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The supplementary material has been included as an appendix at the end of this document.

Title: Comprehensive quantification of production costs for large-scale kelp aquaculture and cost reduction opportunities

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Comprehensive quantification of production costs for large-scale kelp aquaculture and cost reduction opportunities

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Highlights

- A new tool couples kelp production economics, biology, structure, and operations
- The tool was applied to a case of 40ha *Saccharina* farms 20km offshore in 100m depth
- Cost of production (COP) for a baseline farm at this site was \$2618 fresh tonne^{-1}
- COP was most sensitive to vessel rates, yield, maintenance, harvest, and structure costs
- Coupled operational and structural line-of-sight improvements reduce COP to \$383

Abstract

A highly realistic techno-economic analysis (TEA) was developed to assess the cost of production (COP, US $ per fresh tonne kelp) for large-scale kelp aquaculture. The TEA resolves feedbacks across structural design and response, operational requirements and decisions, site properties, and biological response. We apply the TEA to a *Saccharina latissima* farming operation at a 100m deep, 405 hectare site located 20 km offshore in the Gulf of Maine. Our *baseline* scenario included a farm previously designed for minimal structure cost normalized by production capacity and operated according to procedures typical for contemporary US-based kelp farms. Assuming "line-of-sight" farm operations, i.e. those that could be implemented with existing technologies, the structure was redesigned for minimized COP (*improved* scenario). Leveraging the comprehensive nature of the TEA to balance operational and structural design choices, COP was reduced from $2,618 at *baseline* to $383 in the *improved* scenario. Primary cost reduction drivers included: (1) use of purpose-built, correctly sized vessels, (2) heavily mechanized operations, (3) at-sea processing of harvested kelp into a slurry (4) biomass storage in vessel holds, (5) structural design that minimizes loads, maximizes operational efficiency and spatial productivity, and (6) cultivation at maximal depths for site specific light penetration. *Baseline* results were most sensitive to workable wave height thresholds, vessel cruising speed, yield and distance from port. *Improved* scenario COP was most sensitive to yield, farm component lifespan, and structural costs. Results highlight that no single innovation in operations models or structural design will dictate potential COP minima for large-scale kelp farming.

1. Introduction

1.1 Seaweed Farming

Marine macroalgae (seaweeds), kelp in particular, are a versatile crop with many potential social, economic and environmental benefits. Farmed seaweeds may help reduce existing agricultural pressures on terrestrial habitats, freshwater, and nutrients to the extent that they replace more resource intensive foods. Seaweed can also absorb problematic excess nutrients and CO_2 from surrounding seawater, thereby improving local ocean conditions [1–3]. Carbon dioxide removal using marine macroalgae has received particular attention in the last five years [4–6]. Van den Berg et al. [7] categorized these approaches into sequestration and biomass utilization-based pathways. Sequestration pathways include Natural Sequestration, whereby seaweed is grown or restored, and recalcitrant dissolved organic carbon (rDOC) is locked into ocean sediments for >100 yrs, and Human-mediated Carbon Dioxide Removal (CDR), whereby cultivated biomass is intentionally sunk in the deep ocean. Many researchers are rigorously evaluating the potential and economic feasibility of farmed kelp to serve as a CDR [8–11] However, there are important ecological and ethical questions regarding this pathway regardless of the economic feasibility and carbon sequestration efficacy [12,13]. Biomass utilization pathways to avoid emissions include production of seaweed-based products that replace higher carbon footprint products with ones that help reduce emissions in other high-carbon processes; e.g., reducing CH_4 in bovine agriculture by replacing a portion of the feed with seaweed [14–16] or minimizing use of carbon intensive fertilizer in row crop agriculture via application of seaweed based biostimulants [17]. Among other low carbon alternative commodities, cultivated seaweed biomass can be used as an alternative to petroleum-based feedstocks for liquid fuels and plastics [18–21]. Regardless of the end use, expanding production of farmed seaweed could catalyze new opportunities for low-GHG food, fuels, and raw materials.

More than 98% of farmed seaweed produced today originates in Asia [22]. The top seaweed farming nations (*i.e.,* China, Indonesia, and South Korea) make up ~85% of the >35 million metric tonnes yr^{-1} of globally farmed seaweed. Here the seaweed farming industry operates at commodity scales, is fully established, and occupies largely saturated nearshore growing areas [23]. In these regions, production is split between tropical branching rhodophytes (red seaweeds) and temperate phaeophytes (brown seaweeds).

New areas of production for temperate brown seaweeds, principally kelp species, have emerged over the past 15 years in the North Atlantic (east and west) and the northeast Pacific. To date, the predominance of production in these regions has been *Saccharina latissima* (sugar kelp) [24–26]. Australia, New Zealand, and Chile are also emerging regions of production. Improvements in technologies and operations enabling economies of scale, particularly in exposed open ocean settings, present an opportunity to make step-function changes in global seaweed production by growing the industry with a focus on emerging markets outside of Asia.

1.2 Industry Needs

One of the major barriers to the growth of the farmed kelp industry in Northern, temperate regions is the lack of validated and cost-effective business models for producing large quantities of seaweed at offshore, exposed sites where there is more space and lower risk of conflict with other marine stakeholders [20]. Accurate information on the farm-level economics of commercial scale kelp farms is needed to make informed decisions regarding site selection, financing, production optimization, and R&D priorities. Recent efforts to characterize the economics of large-scale seaweed farming have analyzed co-location with offshore wind farms [7], the performance of offshore cultivation rigs designed specifically for deep-water, high-energy sites in the North Atlantic [27], the feasibility of free-drifting carbon fiber lines coupled with biorefining [28], a modular farm array for biofuels applications[11,29,30], and the economic evaluation of CDR via sinking kelp grown on an offshore structure [8]. As site characteristics, structural requirements, and market or operationally driven limitations vary across applications, comprehensive economic analyses are needed to realistically evaluate the wide range of potential industrial macroalgae production methodologies. Most economic models of seaweed production systems apply limited connectivity among model components such as structural, operational or biological evaluations, or fail to resolve the entirety of one or more of these components. Because all aspects of the farming systems are linked, isolated or incomplete models can lead to misidentification of key economic drivers.

1.3 Objectives and Approach

The purpose of this study was to evaluate the cost of producing kelp in the context of contemporary farm and nursery designs that are scaled for water depths and production volumes relevant for industrial supply chains. Production costs were evaluated using a Techno-Economic Analysis (TEA) framework first developed by Coleman et al. [8] for estimation of the levelized cost of carbon sequestration. Our economic modeling framework encompasses components of the kelp aquaculture value chain from nursery to the farm-gate, but is "agnostic" as to the end use. While the model is widely applicable, we demonstrate its utility using a hypothetical 1,000–acre farm located at an exposed offshore site in the Gulf of Maine, USA.

Structural, Biological, and Operational component models were integrated to estimate the comprehensive cost of producing kelp. Importantly, our integrated model resolves system-feedbacks across these component models, consolidating and normalizing the implications of all cultivation aspects and decisions into a single cost of production (COP) quantified in US$ per fresh (not dried) mass of kelp landed. While the parameter space is large and many scenarios can be explored with the modeling framework, we quantify COP for a single location and two contrasting structural and operational models.

2. Methods

2.1 Overview

The COP for representative offshore kelp farm designs and operational models were estimated using an integrated techno-economic model that synthesizes a series of complex relationships between parameters representing farm operations, the cultivation system’s structural properties, the ocean environment, and growth of the kelp biomass. Ultimately this model allows for the balance of trade-offs across operational, structural design, and siting decisions by quantifying the impact on total annualized cost of operating and production volume. To the greatest extent possible, all positive or negative impacts from a given process or assumption are balanced by a negative or positive outcome at the margins. In this way, trade-offs associated with structural or operational decisions are implicitly reflected in the model's quantitative results.

The scope of this study includes the process of producing marine macroalgae biomass from nursery to landing of the biomass onshore. Because any processing thereafter, including drying, is outside the scope of this study, all costs are reported in terms of fresh biomass weight.

The integrated model represents a major revision of the techno-economic model described by Coleman et al. [8] which was developed with the goal of evaluating the cost of sequestering carbon via sinking of farmed kelp biomass beyond the continental shelf. The revised model integrates far more detail across the farming process, providing insight into the impact of discrete structural and operational decisions and requirements, vessel properties, business models, site properties, and site characteristics. The outputs of the revised model are indifferent to the end use of the harvested seaweed, allowing researchers, industry members, and policymakers to use the results for multiple applications.

2.2. Context

2.2.1 Cultivation Site

Competition with other ocean users coupled with nearshore oceanographic changes due to climate change will force large scale kelp farms to locate outside of sheltered, coastal regions [20]. Consequently, we assumed the farm site would be located 20 km from a shore-based operations port on the Maine coastline. Given that the United States lacks a comprehensive legal framework for siting farms in federal waters (i.e., > 3 nm from the coast), we adhered to Maine state lease laws. No aquaculture leaseholder in Maine may possess a single tract that is >100 acres or possess multiple tracts that in aggregate amount to >1,000 acres. Therefore, we assumed ten, 100-acre sites for a total of 1,000 acres (405 ha). Though the Gulf of Maine was selected as the context for this study, the farm designs and nursery assumed here have potential for implementation across most temperate ocean regions.

To ensure that the farm design and associated structural cost would be realistic for offshore conditions, structural analyses referred to data collected from a deep water (100 m), fully exposed site. Representative load cases, i.e. wave and current characteristics in extreme storms, were estimated using historical data from the NERACOOS Buoy E01 (Central Maine Shelf), which is located 3 nm southwest of Monhegan Island, Maine and is fully exposed to extreme wave conditions typical for open ocean areas in the Gulf of Maine. Extreme wave and current magnitudes were estimated using extreme value analysis methods described by [31] applied to the 12 year data set from the E01 buoy. The conditions that define the maximum strengths of the structural components (survival limit state) were defined as the combination of collinear currents and waves each with a return period of 25 years (Table 1). Exposure velocity [32,33] for the site was estimated at 0.85 m/s.

Table 1 metocean conditions used for structural analyses

	significant wave height (m)	**peak period (sec)**	**surface current speed (m/s)**	**Used to:**
extreme conditions*	7.67	8.79	0.75	define structural requirements
monthly storm	3.70	8.66	0.33	quantify line interaction
95th percentile conditions	2.62	5.02	0.36	define floatation requirements
average conditions	0.96	3.03	0.14	quantify weather days

*25-year return period storm for the month of April

2.2.2 Baseline Cultivation Structure

The layout of the cultivation structure heavily influences production efficiency. Coleman et al. [8] the selection of our *baseline* farm design. In that study the farm structure was chosen with the goal of maximizing annual kelp production versus cost of the structure.

2.3 Structural Analysis

2.3.1 Structural Loading

Load capacity requirements for farm structure components were estimated using the Kelsim modeling suite; a Hydro-Static Dynamic Finite Element Analysis approach (H-S DFEA) [34]. This approach uses a time-domain modeling approach specific for aquaculture (e.g.) that incorporates a Morison et al. (1950) methodology. The time-domain modeling approach applies the finite element method to incorporate geometric and material properties of the farm's structural components (e.g. [35]) and includes representative aggregated kelp elements [36–38]. These dynamic analyses, resolved in the time domain, estimate external hydrodynamic and internal structural loads across the farming structure. By fitting peak loads (over a defined threshold) to an extreme value distribution, statistical load maxima are estimated for a given simulated storm event. These loads are then translated into required structural capacity, using safety factors typical for offshore structures (see supplemental material) [39–41].

2.3.2 Tangling Analysis

Substantial interaction between cultivation lines during storms can severely limit farm productivity, and increase operational costs [25,42]. Interaction brings significant risk of cyclic abrasion and tangling, both of which can lead to crop loss, reduced line lifetime, and additional time to untangle the lines during harvest operations. To quantify the extent of this risk, the structural modelling tools described above are used to evaluate the farm with full biomass in the one-month storm for the site. The one-month storm is estimated using metocean data from months within the growing season. Interaction is quantified for all cultivation line elements and is defined as entering a chosen proximity of another cultivation line scaled according to estimated average kelp frond length. The total length of cultivation line that experiences "interaction" for at least 10% of the simulation time is considered at risk of kelp loss and tangling. The average kelp loss and tangling length per interacting length is user defined.

2.4 Biological Model

2.4.1 Yield Estimation

Sugar kelp (S. *latissima*, hereafter kelp) was chosen as the model species as it is the most commonly cultured kelp species in North America and Europe [20,26]. A numerical model was used to estimate the growth of the cultivated kelp as a function of key environmental parameters [43–45]. Important inputs included nitrate concentration, water temperature, solar insolation, and light extinction coefficient (proportional to turbidity). Inputs for this model were estimated using local historical data when available, and, otherwise, generalized trends for the region [46–49] (see Figure 1). Linear Interpolation was used to fill gaps in available data. Water temperature and nitrate concentration are often vertically stratified; however for simplicity, values expected within typical cultivation depths (<6m) were assumed broadly.

