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Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal

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Abstract

To keep global surface warming below 1.5 °C by 2100, the portfolio of cost-effective CDR technologies must expand. To evaluate the potential of macroalgae CDR, we developed a kelp aquaculture bio-techno-economic model in which large quantities of kelp would be farmed at an offshore site, transported to a deep water "sink site", and then deposited below the sequestration horizon (1,000 m). We estimated the costs and associated emissions of land-based nursery production, permitting, farm construction, ocean cultivation, biomass transport, and C Monitoring, Reporting, and Verification (MRV) for a 1,000 acre (405 ha) "baseline" project located in the Gulf of Maine, USA. The baseline kelp CDR model applies current systems of kelp cultivation in a realistic way to deep water (100 m) exposed sites using best available modeling methods. We calculated the levelized unit costs of CO_2eq sequestration (LCOC; \$ tCO_2eq^{-1}). Under baseline assumptions, LCOC was \$17,048 tCO_2eq^{-1}. Despite annually sequestering 628 tCO_2eq within kelp biomass at the sink site, the project was only able to net 244 C credits (tCO_2eq) each year, a true sequestration "additionality" rate (AR) of 39% (i.e., the ratio of net C credits produced to gross C sequestered within kelp biomass). As a result of optimizing 18 key parameters for which we identified a range within the literature, LCOC fell to \$1,257 tCO_2eq^{-1} and AR increased to 91%, demonstrating that substantial cost reductions could be achieved through process improvement and decarbonization of production supply chains. Kelp CDR may be limited by high production costs and energy intensive operations, as well as CDR MRV uncertainty. To resolve these challenges, R&D must (1) de-risk farm designs that maximize lease space, (2) automate the seeding and harvest process, (3) leverage selective breeding to increase C yield, (4) assess the cost-benefit of gametophyte nursery culture as both a platform for selective breeding and driver of operating cost reductions, (5) decarbonize equipment supply chains, energy usage, and ocean cultivation by sourcing electricity from renewables and employing low GHG impact materials with long lifespans, and (6) develop low-cost and accurate ocean CDR MRV techniques.

1. Introduction

Climate change has destabilized ecosystems, global food systems, and infrastructure (Currenti et al., 2019; Mora et al., 2018; Myers et al., 2017; Pei et al., 2020; K. E. Smith et al., 2021). Atmospheric CO_2 concentrations were higher in 2019 than at any point in the previous 2 million years, a result of anthropogenic greenhouse gas (GHG) emissions (IPCC, 2021). To remain below 1.5 °C of warming by 2100, and avoid the worst consequences of climate change, society will not only have to reach net zero GHG emissions, but also achieve net negative emissions by 2050 (IPCC, 2021). These projections dictate that emissions reductions alone will not satisfy the requirements of the Paris Agreement. Rapid decarbonization must be accompanied by large scale removal of atmospheric CO_2 using best available Carbon Dioxide Removal (CDR) strategies.

CDR is defined as the intentional removal of CO_2 from the atmosphere through either engineered or "nature based" approaches. Engineered solutions include direct air capture (DAC) (Marcucci et al., 2017) and point-source carbon capture and storage (CCS) (Anderson & Peters, 2016; Creutzig, 2016). "Nature based" techniques, such as reforestation and afforestation (Edmonds et al., 2013), soil management (P. Smith, 2012; van Minnen et al., 2008), and ocean fertilization (Minx et al., 2018), reduce atmospheric CO_2 by enhancing biological carbon pumps. The portfolio of available CDR technologies must offset emissions in the medium to near term, decarbonize infrastructure that is not readily adaptable, and remove legacy (historic) emissions (Joppa et al., 2021).

