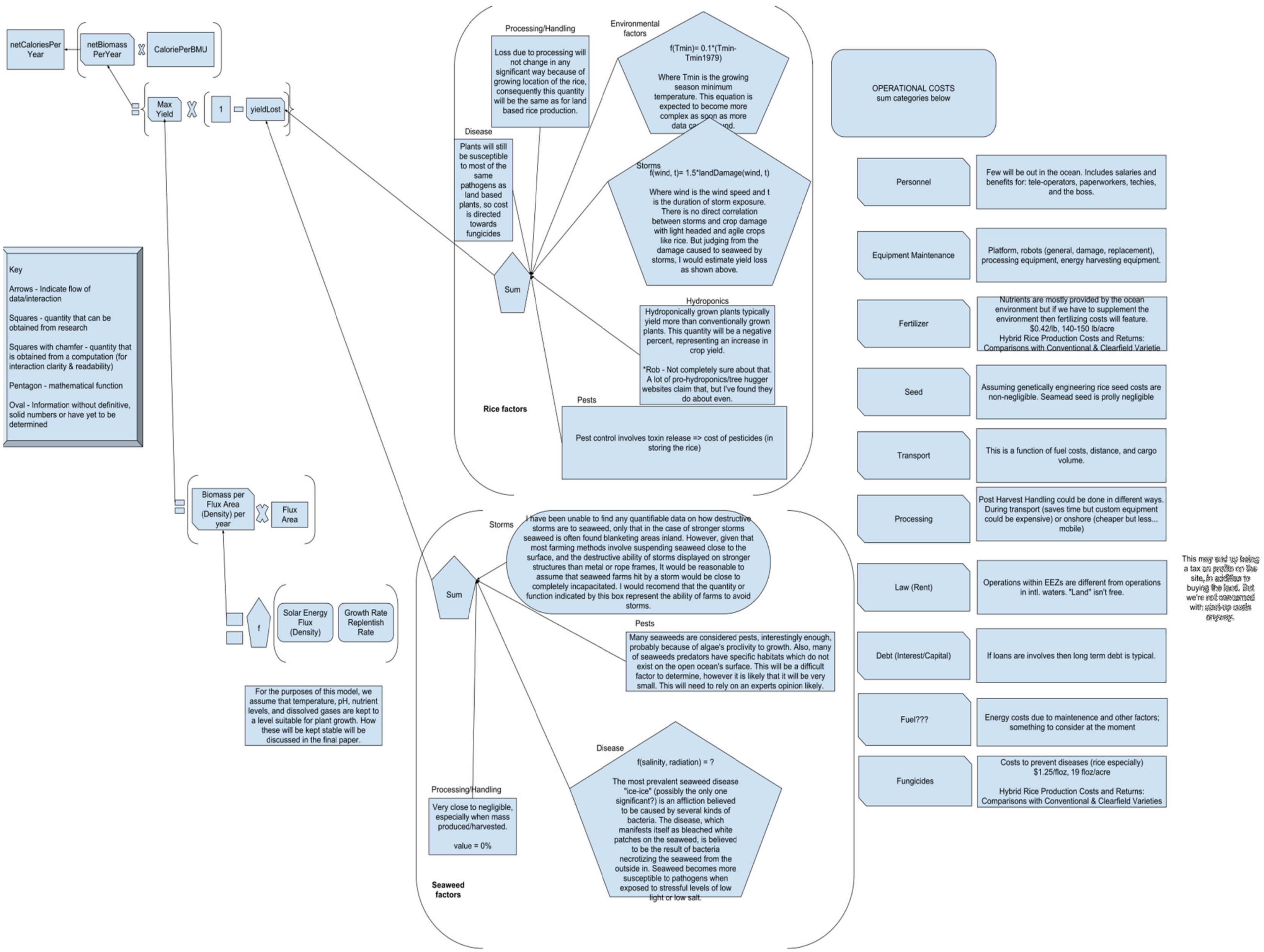
Population graph projections to 2100 for small islands

Appendix B. Contact List

Following is a list of people, experts, and institutes to whom communications were extended to. Italicized list items represent entities with whom we actually managed to converse with.

- *Chris Lumping (Woods Hole Oceanographic Institute)*
- Constance Clark (WPI – Environmental and Sustainability Studies)
- *David Kelly (Bluefin Robotics)*
- Fred Looft (WPI – Environmental and Sustainability Studies)
- Harbor Branch Oceanic Inst (Florida Atlantic University)
- Ingrid Shockey (WPI – Environmental and Sustainability Studies)
- iRobot
- Jeanine Plummer (WPI – Environmental and Sustainability Studies)
- Jim Doyle (WPI – Environmental and Sustainability Studies)
- John MacDonald (WPI – Environmental and Sustainability Studies)
- John Sanbonmatsu (WPI – Environmental and Sustainability Studies)
- *Kent Rissmiller (WPI – Project Center)*
- Khalid Saeed (*WPI – Social Sciences)*
- Laureen Elgert (WPI – Environmental and Sustainability Studies)
- Lauren Matthews (WPI – Environmental and Sustainability Studies)
- Rob Krueger (WPI – Environmental and Sustainability Studies)
- Roger Gottlieb (WPI – Environmental and Sustainability Studies)
- Scott Jiusto (WPI – Environmental and Sustainability Studies)
- Tom Robertson (WPI – Environmental and Sustainability Studies)