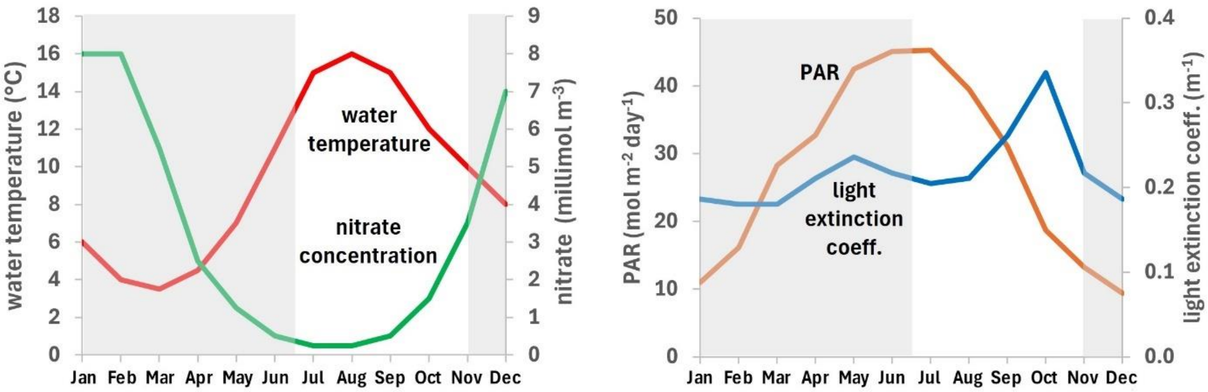

Figure 1 – Growth model environmental inputs - Representative seasonal changes in environmental conditions at the site used to estimate kelp growth. The grey region represents the kelp farming season.

2.4.2 Sagging Analysis

Biological productivity is highly impacted by PAR [50]. Because visible light is absorbed and reflected by water and suspended solids, PAR is highly dependent on depth. Cultivation depths are a function of farm design features including tether lengths at nodes (connection between header line and anchor line) and droppers (tethered buoys connected along length of cultivation lines), mooring stiffness, dropper spacing, and system pretension. To resolve cultivation depths, a static 3D numerical model of the farm was used to estimate depths of the cultivation lines across the cultivation array as a function of yield. Because sugar kelp is generally negatively buoyant in exposed offshore settings [51], increasing yields throughout the season introduces sagging, reducing the exposure to PAR [30]. By incorporating daily yield dependent average cultivation depth into the biological model, the important feedback between farm structural and biological productivity is resolved.

2.4.3 Yield Scaling

Linear yields of 20 kg m^{-1} were assumed for non-depth limited growth conditions on the nominal harvest date (middle of the harvest period) of May 15. This is a notably higher yield estimate than is typically seen in the Gulf of Maine [25], and represents expected yield dividends gained by implementation of a dedicated breeding program. Over the course of 5 years of breeding research the US DOE ARPA-e MARINER program was able to produce multiple strains of *S. latissima* with yields >20 kg m^{-1} (up to 28 kg m^{-1}) [52,53]. This yield is consistent with typical yields of farmed *Saccharina japonica* in East Asia [54]. The biological model reports mass per kelp frond as a function of the prescribed time interval. To scale this value to the expected yield (for the farm structure), the number of fronds per unit length of cultivation line is scaled and held constant throughout the season.

2.5 Workboat Model

Vessels serve as the primary work platform for at-sea farming operations, providing transportation for workers, materials, and biomass to and from the farm site. Vessels allow workers to interact with the farm during at-sea operations such as seeding, maintenance, and harvesting. Work vessels can be designed in an infinite number of configurations including different hull configurations, sizes and capabilities including storage limits, deck space, lifting capacity, cabin space, etc. All features will ultimately have performance tradeoffs including cost, endurance, fuel efficiency, speed, stability, maneuverability, and operational efficiency. Consequently, assuming use of a single vessel type and size for a range of farming scenarios is overly restrictive and may inherently bias specific scenarios. In response, we have built a model that automatically searches the vessel design space to identify characteristics that result in the lowest cost for the farming operation under investigation. The basic premise of this search algorithm is that a vessel should be just large enough to hold and transport the biomass that can be harvested in a single shift, i.e. one trip to and from the home port and the farm site.

Vessel length is automatically determined for the evaluated scenario and governs most vessel characteristics. Lightship (unloaded) vessel displacement (quantified in weight) is determined from user input for length to beam ratios, length to draft ratios, and shape factor. The default for these parameters aligns with those typical for monohull commercial fishing vessels (see supplemental material). Lightship displacement is then used to estimate rated engine power, which impacts idle fuel consumption assumed during on-site operations. Nominal cruising speed is set as a function of vessel length, aligning with typical "hull speeds" for commercial fishing displacement vessels. Because cruise speed is also a variable input, the speed to length ratio is used to estimate the cruise engine power to displacement ratio. Using a standard relation of fuel consumption rate to engine power used, the fuel consumption for the unloaded trip to the farm and the loaded trip from the farm can be estimated. Total fuel consumption over the duration of a shift determines minimum vessel fuel reserves (and resulting weight).

Cabin space and freshwater weight is a function of crew size and shift length. The cabin occupies a portion of the vessel planform area. The number of levels is related linearly to the length of the vessel. Aside from an unused portion in the bow, the remainder of the vessel planform area represents usable work and storage space.

The kelp carrying capacity is a function of hold space, deck space and minimum vessel stability. In this analysis, stability is quantified as the metacentric height of the fully loaded vessel, which must be the greater of windage stability criteria as outlined in the Federal code of Regulation for vessels traversing offshore locations in winter conditions or 0.15m [55]. Approximate weights and vertical distributions of all vessel components (hull, cabin, engine, deck machinery, etc.), active loads (harvested biomass, harvest containers, fresh water, fuel, etc.), Water plane shape and submerged volume are used with the centers of buoyancy and gravity to estimate the metacentric height. Bulk density of kelp lifted from the water and piled in a container [56], hold volume, and usable deck area (total deck space minus area needed for maneuvering and machinery footprints) are then used to iteratively solve for the vessel length that accommodates all design criteria. Options also exist for storage of biomass on the deck only. In this case containers holding the biomass are stacked, the number of levels of stacking are varied to accommodate stability requirements.

The length of the vessel and harvest stack height are solved iteratively alongside estimates of operational efficiencies and transit times to determine the minimum size vessel which supports the maximum biomass harvest during the time available in a given work shift. Shift length is a model input and can range from a few hours to multiple days.

The portion of "Weather days", i.e. days in which operations are not possible due to wave height and / or wind speed at the farming site, are quantified for each relevant portion of the farming season. Weather day frequency is an estimated function of site specific probabilistic significant wave heights for the given time interval and a threshold workable wave height.

2.6 Labor Model

2.6.1 Farm Workers

Vessel crews form the basic unit of the operational labor model. A vessel crew is composed of a captain, a foreman, and deckhands. The foreman is responsible for coordinating crew members and is assumed not to contribute substantially to the at-sea manual tasks. The required number of crew is unique for each at-sea operation.

Salaried workers are assumed; with an individual working 40 hours per week. When more than 40 hours per week is required for a given position, another person must be hired. In addition, a given employee works a maximum of 8 hours per day. Consequently, shifts that exceed that limit require multiple crews on board the vessel. All time spent on the vessel, including time not spent actively working, is included in the 40 hour per week cap.

2.6.2 Office workers

Administrators and managers are needed to schedule farm operations, coordinate vessel crews, handle finances, hire farm workers and engage in various other business administration duties. Also salaried, these workers are hired for the duration of farming season and an additional buffer period each year. The number of administrators hired is a function of the number of total employees, and the number of vessels bought or hired (see supplemental material). The number of managers employed is estimated as a function of the number of independent crews engaged in operations throughout the farming season. Managers are employed for the full season and the prior and following month. Office space and associated utilities are required to support the office workers. The rented space is scaled according to the number of office workers.

2.7 Nursery Model

Coleman, et al., [57] calculated the costs associated with producing kelp "seed spools", (juvenile sporophytes settled on twine-wrapped PVC pipes) in a land-based nursery as a function of annual linear seed string output. We utilized a modified version of this model to estimate the cost of seeded twine ($\$ m^{-1}$), assuming exclusive production for our 1,000-acre offshore farm. The kelp sporophyte rearing technique described by Flavin et al. [42] was assumed. Modifications to the model included shifting labor scaling assumptions to be contingent not on the number of spools in production, but the total number of tanks needed to produce the requisite number of spools per season. This provides different labor scaling and reduces the number of people-hours needed for spool production. Additionally, the total spool capacity per culture tank was increased (see supplemental material). All other parameters and nursery production processes remained unchanged.

2.8 Startup Model

Before normal annual operations can begin, the farming business must undergo a "startup" period, including unique processes that only occur on decade scale cycles. These steps include site characterization, engineering, anchor installation, permitting, and land-based farm assembly and installation of the equipment offshore.

2.8.1 Permitting

Permitting offshore aquaculture farms requires consultation with several government entities, various forms of public engagement, and can take multiple years from initiation to approval (or denial). Important permitting components often include NEPA approval, Army Corps of Engineers (ACOE) approval, consultation with state coastal commissions, coordination with federal marine spatial planners at NOAA, approval from NOAA Fisheries Protected Resource Division, consultation with the Coast Guard, and a permit from state marine resources offices (if operating within state waters) [58].

We assume that consultants are hired on an hourly basis to support the necessary data collection and document preparation. Primary tasks include site selection, preparation of an Environmental Impact Statement (EIS), community outreach, regulatory outreach, habitat surveys, and quantification of risk to marine mammals and other protected species. Each task includes a base time and additional time scaled by characteristics of the site such as footprint area, number of plots, distance from shore, or water depth (see supplemental material). In addition, an administrator is employed to manage contracts, consultants, and regulatory paperwork over the assumed permitting time frame (2 years). A flat permit application fee per plot must be paid; the fee levied by the State of Maine for this purpose was used.

2.8.2 Engineering and Site Characterization

Engineering of aquaculture structures minimizes the risk of structural failure and maximizes operability. Engineering procedures typically include concept design in consultation with the farmers, identification of goals, constraints and performance criteria, characterization of the site (bathymetry, sediment type, and metocean conditions), iterative basic structural analysis and performance evaluation, detailed design, component selection, and deployment planning [56]. We assume that an engineering firm is hired on an hourly basis to manage and support this process. Engineering hours are scaled by the size of the farm (footprint and number of plots) (see supplemental material). Site characterization, which is essential for the engineering process, requires geotechnical, geophysical and metocean surveys. We assume that the effective lifetime of the engineering effort coincides with one permitting cycle (20 years) [59]. Assuming non-stationary site conditions influenced by climate change, site characterization lifetimes are estimated at two permitting cycles (40 years).

2.8.3 Mooring Installation

Installation of drag embedment anchors for highly loaded offshore structures requires specialized high-thrust vessels capable of handling, setting, and proof loading the anchors. While relatively resilient to sediment type and straightforward to install, drag embedment anchors must be set properly and proof loaded to ensure rated holding capacities [60], especially in scenarios where uplift loads are expected. The size and availability of these vessels (quantified as home port distance from the farm site), is estimated as a function of the anchor mass. After mobilization to the farm, the vessel engages in sequential deployment trips from the farm's home port, where mooring equipment is loaded, to the farm site, where the gear is deployed. Node floats, mooring chain, anchor line, node connection plates and mid-line mooring floats are all deployed with the anchor. Key variables include vessel cruising speed (scaled by vessel size), time required per installed anchor, at dock loading times, workday length, deck space (limiting number of anchors per trip), and expected number of "weather days" (see supplemental material). Time for hauling anchors at the end of their lifetime or during replacement of anchor line components is included.

2.8.4 Cultivation Array Assembly and Deployment

Farm assembly and deployment processes depend on the specific layout and design of the cultivation structure. We assumed that structural components would be prepared within a flat outdoor land-based area comparable in size to the array. Once assembled, the entire array is consolidated and rolled around a large buoyant capped HDPE pipe, transported to the sea, and towed out to the farm site. Once onsite, the workboat crews unroll the array, connect the corners to the preinstalled mooring lines, tension the mooring lines using a rented winch (the cost of which is scaled according to required mooring pretension), and then connect the droppers to the cultivation lines.

Required time (per worker) for discrete tasks throughout this process (on land and at sea) are quantified; examples include measuring rope, splicing rope terminations and connections, securing connection hardware, assembling droppers, mooring line attachment, attaching droppers, moving and setting up between tasks, etc (see supplemental material). The time per task is then multiplied by the relevant farm design characteristic (quantities, lengths, etc.). The window (number of days, each with defined work hours) within which these tasks must be completed is given. The number of onshore laborers, at-sea crew, and work vessels is determined accordingly. The array must be assembled and redeployed with a periodicity equal to the shortest lifetime of the array components (typically the cultivation lines).

2.9 Regular Farm Operations

2.9.1 Time Framework

The basic unit of farm work is quantified as a "shift", which includes a chosen number of days starting with loading equipment and people onto the vessel at port and ending with returning to port and unloading people, equipment, and harvested biomass. Each day in a shift can include a set number of work hours, during which the vessel can transit to / from the farm and engage in farm operations.

Regular farming operations are divided into three primary phases: seeding, maintenance, and harvest. Each of these phases is allocated an exclusive portion of the farming season. Seeding begins on November 1, maintenance follows, and harvest is centered on May 15. These dates represent typical timeframes for nearshore kelp farming operations in the Gulf of Maine [42]. Seeding and harvest time requirements are both dependent on the number and total length of cultivation lines; consequently, optimal seeding and harvest windows remain proportional to one another. The maintenance window occupies the remainder of the season. The model automatically sweeps across multiple combinations of operational windows and shift lengths; the combination associated with the lowest cost of production is selected.

Greater weather day portions (see section 2.5 Workboat Model) effectively shorten operational windows and require a higher concentration of operational time in a given period. For multi-day shifts, intended shift lengths are shortened on average according to the estimated portion of weather days.

Total time per operation is estimated as a function of discrete tasks multiplied by the number of tasks, which is a function of the number or length of relevant components. For all tasks that involve lifting a cultivation line to the surface, the difficulty, and hence required time, is increased with cultivation line depth. The number of vessels required per operation is estimated by dividing the required time for a given operation by the total available work time per vessel in a given operational window.

