A COMPARATIVE CO_2 LIFE CYCLE ANALYSIS OF THREE NUTRIENT SOURCES FOR A NOVEL OFFSHORE MACROALGAE FARM IN HAWAI'I

Submitted by
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ABSTRACT

Large-scale offshore seaweed cultivation systems using novel technologies have the potential to sequester large amounts of CO_2, potentially decreasing ocean acidification, while producing biomass that could be converted into fuel. However, low nutrient concentrations in offshore sea surface water (SSW), such as those seen surrounding Hawai'i Island, are a primary constraint to seaweed growth. Nutrient enhancement through the upwelling of deep-sea water (DSW) and artificial fertilization (AF) could provide the additional nutrients required to increase seaweed growth rates, but it is unknown if these novel systems are sustainable. Therefore, the objective of this study was to model the growth of three seaweed species: *Ulva lactuca, Gracilaria parvispora,* and *Halymenia hawaiiana*, to determine the potential CO_2 sequestration capacity. Deterministic models were used to estimate the CO_2 emissions of the various nutrient sources and CO_2 sequestration potential of the three species, using 4 different Specific Growth Rates (SGRs), on the hypothetical 1000-hectare offshore farm. Regardless of SGR and species, SSW had the lowest net CO_2 impact over a 10-year lifespan (sequestration ranged from 234,658 – 923,011 MT of CO_2); DSW showed the greatest net CO_2 impact (sequestration ranged from 234,323 – 1,720,416 MT of CO_2), and the AF system was almost the same as DSW (sequestration ranged from 226,617 to 1,712,709 MT of CO_2). Although all systems sequestered more CO_2 than they produced, questions regarding economic viability of each nutrient source must be answered by future research

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LIST OF ABBREVIATIONS

AF	Artificial fertilization
ANL	Argonne National Laboratories
AOV	Autonomously operated vehicles
ARPA-E – Energy	Advanced Research Projects Agency
Bf	Annual farm production
B_h	Harvested biomass
Blue Fields (limu) Demonstration Project	Blue Fields Offshore Macroalgae
By	Annual biomass harvested
C	Carbon
C %	Carbon content
CO_2	Carbon Dioxide
CO_2 seq	CO_2 sequestration
Cseq	Carbon sequestration
DOE	Department of Energy
Dp	Annual dry production
DSW	Deep sea water
G. parvispora	*Gracilaria parvispora*
GHG	Greenhouse gasses
GREET Emissions Modeling System	Greenhouse Gasses, Regulated
H. hawaiiana	*Halymenia hawaiiana*
HDPE	High density polyethylene

Hy	Harvests per year
ID	Inside diameter
L	Lag time after harvest where seaweed growth is reduced
LCA	Life cycle analysis
LCI	Life cycle inventory
Ln	Natural logarithm
MACMODS	Macroalgae Cultivation Modeling
MARINER	MacroAlgae Research Inspiring Novel Energy Resources
MOE	Makai Ocean Engineering
MT	Metric tons (1,000 kg)
O	Oxygen
OD	Outside diameter
OE	Ocean Era Inc.
OPEC	Organization of Petroleum Exporting Countries
PVFD	Polyvinylidene fluoride
SGR	Specific growth rate
SPM	Single point mooring
SSW	Sea surface water
T	Time in days
TEA	Techno-Economic Analysis
U. lactuca	*Ulva lactuca*
UC Irvine	The University of California, Irvine

UH Hilo	The University of Hawai'i at Hilo
W_f	Weight on the line at harvest
W_i	Weight on the line at start of a growing period and the weight on the line after harvest

CHAPTER 1. INTRODUCTION

Large-scale offshore seaweed farms using novel nutrient enhancement technologies are being investigated in Hawai'i by a consortium of research teams lead by Ocean Era Inc. (OE herein) on The Blue Fields Offshore Macroalgae (*limu*) Demonstration Project (Blue Fields). OE's Blue Fields Project is a part of the Department of Energy (DOE) ARPA-E (Advanced Research Projects Agency – Energy) MARINER (Macroalgae Research Inspiring Novel Energy Resources) program. MARINER is aimed at advancing novel technologies in order to produce economically viable and renewable seaweed biomass through large scale offshore farming offset at least 10% of the United States (U.S) transportation energy demands (MARINER n.d).

The primary challenge Blue Fields faces is growing seaweed in oligotrophic sea surface waters (SSW) surrounding Hawai'i Island. Oligotrophic waters are void of the essential nutrients needed for seaweeds to grow quickly, thus causing most seaweed to grow slowly. Nutrient enhancement technologies could remedy this issue. Nutrient enhancement increases the amount of available nutrients for seaweed to take up, "enhancing" or increasing biomass production and seaweed growth rates (Karl & Letelier 2008: White et al 2010; Minas et al 1986; Tyrell 1999). Nutrient enhancement technologies could expand the areas where large-scale offshore seaweed farming is possible, including many other tropical islands besides Hawai'i. However, it is unknown if these novel seaweed farming systems or the nutrient enhancement methodologies are sustainable. The environmental impact of Blue Fields at the demonstration scale is expected to be minimal because of its size (0.04 hectares). Large scale versions of projects like Blue Fields are needed to support viable biomass stock for fuel production. Therefore, it is important to examine these systems at the industrial scale, while incorporating novel nutrient enhancement methodologies if these technologies are to come to fruition.

Life Cycle Analyses (LCAs) are a well-established method for estimating potential environmental impacts resulting from industrial scale systems (Thomas et al 2020; Curran 1996). LCAs are typically completed prior to the development and deployment of industrial scale systems to ensure they won't have a hazardous impact on the environment. The precautionary principle states that evidence is needed to show that industrial activities, especially those involving novel technologies, will have no negative environmental impacts. To truly understand the environmental impacts of industrial activities, experimentation is needed to provide that evidence, but farming at such large scales is not yet permitted (Marchant et al. 2013). Therefore, to comply with regulatory mandates, sophisticated computer modelling can be used to create LCAs to model the environmental impact of these systems prior to their deployment.

LCAs are commonly used to evaluate the environmental impact of seaweed farming systems (Aitken et al 2014; Seghetta et al 2017; Oirschot et al 2017). LCAs can assess the environmental impact of seaweed farms by examining a range of greenhouse gas emissions (GHG) resulting from the use of resources and the environmental releases throughout the product system and lifetime. The GHG, carbon dioxide (CO_2), is of particular interest because it is a leading cause of climate change issues like glacial melting, ocean acidification, and global temperature increase amongst others (Langton et al. 2019). LCAs can also be used to compare the environmental impact of more than one pathway for a product system, comparing a baseline pathway with improved versions of itself while providing the same product function.

LCAs were developed in this research to compare the environmental impact three different nutrient sources (sea surface water, deep sea water (DSW), and artificial fertilization (AF)) have on a hypothetical 1000-hectare version of Blue Fields. The baseline pathway is the SSW nutrient sourced farm of which the DSW and AF sourced farms were compared against. LCAs consist of four phases: 1. the goal and scope of the study (above), 2. a life cycle inventory (LCI), 3. an impact assessment (results), and 4. a discussion (Thomas et al 2020).

An LCI is a list of all system components, and their subcomponents. The LCI includes data on raw material, mass, lifespan, quantity, and the CO_2 emissions per subcomponent unit basis. LCI data can be generated for an industrial process using information found in a techno-economic analysis (TEA). ARPA-E defines a TEA as an assessment of the overall value (cost & benefit) of a technology (Achayra n.d). Most industrial scale projects contain some type of TEA used to analyze its economic performance prior to being deployed. Information found within a TEA can be used as the basis to create an LCI because it can contain information on engineering specifications or general design. Seaweed takes up CO_2 as it grows, therefore the growth of seaweed, while using the different nutrient sources, had to be incorporated into the LCI and estimated within each LCA pathway. See methodology for more details on the LCI.

This thesis uses a TEA designed by Makai Ocean Engineering (MOE), another Blue Fields team member, as a basis for creating an LCI. MOEs TEA was used to create a detailed list of infrastructure components and their subcomponents needed to deploy and maintain a hypothetical 1000-hectare version of Blue Fields. The data found within the TEA was used to develop an LCI for all subcomponents including data on raw material, mass, lifespan, quantity, and the CO_2 emitted per subcomponent unit basis. SSW was used as the baseline LCA pathway for comparing nutrient sources. MOEs TEA included the nutrient enhancement method of DSW, and AF was created entirely by this research.

The results section of this manuscript focuses on the CO_2 emissions from the baseline scenario and comparing these emissions from using the alternate nutrient sources. The results are based on seaweed growth estimates and their potential CO_2 sequestration capacity. The results finish up by exploring how environmental CO_2 could impact the DSW nutrient source option. The discussion focuses on the feasibility of the various novel technologies implemented throughout the model as well as the limitations of the simple growth model developed by this research in an effort to guide future research.

CHAPTER 2. REVIEW OF THE LITERATURE

2.1 Current Status of Seaweed Production

Seaweeds have been collected and cultivated since the Neolithic period for direct human consumption, as feed for animals, medicinal purposes, and as fertilizers (Buschmann et al. 2017). Seaweeds have been incorporated into the Japanese diet in sushi for over 2000 years, (Himaya & Kim 2015). The Greeks collected seaweed and gave it to their cattle as early as 45 B.C. (Evans & Critchley 2013). The Chinese have been using seaweeds for medical treatments (Anand et al. 2016) as early as 2700 B.C., while the Celtic tribes used seaweed to enrich agricultural soils that were infertile as described by Pliny in 79 A.D. (Pereira et al. 2020).

Seaweeds have three main groups: brown (phylum: Ochrophyta, class: Phaeophyceae), red (phylum: Rhodophyta, class: Rhodophyceae), and green (phylum: Chlorophyta, class: Chlorophyceae) (Chopin et al. 2001: Langton et al. 2019). Brown seaweeds range from 20 meters long (giant kelp) to 2-4 meters long, or to even smaller species ranging from 30–60 cm long. Red and green seaweeds are usually smaller, ranging from a few centimeters to a meter in length (Cai et al. 2021).

Today, the interest in seaweed cultivation has expanded due to its potential to produce food, feed for animals, medicines, fertilizers and more recently, an alternative to fossil fuels. The annual production from seaweed farms was estimated to be approximately 35 million metric tons (MT) valued at 13.3 billion United States dollars (USD) in 2018, with most of the production coming from nearshore facilities (FAO 2020). Seaweed production is a niche activity in the USA with total USA production in 2019 of only 3,394 MT, less than 0.01% of world production (Table 2).