The voluntary market for carbon credits, in units of USD per ton of carbon dioxide equivalent ($\$\ tCO_2eq^{-1}$) sequestered or avoided, reached $1 billion in 2021, representing ~250 million tCO_2eq emissions removed (Forest Trends' Ecosystem Marketplace, 2021). However, credits vary widely in price and permanence of CO_2 removal, a reflection of differences among project methodologies (Fuss et al., 2018). Engineered solutions, such as DAC, potentially sequester carbon on geologic time scales on the order of 1,000's of years (NASEM, 2019). However, DAC credits can be priced > $1,000 tCO_2eq^{-1}, a result of large energy and capital requirements (Sanz-Pérez et al., 2016). Nature based solutions, such as reforestation or improved soil management, can be less energy intensive and potentially more cost effective compared to DAC (P. Smith, 2012). However, storing C within forest biomass or soil can lead to less permanent sequestration (i.e., 10 - 50 years) as these natural C stocks are subject to disturbance from forest fires or floods (L. J. Smith & Torn, 2013). Furthermore, terrestrial-based CDR strategies are limited in scale, as they require converting significant amounts of productive land, potentially placing stress on food systems (Kreidenweis et al., 2016; Msangi et al., 2007). Urgent demand for verifiable, real, permanent, cost effective, and socially and ecologically sustainable carbon credits will only increase. Expanding the supply of effective CDR technologies, and reducing uncertainty regarding costs and spillover effects, will be key in realizing net zero goals (Ng et al., 2020).

Recently, research has focused on whether macroalgae can and should be included within the portfolio of available CDR solutions. Wild macroalgae represent one of the most extensive and productive vegetative biomass stocks, and export a significant portion of net primary production, nearly 44% in the form of dissolved (DOC) and particulate (POC) organic carbon (Duarte & Cebrián, 1996). However, macroalgae primarily grow in rocky nearshore areas not conducive to localized long-term sequestration. The vast majority of this POC and DOC is therefore remineralized and eventually re-enters the atmosphere as CO_2 (Frontier et al., 2021; Krause-Jensen & Duarte, 2016). Long-term sequestration (i.e., > 1,000 years) can occur when exported biomass is incorporated within deep ocean sediments (i.e., > 1,000 m), or is remineralized at depths below the permanent thermocline in areas of the ocean in which bottom waters are locked away from atmospheric exchange for extended periods (Hurd et al., 2022; Krause-Jensen & Duarte, 2016; Ortega et al., 2019). First order estimates suggest that only ~11% of exported macroalgal derived C is permanently sequestered (Duarte & Cebrián, 1996; Krause-Jensen & Duarte, 2016). Keeping in mind the recent debate as to the net contribution of macroalgae to the global C cycle (Filbee-Dexter et al., 2022; Gallagher et al., 2022), these ecosystems potentially sequester ~0.68 $GtCO_2eq$ annually (equivalent to two-thirds of total emissions from the U.S. industrials sector [EPA, 2021]). However, wild macroalgae populations have largely been ignored within blue carbon frameworks (Nellemann et al., 2009) because quantifying the annual contribution from source to sink is challenging (Barrón & Duarte, 2015).

Macroalgae aquaculture, the farming of marine or freshwater organisms, could potentially be leveraged to replicate and scale the important C sequestration contribution from wild beds and generate verifiable C credits. The farmed macroalgae industry has nearly tripled in scale since the turn of the 21st century, increasing from 10.6 million t (wet weight) in 2000 to 32.4 million t (wet weight) in 2018 (FAO, 2020). Production is currently dominated by brown algae species, such as kelps, destined for the food, fertilizer, animal feed, pharmaceutical, and nutraceutical industries (Augyte et al., 2021). However, production of red algaes, such as *Eucheuma* and *Kappaphycus spp*., are not far behind and often trade for the top spot (Kim et al., 2019). Previous efforts to explore the climate change mitigation potential of macroalgae farming have included using raw materials for the production of biofuels (Michalak, 2018; Osman et al., 2020), nutrient management (Racine et al., 2021), and as a supplement within livestock feed to reduce methane emissions (Roque et al., 2021). Early-stage research is also being conducted to evaluate the potential of growing and then intentionally sinking large quantities of macroalgae in the deep ocean, potentially locking the C incorporated within macroalgae biomass away from atmospheric exchange (DeAngelo et al., 2022; Froehlich et al., 2019; Gaines et al., 2019; NASEM, 2021; Peters, 2020).

On the spectrum of CDR technologies, the purposeful sinking of farmed macroalgae lies somewhere between an engineered and nature-based solution. The ability to control the physical and biomolecular composition of biomass through species and phenotypic selection, manipulate farm dynamics, and specify the timing and location of sinking makes farming macroalgae an attractive CDR option. With respect to larger, K-selected macroalgae species, such as Fucales and Laminariales, POC is stored in relatively refractory forms and would be more resistant to grazing after deep-sea deposition, compared to other r-selected opportunistic species, like Ulvacian or Dasyacean (Littler & Littler, 1980; Steneck & Dethier, 1994). Targeted sinking after harvest could also ensure that kelp reaches regions and depths that increase the likelihood of long-term CO_2 removal, such as deep-sea canyons or abyssal plains (Harrold et al., 1998; Masson et al., 2010). These factors potentially offer higher conversion rates of 'exported' biomass to sequestered carbon (Krumhansl & Scheibling, 2012). Kelp farming also requires minimal arable land and freshwater (Bricknell et al., 2020; Grebe et al., 2019; Hu et al., 2021), could be less energy intensive than other 'engineered' solutions (such as DAC), and satisfies many of the United Nations Sustainable Development Goals (Duarte et al., 2021).