2.9.2 Seeding

Conventional seeding practices are assumed [42]. Each vessel seeds only one cultivation line at a given instant. The vessel moves along that line deploying the seed string at a given rate. The time required to travel to, attach to, and set up the seed string spool on a given cultivation line are accounted for. Though unusual for smaller nearshore operations, the cultivation lines are assumed to remain in the water year-round. Consequently, at-sea cleaning of lines (from biofouling) is required and is integrated into seeding operations; the cultivation lines are stripped and cleaned immediately ahead of application of the seed string. The time to stop the operation at each dropper for disconnection and reconnection is accounted for (see supplemental material). Space occupied by crates containing seed string spools is used to estimate the optimal size of the seeding vessels.

Direct seeding, the process of directly applying gametophytes to the on-farm culture substrate, holds potential to greatly reduce nursery costs by eliminating the onshore tank cultivation stage for juvenile sporophyte development. While promising, this approach was not considered here as recent studies highlight the potential for decreased yields from direct seeded lines [61,62].

2.9.3 Maintenance

Maintenance operations include inspection of connections and replacement of components as needed. Frequency (times per year) and time per inspection for each component type connection are given (see supplemental material). A given probability of premature failure governs the average annual time needed to replace a component type ahead of the expected replacement date. Systematic or cascading failure from single component failure is not assumed. In the absence of criteria for a minimum maintenance vessel size, a 10 m long vessel is assumed. Deep water ROVs are used to inspect farm components that cannot easily be raised to the surface. The time required to deploy and navigate the ROV to the component of interest is accounted for.

2.9.4 Harvest

Harvest operations begin with cultivation lines being lifted via deck machinery, e.g. hydraulic knuckle boom cranes, and orienting these lines such that they straddle the length of the deck. The vessel moves along the cultivation line while crew members cut kelp from the line allowing it to fall into containers below. Once the container is full the crew member must move the container into storage and replace it with an empty one. Multiple harvest stations allow the vessel to progress along the line as fast as the combined harvest speed of the crew. The time and / or rate for each discrete action is used to estimate the total time to reach vessel storage capacity. The resulting harvest rate is a function of task timing, individual length of cultivation lines, the linear biomass yield, the container volume, the bulk density of the kelp, and number of harvest stations (see supplemental material). Harvesting is slowed down by cultivation line tangling. The added time is proportional to the total length of interacting cultivation lines (see section 2.3.2).

Unharvested kelp will continue to grow during harvest operations. Linear biomass yield is estimated for each day of the harvest window, according to the biological model described in section 2.4. The aggregate harvest rate provides the basis for an estimated length of cultivation line harvested in a given day which changes inversely proportional to the yield. The total amount of harvestable kelp is limited by the total length of cultivation lines. The "harvest efficiency" is estimated as the ratio of actual harvested biomass versus the biomass that would have been harvested if the harvest occurred entirely within a single day (on the nominal harvest date, May 15). Depending on the harvest window (centered on May 15) and the shape of the growth curve, the harvest efficiency is typically less than 1.

2.9.5 Onshore Operations

All vessel operations require interaction with the shore. People, equipment, supplies, and harvested biomass are loaded and unloaded there. Shoreside infrastructure includes lifting equipment (stationary cranes and or forklifts) and a pier. A storage yard is rented to accommodate equipment (farm components and / or vehicles) while not in use. The size of the yard is scaled proportionally to the total mass of the farm equipment. Harvested biomass stored in vessel holds is pumped out using a high flow rate pump appropriately designed for solids; this necessarily assumes the kelp is turned into a slurry (see section 2.9.6). Biomass transported in containers above deck are unloaded using shoreside lifting equipment.

2.9.6 Mechanization

To decrease task time requirements, operations like seeding lines can be mechanized [63]. While the specific mode of efficiency increase is not resolved in this model, theoretical deck machinery can be added to vessels to aid seeding, maintenance and harvest operations at a cost proportional to the desired performance increase (see supplemental material). Fuel and deck space used by the theoretical machinery is also included. Machinery weight and height are also estimated for vessel stability purposes. A machine for processing kelp into a slurry as it is harvested is also approximated.

2.10 Economic Integration

2.10.1 Labor

Vessel deckhands, foremen, and captains are hired per operational period (i.e., seeding, maintenance, and harvest windows). Pay is prorated from annual salaries for the designated period (see supplemental material). To account for indirect costs of labor, an indirect labor rate is added to all labor salary costs. Administration and insurance costs associated with employing at-sea workers are accounted for separately (see section 2.10.8). Each person uses materials and equipment that must be replaced or replenished regularly; a "consumable" cost per person per day is estimated. Administrators and farm managers are paid a salary proportional to the ratio of total number of hours required in a year versus hours associated with a full-time position (FTE).

2.10.2 Vessels of Opportunity

Two vessel cost models were implemented. The first assumes that vessels of opportunity, e.g. commercial fishing boats, are used for farm operations. Vessels are contracted for the duration of the specific operation (deployment, seeding, maintenance, or harvest). Standby costs are charged as a portion of the nominal day rate whenever the weather does not allow operations offshore.

We assume no limitation on the number or size of vessels available for hire at any given time; consequently, for each operation only vessels of the appropriate size are hired. The applied hourly rate (estimated as a function of vessel displacement), beam to length ratio, and portion of the vessel length occupied by the deck are typical for commercial fishing vessels (see supplemental material). Fuel expenditures were estimated as a function of vessel size, time spent cruising, and time participating in farm operations (and corresponding engine power requirements).

2.10.3 Farm Owned Vessels

The second vessel model assumes that the farming company purchases and operates custom designed vessels with characteristics specially suited for offshore farming operations. The specialized construction allows for an increase in operational efficiency; i.e. task timing is reduced broadly across all operations by a linear factor (25%). Because harvest operations require the largest, most stable vessel, these requirements are used to determine the size and configuration of the farm owned vessels, which are also used for all other operations, including array deployment.

The total cost of the vessel is estimated as a function of the vessel displacement (see supplemental material). The cost of the hull and major subsystems (power & propulsion system, deck machinery, hydraulics, and electronics & plumbing) are estimated as fixed portions of the total cost. The cost of the cabin is a function of the predicted cabin size (see section 2.5 for the sizing procedure). The vessels are purchased with 50% of the cost financed with a 12-year loan compounded annually at 5% interest. The minimum number of vessels purchased by the farm is determined by the maximum number of vessels required to complete any operation (seeding, maintenance, or harvest) in the allowable time window.

Farm owned vessels are assumed to generate a separate revenue stream in the non-kelp-farming portion of the year (the "off-season"), i.e. leasing for use in other marine industries. Off-season daily rates are estimated using the total annualized vessel costs divided among days used (assuming a 36% usage rate), and a 25% profit margin. This off-season revenue offsets the cost of using the vessel during the farming season. The effective day rate of each vessel can be estimated as the total annual cost of owning and operating the required number of vessels (including annualized capital expenditure, annual maintenance, insurance, and dockage) minus the offseason revenue divided by the total number of days working on the farm in a given year.

2.10.4 Structural Costs

Annualized farm component costs included loan payments and depreciating equity. The upfront costs for component categories were estimated as a function of required relevant performance (e.g. breaking strength, net buoyancy, submergence rating, mass, etc.) and quantity (units, length, etc.) (see supplemental material). Anchor sizing assumed muddy seafloor sediments. Shipping costs were estimated as a function of total equipment mass. Each component category is assigned an estimated lifetime assuming continuous use in the open ocean environment (see supplemental material). Average expected lifetime of cultivation lines is reduced proportionally to interacting length (see section 2.3.2). 50% of capital expenditures were assumed to be financed with conventional loans compounded annually with a constant 5% interest rate. Loan terms for each component type were set at 50% of the expected component lifetime.

2.10.5 Startup Costs

Startup costs include those associated with engineering, site surveys, navigating the permitting process, lease licensing, installation of mooring components, assembly and deployment of the farm cultivation array. To support these efforts engineers and consultants are hired on an hourly basis and administrators are hired on an annual basis. Site characterization includes costs associated with field data collection and processing. The daily rate and mobilization distance for anchor laying vessels is estimated as a function of anchor size (see supplemental material) [64]. Assembly and deployment involve labor from farm employees, and use of rented or farm owned vessels (priced at the average in-season per day cost). Direct lease permit costs include lease rental fees scaled by farm footprint area, and per plot application fees. We assume that the farm is required to secure a bond, with a value of 50% of installation costs, ensuring that funds are available for farm removal. Annualized startup costs were calculated by dividing the expenditures by the relevant cyclic timeline. Startup costs are financed according to the same principles applied to capital expenditures.

2.10.6 Direct Maintenance Costs

In addition to labor and vessel needs, maintenance includes replacement of prematurely failing components. This incurs the costs of the component itself and its installation; in our model these are annualized over the lifespan of the component. For anchors, anchor chains, and anchor lines, this includes the average cost of deploying a single mooring leg assembly (total anchor deployment cost divided by the total number of anchors). The purchase cost of the inspection

ROVs is estimated as a function of site depth. Annualized ROV costs include depreciation and maintenance (see supplemental material).

2.10.7 Onshore Costs

To estimate the annual expenditure on shoreside facilities and equipment, the total time for loading and unloading vessels for each operation is summed and an estimated hourly rate is applied (see supplemental material). Energy costs associated with these operations are also included.

2.10.8 Overhead Costs

Overhead costs include the labor-related indirect expenditures, administrator and manager salaries, office and yard space rental, and insurance (see supplemental material). Annual premiums for insurance for loss of farm structures are estimated as a portion of the total installed capital expenditures. This insurance is intended to cover the replacement of farm components in the event of extraordinary component failures. Protection and Indemnity (P&I) insurance annual premiums are scaled according to the total annual on-the-water time for all personnel. Since no assumptions concerning profits were made, the financial impact of taxes was not included in this study.

2.10.9 Mechanization Costs

While the machines that could be used to assist at-sea operations (see section 2.9.6) are not well defined within the scope of this study, costs are approximated as a function of performance. Base costs and incremental costs are scaled by performance increases versus the manual analog and applied on a per machine and vessel basis. Machine depreciation, annual maintenance costs (scaled by purchase cost), and estimated fuel costs are incorporated into total annual machine costs (see supplemental material).

2.11 Sensitivity Analysis

A sensitivity analysis in which key model variables and groups of similar variables (e.g. assembly task time) were independently varied by +/- 40% providing insight into the relative impact of each parameter on COP. While most sensitivity analysis parameters were direct assumptions used only in the operational and economic analysis, studies involving the variance of kelp yield also incorporated impacts on the structural analysis results. The kelp biomass induces major hydrodynamic loads, therefore a difference in yield affects the required capacity of farm components, and consequently the cost of components.

2.12 Operational Improvements

2.12.1 Nominal Operations

Two sets of operational assumptions were defined. “Nominal” (*baseline*) operations refer to those typically employed by western farmers operating nearshore farms. These operations do not involve specialized mechanisms or vessels. Manual interaction with the farm, and use of vessels of opportunity (typically fishing vessels) dominate the nominal operations model.

2.12.2 Line of Sight Operations

The “line-of-sight” (*improved*) operations scenario assumes methodologies that could be implemented using existing technologies but have yet to be widely employed in the context of western kelp farming (Table 2). This includes use of specialized purpose-designed vessels, powered mechanisms for aiding vessel based seeding, maintenance and harvest operations, multi-day trips to the farm (including overnight work), a reduction in number of deckhands, use of vessel hold space for storage of harvest, use of larger harvest containers, a higher wave height threshold for weather days, use of a machine for chopping biomass as its harvested (to increase the bulk density), and use of a pump for unloading harvested biomass on shore. Some of these advancements are currently being developed or are already employed in industrial scale seaweed farming in east Asia [23].

Table 2 Key differences between the nominal and “line of sight” operations models

	operations model	
	baseline	improved
harvest stations per vessel	4	1
harvest container unload time (minutes)	2	1
harvest container volume (m3)	1.5	5
use of farm-owned vessels	no	yes
use of on-board kelp grinder	no	yes
mechanized operations	no	yes
weather day sig. wave height threshold (m)	0.75	1.0
use of multi-day vessel shifts	no	yes
max. work time per day (hrs)	10	24
use of vessel holds for kelp storage	no	yes

3. Results

3.1 Improved Farm Design

The integrated structural, biological, operational, and economic model was used to generate a second-generation farm design with minimized COP (Figure 2 and Table 3). As opposed to the *baseline* farm, which was designed for maximal structural efficiency, the *improved* farm was designed in the context of the COP evaluation metric in which all cost and productivity implications are accounted for. This process allowed for a careful balance of all design and operational decisions.