Phyla and Major Types	**Total Production (cultivation and wild) (MT)**
PHAEOPHYCEAE (Brown Seaweeds)	16,393,764
Laminaria & Saccharina	12,273,519
Undaria (Wakame)	2,563,477
Fugisforme sargassum	303,797
RHODOPHYCEAE(Red seaweeds)	18,251,474
Pyropia/Porphyra (Nori)	2,984,123
Gracilaria	3,638,554
Eucheuma/Kappahycus	9,817,689
CHLOROPHYCEAE (Green Seaweeds)	16,944
Caulerpa	1,090
Codium	3,258
Monostroma (Green Laver)	6,321
Ulva spp.	2,155

Table 1: Global production and value of seaweeds by group and major species, both cultivated and wild harvested. Total production is broken down by phyla and family. This table was produced from data found in Cai et al. 2021.

Global seaweed production (cultivated and wild harvested) increased substantially to 36 million MT in 2019; valued at $14,700 million USD (FAO 2020) with over 56% of production occurring in China (Cai et al. 2021, Table 2).

Region/ Country	**Total (cultivated and wild) production (MT)**	**Share of the world total (%)**
Asia	34,881,600	97.38
China	20,351,442	56.82
Indonesia	9,962,900	27.81
Korea	1,821,475	5.09

Philippines	1,500,326	4.19
Korea	603,000	1.68
Japan	412,300	1.15
Malaysia	188,110	0.53
Americas	488,144	1.36
Chile	427,508	1.19
Europe	287,386	0.8
Norway	163,197	0.46
Africa	145,259	0.41
Tanzania	106,069	0.3
Oceania	16,572	0.05

Table 2: Global production (cultivated and wild harvested) seaweed by region and major countries. The table includes a percentage of how much production occurs in each area or country. Data taken from Cai et al. 2021.

2.2 Ecosystem services

Seaweed farming's value is not limited to its value from the direct sale of biomass, but also its potential ecosystem services such as habitat creation, increasing fish available for catch, bioremediation, and CO_2 capture. The recognition of the value and services associated with offshore seaweed cultivation provides both financial and environmental motivation encouraging aquaculturists to consider seaweed cultivation.

Seaweed farms could have similar habitat forming effects as artificial reefs, increasing species abundance and richness of invertebrates and fishes (Sayer et al. 2005). Survival rates of juvenile fish, species diversity, fish biomass, density, and size can be improved (Roesijadi et al. 2012; Manel et al. 2019). Farmed seaweed can increase food supply for primary consumers like herbivorous fish, turtles, and crabs (Winder & Sommer 2012: Platt et al. 2003). Secondary consumers like bigger fish eat the primary consumers (McClelland & Valiela 1998). A model created by Sayer et al. (2005) showed that small artificial habitats can drastically reduce declines in fishery catches.

Seaweed being used for direct human consumption is increasing in popularity due to its composition and attributes as a healthy food product (García-Poza et al. 2020: Langton et al. 2019). Seaweeds range from 10-30% protein, are usually low in fat, high in carbohydrates, contain essential oils (omega 3), minerals and antioxidants such as Iron, iodine, and vitamin A (Kim 2012: Tanna and Mishra, 2019). An increase in the use of fatty acids from seaweed has been shown to be an alternative replacement for fish oil (Lenihan-Geels et al 2013).

Seaweed farming can recycle excess nutrients found in agricultural runoff that reach the coastline (Duce et al 2008). Nutrient runoff causes undesirable effects in marine ecosystems, including harmful algal blooms, dead zones, and the death of coral reefs. Scientists estimate that large scale seaweed farming could recover 30% of the nitrogen, and 1/3 of the phosphorus entering the ocean (Bjerregaard et al. 2016). This captured N and P can then be used as fertilizer (Langton et al. 2019).

Seaweed also takes up or sequesters CO_2 through photosynthesis. The oceans absorb CO_2 as a part of the carbon cycle. When CO_2 dissolves in seawater it can form aqueous CO_2, and carbonic acid (H_2CO_3). As increasing amounts of CO_2 is emitted because of anthropogenic activity, increasing amounts of carbonic acid are reducing the pH levels in the oceans (Langton et al 2019). Offshore seaweed farming could potentially mitigate or provide a local buffer from ocean acidification through the photosynthetic removal of CO_2 while at the same time providing a biological substrate to produce biofuel, thus reducing the need to burn fossil fuels (Langton et al. 2019).

2.3 The DOE, MARINER and Blue Fields

The 1973 oil crisis triggered the U.S DOE to examine seaweed as a fuel source when the Organization of Petroleum Exporting Countries (OPEC) raised the price of crude oil by 70 % (Gershon 2021). The DOEs Aquatic Species Program (ASP) and Marine Biomass Program (MBP) were launched to research the factors that limit large scale offshore seaweed production (Sheehan et al. 1998; Langton et al. 2019). Seminal experiments showed large scale offshore production in the tropics was possible through nutrient enhancement in the "Iron Ex Experiments" and "Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products".

Iron Ex utilized AF while the second experiment examined natural DSW upwelling as potential nutrient sources for large scale offshore farming. Experiments also examined the technical challenges faced by large scale offshore biomass production (Coale et al. 1998 & Roesijadi et al. 2010). Unfortunately, experiments were unable to meet the structural requirements needed to support offshore farming at that time. Eventually the interest in converting seaweed into fuel died off when fossil fuels became cheap and readily available once the fuel crisis subsided. Now, in the 21st century, interest in commercial offshore seaweed production has returned.

The DOE is again investing substantial sums of money into offshore seaweed farming. The DOE ARPA-E MARINER program is aimed at advancing offshore seaweed farming technologies that were abandoned in the 1970's. Novel technologies developed within the MARINER program could provide economically viable and renewable marine biomass while expanding the areas where offshore seaweed farming is commercially feasible.

The Blue Fields project, led by OE is addressing the primary challenges associated with offshore seaweed farming in the tropics including growing seaweed in the oligotrophic SSW surrounding Hawai'i by constructing a small-scale seaweed farm in significant offshore depths capable of withstanding the destructive power of the environment (Ocean Era Inc. 2019). An offshore seaweed array for the cultivation of a native Hawaiian seaweed species will be deployed 3 - 3.5 Nautical Miles (NM) (5.6 – 6.5 km) west of Kailua-Kona, or1.5 NM (2.8 km), South South-East (SSE) off of Kaiwi Point, in Kailua-Kona on Hawai'i Island (Figure 1).

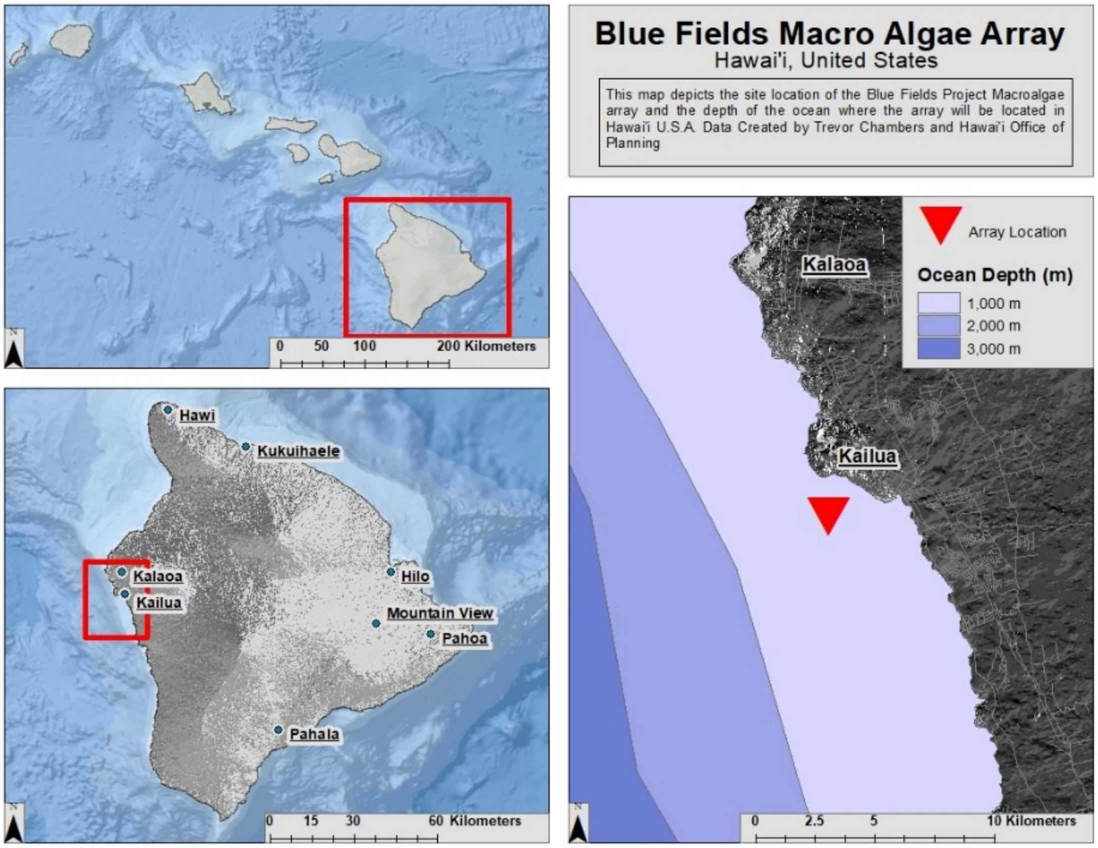

Figure 1: The location of the Blue Fields demonstration project and the same location at which the hypothetical 1000-hectare farm is located which is approximately 6 km west or 3 km, South South-East off Kailua-Kona on Hawai’i Island, Hawai’i USA. The center point of the farm is located at 19° 37' 54.9149" N and 156° 01' 24.9638" W. Data used to create this map was created by Trevor Chambers and the State of Hawai‘i Office of Planning and Sustainable Development.