There are still considerable questions regarding the environmental, biological, geological, and, perhaps most importantly, economic feasibility of kelp aquaculture based CDR (DeAngelo et al., 2022; Hurd et al., 2022; Troell et al., 2022). To satisfy the removal requirements of the IPCC of ~10 $GtCO_2$ $year^{-1}$, assuming a target sequestration price of \$100 tCO_2eq^{-1}, the CDR sector will need to grow into a ~\$1 trillion market by 2050 (IPCC, 2021; REFINITIV, 2022). Policy makers, researchers, and investors will require accurate estimates of the economic and environmental performance, efficiency, and long-term scaling potential of available CDR technologies to make decisions regarding allocation of climate resources and research and development (R&D) funding (Fuss et al., 2018). To justify further public and private financial support for kelp aquaculture CDR, it must be demonstrated that there is a pathway to cost-effectively generating kelp C credits.

Froehlich et al. (2019) analyzed global production data and determined that the cost of producing carbon credits from macroalgae ranged from \$71 - \$27,222 tCO_2eq^{-1}. While the upper end of this range is far greater than current market prices, the ability to potentially sequester CO_2 at a price point of under \$100 tCO_2eq^{-1} warrants further study. Global production models offer valuable insights into the potential of this novel concept (DeAngelo et al., 2022; Duarte et al., 2017, 2021; Froehlich et al., 2019). However, seaweed production cost estimates can vary widely by region, species, and husbandry method (van den Burg et al., 2016). A site-specific and exploratory analysis of this low technology readiness level concept is thus required to provide insight into specific R&D needs (Thomassen et al., 2019).

The primary goal of this study was to analyze the economics of macroalgae CDR to determine a hyper-realistic baseline cost, quantify uncertainty, identify pathways for optimization and future cost reduction, and categorize research priorities. Evaluating the potential social and environmental risks associated with large-scale macroalgae farming and sinking remains a critical, yet understudied, aspect of the concept (Boyd et al., 2022; Hurd et al., 2022), but falls outside the scope of this analysis. Rather, we attempt to provide a rigorous assessment of the costs and climate potential of this emerging technology. Through an extensive literature review, expert consultations, and detailed economic and engineering analysis, we constructed a biological-techno-economic model (BTEM) of a hypothetical kelp CDR operation located within the Gulf of Maine (GOM), a region of the U.S. with an established aquaculture permitting process and an expanding kelp farming sector (Grebe et al., 2019; St-Gelais et al., 2022). We quantified the effects of scale, production methods, and project emissions on the levelized costs of producing verified carbon credits (\$ tCO_2eq^{-1}) over a 30-year horizon. The results of this work provide a replicable framework with which to guide future R&D and are relevant to both the CDR and kelp aquaculture industry generally, as the emphasis on scaling up kelp production is an active area of interest for policy makers, investors, and macroalgae farmers.

2. Methods

2.1 Bio-techno-economic model (BTEM) overview

Global models of kelp CDR approaches have been incredibly valuable tools to evaluate scalability and costs over large geographic regions (DeAngelo et al., 2022; Frohlich et al., 2019). However, due to complexities associated with choice of species, site-specific factors, and cultivation strategies, we contend that more granular regional analyses can help identify pathways for cost reductions that would not otherwise be apparent in global analyses. To create a baseline for kelp aquaculture CDR, we constrained the design space to a single kelp species (*S. latissima*; hereafter kelp), region (GOM), and available husbandry practices, defined as methods or technologies that have been demonstrated commercially (albeit at smaller scales than evaluated here).

