ADVANCED RESEARCH PROJECTS AGENCY – ENERGY RESEARCH PERFORMANCE PROGRESS REPORT

MACROALGAE RESEARCH INSPIRING NOVEL ENERGY RESOURCES (MARINER) DE-FOA-0001726

Award: DE-AR0000925
Prime Recipient: Catalina Sea Ranch, LLC
Project Title: Design of Large Scale Macroalgae Systems (MacroSystems)
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Date of Report: 7/30/2018
Reporting Period: 4/1/2018 to 6/30/2018

Technical - Accomplishments and Milestone Updates

N/A

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PRIME RECIPIENT: CATALINA SEA RANCH, LLC

PROJECT TITLE: DESIGN OF LARGE SCALE MACROALGAE SYSTEMS (MACROSYSTEMS)

PRINCIPAL INVESTIGATOR: PHIL CRUVER

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REPORTING PERIOD: 4/1/2018 TO 6/30/2018

Contents

1. Progress Towards Objectives 4
2. Technical - Accomplishments and Milestone Update 6
2.1. Design of Experimental Deployment Systems (Task 1) 6
2.1.1. Efficient Hatchery Systems, Increase Yield and Direct Seeding Systems (Task 1.1) 6
2.1.2. Engineering Design of an Offshore Cultivation System and Description of the Scaling Factors Necessary (Task 1.2) 7
2.1.3. Develop Design and Deployment Plan for Mechanical Harvesting (Task 1.3) 12
2.2. Range of Deployment (Task 2) 12
2.2.1. Assessment of Environmental Conditions of CSR's Site (Task 2.1) 12
2.2.2. Survey and Map Suitable Areas for Large Scale Deployment (Task. 2.2) 22
2.2.3. Engineering Design and Deployment Plan of a Proven Sustainable Nutrient Supply System (Task 2.3) 32
2.2.4. Material Specification and Research 32
2.2.5. Upwelling Technologies 32
2.2.6. Modeling of an Upwelling System 33
2.2.7. Strength Tests of the Deep Water Pipe 33
2.2.8. Design of the Solar Pumping System 35
2.3.: Techno-Economic Models and Sustainability Assessments (Task 3) 38
2.3.1. System Productivity Major Drivers (Task 3.1) 38
2.3.2. Mass Energy Balances, Net Energy Returns (Task 3.2) 39
2.3.3. TEA And Economic Viability Including Risk Assessment And Sensitivity (Task 3.3) 39
2.3.4. Environmental Impacts Of Solutions (Task 3.4) 40
2.4. Complete Phase II Proposal (Task 4) 45
2.4.1. Compile Reports And Plans Into Deployment Manual (Task 4.1) 45
2.4.2. Business Related Plan Items (Task 4.2) 45
3. Additional Performance Updated 46
3.1. Issues, Risks, and Mitigation 46
3.2. Changes In Approach 46
3.3. Changes In Project Personnel 46
4. Technology to Market (T2M) 47
4.1. Publications 47
4.2. Other Project Output 47
4.3. Follow-on Funding 47
5. Administrative and Legal Updates 48
5.1. Disclosures 48

5.2. Conflicts of Interest Within Project Team 48
6. Cost Updates........ 49
7. APPENDIX A: Detail Drawing from the FEA specification 50
8. APPENDIX B: Methodical Approach for Site Survey; Mapping 53
8.1. Chronological Outline (NOAA)........ 53
8.2. Research 53
8.2.1. Assessment........ 53
8.2.2. Model Table 58
8.2.3. Model Reference Links 60
8.2.4. Literature Review........ 61
8.3. Data Analysis 62
9. APPENDIX C: Techno-Economic Assessment – MacroSystems........ 64
9.1. System boundaries and underlying assumptions........ 64
9.1.1. Species 64
9.1.2. Geographic Location........ 65
9.1.3. Nutrient availability 65
9.2. Technical Description 66
9.3. Principle Drivers 66
9.3.1. CAPEX 66
9.3.2. OPEX 67
9.3.3. Yield........ 68
9.3.4. Energy Consumption........ 68
9.4. Ecosystem Services and Bioremediation Opportunities 69
9.4.1 Carbon Fixation in Kelp Forests and GHG emissions from the MacroSystems........ 69
9.4.2. Increasing the Net Release of CO_2 into the Atmosphere 70
9.4.3. Economic Valuation of Marine Ecosystem Services 70
9.5. Scaling Factor 71
9.6. Conclusion 71
9.7. References........ 72

1. Progress Towards Objectives

MacroSystems will use disruptive techniques to make macroalgae cultivation a commercially attractive business investment on a near-term basis – in this case less than 3 years! To fulfill this goal, MacroSystems has defined ten specific objectives (SO) that will be achieved in related tasks:

SO1: Develop a Production Plan for Selective Breeding to Increase Yield. (Task 1)

The genetic parental material of *Macrocystis pyrifera* (*M. pyrifera*) will be derived from regional sources in the Southern California Bight and nearby areas. Pre-selected parents with high biomass will be used as the start of a selective breeding program for higher biomass. MacroSystems will collaborate, if possible, with the MARINER Category 5 team from the University of Wisconsin-Milwaukee.

SO2: Production Plan for Direct Seeding and Deployment. (Task 1)

The major design elements have been defined and integrated into the total concept. The final decisions were settled during the ARPA-E halftime meeting. Most of the input for the Techno-Economic Assessment (TEA) related to hatchery and seeding has been provided.

SO3: Develop Engineering Design and Deployment Plan of the Cultivation Systems and Description of the Scaling Factors Necessary. (Task 1)

Ocean Rainforest and partners have conceptually designed a rig for the offshore cultivation of *M. pyrifera*, the MacroSystems Cultivation Rig ("MS1"). MS1's hydrodynamic robustness/resilience is being analyzed now in Finite Element Analysis simulations. The FEA results will then inform another iteration of the design of the MS1 until the rig is ready for its first deployment. The FEA will be conducted in collaboration with Maine Marine Composites (MMC) to perform a structural analysis on a new rig for cultivating *M. pyrifera*. The FEA is expected to be completed in the second quarter of the project.

SO4: Develop Engineering Design and Deployment Plan for Mechanical Harvesting (Task 1)

The work on this task will commence in the second quarter of the project.

SO5: Create a Flow Description of All Processes and Units Necessary From Hatchery to Processing the Biomass into a Storage Stable Condition for End-User Products within the Feed and Energy Market. (Task 2)

The flow description is in progress and will be finalized in the second quarter of the project.

SO6: Engineering Design and Deployment Plan of a Proven Sustainable Nutrient Supply System at the Cultivation Sites. (Task 2)

The Climate Foundation team has been assessing and testing different materials, upwelling technology designs and renewable power sources for the MacroSystems nutrient upwelling system. Modeling and calculating the physical and mechanical forces of early versions of the MacroSystems upwelling system has been completed. Additionally, the Climate Foundation is planning to test a nutrient supply system in Eastern Indonesia, which will have similar features as the nutrient supply system for MacroSystems. This planning process and testing will help to avoid risks associated with the design and anticipated testing of the MacroSystem nutrient upwelling system.

SO7: Identify Suitable Areas for Large Scale Deployment of Macroalgae Cultivation Systems. (Task 2)

Preliminary evaluations have been performed on the wave, wind, and coastal ocean current datasets around the Catalina Sea Ranch aquaculture facility for environment and infrastructure thresholds. Storm trends and climate datasets will provide analysis of the expected environmental conditions at the Catalina Sea Ranch into the near future. The survey and mapping of suitable areas for large-scale deployment of macroalgae cultivation systems within the U.S. Exclusive Economic Zone (EEZ) have commenced in the first quarter and consists of two subtasks: (1) the environmental analysis and fuzzy logic linear overlay; and (2) the identified social and marine infrastructural constraint of developing regions.

SO8: Conduct a Techno-Economic Assessment (TEA) Based on Models Developed for the Specific Systems Designs. (Task 3)

The work on TEA progressed well in the first quarter of the project. A methodology description relevant for the MacroSystem project has been made to serve as a structured theoretical foundation appropriate for the scope of the ARPA-E Phase 1 consisting of:

1) Setting up harvesting yield and energy balances of cultivation scenarios related to different cultivations systems. This is followed by a feasibility assessment of the required assumptions and results.
2) An economic evaluation including the formulation of cost functions, cost calculations and analysis of important aspects, and calculation of economies of scale pertaining to *M. pyrifera.*
3) A technical assessment of the risks and mitigation strategies related to the different cultivation scenarios.

A Microsoft Excel-based TEA model is currently being developed based on this theoretical approach which includes the collection of actual data on cost and performance.

SO9: Conduct Sustainability Assessment of the Processes from Hatchery to Landed Biomass for the Proposed Systems, Including 5:1 Energy Return Targets. (Task 3)

Climate Foundation is assessing challenges and risks comprising environmental, biological, biogeochemical, technical and operational risks. During the first quarter, work has focused on identifying, evaluating and thoroughly analyzing remediation techniques and approaches to include them in the planning. The final document is intended to provide a frank assessment of potential or perceived risks envisioned at present for MacroSystem development. While it is not possible to predict all risks in advance, the environmental risk assessment and analysis is intended to convey the likely challenges in the months ahead as we develop MacroSystem technology and increase its utility. The most prominent of those concerns will be detailed in the final document.

SO10: Produce a Deployment Execution Plan for Phase II. (WP4)

Ongoing work is taking place regarding permit (application submitted) and tech-to-market investigations, and also, contact has been made to potential team members and investors for a Phase 2. The final work in Phase 2 planning will commence in the second quarter of the project.

2. Technical - Accomplishments and Milestone Update

2.1. Design of Experimental Deployment Systems (Task 1)

The objective of Task 1 is to produce designs of hatchery, cultivation and harvesting systems with the potential to be scaled up to 1,000 ha.

2.1.1. Efficient Hatchery Systems, Increase Yield and Direct Seeding Systems (Task 1.1)

Seeding

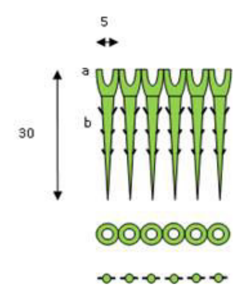
Two concepts of seeding will be tested:
1. Direct precision seeding on a distance of approximately 30 cm using glue with 1 mm size plantlets
2. Propagule planting with plantlets of approximately 1 cm in a protective cup; gunned into a substrate

For the direct seeding, the glue needs to be improved to be able to deploy instantly at sea, but also to glue plantlets of 1 mm. A second prototype of the seeding apparatus is designed, and the concept will be tested. This included the automated 2 step seeding (first: seed, second: the glue to cover the seed). The apparatus is able to seed precise patches at the required distance. The machine is currently designed and a prototype will be built next month adapted to 3 m cultivation ropes.

The logistics and operational aspects of seeding need to be developed/defined by Hortimare.

Propagule seeding requires the design of a propagule. Two options are evaluated: a pin like propagule with plantlets needs to be gunned by air pressure; and, a cloth tag concept is considered. This is easier to develop because the tagger is commercially available off-the-shelf. The cloth tag itself has to be changed to a small cup.

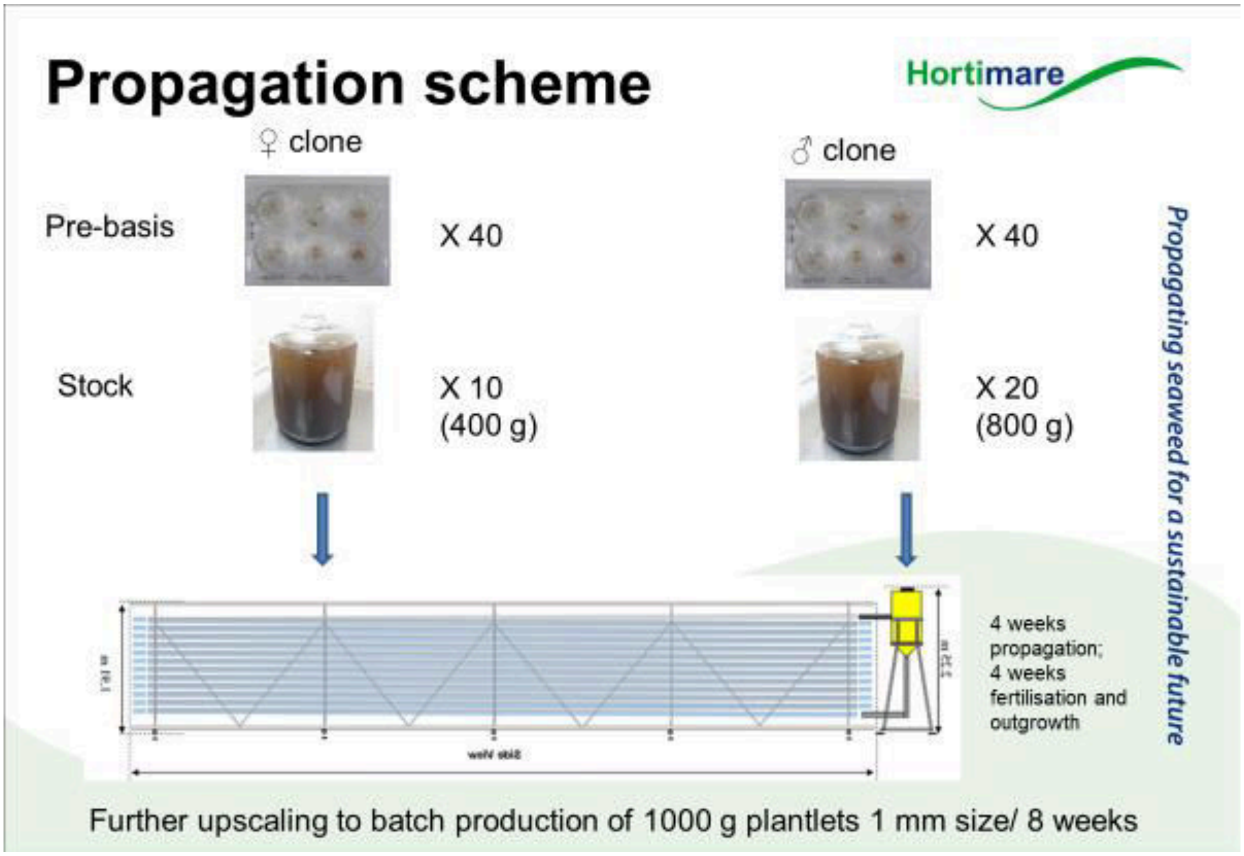
To be defined:
-rope specification
-glue specs
-seeding and deployment process
-cost of seeding
-design of gunning apparatus



Hatchery

Definition of the hatchery process:

- Phase 1: propagation to plantlets of 1 mm; using flasks and bio-reactors.
- Phase 2: outgrowth to plantlets of 1 cm
- Plant raising in trays of connected propagules, ready to deploy.



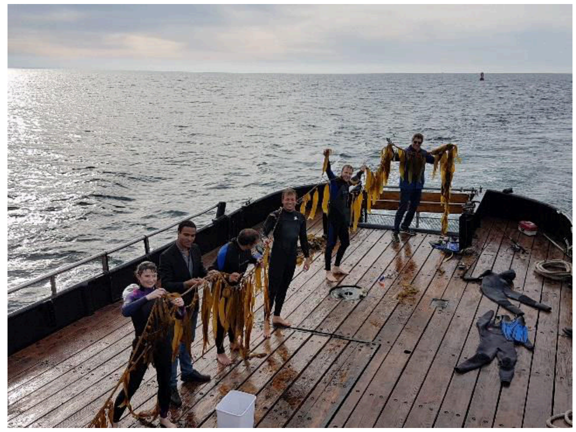
Hatchery needs, size and process are defined.

To be completed:

-Specific hatchery handbook including all equipment, materials, logistics, processes, and labor.
-Dimensioning tube bioreactor to needs in phase 2
-Fertilization chamber design

2.1.2. Engineering Design of an Offshore Cultivation System and Description of the Scaling Factors Necessary (Task 1.2)

The MacroSystems team commenced discussion and fact finding during the kick-off meeting in January 2018, when partners visited the cultivation site of Catalina Sea Ranch and went diving for *M. Pyrifera* to select samples for hatchery and morphology studies.



In April 2018 the team met again in the Faroe Islands to study the open ocean rig system of Ocean Rainforest. Following an offshore site visit the team had a two day production brain-storming workshop to discuss potential rig design and evaluate options of seeding and harvesting.

Several sub-group meetings have been held via Skype in addition to the weekly progress meeting, where rig designs have been discussed. This work led to the scope of work for the FEA.

The scope of this work is to further the understanding of the rig behavior under environmental loading as well as other *Macrocystis* biomass related loads. The provided design is complete but subject to design improvements as supported by FEA analysis, feedback from ARPAE and other advances in aquaculture.

The primary aim of this work is to increase understanding rather than producing binary pass/fail results and this qualitative/quantitative emphasis split shall be reflected in the reporting of results.

Description

The MacroSystems MS1 rig is a suspended horizontal line, supporting the growth of vertically growing *Macrocystis* plants. To increase the amount of seeded area numerous seed-lines are uniformly spaced along the span of the horizontal line. See Fig 1 and 2 for illustrations of bare and fully-grown rig.

Refer to Appendix A for to-scale drawings and Appendix B for further illustration details.

Input

The model inputs are described in three sections addressing the *Rig design*, the *Environment* and *Seaweed loading* respectively. These may leave the structure under-specified in which case the modeler should proceed with reasonable context sensitive assumptions and the change made in the final report.

Design

Refer to drawing MS-1001, Appendix A, for dimensional details of the rig and mooring.

The following structural dimensions and material choices are subject to change and should the analyst find that alterations are required, then these should be made, recorded and the analysis continued.

Example: If the mooring chain is found to be too short or light to offer sufficient flexibility, it should be altered for further modeling work.

Main Floats

Main floats are presumed to be spherical 10 ton force floats, submerged by 50% at initial conditions. Floats are tied to main rig by 20m chain and joint is provided by steel coupling plate and shackles.

Mid Line Weight

A 500N weight is suspended at mid-point of horizontal line.

Anchors

Anchors shall be represented by fixed ground points with moment releases applied.

Moorings

Moorings have 4:1 scope (200m long) constructed with 1 shot of 1½" chain and 15mm wire rope. These should be modeled as tension only elements with no stiffness and moment releases applied.

Horizontal Line

The backbone of the rig is designed with nylon type *Tipto-Lon Octoply 44mm* rope. Further size options are provided below as required.

Brand	Dia	Weight/m	Spec Grav	Break Strength	UV	Elongation
	mm	Kg/m	kg/m3	Ton		
Tipto-lon Octoply-44	44	1.19	1140	35.8	Good	20-40%
Tipto-lon Octoply-48	48	1.42	1140	42	Good	20-40%
Tipto-lon Octoply-52	52	1.67	1140	48.8	Good	20-40%

Table 1: Horizontal Line Materials

Vertical Seed Lines

Seed lines are knotted onto the horizontal line and made from Polyethylene type, e.g. *Gripogreen 10mm* rope.

Brand	Dia	Weight/m	Spec Grav	Strength	UV	Elongation
	mm	Kg/m	kg/m3	Ton		
Gripogreen 10	10	0.04	910	1.56	good	10-20%

Table 2: Vertical Line Materials

Environment

The environment effects are presented as current load and ocean waves – discrete wind loading shall be ignored. All analysis shall presume the medium is seawater.

Current load

Current is 2.5kts (1.3m/s) orthogonal to the horizontal line.

Wave load

Non-breaking significant wave height is taken as 6m and dominant period as 10s. If the analysis tool can model breaking waves, then this should be done in analysis 4 as an additional case.

Seaweed Case 1

This is the base case, immediately after seeding with no seaweed growth. The rigging is bare and without any seaweed provided buoyancy (Figure 1).

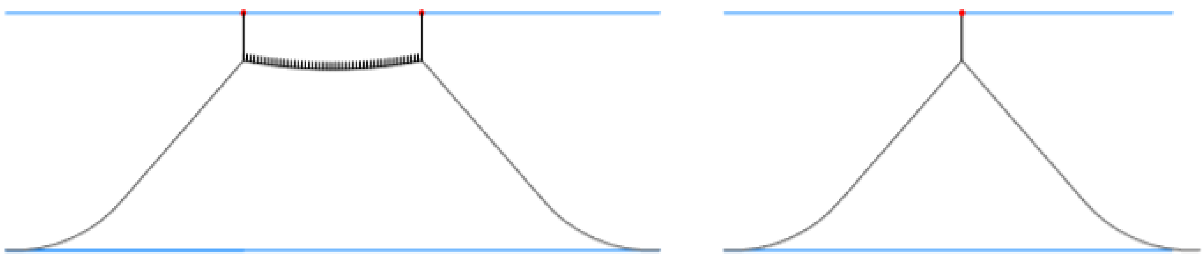


Figure 1: Rig without Seaweed

Seaweed Case 2

This case represents the supporting of a great number of macrocystis plants with fully developed surface canopy structure. This is the max-load case, both in terms of current drag, wave dynamics and buoyancy (Figure 2). Note that Figure 2 provides an illustration of how the seaweed may look and is not intended to constrain the model in terms of the deflection angle portrayed – current, drag and buoyancy modeling will determine this.

To representatively model the macrocystis loading, the following shall be used:

- 4 plants per meter of horizontal line, dispersed uniformly
- 4 stalks per plant
- Stalks are up to 40 meters long, 5mm diameter cylinders without any structural stiffness. For every meter of stalk, one 4"x4" drag plate (representing a blade) is attached, without stiffness and only providing surface effect drag.
- *Macrocystis* plants are positively buoyant, at 1000kg/m3.

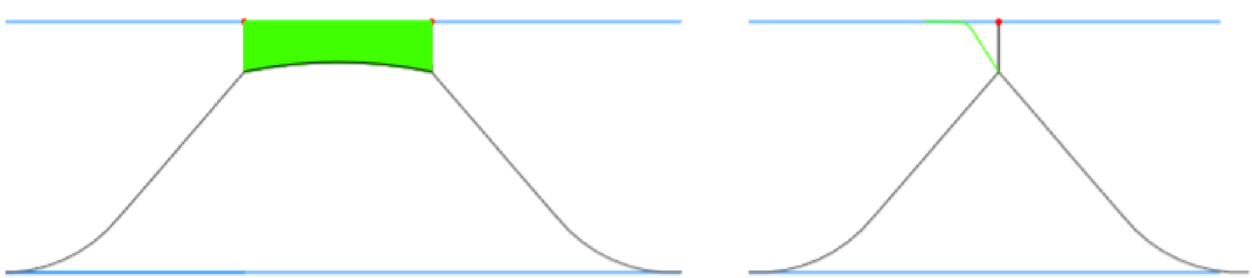


Figure 2: Fully grown Seaweed

Seaweed Case 3

This case represents the rig immediately after harvesting, when 23m of macrocystis have been removed and 17m left in place (Figure 3). This case provides an intermediate sense-check against the results of case 1 and 2. Note that Figure 3 provides an illustration of how the cut seaweed may look and is not intended to constrain the model in terms of the deflection angle portrayed – current, drag and buoyancy modeling will determine this.

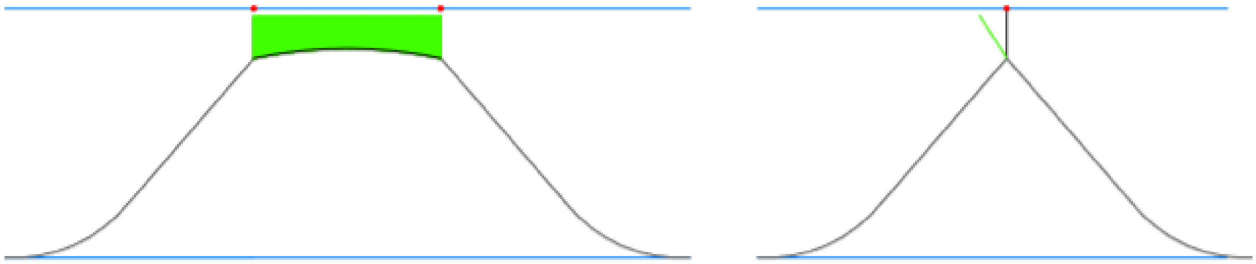


Figure 3: Partially Harvested Seaweed

Analysis

The following analysis cases shall be reported separately to increase understanding of static and dynamic effects on the rig design.

Analysis 1

Model run without any load case applied. Initial loading tensions provided by mooring and floatation tensions. Key insights sought:

- Tension in mooring and horizontal lines
- How much chain is lifted off seabed.

Analysis 2

Model run without environmental loads but with seaweed case 2 applied. Low nominal current can be applied for model solvability if required. Key insights sought:

- Effectiveness of rig weighting under maximum buoyancy load
- Effect of initial condition rig tension on floating tendency.

Analysis 3

Base low-load analysis, full environmental load case and seaweed case 1 applied. Key insights sought:

- Rig loads and deflections under self-weight in-current and waves.

Analysis 4

Max load analysis with full environmental load case and seaweed case 2 applied. If possible, this analysis shall also include plunging breaking-wave modeling. Key insights sought:

- Max structural loads, used for sizing & material selection
- Assessment of structural and mooring flexibility
- Max loads on seaweed during wave breaking.

Analysis 5

Mid-load analysis with full environmental load case and Seaweed case 3 applied.

Results and Discussion

The final report shall provide results from each analysis followed by a brief discussion summarizing modeling adjustments, suggestions for parametric optimization of material selection and sizing and any identified conceptual design flaws of the rig.

This qualitative element of the report is important and if possible should be completed after an initial feedback session between the analyst and designer.

Each analysis section shall present results in a format covering the following points:

- Key structural static and dynamic loads on rigging and mooring.
- Deflections of main horizontal line in X & Y directions (orthogonal on line) as in Figures 1, 2 and 3 and Appendix B.
- Images showing the general behavior of the rig.
- Results summary output file provided in appendices

The FEA will be conducted in collaboration with Maine Marine Composites (MMC) to perform a structural analysis on a new rig for cultivating *M. Pyriferea*. MMC is collaborating with the U.S. Naval Academy, the University of New England, and Callentis Consulting to develop techniques for numerical modeling of macroalgae under ARPA-E's MARINER program, and we will apply these techniques to the new rig developed by MacroSystems. The FEA work is expected to be completed by the end of the second quarter of the project).

Detailed drawings specifying the scope of work for FEA are presented in Appendix A.

2.1.3. Develop Design and Deployment Plan for Mechanical Harvesting (Task 1.3)

MacroSystems intends to transfer their practice of partial harvest without destruction – or coppice – of macroalgae above the growth zone on the frond. This enables a regrowth of the biomass without seeding – and reduces the CAPEX of the growth substrates and improve the overall TEA performance. The harvesting system has to work with the cultivation system, and thus the logical sequence implies effort on harvesting devices and systems will follow a conclusion of the FEA and decision on the final design of the cultivation rig. However, the team has already now begun investigations into different harvesting systems, and based on feedback received during ARPA-E site visit in June 2018, the team is designing novel harvesting technology without fossil fuels focused on *M. pyrifera* physiology (apical meristem).

2.2. Range of Deployment (Task 2)

The objective of task 2 is to identify suitable areas for large scale deployment of macroalgae cultivation systems, and delineate a scalable macroalgae supply chain flow into a storage stable condition. Appendix B contains a detail description of the medidogical approach for site surveys and mapping with references.

2.2.1. Assessment of Environmental Conditions of CSR's Site (Task 2.1)

Task 2.1 is the environmental analysis (T2.1) of the Catalina Sea Ranch (CSR) located on the San Pedro shelf in U.S. federal waters outside the Port of Long Beach, CA. A NOMAD buoy was granted to CSR for real-time observations. The buoy was non-operational for much of 2018 so California Cooperative Oceanic Fisheries Initiative (CalCOFI), San Pedro Ocean Timeseries (SPOT) and Coastal Data Information Program (CDIP) supplemented the missing NOMAD buoy data as well as provided the last decade of hydrographic data for the proposed analysis. T2.1 will include a three-dimensional analysis of temperature, salinity, dissolved oxygen, nutrient, pH, and radiation (KdPAR) data to the CSR site.