Appendix C. Interaction Diagram



Key

Arrows - Indicate flow of data/interaction

Squares - quantity that can be obtained from research

Squares with chamfer - quantity that is obtained from a computation (for interaction clarity & readability)

Pentagon - mathematical function

Oval - Information without definitive, solid numbers or have yet to be determined

For the purposes of this model, we assume that temperature, pH, nutrient levels, and dissolved gases are kept to a level suitable for plant growth. How these will be kept stable will be discussed in the final paper.

Rice factors

Processing/Handling: Loss due to processing will not change in any significant way because of growing location of the rice, consequently this quantity will be the same as for land based rice production.

Disease: Plants will still be susceptible to most of the same pathogens as land based plants, so cost is directed towards fungicides

Environmental factors: f(Tmin)= 0.1*(Tmin-Tmin1979)

Where Tmin is the growing season minimum temperature. This equation is expected to become more complex as soon as more data ca und.

Storms: f(wind, t)= 1.5*landDamage(wind, t)

Where wind is the wind speed and t is the duration of storm exposure. There is no direct correlation between storms and crop damage with light headed and agile crops like rice. But judging from the damage caused to seaweed by storms, I would estimate yield loss as shown above.

Hydroponics: Hydroponically grown plants typically yield more than conventionally grown plants. This quantity will be a negative percent, representing an increase in crop yield.

*Rob - Not completely sure about that. A lot of pro-hydroponics/tree hugger websites claim that, but I've found they do about even.

Pests: Pest control involves toxin release => cost of pesticides (in storing the rice)

Seaweed factors

Storms: I have been unable to find any quantifiable data on how destructive storms are to seaweed, only that in the case of stronger storms seaweed is often found blanketing areas inland. However, given that most farming methods involve suspending seaweed close to the surface, and the destructive ability of storms displayed on stronger structures than metal or rope frames, It would be reasonable to assume that seaweed farms hit by a storm would be close to completely incapacitated. I would recomend that the quantity or function indicated by this box represent the ability of farms to avoid storms.

Pests: Many seaweeds are considered pests, interestingly enough, probably because of algae's proclivity to growth. Also, many of seaweeds predators have specific habitats which do not exist on the open ocean's surface. This will be a difficult factor to determine, however it is likely that it will be very small. This will need to rely on an experts opinion likely.

Disease: f(salinity, radiation) = ?

The most prevalent seaweed disease "ice-ice" (possibly the only one significant?) is an affliction believed to be caused by several kinds of bacteria. The disease, which manifests itself as bleached white patches on the seaweed, is believed to be the result of bacteria necrotizing the seaweed from the outside in. Seaweed becomes more susceptible to pathogens when exposed to stressful levels of low light or low salt.

Processing/Handling: Very close to negligible, especially when mass produced/harvested.

value = 0%

OPERATIONAL COSTS sum categories below

Personnel	Few will be out in the ocean. Includes salaries and benefits for: tele-operators, paperworkers, techies, and the boss.
Equipment Maintenance	Platform, robots (general, damage, replacement), processing equipment, energy harvesting equipment.
Fertilizer	Nutrients are mostly provided by the ocean environment but if we have to supplement the environment then fertilizing costs will feature. $0.42/lb, 140-150 lb/acre Hybrid Rice Production Costs and Returns: Comparisons with Conventional & Clearfield Varietie
Seed	Assuming genetically engineering rice seed costs are non-negligible. Seamead seed is prolly negligible
Transport	This is a function of fuel costs, distance, and cargo volume.
Processing	Post Harvest Handling could be done in different ways. During transport (saves time but custom equipment could be expensive) or onshore (cheaper but less... mobile)
Law (Rent)	Operations within EEZs are different from operations in intl. waters. "Land" isn't free.
Debt (Interest/Capital)	If loans are involves then long term debt is typical.
Fuel???	Energy costs due to maintenance and other factors; something to consider at the moment
Fungicides	Costs to prevent diseases (rice especially) $1.25/floz, 19 floz/acre Hybrid Rice Production Costs and Returns: Comparisons with Conventional & Clearfield Varieties

This may end up being a tax on profits on the site, in addition to buying the land. But we're not concerned with start-up costs anyway.