The bio-techno-economic model (BTEM) was made up of four components: (1) an ocean cultivation submodel, (2) a kelp biological submodel, (3) a Life Cycle Assessment (LCA) submodel, and (4) a C credit verification framework (**Figure 1**). The ocean cultivation submodel quantifies the costs of outplanting seeded twine, installing and maintaining a cultivation structure suitable for open-ocean conditions, and harvesting/sinking kelp. The biological submodel calculates the total quantity of CO_2eq sequestered each year as a function of kelp biomass yield. The LCA submodel quantifies project emissions, which must be deducted from the net C sequestration budget of the project. Lastly, the verification framework incorporates the costs, and C discounts, associated with selling C credits on open markets.

The BTEM was developed with a 30-year design life, the upper end of the lifespan for agricultural buildings (CEN, 1990), in which costs and C credits were aggregated annually. The primary model output was the levelized cost of CO_2 sequestration (LCOC; \$ tCO_2eq^{-1}), which represents the unit cost of sequestering a single ton of CO_2eq. LCOC was calculated by dividing the discounted sum of cash outflows over a period of time by the discounted sum of carbon credits produced during that same period of time. LCOC (\$ tCO_2eq^{-1}) was calculated as:

$$LCOC = \left(\sum_{i=0}^{n} \frac{OC_t + VC_t}{(1+r)^t} + I_0\right) * \left(\sum_{i=0}^{n} \frac{CC_t}{(1+r)^t}\right)^{-1}$$

where n was the lifespan of the operation (30 years), OC was ocean cultivation costs in year t, VC was verification costs in year t, I_0 was the initial investment in year 0, CC was the number of C credits sold in year t, and r was the discount rate (6.75%) used in the analysis (January 2020 bank prime lending rate +2%). The upfront investment in capital expenditures (cap-ex), permits, and anchor installation costs (I_o) was not discounted as it was paid out in the present (year 0). The following sections describe in more detail the components of submodels 1 - 4.

2.2 BTEM submodel (1): Ocean cultivation

The ocean cultivation submodel calculates an estimate of the costs required to lease, install, and operate a kelp farm in Maine state waters (0 - 3 nm from land). The U.S. lacks an established pathway to securing farming rights (i.e., a lease or equivalent legal tenure) within the federally managed Exclusive Economic Zone (EEZ) of 3 - 200 nm from shore (Otts, 2021). Maine, a state with an established aquaculture sector (DMR, 2021), was thus chosen as the study region. In Maine, no leaseholder may be in possession of a single tract that is greater than 100 acres (40.5 ha), but leaseholders may obtain multiple tracts that, in aggregate, amount to 1,000 acres (404.7 ha). We therefore designed a modular cultivation structure that occupies a footprint of 100 acres which can be replicated to fill the allotted 1,000 acres.

Relatively large prospective lease sites will likely be located in exposed ocean areas subject to wind, waves, and currents. The cultivation structure was thus designed for a representative site located SW of Monhegan Island, ME USA, ~20km from the Maine coastline. Twenty years of historical wave and current data from the site (NERACOOS, 2022) were fit to an extreme value distribution and extrapolated to compute 10-year and 50-year design values. Since kelp cultivation systems are comprised of flexible biomass components subject to nonlinear wave and current forces, neither static analysis nor typical ocean structural modeling techniques are sufficient for determining the required capacity of mooring lines, anchors, floats, etc. Therefore, we developed a time domain numerical model of the candidate structures using a Hydro-Structural Dynamic Finite Element Analysis approach (HS-DFEA). This HS-DFEA approach solves the equations of motion at each time step using a nonlinear Lagrangian method to accommodate the large displacements of structural elements, as described in the NOAA Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico (Fredriksson & Beck-Stimpert, 2019). Forcing was based on a modified Morison equation approach (Morison et al., 1950). Similar models have been utilized for aquaculture systems consisting of nets (DeCew et al., 2010; Klebert et al., 2013; Tsukrov et al., 2003) and mussel droppers (Dewhurst, 2016; Knysh et al., 2020). These applications incorporate specific empirical hydrodynamic coefficients, and some characterize flow reduction e.g. (Patursson et al., 2010) or use a priori estimates of flow speed reduction through the structure (Dewhurst et al., 2019; Gansel et al., 2018).

Wave and current loading on buoy and line elements (including macroalgae elements) were calculated at each time step according to the relative motion between the structural elements and the surrounding fluid. The hydrodynamics of the macroalgae were incorporated using the results from Fredriksson et al. (2020) and included a reduction in current speed through the farm based on a spatially-averaged momentum balance approach (Rosman et al., 2010).