Analysis of hydrographic data over monthly and seasonal timescales provide a stability assessment of environmental and oceanographic parameters throughout the year. Without isotopic data, the station grid and ocean currents will be used to model nutrient flux over time. Hydrographic profile (xz plane) and future vertical sections for select Pacifica Decadal Oscillation (PDO) event years (2011 La Nina, 2013 normal and 2015 El Nino) allow for similar stability assessments over the last decadal period as well as reveal PDO patterns in the thermocline, isocline, and nutricline. Top-down (xy plane) cross section interpolations indicate where parametric changes in ocean fronts may be found at different depths. Preliminary evaluations have been performed on wave, wind, and coastal ocean current datasets around the CSR facility for environment and infrastructure thresholds. Storm trends and climate datasets will provide analysis of the expected environmental conditions at CSR into the near future.

Data was gathered from CalCOFI, SPOT, and CDIP databases to supplement the missing NOMAD buoy data located at CSR. Initially for task 2.1, a subset of CalCOFI stations surrounding the San Pedro shelf and the SPOT station were selected for hydrographic data for site specific analysis. Seasonal CalCOFI and monthly SPOT datasets were averaged over yearly timescales and multiple depths from 2000-2017. CalCOFI conductivity temperature depth (CTD) profiler station data was evaluated during Pacific Southern Oscillation (PSO) pattern for the years 2011 La Niña, 2013 normal, and 2015 El Niño event years. The CDIP program provided physical oceanographic, wind, wave, and period data for surface sites around the San Pedro shelf.

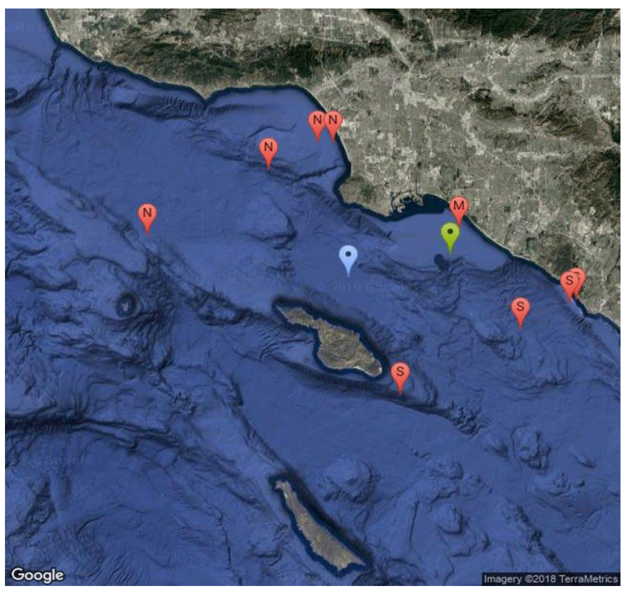
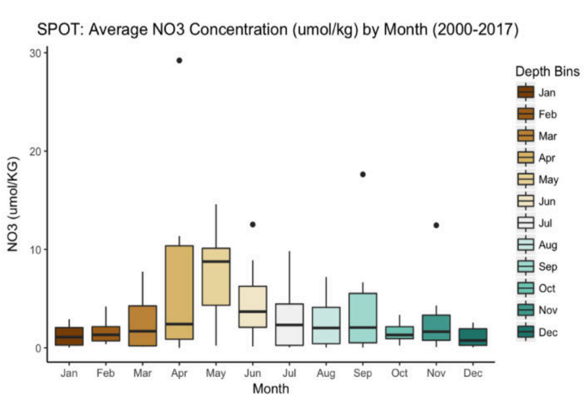


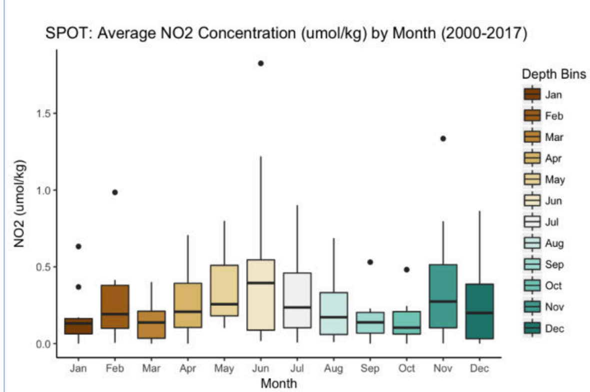
Figure 4. A subset of selected station data around the CSR location. CalCOFI transect stations are in red, SPOT station is in blue, and the CSR location in green.

Region	Station ID	Location (Lat, Lon)	DataBase
North San Pedro (N)	86.7 33.0	33 53.5 N 118 29.3 W	CalCOFI
N	86.7 35.0	33 49.4 N 118 37.7 W	CalCOFI
N	86.7 40.0	33 39.4 N 118 58.5 W	CalCOFI
N	86.8 32.5	33 53.4 N 118 26.6 W	CalCOFI
Middle San Pedro (M)	**88.5 30.1**	**33 40.5 N 118 5.1 W**	CalCOFI
M	**SPOT**	**33 33 N 118 24 W**	USC SPOT
South San Pedro (S)	90.0 27.7	33 29.6 N 117 44.9 W	CalCOFI
S	90.0 28.0	33 29.1 N 117 46.0 W	CalCOFI
S	90.0 30.0	33 25.1 N 117 54.4 W	CalCOFI
S	90.0 35.0	33 15.1 N 118 15.0 W	CalCOFI

Table 3. A subset of selected station locations including region, station ID, latitude & longitude, and database around the CSR location.

SPOT monthly deep chlorophyll max (DCM) (Figure 4) depth data averaged over years 2000-2017 show a strong seasonal signal in the nitrate, nitrite, and phosphate measurements. These indicators reveal stability within the San Pedro upwelling region over time. The silicate signal reflects the biotic factors such as diatom growth in response to nutrient seasonal patterns. The ammonia signal reflects the abiotic and biotic fixation factors prominent in peak spring (April) and peak summer (August) months.





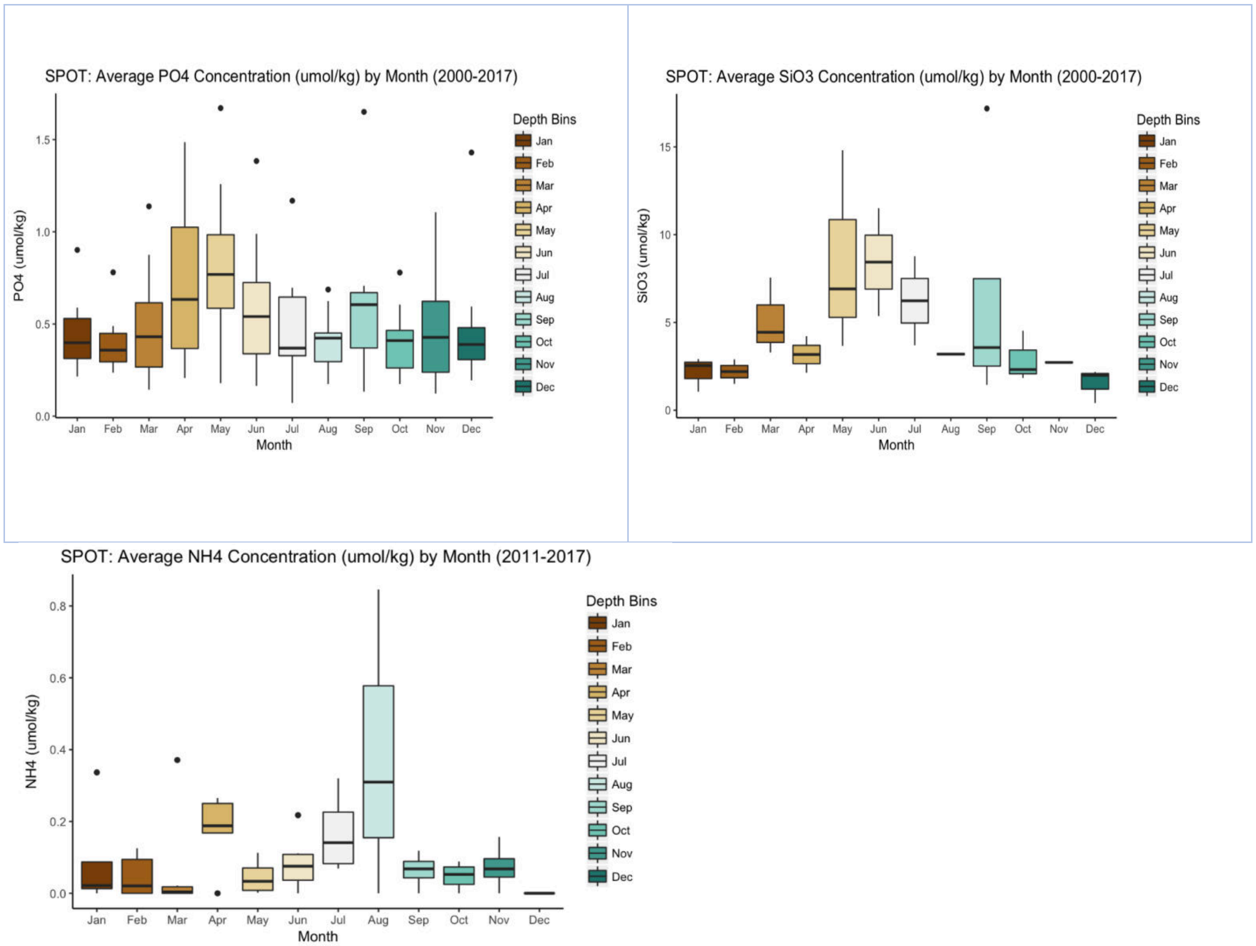
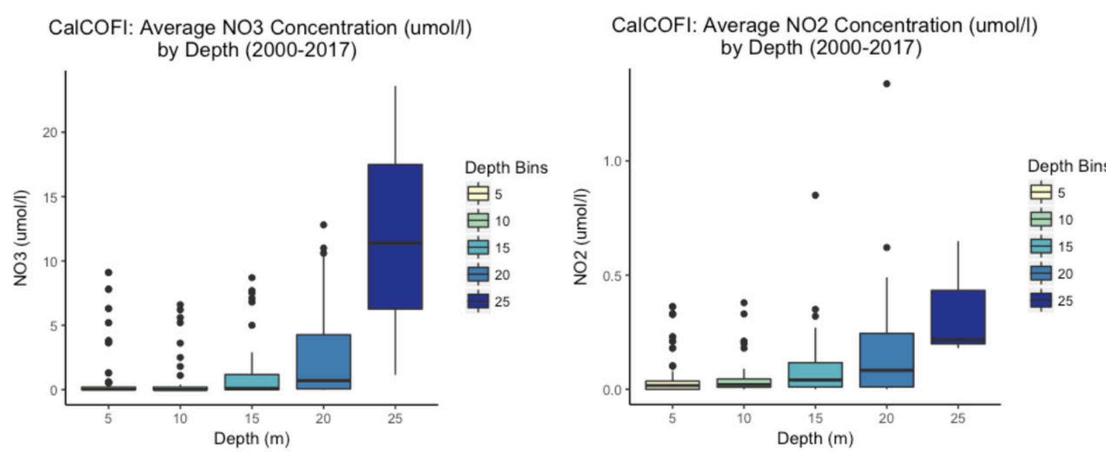


Figure 5. SPOT monthly averaged DCM data for years 2000-2017 for most measurements and 2011-2017 for ammonia. From top left to bottom center nitrate, nitrite, phosphate, silicate, and ammonia.

The CalCOFI program produces extensive, continuous, and reliable datasets for the Southern California region. Depth (Figure 6) and seasonal (Figure 7) environmental analysis plots were developed utilizing the CalCOFI datasets from the closest location to CSR (region M station ID: 88.5 30.1).



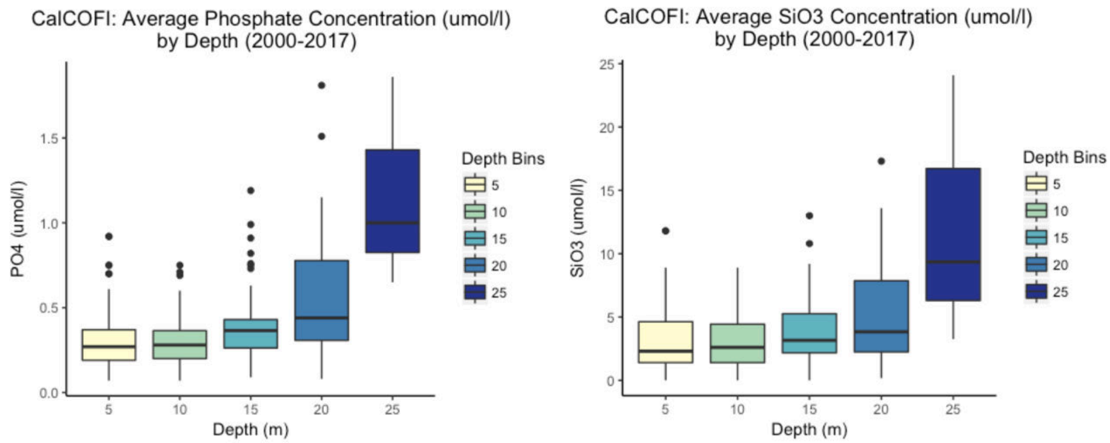
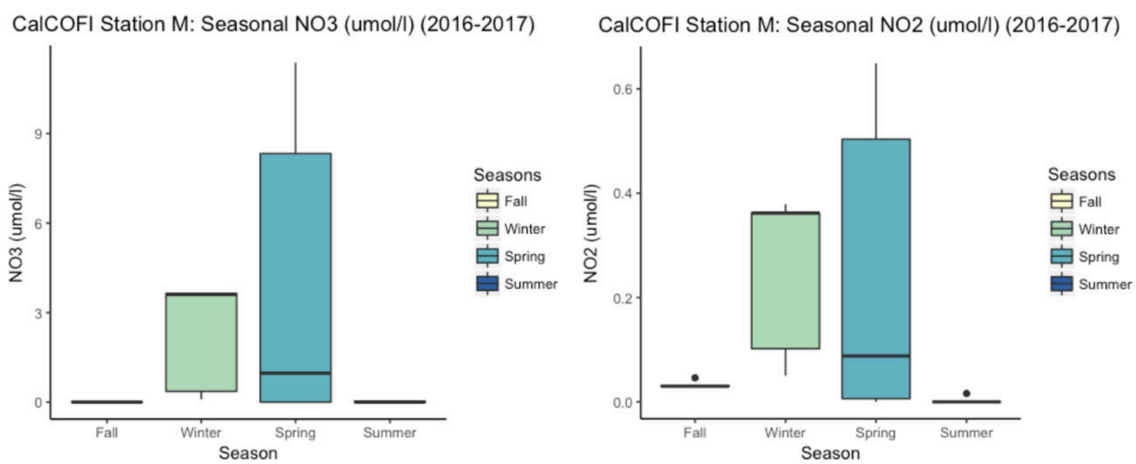


Figure 6. Region M Station ID 88.5 30.1 CalCOFI depth data averaged for the years 2000-2017. From top left to bottom center nitrate, nitrite, phosphate, and silicate.

Seasonal CalCOFI (Figure 6) dataset signals indicates a possible strong variable nutrient signal possibly from Spring upwelling or peak PDO southern California rains resulting in eutrophication events. Further analysis is needed here in the form of flux or transport models using cross-sections from the surrounding station location.



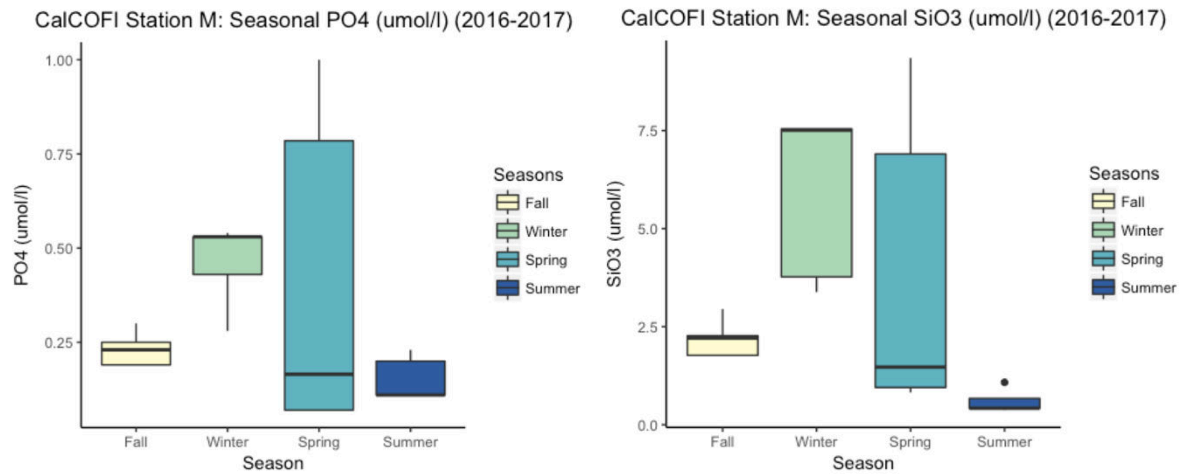


Figure 7. Region M Station ID 88.5 30.1 CalCOFI seasonal depth averaged data for the year 2016-2017. From top left to bottom center nitrate, nitrite, phosphate, and silicate.

Additionally, CalCOFI San Pedro shelf station (region M station ID: 88.5 30.1) CTD profiles (Figures 8-10) were processed for the PDO 2011 La Nina, 2013 normal, and 2015 El Nino event years. The purpose was to support environmental analysis of seasonal PDO patterns for the thermocline, isocline, and nutricline close to the CSR site. The observational deployment depths for shallow stations, such as the San Pedro shelf station, varies with bathymetric reading, sea state, and the experience of the operating technicians. CalCOFI is missing station (region M station ID: 88.5 30.1) data for Spring of 2011 (Figure 8).

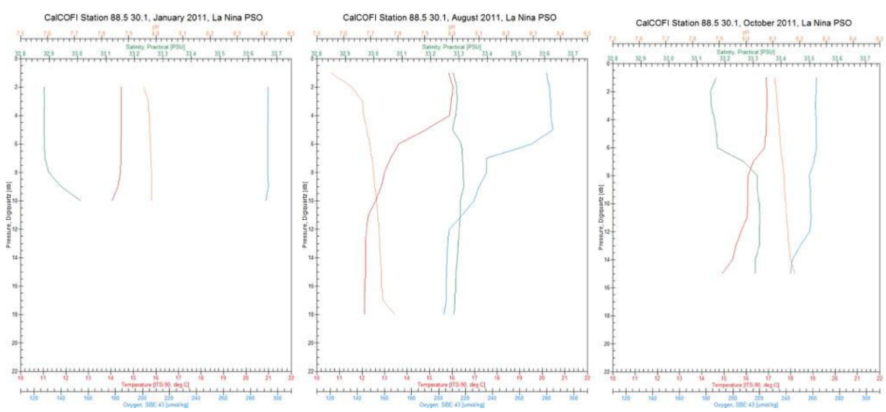


Figure 8. Region M Station ID 88.5 30.1 CalCOFI seasonal CTD profile plots for the PDO event year La Niña 2011. The profiles plots include temperature, salinity, dissolved oxygen, and pH measurements for January, August, and October of 2011.

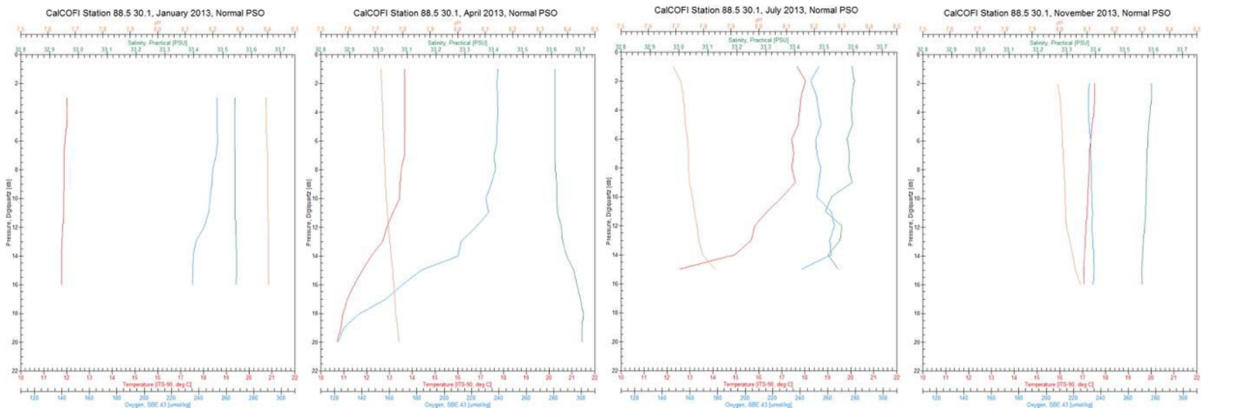


Figure 9. Region M Station ID 88.5 30.1 CalCOFI seasonal CTD profile plots for the PDO event year Normal 2013. The profiles plots include temperature, salinity, dissolved oxygen, and pH measurements for January, April, July, and November of 2013.

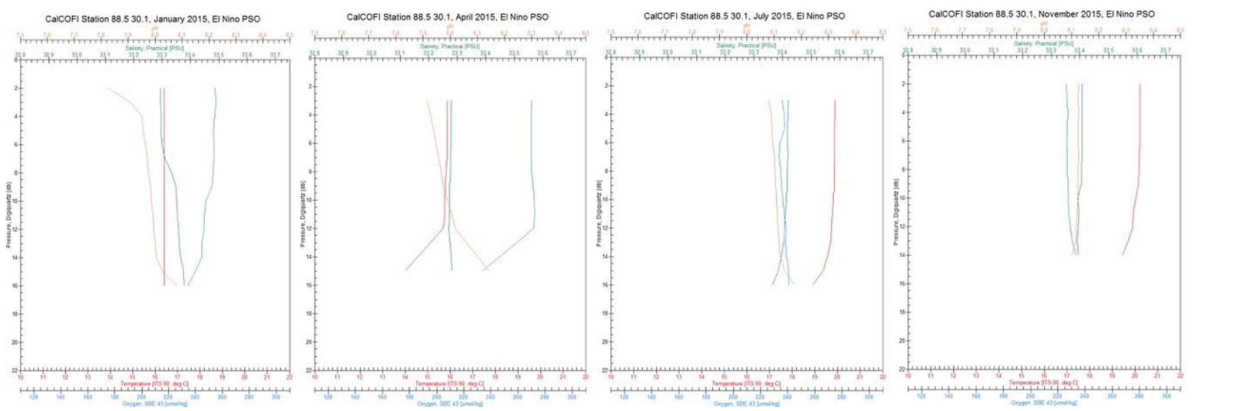


Figure 10. Region M Station ID 88.5 30.1 CalCOFI seasonal CTD profile plots for the PDO event year El Niño 2015. The profiles plots include temperature, salinity, dissolved oxygen, and pH measurements for January, April, July, and November of 2015.

Interpolated layers were also developed from CalCOFI datasets to visualize transport at various depths around the CSR site. Temperature, salinity, and nutrient data was gridded at surface, 25 < z < 50m (approximate DCM), & 150 < z < 200m. Summer minimum nutrient datasets were developed for surface, DCM, and 200m depth averages from CalCOFI datasets.

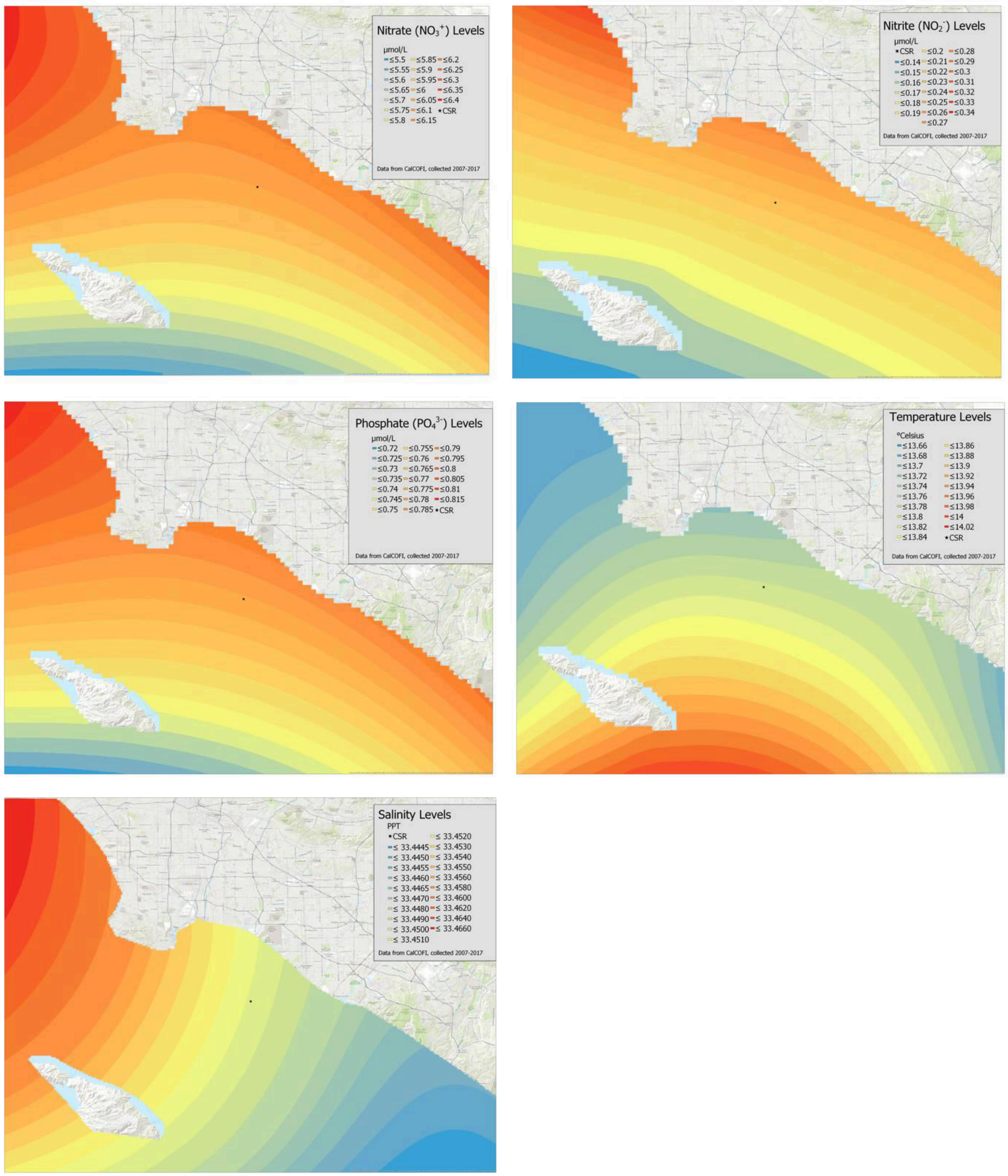


Figure 11. CalCOFI seasonal averaged 20-50m (approximate DCM) depth data for the years 2000-2017. From top left to bottom left nitrate, nitrite, phosphate, temperature and salinity.

San Pedro shelf North (SPN) and South (SPS) stations (Figure 11) of CDIP provided visualization of wave data adjacent to the CSR location.