Ocean Era originally planned on using a wave generated pump to deliver nutrient enhanced DSW to the algal growth platform to enhance seaweed biomass production in the oligotrophic waters that surround Hawai’i Island. At The Blue Fields Project site, the DSW at 300 meters depth has an estimated concentration of 12 µmol of inorganic nitrate and nitrite compared to 0.5 µmol /L at 10 m below the sea surface (Ocean Era 2019). OE has partnered with Makai Ocean Engineering (MOE) to design and build a prototype wave action pumping mechanism that will deliver nutrient rich deep DSW to their small-scale offshore farm at the location where seaweed is growing underwater. The pump was expected to deliver a 2.5% concentration of DSW from approximately 300 meters deep. The controlled delivery of DSW was expected to enhance nutrient fixation resulting in increased organic matter production and net carbon sequestration (Karl & Letelier 2008: White et al 2010; Minas et al 1986; Tyrell 1999). However, due to deployment costs and COVID 19 implications, OE will now use sea surface water as the nutrient source for the offshore array. Although seaweed will likely have lower growth rates with no nutrient addition, Hawaiian seaweeds evolved in oligotrophic waters, so no nutrient source must be examined as is being done by OE in Blue Fields. While OE cannot examine DSW pumping as a nutrient source at this time, they have examined how additions of AF and DSW increase the growth rates of several native Hawaiian seaweeds in their onshore trials including *Ulva lactuca, Gracilaria parvispora,* and *Halymenia hawaiiana*.

To make informed predictions of cultivation in the off-shore environment, OE ran land-based trials (N-T43, N-T36, and N-T37) using *Ulva lactuca, Halymenia hawaiiana,* and *Gracilaria parvispora* and measured SGRs. I used the SGRs in our model based on these trial data. The objective of the N-T43 trials was to examine how *U. lactuca* average SGR changes over 4 weeks while using SSW, and the addition of 2.5% of DSW. Cultivation in only SSW yielded an average SGR of 9.9% while the addition of DSW yielded an SGR of 12.7%. The objective of the N-T36 trials was to compare *Halymenia hawaiiana* biomass production with the addition of nutrients from DSW and to observe nutrient limitation throughout a cascade design. A cascade trial was set up with 9 tanks at a 340 L volume, with 3 tanks per series. Tanks X1, X2, and X3 received only SSW in tank X1. Only these tanks results could be used in this research because the DSW trials used a higher concentration of DSW than what is available using the DSW nutrient source.

The trial was run for 1 month. Stocking density was 300 g of *Halyemenia* for a stocking density of 1g/L. The average SGR for *Halymenia hawaiiana* after 21 days was 3.4%.

The objective of the N-T37 trials was to determine the optimal light level for *G. parvispora* in outdoor culture tanks and determine its potential for offshore aquaculture cultivation. Nine tanks with varying levels of shade were used: Tank 1: no shade (PAR= 1400-2500 µmol/m2/s), Tank 2: 1 shade cloth (PAR= 200-500 µmol/m2/s), and tank 3: 2 shade cloths (PAR= 10-40 µmol/m2/s), (n=3 for each). All tanks received 2.5% DSW additions. Starting stocking density was 200g of clean biomass, at a density of 200 g/340L = 0.6g/L (Fig. 13). Trials were run for 2 weeks. The experiment was cut short due to bacterial overgrowth on the *Gracilaria* biomass in all tanks. Overall, highest biomass was observed in the tank with no shade cloth (average SGR = 3.8%). The treatment with 1 shade increased and then decreased in biomass (average SGR = 0.0%) and the treatment with 2 shade cloths lost biomass (average SGR = -1.8%). Finally, through email the lead phycologist at Ocean Era stated the *G. parvispora* had an average SGR of 7% while being supplemented with fertilizer in an undocumented trial.

CHAPTER 3: METHODOLOGY

3.1 Research Question

How will the net CO_2 impact of hypothetical 1000-hectare offshore seaweed farm be affected by using three different nutrient sources: oligotrophic waters using surface seawater, DSW, or artificial fertilizer as the nutrient sources.

Hypotheses

H_0: There is no difference in the amount CO_2 taken up by seaweed and released into the environment due to the cultivation of seaweed using different nutrient sources.

H_a: There is a difference in the amount of CO_2 taken up by seaweed and released into the environment due to the cultivation of seaweed using different nutrient sources.

The net impact of using different nutrient sources on the CO_2 emissions of large-scale offshore seaweed farms was assessed based on plans developed for a 1000-ha offshore seaweed farm intended for deployment off the coast of Kailua-Kona, Hawai'i (Figure 1) (Makai Ocean Engineering TEA v10). Three nutrient source scenarios were examined: ambient sea surface water (SSW), nutrient rich deep-sea water (DSW), and supplementation with artificial fertilizer (AF).

3.2 Summary of the Methods

The SSW nutrient source scenario is the baseline pathway for the LCA. The SSW nutrient source scenario assumes the nutrients required for seaweed to grow are provided by natural ocean currents. All LCA pathways assume the only limiting nutrient is nitrogen (N) based on Ocean Era Environmental Site Assessment Report from 2019. N (nitrate + nitrite) concentrations of the SSW at the hypothetical farm location are estimated to be approximately 0.5 μmol / Liter (Ocean Era Inc. 2019). The SSW nutrient source scenario requires no additional infrastructure for a nutrient source.

In contrast, the DSW and AF nutrient source scenarios do require additional infrastructure to deliver more N to the hypothetical farm, thus increasing production and potentially CO_2 recycling. However, these nutrient enhancement methods also require more CO_2 emissions because of their infrastructure. MOE has designed, built, and tested a working prototype of a wave driven pumping mechanism. The hypothetical farm assumes the wave driven DSW pumping mechanism will be scaled up for use on the 1000 ha hypothetical farm. The DSW nutrient source scenario employed the use of 2000 wave action pumps that deliver nutrient rich DSW to seaweed at a concentration of 2.5% DSW to 97.5% SSW from a depth of 300 meters at the hypothetical farm location. OE estimates N is in concentrations of 12 μmol / Liter at a depth of 300 meters at the hypothetical farm location (Ocean Era Inc. 2019). MOE states in version 10 of their TEA that a single pump delivers DSW at a rate of 0.32 cubic meters/ second (m^3/s). Therefore, 2000 pumps will deliver 631 m^3/s to the farm or approximately 3,344 MT of N / year when DSW is the nutrient source. The DSW nutrient source scenario was examined because it is one of the novel nutrient enhancement technologies being developed within MARINER, but because it requires 2000 wave action pumps (and additional parts) it could be costly because MOE in their TEA states a single pump costs approximately $200,000.

A potentially more economically viable nutrient enhancement methods could be AF because it is assumed to be relatively cheaper than the novel DSW pumping options, the technology is not new, and it is simple. Therefore, the AF nutrient source scenario was built around the idea of delivering the same amount of N as the DSW nutrient source scenario. Instead of using wave action pumping the AF scenario uses the industrial fertilizer Urea which has a N concentration of 44% (Minnesota Crop News 2022). Therefore, the AF option required approximately 95 MT of Urea each year.

Cost data and engineering parameters for the hypothetical 1000-hectare farm using DSW as a nutrient source were available in a techno-economic analysis (TEA) produced by MOE. The data found within the TEA was used as the basis of a life cycle inventory (LCI). This LCI was then used in conjunction with the Argonne National Laboratory (ANL) Greenhouse Gases, Regulated Emissions (GREET) model (U.S DOE. 2019) to estimate CO_2 emissions required to produce each part of the hypothetical farm. The model assumes all parts of the farm have a lifetime of 10 years with respect to the annual AF Urea usage and the fuel usage needed to maintain the farm with workboats.

The TEA used to create the LCI had separated the different parts of the farm into 6 components: Nursery, Mooring, Array, Nutrient Supply, Harvest, and Collection. The hypothetical farm was also divided into six similar components that were used in the creation of the LCI (Figure 2). The 6 components were: Nursery, Mooring, Array, Growth, Harvest, and Collection. The only difference being the growth component replacing the nutrient supply component. Located within the growth component is where the different nutrient sources, and different species of seaweed can be examined within the life cycle to determine how these parameters affect the net CO_2 impact of the hypothetical farm. Each farm component was further subdivided into their major constituent subcomponents (Figure 2). The CO_2 emissions from each subcomponent were estimated from the LCI and GREET model predictions then summed. All components and subcomponents were derived from the TEA including the DSW nutrient source.

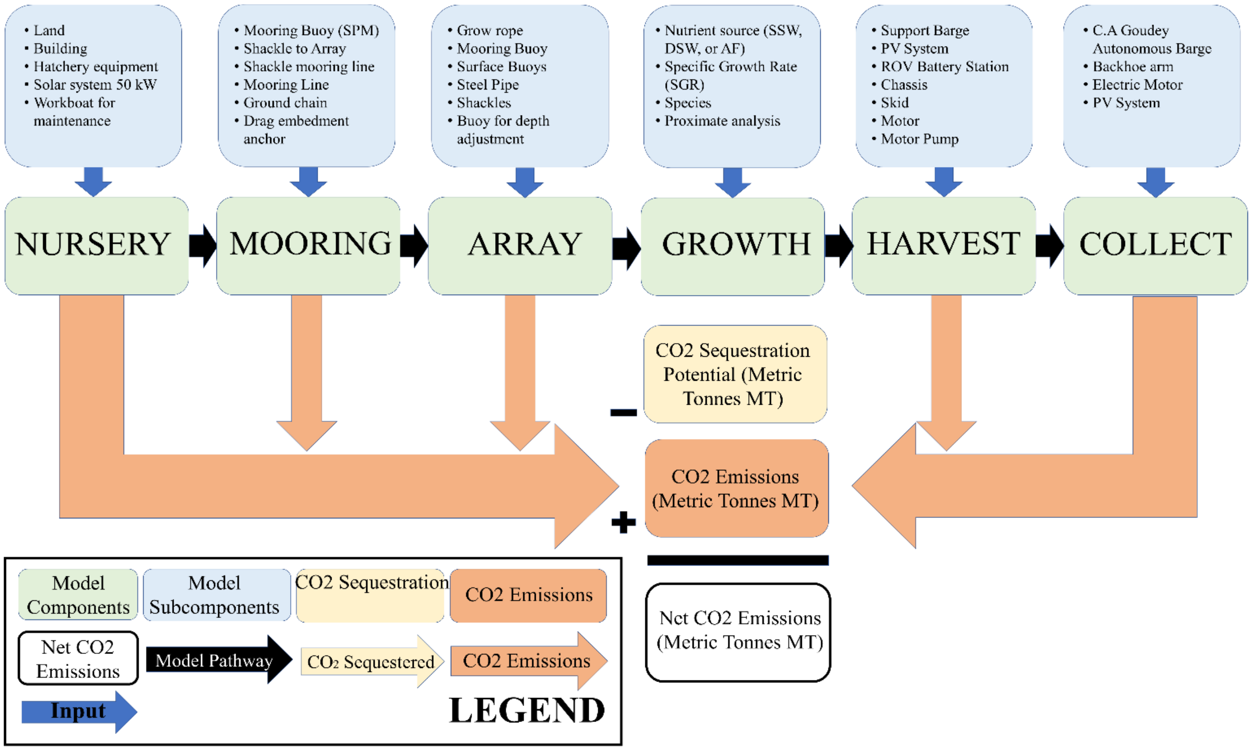

Figure 2: The 6 components outlining the CO_2 system boundary for the hypothetical 1000-hectare farm. Each major component (green boxes) further delineates its major subcomponents (Blue boxes). The CO_2 emissions from each subcomponent were estimated using GREET and from the LCI and GREET model predictions then summed. Within the growth component is

where the different nutrient sources, and different species of seaweed can be examined within the life cycle to determine how these parameters affect the net CO_2 impact of the hypothetical farm.