Table 3 key design differences between the *baseline* and *improved* farms

	farm design	
	baseline	improved
array length (m)	1437	805
array width (m)	144	234
mooring scope	3.00	1.64
node float net buoyancy (kN)	15.2	380
cultivation line spacing (m)	3.99	3.90
node and dropper tether length (m)	2.08	10.1
dropper spacing (m)	3.72	106
chain mass per length (kg/m)	294	164
chain length (m)	55.0	2.72
header line length (m)	603	250
anchor line length (m)	233	145
anchor line pretension (kN)	56.1	328
anchor mass (tonne)	7.80	6.69
total cultivation line length (km)	36.7	43.9
anchor and header line material	nylon	polyester

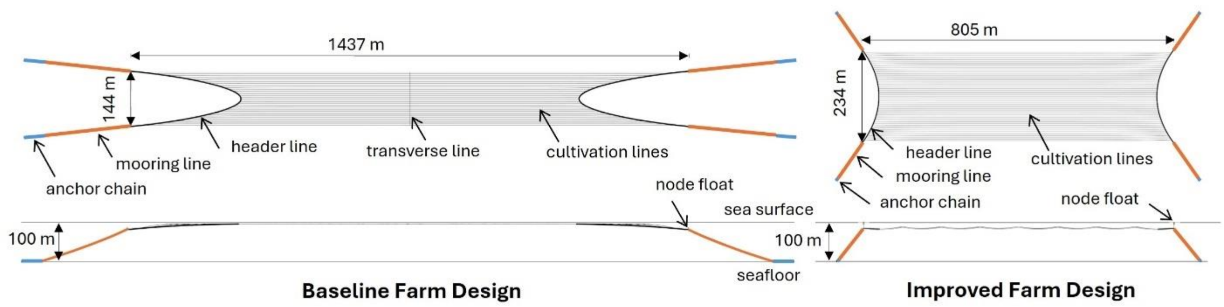

Figure 2 - *Baseline* and *improved* farm designs - plan (top) and profile (bottom) views of the *baseline* (left) and *improved* (right) farm designs. Anchors and droppers are not shown.

3.2 Structural Model

The engineering methods described in section 2.3.1 yielded size and cost estimates for the *baseline* and *improved* farm structures. The *improved* farm achieves greater production capacity, exhibits lower structural loads (Figure 3), and requires shorter lengths of highly loaded ropes, resulting in significantly lower total annualized structural costs (Figure 4). Furthermore, with the *improved* farm design, less kelp is lost due to less interaction between cultivation lines; 2.4% of cultivation line length as opposed to 23.5% for the *baseline* design.

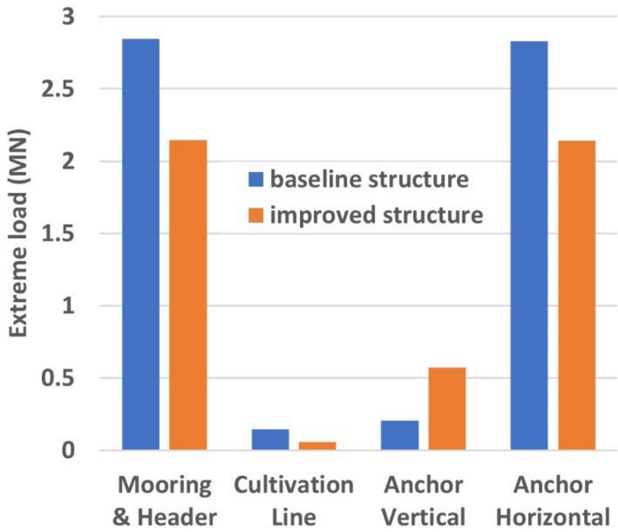

Figure 3 - Structural loads - Relative extreme component loads estimated for *baseline* and *improved* farms

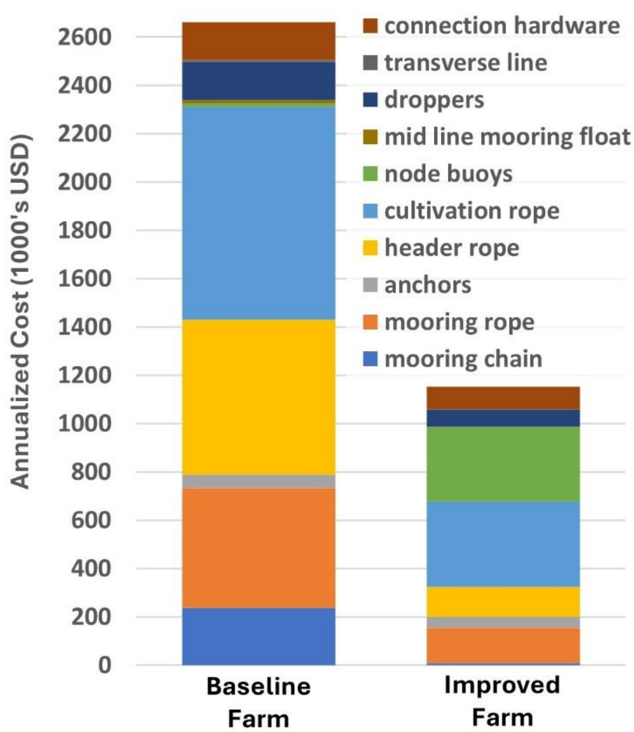

Figure 4 – Structural Costs - Annualized structural costs for the entire 1000-acre farm discretized by component type for the *baseline* and *improved* farm designs.

3.3 Operations Model

For equitable comparison of COP across farm design and operations scenarios, operational decisions were optimized for each scenario. Different combinations of shift lengths, workday lengths, and operational windows can lead to very different production costs for the same farming system or set of operational assumptions. Table 4 highlights some of the key differences between these optimized models for our four scenarios. For example, optimized harvest windows vary between 30 and 40 days across the four scenarios.

Table 4 Key assumptions, decisions, and outcomes as a result of per scenario operational optimization

Farm Design **Operations**	baseline baseline	baseline improved	improved baseline	improved improved
harvest window (days)	30	35	30	40
seeding window (days)	30	38.5	30.0	44.7
shift length (days)	1	1	1	1
workday length (hrs)	10	24	10	24
season length (days)	210	212.5	210	215
annual weather days (days)	149	119	149	120
harvest efficiency	0.95	0.98	0.95	0.94

Figure 5 shows that for scenarios including the *baseline* operational model, vessel costs dominate. For *improved* operations scenarios, vessel costs are reduced more than labor costs, leading to labor costs being the dominant proportion of COP in these scenarios.

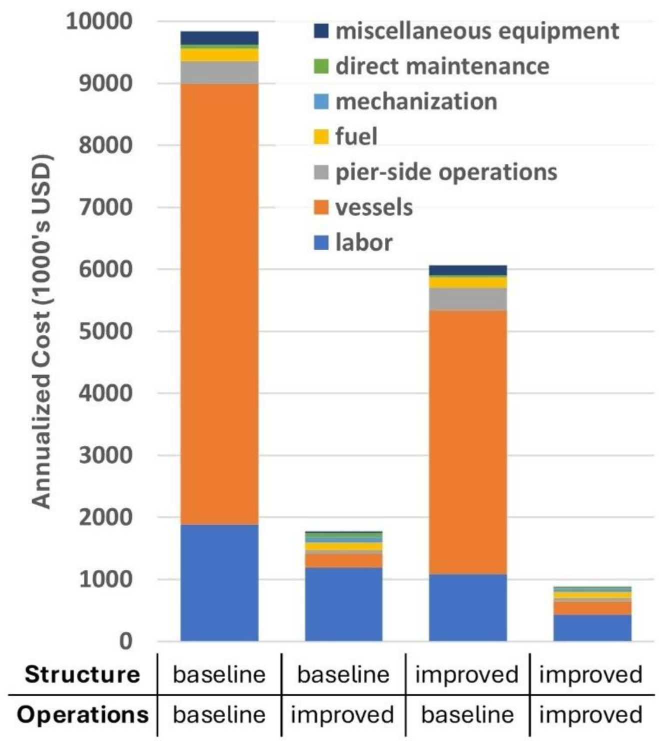

Figure 5 Marine operations costs - Annualized marine operational costs for each farm design and operations scenario. Costs are discretized by key expenditure categories.

Administrative, management and insurance costs are reduced in the *improved* operational model and further reduced in the context of the *improved* farm design (Figure 6). These costs are proportional to labor costs and structural requirements, and as such, these trends map accordingly.

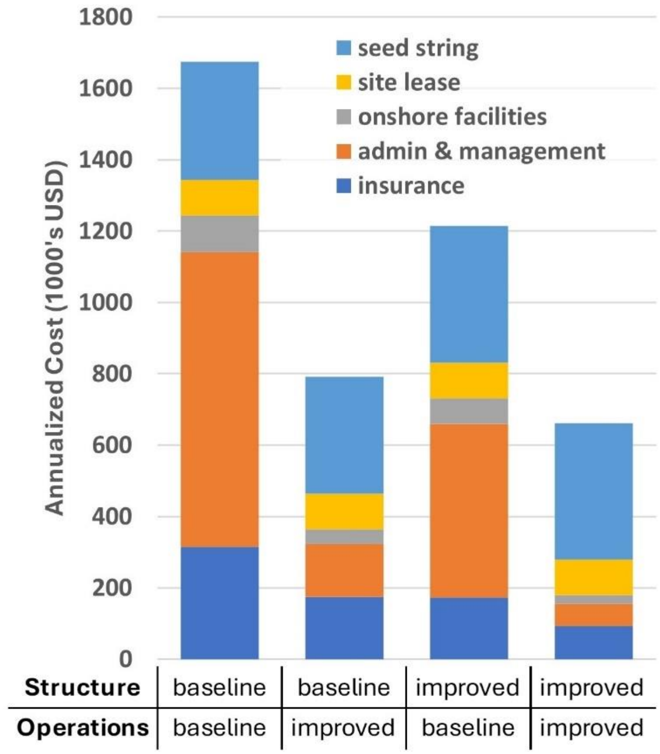

Figure 6 – Non-marine operations costs - Relative annualized non-marine operating costs discretized by key cost categories.

3.4 Biological Model

Kelp yield was estimated from November 1 through June 15 (the typical kelp farming season in the Gulf of Maine) using the biological model described in section 2.4. In Figure 7, a lower harvest efficiency from the combined effect of widening harvest windows and increasingly non-linear kelp growth is evident. Furthermore, because the biological model predicts rapid growth in the last third of the growth season, harvest timing and duration can strongly influence harvest biomass estimates. Losses from tangling and abrasion in the *baseline* farm also result in lower yields than those for the *improved* farm.

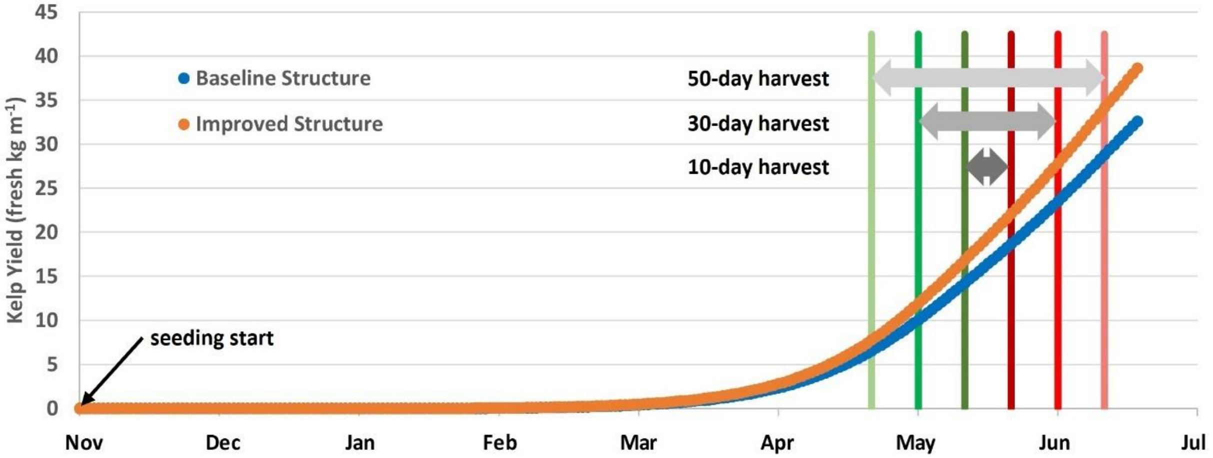

Figure 7 – Kelp growth - Estimated kelp yield as a function of date in the context of the *improved* and *baseline* farm designs. Losses from tangling and abrasion are included. Different harvest window durations are shown for reference

3.5 Vessel Model

For each farm design and operational scenario, vessel sizes were optimized for the lowest cost (Table 5). Constraints included maintenance of appropriate functionality including storage capacity, loaded stability, cabin space, deck space, and engine rating. Line-of-sight operational improvements (see section 2.12.2) clearly impact vessel operational efficiency with dramatically increased harvest capacities.

Table 5 Key operational vessel characteristics for the four farm and operational scenarios. Non-integer numbers of vessels reflect vessel use over only a portion of the available operational window.

Farm Design **Operations**	baseline baseline	baseline improved	improved baseline	improved improved
array deployment vessel length (m)	11.7	17.5	16.1	22.3
seeding vessel length (m)	7.29	17.5	16.1	22.3
maintenance vessel length (m)	10.0	17.5	10.0	22.3
harvest vessel length (m)	16.6	17.5	17.4	22.3
harvest capacity per vessel (fresh tonnes / shift)	14.0	143	17.9	357
seeding capacity per vessel (km/shift)	1.34	12.9	8.23	27.8
number of deployment vessels	46.8	2.00	3.59	1.00
number of seeding vessels	41.4	1.88	17.3	0.90
number of maintenance vessels	17.4	1.30	3.52	0.28
number of harvest vessels	33.1	1.88	35.0	0.90

3.6 Labor Model

Labor needs were quantified for the four farm design and operational scenarios (Figure 8). Both farm design and operational improvements reduced annual labor needs. The number of deckhands needed was particularly reduced. Reductions in administrator and manager needs were driven by reductions in the size and number of vessel crews and vessels hired or purchased.