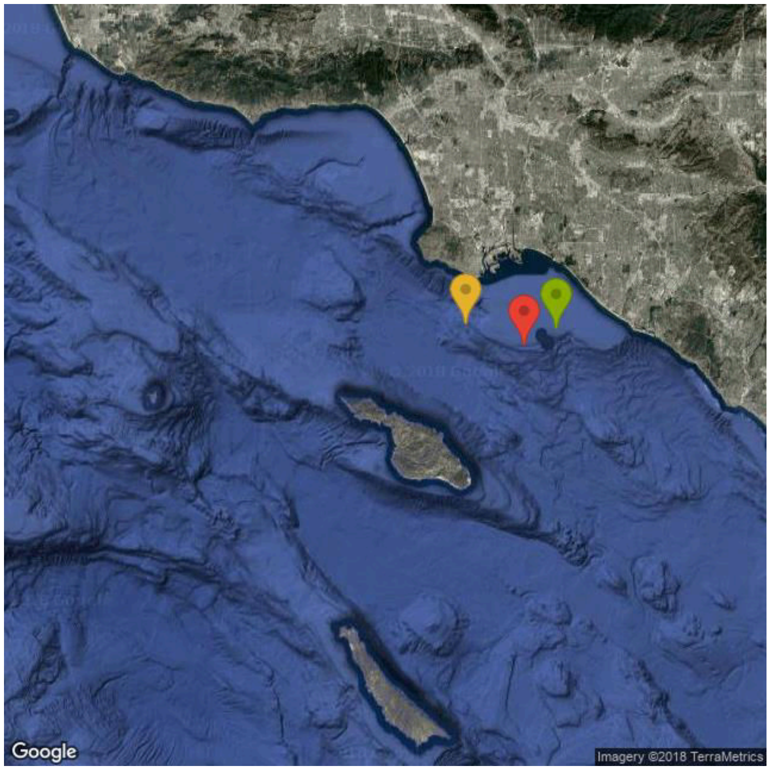
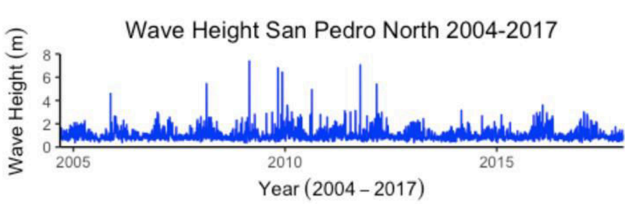
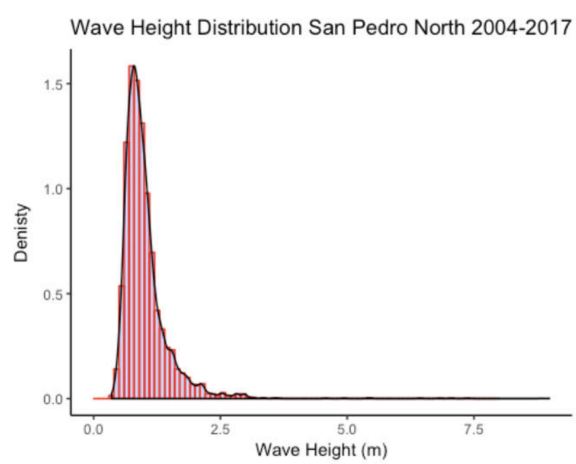


Figure 12. Two CDIP stations (SPN & SPS) were selected adjacent the CSR location. The northern station seen in yellow, the southern station in red and the CSR location in green.

The San Pedro North (SPN), CA CDIP station (46222) is located 33.618 N 118.317 W (33°37’4" N 118°19’0" W) and operated by Scripps Institution of Oceanography (SIO) (Figure 13). The data was acquired from: http://www.ndbc.noaa.gov/station_history.php?station=46222

SIO has been collected from 08/09/2004 - 12/31/2017.





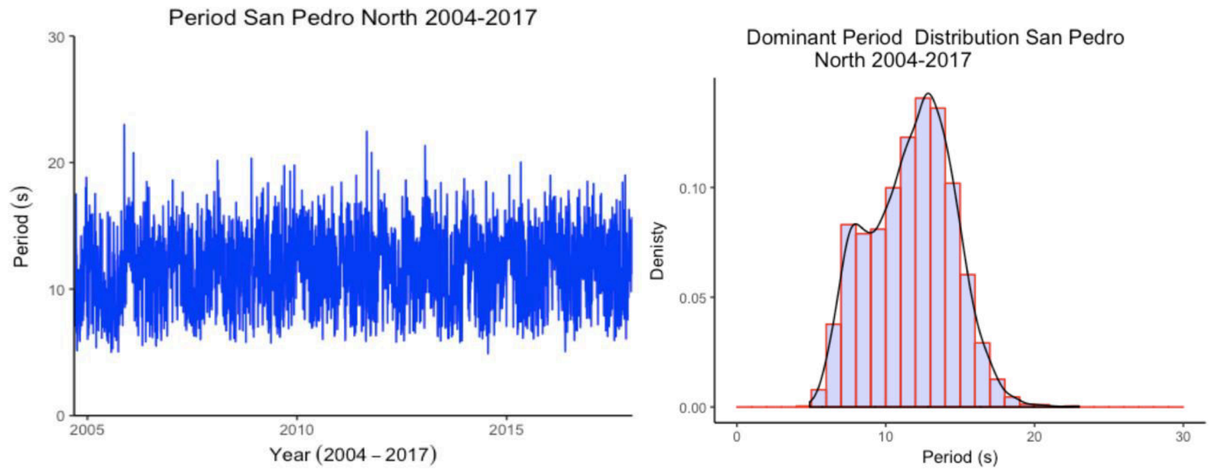
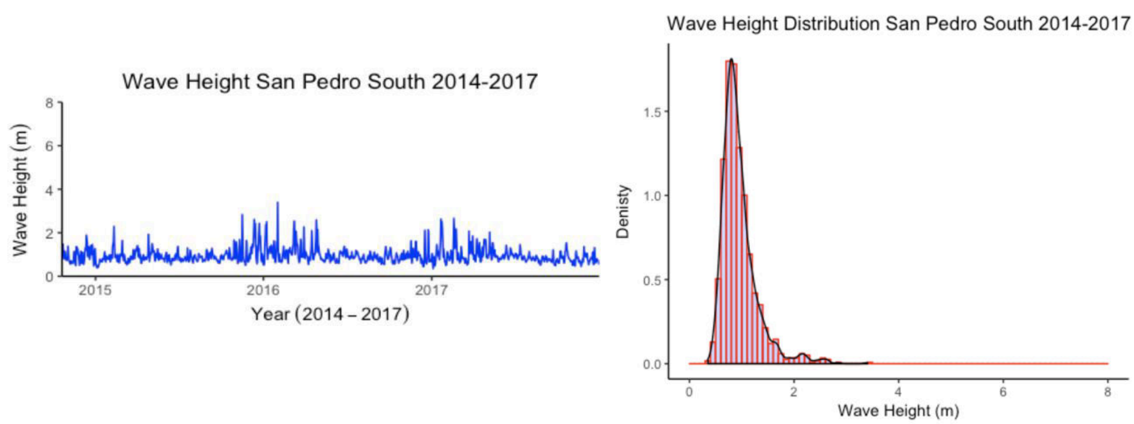
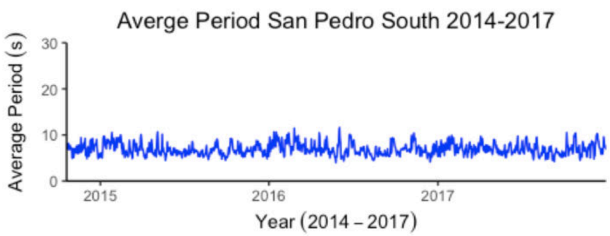


Figure 13. The SPN Shelf station was selected for the adjacent location with CSR. From left to right top to bottom SPN station wave height, wave height distribution, average period, and dominant period distribution for operational years 2014-2017.

The San Pedro South (SPS), CA CDIP station (46253) is located 33.576 N 118.181 W (33°34’33" N 118°10’53" W) and operated by SIO (Figure 14). The data was acquired from: http://www.ndbc.noaa.gov/station_history.php?station=46253. SIO only recently began collection of this buoy site from 10/20/2014 - 12/31/2017.





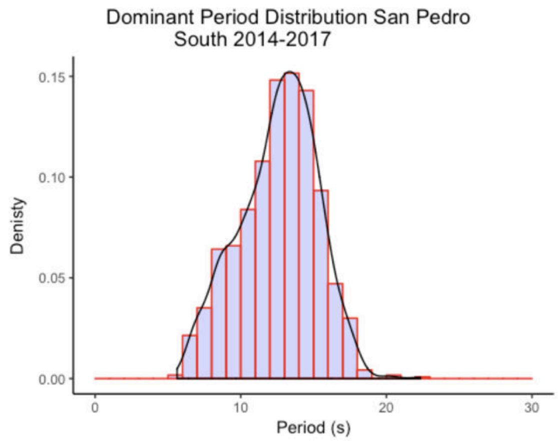


Figure 14. The SPS Shelf station was selected for the adjacent location with CSR. From left to right top to bottom SPS station wave height, wave height distribution, average period, and dominant period distribution for operational years 2014-2017.

To complete the analysis of the environmental conditions at CSR several other factors need to be analyzed. Light attenuation or radiation profiles and extreme weather/climate change predictions must be made. Light profile data will be collected from the NOMAD buoy, NOAA KdPAR, and CalCOFI profile data. Extreme weather input will come from a non-comprehensive weather history table compilation of recorded Southern California storms dating back to the late 1700s. The History of Significant Weather Events in Southern California, organized by weather type, will be used similarly to the NCEIs storm watch data events for a more comprehensive analysis of storm weather and extreme events conditions around CSR. Storm events will be tracked through identification of extreme weather event time-dates, observed trends, and collected cross referenced wind wave data from collocated buoys. Additional global climate models may be used to predict the influences of climate change on event extremity to ensure the kelp growing rig can withstand upcoming conditions.

2.2.2. Survey and Map Suitable Areas for Large Scale Deployment (Task. 2.2)

Task 2.2 is the survey and mapping of suitable areas (T2.2) for large scale deployment of macroalgae cultivation systems within the U.S. EEZ. T2.2 is comprised of two subtasks, the environmental analysis and fuzzy logic linear overlay and the identified social and marine infrastructural constraint of development regions. The social and marine infrastructure constraint development analysis will utilize certain binary boundary condition constraints based on existing laws, hazards, and infrastructure that make development within identified areas infeasible. The current status of constraint development for our team includes the EEZ, suitable depths (20-200m), limited coastal infrastructure (anchorage areas, danger zones and restricted areas, and artificial reefs), and habitats & areas of particular concern (HAPCs). Further development of the constraint layers will incorporate marine reserves, sensitive habitats, existing mineral, oil and gas infrastructure, densely navigated waterways, and obstructions. The environmental analysis is comparable to T2.1 analysis. However, for T2.2 the fuzzy logic linear overlay will consist of function-specific membership for temperature, nitrate, and phosphate data on seasonal and top-down depth analysis utilizing highest resolution global EMU and WOA datasets. Research continues into radiation (KdPAR), current and phosphate max/min metrics, and potential uses/capabilities of fuzzy overlay. A comparison of interpolations from CalCOFI and NOAA World Ocean Atlas (WOA) data will be completed to determine the optimal interpolation level. Profile data will be created from EMU datasets to describe the nutricline and the vertical and horizontal distances from potential sites to deploy the artificial upwelling system. Current maximum data from HYCOM + NCODA will be analyzed to determine the economic infeasibility of artificial upwelling within areas of currents above ~40 cm/sec.

Task 2.2 has two differentiable subtasks associated within its development. The environmental analysis and fuzzy logic linear overlay will be embedded within the identified social and marine infrastructural constraint development mask. The social and marine infrastructural constraint (SMIC) development analysis will utilize certain boundary conditional constraints based on existing laws and infrastructure that make development within identified areas infeasible. Both subsections will incorporate weighted feedback for further suitability analysis.

2.2.2.1. Environmental Raster Development and Fuzzy Logic Linear Overlay

The differential between Ecological Marine Units (EMU) data points and NOAA World Ocean Atlas (WOA) data was determined to be a gain in spatial resolution for loss in temporal resolution. EMU data is modeled from WOA data in most cases from 1 arc degree monthly resolution to an annualized ¼ degree resolution. Both datasets are being used.

Fifteen rasters were created from five groups of usable feature layers in NOAA dataset. All the NOAA World Ocean Atlas data (yearly, seasonal, and monthly) was downloaded in .csv format since there was some difficulty extracting the shapefiles. Nutrient data was plotted at depths of 5m, 10m, 15m, 20m, 25m, 50m, 150m, and 500m.

Several unsuccessful attempts were made to convert the web layers to rasters for the suitability maps. The JSON files were also unusable because they were not in GeoJSON format and therefore could not be mapped. The full layers with giant extents were provided by NOAA, which could not be converted into a usable format. Data from the GLORIA Substrate was determined to be inadequate for the project's purposes due to most of the data lying outside the domain of interest. Argo float research data was also ignored due to the data being difficult to grid and less consistent than the ERDDAP data found on 6/29. The nitrate data from WOA did not compare directly with the Aquamapper layers data, but this was due to a symbolic issue so the data from WOA is being used.

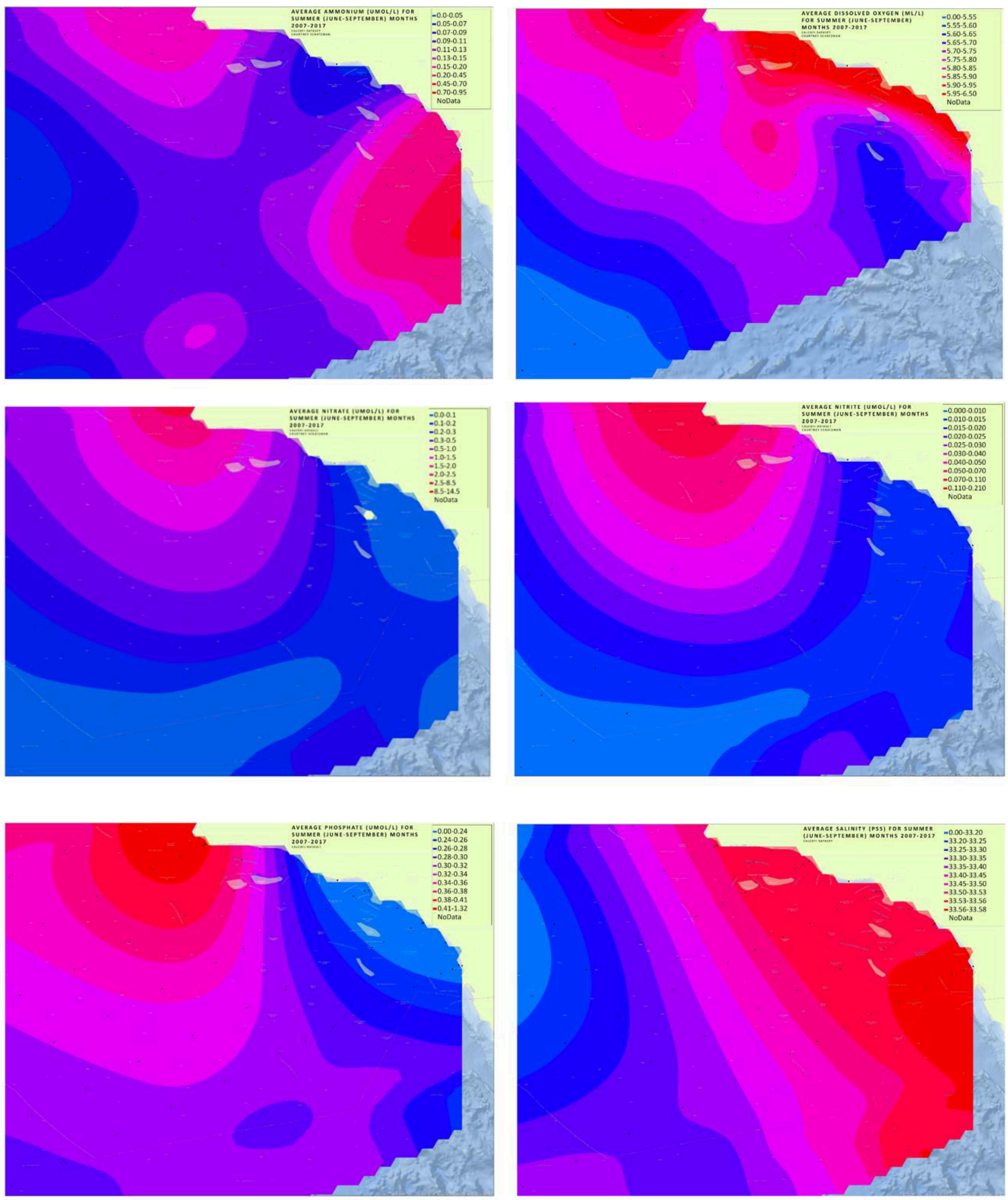
The EMU package was downloaded and the nitrate data was processed into csv and raster at ¼ degree resolution. NOAA geodatabase data for Southern California was compared to World Ocean Atlas (WOA) data. WOA data was downloaded directly for temperature, nitrate, phosphate, and salinity as the rasters provided by NOAA had all depths averaged for each parameter. For our purposes it's important to only examine the top 20 meters as that is the area where the macrocystis will be growing. R scripts were written to create dataframes with seasonal averages of the top 20 meters of nitrate, phosphate, and temperature. These new dataframes were then converted to rasters in R and loaded into ArcGIS for kernel interpolation *(Figure 16)*. This process will be done at a monthly scale as well.

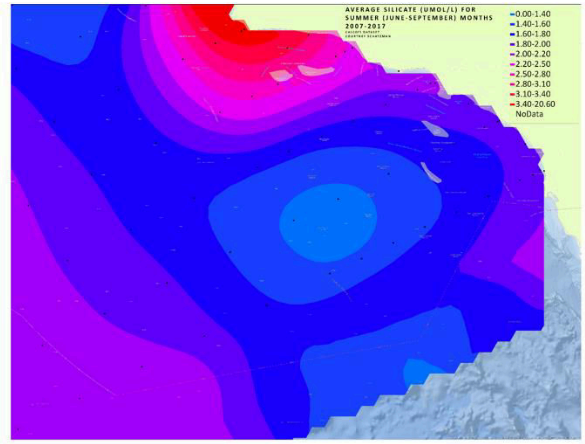
Layer types were determined and WOA temperature data was added into NOAA gdb file. Diffuse attenuation data was downloaded and converted from netcdf to raster. All relevant ERDDAP data was downloaded and organized.

The Fuzzy Overlay tool was determined to be most suitable for binary constraint layering. The determination to perform a weighted overlay after the fuzzy overlays was made.

A response email from NOAA brought the viability of interpolation into question. NOAA stated that the data they had sent was already interpolated but had previously stated that it was all observation based and empirically derived. As a result, they strongly advised against further interpolation as that would exponentially compound error. With the current resolution nutrient data of one arc degree, there would be approximately 100 hectares in each non-interpolated pixel, rendering the data unsuitable if not interpolated as these regions would be assumed to be homogenous. This response necessitated the review of all data NOAA had sent to ensure that no other completed work had been done incorrectly. During a follow-up phone call with NOAA, they agreed that the data were indeed empirical as we had thought, and their previous email contained incorrect assertions.

Interpolated layers were developed from CalCOFI datasets to visualize transport at various depths around the Southern California. Temperature, salinity, and nutrient data was gridded at surface, 150 < z < 200m & 25 < z < 50m. Summer minimum nutrient datasets were developed for surface, DCM, & 200m depth averages from CalCOFI datasets (Figure 15).





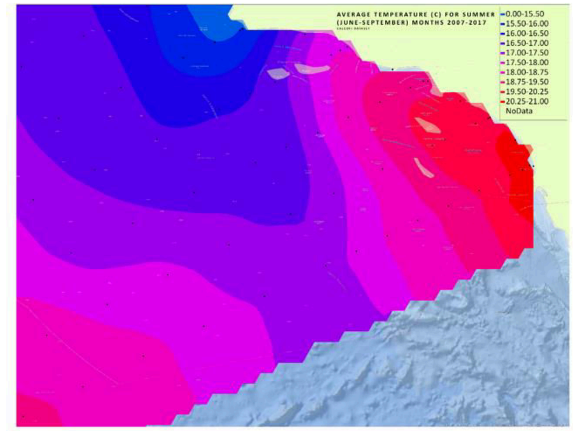
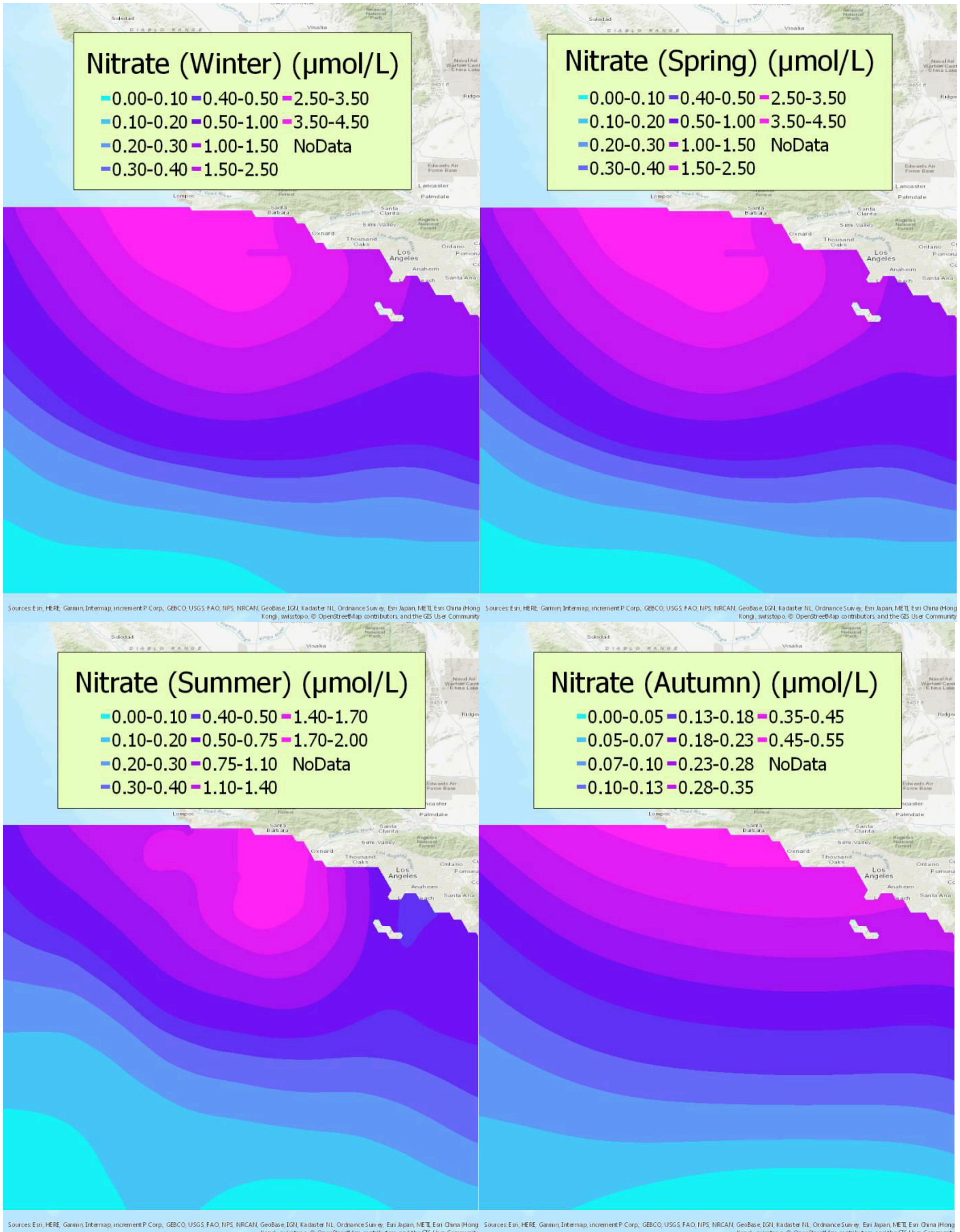
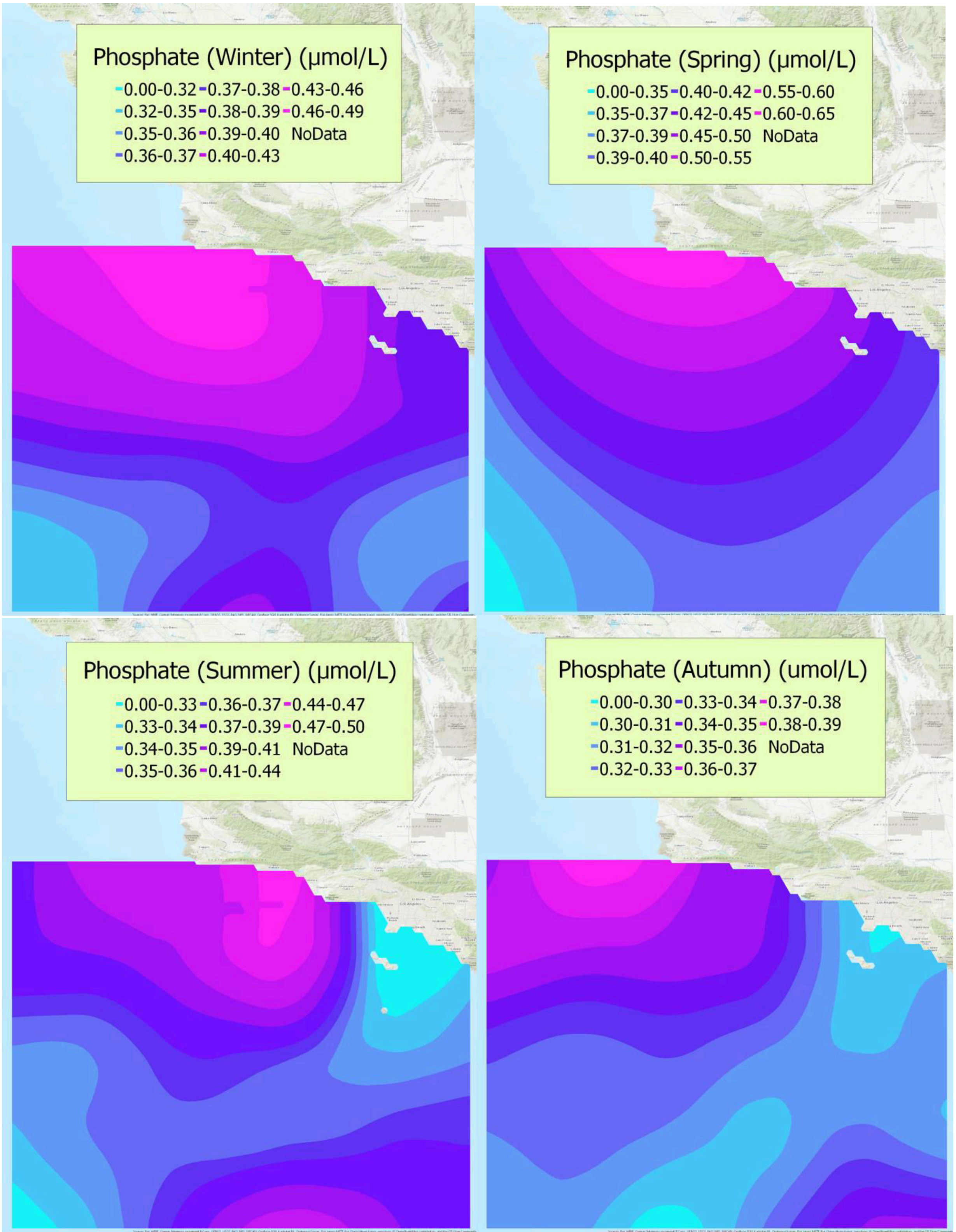


Figure 15. Summer Surface SoCal CalCOFI preliminary interpolation model to apply later to other regions.