Simulating seaweed growth and their subsequent CO_2 sequestration potential was performed to estimate how growing seaweeds could reduce the immediate CO_2 footprint of these large-scale systems. Three native Hawaiian seaweeds were selected for growth simulation in this study: *Ulva lactuca, Gracilaria parvispora* and *Halyemenia hawaiiana*. These species were selected because they had been selected as species for production in the hypothetical offshore seaweed farm and data on how their specific growth rates (SGR) responded to under the different nutrient scenarios were available. The growth models used estimated mean values of SGR for the three algae species derived from shore-based experiments. This study also used the quantitative analysis of nutrients or proximate analysis results produced by OE for these species and the SGR equation to model seaweed growth. Unfortunately, Ocean Eras onshore nutrient experiments did not harbor any estimates of error or uncertainty, so neither do the growth model results.

The CO_2 emissions estimates from constructing and deploying each farm component were added together with the different CO_2 emission estimates found for each nutrient source. The CO_2 sequestration potential for seaweeds grown at different hypothetical growth rates were then estimated. The differences between the CO_2 emissions produced from constructing and deploying the offshore seaweed farm under each nutrient scenario and the estimated CO_2 sequestration of the algae produced by the farm under that nutrient scenario were estimated to compare the environmental impact these different nutrient sources have on the environment while providing the same product function (Thomas et al 2021).

3.3 Life Cycle Inventory (LCI)

Nursery

The onshore nursery for the hypothetical farm would be located at the Hawai’i Ocean Science and Technology (HOST) Park administered by the Natural Energy Laboratory of Hawai’i Authority (NELHA). The nursery would require a 465 m^2 building placed on a concrete slab sited on a parcel of cleared land of equal or greater size that had already been cleared and was ready for development. The onshore nursery also requires 5,000 pieces of equipment including a 50-kW photovoltaic (PV) solar system and five welded aluminum workboats with 500-hp outboard engines. In order to estimate its carbon footprint, the model assumes each piece of hatchery equipment weighs 0.001 MT and is made of steel. Further, the model assumes each workboat operates 8 hr/day every day for the duration of the modeled 10-yr period. While Ocean Era will use unleaded gasoline, this fuel type was not an option available in the GREET database. Therefore, the model assumes the workboats run on “Reformulated Gasoline (E10)”, but this likely underestimates CO_2 emissions.

Subcomponent	**CO_2 e**
concrete pad	0.388
steel building	109.170
nursery equipment	1.203
photovoltaic system 50 kW	0.809
workboats	9.878
Fuel Use	1536.286

Table 3: CO_2 emissions estimates for each subcomponent of the onshore nursery for the hypothetical 1000-hectare offshore seaweed farm.

Mooring

The hypothetical 1000-hectare farm requires 80 individual Single Point Moorings (SPM) that were designed by MOE. Each SPM will be moored to the ocean bottom in approximately 300 meters of water. Each SPM utilizes 3 steel drag embedment anchors weighing 14.776 MT each. Each anchor is capable of withstanding 38,446 newtons of force. Attached to each drag embedment anchor is 100 meters of Grade 2 steel "mooring chain" weighing 0.0085 MT / meter. Each mooring chain can withstand 2,898,007 newtons of force before breaking. The mooring chains are supplied by Waterman Supply. Attached to the mooring chain are 3 mooring ropes. Each mooring rope is 110 meters in length, and it is made of High-Density Polyethylene (HDPE). The model assumes each mooring rope has a weight of 0.003 MT / meter of rope and is supplied by Samson Rope. Collectively the mooring chain and mooring rope comprise the mooring line. The 3 mooring lines come together at 8 m^3 multi-anchor swivel SPM buoy. The mooring buoy is assumed to be made of steel and has a weight of 2.4 MT. The model assumes the buoy is supplied by Ocean Scientific International Ltd (OSIL n.d). Ten steel shackles are needed to connect the mooring lines to the drag embedment anchors, and the mooring lines to the buoy. Each shackle weighs 1.368 MT and is assumed to be supplied by Steel Wire Rope Ltd (SWR n.d). Using the information contained in this paragraph an LCI was created for the LCA mooring component. The LCI data was used in conjunction with the ANL GREET database to estimate the CO_2 emissions required to construct and deploy all 80 moorings (Table 4).

Subcomponent	**CO_2 e**
Mooring Buoy (SPM)	46.2

Shackle to array	26.3
Shackle mooring line	237.1
Mooring Line	16.0
Ground chain	492.6
Drag embedment anchor	853.5

Table 4: CO_2 emissions estimates for each subcomponent of the mooring for the hypothetical 1000-hectare offshore seaweed farm.

Array

The hypothetical farm utilizes 80 growth arrays. Each growth array is 500 m long by 250 m wide for a total area of 125,000-m^2 per array (12.5 ha). A series of 500-meter-long algal lines spaced 0.5 meters apart for a total of 250,000 m of line per array. The grow rope is made of HDPE and weighs 0.00004 MT / meter of grow rope. The grow rope is wrapped around a larger 1-inch HDPE rope weighing 0.00025 MT / m. These novel SPMs required the additional components based on MOEs TEA: nine, 500-meter lengths of Structural Space lay that can withstand 44,482 newtons of force, three, 25-meter lengths of rope connecting the Mooring Buoy to the Array via bridle. These ropes withstand 285,536 newtons of force, fifty, 5-meter-wide buoys connected to the bridles. Collectively, the buoys have a buoyant force of 222,411 newtons, One, 500-meter-long Steel Pipe used to spread the front and back of the array, twenty, 25 meter long 12-inch diameter HDPE pipes used for intermediary spreading, one-thousand shackles for structural integrity. Each one withstanding 2,758 newtons of force, three bridle shackles that have a breaking capacity of 2,595,982 newtons, one-hundred, shackles connected to the buoys that have a breaking capacity of 222,411 newtons, and fifty, buoys for depth adjustment. Using the engineering parameters presented by MOE in their TEA the quantity of each subcomponent, its material, and weight was used to estimate the amount of CO_2 that would be emitted by building all 80 of these SPMs for the hypothetical farm (table 2).

Subcomponent	**CO_2 e**
Grow rope + HDPE	141.89
1" HDPE	998.40
Structural space lay	6,963.39
Mooring Buoy to Array Bridle Rope	0.30
Rope to Surface Buoys	0.78
Steel Pipe Front & Back Spreader	909.36
HDPE Pipe Intermediary Spreader, 12" OD	7,515.13
Shackles structural	2.50
Shackles bridle	21.26
Shackles to buoys	25.80
Buoy for depth adjustment	78.94

Table 5: CO_2 emissions estimates for each subcomponent of the array component for the hypothetical 1000-hectare offshore seaweed farm.

Harvest

The hypothetical 1000-hectare farm utilizes autonomous harvesters being developed within the MARINER program. The farm requires 27 fully autonomous AOV harvesters according to the MOE TEA Version 10. Each Harvester requires a multitude of subcomponents further divided into 4 catagories:1. The support barge, 2. The ROV, 3. The Skid, and 4. Equipment. The support barge subcomponents includes: A single steel barge weighing 0.001 MT (E-Touch Engineering n.d), a lead acid battery pack weighing 1.392 MT (Unbound Solar n.d), A propulsion system powered by four 0.096 MT lead acid batteries (Torqeedo n.d), A monocrystalline Silicon Photovoltaic system weighing 1.616 MT, one 0.12 MT steel ROV battery recharging station (Sub Sea Tech n.d), and 1 watertight HDPE housing for hydraulics (Seafloor n.d). The ROV component requires one 126 cubic ft flotation device made from HDPE weighing 0.736 MT (Diab n.d), an aluminum chassis weighing 5 MT (Deep Ocean n.d), one 0.013 MT steel bottle (GCS n.d), 2 aluminum power bottles weighing 0.007 MT each (Prevco Subsea LLC n.d), eight aluminum thrusters weighing 0.002 MT each (Technadyne n.d), 20 steel cables weighing 0.0003 MT each (Seacon n.d), one aluminum instrument J box weighing 0.011 MT (Slayson n.d), An aluminum sonar sensor weighing 0.012 MT (Sonardyne n.d), An aluminum LIDAR sensor weighing 0.027 MT (3D at Depth n.d), an aluminum current meter weighing 0.004 MT (Ocean Scan n.d), an aluminum depth meter weighing 0.00027 MT (Impact Subsea n.d), one aluminum Linear Variable Differential Transformer (LVDT) weighing 0.00027 MT (TE Connectivity n.d), one inertial measurement unit (IMU) weighing 0.00005 MT (Parker Hannifin Corporation n.d), 2 aluminum cameras weighing 0.0122 MT each (Kongsberg Seatex n.d), 4 aluminum lights weighing 0.00045 MT each (Deep Sea Power & supply n.d), and one stainless steel transformer j box weighing 0.077 MT each (Fisheries Supply n.d). The Skid required one, 1.2 MT aluminum chassis (Connecter Subsea Solutions), one steel motor pump weighing 0.015 MT (Forum Subsea Technologies n.d), one stainless steel eductor pipe weighing 0.04292 MT (Stainless Steel Fittings n.d), one stainless steel eductor weighing 0.005 MT (McMaster Carr n.d), and four aluminum fairleads weighing 0.003 MT each. The equipment group required one aluminum tooling j box weighing 0.004 MT each (Acteon n.d), 10 steel cables weighing 0.00025 MT each (Seacon n.d), and 15 stainless steel cavitation jet heads weighing 0.0011 MT each (Dive Wise n.d). Using the information presented above the LCI for the harvester was created and used to estimate the amount of CO_2 emitted for building 27 harvesters (Table 6).