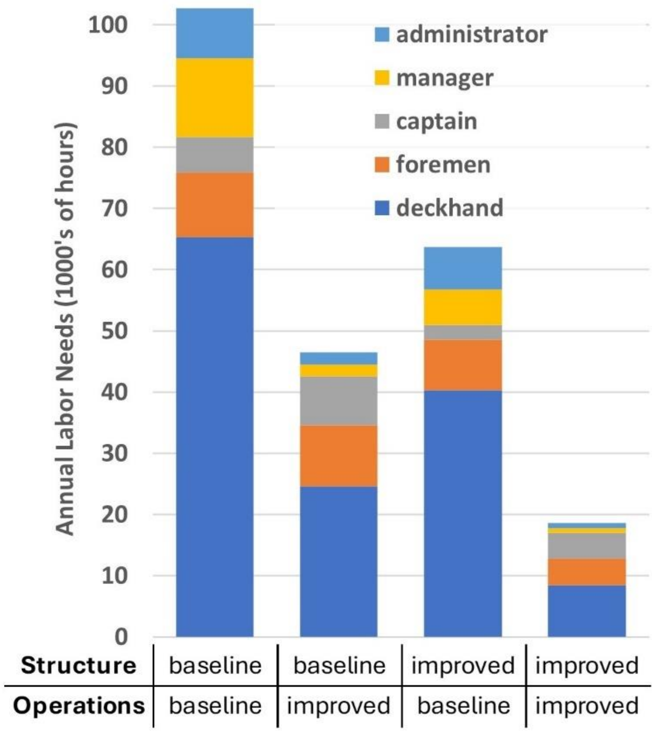

Figure 8 – Labor needs - Labor needs for the four farm design and operational scenarios. Labor is quantified for each employee type in terms of hours per year.

3.7 Nursery

Nursery costs were estimated as a function of seed string length produced. Because production was assumed to be exclusively for the evaluated farm, seed string length produced corresponded to that required by the farm each year. Figure 9 shows how at the production volumes of interest to this study (>300 km yr^{-1}) only marginal cost savings are realized via increasing nursery scale. It should be noted that nursery design and operations were held constant and did not change for any scenario.

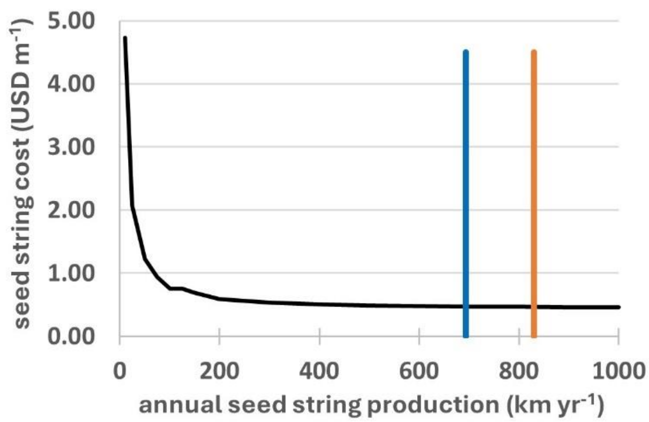

Figure 9 – Kelp seed costs - Estimated cost per length of produced seed string as a function of total annual production volumes. The length needed for the *baseline* and *improved* farm are indicated by the blue and orange vertical lines respectively.

3.8 Startup

Figure 10 indicates incremental reduction in startup costs with improvement in farm design and operational model. Costs associated with array assembly and deployment are particularly impacted; these reductions can largely be attributed to the use of fewer droppers in the *improved* farm design (413 vs. 9870 per plot) and the increased rate of operation in the *improved* operations model. Similarly, permitting costs, which includes a marine bond for farm decommissioning is impacted by the number and deployment rate of droppers.

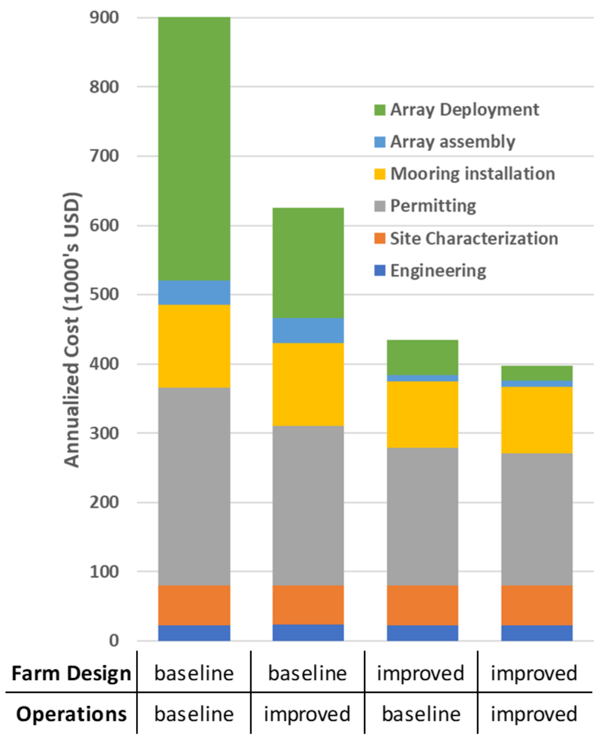

Figure 10 – Startup costs - Relative annualized startup costs for our four scenarios, discretized by category.

3.9 Economic Model

Farm-gate kelp production costs (cost of production, COP), in units of USD per fresh metric ton of kelp produced, was the primary model output. COP was calculated by normalizing the sum of all annualized costs by the estimated annual kelp production (Table 6). The model does not encompass any drying, milling, blanching, or other post-harvest processing. Furthermore, the relationship between wet weight and dry weight (typically 10-13%) can be a function of variables not resolved in this analysis, so cost per dry weight is not estimated. COP provides a metric with which to directly compare the outcome of discrete farm design changes, operational decisions or requirements, market trends, site properties, vessel properties, business choices, and / or the physical properties of the cultivated biomass.

Table 6 High level economic results for the four scenarios of interest. Yields on the nominal (middle) harvest date, May 15, are provided for reference.

Farm Design	baseline	baseline	improved	improved
Operations	baseline	improved	baseline	improved
Cost of Production (USD / fresh tonne)	2618	988	1085	383
total production before tangling (fresh tonne)	7336	7336	8723	8723
total production after tangling (fresh tonne)	5760	5927	8174	8082
yield before tangling (kg/m)	20	20	19.9	19.9
yield after tangling (kg/m)	16.5	16.5	19.5	19.5

Table 6 highlights that biomass loss from tangling is particularly influential on production costs. While the *baseline* farm has a similar yield before tangling, the heavy loss from tangling drives down production volume and drives up cost of production.

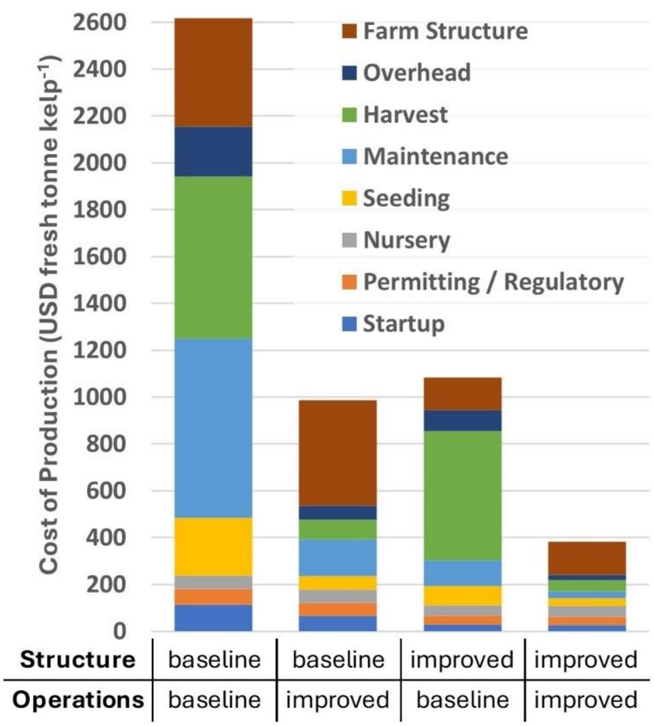

Figure 11 - Production Costs - Cost of Production across farm structure and operational model scenarios discretized into key cost categories

Figure 11 illustrates how both operational and structural improvements allow for similar scales of reduction in COP. Transition to *improved* operations significantly reduces harvest, maintenance and seeding costs. A transition to the *improved* farm design reduced structural and maintenance costs most significantly. Associated reductions in operational costs are largely driven by increased productivity, but also improved operational efficiency from streamlined interactions with the structure.

When implemented as part of the nominal operations model in the context of the *improved* farm design, densification of kelp through grinding, use of the vessel holds for storage and pumping of the kelp slurry at the pier collectively account for 54% of the estimated reduction in COP when transitioning from the nominal to line-of-sight operational models.

3.10 Sensitivity Analysis

The reduction potential for different model inputs are presented in Figure 12 and Figure 13. Reduction potential is calculated according to (1)

$$Reduction\ Potential\ = 1 - \frac{COP_{new}}{COP_{nominal}} \tag{1}$$

Where COP_{new} is the lesser of the two sensitivity study results (+ or - 40% the nominal input) for each variable.

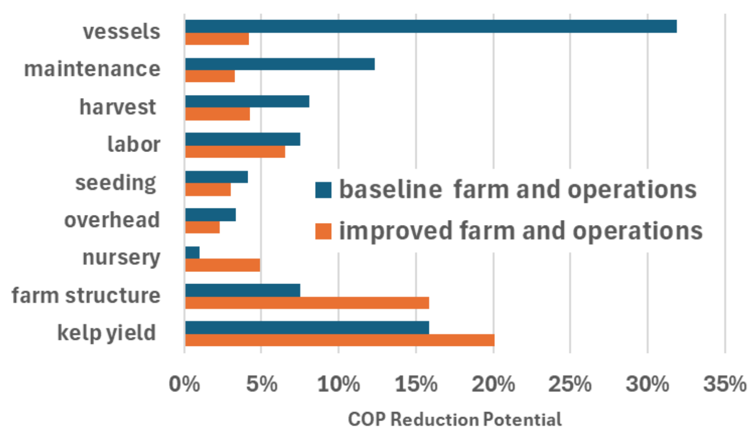

Figure 12 – High-level sensitivity study - COP reduction potential associated with a 40% change in aggregated cost and performance categories outlined in section 2.10 for both the *improved* farm and operation scenario and the *baseline* farm and operations scenario. Only cost and performance categories with reduction potential greater than 2% are shown.

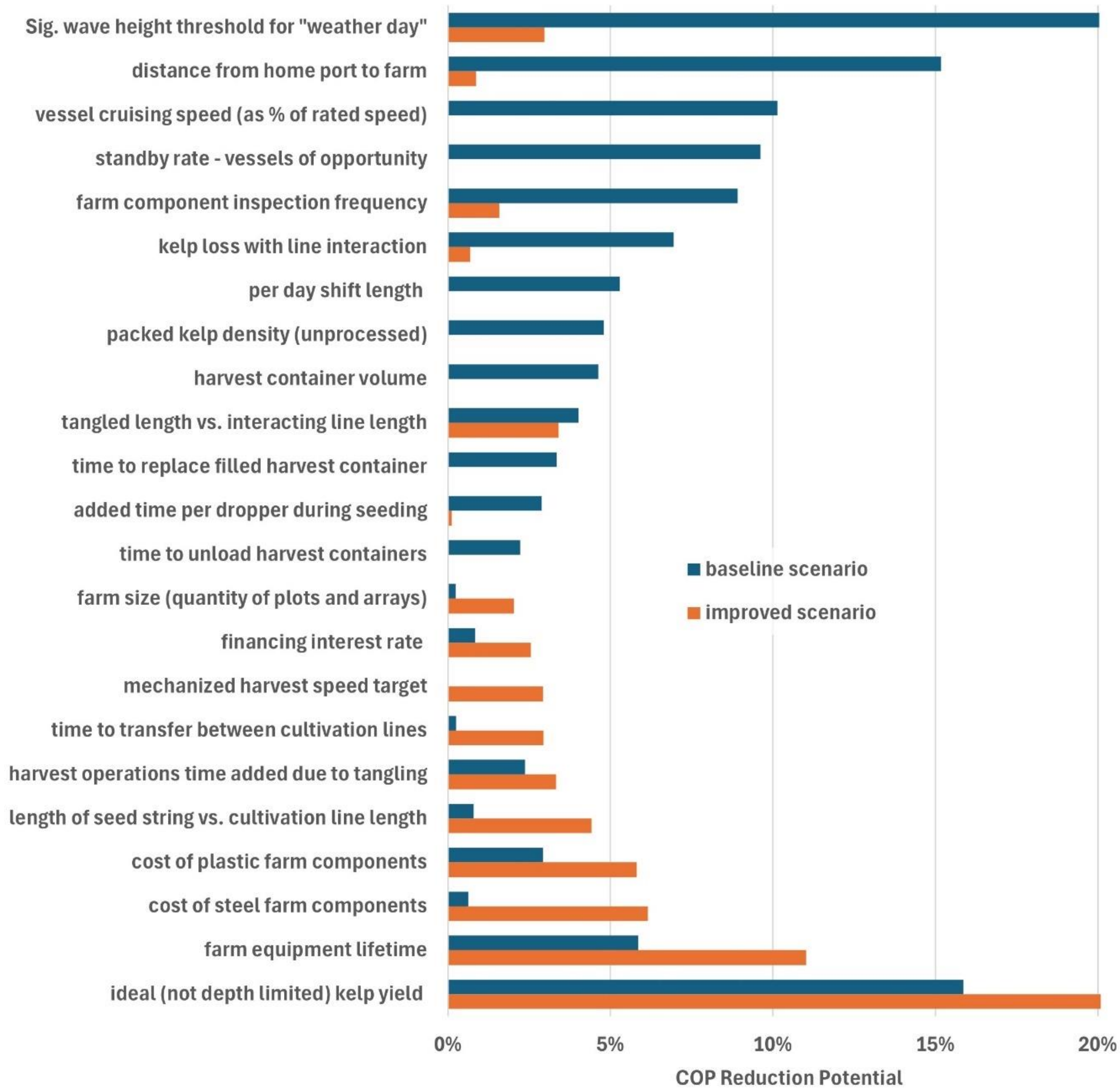

Figure 13 – Detailed Sensitivity study - Reduction potential for a 40% change in discrete model inputs across the *baseline* farm and operations scenario and the *improved* farm and operations scenario. Only variables that resulted in >2% reduction potential are shown.