Nitrate (Winter) (µmol/L)
0.00-0.10
0.10-0.20
0.20-0.30
0.30-0.40
0.40-0.50
0.50-1.00
1.00-1.50
1.50-2.50
2.50-3.50
3.50-4.50
NoData
Nitrate (Spring) (µmol/L)
0.00-0.10
0.10-0.20
0.20-0.30
0.30-0.40
0.40-0.50
0.50-1.00
1.00-1.50
1.50-2.50
2.50-3.50
3.50-4.50
NoData
Nitrate (Summer) (µmol/L)
0.00-0.10
0.10-0.20
0.20-0.30
0.30-0.40
0.40-0.50
0.50-0.75
0.75-1.10
1.10-1.40
1.40-1.70
1.70-2.00
NoData
Nitrate (Autumn) (µmol/L)
0.00-0.05
0.05-0.07
0.07-0.10
0.10-0.13
0.13-0.18
0.18-0.23
0.23-0.28
0.28-0.35
0.35-0.45
0.45-0.55
NoData


Phosphate (Winter) (μmol/L)
0.00-0.32
0.32-0.35
0.35-0.36
0.36-0.37
0.37-0.38
0.38-0.39
0.39-0.40
0.40-0.43
0.43-0.46
0.46-0.49
NoData
Phosphate (Spring) (μmol/L)
0.00-0.35
0.35-0.37
0.37-0.39
0.39-0.40
0.40-0.42
0.42-0.45
0.45-0.50
0.50-0.55
0.55-0.60
0.60-0.65
NoData
Phosphate (Summer) (μmol/L)
0.00-0.33
0.33-0.34
0.34-0.35
0.35-0.36
0.36-0.37
0.37-0.39
0.39-0.41
0.41-0.44
0.44-0.47
0.47-0.50
NoData
Phosphate (Autumn) (umol/L)
0.00-0.30
0.30-0.31
0.31-0.32
0.32-0.33
0.33-0.34
0.34-0.35
0.35-0.36
0.36-0.37
0.37-0.38
0.38-0.39
NoData

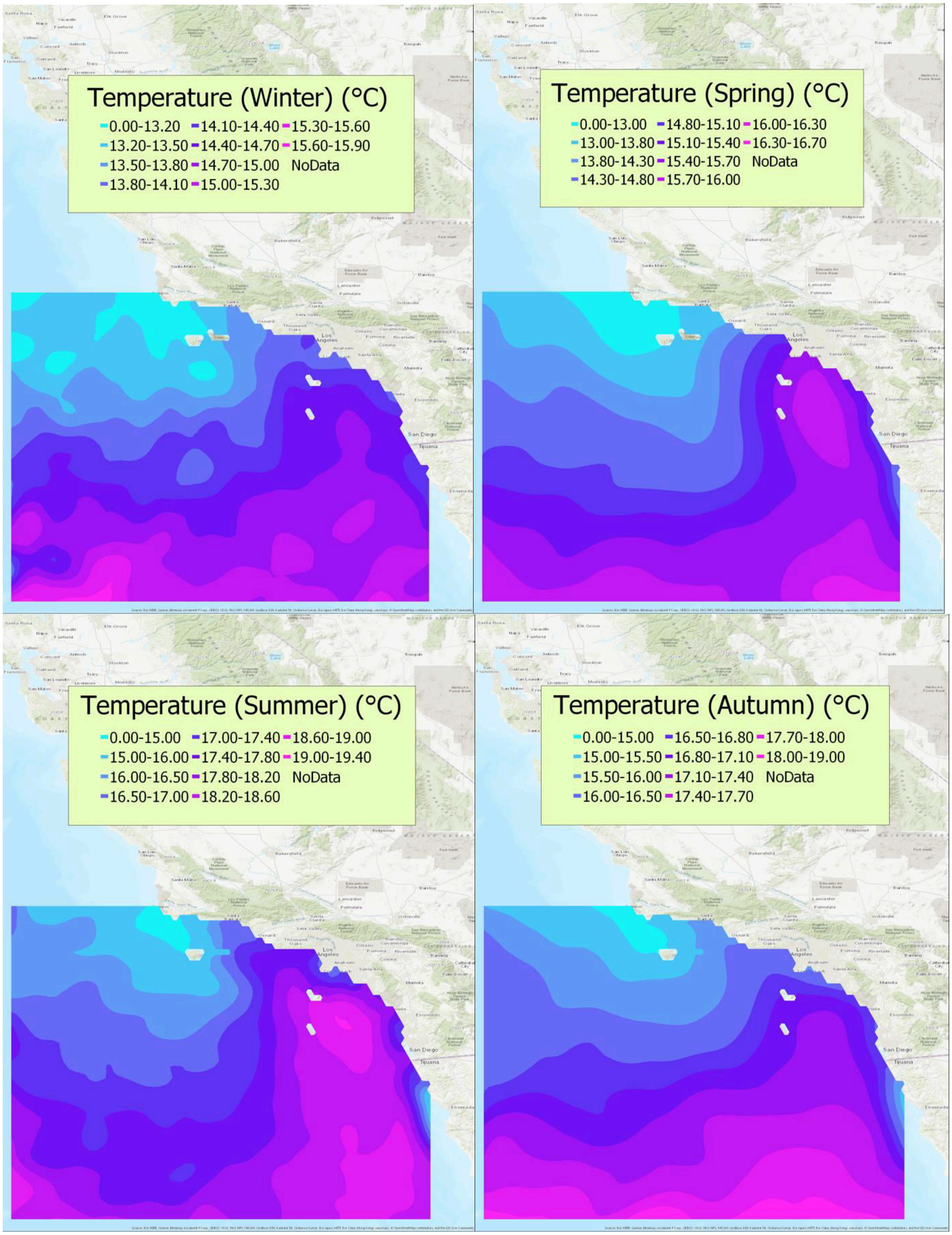


Figure 16. NOAA World Ocean Atlas seasonal interpolations using the averaged top 20 meters for nitrate, phosphate, and temperature.

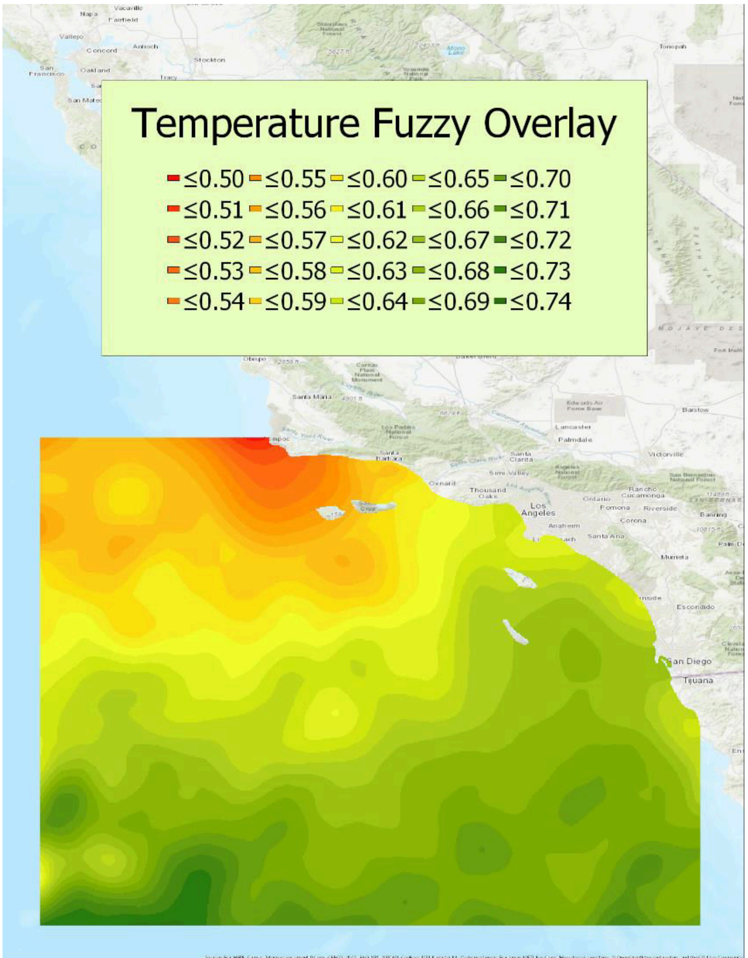


Figure 17. NOAA World Ocean Atlas temperature suitability map using Fuzzy Linear membership of interpolated seasonal data and Fuzzy "AND" overlay. Values represent relative suitability (0.0 = definitely unsuitable, 1.0 = definitely suitable).

The fuzzy overlay will consist of linear membership for temperature and fuzzy large for nitrate and phosphate data. Research continues into light (kd), current and phosphate max/min metrics, and potential uses/capabilities of fuzzy overlay. KdPAR (photosynthetically active radiation) data has just been provided by NOAA. Fuzzy layering for temperature (Figure 17), nitrate, and phosphate will be performed as well. Parameters recently researched will be added and overlaid.

Given the resolution of the WOA data at one arc degree for nutrients, a comparison of interpolations from CalCOFI and NOAA WOA data will be completed to determine the optimal interpolation level. The idea behind this is to do a gut check across the kernel interpolation with the CalCOFI and WOA given that we know the high-quality and resolution of CalCOFI datasets. We could for example randomly select 50 cells from both and fit a regression to it to see how close we are to a 1:1 relationship, which would provide some additional insight. Nitrate versus depth profiles will be created from EMU data extracted to csv to identify the depth of the nutricline and the vertical and horizontal distances from potential sites to deploy the artificial upwelling system. Current maximum data from HYCOM + NCODA will be analyzed to determine the economic feasibility of artificial upwelling in areas with currents above ~40 cm/sec.

2.2.2.2. Social and Marine Infrastructural Constraint (SMIC) Development Analysis

NOAA supplied geodatabase files for our preliminary SMIC. The SMIC model currently being developed (*fig 3.2.4*) for the Southern California region will be applied to the other regions of interest.

MARINER developmental mandates are restricted to federal waters. The initial SMIC is zoned between 3-mile state waters boundary and the 200-mile federal EEZ. Further bounding in this area is constrained between the maximum feasible farm infrastructure depth (200 meters) and the appropriate growth depth for kelp (20 meters). The federal waters region was used as defined along with suitable depths, which were selected using Gentry et al 2017 global depth raster to highlight the intersection of suitable areas.

Existing coastal infrastructure layers were then examined as areas to omit. Anchorage areas, danger zone and restricted areas were removed from developable areas as is. A 50-meter buffer was created around artificial reefs within the developable depths of our map and erased from suitable areas.

Aspects of habitats areas of particular concern (HAPC) were evaluated for ecological suitability and for consideration of ground fish habitat. HAPC tables include specific conditions and habitats for those species (HAPC_Siten) columns. The documentation for conditions can be found: http://www.pcouncil.org/wp-content/uploads/2017/03/GF_FMP_FinalThruA27-Aug2016.pdf.

A majority of the HAPCs (estuaries & seagrass) were found within 3-mi state waters and therefore of little concern. Rocky substrate cannot be anchored to thus rocky reefs were removed from the development areas. Existing Kelp beds were deemed acceptable for development, however like seagrass and estuaries, the majority of existing kelp beds were found in 3-mi state waters. Based on the Pacific Coast Groundfish Fishery Management Plan (PCGFMP) further consideration for HAPCs will be used to evaluate ground fish habitats. NOAA's position does not place additional restrictions on area of concern however they support preservation efforts. Therefore, a weighting schema of "less than ideal" will be applied to ground fish habitats to reflect the PCGFMP non-fishing habitat needs noted in sections 7.1, 7.2 and Appendix D.

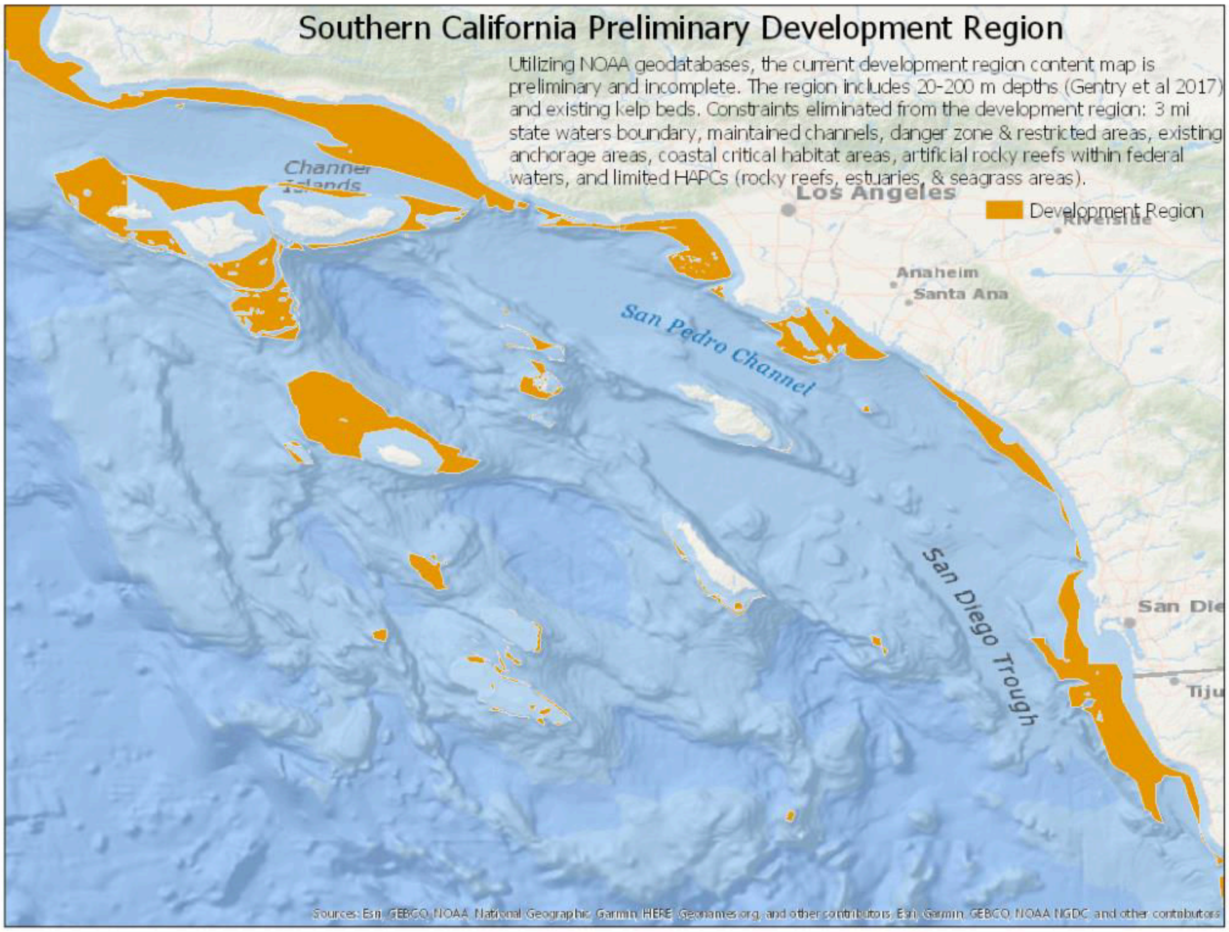


Figure 18. Preliminary SMIC Map which incorporates federal waters, suitable depths, coastal infrastructure (anchorage areas, danger zones & restricted areas, and artificial reefs), and aspects of HAPCs.

To complete the SMIC development marine reserves, sensitive habitats, existing mineral, oil & gas infrastructure, densely navigated waterways, and obstructions need to be evaluated and added to the development model. Additional constraints will be assessed from the following geodatabase layers:

- Marine Reserves, cetacean habitats, fishing habitats, and National Wildlife Refuge (NWR) systems.
- Submarine sea cables (trial buffer zones at 50m & 500m)
- Existing oil and gas leases, oil drilling platform areas (1km diameter or 500m radial buffer), oil and gas pipelines (500m buffer).
- Acoustic test zones, and prohibited areas
- Pilot boarding areas, vessel traffic and lanes (vessel trafficked areas less 5% Gentry et al 2017, Halpern et al 2015)
- Wrecks and obstructions

2.2.3. Engineering Design and Deployment Plan of a Proven Sustainable Nutrient Supply System (Task 2.3)

For task 2.3, the Climate Foundation team has been assessing and testing materials upwelling technology and renewable power sources for the anticipated nutrient upwelling system. Modeling and calculating physical and mechanical forces of early versions of the anticipated upwelling system was conducted. Additionally, the Climate Foundation is currently planning to test a nutrient supply system in Eastern Indonesia, which will have similar features as the nutrient supply system anticipated for MacroSystems. This planning process and testing will help to avoid risks associated with the design and anticipated testing of the MacroSystem nutrient upwelling system.

During the technical workshop in the Faroe Islands, Brian von Herzen presented the engineering design and deployment of the nutrient supply system of Climate Foundation. The team discussed how best to integrate it in the design of the rig under the expected environmental conditions and given Ocean Rainforest's experience with the MACR cultivation system. Models of the behavior of kelp growth and waves' effects on the rig and the nutrient supply system were discussed.

2.2.3.1. System Engineering of Structure Interfaces

The team focused on compiling the necessary background knowledge to finalize the design and move forward with prototyping.

2.2.4. Material Specification and Research

The Climate Foundation conducted material research on different HDPE pipes, pipe dimensions and pressure ratings, flexible pipes, check valves and steel cables. Available options on pipe joining were discussed. After the chosen materials passed the necessary relevant physical and mechanical requirements, the selection of possible materials was further reduced to satisfy economic criteria. As a next step, a detailed list of all required materials will be produced.

2.2.5. Upwelling Technologies

The Climate Foundation summarized and assessed options to design several upwelling technologies. Using inertial forces, there could be a system that consists of a pipe attached to a buoy that is oscillating up and down due to the displacement of the buoy with the surface waves. At the bottom of the pipe is a one-way valve (check valve). The wave motion causes the buoy/pipe system to rise and fall.

The wave-driven pump uses wave energy to produce periodic pumping to the top of the pipe that lifts the water vertically to the seaweed array. The air-lift pump is based on the injection of air bubbles at partial depth in a pipe to induce upwelling by introducing a hydrostatic head due to the upward flow of the aerated water. Some research into using a wave-driven buoy to provide compressed air, including a theoretical model and lab-scale testing, was completed by Fan (2013)[1].

The salt fountain system uses a pipe that is inserted vertically into an area with both a temperature and salinity gradient. Half the pipe has warmer, salty water moving down the pipe, with cooler fresher water moving up the pipe. The pipe allows thermal diffusion, but no exchange of salt, so heat will be exchanged

[1] Fan,W. J. Chen, Y. Pan, H. Huang. C. Chen & Y. Chen (2013) Experimental study on the performance of an air-lift pump for artificial upwelling. *Ocean Engineering*, 59, 47-57

with the surrounding water. This effect causes the cooler, lower salinity water to warm and rise up the pipe, as the saltier water descends Deep seawater must be drawn up using a pump or other mechanism to initially fill the pipe with deep seawater and initiate the salt fountain. Similarly, warm salty water is pumped down the pipe to set up the initial conditions.

2.2.6. Modeling of an Upwelling System

The team also worked on modeling the flow of a pipe upwelling subsystem with input parameters including pipe length, diameter, and buoy displacement given initial starting conditions of random waves typical to the deployment site. The team also created a MATLAB code for calculating the bending moment and the necessary buoy volume for a small 3m scale pipe, which can be easily modified to calculate full scale. The code also calculates drag forces from the pipe.

Mean nitrate has an increasingly positive effect over 5 μmol L-1, but average values are below that in 20m depths. At -150m, values of 25 μmol L-1 NO3 can be found. A vertical pipe can pump up nutrient rich water with renewable energy (wave power and solar energy). The current system involves flexible perforated diffuser pipes to provide nutrient rich deep water to the seaweed. Currently we are working on fluid diffusion calculations to elucidate macro nutrient diffusion of the anticipated MacroSystem rig design.

2.2.7. Strength Tests of the Deep Water Pipe

We develop a low-tech joining system that enables us to connect pipelines exceeding 1km in length and that pipeline could be extended further in future implementation technique is scalable to several km in length.

To ensure that the 1.2km long conjoined pipe is able to withstand pressure, tension and elongation to the same extent as a whole pipe, we conducted strength tests in Woods Hole in May 2018. 200 cycles of stretching and contracting showed that the pipe returned to same length within 1-2cm. Figure 19 and 20 show results of undertaken tests. Pressure tests suggested that the spliced pipe is stronger than the original pipe material.

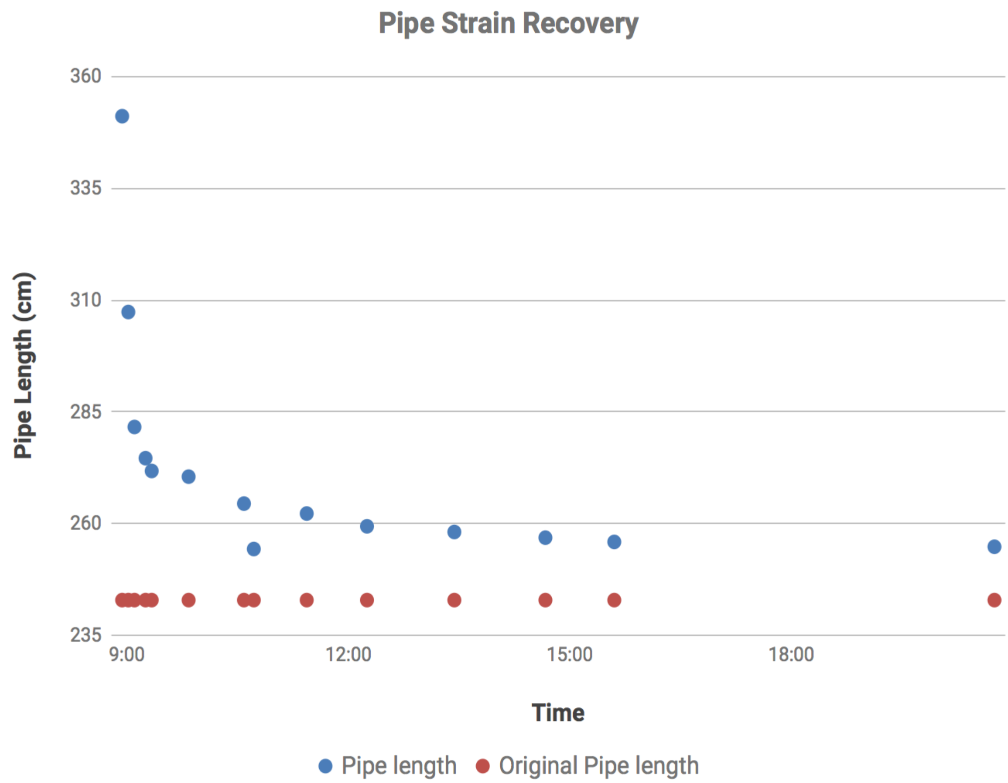


Figure 19: Pipe Strain Recovery

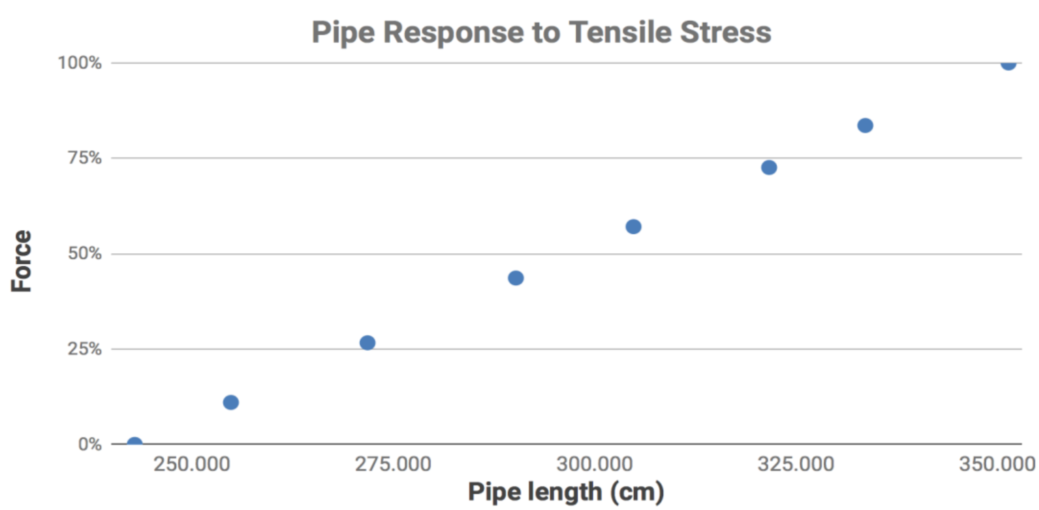


Figure 20: Pipe Response to Tensile Stress

2.2.7.1. Eastern Indonesia test Deployment

With Australian funding, the Climate Foundation is building and testing a small-scale nutrient upwelling system in eastern Indonesia to demonstrate and validate its effectiveness and potential for large-scale deployment in US EEZ waters. A test system will be fabricated, assembled and installed on-site. System operators will be trained, full system documentation will be handed over, and local seaweed farmers will be involved. We will compare in a trough based system the growth of specific economic algae's with water from the surface and water from deep and do a comparison on the growth differential. Since we are using red macroalgae species for our 2018 growth tests, the results may vary for *Macrocystis* off the coast of California. While we are getting into design specification of the nutrient upwelling system for the MacroSystem, this planning process and testing of the nutrient upwelling system in eastern Indonesia is helping us debug the design at early stages.

2.2.8. Design of the Solar Pumping System

For the MacroSystem nutrient supply system we anticipate a combination of wave energy and solar energy to provide nutrient rich deep water to the cultivated *Macrocystis.* Currently, we are developing a cost- effective solar pumping system for our test deployment in Indonesia. Specifications of this design can be easily adapted to the MacroSystem design in a next step.

In eastern Indonesia, a local boat type used by fishermen called "Jukung" will be upgraded to accommodate up to 10 solar panels on a roof. The outriggers of the boat can be supported with floatation barrels and are arranged like two hulls of Catamarans. The Catamarans typically have less hull volume, higher displacement, and shallower draft than monohulls of comparable length. The two hulls combined also often have a smaller hydrodynamic resistance than opposed monohulls. The catamaran's wider stance on the water can reduce both heeling and wave-induced motion, when compared with a monohull, subsequently reducing ed wake. It is a geometry-stabilized craft, deriving its stability from its wide beam, rather than from a ballasted keel as with a monohull sailboat (Figures 21, 22, 23).