Subcomponent	**CO_2 e**
Support Barge	

Barge	64.98418523
Battery pack	0.00000255
Propulsion System (Cruise 10 FP)	0.00000070
PV System (0.4 size)	989.40484737
ROV Battery Station	0.77981022
Misc Hydraulic Related	0.07989165
Flotation (ft3)	3.92194608
Chassis	104.99954105
Control Bottle Assembly	0.08317976
Power Bottle & Battery	0.31246786
Thrusters	0.28559875
Cables & Connectors	0.03249209
Instrument J-Box	0.22291209
ROV	
SONAR	0.24149894
LIDAR	0.56468753
current	0.07349968
depth	0.00570815
LVDT	0.00000001
IMU	0.00016800
Cameras	0.51071777
Lights	0.03779983
Transformer J-Box	0.00000016
Skid	
Chassis	25.19988985
Motor Pump	0.09422707
Eductor Piping	0.00000009
Eductor	0.00000001
Fairleads	0.24908896
Equipment	
Tooling J-box	0.07979965
Cables & Connectors	0.01624605
Cavitation Jet Head	0.00000004

Table 6: CO_2 emissions estimates for each subcomponent of the 27 harvesters required for the hypothetical 1000-hectare offshore seaweed farm.

Collection

The C.A. Goudey and Associates team is leading the development of an autonomous marine tow vessels to enable large-scale seaweed farming as a part of MARINER. Their AOV collection vessels will enable large scale seaweed farming systems over larger areas by eliminating the schedule constraints of a manned vessel. Their AOV collection vessels could tow pre-seeded longlines to the farm, transporting harvested seaweed back to collection points, and relocate farm infrastructure (arpa-e.energy n.d). The hypothetical 1000 ha farm requires 3 C.A Goudey and Associates AOV collection vessels according to the MOE TEA. Each autonomous vessel requires one aluminum Goudey Autonomous Barge weighing 1.28 MT (Bord a Bord n.d), 3 steel backhoe arms weighing 0.56 MT each (Harbor Freight n.d), one steel motor weighing 0.039 MT (Golden Motor n.d), three steel grippers weighing 0.024 MT each (Tool Tuff Direct n.d), and one 1.6 MT PV system (Unbound solar n.d). Using the information presented above the LCI for the collection component was created and used to estimate the amount of CO_2 emitted for building 3 autonomous collectors (Table 7).

Subcomponent	**CO_2 e**
Goudey Autonomous Barge	2.99
Backhoe arm	1.21
Electric motor 20 kW	0.03
Gripper	0.05
PV System (0.2)	0.99

Table 7: CO_2 emissions estimates for each subcomponent of the collector components for the hypothetical 1000-hectare offshore seaweed farm.

Sea surface water (SSW)

The SSW nutrient source scenario assumes the nutrients required for seaweed to grow are provided by natural ocean currents. The nitrogen (nitrate + nitrite; N hereafter) concentrations of the SSW at the hypothetical farm location are estimated to be approximately 0.5μmol / L. Ocean currents are estimated to be traveling at an average velocity of 0.5 m/s (Ocean Era Inc. 2019). The SSW nutrient source scenario requires no additional infrastructure. The SSW nutrient source scenario requires all of the previously outlined infrastructure from the nursery, mooring, array, harvest, and collection sections above.

The SSW nutrient source scenario serves as the baseline pathway for the LCA. This SSW baseline will be compared to the nutrient enhanced scenarios. To do this, the CO_2 emissions associated with the additional infrastructure required for both DSW and AF nutrient sources were added to this baseline scenario.

Deep sea water (DSW)

The DSW nutrient source scenario requires additional infrastructure compared to the SSW nutrient source scenario. The most impactful subcomponent for the DSW nutrient source scenario was the addition of prototype wave action DSW pumps designed by MOE. The DSW nutrient source scenario employed the use of 2000 wave action pumps. The 2000 pumps were divided evenly throughout each of the 80 individual systems. Therefore, each system required 25 DSW pumps. Each pump is 1 meter long and has an inside diameter (ID) of 0.3-meters according to the MOE TEA. The DSW LCA module assumes each pump is made of steel and weighs 0.079 MT (Hayward Pipe & Supply Company Co, Inc n.d). Each individual DSW system also requires five, 500-meter-long HDPE pipes with 0.2-meter OD (Outside Diameter). Each HDPE pipe has an outside diameter equal to 31 times its wall thickness. Each HDPE pipe weighs 0.02 MT / meter (JM Eagle n.d), five, 30-meter lengths rope for rigging. Each meter of rigging weighs 0.011 MT (Union n.d), one 100-meter section of 1 meter OD steel pipe for DSW plumbing. Each DSW pipe has an outside diameter equal to 26 times its wall thickness and weighs 0.153 MT / meter (Pipe STD n.d), one steel ballast weighing 0.4 MT (OSIL n.d), and one steel intake anchor weighing 14.776 MT (MOE TEA v10). Using the information presented above the LCI for the DSW component was created and used to estimate the amount of CO_2 emitted for using DSW as a nutrient source (table 8).

Subcomponent	**CO_2 e**
Tidal Spar Pump	37.90
HDPE pipe DR 31' OD	1.61
Rigging (shackles)	1.05
DSW Pipe 26' OD	2.41
ballast	7.70
Intake anchor	284.50

Table 8: CO_2 emissions estimates for each subcomponent of the DSW nutrient source option for the hypothetical 1000-hectare offshore seaweed farm. The CO_2 emissions estimated from the DSW nutrient source option were added to the SSW baseline scenario to compare how their emissions differ.

Artificial fertilization (AF)

The AF nutrient source scenario was built upon the idea of supplying the same amount of N as the DSW nutrient source option. MOE estimated that 25 DSW pumps are needed to deliver a concentration of 2.5% DSW to 97.5% SSW to each of the 80 arrays from a depth of 300 meters.

A single pump delivers DSW at a rate of 0.32 m^3/s. Twenty-five pumps deliver DSW at a rate of 125,000 GPM per array. Concentrations of N in the DSW are estimated to be approximately 12 µmol / L (Ocean Era 2019). Approximately 42 MT of N will be brought to the surface for each array each year using DSW. The entire farm requires 3,344 MT of N / year when DSW is the nutrient source.

The AF nutrient source option uses only Urea fertilizer as the source to match the amount of N delivered in the DSW scenario. The Urea used in this research has a N concentration of 44% per MT (Minnesota crop News). Therefore, 7,600 MT of Urea are needed each year to support the same N concentrations as DSW. The additional infrastructure needed for the AF scenario was built around the amount of Urea needed each year to supply the farm with 7,600 MT of Urea. The AF nutrient source scenario requires an additional 297 m^2 steel outbuilding placed on a concrete slab. The steel weighs 290 MT and the concrete weighs 26 MT respectively (Survival Tech Shop n.d & Civil Click n.d). The AF scenario also requires a Toyota 8FG45U steel forklift that weighs 6.61 MT (Construction Equipment Guide n.d). The AF module assumes the 7,600 MT of Urea is attached to the front of the array in slow-release bags. These bags are replaced every week as a part of the maintenance operations included in the nursery component. Therefore, 104,000 slow-release nylon nags are needed each year for the AF scenario (The Brew Bag n.d). Using the information presented above the LCI for the AF component was created and used to estimate the amount of CO_2 emitted for using AF as a nutrient source (Table 9). The onshore nursery and the AF nutrient source option both required additional emissions from the annual fuel use used in maintenance and the annual use of Urea.

Subcomponent	CO_2 e
steel building	69.87
concrete building	2.46
forklift	1.59
Urea	788.33
nylon	8.45

Table 9: CO_2 emissions estimates for each subcomponent of the AF nutrient source option for the hypothetical 1000-hectare offshore seaweed farm. The CO_2 emissions estimated from the AF nutrient source option were added to the SSW baseline scenario to compare how their emissions differ.

Environmental CO_2 additions

The SSW and AF nutrient source scenarios do not use a natural influx of nutrients found within the locality of the hypothetical farm. The DSW nutrient source option utilizes nitrogen rich DSW from 300 meters to enhance seaweed growth rates; however, nitrogen may not be the only nutrient being pumped upwards to the farm. As 630 m^3 of this nutrient rich DSW is pumped up from 300 meters per second, if this water is being pumped from below the mixed layer, CO_2 that was previously stored could also be brought upwards. It is unknown at this time if the nutrient rich DSW will be pumped from below the mixed layer offshore of Kona, but if it is it could have unknown implications. This potential CO_2 addition from the DSW nutrient source option was added to the end of the results section because the original LCAs assumed that DSW was taken from the mixed layer.

DSW typically has higher concentrations of CO_2 compared to SSW, especially below the mixed layer. There are no estimates of CO_2 concentrations for DSW at 300 meters depth at the hypothetical farm site, nor are there any estimates of where the mixed layer ends or begins at this location. Using SSW CO_2 concentration data taken from station ALOHA, off the north shore of O'ahu in Hawai'i, the amount of CO_2 that could be brought to the sea surface when using DSW as a nutrient source was estimated to be 420 pCO_2 (partial pressure of CO_2) (NOAA n.d). Assuming the CO_2 concentration of SSW is the same at 300 meters depth (even though it is likely higher as depth increases), 420 pCO_2 was converted to 9,543 µmoles of CO_2 per liter. The amount of CO_2 that could be brought to the surface was then estimated by adding it to the amount of water pumped up with the DSW nutrient source. Approximately 84 million MT of CO_2 would be pumped up along with the DSW if it was used as a nutrient source, and if this water was taken below the mixed layer of the ocean where the CO_2 was previously stored.

3.4 CO_2 Sequestration Methodology

Fours things were required to estimate the amount of potential CO_2 taken up by seaweed grown on the farm: 1. Species selection, 2. Understanding how the selected species grow under different conditions, 3. The chemical composition or proximate analysis of each selected and 4. Estimating CO_2 sequestration potential using mass balance.

Species selection

This thesis examines *Ulva lactuca, Gracilaria parvispora,* and *Halyemenia hawaiiana* as possible species that could be grown on the farm in monoculture only. These species are native to Hawai'i, and OE has selected them as the potential candidates for their offshore demonstration project. This is important because OE has already examined how different concentrations and combinations of SSW, DSW and AF affect the growth and composition of these species. The data produced by OE was readily available. Table 10 shows the average specific growth rate obtained for these three species while using the three different nutrient sources. This data summary table was created from multiple experiments over a large amount of time. Since these data were taken from different trials, there is some missing data. Preliminary results gave SGRs ranging from 3% to 12% / day and since there is no error associated with these values, and because there is data missing, seaweed production was computed using the following SGRs: 3%, 6%, 9% and 12% /day. The growth model assumes SGRs of 3% and 6%/day are possible for all nutrient sources, while 9% and 12% / day are only possible with nutrient enhancement (DSW and AF).