Figure 13 highlights that COP associated with the *baseline* farm and operations scenario and the *improved* farm and operations scenario are sensitive to a different set of variables.

Commonalities are largely limited to yield and variables that influence structural costs, suggesting that key cost drivers are largely scenario dependent.

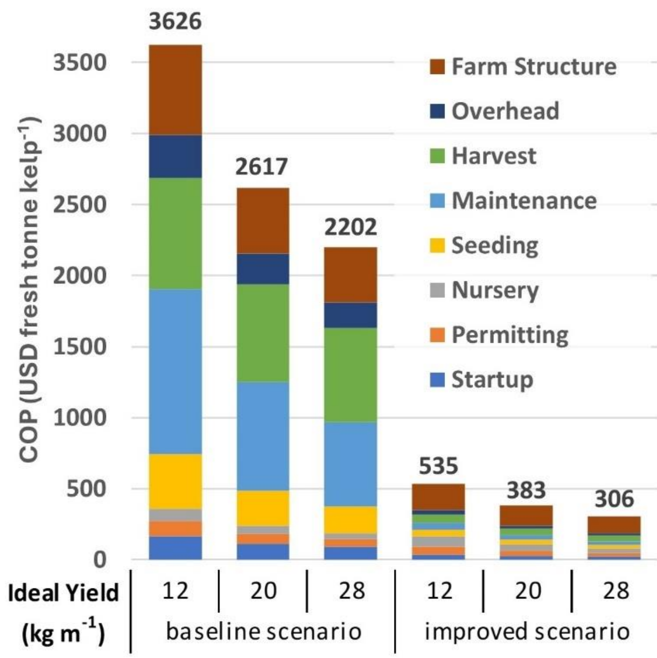

Figure 14 - Sensitivity to yield - Sensitivity of COP to ideal yield. COP (discretized by cost category) for the *baseline* and *improved* scenarios with varying ideal yield (yield before reductions due to depth of growth and losses from tangling). Total COP for each scenario is provided above each bar.

Figure 14 illustrates how the benefits from increasing yield are lessened by resulting system-feedback implications. Increasing kelp yield directly increases structural loads, node and dropper buoyancy requirements, the extent of interacting cultivation line length and resulting tangling and kelp loss, and the vessel time required to harvest the added biomass. Because all of these factors are important cost drivers, they can noticeably offset some of the gains in spatial and operational efficiency with increased yield. This trend is evident from the relatively marginal reductions in farm structure and harvest costs with increasing yield.

4. Discussion

4.1 Comparison with Other Studies

Studies investigating the economics of seaweed farming have estimated COP for a wide range of scenarios including varying contexts (sites), biomass growth predictions, and farm structures. The results vary as widely as the assumptions. Table 7 highlights assumptions and results from a selection of these studies. Large variability across TEA model frameworks prevents direct comparison among some results.

Table 7 Comparison of key results and assumptions from a selection of published studies investigating the economics of seaweed farming. For studies where results from a range of input assumptions are reported, we used the "mid-point" or average input assumptions for comparison.

		This Study (*baseline* scenario)	**This Study (*improved* scenario)**	**Coleman et al. 2022**	**Bak et al. 2018**	**Brayden and Coleman 2023**	**Hasselstrom et al. 2020**	**Kite-Powell et al. 2022**
Expected Yield	fresh kg m^{-1}	20.0	20.0	12.5	undefined	undefined	8.00	15.0
Yield at Harvest	fresh kg m^{-1}	16.5	19.5	12.5	5.80	6.32	8.00	15.0
Water Depth	m	100	100	100	60.0	~5-25	undefined	50.0
Farm Area	ha	404	404	404	1.00	3.20	2.00	1000
Cultivation Line Length	km ha^{-1}	0.92	1.09	0.92	2.50	2.45	2.34	10.9
Production	WMT ha^{-1}	14.26	20.0	11.4	14.5	15.5	18.7	164
Structural Costs	US$ fresh $tonne^{-1}$	462	143	109	893	undefined	919	6.54
Cost of Production	US$ fresh $tonne^{-1}$	2618	383	911	1606	1452	1144	30.0

The *baseline* scenario in this study results in higher-than-average production costs, while the *improved* scenario results in lower-than-average production costs when compared to the other TEAs. The diversity of scenarios and results is insightful for predicting the potential range in

COP for real operations. However, relative evaluation of a farm design's merit is not feasible given the variety of contextual assumptions, and methods for defining key parameters. For instance, farm area is poorly defined in most studies, i.e. whether this refers to the mooring footprint (as in this study) or only the horizontal area occupied by the cultivation substrate (which can also include expected deformation or not). These two parameters can differ by an order of magnitude for the same farm (the discrepancy increases with water depth), yet the reference terminology is often the same. The ratio of cultivation area to mooring footprint for the farms investigated in this study was 0.36 and 0.42 for the baseline and improved farms respectively. The study by Kite-Powell et al. [29] stands out in its assumption of farm scale and estimates of structural costs for the assumed harvest yield.

Brayden and Coleman [25] collected and processed data from active kelp farms in the shallow protected waters of coastal Maine. Farms in this context are largely managed and operated by individuals already engaged in marine industries with preexisting ownership of vessels and in most instances receive no-cost seed through partnerships with local processors. As a result, these results do not include costs associated with administration, office rent, engineering, site characterization, permitting consultant support, seed string, salaried workers, vessel standby costs and include only partial accounting of total costs incurred with use of a vessel. When accounting for these differences, assuming that only 50% of true vessel costs were considered, the comparable cost of production in the context of the offshore farm model evaluated here equates to \$1,434 fresh tonne^{-1} and \$258 fresh tonne^{-1}, for the *baseline* and *improved* scenarios respectively. This suggests that implementation of the *baseline* farm and operations would result in production costs similar to modern near-shore farming practices in Maine.

Model-based economic investigations, e.g. [19,29], largely assume stationary productivity values and minimum feasible cultivation line spacing distances (resulting in no biomass loss from line interaction). The study presented here is unique in its quantitative estimate of biomass loss and operational costs resulting from interaction between cultivation lines. The application of a biological model that responds to site specific environmental conditions and structural design features is also unique to this study.

In comparison to the analysis presented by Coleman et al [8], this study implements a more complete model of the complex interconnectivity of structural design features, operational decisions, physical limitations, site properties, operational requirements, biological response, and market driven material and labor costs. This resulted in a 187% increase (+\$1707 fresh tonne^{-1}) in estimated COP for the same farm and site (the *baseline* farm and operations). Novel feedbacks included in this model include (1) structural implications, operational costs, and tangling risks associated with increasing yield, (2) a vessel model that reflects real market trends, weighs vessel performance vs. cost (i.e. transit speed, stability, and shelter) and responds to the specific operational limitations and requirements of the given scenario (e.g. crew housing, harvest rates, or weather restriction), (3) discrete operational tasks (and timing for those tasks) are linked with structural design features, and secondary implications of those features i.e. tangling and abrasion, (4) startup costs that scale with structural requirements and site characteristics, (5) overhead costs that scale with operational requirements and structural costs, and (6) interdependency of structural design features, operational planning (e.g. harvest window), biological growth, and the resulting landed biomass.

4.2 Findings from System-Feedbacks

4.2.1 Structural

Structural improvements not only lower the cost of farm components for a given amount of production, they can also directly impact operational costs. Examples of this influence include: (1) a greater number of cultivation lines increases the total time shifting between cultivation lines during harvest or seeding operations; the speed of this operation is also impacted by the depth of the cultivation line, (2) a greater number of droppers slows seeding and deployment time, (3) tangling of cultivation lines slows harvest operations and decreases their replacement interval, (4) more connections increases inspection time requirements (increased maintenance costs), and (5) use of more durable components can reduce maintenance needs. This effect is highlighted by the fact that only 21% and 51% of the reductions in COP with farm structure improvements were due to reductions in farm component costs for the *baseline* and *improved* operational scenarios, respectively.

Often, the greatest impact from structural design improvements is mitigation of tangling risk. Because losses from tangling are assumed to occur near the end of the season, the farm structure must accommodate extreme storm loads assuming full yield (without loss from tangling) for that time interval (typically mid-season). In the context of a farm prone to tangling, a significant portion of structural capacity and the associated expense is not effectively utilized. Because COP is the annual cost of farming normalized by harvested biomass, an increase in harvested biomass for the same cost (e.g. less tangling) will result in lower COP in all categories. In this study, the

COP for the *improved* farm design was reduced by 22% as a result of the estimated 90% reduction in biomass loss from tangling.

Substantial investment is required to navigate the regulatory environment and secure an aquaculture permit [65]. In the context of *improved* structure and operations scenario, these costs account for 9.4% of COP. Thus, maximizing production per farm footprint (lease area) is impactful. While reducing cultivation line spacing, anchor scope and header length maximizes this performance metric, other related effects can reduce COP. For example, uninhibited reductions in these variables would lead to an increase in tangling, expensive nodal flotation (or accessibility issues due to submergence) and / or high structural loads (and associated structural cost).

Because structural design influences biological productivity, design of the structure in the specific context of the farming site's environmental characteristics is important. Light intensity (dependent on cloud cover and latitude), water turbidity (typically lower offshore), temporal changes in the local thermocline and nutricline, current profiles, water depth and typical wave height and period all influence the ideal depth of cultivation from the perspective of biological productivity and minimization of structural loads. "Cultivation depth" is influenced by node and dropper tether lengths, and cultivation line sag. Cultivation sag is a function of mooring pretension, dropper spacing, and temporally changing kelp mass and density. These design features also have other cost implications, e.g. tangling, installation cost, accessibility, etc. Resolving this feedback allowed leveraging of the clearer (lower turbidity) water at the offshore site (when compared to typical nearshore locations on the same dates) to locate the *improved* farm's cultivation array at greater depth (10.1m vs. 2.1m node and dropper tether lengths) with minimal impact to kelp growth. This resulted in a 35% reduction in extreme mooring loads normalized by biomass production capacity (before losses from tangling).

To achieve meaningful reductions in COP through farm design modifications, a complex series of tradeoffs must be weighed against one another. Every design decision has implications for structural costs, operational requirements, and biological productivity. In almost all cases, moving a design parameter in one direction will have both negative and positive consequences in different performance metrics that impact COP. Figure 15 highlights the typical benefits and detriments of changing common design features. A versatile comprehensive economic analysis tool such as the integrated structural, biological, operational economic model presented here is helpful for navigating this complex web of tradeoffs. This is evidenced by the 60% reduction in COP with the *improved* farm design. Whereas the *baseline* farm was designed with prioritization of structural efficiency (structural costs normalized by production capacity), the design of the *improved* farm focused on minimizing COP. The resulting discrepancy in COP exemplifies how pursuit of a single performance parameter can lead to economically inefficient designs.

Critical Farm Results

Design Features — *Effect on:* / *from increase in:*	CAPEX	OPEX	Install Cost	Tangling Risk	Spatial Efficiency	Access	Growth
array length vs width	↓	↓	↓	↑	↑	-	-
header line length	↓	-	-	↑	↑	-	-
anchor line scope	↑	-	↓	↓	↓	↑	-
anchor chain length	↑	-	↑	↓	↑	↑	-
system buoyancy	↑	-	-	↓	↑	↑	↑
grow line spacing	-	↑	-	↓	↓	↑	↑
cultivation depth	↓	-	-	↓	↑	↓	↓
mooring pretension	-	-	↑	↓	↑	↓	-
dropper buoy frequency	↑	↑	↑	↓	-	↑	↑

↑ *increase*
↓ *decrease*
beneficial
\- *neutral*
detrimental

Figure 15 – Farm design tradeoffs - A matrix of typical design parameters versus economic performance tradeoffs for seaweed farms. The multi-faceted implications of increasing a given design feature are evident.

4.2.2 Operational

Operational decisions are highly impactful to COP. To realize maximal COP reductions, operational decisions should be optimized in the context of specific farming structures, cultivated species, site characteristics and environmental conditions. Influential operational decisions include: (1) chosen harvest and seeding windows, (2) workday length, (3) number of days in an operational shift, (4) vessel sizes, (5) number of crew per operation, (6) extent of mechanization, (7) extent of at-sea biomass processing (e.g. densification of kelp into a slurry), (8) harvest container size and / or use of the vessel hold for storage of harvested biomass, (9) use of farm owned specialized custom designed vessels, (10) methods of unloading biomass at the pier, and (11) vessel cruising speed.

As with farm design decisions, operational decisions must be weighed in aggregate. In many cases, benefits from changes to a single variable here may only appear when paired with changes in other variables. Examples of this coupling include (1) use of at-sea biomass processing and at-pier harvested biomass unloading methodology, (2) the size of vessels, number of crew, and extent of mechanization, and (3) the length of the harvest window, workday length, and number of days in a shift.