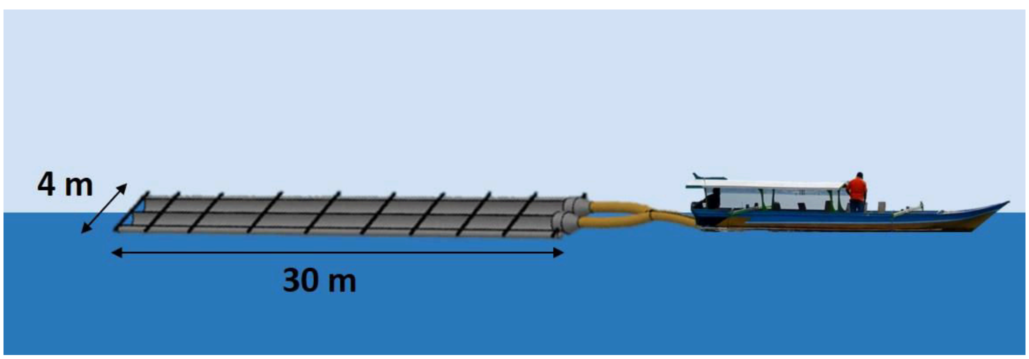


Figure 21: Schematic representation of the raft attached to a solar boat (solar panels boat). NB: proportions are not respected

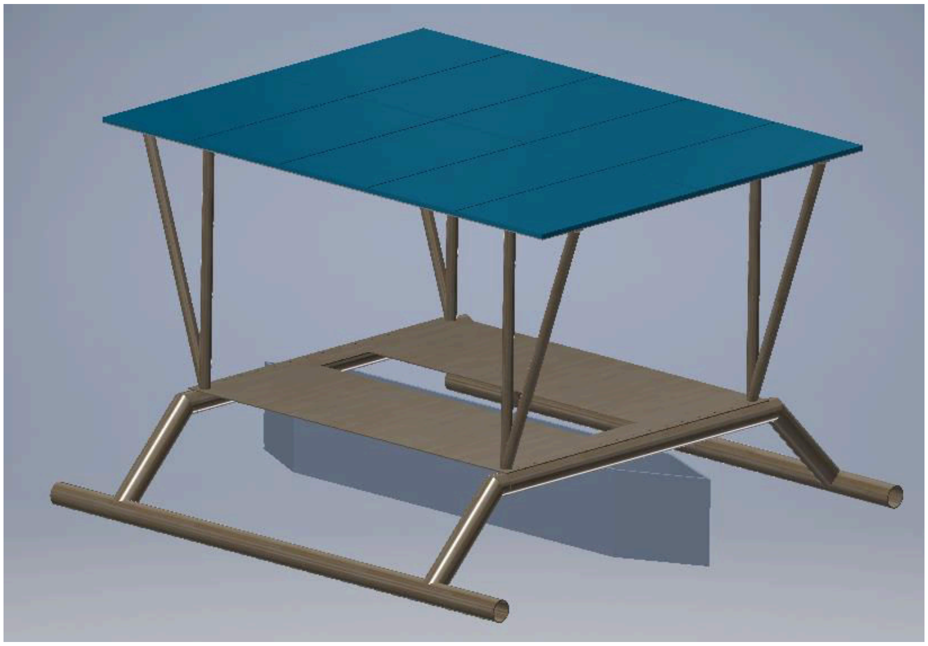


Figure 22: Orthogonal view of the solar roof

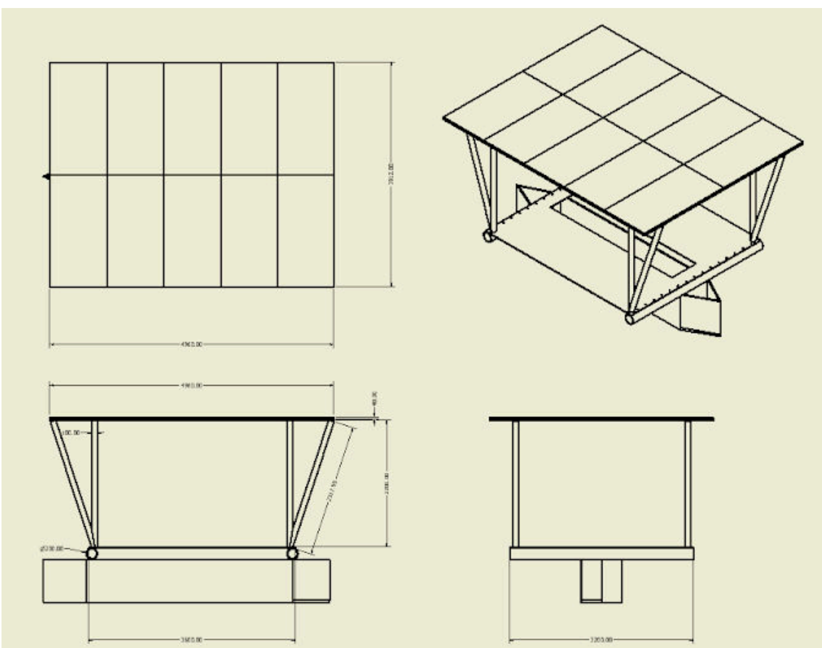


Figure 23: Drawing view of the solar roof

The solar pumping system consists of 10 pieces of 350W poly solar panel, 36V at a size of 1960mm, 990m, 40mm per piece. The DC solar pump is powered with 1000 Watt producing a maximum water heat of 40m and a water flow of 15 m^3/hr. The design also includes a water level sensor, a PV combiner box, PV cable, MC4 connector and mounting brackets. A schematic of the anticipated system can be seen in Figure 24.

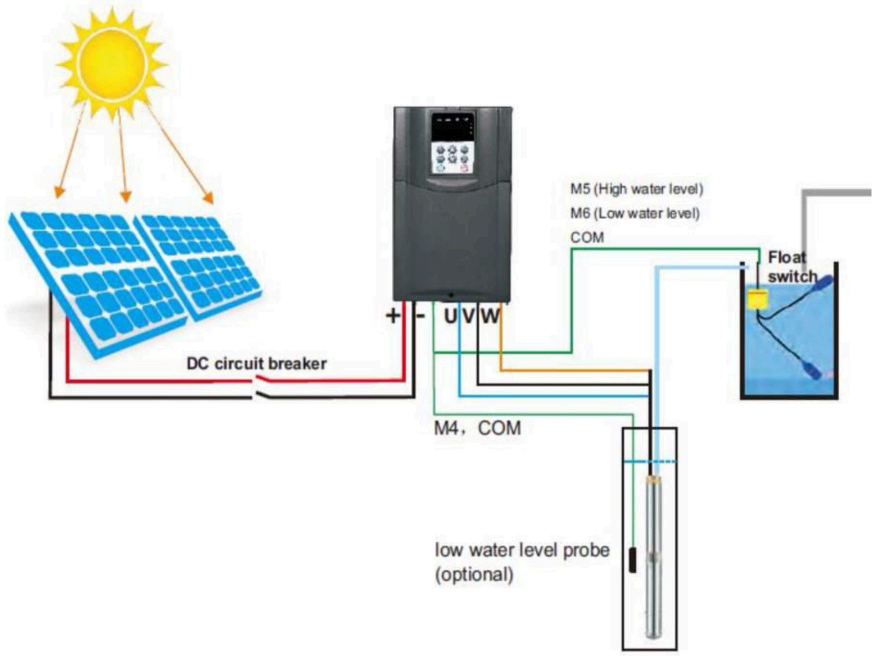


Figure 24: Bluesun Solar Energy Tech. solar pumping system

Since our setup in eastern Indonesia requires a significant amount of pumping power to ensure comparable test results, in different experimental setups, the number of solar panels will be significantly less for the MacroSystem design, especially considering the combination with wave-energy. For the MacroSystem design we are also working on the possibility of replacing the energy intense solar pumps with several solar propellers.

Detailed analysis of pilot location for testing the nutrient supply system in eastern Indonesia

The nutrient testing system will be anchored offshore at a distance of 1.70 km from shore and 20m below the water's surface. This location is particularly suitable as it can reach deep water at a 200m depth, by using a 900m long hose. The deep water can be easily accessed and pumped to the seaweed on the double trough.

The double trough, fixed on a solar house boat, will be connected to a deep-water hose that will pump the water from 200 m depth (Figure 25).

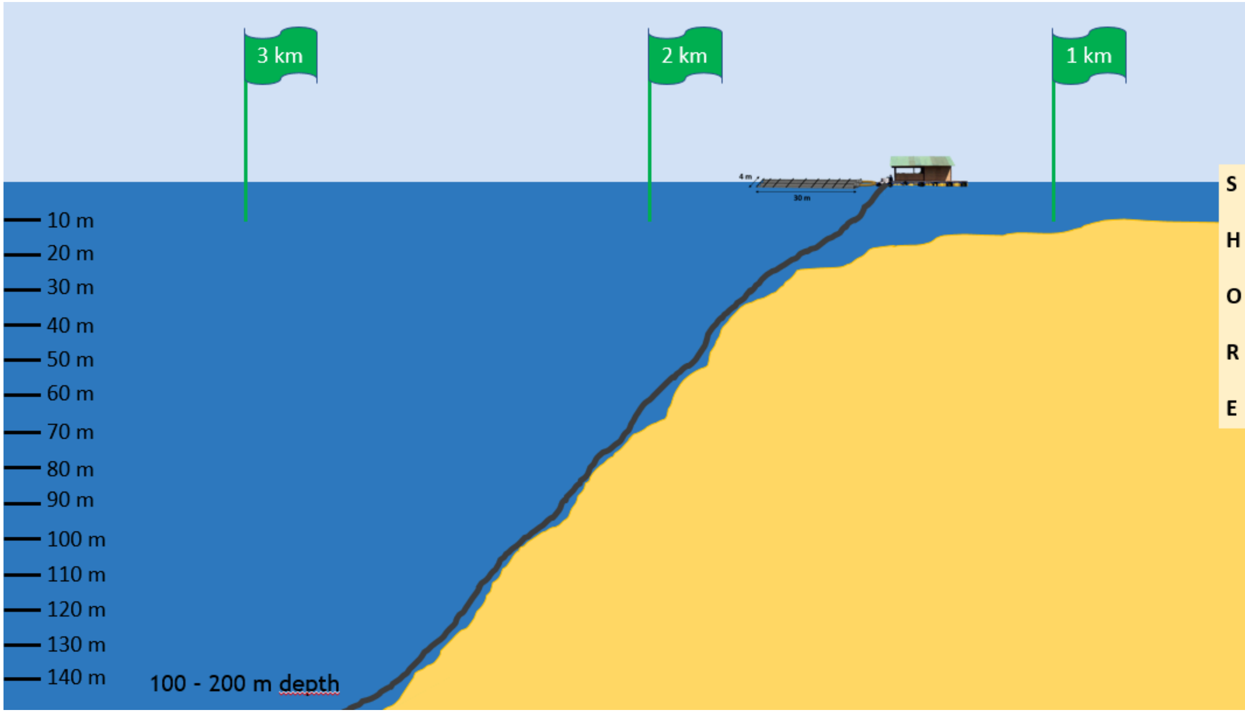


Figure 25: raft and solar boat location

The hose will be connected to a pump in order to pump the deep-water into the raft. The pump, on the raft floor or lower, if submerged, will be connected to solar panels deployed on the gazebo roof of the bamboo raft to supply the energy required by the pump.

2.2.9. Next steps

a. Detailed planning on how to integrate the anticipated nutrient upwelling system into the current MacroSystem design in the most cost effective way. Within this task a detailed list of all required materials will be produced.

b. Integrate the outcome of the fluid diffusion calculations and additional system modeling of the anticipated MacroSystem rig design.

c. Adapt the specifications of the design of the solar pumping system for the eastern Indonesian test deployment into the MacroSystem nutrient supply design.

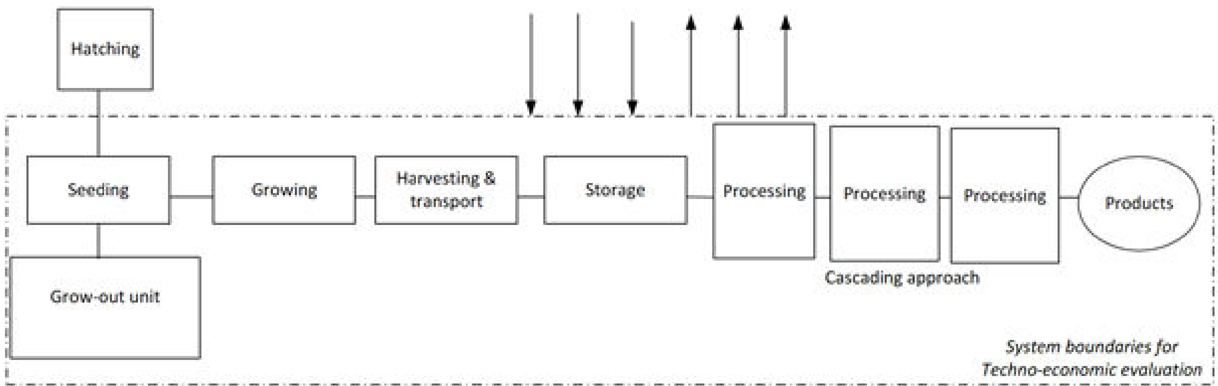
d. Create images and views of the anticipated nutrient supply system.

2.3.: Techno-Economic Models and Sustainability Assessments (Task 3)

The objective with task 3 is to demonstrate via techno-economic modeling macroalgae biomass production at a cost of ≤ $80/DMT of harvested biomass. The techno-economic assessment will investigate the technical and economic viability of the processes, and the environmental impacts of solutions together with an sustainability assessment will assess the environmental implications associated with the MacroSystems concept.

2.3.1. System Productivity Major Drivers (Task 3.1)

The diagram below offers a skeletal overview of critical drivers that play a significant role in the economic feasibility of offshore cultivation and harvest of *M. pyrifera*. As indicated by the bounding box, the capital costs associated with algal grow-out are included in the economic feasibility assessment. In addition the assessment will assess cost for different hatchery systems/scale, and include the cost as a unit cost/meter in the CAPEX of the cost of seaweed cultivation. Similarly, the TEA does not include the capital costs associated with processing following the pre-treatment of the algae into a storage stable condition.



2.3.2. Mass Energy Balances, Net Energy Returns (Task 3.2)

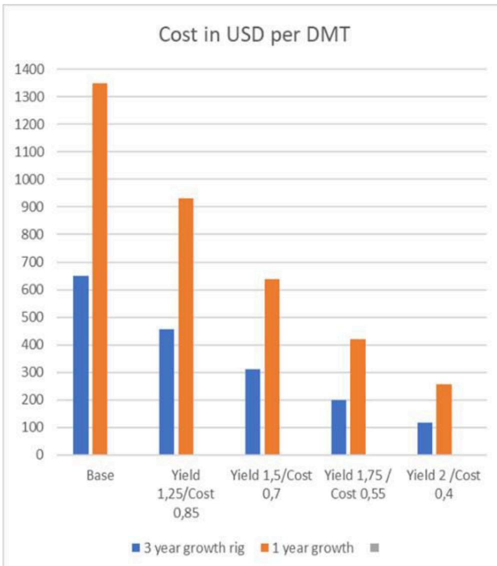
Energy consumption represents the broadest category in the TEA and takes into account the cost of seeding, harvesting, and processing *M. pyrifera*.

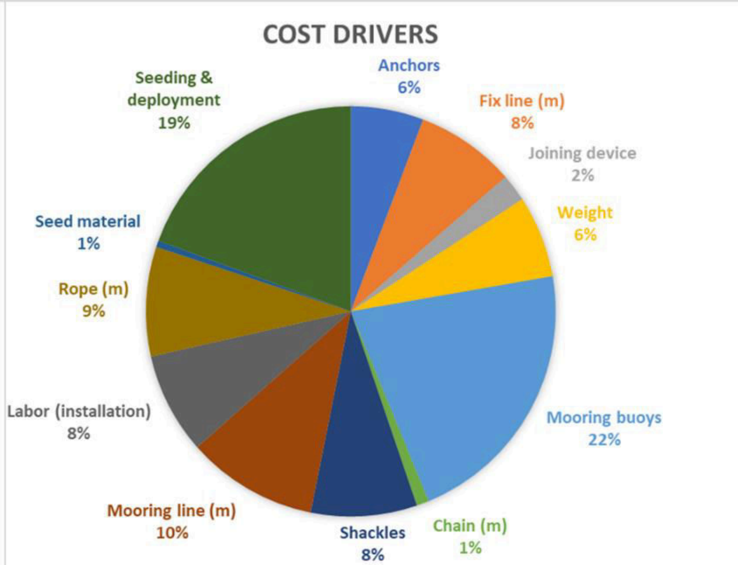
Although limited data exist as to the energy requirements necessary to cultivate and harvest *M. pyrifera*, some studies regarding the potential for co-production of biofuel from brown algae offers some indication as to what the input costs may be. In an economic model derived by Aaron Philippsen in 2010, the energy inputs for cultivation and harvesting of brown seaweeds include: sporeling electricity, sporeling heating fuel, boat fuel, drying system electricity, transport fuel, process fuel, and process electricity. The work has commenced during the 1st Quarter of the project to structure and collect information on mass energy balances.

2.3.3. TEA And Economic Viability Including Risk Assessment And Sensitivity (Task 3.3)

The task will evaluate the macroalgae feedstock and production methods (hatchery, cultivation, harvesting and pretreatment methods into a storage stable condition). Data from WP1 and WP2 will be used to define and design production trains. A conceptual process design will be developed with mass and energy balances and main dimensions of process equipment.

The economic feasibility of commercial-scale cultivation and harvest for *M. pyrifera* is principally dependent on a series of cost drivers, which is defined as a type of cost that is relatively large in comparison to the other costs of a similar nature. For the purposes of the MacroSystems initiative, the principle cost drivers can be characterized as the CAPEX, OPEX, yield, and energy consumption associated with seeding, harvesting, and processing macroalgae. Within each of these categories, specific line items will be considered cost drivers so as to allow for a more precise evaluation of the economic feasibility of cultivation and harvesting.





An example of cost-driver currently identified is in the diagram above – however the TEA work has so far identified 15 parameter with in total 50 variables that we will assess in the 2nd quarter of the project and enable a conclusion of the most promising cultivation configuration in terms of hatchery, rig and harvesting design in terms of technical feasibility and economic performance. These configurations will be de-risked in a Phase 2 test.

Further details about the TEA methodology are in Appendix C. Furthermore, a Microsoft Excel based TEA model is under development enabling the necessary calculations and analysis.

Although the opportunities and challenges associated with large-scale cultivation of *M. pyrifera* remain fairly abstract, the strategy for the techno-economic assessment proposed herein is intended to offer a foundational framework for future development of the macroalgae industry. By taking into account the general economic formulas associated the cost of cultivation and harvesting, along with general assumptions regarding the MacroSystems pilot site, one is able to evaluate the economic feasibility of commercial scale cultivation and harvest of *M. pyrifera*. In doing so, the MacroSystems team strives to fulfill the requirements established by the ARPA-E Phase 1 Proposal to explore the potential for commercial-scale cultivation in the United States Exclusive Economic Zone.

2.3.4. Environmental Impacts Of Solutions (Task 3.4)

2.3.4.1. Identification Of Risk Categories

The risk identification process started during the technical workshop in the Faroe Islands in the first week of April to actively involve the full project team. The team discussed seeding and hatchery, rig design and engineering, environmental conditions, site specific elements as well as the anticipated nutrient system and techno-economics. Setting the objectives helped to identify first risks of activities, processes, opportunities and challenges. Potential risks have been identified by all members of the project team by brainstorming and have been documented and followed up.

The approach that was chosen to identify potential risks was to first identify all the functional success criteria for the project. Then we must identify all the possible modes by which these functions might fail to perform. The overall perspective of objectives, what specifically needs to be achieved as well as the intended outcome and what the foundational assumptions are to achieve is defined by the MARINER program. Decisions concerning risk acceptability and risk treatment are based on operational, technical, environmental, biological or other criteria, depending on the project objectives.

Key risks were divided into the type of risks: Engineering and operational, Environmental and biological and Biogeochemical risks. We investigated for each risk category, what is at risk, in other words the areas of impact in the event that the risk materializes and the type of exposurDefinition and evaluation of environmental, biological and geochemical risks

As a first step, we focused on defining and evaluating potential or perceived environmental, biological and geochemical risks. Following the initial risk identification phase, we differentiated those that seem minor and do not require further attention from those that require follow-up, evaluation and remediation techniques and options. The purpose of this risk analysis is not to compute project risk values, but to be better able to mitigate and manage potential project risks and should be a step toward identifying active measures to manage the risks.

For this step to be undertaken successfully, the literature and relevant published material was comprehensively reviewed regarding environmental, biological and geochemical risks that are specifically related to the MacroSystem, thereby identifying knowledge gaps and shortfall areas. During the first project quarter we focused in systematic reviewing the literature on environmental, biological and geochemical risks with a focus on journal papers.

Having reviewed the literature, there is at present a clear need to develop MacroSystem at small scale and characterize its performance for production and effects on the environment. Critical areas for development will involve large-scale field experiments tightly coupled to high-resolution three-dimensional computational models with embedded biogeochemistry.

2.3.4.2. Definition And Evaluation Of Engineering And Operational Risks

Although, we mainly focused on the environmental, biological and geochemical risks during the first project quarter, we added to our literature research certain topics on the engineering and operation risks to be able to integrate findings, which are relevant to de-risk the MacroSystem design.

We have been analyzing information from historical cultivation and harvesting techniques and evaluate previous function and how best practices could be integrated into new innovative solutions to de-risk the design. Previous nutrient delivery system tests that used similar methodology were analyzed. Differences to our system were pointed out and evaluated as to why the risk identified in the previous study would not account for our system. If a certain risk is identified as being relevant for our system as well, we started to evaluate how to mitigate this risk.

Additionally, the Climate Foundation is currently planning to test a nutrient supply system in eastern Indonesia, which will have similar features as the nutrient supply system anticipated for the MacroSystem. This planning process and testing will tremendously help to early de-risk the design and anticipated testing of the nutrient supply system of the MacroSystem concerning engineering and operation aspects.

2.3.4.3. Remediation Techniques And Options Of Environmental, Biological And Geochemical Risks

Risk remediation planning includes front-end planning of how major risks will be mitigated and managed once identified. Therefore, risk remediation strategies and specific monitoring suggestions will be incorporated in the environmental risk analysis. Our risk remediation techniques and options will characterize the root causes of risks that have been identified, evaluate risk interactions and common causes, identify alternative mitigation strategies, methods, and tools for each major risk and assess and prioritize mitigation alternatives.

We are more than halfway through identifying possible remediation techniques and their effectiveness i.e. the degree the risk can be managed for the environmental, biological and geochemical risks and will be further adapted in the following months. Remediation techniques and options for engineering and operational risks will be evaluated in the next quarter.

2.3.4.4. Perspective On Risks

We have identified risk categories, developed preliminary definitions and evaluation of implementation plans regarding remediation actions in our operations. The following are some examples of the main ones.

Engineering and operational risks

The following risk categories have been identified for the engineering and operational risks. Full risk evaluation and remediation actions still need to be analyzed and described.

Equipment durability in rough oceans. Many open-ocean operations of the 1970's and 1980's did not survive ocean storm conditions. MacroSystem is designed to operate at depths of 20m, deep enough to remain out of harm's way from ships or waves above 2-3m high. Some kelp may be lost but the structure will remain intact and passing ships undamaged, because like a submarine, it is designed to decouple from the surface in heavy seas.

We plan to approach open-ocean resiliency in stages to reduce risk. As we gain experience, we will increase the area of the deployment. Our plan to monitor, repair and replace the MacroSystems will evolve over time from highly manual and intermittent to more automatic with more regular check-in intervals.

Offshore harvesting complications: The harvesting has been refined by steamship kelp cutters in operation since the 1800's. To lower to amount of carbon emissions generated from harvesting it is important to operate electric harvesting vessels, using turbine generation and batteries. This question will be further discussed as the design of possible large-scale harvesting solutions matures.

Additional potential risks, which have to be evaluated and remediation techniques identified are:

Risks regarding the Integration of the anticipated nutrient upwelling system into a MacroSystem and Equipment and on-going maintenance.

Environmental and biological risks

The following potential and perceived environmental and biological risks have been identified, scientific proof and reasoning for why a potential perceived risk does not account for our system design are discussed and remediation techniques and options have been evaluated. Following, we have a small summary of each risk based on the current status of the environmental risk assessment and analysis..

2.3.4.5. Carbon Fixation In Kelp Forests And GHG Emissions From The Macrosystem

A key aspect of macroalgae growth is that there is a much higher carbon to phosphorus ratio in seaweed than in the deep sea. For a phosphorus limited process, substantial net sequestration occurs because the P is more efficiently utilized for carbon sequestration by seaweed than by plankton. While plankton and oceanic waters have a ratio as low as 117:1 C:P, seaweed C:P ratios start at 220:1 and can exceed 800:1. Macrocystis has a ratio of 220:1, providing a substantial net carbon drawdown benefit to restoring overturning circulation and regenerating kelp forests and fish habitat. Each square kilometer of the MacroSystem can potentially sequester up to 2000 tons carbon per year. To take into account the 106-117 carbon atoms upwelled for every phosphorus, we are multiplying our total of 2000 tons carbon per square kilometer per year with the difference of the C:P ratio between our targeted macroalgae species, which can fix up to 220 carbon atoms for every phosphorus atom made available, and the upwelled water. This gives us a net carbon sequestration ratio of (220-117):220 or 103:220. Therefore our net carbon fixation totals 936 tons of carbon per square kilometer per year in the first years, increasing later as processes are refined.

2.3.4.6. Hypothetical Changes In Pelagic Ecosystem Structure

Some researchers discussed changes to the pelagic ecosystem structure as potential side effects from restoring nutrient levels to pre-industrial era on a large-scale. Changes to the structure and function of the biological communities especially in the euphotic zone may affect fisheries directly or indirectly.

In addition to sufficient nutrients for primary production, we are also providing habitat for forage fish. Some critics have said that seaweed cultivation rigs are just Fish Aggregation Devices (FADs) and that we will attract many fish as they migrate, and distract them from their migratory routes. In order to probe this question, we can measure the fish habitat created, and recruitment of juvenile fish to the MacroSystem. We plan to validate and develop techniques to track the fish grown on the rig as we scale the design.

Mammal habitat effect, risk of entanglement. The perceived potential risk of marine mammal entanglement associated with new large-scale mariculture applications might be an impediment to the expansion of mariculture. This is particularly true if it involves buoys and netting or other types of aquaculture structures. However, MacroSystem does not need to use such structures. It can eliminate fish pens and fish feed used in traditional aquaculture systems, which too much reduces the potential entanglement risks associated with seaweed cultivation. Environmental assessments are facilitated by having previous ground truthing mammal data and recordings demonstrating how mammals can see/hear and avoid such structures or otherwise interact with them. Marine Passive Acoustic Monitoring (MPAM) is a technique that is well suited for this challenge and can enable us to understand mammal and fish interactions with the MacroSystem in a continuous way that otherwise would be difficult to achieve. This early data can inform and streamline these environmental processes so that MacroSystem can be more smoothly adopted, based on these early research findings. Additionally, deployment sites should be carefully selected in order to not deploy the MacroSystem into mammals breeding and foraging habitat and migration routes. Continuous monitoring and reporting can be done to detect and act on the presence of marine mammal species in the array area.

Eutrophication and anoxia. Eutrophication involves excess nutrients, typically nitrogen and phosphorus, causing algae blooms. These algae blooms cause numerous detrimental effects such as anoxic (low oxygen) environments due to respiration when photosynthesis is not active. Such effects are typically caused by excess nutrients entering the ocean from fertilizers or waste dumping in rivers and coastal environments. However, 99% of the blue ocean mixed layer has the opposite situation of 'oligotrophication' (nutrient depletion). This situation, seen across most of the subtropical and tropical oceans, can be addressed with some forms of seaweed mariculture that restores overturning circulation of the mixed layer. Japanese literature reports that 100M square kilometers of Pacific Blue Ocean has oligotrophication, and that the loss of the Tasmanian Macrocystis kelp forest is due to oligotrophication.

Harmful Algal Blooms (HABs) stimulated by MacroSystem perturbations. HABs are typically associated with excess nutrient loads and other environmental factors. While it is conceivable that the nutrient supply system of the MacroSystem could contribute to nutrient supply for HABs through nutrient upwelling, the prevalence of HABs is associated with many environmental factors that include increased temperature, stratification and ocean acidification. The MacroSystem ameliorates those conditions, lowering temperature, stratification and acidification. Nonetheless, we plan to monitor conditions upstream and downstream to ensure HAB safety.

Spreading kelp disease and invasive species. Considering the anticipated large-scale application of the MacroSystem, the potential exists to increase disease transfer. To avoid this concern, the MacroSystem will only contain local species of macroalgae. When MacroSystem operates within a region, it will utilize the principles of extensive aquaculture, unlike penned aquaculture systems that can increase disease prevalence.

Local shifts in plankton abundance and assemblages. One concern with restoring localized overturning circulation of the mixed layer is that it will locally alter plankton abundance and/or shift plankton assemblages due to local changes in nutrient flux and water temperatures. However, for each deployment region, the nutrient supply system of the MacroSystem will restore the amount of upwelling that occurred pre-industrially, before anthropogenic climate change began curtailing natural upwelling. Therefore, MacroSystem upwelling is being designed to mimic the regional ecosystem services that were present pre-industrially. Such restoration can be monitored and sampled to validate ongoing plankton abundance and assemblages.

Biogeochemical risks

Upwelling carbon subsequently released to the atmosphere. One of the concerns with upwelling is that more carbon might be upwelled than is sequestered. *A Need for Accelerated Carbon Sequestration* found in Section 4.1 discusses how, due to the difference in Redfield ratios (C:P) of seaweed (>220:1) and ocean water (117:1) almost all phosphorus will be consumed, therefore our seaweed mariculture will draw down more carbon than that which is upwelled.

Exceeding perceived claimed technical limits for carbon export. Oschlies et al. (2010) examined Lovelock and Rapley's (2007) upwelling concept with simulations performed by an Earth system model using historical data and predicting future scenarios. The carbon sequestration potential of upwelling in these simulations was shown to be limited at best. Based on this information scientists had previously advised against the usefulness of artificial upwelling in achieving carbon balance. However, the claimed scientific limits for carbon capture are not applicable to our systems, as the MacroSystem use macroalgae rather than microalgae. Macroalgae has a much higher Redfield ratio (in some cases >550:1 compared to 117:1) and does not suffer from shallow remineralization. This allows macroalgae to sink carbon, mostly unimpeded, at a rate of hundreds of meters per day towards the bottom of the ocean, where it remains for millennia.