Three candidate farms were initially chosen. All three designs were based on a 4-point spread mooring array system with horizontal grow-lines traversing the length of the structure. Grow-lines were spaced 4 m apart and were maintained at 2 m depth with surface floats. The three designs were identical in structure and materials, but differed with respect to the ratio of farm length to width (i.e., aspect ratio), and thus the size of the "growing area" within each 100-acre plot (**Figure 2**). Farm design "a" had an aspect ratio of 1.6, with a grow-area length of 200 m, a grow-area width of 320 m, and 10,740 m of planted grow-line. Farm design "b" had an aspect ratio of ~2.5, with 14,742 m of planted grow-line. Farm design "c" had the largest aspect ratio (10), with a grow-area length of 1,437 m, grow-area width of 143 m, and 35,914 m of planted grow-line.

For each candidate farm design, several realizations of a 50-year storm were evaluated. Both wave-dominated and current-dominated 50-year events were examined for incident wave and current headings parallel to, normal to, and at 45 degrees from the grow lines, in accordance with Norwegian finfish cage design standard NS 9415 (Standards Norway, 2009). For each one of these simulations, defined as load cases, the maximum expected tensions and forces were found by simulating the farm design using the HS-DFEA method, and deriving an extreme value distribution for the maximum loads to calculate those expected in a one-hour storm. Using the modeling techniques that incorporated the macroalgae hydrodynamic coefficients, we calculated the minimum breaking strength of the structural and mooring components required to achieve safety factors of 1.5 - 1.8 as recommended for various components of offshore structures (ABS, 2012; NAVFAC, 2012). Furthermore, the API RP 2SK (2005) recommends a reduction factor be included when high-capacity drag embedment anchors are loaded at a non-zero uplift angle (API, 2005). Each kelp cultivation structure ("a", "b", and "c") was designed such that the maximum uplift angle was within the acceptable limit of 20 degrees, as per API RP 2SK. This reduction factor was included when calculating the required rated capacities of the anchors. We included an additional 15% margin on all component capacities based on preliminary uncertainty estimates in the numerical modeling approach as indicated from full-scale validation experiments.

Taking into account the required safety factors, we computed the minimum allowable capacity (e.g., breaking strength) of major structural components for each candidate design based on the results of the dynamic simulations of the system in the specified storm conditions. Breaking strength estimates were then used to identify the equipment required to anchor the farms at the proposed cultivation site. The cost of each component of the farm was then estimated based on quotes from suppliers (**Table S1**). The large aspect ratio of farm design "c" resulted in increased loads on the system due to the higher total biomass and the large angle between the mooring lines and the applied loads when the wind, wave, and current forces are normal to the grow lines. Despite the increased equipment expenses associated with these larger forces, the benefit of a more expansive grow-area, and thus higher kelp yields per 100-acre plot, outweighed the costs of larger anchors, buoys, etc. When expressed in terms of $ of cap-ex per kg of kelp yield, design "c", with an aspect ratio of 10:1, outperformed the other two structures. Results were $1.95, $1.69, and $1.31 per kg of biomass for "a", "b", and "c", respectively. Therefore, farm design "c" was chosen for further CDR analysis.

The primary costs within submodel (1) included the upfront investment in permits and the cultivation structure (I_0) and annual farm operations (ocean cultivation costs; *OC*). *I* accrued in year 0, and was made up of cap-ex, lease application fees, permitting costs, professional engineering fees, and mooring installation costs. We assumed a 50:50 split between debt and equity to calculate cap-ex and a contingency factor of 2.5% was used for each component of the farm (**Table S1**). Installing drag-embedment anchors requires significant vessel capacity. Drawing on marine hydrokinetic offshore construction, we estimated that installation costs for the 1,000-acre baseline farm would be $155,266 per 11-ton anchor (Jenne et al., 2015). This covers the cost of a contracted vessel and crew, fuel, and travel to and from the site (**Figure S1**). Decommissioning costs were not included within our analysis as they fall outside of the "lifetime" of the project, but would likely be as expensive, if not more, than construction. Based on estimates from the offshore wind sector, we also assumed a one-time payment of $300,000 to a professional marine contractor with engineering capabilities to design the structure, select properly rated components and equipment, create site drawings and installation plans, and conduct the HS-DFEA simulations.