Investment in operational equipment (machines, vessels, etc.) must be weighed against more versatile contract-based labor and / or vessels. In particular, due to the generally high sensitivity of COP to vessel costs (see Figure 12), any operational decision that impacts the vessel characteristics, particularly size, must be weighed carefully against the alternatives. The 65% reduction in COP with the *improved* operations scenario, which primarily includes use of farm owned operations vessels and machinery, suggests that when coupled with optimization of vessel size, operational window and shift durations, such operational changes can be impactful.

4.3 Comparison Among Investigated Scenarios

Four farming scenarios were considered for the same 1000-acre farm located at an offshore exposed site: each a combination of nominal (*baseline*) or line-of-sight (*improved*) operations models and the *baseline* or the *improved* farm structure. Results indicate a 85% reduction in COP across the extremes of this spectrum (*baseline* farm and operations to *improved* farm and operations). Figure 11 suggests that realistically actionable operational and structural improvements can offer similar reductions in COP (60-65%) and can be compounded for the greatest reductions. While many insights can be gained from the results presented here, only the most consequential are discussed.

4.3.1 Operational Improvements

Transition to the *improved* operations model decreases operational (harvest, maintenance, seeding, and array deployment) costs by 82% and 85% for the *baseline* and *improved* farm structure scenarios, respectively. Figure 5 illustrates major reductions in vessel costs, and, to a lesser extent, labor costs. Vessel costs dominate the operations costs for the *baseline* operation scenarios. Here, vessels of opportunity with low operational efficiency are hired for operational windows, which includes in total 149 days (71% of the season) standby time due to weather days (see Table 4). When using in-house vessels, weather days do not add cost.

Mechanization of operations (harvest in particular) and a reduced number of vessels in the *improved* operations model results in a 55% and 71% reduction in total labor needs for the *baseline* and *improved* farm structure scenarios respectively. In particular, labor needs for deck hands, manager and administrator positions are reduced most significantly (see Figure 8). Reductions in manager and administrator needs (82% and 87% respectively), and indirect labor costs such as P&I insurance, are reflected in the reduced COP due to overhead (72% and 75% respectively). Though COP due to labor is reduced with line-of-sight operations (-\$126 and -\$79 fresh tonne kelp^{-1}, respectively), the reduction is marginal compared to the reduction in vessel costs (-\$1,197 and -\$494 fresh tonne kelp^{-1}, respectively). Consequently, labor costs dominate operating costs in the *improved* operations scenarios (~20% of COP is due to labor costs while 4-7% is due to vessel costs regardless of farm design scenario).

Densification of harvested biomass through grinding or blending helps reduce COP. Though use and maintenance of the associated equipment adds costs, the ability to hold more harvested biomass on a vessel of a given size leads to greater cost reductions. Benefits from densification are amplified with improved harvest rates from mechanization, use of the vessel hold for storage, and pumping of the kelp slurry at the pier. These changes allow for increased vessel storage per vessel size (since deck space is freed up and stability is increased), reduced container handling time and increased offloading rates. When implemented independently in the context of the *improved* farm, these changes account for 54% of the reduction in COP with implementation of the *improved* operations model. Generally, increased harvest rates are only marginally helpful without the ability to scale offloading rates proportionally.

4.3.2 Structural Improvements

The *baseline* and *improved* farm designs were estimated to respectively result in 23.5% and 2.4% of cultivation line length interacting during the one-month storm scenario; suggesting a 10x loss of kelp in the *baseline* design compared to the *improved* farm design. The superior performance of the *improved* farm design is largely due to a deeper cultivation array, higher mooring pretension, shorter cultivation lines, shallower header lines, and stiffer mooring lines (see Table 3 and Figure 2). All these factors allow for less deformation in storm conditions and corresponding interaction between cultivation lines.

While reduced structural loading is influential in the transition from the *baseline* to the *improved* farm design, figuresFigure 3 andFigure 4 suggest that this accounts for only a portion of structural cost reductions. Most notably, cultivation line costs normalized by kelp production capacity (before losses from tangling) are reduced by 66%. The shorter cultivation lines of the *improved* farm result in lower tensions in those lines. Shorter cultivation lines generally have lower strength requirements and consequently lower costs per length. Similarly, header line and anchor line lengths are reduced (59% and 38%, respectively) due to slimmer header curve and lower anchor line scope, respectively, allowing for greater cost reduction than would be possible with load reduction alone. The additional cost of larger node floats (+2400%), which are the result of decreased anchor line scope, offsets these savings somewhat. Additionally, the minimal use of anchor chain and the added anchor costs, due to greater uplift forces with minimal chain and low mooring scope, appears to be advantageous.

Dropper quantity impacts array deployment, seeding and maintenance costs. In each of these operations, each additional dropper represents an independent task (disconnecting, connecting, and / or inspecting), which incurs additional labor, vessel, administrative and management time (and hence cost). Node floats serve as the primary buoyancy mechanism for the *improved* farm; 4 node floats each with 380 kN of net buoyancy are aided by 413 droppers each with 1.4 kN of net buoyancy. In contrast, the *baseline* farm uses droppers as the primary mechanism for floating the farm; 9,870 droppers each with 0.14 kN of net buoyancy are aided by 4 node floats with 15 kN of net buoyancy. This distributed floatation can help mitigate excessive deformation (vertically and horizontally), reduce farm wide submergence, encourage better exposure to sunlight, and reduce complications associated with deploying large heavy node floats. However, the results presented in Figure 5Figure 11 suggest that in the context of high mooring pretensions, the benefits of using many droppers is not worth the added operational costs. With the *improved* farm design, COP attributed to array assembly, deployment, and maintenance are reduced by 86% and 81% (-\$725 and -\$155 fresh tonne kelp^{-1}) for the *baseline* and *improved* operations scenarios, respectively; the majority of which is attributed to a reduction in dropper related tasks.

Transition from the *baseline* to the *improved* farm structure design results in a 69 % reduction in production normalized structural costs ($ USD / tonne fresh weight kelp), or a ~60% reduction in COP regardless of operational model. Nonetheless, with cost reductions from *improved* operations, structural costs remain the largest single cost category, accounting for 45% and 37% of the total COP in the *baseline* and *improved* farm structure scenarios, respectively. This suggests that with *improved* operations, farm design is the most impactful mode of reducing COP.

4.3.3 Sensitivity Study Insights

The sensitivity analysis presented in Figure 12 Figure 13 illustrates how opportunities for reduction in COP are highly dependent on farm design and operational model. Categories with commonly high sensitivity were limited to (1) ideal kelp yield, (2) labor costs from wages and / or time needs, (3) structural costs (*i.e.,* structural efficiency and component lifetime), and (4) the degree and impact of tangling. Improvements pertaining to these factors may be the only universal pathways to reduce COP. While kelp yield is particularly influential in both scenarios, associated improvements are not easily achieved. Breeding programs may help achieve larger yields, but suitability of the cultured species to the site and design of the structure to promote maximal productivity may be ultimately more impactful. Biomass loss from line interaction is a problem for the *baseline* farm design. However, Figure 13 suggests that the operational costs of tangling are also influential in the context of structural and operational improvements. Here, the more streamlined operations are more heavily impacted by tangling related slowdowns, such that even a small amount of tangling can have a relatively large impact on COP. For example, with interaction across 2.4% of cultivation line length (as opposed to no interaction) COP is increased by 4.6%.

The outcome of the *baseline* scenario is highly sensitive to variables pertaining to operational costs (primarily vessel costs) and interaction among cultivation lines. Figure 5 clearly illustrates how vessel costs dominate operational costs for the *baseline* operations model accounting for 72% and 70% of operations cost in the *baseline* and *improved* farm structure scenarios, respectively. The workable wave height threshold is the single most influential factor for the *baseline* scenario. This threshold impacts the number of weather days and associated standby costs; in the *improved* operations scenario a 0.25 m increase in the significant wave height threshold (+33%) reduced the portion of weather days by 15%. Decreases in the distance between farm and home port and increases in vessel speed and workday length can increase the time available for operations on site versus time spent travelling, allowing greater utilization of vessel and labor resources. These relationships are particularly important in the context of the *baseline* operations scenario in which per day work windows are finite and day rates for vessels of opportunity are high.

In the context of the *improved* farm, in addition to those that are universally important, impactful variables are those associated with nursery operations, speed of harvest (including mechanization), and farm size. While the cost of seed itself is not sensitive to farm design or operations, Figure 6 and Figure 11 shows how nursery related costs represent a relatively large portion of COP in this context. The use of in-house vessels designed specifically for harvest operations means that COP in this scenario is particularly sensitive to parameters that impact harvest efficiency, i.e. mechanization and cultivation line transfer time. Whereas there are minimal efficiencies to be gained with farm scale in the context of the *baseline* scenario, increasing farm scale in the *improved* scenario is moderately impactful. The key difference here is the use of far fewer (just one rather than 47) vessels which are larger, more expensive, and more efficient. Investment in such vessels becomes more impactful with increasing farm scale, since larger vessels are more cost efficient (*i.e.,* more storage capacity per vessel cost).

4.4 Limitations of This Study

Every site, cultivated species, operational model, farm scale, and farm design concept has unique characteristics that should be leveraged to minimize COP. The results presented in this study are not universally representative across all manifestations of offshore macroalgae farming. Only four scenarios out of an infinite number have been investigated. This study represents an example of the type of results and insights that can be generated using an integrated biological, structural, operational economic model of a seaweed farm.

Although this study incorporates significantly more detail and interdependencies than most other studies with similar goals, there remains opportunity for misrepresentation of real farming practices. Every effort to define realistic values for the 236 model inputs was made. However, many of these inputs are not well defined in the literature and / or require extrapolation of existing practices or technologies to novel contexts (e.g. offshore) and applications (for kelp farming). Therefore, the assumed values inherently include undefined error bounds. Wherever literature or observational based justification of assumptions was not possible, the authors' personal experience with seaweed farm operations was used to intuit estimates. Furthermore, in the context of these data shortcomings, many relationships that are likely nonlinear have been linearized. Though unlikely to impact evaluation of the farm types or operational models with moderate differences from the *baseline* scenario, outlier scenarios may suffer from discrepancies between linear extrapolations and real non-linear scaling relationships.

Figure 13 suggests that the assumed ideal yield may be the most universally important variable in the model. However, this variable actually represents an amalgamation of many biological, operational and structural factors. The biological model estimates kelp frond growth as a function of ambient water quality and light exposure, which are functions of structural design (since these characteristics are a function of depth). However, the consequences of population scale, e.g. light and nutrient shading, are not accounted for, which creates the need to assume a kelp yield regardless of growth model outputs. If these factors could be properly incorporated into the model, then yield could be a function of frond growth, structural properties such as line spacing, and planting density (i.e. fronds per length of cultivation line). Rather than assuming that a given yield is possible for a scenario, productivity would become a function of farm design decisions, the operational model, and specific environmental characteristics at the site. The biological model itself could even be modified to accommodate genetic advantages.

The sensitivity analysis presented in Figure 12Figure 13 represent discrete sampling points of nonlinear results. Consequently, the discrete sampling of +/- 40 % of the nominal value, may land on local maxima or minima. Without high resolution sampling, it is not possible to know if a discrete sample is representative of the greater trends associated with that parameter. Furthermore, the +/- 40% sensitivity sampling may not be representative of the realistic range for all parameters. Thus, the sensitivity analysis results should not be treated as targets or potential real COP values, rather these results should be interpreted as an estimate of the relative importance of different model variables under distinct scenarios.

The nursery model used here assumes basic open loop seed production. That is, wild broodstock parents are sourced annually to provide sporogenic material for producing seed. However, we utilize a yield in the production model (20 kg m^{-1}) that would likely require a dedicated and sustained selective breeding program and rely on continuous culture of gametophytes to fully close the life cycle. Breeding programs in Japan, China, and South Korea have significantly increased farmed kelp yields in those regions [54,66]. There would be considerable costs to maintaining such a program. However, those costs are not included in the model and may be offset if directly seeding grow-lines (and eliminating a nursery seedling phase) can be shown to be reliable. There are many potential economic frameworks under which a breeding program may operate (i.e., fully privatized, highly subsidized, or public). The extent to which the innovation costs related to developing gametophyte cultures and selected strains would be passed on to the farmer under each of these frameworks are difficult to quantify and their inclusion here would have introduced large uncertainty to the nursery model. A detailed gametophyte-based selective breeding and nursery TEA should be established as a follow on to the Coleman et al. [57] model to better estimate likely future seed costs.

5. Conclusion

Farming of macroalgae in the open ocean environment is inherently challenging, but with appropriate scales, farm design, operational technology and models, biomass can be produced at significantly lower costs than many recent studies have suggested for nearshore and offshore cultivation. This study highlighted that designing macroalgae farms alongside a comprehensive structural, biological, and operational economic analysis that levelizes all trade-offs in terms of production-normalized annual costs can result in significant and meaningful economic improvements. An overly narrow focus on any single aspect of the farming system, leads to inadequate consideration of important trade-offs and feedbacks in the design process. This in turn can introduce the risk of arriving at an economically suboptimal farm design. This study suggests that in the context of a 100 acre site 20 km offshore in 100 m of water fully exposed to the extreme storms in the Gulf of Maine, *baseline* production costs can be reduced on the order of 60% when implementing: (1) deeper cultivation lines, (2) shorter header lines, (3) fewer droppers, (4) higher mooring pretension, (5) lower mooring scope, (6) less mooring chain, and (7) larger node floats.