Global Macronutrient Balance: There is a concern that upwelling from the our anticipated nutrient supply system will lead to a reduction in available nutrients and thus reduce ecosystem productivity. However, the ocean is not pristine. Anthropogenic effects have increased the sea surface temperature by 1°C and in some regions by over 3°C. This increase in temperature has caused a temperature-induced density gradient that is preventing natural upwelling. Thus the upwelling for the MacroSystem will assist in restoring that natural process. Previous attempts have also received criticism as the majority (90%) of the nutrients can go unutilized due to sinking effects. Our nutrient upwelling system uniquely establishes appropriate buoyancy conditions of the upwelled water in order to maximize its utilization. All of the phosphate will be utilized in the mixed layer either at macroalgae ratios (e.g. ~550:1) or Redfield ratios (117:1).

Iron as a limiting micro-nutrient: The London Dumping Convention was also written to deter companies from sequestering carbon using Ocean Iron Fertilization (OIF). The availability of nutrients in the oceans and their means of supply vary considerably from one region to another due largely to differences in physical characteristics and different natural inputs. In the case of the MacroSystem the likelihood of modifying the global iron balance is minimal, since it is not artificially fertilized with iron.

2.3.4.7. Next Steps

1. Final refinement of the definition and evaluation of environmental, biological and geochemical risks
2. Final refinement of the remediation techniques of environmental, biological and geochemical risks
3. Definition and evaluation of engineering and operational risks
4. Further literature reviews regarding engineering and operation risks
5. Remediation techniques and options engineering and operational risks
6. Specialist Expert Judgement
7. Integration of the outcomes into the deployment manual

2.4. Complete Phase II Proposal (Task 4)

The objective with task 4 is to compile reports and plans into Deployment Manual. This is an ongoing task, but in the second and third quarter of the project data will be available from the other tasks to compile the Deployment Manual.

2.4.1. Compile Reports And Plans Into Deployment Manual (Task 4.1)

All reports and plans from Task 1, 2, and 3 will be compiled into a master Deployment Manual. This manual will be utilized during the Phase 2 pilot test.

2.4.2. Business Related Plan Items (Task 4.2)

In this task the business related aspects of MacroSystems will be described, including tech-to-market at capitalisaiton from private investors to match and build on the ARPA-E funding. Work has commenced in this respect, and the MacroSystems team is in contact with potential buyers of cultivated Macrocystis in food, costmetics, animal feed, ferilizers and biofuel markets.

Furthermore, Catalina Sea Ranch is in the process of obtaining an expansion extending their existing permit for seaweed cultivation using the MR1.

3. Additional Performance Updated

3.1. Issues, Risks, and Mitigation

Issues, risks and team mitigation plans have been described in the corresponding sections above.

3.2. Changes In Approach

There have been no changes in the approach taken by the MacroSystems team.

3.3. Changes In Project Personnel

Climate Foundation and Primary Ocean Producers have been added to the MacroSystems team.

Bigelow Labs and University of California Irvine have been removed from the MacroSystems team.

4. Technology to Market (T2M)

4.1. Publications

Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting.

4.2. Other Project Output

We have sent samples for characterization purposes to cosmetic, fertilizer and biofuel producers.

4.3. Follow-on Funding

If MacroSystems wins the Phase II, we have investors who have agreed to invest follow on funding.

5. Administrative and Legal Updates

5.1. Disclosures

The current and prending MacroSystem team members have signed a team agreement that includes intellectual property as well as the opportunity for a future joint venture for a potential Phase II contract.

5.2. Conflicts of Interest Within Project Team

There are no conflicts of interest within the MacroSystems project team.

5.3. Performance of Work Within the United States

The MacroSystems team includes overseas sub-contractors including Ocean Rainforest and Patagonia Seaweeds and Hortimare. ARPA-E contracting officers have previously approved these sub-contractors as team partners.

6. Cost Updates

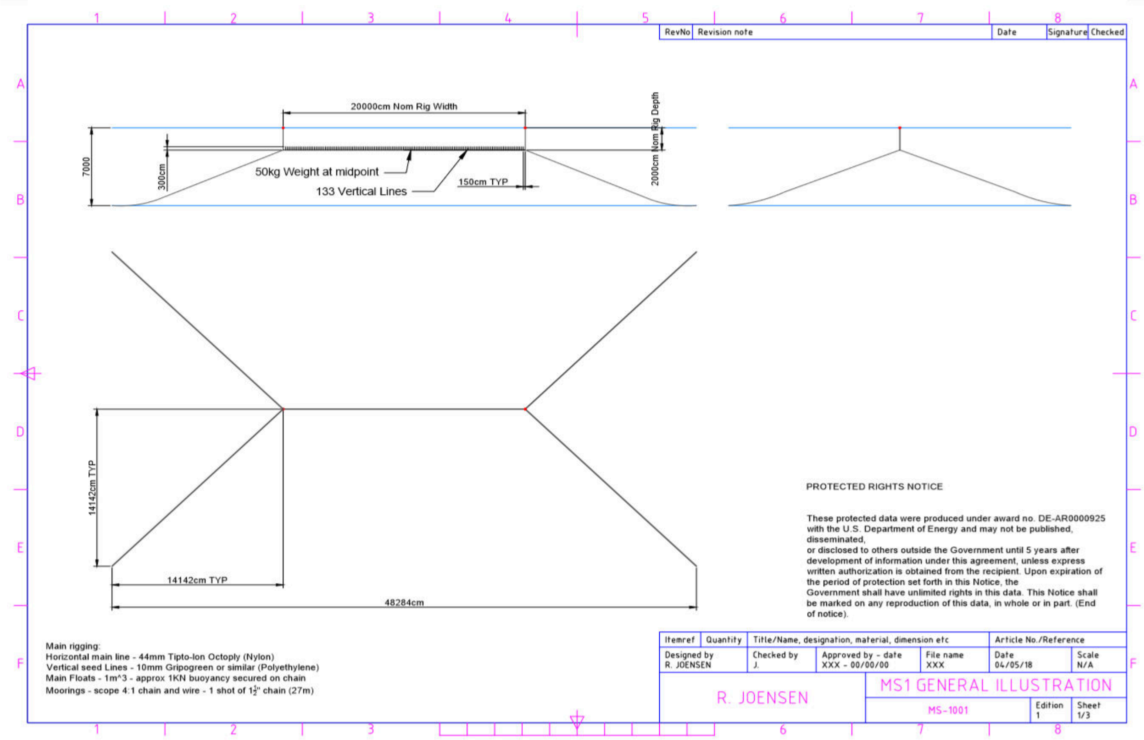
6.1. Budget Status

The prime recipient, Catalina Sea Ranch, LLC., verifies that budget amounts submitted for reimbursement to ARPA-E during the quarter are accurate and complete. A request for budget modification was submitted to contract personnel on June 18, 2018. The status of this budget modification is still pending.

6.3. Submit Page

The prime recipient, Catalina Sea Ranch, LLC., verifies that the information provided in the Research Performance Progress Report is accurate and complete as of the date shown.

7. APPENDIX A: Detail Drawing from the FEA specification



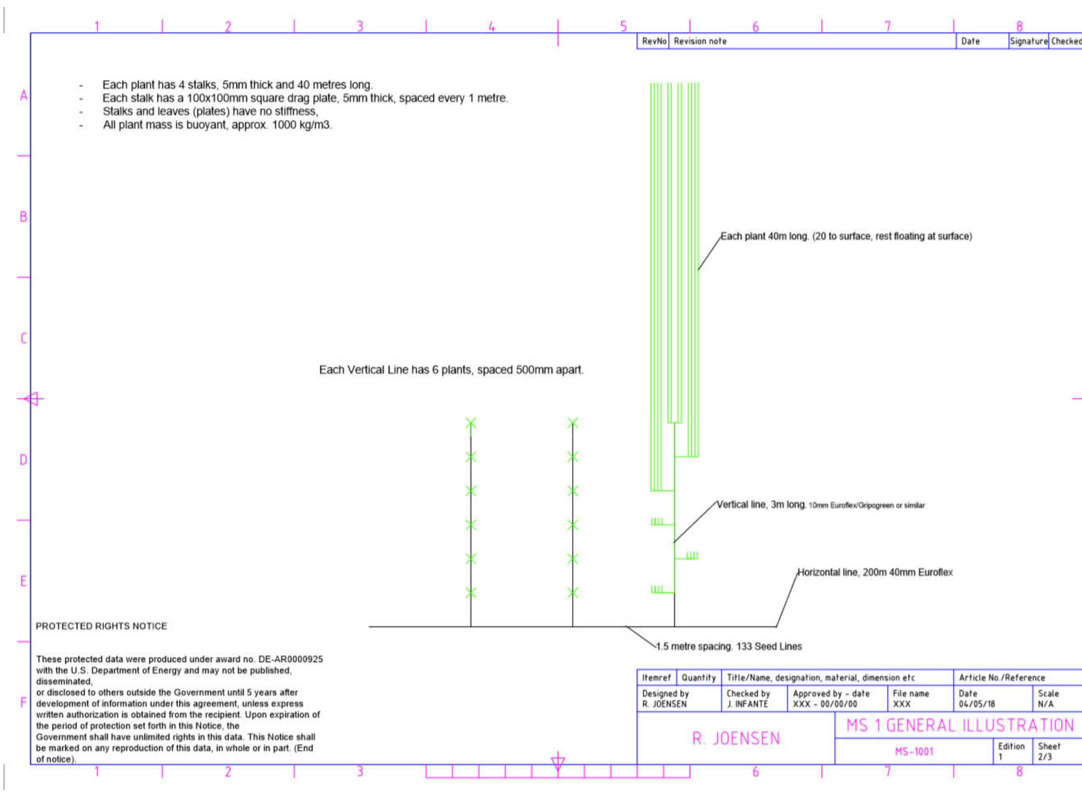


Figure 26: MS1 General Illustration

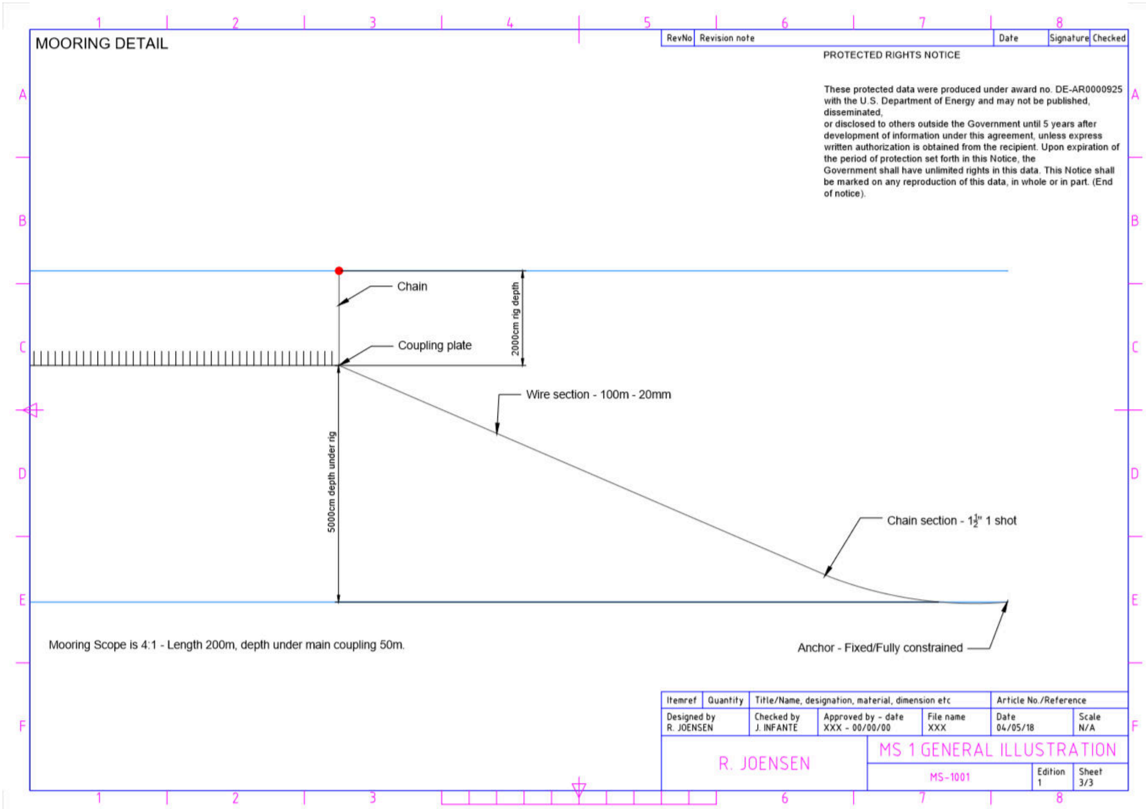
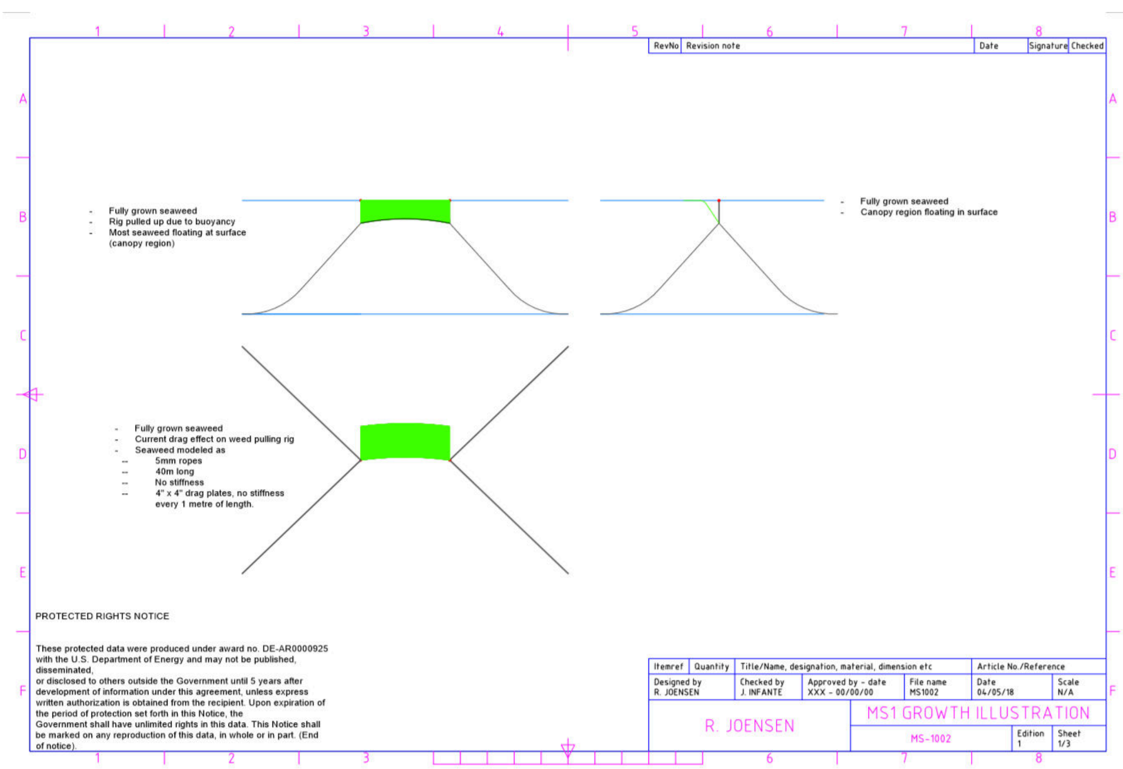
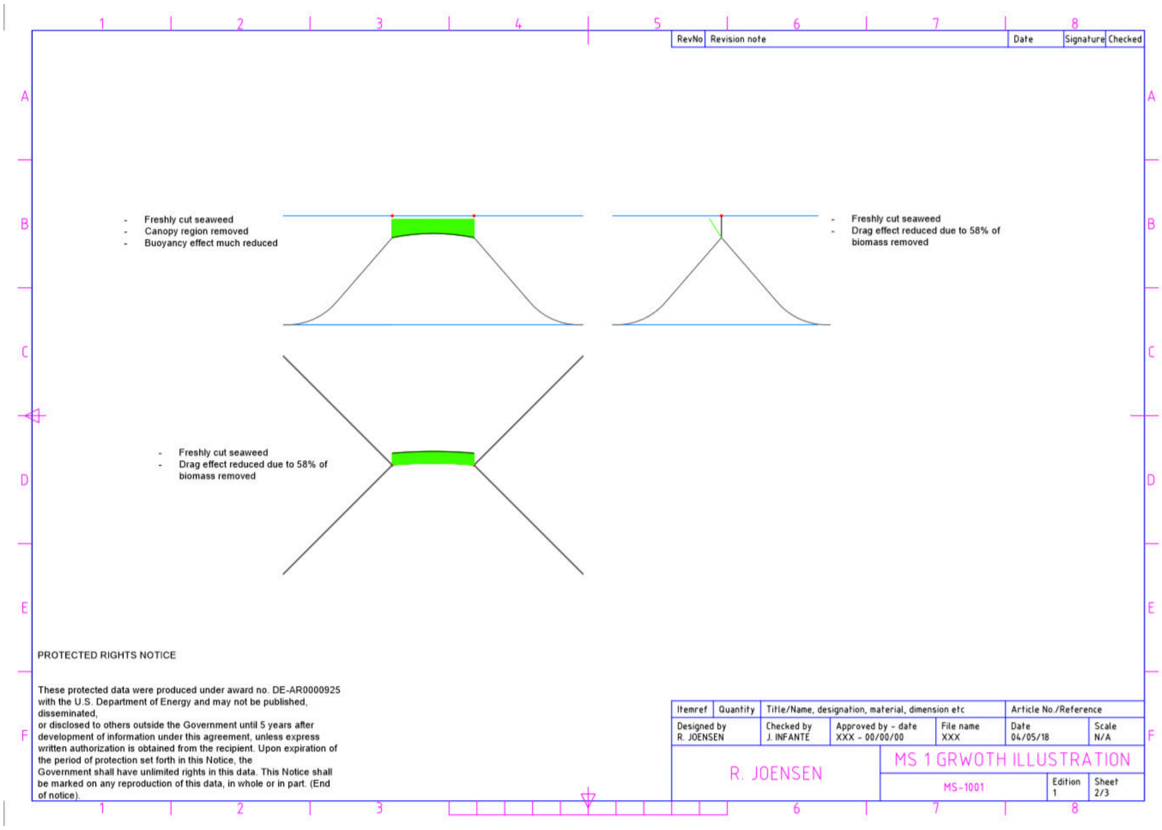


Figure 27: MR1 Growth Illustrations




RevNo | Revision note | Date | Signature | Checked
- Freshly cut seaweed
- Canopy region removed
- Buoyancy effect much reduced
- Freshly cut seaweed
- Drag effect reduced due to 58% of biomass removed
- Freshly cut seaweed
- Drag effect reduced due to 58% of biomass removed
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R. JOENSEN
MS 1 GRWOTH ILLUSTRATION
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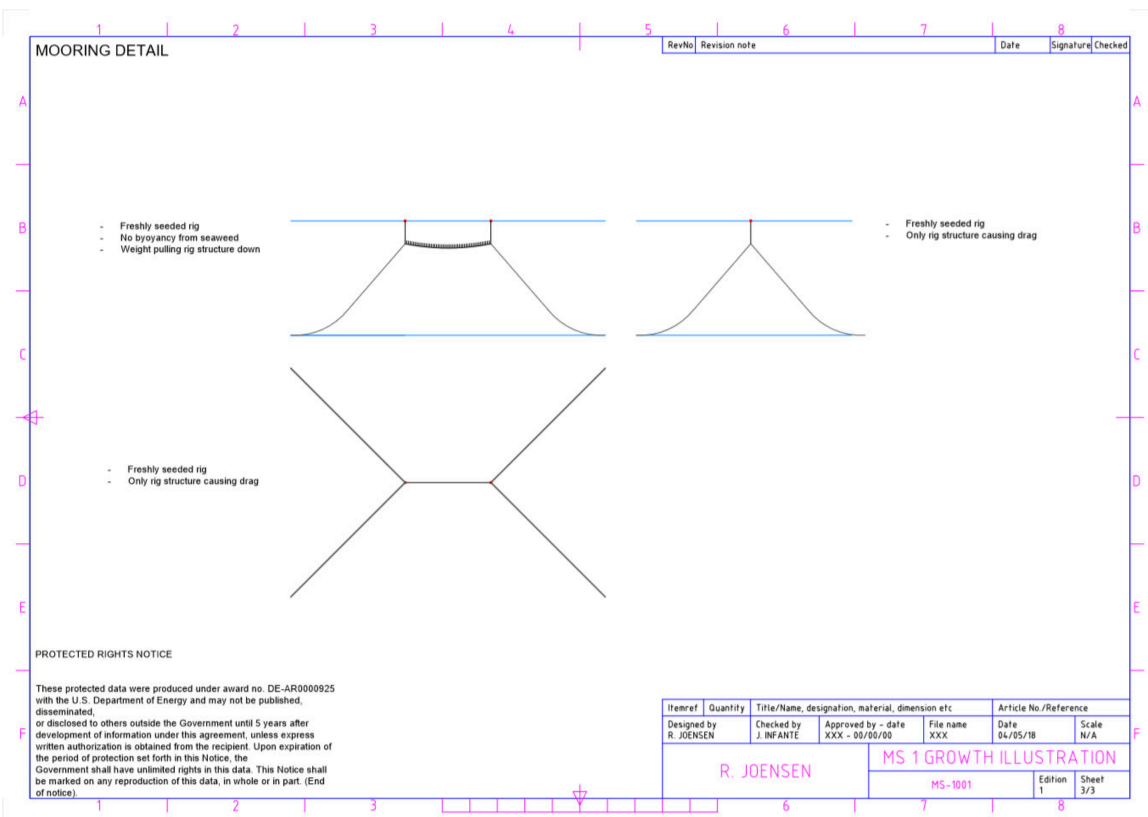
Edition 1
Sheet 2/3


MOORING DETAIL
RevNo | Revision note | Date | Signature | Checked
- Freshly seeded rig
- No byoyancy from seaweed
- Weight pulling rig structure down
- Freshly seeded rig
- Only rig structure causing drag
- Freshly seeded rig
- Only rig structure causing drag
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Sheet 3/3

8. APPENDIX B: Methodical Approach for Site Survey; Mapping

8.1. Chronological Outline (NOAA)

- Data content from NOAA April 17th gdb files
    - Social/regulatory parameters and minimal environmental parameters (1 arc tabular nitrate, phosphate, chlorophyll A, temperature, and salinity inputs averaged over entire water column profile).
- NOAA scalability analysis webinar unveiling the MARINER Aquamapper online tool May 31st
- Updated data content from June 27th gdb files
    - Environmental parameters were expanded upon. Most of these rasters were not correct for our purposes and were provided approximately three months after we had begun our environmental assessment, so we had already collected all of the data they provided and more.
    - Email in response to our questions to them was written at a basic level not belying our team competence and included assumptions and assertions on the part of NOAA which were incorrect and caused us to unnecessarily doubt our methodology. Details of this are included in our notes from the emails and calls exchanged.
- Additional data sources from emails and links July 5th, and again on July 16th. Following the call on July 17th NOAA appeared to realize our team competence and positively changed the tone of our interactions.
- Each following section is presented in chronological order.

8.2. Research

8.2.1. Assessment

- Required data types
- Software requirements
- Spatial/temporal scales, both minimum and optimal requirements
- Application and documentation links

Initially, there was no contact or information provided by NOAA regarding what data would be provided to us and at what spatial and temporal resolutions. Following the literature review it was determined that we might need to run available data through regional hydrodynamic models in order to get the optimal spatial and temporal resolutions suitable for our purposes. To try to save the time of developing our own models we attempted to work with all available models, and created a model table with links, data associated, questions/comments, potential uses and model capacities (reproduced below).

For task 2.1 datasets from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) and the San Pedro Ocean Time Series (SPOT) were determined to have the best spatial and temporal resolution for the environmental parameters surrounding the Catalina Sea Ranch (CSR) farm site.

For task 2.2 the NOAA World Ocean Atlas was determined to have the most complete datasets for environmental parameters covering the U.S. Exclusive Economic Zone. These datasets however did not have sufficient resolution for a complete siting analysis and thus the above models were considered.

The Lester 2018 Aquaculture Spatial Planning model was fully assessed to determine which data, rasters, and scripts might be suitable for use or templates for our siting analysis. Initially, everything was examined except MATLAB data because we did not have a MATLAB license. An excel file titled

"Seagrant_final" was found that included a full bio economic model of kelp (biomass to market value) indexed. After creating a *macrocystis pyrifera* growth model in later stages this index will provide a useful comparison to determine ideal siting to maximize bioeconomic outputs. They used Aquamodel for finfish siting but made no mention of a kelp siting model, so research was done to determine how they accomplished the kelp aspects of their siting analysis. We had hoped to find the kelp data and modeling in the MATLAB content, but following the acquisition of a MATLAB license we determined that it was not posted. This was confirmed after meeting with Dr. Tom Bell who performed the kelp modeling work and stated that Dr. Lester asked if he wanted his kelp modeling work to be posted, which he did not. He also confirmed our plan on kelp modeling to use the CalCOFI nutrient data and CDIP wind and wave data modeled through the Regional Ocean Modeling System (ROMS).

Following meeting Dr. Tom Bell, the team discussed which model types would be appropriate specifically for the next phase of analysis. NOAA uses a highly complex model called Wavewatch III (WWIII) that we could not run on our personal computers but could use hindcast analysis from. These hindcasts are provided in multiple formats through the National Renewable Energy Laboratory (NREL). The Coastal Data Information Program (CDIP) was suggested by Dr. Bell as a simpler yet similarly effective way of modeling wind and waves and analysis of currents. The CDIP model appears to be a buoy driven model using linear wave propagation as opposed to the NOAA WaveWatch III model which initializes the coastal model with offshore predictions from an ocean basin-scale wind-wave model.

CDIP and CalCOFI are run largely out of the Scripps Insitution of Oceanography (SIO) and both contribute to the U.S. Integrated Ocean Observing System (IOOS), aligning with collection of CSR onsite data by the NOMAD buoy. The NOMAD buoy has been un-operational for approximately a year and needs to be defouled and re-calibrated. However, once it is operational again, data formatting should be consistent with both CDIP and CalCOFI, thus those datasets were considered most appropriate for our uses in task 2.1.

The Seaweed Aquamodel was deemed a potential time saver with a plug in for EASy GIS. It calculates the growth and nutrient assimilation of macroalgae farms and the associated effects on carbonate chemistry. It was used by the only existing kelp farm on the west coast for the simulation of the Hood Head (Dr. Joth Davis) sugar kelp (S*accharina latissima)* farm. Aquamodel, which came out before the Seaweed Aquamodel, was used by Lester et. Al 2018 for the Aquaculture Spatial Planning for finfish aquaculture in the Southern California Bight. Seaweed Aquamodel was designed to select optimal farm sites (water Q, temp., nutrients, flow rates, wave/wind), to map infrastructure, environmental and ecological conditions. Dr. Davis was contacted about his use of the Seaweed Aquamodel and expressed concern that this model oversimplifies the influence of hydrodynamics. The team devised a plan to contact Dr. Dale Kiefer for access to Seaweed Aquamodel for the next phase of analysis in conjunction with the Aquaculture Spatial Planning Model (ASP) and the Regional Ocean Modeling Systems (ROMS).

The Seaweed Aquamodel was funded for fish aquaculture siting by NOAA SeaGrant so it was hypothesized that it should be at least somewhat publicly accessible. However, it turned out to be totally proprietary with only a free trial period. This free trial period will be reserved for a later time in our analysis to compare results and perform a basic sanity check. Our results could be used to calibrate and improve the Seaweed Aquamodel at a later time as an additional output.

https://wsg.washington.edu/research/fish-aquaculture-simulation-model-and-gis-validation-and-adaptation-for-government-management-use/

Dr. Samantha Stevenson's latest work focuses on climate modeling of extreme events and the effects of the El Niño Southern Oscillation (ENSO) on sea surface temperature and wind stress. Per Dr. Stevenson's suggestion, the Line P and Station papa datasets were looked into, and Katherine Zaba's glider data was investigated. The Line-P program was historically a weather station, now currently a NOAA buoy occupied ocean station located at 50 N 145 W. Line-P is frequently surveyed, managed, and coordinated by Institute of Ocean Sciences from Fisheries and Oceans Canada (DFO) https://waterproperties.ca/linep/index.php. Line-P will provide excellent added input to our siting analysis in the Northern Pacific part of the U.S. EEZ. Katherine Zaba is a researcher with Scripps Institution of Oceanography (SIO) and her glider data is part of the California Underwater Glider Network (aka Spray Project) which operates from southern to central coast of California http://spraydata.ucsd.edu/projects/CUGN.