To secure a standard aquaculture lease >3 acres in Maine, applicants must pay a $2,000 application fee for each lease application (i.e., per 100 acre plot), also assumed in year 0. Based on consultations with the Maine Department of Marine Resources and the U.S. Army Corps of Engineers, we also included a $2,447,500 pre-leasing cost to hire consultants to help navigate the National Environmental Policy Act (NEPA) requirements, and conduct baseline environmental monitoring on fish and marine mammal aggregations within the proposed lease site through the use of *in situ* instrumentation, such as passive acoustic monitoring for cetaceans and geophysical-geotechnical and benthic habitat surveys (Jenne et al., 2015). While this is not currently required for leases within state waters, consultations with regulators indicated that an installation of this size would likely require additional monitoring (**Table 1**).

The cost of annual farm operations (*OC*) was then further decomposed into fixed costs (*FC*) and operating expenses (*OE*) as follows:

$$OC = FC + OE$$

FC included replacement cap-ex based on the useful life of components, interest, lease fees, insurance, and regulatory fees (**Table 2**). The remaining portion (50%) of the initial investment in cap-ex was financed using a 30-year term loan with a 5% interest rate and annual repayment schedule, which began in year 1. Maine leaseholders must annually pay \$100 acre^{-1} in lease rental fees (DMR, 2021). We also assumed an additional fee equal to 5% of annualized cap-ex (van den Burg et al., 2016) to cover insurance and any other miscellaneous fixed costs.

OE included seeded twine, labor, vessel operations, and farm maintenance (**Table 2**). We assumed the operation was required to construct a land-based nursery that produced twine exclusively for kelp CDR. The nursery would follow the most widely adopted kelp protocols (Coleman et al., 2022; Flavin et al., 2013; Forbord et al., 2018; Redmond et al., 2014). In the summer, juvenile sporophytes would be grown within the facility on PVC spools wrapped with 2 mm twine. The spools would then be transferred to the cultivation site in the fall when the seeded twine would be wrapped around the grow-line. We used the kelp nursery model described in Coleman et al. (2022) to calculate the cost of seeded twine (\$ m^{-1}). At a scale of 1,000 acres, the farm would contain 359,140 m of grow-line. Based on a conversion of seeded twine to grow-line of 1.8 (Engle et al., 2020), the operation would require 646,452 m of seeded twine each year at a cost of \$0.91 m^{-1} (Coleman et al., 2022) (**Figure S2**).

Labor was decomposed into three categories: (1) seeding in the fall, (2) overwinter maintenance, (3) and harvest in the summer (Bak et al., 2018; Correa et al., 2016; Dijk & Schoot, 2015; Hasselström et al., 2020; Zuniga-Jara et al., 2016) (**Table S2**). Full time equivalent (FTE) person hours for seeding and maintenance were assigned to each task based on the quantity of grow-line within the farm (FTE person hours per km of grow-line). Harvest labor requirements were calculated based on final yield (FTE person hours per harvested wet ton). We assumed a labor rate of \$25 hour^{-1}. The vessels required for seeding, maintaining, and harvesting kelp within exposed offshore conditions are only needed seasonally and would likely be contracted. Based on Hasselström et al. (2020), we assumed a cost of \$3,845 day^{-1} for seeding and harvest vessels, and \$333 day^{-1} for overwinter maintenance vessels. A value of \$5,000 per 100 acre plot for annual expendable and maintenance supplies was also assumed annually (Hoagland et al., 2003; Rubino, 2008).

Given the potential verification and regulatory challenges of measuring C flux from the release of free-floating kelp lines[1], we decided to quantify the requirements of transporting the kelp biomass to a predetermined "sink" site with adequate depth. The chosen site lies at the edge of the continental shelf (depths of >1,000 m), a ~350 km trip (one-way) from the Monhegan Island case study site. Based on consultations with marine construction contractors, we assumed an hourly rate (including crew, equipment, and fuel) of \$700 h^{-1} for the use of 2,000 hp tugboats and \$62.5 hour^{-1} for each 2,000 t capacity ocean-going barge required to transport biomass (Hughes Marine, *pers. comms., February, 2022*). The tug has a cruising speed of 10 km hour^{-1} and a specific fuel consumption of 8.7 kg of diesel per 1,000 ton-km (Teodorović & Janić, 2017). We also included the cost (\$6 ton^{-1}) and mass (0.14 tons per ton of wet kelp) of reclaimed concrete required for sinking ballast within our transport calculations (**Supplementary Materials**).