Nutrient source (Nitrate/nitrite (μg/L))	*Ulva lactuca*	*Gracilaria parvispora*	*Halymenia hawaiiana*
SSW (3.62)	9.9%	N/A	3.4%
2.5% DSW (12)	12.7%	N/A	3.8%
AF (2.6 – 5.6)	N/A	7%	N/A

Table 10: The average specific growth rate (SGR) of *U. lactuca, G. parvispora*, and *H. hawaiiana* based on Ocean Eras onshore trials. These SGRs were used alongside proximate analysis results provided by OE to model growth and subsequent CO_2 sequestration potential.

Understanding how the selected species grow under different conditions

Ocean Era and other seaweed farmers are primarily concerned with SGR because the higher this value is, it is likely the more seaweed will be produced. SGR can also be used to estimate the growth of seaweed along with a few assumptions. Using variations of the SGR equation to estimate growth is not uncommon for seaweed studies (Yong & Wilson 2013; Fossberg et al 2018).

Equation 1: $\mathrm{SGR} = \ln(W_f) - \ln(W_i)/t$

Where W_i is the initial wet weight, W_f is the harvest wet weight and t is the time in days between harvest.

Initial Weight (W_i)

The model assumes the initial biomass weight (W_i) is 500 grams / meter of line (0.5 kg/m). W_i is both the weight of seaweed at the time of seeding and the weight remaining on the line after each harvest. Based on discussions with Ocean Era's lead phycologist, 500 grams / meter will be left on the lines after each harvest (thus steady state Wi will be 500 g/m).

Harvest Weight (W_f)

Kite-Powell et al 2022 indicated a W_f of 5 kg/ meter could be possible in the tropics. After consulting with one of the experts and authors on the paper about this research it was decided that 3 kg/ meter would be optimistic. The model assumes the harvest weight (W_f) is 3 kg / meter. This decision was based on the lower nutrient levels, cooler water temperature, and a continuous culture period for the tropics.

Time (t)

Determining t or the number of days in between each harvest for each predetermined SGR (3%, 6%, 9%, and 12%/ day) is calculated by solving equation 1 for t:

Equation 2: $t = \ln(W_f) - \ln(W_i)/SGR$

Harvesting and/or handling could stunt growth for a short amount of time. To estimate the amount of seaweed being grown using SGR as a function of time, it is essential to model to incorporate a lag time (Zwietering et al 1991). To accommodate for this, a lag period (L), estimated to be 3 days, was included after each harvest based on consulting the experts. The new t or the number of days in between each harvest for each pre-determined SGR (3, 6, 9, and 12%) is calculated by adding the lag period (L) of 3 days to equation 2:

Equation 3: $t = (\ln(W_f) - \ln(W_i)/SGR) + L$

Annual farm production (Bf) (annual wet weight) for the hypothetical farm for each SGR was computed as follows:

The number of harvests per year (H_y) with lag (L):

Equation 4: $H_y = 365/(t+L)$

The Harvested Biomass (B_h) of seaweed per meter of line:

Equation 5: $B_h = W_t - W_i = 3{,}000 - 500 = 2{,}500$ g / m-1

Annual biomass harvested (B_y) per meter of line:

Equation 6: $B_y = H_y * B_h$

Annual farm production (B_f) per year for farm:

Equation 7: $B_f = B_y *$ total length of lines in meters

Proximate analysis

Proximate analyses of seaweeds harbor a plethora of data on species specific chemical composition but modeling seaweed production and estimating CO_2 sequestration required only moisture content (% wet) and Carbon content (% C). Ocean Era's analyses provided the data for *U. lactuca* and *H. hawaiiana* while the data for *G. parvispora* came from McDermid and Stuercke (2003) (Table 11).

Species	*U. Lactuca*	*G. Parvispora*	*H. hawaiiana*
C %	26.60%	41.60%	27.20%
Moisture %	82.30%	90.40%	90.70%

note: *H. hawaiiana* was previously named "*Halymenia formosa*" (Hernández-Kantún et al 2012).

Table 11: Moisture content (% wet) and Carbon content (% C) for *U. lactuca, G. parvispora,* and *H. hawaiiana*. Ocean Era's analyses provided the data for *U. lactuca* and *H. hawaiiana* while the data for *G. parvispora* came from McDermid and Stuercke 2003.

Estimating CO_2 sequestration potential

CO_2 sequestration potential for each species and SGR was then calculated as follows:

First Annual Dry production (D_p) for each candidate seaweed species of interest (MT) and each SGR was estimated:

Equation 8: $$\text{Dry Production (Dp)} = B_f - (B_f * \text{Moisture Content\%})$$

Where B_f is the Annual Wet Production (B_f) per year for the entire farm using a specified SGR, and moisture content % is the wet percentage of each seaweed species (Table 9).

Carbon sequestration (Cseq) then had to be estimated for each SGR and species by multiplying the amount of Dry Produced by the Carbon content (C %) in each seaweed species found in the proximate analysis table:

Equation 9: $$\text{Cseq} = D_p * C\ \%$$

Third, CO_2 sequestration potential was then calculated for each species and SGR by multiplying the amount of accumulated C (Cseq) in the annual Dry seaweed produced (Dp) by a conversion factor of approximately 3.66. The number 3.66 is the molecular weight conversion factor of C to CO_2 when Carbon (C) weighs 12.0116 grams / mol, Oxygen (O) weighs 15.9997 grams / mol, and CO_2 weighs 44.0110 grams / mol. The ratio or factor of C to CO_2 is found by:

Equation 10: The factor of C to CO_2 = weight of CO_2 / weight of C.

or

$$3.6640 = (44.0110 \text{ grams / mol}) / (12.0116 \text{ grams / mol})$$

Therefore, CO_2 sequestration (CO_2 seq) potential was estimated per unit of weight of dry matter for each species and each SGR with the following equation:

Equation 11: CO_2 seq = Cseq * 3.6640

This conversion factor is commonly used in other studies to estimate CO_2 sequestration (Sondak and Chung 2015; Froehlich et al. 2019; Cummins & Curran 2020).

3.5 LCA methodology

The LCA uses Life Cycle Inventory (LCI) information derived from the LCI section above to estimate CO_2 emissions using information from the GREET database (Table 10). Each subcomponent's emissions are added up to determine total CO_2 emissions for a single component.

GREET (Greenhouse Gasses, Regulated Emissions modeling system) has a database that was used to determine the MT of CO_2 emissions required to produce, ship, and use 1 MT of each raw material used throughout the LCI. GREET is a publicly available LCA tool used to examine life-cycle energy and environmental effects of vehicle/fuel systems. GREET can be used to produce results on emissions like: CO_2e, CH_4, N_2O, black carbon, and albedo. GREET incorporates open literature and results from researchers through the DOE and other agencies (Argonne National Laboratory). GREET is based on Microsoft Excel, so it is much easier (and less expensive) to modify than proprietary LCA modeling software (U.S DOE 2019). The LCAs created in this research were also created in GREET.

CO_2 emissions were estimated for 3 scenarios 1. SSW, 2. DSW, and 3. AF. While emissions are adequate to evaluate the different CO_2 footprint for each nutrient source, they are inadequate in evaluating the net CO_2 impact for the entire farm. Therefore, the CO_2 uptake potential of *Ulva lactuca*, *Gracilaria parvispora* and *Halymenia hawaiiana* using SGRs of 3%, 6%, 9% and 12% /day were modeled, to quantify the net CO_2 impact of the three nutrient source models after a total of 10 years on a 1000 ha hypothetical offshore seaweed farm, in oligotrophic subtropical waters. All this modeling was done in Excel.

CHAPTER 4. RESULTS

The primary purpose of this research is to compare, using Life Cycle Analysis, the net CO_2 impact of using three different nutrient sources: SSW, DSW and AF on a hypothetical 1000-hectare version of the Blue Fields project being conducted in the oligotrophic subtropical waters off Hawai'i Island. Examining the impact of alternative nutrient sources supports the development of novel nutrient enhancement technologies being funded by MARINER. CO_2 emissions associated with the deployment and operation of the farm are the same for five of the farm components: the Nursery, Mooring, Array, Harvest, and Collection. The sixth component, Growth, differs depending upon the nutrient sources, the three seaweed species (*Ulva lactuca, Gracilaria parvispora* and *Halymenia hawaiiana*), and at specified SGRs (3%, 6%, 9%, and 12% / day).

4.1 CO_2 Emissions

CO_2 emissions were estimated for the construction, installation, and operation for each component of the baseline SSW nutrient sourced farm including the nursery, SPM, Array, Harvesting, and Collection components. The components required for launching the baseline SSW scenario emitted a total of 21,184 MT of CO_2 during the first year. During years 2 to 9, nursery fuel use and farm maintenance emitted an additional 1,484 MT of CO_2 per year. As harvest and collection is to be done with novel MARINER technologies fueled by alternative sources, they will have no CO_2 emissions. The baseline SSW farm will emit 35,011 MT over 10 years. (Figure 3). Further details of these emissions can be found in Appendix A.