This same comprehensive model can also identify operational frameworks and technologies that instigate step changes in production costs. This study suggests that in the context of the offshore site considered here, production costs can be reduced on the order of 65% when implementing: (1) on-board processing of harvested kelp into a slurry, (2) storage of that biomass in the vessel hold, (3) farm-owned custom built ocean going vessels, (4) mechanization of vessel operations, and (5) around the clock operations. While requiring substantial initial investment, the long-term bottom line is improved over more versatile contractor-based operational models. Optimization of farm owned vessels for size and storage capacity in the context of the specific operational model and farm design can be particularly impactful. When structural and operational improvements were combined, estimated production costs were reduced by 85% when compared to the *baseline*, reflecting a step change in the economics of large-scale kelp farming.

To better support the growing seaweed farming industry, further development of the integrated model should include: (1) validation of the model against economic data gathered from a commercial scale farming operation in exposed waters, (2) transformation of approximated linear scaling trends into more realistic non-linear relationships, (3) adaptation to other farm design concepts, operational models, and macroalgae species, (4) co-optimization of all operational parameters alongside farm design choices, and (5) incorporation of crowding / self-shading dynamics, cross-farm wakes, and novel strain traits in the biological model to more accurately resolve kelp yield and it's farm-wide variation.

Author Contributions

Zachary Moscicki: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing - Original draft, **Adam T. St. Gelais**: Writing - Original draft, Writing - review & editing, **Struan Coleman**: Methodology, Writing - Original draft, Writing - review & editing, **Alexander Kinley**: Formal Analysis, Software, Visualization, **Tobias Dewhurst**: Conceptualization, Supervision, Writing - review & editing, Project Administration, **Scott Lindell**: Writing - review & editing, **David W. Fredriksson**: Writing - review & editing, **Damian C. Brady**: Conceptualization, Supervision, Funding Acquisition, Writing - review & editing, Project Administration

Declaration of Competing Interest

Zachary Moscicki, Alexander Kinley, and Tobias Dewhurst report employment at Kelson Marine Co. Scott Lindell reports inventorship on PCT patent application No. 23682.80 "Seaweed seeders and methods for using them".

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Data Statement

Most data used in this study is included in the supplemental material. Please contact the corresponding author for further inquiries.

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Appendix A: Supplementary Material

The following tables include additional data, estimates, and assumptions used in the calculation of cost of production (COP). All currency ($) is in US dollars.

Engineering and Site Characterization		
Engineering rate	200	$ hours^{-1}
Base Engineering hours	1	hours acres^{-1}
Additional Engineering hours	1	hours acres^{-1}
geophysical survey cost per farm area	500	$ acres^{-1}
geotechnical survey cost per plot	1000	$ (m water depth)$^{-1}$
metocean survey cost per farm area	250	$ acres^{-1}

Regulatory		
Lease rent fees	100	$ acres^{-1}
permitting consultant rate	200	$ hours^{-1}
Base EIA drafting hours per farm area	10	hours acres^{-1}
additional EIA hours per farm area	2	hours acres^{-1}
time for community outreach hours x distance from port	400	hours km
regulatory outreach per farm area	4	hours acres^{-1}
NEPA process support per farm area	10	hours acres^{-1}
site selection per farm area	1	hours acres^{-1}
admin requirements per farm area	0.001	FTE acre^{-1}
habitat survey and analysis cost per farm area	1000	$ acres^{-1}
marine mammal monitoring and risk analysis base cost per plot	3000	$ (m water depth)$^{-1}$
marine mammal monitoring and risk analysis per plot	250	$ (m water depth)$^{-1}$
application fee per farm plot	2000	$
marine bond value vs. install cost	50%	

General Operations		
single day - worktime per day	10	hours
multiday - worktime per day	24	hours
vessel shift length when interrupted by weather	75%	

Array Assembly		
assembly window	90	days
assembly area rental rate per month	1000	\$ hectare^{-1}
laborers per foreman	5	
workdays vs rest (weekend) days	71%	
time to set up between tasks	2	minutes
time to prepare anchor line terminations	15	minutes
time to prepare cultivation line terminations	15	minutes
time to prepare header terminations	15	minutes
time to connect cultivation lines	4	minutes
time to measure line	3	minutes (100 m)$^{-1}$
time to prepare header connections	10	minutes
time to pack / roll array around floatation	10	minutes (100 m)$^{-1}$
time to prepare dropper attachments	1.5	minutes
time to assemble droppers	2	minutes

Anchor Deployment		
vessel mobilization distance per anchor mass	412	km tonne^{-1}
vessel mobilization time at home dock	2	days
vessel mobilization rate vs. standard day rate	66%	
vessel day rate per anchor mass	8333	\$ tonne^{-1}
time per anchor deployment	1.0	hours
weather days vs work window	20%	
vessel standby rate vs standard rate	88%	
loading at dock per day	1.0	hours
time per anchor removal vs. deployment	75%	
vessel displacement per anchor mass (ratio)	100	
length of workday	24	hours
max. number of anchors transported simultaneously	8	

Array Deployment		
operational window length	45	days
deckhands per crew	2	
foremen per crew	1	
array tow speed	9.26	km hr^{-1}
deck space per dropper	0.15	m^2
time per dropper connection	0.5	minutes
winch daily rental rate per expected load	5.1	\$ kN^{-1}
movement / set up between	2.0	minutes
time to connect droppers (nominal)	0.6	minutes
time to connect transverse to cultivation lines (nominal)	3.6	minutes
time to pretension anchor lines	30	minutes
time to connect array to moorings	15	minutes
time to unroll array	15	minutes $(100\ m)^{-1}$
Seeding		
seeding speed without cleaning	1.9	km hr^{-1}
speed with cleaning vs. without cleaning	50%	
time to connect to new cultivation line	7.5	minutes
deck space required per seeding spool	0.05	m^2
foremen and captains per crew	1	
deckhands per crew	2	
Loading time per spool	0.30	minutes
added time per dropper when seeding	0.5	minutes
Maintenance		
deckhands per crew	2	
foremen and captains per crew	1	
probability of premature component failure	2.5%	
purchase cost of ROV vs rated water depth	100	\$ (m water depth)$^{-1}$
ROV annual maintenance vs purchase cost	10%	
ROV expected lifetime	10	years
ROVs per maintenance vessel	1	
cultivation Line lifetime reduction after tangling	90%	
nominal cultivation line lifetime	10	years
grow line inspection frequency check after tangling	50%	
nominal dropper maintenance check interval	3	years
equipment load and unload time	0.25	hour
typical maintenance equipment mass	0.5	tonne

Harvest		
time to load container	1	minutes
harvest speed per deckhand	4	m minute^{-1}
time to replace filled container	10	minutes
increase in replacement time with # stack levels	10	% (stack level)$^{-1}$
time to connect to new cultivation line	7.5	minutes
nominal kelp pile bulk density	300	kg m^{-3}
kelp slurry density	900	kg m^{-3}
deck space per harvest station	3	m^{2}
harvest container cost	467	$ m^{-3}
harvest container lifetime	10	years
vessel standby (weather day) rate vs standard rate	50%	
additional ops time per length of tangled line	0.5	minute m^{-1}
harvest container mass per surface area	7.5	kg m^{-2}
kelp slurry pumping rate	3	m^{3} minute^{-1}
yield loss at per length of cultivation line interaction	75%	
unloading time per harvest container	2.0	minutes
Labor		
deckhand annual salary	52,000	$
foreman annual salary	62,400	$
captain annual salary	70,000	$
annual administrator salary	65,000	$
annual manager salary	80,000	$
standard hours per week	40	hours
cost of consumables per person	15	$ day^{-1}
Overhead		
annual administrative time per employee	30	hours
annual administrative time per vessel hired	40	hours
annual administrative time per vessel owned	120	hours
# of crews per manager	5	
indirect labor burden rate	10%	
office space per office worker	18.6	m^{2}
monthly office rent per area	21.5	$ m^{-2}
period of manager employment vs season duration	125%	
monthly shoreside facility operating exp vs rent	15%	
P&I insurance per on-the-water FTE	500	$ month^{-1}
annual farm insurance premium vs. cost of installed farm	0.5%	
shoreside storage space monthly cost per mass of farm gear	1	$ tonne^{-1}

Shoreside Operations		
base rate for use of shoreside infrastructure	50	\$ $hours^{-1}$
additional rate for use of shoreside equipment use per equipment mass	50	\$ $tonne^{-1}$
hourly rate for pier use per vessel length	10	\$ m^{-1}
power use during shoreside ops per lifted mass	100	kW $tonne^{-1}$
additional time of shoreside equipment use vs direct use	20%	

Vessels - General		
freeboard vs length	3.3%	
deck mass per area vs hull mass per area	50%	
hold volume vs total below work deck volume	40%	
gunwale height	0.75	m
windage area for cabin and deck machinery vs hull	75%	
maximum heel angle due to wind	14	deg
vessel length vs. beam	3	
nominal cruising speed vs vessel length	3.93	km $hour^{-1}$ $m^{-0.5}$
cost of marine diesel	1.25	\$ $liter^{-1}$
fuel consumption during operations vs consumption at rated power	10%	
minimum open deck space needed for operations	10	m^2
time to prepare or clean up vessel per length of shift	0.25	hours day^{-1}
used engine power vs fuel consumption	3.64	kW $liter^{-1}$ hour
Displacement shape factor	0.84	
vessel length vs. lightship draft	9	
rated engine power vs vessel displacement	3.05	kW $tonne^{-1}$

Vessels - Hired		
deck length vs vessel length	60%	
hourly cost per displacement (multiplier)	47.4	\$ $tonne^{-1}$
hourly cost per displacement (power)	0.459	
portion of ship weight above deck	25%	

Vessels - Farm-Owned		
daily dockage fee per vessel length	3.3	$ m^{-1}
annual insurance premiums vs purchase cost	2%	
nominal cost per lightship displacement	8269	$ tonne^{-1}
drive train mass vs engine mass	75%	
average days used per year	36%	
navigation system cost	100	$ month^{-1}
required cabin space per crew size - day trip	6	m^{2} person^{-1}
required cabin space per crew size - multi day trip	10	m^{2} person^{-1}
cabin mass per area	0.23	tonne m^{-2}
height per cabin level	2.5	m
number of cabin levels per vessel length	0.08	levels m^{-1}
length of navigation station	2	m
% length vessel unused in bow	10%	
cabin width vs vessel beam	80%	
cabin cost per weight vs hull cost per weight	200%	
water reserved per crew member	113	liter day^{-1}
fuel reserve per shift	50%	

Nursery		
nursery grow-out duration	44	days
tanks per technician	7.5	
energy costs	0.16	$ kWh^{-1}
facility construction costs	2048	$ m^{-2}
annual twine loss	5%	
seed twine length required vs. grow line length	180%	
Spacing between spools in tank	8.8	cm
Tank volume	1800	liter

Mechanization		
base cost of kelp blender	5,000	\$
base cost for harvest machinery per harvest station	7,500	\$
mechanized harvest speed target per harvest station	32	m $minute^{-1}$
base footprint of harvest machinery per harvest station	1	m^2
harvest machine footprint increase per increase in harvest speed	0.01	$m^2\ \%^{-1}$
ratio of harvest container move time reduction to harvest speed increase	50%	
base cost for seeding machinery	5,000	\$
seeding mechanization speed target	3.7	km $hour^{-1}$
base footprint of seeding machinery	0.5	m^2
seeding machine footprint increase per % increase in speed	0.01	$m^2\ \%^{-1}$
seeding machines per vessel	1	
speed reduction due to cleaning with mechanization	25%	
target maintenance increase in speed	100%	
base cost of maintenance machinery	10,000	\$
maintenance machines per vessel	1	
expected machinery lifetime	10	years
annual maintenance costs vs initial cost	10%	
base fuel consumption for al machinery	0.5	liter $hour^{-1}$
machine fuel consumption per % increase in speed	0.005	liter $hour^{-1}\ \%^{-1}$
additional machinery cost per % increase in rate over manual vs base cost	1%	
height of deck machinery CG above vessel deck	2	m
kelp slurry pump initial cost vs pump rate	13,774	\$ m^{-3} minute
kelp slurry pump fuel consumption vs. pump rate	8.8	liter $hour^{-1}$ m^{-3} min.

Farm Component Shipping		
shipping costs	0.16	\$ ton^{-1} $mile^{-1}$
average shipping distance	2000	mile

Farm Structure

	safety factor	component lifetime (years)		inspection interval (years)		inspection duration (hours)	purchase cost ($ unit^{-1})		
farm design	both	base.	impr.	base.	impr.	both	base.	impr.	unit
anchor chain	1.92	10	10	2.0	2.0	0.75	893	496	m
anchor line	2.09	9.9	12.3	2.0	2.0	0.75	482	279	m
header line	2.09	9.9	12.3	1.0	1.0	0.50	481	270	m
transverse line	2.09	10	10	1.0	1.0	0.10	42.3	N/A	m
cultivation line	2.09	8.4	9.8	1.0	1.0	0.15	18.6	7.24	m
dropper float	N/A	20	20	2.7	3.0	0.07	27.4	291	float
dropper tether	2.09	10	10	2.7	3.0	N/A	0.07	0.73	m
node float	N/A	20	20	1.0	1.0	0.50	5.17E+3	129E+3	float
node tether	1.92	10	10	0.0	0.0	N/A	7.67	192	m
midline mooring float	N/A	10	10	2.0	2.0	0.33	3.31E+3	N/A	float
midline mooring float tether	1.92	10	10	0.0	0.0	N/A	2.06	N/A	m
anchor	1.15	30	30	2.0	2.0	0.75	31.2E+3	26.7E+3	anchor
large connecting hardware	2.09	10	10	2.1	2.1	N/A	1.92E+3	1.42E+3	item*
mall connecting hardware	2.09	10	10	2.1	2.1	N/A	1.89	15.3	item*

*** average cost across category**