Additional research into storm/climate change predictions led to the National Centers for Environmental Information (NCEI) which publishes storm data by month and can be cross-referenced with the National Data Buoy Center (NBDC). Through identification of extreme weather events and trends we can collect wind wave data from collocated buoys and use that data in predictive climate models. A non-comprehensive weather history table was compiled of recorded Southern California storms dating back to the late 1700s. History of Significant Weather Events in Southern California organized by weather type will be used similarly to the NCEIs storm watch data events for a more comprehensive analysis of environmental conditions at CSR.

At the suggestion of Dr. Samantha Stevenson, Dr. Baylor Fox-Kemper's work was researched and he was contacted regarding the integration of WWIII into global models like ROMS. He was unable to assist at the time contacted. Additional scientific researchers such as Dr. Dave Siegel at UCSB and Elliot Lee Hazen at NOAA/UCSC were met with to discuss their own and their colleagues unpublished models. The California Current Coastal Upwelling Indices (CUTI and BEUTI) created by Mike Jacox at NOAA/UCSB were considered to provide estimates of vertical transport and vertical nitrate flux. It is not yet determined if these indices will be useful, particularly given that they are calculated for one-degree latitude bins and the vast majority of our analysis will be at a finer scale.

Further research was performed to determine how to use the wind and wave models with CDIP data. The current iteration of the model table was finished at this point.

The use of SeaSketch was evaluated for basic GIS visualizations easily accessed by a number of team members. https://www.seasketch.org/home.html. SeaSketch provides analytical feedback about your sketched zone within seconds. It requires no software and is designed for collaboration and engaging various stakeholders. These reports can identify habitats protected, potential social or economic costs and benefits, and other metrics that can inform the development of broadly supported marine spatial plans. They can even include advanced analyses such as Marxan and Cumulative Impacts. However, the GIS work was determined to be done more efficiently by select members of the team in ArcGIS pro using a combination of RStudio and Python scripting libraries.

ROMS and NPDZ models were reviewed again as it appeared that the data we have covering the US EEZ and the data provided from NOAA will be unlikely to have the resolution desired in our analysis. Following the unveiling of the MARINER Aquamapper online tool after the 5/31/18 webinar, all layers were reviewed to determine which layers were pertinent.

The resolution of layers was determined and questions formulated for NOAA, to James Morris and to Seth.Theuerkauf@noaa.gov who is managing the Southern California region. Our initial questions (reproduced below) were composed into an email and sent to NOAA on June 27th, and were replied to on July 2nd via email and a July 3rd phone call.

a. What datasets/databases were used? Are they the same as listed on the attached DOE pdf sent about the regional geodatabases?

b. How were nutrients measured, and was a model used? If so, which one(s)? Do you have monthly or seasonal averages?
c. Is the resolution of models used for nutrients and for currents (including wind/wave) 1 arc degree, and would it be possible to get a higher resolution?
d. Why do some geological layers appear to be missing from the bottom? Especially, why is hard bottom not listed as a substrate, and why were no benthic substrates listed as rocky? While it's clear usSEABED was used, it isn't clear to us what we are to assume about any area with unlisted substrate.

Due to the current non-functioning status of the NOMAD buoy, the team attempted to win a wave buoy short-term free sensor through the Spoondrift Spotter (spoondrift.co) innovation challenge. Spoondrift Spotter is a globally-connected wave buoy for high-quality ocean wave and current data, so it would be ideal to get a buoy in the water as soon as possible while the NOMAD is repaired.

Following the call with NOAA in which they stated their awareness of the data resolution's probable insufficiency, the search continued for more nutrient data outside of California and for additional data throughout the West Coast that might contain appropriate spatial and temporal resolutions. The ERRDAP considerable dataset was identified to fill in gaps in the provided data sets. Argo float data was researched and assessed to be used for a creation of a nutrient grid pattern outside of Southern California. "Internal dynamics of NPZD type ecosystem models" (Heinle, 2013) models which simulate the concentrations for four marine ecosystem components: dissolved inorganic nitrogen (N), phytoplankton (P), zooplankton (Z) and detritus (D) given in mmol Nm^{-3}, was assessed for potential use on nutrients in Southern California to then apply to other regions.

Different methods of performing a suitability analysis were researched. Contact was made with Dr. Sarah Lester and Dr. Rebecca Gentry to go over the methods they had used for performing the suitability analyses published in Nature and their accompanying data repositories as mentioned in Literature Review. The best option was determined to be a fuzzy overlay due to the interconnectedness of many of the constraints. In order to accurately portray the relative suitability of each constraint type, different methods were employed to create the overlay. Temperature was done by ranking data points according to a linear membership, such that prohibitively low temperatures (<0°C) were given a score of 0, prohibitively high temperatures (>20°C) were given a score of 1, and intermediate values scaled linearly between 0-20. Nitrate and phosphate data will be ranked with a fuzzy large membership, which ranks high values as more suitable than low. Membership tools will be applied as next steps following the data analysis on nutricline locations. The fuzzy overlays have been and will continue to be implemented with the "AND" overlay, which outputs the lowest value of the overlaid cells onto the final raster. This method was chosen so that the final raster would show the lowest possible suitability value for each cell. It was determined that an area would be unsuitable for macrocystis if nitrate levels dropped below 1 μmol/L for longer than a month so temporal components will be added. Following the initial siting analysis for natural temperature and nutrient conditions, an additional analysis will be performed regarding the artificial upwelling techniques in task 2.3 to add additional suitable areas with use of the technology.

Pacific Coast Groundfish FMP regulations were reviewed. These are the most significant aspect of Habitat Areas of Particular Concern (HAPC) relevant to constraint layers and there is significant overlap of HAPC within development region. Based on the Pacific Coast Groundfish Fishery Management Plan (PCGFMP) further consideration for HAPCs will be used to evaluate ground fish habitats. A weighting schema of "less than ideal" will be applied to ground fish habitats to reflect the PCGFMP non-fishing habitat needs noted in sections 7.1, 7.2 and Appendix D (found in Amendment 19) of the plan.

The NOAA geodatabase files do not have the usSEABED data available on Aquamapper. The Aquamapper tool supplied web layers which cannot be manipulated locally. NOAA explained that this formatting was for security reasons and later supplied the updated Aquamapper rasters in geodatabase format. NCEIs hydrographic datasets were searched to located and identify data gaps:

a. Located: https://www.ngdc.noaa.gov/geosamples/surveydelimited.jsp
b. Isolated Southern CA region of interest with Seabed data via mapping application
c. Then downloaded data by selecting each individual survey in the region (x > 50)
d. The data will need to be further processed into csv files, cleaned, uniformly referenced (ex: substrate, SD => Sand) and loaded into ArcGIS then interpolated.

To expand the dataset to the entirety of the US Pacific EEZ region in a timely manner, the NCEIs data manager was contacted. Following the June 27th interaction with NOAA, we were able to obtain geodatabase files of usSEABED data for the entire US EEZ. Hard bottom data was however not included in these datasets and NOAA has been unable to secure any comprehensive reliable hard bottom layers.

On July 16th, additional data provided by NOAA was downloaded and worked into maps. KdPAR data was added from new zip files. Kd490 data from the geodatabase provided is between –6.553 with an upper bound of .2-.6; the new data (labeled KdPAR rather than just kd) is 0-98. These are clearly different units and neither had units associated so clarity with NOAA was sought. The appropriate Kd metric to use for kelp aquaculture was researched, whether Kd490 OR KdPAR. Light attenuation is traditionally quantified as the diffuse attenuation coefficient of the downwelling spectral irradiance at wavelength 490 nm (Kd490) or the photosynthetically available radiation (KdPAR). Research indicates KdPAR is a percentage of light attenuation and following the most recent phone meeting with NOAA on July 20th it was determined that KdPAR was most suitable for the light attenuation measurement for farming giant kelp. Light, current, nitrate and phosphate max/min and optimal metrics were researched, and listed in a separate document.

8.2.2. Model Table

Table 4. This table represents an overview of models researched for application in tasks 2.1 and 2.2.

Model/Code Name	Data Associated Spatial-Temporal Scales	Capabilities	Questions/Comments
NOAA WaveWatch III (NWW3)	NOMADS data Use pygrib	Wave hindcasts and wave forecasts. These simulations consider atmospheric wind forcing, nonlinear wave interactions, and frictional dissipation, and they output statistics describing wave heights, periods, and propagation directions for regional seas or global oceans.	Very complex model taking days to run. Hindcasts are available via NREL. Could be a simpler way with layering CDIP wind/wave data, and use WWIII hindcast results to verify.
Navy Operational Global Ocean Model (NCOM/ HYCOM)	NOMADS data Model cycle is 1 day. NCOM regional/global .gz files provided by Naval Oceanographic Office 1/8 deg. Global model – 1/12 deg. Eddy resolving HYCOM model. NetCDF files. Regional Model – 1/36 deg (3 km) resolution.	HYCOM assimilates satellite altimeter observations, satellite and in situ sea surface temperature, as well as available in situ vertical temperature and salinity profiles from XBTs, ARGO floats, and moored buoys, using the NRL-developed Navy Coupled Ocean Data Assimilation (NCODA) system. The NetCDF files contain ocean temperature, salinity, eastward and northward currents, and elevation.	NCOM global replaced by HYCOM in 2013. HYCOM 2013-present. NCOM 2009-2013 global, and 2009-present regional. Potentially also use NOGAPS analysis (from 1997-2008) in GRIB1 file format.
Global Couples Climate Models/Coupled Model Intercomparison Project (CM2.X / CMIP5)	Climate prediction model associated with NOMAD data	CM2.X consists of two climate models, which were designed to model the changes in climate over the past century and into the 21st century. The U.N. Intergovernmental Panel on Climate Change (IPCC) coordinates global analysis of climate models under the Climate Model Intercomparing Project (CMIP). CMIP5 is in its fifth iteration. Data are available through the Program for Climate Model Diagnosis and Intercomparing (PCMDI) website.	
NOAA Geophysical Fluid Dynamics Lab (GFDL)(ESM2M)	Earth systems models w/code and data. Ocean circulation models. Run in FMS software. NOMADS data	Able to simulate the ocean climate system using two distinct and complementary models. ESM2M is an ensemble approach using level based Modular Ocean Model (MOM) and the Generalized Ocean Layer Dynamics (GOLD) code.	Stevenson suggests using for modeling climate change predictions.

Community Earth System Model (CESM)	Also includes Aquaplanet simpler model, a data ocean model to run the full CAM parameterization suite while retaining much simpler surface conditions than the complex combination of land, ocean and sea-ice.	Ensemble approach. CESM is a fully-coupled, community, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.	CESM is sponsored by the National Science Foundation (NSF) and the U.S. Department of Energy (DOE). Administration of the CESM is maintained by the Climate and Global Dynamics Laboratory (CGD) at the National Center for Atmospheric Research (NCAR).
Seaweed Aquamodel	Simulation of Hood Head (Joth Davis) sugar kelp farm. Used by ASP for finfish aquaculture "Sugar Kelp Dynamical Model"	Plug in for EASY GIS Calculates the growth and nutrient assimilation of macroalgae farms and effects on carbonate chemistry. Designed to select optimal farm sites (water Q, temp., nutrients, flow rates, wave/wind). Mapping of infrastructure, environment and ecological conditions	Davis mentions that this model oversimplifies the influence of hydrodynamics. Was it used to model sugar kelp also in ASP? If not, why?
Mapping Global Potential Aquaculture (SNAPP)	R-script and GIS rasters 0.042 degree resolution (constraints map to 0.0083 degrees)	Potential to use script & rasters for excluding unusable areas, locally and globally	Sarah Leser and Becca Gentry
Aquaculture Spatial Planning (ASP) Model	MSP paper from 2018 – some data used and scripts on github. SeaGrant_Final includes exclusion mapping csv or xlsx Tom Bell giving us kelp/mussel models	Uncertain. Siting models for kelp/mussels not posted.	Contact Sarah Lester, Gentry. Need to dig in data used and open files in R & MATLAB Requirements 1.) This folder must be put into the root folder (i.e. '~' in OSX and C:/ in Windows) 2.) Both MATLAB and R must be installed 3.) MATLAB must be installed with the following Toolbox Mapping Toolbox, Bioinformatics, Parallel Optimization.
Kelp Model from ASP via Tom Bell	CDIP wind/wave data coupled with ROMS		Confirmed our plan, didn't do anything differently on the southern California kelp siting than what we determined.
Scripps Couples Ocean Atmosphere Regional Model (SCOAR)	Nested ROMS, SST & Surface Current model; regional coupled models	The SCOAR model is portable, which is designed to be applied to different geographic regions and under different climate regimes, making it an ideal tool to study process-modeling of coupled air-sea interactions.	

Regional Ocean Modeling System(ROMS)	6-7 km resolution	Multi-level nesting capabilities – standalone or coupled to atmospheric and/or wave models. Includes sanity check and several coupled models.	Davis using this as large scale. Run embedded with Biogeochemical Elemental Cycling (needs 2 adjustments)
California Current Coastal Upwelling Indices (CUTI/BEUTI)	Two new upwelling indices that leverage state-of-the-art ocean models as well as satellite and *in situ* data to improve upon historically available upwelling indices for the U.S. west coast. Calculated for 1 degree latitude bins.	**CUTI** provides estimates of vertical transport near the coast (i.e., upwelling/downwelling). It was developed as a more accurate alternative to the previously available 'Bakun Index'. **BEUTI** provides estimates of vertical nitrate flux near the coast (i.e., the amount of nitrate upwelled/downwelled), which may be more relevant than upwelling strength when considering some biological responses.	Mike Jacox @ NOAA/UCSC

8.2.3. Model Reference Links

NOAA Coastal Aquaculture Planning Portal (CAPP) -https://coastalscience.noaa.gov/research/marine-spatial-ecology/coastal-aquaculture-planning-portal-capp/

NWW3 - http://polar.ncep.noaa.gov/waves/ensemble/download.shtml

http://polar.ncep.noaa.gov/waves/wavewatch/manual.v4.18.pdf --> User manual and system documentation

NCOM/HYCOM – http://www.opc.ncep.noaa.gov/Current_fcasts.shtml

https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/navoceano-ncom-glb --> NCOM model data

https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/navoceano-hycom-glb[Symbol] HYCOM model data

GFDL/ESM2M - https://www.gfdl.noaa.gov/earth-system-model/

http://mdl-mom5.herokuapp.com/web/docs/project/quickstart --> code associated

CESM – http://www.cesm.ucar.edu/models/

http://www.cesm.ucar.edu/models/simpler-models/aquaplanet.html --> simpler model associated with; data ocean model where SST must be specified

Seaweed Aquamodel - http://www.aquamodel.net/Seaweed.html

SNAPP - https://knb.ecoinformatics.org/#view/doi:10.5063/F1CF9N69

ASP - https://github.com/AquacultureSpatialPlanning/MSP_Model

https://cdip.ucsd.edu/?nav=documents&sub=faq&xitem=models[Symbol] wind/wave data associated

SCOAR - https://hseo.whoi.edu/scoar/

ROMS - https://www.myroms.org/

CUTI/BEUTI - http://mjacox.com/upwelling-indices/

ERDDAP – https://coastwatch.pfeg.noaa.gov/erddap/index.html

COASTAL AQUACULTURE PLANNING PORTAL THROUGH NOAA CAPP - https://coastalscience.noaa.gov/research/marine-spatial-ecology/coastal-aquaculture-planning-portal-capp/

AquaMapper Tool -

https://noaa.maps.arcgis.com/apps/webappviewer/index.html?id=4f12cbde0c22488196dda69d495116cc

8.2.4. Literature Review

All literature associated with the Technical Volume was read to gain a familiarity of the background of the project and to understand the big picture of all four task subgroups.

Regarding the tasks 2.1 and 2.2, particular time and attention was focused on:

1. "Mapping the global potential for marine aquaculture" (Gentry et. al, 2017) and its accompanying data (KNB SNAPP repository), working through all associated 38 files to determine what we could use as a template or partial template in our siting analysis.

2. "Marine spatial planning makes room for offshore aquaculture in crowded coastal waters" (Lester et. al, 2018) and the accompanying data on the Github Aquaculture Spatial Planning (ASP) repository Marine Spatial Planning Model (MSP_Model), also to determine potentially usable rasters and scripts for our analysis. Focus on "simultaneously minimize inter-sectoral impacts and maximize individual sector values"

3. "A GIS modelling framework to evaluate marine spatial planning scenarios: Co-location of offshore wind farms and aquaculture in the German EEZ" (Gimpel et. al, 2015)

4. Schiel, D.R., Foster, M.S., (2015) *The biology and ecology of giant kelp forests.* University of California Press, Oakland, California.

5. Buck, B. H., Langan, R. (2017) *Aquaculture Perspective of Multi-Use Sites in the Open Ocean: The Untapped Potential for Marine Resources in the Anthropocene.* Springer Open Access.

6. "Macroalgae Analysis: A National GIS-based Analysis of Macroalgae Production Potential Summary Report and Project Plan" (Roesijadi et. al, 2011). Report prepared by the Pacific Northwest National Laboratory for the U.S. Department of Energy; the overall project objective was to conduct a strategic analysis to assess the state of macroalgae as a feedstock for biofuels production. This paper provided a fairly comprehensive overview of the basic plan for siting macroalgae applying GIS-based spatiotemporal models and growth models.

7. "Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products" (Roesijadi et. al, 2008). An independent research and development report comprehensively covering: the seaweed industry, biobased seaweed products, offshore seaweed farms for biofuel production, structures and technologies for offshore farms, environmental factors that affect offshore seaweed farming, environmental impacts of large-scale offshore seaweed aquaculture installations,

seaweed biotechnology, techno-economic feasibility of offshore seaweed, and a science and technology roadmap.

8.2.5. Additional papers

-- Understanding how to model and predict the effects of El Niño events and climate change, in part in preparation for the meeting with Dr. Samantha Stevenson.

a. "Increasing frequency of extreme El Niño events due to greenhouse warming" (Cai et. al, 2014)
b. "Forced changes to twentieth century ENSO diversity in a last Millennium context" (Stevenson et. al, 2017)
c. "Climate Variability, Volcanic Forcing, and Last Millennium Hydroclimate Extremes" (Stevenson et. al, 2018)

-- "Optimization of biofuel production" (Sayre, 2009)

-- "Application of fuzzy measures in multi-criteria evaluation in GIS" (Jiang, 2000)

-- "Internal dynamics of NPZD type ecosystem models" (Heinle, 2013)

-- "Others"

8.3. Data Analysis

Environmental indicators of CSR were evaluated to satisfy conditions for task 2.1. This is in process using several datasets and methods outlined in this Data Analysis section. Kernel interpolations were performed at high and low resolutions using multiple datasets. Layouts with interpolated data for nitrate, nitrite, phosphate, temperature, salinity were created and exported to PNGs, some of which are reproduced (Figure 28). Initial maps were created of yearly averages for Southern California as well as the CSR specific sub-regions (with CSR's location marked) to evaluate spatial representation of environmental factors. A gridded mean of seasonal temperature, salinity, & nutrient CalCOFI tabularized data was analyzed. ArcGIS was used to interpolate CalCOFI data over Southern California and the CSR San Pedro Shelf region for a general spatial distribution of each parameter by the surface depth, averaged deep chlorophyll max depth, and 150m depth. Coastal Data Information Program (CDIP) provided wave data for surface sites around the San Pedro shelf.

An Aquamapper tool was developed by NOAA to assist Category 1 teams with the spatial analysis of 2.2. However, Aquamapper web layers were not downloadable in a usable form and cannot be manipulated, analyzed or converted into other file types locally. The tool was helpful in identifying regions of interest and data that was not available through the geodatabase layers provided for by NOAA. All layers were examined individually to compare temporal and spatial resolution to expected needs. The map was broken up into 7 regions (Southern California, Central California, Northern California, Oregon, Washington, Alaska, and Maine) in order to quicken runtime processing of the tools on each region individually.

To satisfy requirements for task 2.2 a suitability model is in the process of development using Python, R and ArcGIS software. A python script and GIS model will be used independently for developing suitability maps and weighted overlays. The GIS model will be used specifically for the Social Development Constraints Model as outlined in the following section. Python scripts were written to perform the fuzzy overlay analysis and to determine the layer types of the downloaded shapefiles. Those details are further examined in the Environmental Raster Development and Fuzzy Logic Linear Overlay section.

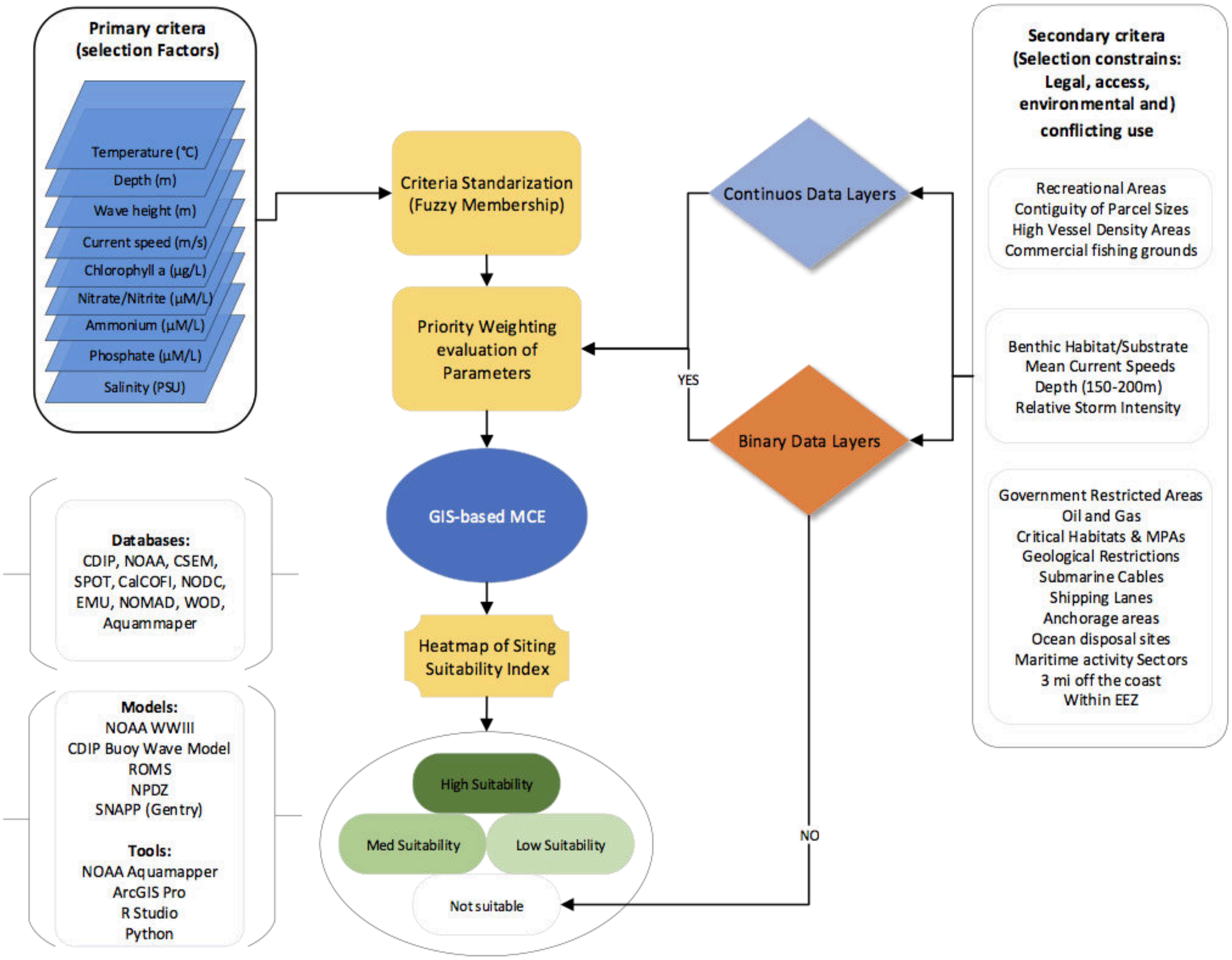

Figure 29. Visual representation of component model for project framework development utilized to satisfy task 2.2 requirements.

9. APPENDIX C: Techno-Economic Assessment – MacroSystems

The purpose of this techno-economic assessment (TEA) is to explore the viability of a multi-level approach to the cultivation and harvest of *M. pyrifera* in an offshore environment in San Pedro, California. In line with the ARPA-E Phase 1 initiative, the TEA is intended to guide future research and innovation within the U.S. macroalgae industry. It offers a feasibility assessment of the opportunities and challenges that might be associated with cultivation by taking into account the projected yields of the species in comparison to the expenses associated with growing the biomass.

To generate a TEA appropriate for the scope of the ARPA-E Phase 1 Proposal, the evaluation of the capital expenditures (CAPEX) and operational expenditures (OPEX) of the proposed offshore cultivation and harvest strategy is based on a Macroalgae Cultivation Rig (MACR) developed by Ocean Rainforest Sp/f. For the purposes of the ARPA-E Phase 1 proposal, the economic analysis will be two pronged so as to show the cost structure of the MACR and highlight important aspects. The elevation will consist of:

- Setting up harvesting yield and energy balances of cultivation scenarios related to different cultivations systems. This is followed by a feasibility assessment of the required assumptions and results.
- An economic evaluation containing the formulation of cost functions, cost calculations and analysis of important aspects, and calculation of economies of scale pertaining to *M. pyrifera.*
- A technical assessment in the risks and mitigations strategies related to the different cultivation scenarios.

9.1. System boundaries and underlying assumptions

Figure 30 offers a skeletal overview of critical drivers that play a significant role in the economic feasibility of offshore cultivation and harvest of *M. pyrifera*. As indicated by the bounding box in the Figure 30, the capital costs associated with algal grow-out are included in the economic feasibility assessment. In addition the assessment will assess cost for different hatchery systems/scale, and include the cost as a unit cost/meter in the CAPEX of the cost of seaweed cultivation. Similarly, the TEA does not include the capital costs associated with processing following the pre-treatment of the algae into a storage stable condition.

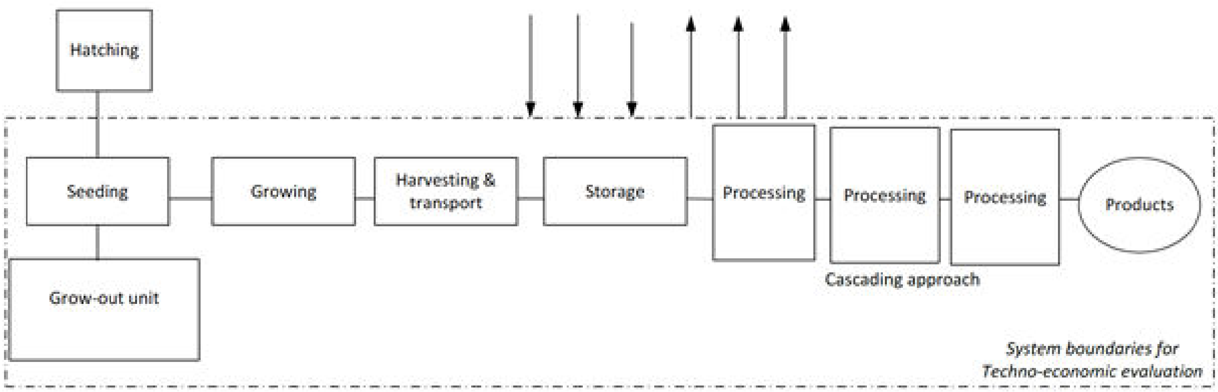

Figure 30: general schematic illustrating the parameters included in the Techno-Economic Assessment for the cultivation and harvest of M. pyrifera.