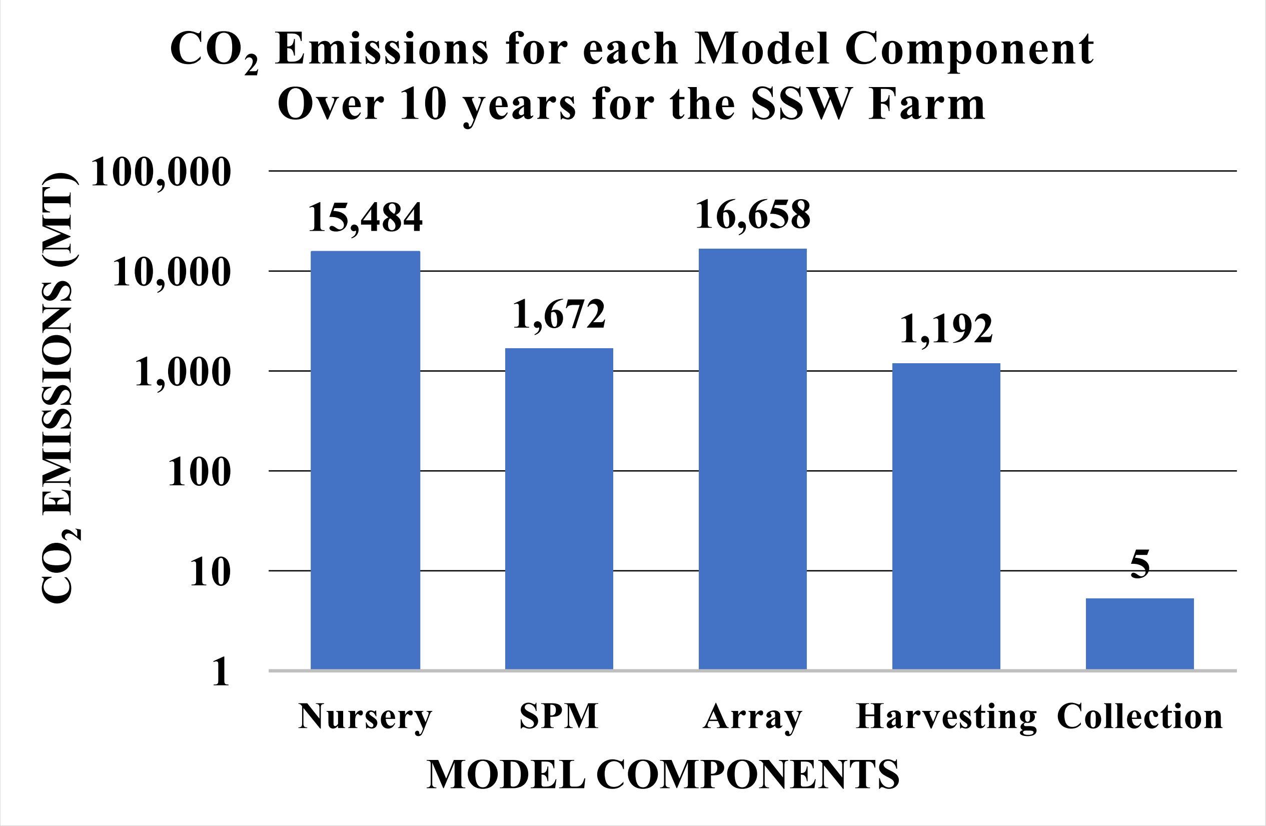

Figure 3: CO_2 emissions required to build, deploy, and operate the baseline SSW nutrient sourced farm for 10 years.

Supplementing the nutrients from DSW or AF requires addition of wave-powered pumps and DSW distribution systems and fertilizer handling and distribution systems, respectively. The CO_2 emissions associated with the DSW from the mixed layer are minimal (only 336 MT over 10 years) because the pumps are powered by wave energy. The AF scenario on the other hand, increased total CO_2 emissions dramatically to 43,053 MT of CO_2 after 10 years. This is because of the annual 7,600 MT of Urea needed to replicate the same amount of N as the DSW nutrient source (Figure 4).

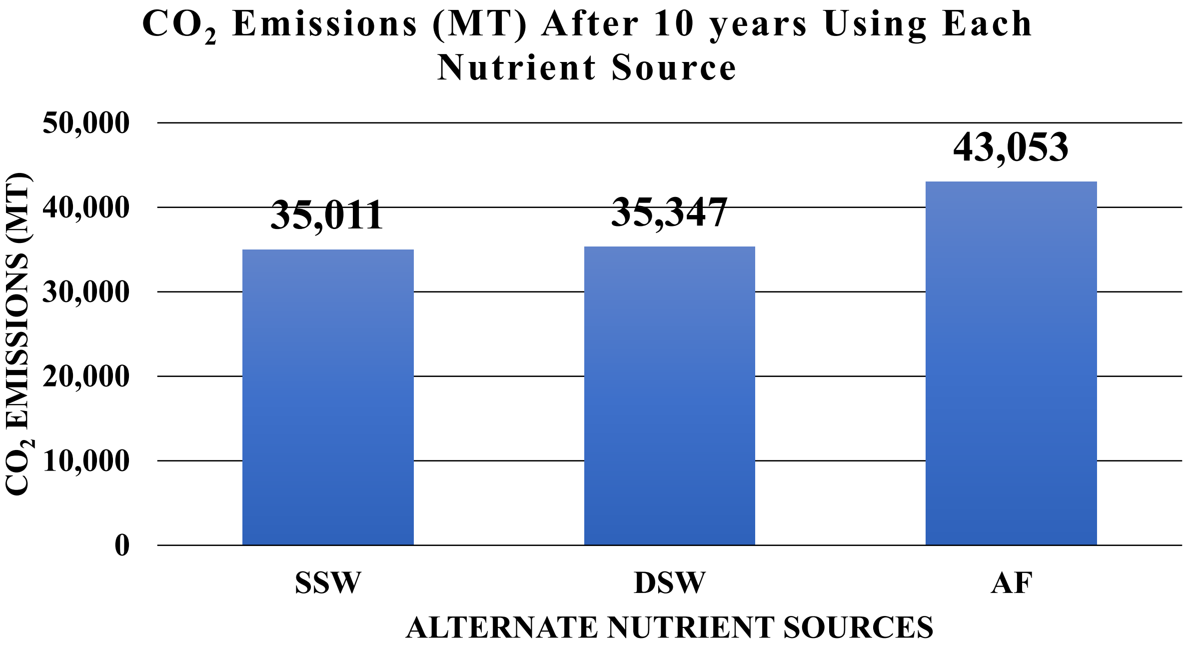

Figure 4: CO$_2$ emissions required to build, deploy, and operate the three different nutrient sourced farms for 10 years. This figure shows the respective CO$_2$ emissions in Metric Tons (MT) associated with each nutrient sourced farm component after operating for 10 years.

4.2 CO$_2$ Sequestration Potential

The growth of *U. lactuca, G. parvispora* and *H. hawaiiana* were modeled using the series of data and equations found in the "Growth modelling" section in the methods. The total dry production for each species growing at each specified SGR over the farm's 10-year life varied from 270,400 MT of *Halymenia* growing at 3%/d to 1,801,600 MT of *Ulva* growing at 12%/d (Table 12).

SGR	*Ulva lactuca*	*Gracilaria parvispora*	*Halymenia hawaiiana*
3%	515,200	279,200	270,400
6%	983,200	532,800	516,800
9%	1,410,400	764,800	740,800
12%	1,801,600	976,800	946,400

Table 12: Total dry production for *U. lactuca, G. parvispora,* and *H. hawaiiana*, at 3, 6, 9, and 12% / day specific growth rates, over 10 years.

Using the C content for each seaweed, total DM production was converted to C sequestered and then CO_2 sequestered over the 10-year life for the farms. (Figure 5). Growth rate and the composition of the seaweed have enormous effects on CO2 sequestration potential.

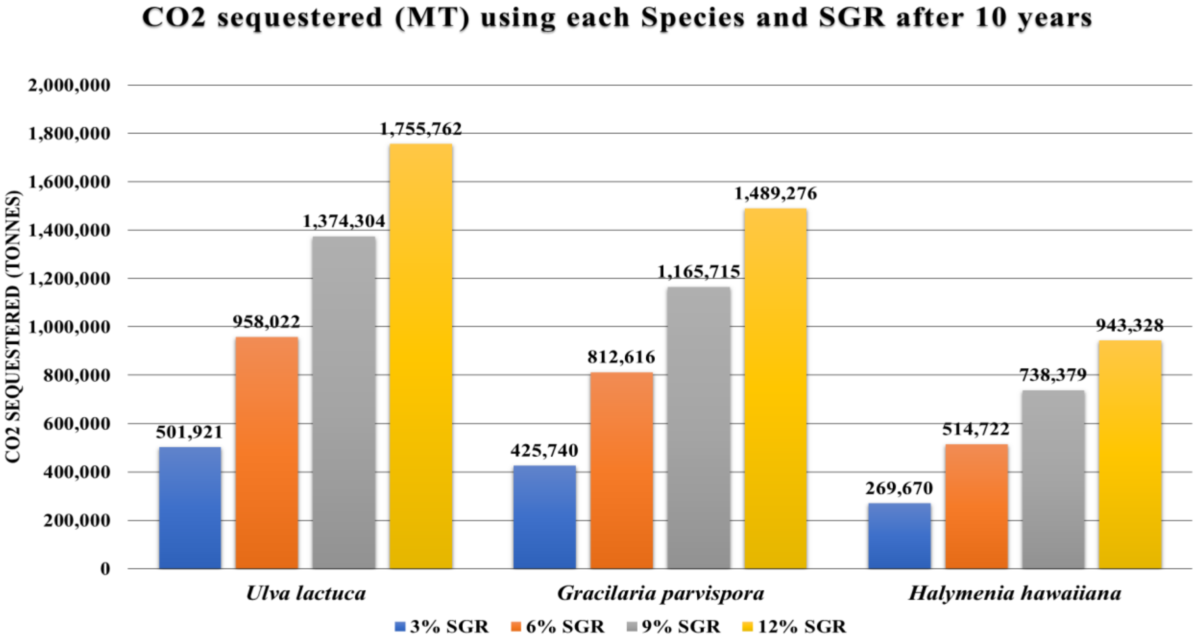

Figure 5: CO_2 sequestration potential for *U. lactuca, G. parvispora,* and *H. hawaiiana*, at 3%, 6%, 9%, and 12%/day specific growth rates, after 10 years.

4.3 Net CO_2 Impact

The net CO_2 impact for each nutrient source scenario was found by adding the total amount of CO_2 emitted over 10 years for each nutrient source and subtracting the total amount of CO_2 taken up by each candidate seaweed species growing at each SGR. Only the lower SGRs, 3% and 6%/d are possible with SSW alone. Regardless of SGR and species, SSW had the lowest net CO_2

impact over a 10-year lifespan (sequestration ranged from 234,658 – 923,011 MT of CO_2); DSW showed the greatest net CO_2 impact (sequestration ranged from 234,323 – 1,720,416 MT of CO_2), and the AF system was almost the same as DSW (sequestration ranged from 226,617 to 1,712,709 MT of CO_2). *U. lactuca* sequestered the largest amount of CO_2 over 10 years for all nutrient sources and all SGRs. *H. hawaiiana* sequestered the least amount of CO_2 after 10 years regardless of nutrient source or SGR (Figure 6).