Appendix D. Rice Yield Factors

Rice description	factor	Units
disease(fungal infection)	Likely negligible in the open ocean	%of base crop lost
pests	Likely negligible in the open ocean	%of base crop lost
hydroponic effect	Negligible	%increase of crop harvested (calculated after losses)
winds	x=windspeed y=percentloss y=0.000014(x^3)-0.00589(x^2)+0.92833(x)-29.923[117]	%loss/windspeed(km/h)
storms	Dependent on location of farm	frequency/latitude&longitude (assume 100% destruction per storm)
crop yield	3085.00[118]	kg/acre
Price	1115	$/metric ton (as of February 15,2012)[119]

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[117] Banerjee, Chirantan, and Ernst Berg. "EFFICIENCY OF WIND INDEXED TYPHOON INSURANCE FOR RICE." Institute for Food and Resource Economics, University of Bonn, Germany, 2 Sept. 2011. Web. 21 Jan. 2012. <http://ageconsearch.umn.edu/bitstream/114240/2/Banerjee_Chirantan_13.pdf>.

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Appendix E. Seaweed yield factor

Seaweed (Macro. P.)		
description	**factor**	**units**
disease(fungal infection)[120]	negligible	%of base crop lost @specific salinity and light
pests	negligible in open ocean	%of base crop lost, negligible in open ocean- primary pest is urchin
storms rate	Farms located away from storms[121]	frequency/latitude&longitude (assume 100% destruction per storm)
storm damage	negligible	No breaking waves off shore, which severely reduces damage to crop
crop yield	6000	kg(wet)/acre (calculated using numbers below)
Average Mass of Frond Per Length	0.4	kg/m of Frond[122]
Frond Density at Holdfast level	4.2	Fronds / m^2[123]
Growth	0.6	m/day (in high nutrient growing season)
Calories per kg		
Agar (Wet 90%)	260	cals[124]
Agar(Dry)	3000	cals
Laver (Wet 85%)	350	cals[125]
Laver (Dry)	2300	cals
LAW	Cannot cut 1 ft below surface level	AD&F regulations 5 AAC 37.300[b][126]
Harvestable Biomass (wet) per Sqr Meter per Day (Assuming max daily growth rate)	0	kg/m^2/day

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[120] "FAO Fisheries & Aquaculture - Laminaria Japonica." *FAO Fisheries & AquacultureÂ Laminaria Japonica*. Food and Agricultural Organization of the United Nations. Web. 20 Feb. 2012. <http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en>.

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[123] ibid

[124] "Nutrition Facts." *Seaweed, Agar, Dried*. SelfNutritionData. Web. 02 Mar. 2012. <http://nutritiondata.self.com/facts/vegetables-and-vegetable-products/2763/2>.

[125] ibid

[126] Van Tamelen, Peter G., and Doug Woodby. "Macrocystis Biomass, Quality, and Harvesting Effects in Relation to the Herring Spawn-on-Kelp Fishery in Alaska." Alaska Fishery Research Bulletin, 2001. Web. 20 Feb. 2012. <http://www.sf.adfg.state.ak.us/FedAidpdfs/AFRB.08.2.118-131.pdf>.

Appendix F. Operation Cost Values.

Operation costs		
description	**factor**	units
personnel	$75,000 - $100,000 per person	$/(year
equipment maintenance	estimated at a few hundred thousand per year	$/10 acre farm/year
fertilizer	Unnecessary for seaweed, 63 for rice[127][128]	$/acre/year
seed	98 for rice[129], 0.5 for seaweed[130]	$/acre/year
Fungicide	Negligible for seaweed, 14.25 for rice	$/acre/year
transport[131]	fuel efficiency of boat (75) * 3.85 * distance	$/(3/4 of exclusive economic zone)
processing	1392(seaweed)[132] 86.38(rice)[133]	$/(mass produced by one acre)
law	% of profits, only when outside an EEZ	$/year
fuel	2.63*10(-5)	$/kJoule
Diesel Fuel	3.79*10(4)	kJ/$

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[127] "FAO Fisheries & Aquaculture - Laminaria Japonica." *FAO Fisheries & AquacultureÂ Laminaria Japonica*. Food and Agricultural Organization of the United Nations. Web. 20 Feb. 2012. <http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en>

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Appendix H. Authorship

Section	**Author**
Abstract	Jeff Thomas
Executive Summary	Jeff Thomas
1. Introduction	Robert Le
2.1 Need	Robert Le
2.2 Maritime Considerations	William Terry
2.3 Law	Jeff Thomas
2.4 Current Costs	Sidney Batchelder
3.1 Population	William Terry
3.2 The Crop	William Terry
3.2.1 Production Factors	William Terry
3.2.2 Rice (Oryza sativa)	William Terry
3.2.3 Seaweed (Porphyra tenera)	William Terry
3.3 Farm Structure	Jeff Thomas
3.3.1 Growing Area Design	Jeff Thomas
3.3.2 Station Design	Jeff Thomas
3.4 Environmental Concerns	Jeff Thomas
3.5 Robotic Integration	Sidney Batchelder
3.5.1 Automation	Sidney Batchelder
5.5.2 Autonomy	Sidney Batchelder
4.1 Model Construction	Robert Le
4.2 Model results	Robert Le
4.3 Conclusions	Robert Le
4.4 Future Work	Robert Le