9.1.1. Species

The genus *Macrocystis* represents one of the most widely distributed species of macroalgae in the world. Notwithstanding its large range, forests of *Macrocystis* (greater than $1km^2$) are restricted to the Southwestern coast of the United States. The particularly high density of the genus in the region can primarily be attributed to the broad, sub-tidal, and rocky nature of the marine environment (Graham et al. 2007). Recognizing that the oceanography of the western coast of the United States is uniquely well suited for the genus, exploring commercial scale cultivation would appear to be a logical choice.

The general environment aside, *M. pyrifera* should be considered ideally suited for the scope of the ARPA-E Phase 1 initiative due to the fact that the maximum depth for the species does not exceed 30m (Graham et al. 2007). For the purposes of the TEA and associated analysis of system productivity and drivers, one can assume that the MacroSystems initiative will only cultivate *M. pyrifera*. All other organisms found on or around the rig will be considered biological fouling.

9.1.2. Geographic Location

Although the exact location of the pilot site represents and ongoing evaluation as part of Task 2.1 in the MacroSystems initiative, the general environmental conditions of the San Pedro Bay area can be gathered from the Catalina Sea Ranch facility and The National Data Buoy Center – a branch of the National Oceanic and Atmospheric Administration (NOAA). As described by Catalina Sea Ranch, the average depth of the aquaculture facility is between 45 and 49 meters. As revealed by averaged data from buoys in San Diego, Santa Monica, and San Pedro:

- Wind speed and direction at the surface of the water is 5.0m/s from the southwest (257.280° clockwise from North)
- Annual temperature at the surface of the water is 16.9°C with a range between 14.5°C and 18.8°C
- Annual sea level pressure is 1015.046 hPa –equivalent to 1.00atm.
- Wave frequency and direction is 0.15 waves per second from a direction of 238.541° clockwise from North
- The annual significant wave height, taken as the average of the highest one-third of waves passing over the buoy during the sampling period, is 1.4m, with a range between 2.12m in the winter and 1.00m in the summer

9.1.3. Nutrient availability

The southern coast of California – particularly the area in close proximity to Catalina Island – maintains a nutrient environment that is uniquely suited to the growth of *M. pyrifera*. Due to its characterization as of the largest and most dense *M. pyrifera* forests in the U.S., one can assume that there are sufficient nutrients in and around the island to support substantial biomass growth. Although slight reductions in nutrient availability have been recorded in the summer months, the kelp forest continues to flourish year round. Due to the continued existence of the kelp forests, however, the lower nutrient availability that may be associated with a delay in upwelling during the summer months (Barth 2007) does not inhibit the growth of *M. pyrifera*.

In an effort to confirm this assumption, however, Task 2.1 for the ARPA-E Phase 1 proposal attempts to study the volatility of nutrients within the pilot site that have been judged essential for *M. pyrifera* growth. Based on data analysis, the average nutrient availability each year in the pilot site ranges between:

Nutrient	Maximum Concentration ($\mu mol/l^{-1}$)	Minimum Concentration ($\mu mol/l^{-1}$)
Nitrate (NO_3)	9.0	1.0
Nitrite (NO_2)	0.4	0.1
Phosphate (PO_4)	0.75	0.3
Ammonium (NH_4)	0.3	0.0

Figure 31: All information pertaining to nutrient availability is derived from the Quarterly presentation: "Task 2.1 Modeling Nutrients Environmental Conditions."

9.2. Technical Description

In an effort to provide more thorough description of the rig design proposed for commercial-scale cultivation of *M. pyrifera*, one must first evaluate the specific materials necessary to construct such a rig. As described in the Finite Element Analysis, the Macrocystis rig (MC1) consists of a suspended horizontal line, smaller vertical growth lines, a variety of floats, and weights. For a more complete visual illustration of the rig design and mooring system, please see Figures 1 and 2 from the Finite Element Analysis in Task 1.2.

As state-of-the-art technology, a 200m long segment of Tipto-Lon Octoply 44mm nylon rope forms the horizontal line on the structure. From this backbone, 133 seeded lines spaced 1.5m apart will support the rapid growth of *M. pyrifera.* The seeded lines will be 3m in length and will be made from a Polyethylene type, such as Gripogreen 10mm. To increase the integrity of the structure, **2** main floats will be added to the rig using a 20m chain. The floats are assumed to be 10KN floats that will be attached to the rig by steel coupling plate and shackles. At the midpoint of the line, a 500N weight will be suspended so as to offset the buoyancy of the *M. pyrifera* as the algal species grows. The 200m mooring system will consist of 1 shot of 1½" chain and 15mm wire rope, which will be attached to two fully-fixed anchors.

By taking into account each aspect of the proposed rig design, one is then able to more easily assess the economic feasibility of installing such a rig structure in the San Pedro Bay.

9.3. Principle Drivers

The economic feasibility of commercial-scale cultivation and harvest for *M. pyrifera* is principally dependent on a series of cost drivers, which is defined as a type of cost that is relatively large in comparison to the other costs of a similar nature. For the purposes of the MacroSystems initiative, the principle cost drivers can be characterized as the CAPEX, OPEX, yield, and energy consumption associated with seeding, harvesting, and processing macroalgae. Within each of these categories, specific line items will be considered cost drivers so as to allow for a more precise evaluation of the economic feasibility of cultivation and harvesting.

9.3.1. CAPEX

For the purposes of the TEA, CAPEX is defined as the yearly cost of investment on a MACR. The CAPEX associated with offshore macroalgae cultivation can be subdivided into expenditure on the cultivation rig and on the growth lines, divided by the number of years over which the rig and the growth lines are depreciated.

$$CAPEX_{TOTAL} = TC_{RIG} / d_{RIG} + TC_{GL} / d_{GL}$$

Where TC_{RIG} is the total cost of the rig and TC_{GL} is the total cost of the growth lines. The rig and the growth lines have different depreciation profile. The rig is depreciated over 5 years, $d_{RIG} = 5$, while the growth lines are depreciated over 3 years, $d_{GL} = 3$, due to multi annual growth without re-seeding.

Elaborating further on the two factors associated with the total CAPEX of macroalgae cultivation, the total cost of a rig can be subdivided into the sum of material costs (MC_{RIG}) and deployment costs (DC_{RIG}):

$$TC_{RIG} = MC_{RIG} + DC_{RIG}$$

The material costs include those associated with anchors, chains, the horizontal fixed line and cost of fittings and signal buoys:

$$MC_{RIG} = p_{anchors} \cdot q_{anchors} + p_{chains} \cdot q_{chains} + p_{h\text{-}line} \cdot q_{h\text{-}line} + C_{fittings}$$

Where p denotes the price of the material and q denotes the quantity necessary for the rig. $C_{fittings}$ denotes the total cost of fittings and signal buoys. Based on the economic model for the cultivation of *Saccharina latissima* and *Palmaria palmata*, the unusually high costs of anchors and chains for the installation of the rig system should be considered significant drivers (Bak et al. 2018).

In a similar vein, the total cost of the rig (TC_{RIG}) also affects the CAPEX of *M. pyrifera* cultivation. Following from Ocean Rainforest's economic assessment in Urd et al. 2018, the deployment costs (DC) are defined as:

$$DC_{RIG} = (p_{vessel} + p_{labour}) \cdot q_{deployment\ hours}$$

Where p_{vessel} is the hourly cost of vessel operation offshore, p_{labor} is the hourly cost of labor and $q_{deployment\ hours}$ is the total number of operation hours needed for deployment. Due to the labor intensive and highly variable nature of the rig deployment, DC_{RIG} can represent up to 23% of the total CAPEX costs associated with *M. pyrifera* cultivation (Infante 2012).

In addition to the cost of the rig, the growth lines represent a secondary variable that dramatically affects the CAPEX associated with cultivation. Extrapolating the costs per kg of fresh seaweed from previous economic models, the growth lines represent more than half of the total cost of the rig per year. Combining the annual cost of the growth lines with that of the MACR installation, the CAPEX represents more than 80% of the cost of macroalgae cultivation and harvesting (Urd et al. 2018).

Due to the comparatively large percentage the growth lines and MACR installation contribute to the CAPEX, a series of scenarios have been investigated to assess various strategies to reduce the total cost of production. In one scenario, the number of harvests per year was increased from one to three. Even though the operational cost climbed with the higher frequency of harvest, the other cost elements and the total cost declined due to increases in biomass yield.. Taking all three of these alternative scenarios into account, one is more easily able to assess the economic feasibility of cultivation and harvesting.

CAPEX represents a critical consideration in evaluating the economic feasibility of macroalgae cultivation and harvesting due to its dependence on the average growth of seaweed per growth period in fresh weight per meter growth line. Recognizing that a foundational aspect of the ARPA-E MARINER initiative is to support commercial research and development of macroalgae cultivation in the U.S., the CAPEX associated with the rig design proposed herein represents a critical factor in making this evaluation.

9.3.2. OPEX

In a similar vein, OPEX refers the costs cultivation offshore, monitoring, maintenance, and harvesting for *M. pyrifera*. Notwithstanding the general impact of OPEX on a TEA for macroalgae cultivation and harvesting, the variable nature of the parameter dramatically impact the total cost of cultivation.

With respect to the MacroSystems economic model, the yearly operational expenditure OPEX can be calculated as:

$$OPEX = OC \cdot N_{harvests\ per\ year}$$

Where $N_{harvests\ per\ year}$ indicates the number of growth periods in a year and OC represents the operational costs for a growth period – including cultivation & harvest. Based on the proposed rig design, annual operation costs are given through the relationship:

$$OC = (p_{vessel} + p_{labor}) \cdot (q_{inspection\ hours} \cdot N_{inspections} + q_{harvesting\ hours} \cdot N_{GL})$$

Where p_{vessel} is the hourly cost of vessel operation offshore, p_{labor} is the hourly cost of labor and $q_{inspection\ hours}$ is the number of hours spent on each inspection, $N_{inspections}$ is the number of inspections in each growth period, $q_{harvesting\ hours}$ is the time spent on harvesting each growth line and N_{GL} is the number of growth lines.

In line with previous economic models describing the feasibility of *M. pyrifera* cultivation, the two driving factors for OPEX are harvesting vessel labor and fuel. Excluding depreciation, these variables account for up to 77% of the OPEX for the MacroSystems rig.

Applying the three alternative scenarios proposed in the discussion of CAPEX to calculations of OPEX, the number of harvests per year seems to be the most influential in reducing the overall cost. Although the adjustment from one to three harvests per year results in an initial increase in cost, the notably higher yield from multiple harvests quickly offsets this spike. Following this surge, the OPEX remains fairly stable whereas the CAPEX decreases (Urd et al. 2018). As a result, the OPEX does not appear to have as significant of an impact on the economic feasibility of *M. pyrifera* cultivation as CAPEX.

9.3.3. Yield

In order to determine the revenue function and the function for cost per unit seaweed, one must first identify the yield of harvested biomass during the growth period. The yield (Y) in kg is calculated as:

$$Y = G \cdot N_{GL} \cdot q_{rope} \cdot N_{harvests\ per\ year}$$

Where G is the average growth of seaweed per growth period in fresh weight per meter growth line, N_{GL} is the number of growth lines, q_{rope} is the length of each growth line and $N_{harvests\ per\ year}$ indicates the number of growth periods in a year.

Given that the number of harvests per year, the number of growth lines, and the length of the growth lines are entirely dependent on the design of the MacroSystems rig, the largest cost driver for yield must be considered the average growth of seaweed per line. By adjusting the other parameters to match the proposed rig design, as well as compiling data on the average growth per meter of *M. pyrifera*, one would be able to assess the total annual yield of the seaweed in the base case scenario. Through extrapolation, one would then be able to evaluate the relative impact on cost for cultivation and harvesting in all three alternative scenarios. By manipulating these parameters, the MacroSystems team would come to better understand the rig specifications that would maximize yield.

9.3.4. Energy Consumption

Energy consumption represents the broadest category in the TEA and takes into account the cost of seeding, harvesting, and processing *M. pyrifera*.

Although limited data exist as to the energy requirements necessary to cultivate and harvest *M. pyrifera*, some studies regarding the potential for co production of biofuel from brown algae offers some indication as to what the input costs may be. In an economic model derived by Aaron Philippsen in 2010, the energy inputs for cultivation and harvesting of brown seaweeds include: sporeling electricity, sporeling heating fuel, boat fuel, drying system electricity, transport fuel, process fuel, and process electricity.

To calculate sporeling electricity and heating, one can use the total electricity and heat input necessary to support each batch of sporelings and the dry-weight yield of mature seaweed per batch of sporelings. Taking this into account, the energy requirements for sporeling production can be calculated as:

$$E'_{SE} = \frac{(E_C + E_L + E_P) \cdot Y}{B}$$

Where E'_{SE} gives the total electricity input, Y is the dry weight yield, and B indicates the number of sporeling batches. Furthermore, E_C, E_L and E_P are the total electricity input per batch of sporelings for cooling, lighting, and circulation pumps, respectively.

The energy requirements for the boat operation (E'_{BF}) – including sporeling and seaweed transport, support operations, and boat idling – can be determined with the relationship:

$$E'_{BF} = (T_{TR} + T_{SO} + T_{IDL})$$

Where T_{TR} represents the amount of fuel used to transport the mature sporelings, T_{SO} gives the amount necessary for any additional support operations, and T_{IDL} describes the total fuel used as the boat idles. Each of these three values can be calculated by dividing the amount of fuel used by the ten times the yield ($T_{TR} = \frac{10 \cdot fuel\ consumed}{Y}$).

The electricity requirements for drying the seaweed can be determined using the mass flow of the water removed from the biomass, the efficiency of the drying technology, and the drying heat. As shown by Philippsen, these variables yield an energy demand of:

$$E'_{DE} = \frac{H \cdot m'_{WR}}{COP_H}$$

Where E'_{DE} indicates the total energy requirement for drying the biomass, H is the drying heat required to remove a unit of water, m'_{WR} indicates the specific mass flow of the water removed, and COP_H is the coefficient of performance of the heating technology. To that end, m'_{WR} can be calculated using the relationship:

$$m'_{WR} = M_f - \frac{M_d(1-M_f)}{1-M_d}$$

In this scenario, M_f indicates the moisture content of the fresh seaweed and M_d indicates the desired moisture content of the dried seaweed.

9.4. Ecosystem Services and Bioremediation Opportunities

In addition to the economic opportunities associated with raw algal biomass, commercial-scale cultivation and harvest of *M. pyrifera* could capitalize on the growing nutrient trading industry. Research suggests that the species has a relatively high capability for absorbing carbon, nitrogen, and phosphorus.

9.4.1 Carbon Fixation in Kelp Forests and GHG emissions from the MacroSystems

Carbon fixation in kelp forests can substantially exceed the carbon fixation per hectare of terrestrial forests, partly because terrestrial plants photosynthesize at 0.2-2% efficiency, whereas ocean seaweed efficiency can exceed 8%. With far more open ocean available to us than the available area for terrestrial forests, the MacroSystem has distinct advantages of scalability.

Based on multiple references citing at least 2000 gC/m2/year for kelp forests, giant kelp and many other seaweed species can sequester under optimal conditions up to 7,320 tons of carbon dioxide per square kilometer per year. Seaweed fixes carbon via photosynthesis to carbohydrates ($C_6H_{12}0_6$). A key aspect of macroalgae growth is that there is a much higher carbon to phosphorus ratio in seaweed than in the deep sea. For a phosphorus limited process, substantial net sequestration occurs because the P is more efficiently utilized for carbon sequestration by seaweed than by plankton. While plankton and oceanic waters have a ratio as low as 117:1 C:P, seaweed C:P ratios start at 220:1 and can exceed 800:1. Macrocystus has a ratio of 220:1, providing a substantial net carbon drawdown benefit to restoring overturning circulation and regenerating kelp forests and fish habitat. Each square kilometer of the MacroSystem can potentially sequester up to 2000 tons carbon per year. To take into account the 106-117 carbon atoms upwelled for every phosphorus, we are multiplying our total of 2000 tons carbon per square kilometer per year with the difference of the C:P ratio between our targeted macroalgae species, which can fix up to 220 carbon atoms for every phosphorus atom made available, and the upwelled water. This gives us a net carbon sequestration ratio of (220-117):220 or 103:220.

Therefore our net sequestration totals 936 tons of carbon per square kilometer per year in the first years, increasing later as processes are refined.

9.4.2. Increasing the Net Release of CO_2 into the Atmosphere

Water below the nutricline is rich in nutrients remineralized in the deep ocean from organic matter (Rackley, 2017). This organic matter also contains carbon. Shepherd et al. (2007) claims that upwelling of nutrients might pose a risk of being a net source of CO_2 to the atmosphere because the upwelled water might contain dissolved inorganic carbon (DIC).

A significant effect has to be considered: the water composition pumped from the depth (C:N:P) differs from that of the settling particles. As it is widely accepted that nitrogen is preferentially remineralized relative to carbon from sinking organic material (Anderson & Sarmiento 1994; Christian et al. 1997), consequently, the upward flux will allow a sinking flux of carbon larger than that contained in the upwelled water, thus potentially allowing a net air-sea flux of CO_2 to occur (Lampitt et al. 2008). Moreover, as the upwelled water will be released within the MacroSystem carbon will be used for seaweed photosynthesis.

As discussed, the MacroSystem can capture twice as much carbon as is being brought up with the deep water. According to Redfield, for every phosphorus atom, ~117 carbon atoms are upwelled. Macrocystic fixes around 220 carbon atoms for every phosphorus atom made available. When exported, this represents a net carbon sink of 103 carbon atoms per phosphorus atom (Atkinson and Smith, 1983).

Dissolved nitrogen compounds (e.g. nitrate, nitrite, ammonia, creatine and urea) are a limiting factor to growth in the surface waters of the ocean. The average dissolved nitrogen concentration of the world's oceans is almost 500 g N / m^3 in the deep ocean and around 15 g N / m^3 in the surface layer (upper 100m) (Roesijadi et al. 2008). Consequently, nitrogen fixation alone is not sufficient to maintain high productivities in the surface waters and thus the nitrogen utilized on surface must come from deep ocean waters or from land-based sources.

According to Roesijadi et al. (2008), if offshore seaweed farms were to cover around 10,000 km², with an expected yield of 1,000 metric ton of seaweed per km² per year, and an average ash-free dry weight (AFDW) of 3% nitrogen, they expect that the farms would fix and remove from the oceans approximately 300,000 metric ton of nitrogen per year. As the surface oceans contain almost 2 x 10^{15} metric ton of nitrogen in a form usable by seaweed, then the potential removal by offshore seaweed farms envisioned here is negligible in the world ocean (Roesijadi et al. 2008).

9.4.3. Economic Valuation of Marine Ecosystem Services

Although the market for carbon credits has become increasingly popular over the course of the last few years, nutrient trading credits associated with the removal of nitrogen and phosphorous from the aqueous environment represents a budding opportunity in the international sphere. Although the value of carbon, nitrogen and phosphorous credits will fluctuate dramatically over the course of the next decade, global interest in sustainable development seems to affirm the economic value of bioremediation.

With respect to the economic assessment of such a market targeted for bioremediation, one must first determine the dry weight chemical composition of *M. pyrifera*. While the exact tissue composition is highly dependent on nutrient concentrations in the surrounding environment, *M. pyrifera* typically contains 23-28% carbon (Wheeler and North 1981). Furthermore, the species maintains a nitrogen tissue composition of between 2.31-2.42% (Buschmann et al. 2008) and phosphorus is estimated at 0.2% (Hurd et al. 2014).

Following a review of existing trading programs, the approximate value for carbon, nitrogen, and phosphorous remediation credits is:

Nutrient	Credit Value	Unit	Source
Carbon	$15	Ton	State and Trends of Carbon Pricing 2017. World Bank
Nitrogen	$5.50	Kg	Ferreira and Bricker 2016
Phosphorus	$23,000 – 41,000	Kg	Nobles et al. 2014

Although these values must be considered highly volatile, potential economic opportunity associated with bioremediation can be determined through the relationship:

$$R = Y \cdot N \cdot MV$$

Where R indicates the total revenue, Y is the dry weight yield in kg, N is the percent tissue composition of the given compound, and MV is the market value of the remediation credit. Specifically for carbon, one would also need to multiply a factor of .001 to account for the conversion from tons and kilograms. By subtracting the value R to the overall cost estimates, one would be able to more accurately assess the economic feasibility of industrial scale cultivation and harvest of *M. pyrifera* within the context of the MacroSystems initiative.

9.5. Scaling Factor

Taking into account the projected growth of the macroalgae industry, one must apply a scaling factor in order to more accurately assess the economic feasibility of commercial scale *M. pyrifera* production. By modifying the yield function to account for economies of scale, one finds:

$$\text{Annual production} = Ye^{x}$$

Where Y assumes that the yield in year 1 is 100 tons, e indicates the growth factor, and x = 1,2,3, etc. One must also take into account the cost reduction that would be attributed with each doubling of annual production through the relationship: r/100-1. Based on this formula, one is able to more accurately compare the OPEX and CAPEX associated with macroalgae cultivation and harvest. As per the economic model generated by Ocean Rainforest, the combination of economies of scale, along with the cost reduction from doubling of annual yield, reveals that large-scale production will have more of an impact on the OPEX rather than the CAPEX.

9.6. Conclusion

Although the opportunities and challenges associated with large-scale cultivation of *M. pyrifera* remain fairly abstract, the strategy for the techno-economic assessment proposed herein is intended to offer a foundational framework for future development of the macroalgae industry. By taking into account the general economic formulas associated the cost of cultivation and harvesting, along with general assumptions regarding the MacroSystems pilot site, one is able to evaluate the economic feasibility of commercial scale cultivation and harvest of *M. pyrifera*. In doing so, the MacroSystems team strives to fulfill the requirements established by the ARPA-E Phase 1 Proposal to explore the potential for commercial-scale cultivation in the United States Exclusive Economic Zone.

9.7. References

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Schedule - Updates

WBS	Task Name	Mile-stone	Baseline Start	Baseline End	Actual Start	Actual End	% Comp
M1.0	Final SOPO, tasks and milestone schedule complete		7/31/2018	7/31/2018			0%
1	Design of Experimental Deployment Systems		5/1/2018	1/31/2019	5/1/2018		0%
1.1	Efficient hatchery systems, increase yield and direct seeding		5/1/2018	1/31/2019	5/1/2018		75%
1.2	Engineering design of cultivation system / description of scaling factors.		5/1/2018	10/31/2018			0%
1.3	Engineering design and deployment plan for mechanical harvesting		8/1/2018	1/31/2019			0%
M1.1	Draft Review		10/31/2018	10/31/2018			0%
M1.2	Draft design package		1/31/2019	1/31/2019			0%
M1.4	Complete design package		1/31/2019	1/31/2019			0%
2	Range of Deployment		5/1/2018	1/31/2019	5/1/2018		0%
2.1	Assessment of environmental conditions of CSR's site		5/1/2018	10/31/2018	5/1/2018		33%
2.2	Survey and map suitable areas for large scale deployment		5/1/2018	10/31/2018	5/1/2018		50%
2.3	Engineering design and deployment plan of nutrients system		8/1/2018	1/31/2019	5/1/2018		75%
M2.1	Presentation at "Half time" Category 1 meeting		1/31/2019	1/31/2019	7/26/2018	7/26/2018	100%
M2.2	Draft Design Package		1/31/2019	1/31/2019			0%
3	Techno-economic models		8/1/2018	1/31/2019	5/1/2018		0%
3.1	System productivity major drivers		8/1/2018	1/31/2019	5/1/2018		70%
3.2	Mass energy balances, Net energy returns		8/1/2018	1/31/2019	5/1/2018		50%
3.3	TEA and Economic viability including Risk Assessment and Sensitivity		11/1/2018	1/31/2019	5/1/2018		20%
3.4	Environmental impacts of solutions		5/1/2018	1/31/2019	5/1/2018		50%
3.5	Sustainability assessment		11/1/2018	1/31/2019			0%
M3.1	Draft TEAs		1/31/2019	1/31/2019			0%
M3.2	Complete TEAs		1/31/2019	1/31/2019			0%
4	Complete Phase II Proposal		8/1/2018	1/31/2019			0%
4.1	Compile reports and plans into Deployment Manual		8/1/2018	1/31/2019	5/1/2018		20%

DE-AR0000925 : Catalina Sea Ranch, LLC - Cruver
Q3 of FY 2018: April 1, 2018 - June 30, 2018

WBS	Task Name	Mile-stone	Baseline Start	Baseline End	Actual Start	Actual End	% Comp
4.2	Business Related Plan Items		11/1/2018	1/31/2019	5/1/2018		10%
M4.1	Completion of Phase II Proposal		1/31/2019	1/31/2019			0%
M4.2	Final Design and Phase II Proposal Presentation at Category 1 Meeting		4/30/2019	4/30/2019			0%
N/A	N/A		1/1/2011	1/1/2011			0%

Additional Performance Updates

A) ISSUES, RISKS, AND MITIGATION

N/A

B) CHANGES IN APPROACH

N/A

C) CHANGES IN PROJECT PERSONNEL

Climate Foundation and Primary Ocean Producers have been added to the MacroSystems team.

Bigelow Labs and University of California Irvine have been removed from the MacroSystems team.

Technology To Market (T2M)

A. PUBLICATIONS

Journal Article

- Urd Bak, Director of Research, *Algal Research* **33**, 36-47 (2018), DOI: 10.1016/j.algal.2018.05.001

B. OTHER PROJECT OUTPUT

N/A

C. FOLLOW-ON FUNDING

N/A

Administrative and Legal Updates

DISCLOSURES

E. Does the prime recipient perform any work under the Award outside of the United States/U.S. Territories? ARPA-E requires 100% of the Total Project Cost to be expended in the United States/U.S. Territories. The Prime Recipient may perform certain work overseas if authorized in advance by the ARPA-E Contracting Officer (e.g., by approval of a Foreign Work Waiver Request). If Yes, provide details.

The MacroSystems team includes overseas sub-contractors including Ocean Rainforest and Patagonia Seaweeds and Hortimare. ARPA-E contracting officers have previously approved these sub-contractors as team partners.

DE-AR0000925 : Catalina Sea Ranch, LLC - Cruver
Q3 of FY 2018: April 1, 2018 - June 30, 2018

Cost Updates - LEAD: Catalina Sea Ranch, LLC (DE-AR0000925)

Design of Large Scale Macroalgae Systems (MacroSystems)

ARPA-E RECORDS ONLY (invoices edited by performer are highlighted)

Invoice #	Date	Total	Federal Share	Performer Share	Shortpays	TT&O	Personnel	Fringe Benefits	Travel	Equipment	Supplies	Contractual	Construction	Other	Indirect
AR0000925-01	6/11/2018	$159,534.05	$143,580.64	$15,953.41	$0.00	$0.00	$60,247.50	$0.00	$2,332.58	$0.00	$0.00	$85,786.57	$0.00	$0.00	$11,167.40
Total:		$159,534.05	$143,580.64	$15,953.41	$0.00	$0.00	$60,247.50	$0.00	$2,332.58	$0.00	$0.00	$85,786.57	$0.00	$0.00	$11,167.40
% Expended in Budget Category:		29.01%	29.00%	29.02%		0.00%	45.43%	0.00%	44.71%	0.00%	0.00%	25.51%	0.00%	0.00%	39.16%
Remaining:		$390,459.95	$351,441.36	$39,018.59		$112,534.85	$72,373.50	$0.00	$2,884.42	$0.00	$0.00	$250,531.43	$0.00	$47,322.00	$17,348.60

Overall Proposed Cost Share: 10.00 %   Invoiced Cost Share to Date: 10.00 %   Proposed TT&O to Federal Share: 22.73 %   Actual TT&O to Federal Share: 0.00 %

Agree that the information provided is accurate and correct: ■ Yes □ No

Certification of Compliance

I certify that I have the authority to make the following certification and to submit this Research Performance Progress Report on behalf of the Prime Recipient. On behalf of the Prime Recipient, I further certify that the information provided in this Research Performance Progress Report is accurate and complete as of the date shown below. I understand that false statements or misrepresentations may result in civil and/or criminal penalties under 18 U.S.C. § 1001.

Signature: Maria Smith

Submitted by: Mrs. Maria Smith (maria@catalinasearanch.com), Catalina Sea Ranch, LLC

Submitted Date: 7/30/2018 10:07:55 PM