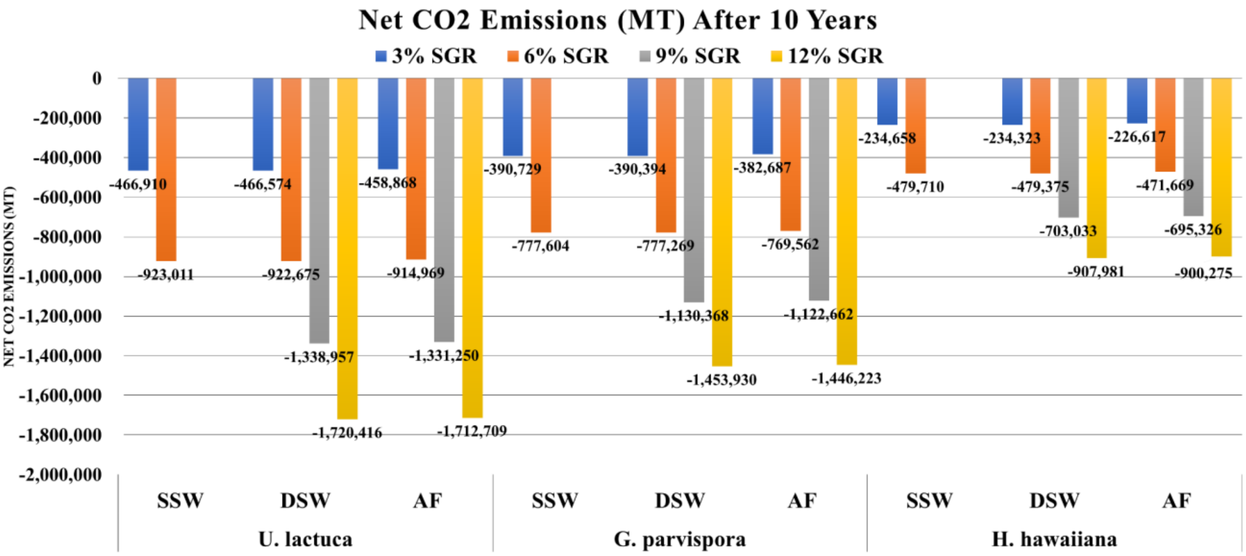

Figure 6: Net CO_2 impact for Sea surface water, deep sea water, and artificial fertilization as a nutrient source, while growing *U. lactuca, G. parvispora* and *H. hawaiiana* at four different specific growth rates (3%, 6%, 9% and 12%/day) for 10 years on a 1000 ha offshore seaweed farm located west of Hawai'i Island, Hawai'i U.S.A.

If the nutrient rich DSW was taken from below the mixed layer, CO_2 that was previously stored would also be brought upwards into the mixed layer. Pumping 631 of this m^3/sec DSW would bring an estimated 84 million MT of CO_2 into the mixed layer overwhelming any CO_2 sequestered by the seaweed by almost 2 orders of magnitude. Thus, using DSW from below the mixed layer could be environmentally unsound.

CHAPTER 5. DISCUSSION & CONCLUSION

5.1 Discussion

This thesis is an integral part of the process to obtain permits and funding for large scale seaweed culture in oligotrophic tropical waters. Demonstrating, even in theory, that these farms will sequester substantially more CO_2 than they emit is a strong reason for their deployment. Given the high cost and regulatory difficulties, the simulations done for this thesis are the first step before moving offshore.

There are many ways seaweed could be grown offshore (see examples in Buck & Bukholtz 2004 and Chopin et al 2012). My focus was on a design proposed by Ocean Era Inc off the western shore of Hawai'i. As these waters are oligotrophic, the growth rate of the seaweed will be lower than in nutrient-rich waters with major negative impacts of economic viability. Thus, possibilities for nutrient supplementation and net CO_2 impacts had to be examined.

Net CO_2 impact is estimated by subtracting CO_2 equivalent sequestered in the seaweed from the CO_2 emissions for construction, deployment, and operation of the farms. The variance in emissions from the farms was directly related to nutrient source (which is part of the growth component). The CO_2 footprint of the other 5 components were essentially the same regardless of nutrient source. SSW relies on natural currents to supply the nutrients without any additional CO2 emissions. DSW from the mixed layer has minor increases in emissions from the CO2 footprint of the pumps and distribution system but does not have CO2 emissions from operations (as the pumps are wave-powered). AF has a minimal footprint for fertilizer storage and distribution but with an annual footprint if 800 MT of CO_2 associated with fertilizer manufacture and transportation. None of the footprints for these three sources (SW, DSW from mixed layer, and AF) exceeded 20% of seaweed sequestration potential even at low SGRs. As will be discussed later, that is not the case if the DSW is sourced below the mixed layer. Thus, except for DSW sourced below the mixed layer, CO_2 sequestration potential is the primary determinant of net CO_2 impact.

CO_2 sequestration is dependent upon the types of seaweed, their chemical composition, and growth rates. The three native Hawaiian seaweeds *Ulva lactuca, Gracilaria parvispora* and *Halyemenia hawaiiana* were selected for inclusion in this study to meet environmental constraints limiting the farms to local species and preliminary growth trials in tanks. Although the selected SGRs derived from the tank studies are like SGRs attained with seaweed species in other parts of the world, their accuracy, precision and estimates of variability need to be determined. Of particular concern, given their importance in the simulation models, are biomass at harvest (assumed to be 3 kg/m of line but it could be higher or lower); biomass remaining on the line after harvest (i.e., the initial weight); and the length of the lag period. Further, the effects of herbivory were not considered in the simulations, and variability had to be estimated (which precluded the use of stochastic models). Obtaining verified estimates of these parameters will require data from offshore trials.

The low nutrient content of SSW limits seaweed growth. Even with that limitation, SSW farms can sequester much more CO2 than they emit. But whether those farms are feasible will depend on economics which are beyond the scope of this thesis. Similarly, using DSW from the mixed layer and AF have great potential to sequester CO_2 but their economic viability has yet to be determined.

Aside from nutrient availability and growth rates, seaweed growth modelling typically includes environmental factors such as: temperature, light, herbivory, and self-shading. Hydrodynamic models of seaweed farms typically include estimates of nutrient mixing and uptake. My simplified model did not explicitly include any of these factors. The University of California, Irvine (another MARINER team) is examining how nutrients fluctuate around the offshore project site. Their research uses the MacroAlgae Cultivation MODeling (MACMODS) system that integrates an open-source regional ocean model with a fine-scale hydrodynamic model capable of simulating forces and nutrient flows in various farming systems.

This research examined 3 potential nutrient sources (SSW, DSW, and AF); however, there are other options. The use of anthropogenic run off offers an opportunity to use it as a nutrient source for these farming systems. As seaweed grows, it could potentially mitigate issues exacerbated by pollution in coastal tropical marine environment (Hasselstrom et al 2018). Unfortunately, the use of anthropogenic runoff is impractical for offshore systems in the oligotrophic tropical environment. This is because nutrient concentrations dilute rapidly with distance from the coast, and because nearshore areas where nutrient recycling would be optimal are unlikely to be open for commercial seaweed facility development. Exceptions exist such as the dead zones in the Gulf of Mexico.

A widely accepted alternative to SSW, DSW, AF, or nutrient recycling is Integrated Multi-trophic Aquaculture (IMTA). IMTA relies on aquatic species from different trophic levels to utilizing species' uneaten feed, waste, nutrients, and by-products to be recaptured and converted into fertilizer, feed, and energy for seaweed (Chopin et al. 2012). Unfortunately, because IMTA relies on synergistic interactions between multiple species, this method of nutrient delivery poses engineering and economic risks on multiple biological cycles (Chopin et al. 2012: Abreu et al. 2011). Even if these issues could be minimized, to subject a 1000-hectare farm to the engineering and biological issues associated with IMTA would entail extreme risk which is why it was not examined in this research (though co-culture with other species should not be ruled out).

If DSW is sourced below the mixed level (the depth of which varies depending on the site), nitrogen may not be the only nutrient being pumped upwards to the farm. CO_2 that was previously stored in the DSW would also be brought upwards increasing the amount of CO2 in the mixed surface layer. My preliminary estimates of 84 million MT of CO2 brought to the surface by a 1,000-ha farm pumping from the stored layer can be considered a low estimate as pH changes with depth will increase CO_2 concentrations. Even the low estimate adds almost 2orders of magnitude of CO_2 to surface waters than is sequestered by the seaweed. Pumping from below the mixed layer to surface seaweed farms is not a viable means of removing CO_2.

This study assumes that harvest and collection is all done autonomously. However, the initial Blue Fields demonstration project will utilize manned vessels to complete these jobs. Until this demonstration has proved that offshore farming in the tropics is commercially feasible and a larger scale version of this farm is put offshore, and that these underwater autonomous technologies have been proven, it is likely seaweed will be harvest by hand. Luckily, when and if these large scales farms come to fruition, hopefully within the next 10 years, it will likely be at a time when autonomous technologies are better understood. While it is appropriate to examine multiple MARINER technologies on a MARINER project, future research should include potential CO_2 emissions from harvesting and collecting by hand or other mechanical designs.

This study did not include the conversion of seaweed into fuel, which is the main goal of MARINER. While a conversion into fuel would surely increase the amount of CO_2 emissions drastically due to the required infrastructure, utilities, and power needed, after collection there is a multitude of uses for seaweed. Although more research is needed on this topic, seaweed can potentially be cut off and dropped into the deep ocean to immediately store CO_2, or it can be recycled within the carbon cycle. This can be done by using seaweed for direct consumption, as feed for animals, or as fertilizers for farming and many other uses (Javed et al. 2019). This study focuses on novel technologies, the CO_2 impact of these systems (including the conversion into biofuel) should be compared to emissions associated with offshore oil extraction and an equal amount of refining.

5.2 Conclusion

This research took an interdisciplinary approach to better understand how novel nutrient sources affect large scale offshore seaweed farming, on a hypothetical 1000-hectare farm over 10 years in Hawai'i. The primary goal of this thesis was to examine the CO_2 impact three different nutrient sources (SSW, DSW, and AF) have on the farm. All three native Hawaiian species of seaweed (*U. lactuca, G. parvispora,* and *H. hawaiiana*) growing at four different growth rates (SGRs: 3%, 7%, 9% and 12% per day) showed considerable potential (over 10 years on the 1000-hectare farm) to sequester much more CO_2 than was emitted in the construction, deployment, and operation of the farm. Using SSW alone sequestered the least amount of CO_2 while DSW from the mixed layer and AF sequestered substantially more. Pumping large quantities of DSW from below the mixed layer as a means of nutrient supplementation is not advisable as enormous amounts of CO_2 stored in those waters would be brought into the surface layers.

This thesis and its simulations are based on the best available information. Much of it is extrapolated from short term tank studies and a list of components from a preliminary TEA. Much more detailed research is required, particularly offshore, to obtain better estimates, including variances, of the seaweed growth parameters.

Seaweed farms in oligotrophic tropical waters will probably require nutrient supplementation. Placing these systems in highly nutriefied waters would eliminate the need for such enhancement by lowering their cost, maintenance, and environmental impact. It could also have ecosystem benefits producing oxygen in areas where it is currently being taken up by phytoplankton and other harmful algae like in the Gulf of Mexico. Aside from their nutrient pollution mitigation potential, these farms create artificial habitat enhancing the local fisheries.

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