2.3. BTEM submodel (2): Biological

The biological submodel determines the annual quantity of CO_2eq sequestered as a function of yield (kg m^{-1}; wet weight), a conversion from wet (WW) to dry (DW) weight and a conversion from DW to C content. The biomolecular composition and growth of *S. latissima* can

[1] https://www.fastcompany.com/90548820/forget-planting-trees-this-company-is-making-carbon-offsets-by-putting-seaweed-on-the-ocean-floor

vary by region, season, and cultivation method (Manns et al., 2017; Ometto et al., 2018). Yields as high as 24 kg m^{-1} (Kim et al., 2019) and as low as 0.5 kg m^{-1} (Bruhn et al., 2016) have been reported from sugar kelp in northern temperate farming regions. Stekoll et al. (2021) identified a published average of 12.5 kg m^{-1}, which aligns well with reported yields of 12.7 kg m^{-1} from a location about 87 km southwest of the case study site (St-Gelais et al., 2022). These values are derived from studies on kelp produced primarily for human food applications, in which maximum biomass yield was balanced with blade quality and fouling by epibionts. For CDR applications, producers may be able to harvest later in the growing season (i.e., August or September) and maximize growth and potential CO_2eq. However, we assumed a baseline (and thus likely conservative) estimate of 12.5 kg m^{-1}. Based on a review of 14 studies, we then assumed an average +/- SD (n = 67) conversion of 13.33 +/- 3.17% of wet kelp to dry kelp, and an average +/- SD (n = 40) conversion of 28.59 +/- 4.02% of dry kelp to C (**Table S3**). C was converted to potential CO_2 using a stoichiometric molecular weight conversion factor of 3.67 (Duarte et al., 2017; Pendleton et al., 2012). Lastly, we assumed that 100% of potential CO_2 was delivered to a depth of >1,000 m as a result of transport to the edge of the continental shelf and sinking. There is considerable uncertainty regarding the eventual fate of kelp derived C were it to be injected below the sequestration horizon (Krumhansl & Scheibling, 2012; Smale et al., 2021). Resolving those questions, while beyond the scope of this study, will be essential in determining the true potential of macroalgae CDR (NASEM, 2021).

2.4 BTEM submodel (3): Life Cycle Assessment (LCA)

Emissions from the processes required to produce and sink each year's "crop" of kelp must be deducted from the final quantity of CO_2eq sequestered in the deep ocean to calculate the net C budget of the project. To quantify project emissions, we developed a Life Cycle Assessment (LCA) model. Environmental LCAs are useful for quantifying the sustainability of a system across the full value chain (i.e., from cradle to grave), as described in Czyrnek-Delêtre et al. (2017) and Parsons et al. (2019). The environmental impact of a product is commonly evaluated according to the guidelines of CML 2 baseline 2000 (v2.05; Institute of Environmental Sciences, Leiden University) which includes a suite of metrics, such as abiotic depletion, acidification, eutrophication, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, and global warming potential (GWP) over 100 years (Guinee, 2002; Seghetta et al., 2016). We developed a kelp aquaculture LCA focused solely on the GWP (tCO_2eq) of the farm within a typical year (Thomas et al., 2021; van Oirschot et al., 2017).

The aim of the LCA was to calculate the total quantity of CO_2eq emissions produced by the project that must ultimately be deducted from the quantity of sequestered CO_2eq. Therefore, the functional unit of the LCA, i.e., the unit in terms of which the impacts are expressed, was tCO_2eq emitted $year^{-1}$. The system boundaries were set to include emissions encompassing the full baseline BTEM, from the land based nursery, to open-ocean cultivation (cradle to farm-gate), and lastly biomass transport and sinking (cradle to grave). The Life Cycle Inventory (LCI) was developed by quantifying both the energy (i.e., electricity and marine fuel) and materials (i.e., mooring lines, anchors, nursery infrastructure, and expendable supplies) consumed within each year across the full value chain of the 1,000 acre baseline kelp CDR operation. Emissions factors for all energy and materials were sourced from LCA databases, such as EcoInvent (version 3.2), and literature reviews (Thomas et al., 2021). Lastly, we conducted an "Impact Assessment" to translate the inputs and outputs of the baseline BTEM into emissions, expressed in terms of the functional unit: tCO_2eq emitted $year^{-1}$ (**Table S4**).

2.5 BTEM submodel (4): Verification framework

Selling carbon credits within compliance or voluntary markets requires third party verification to ensure the CDR project meets the IPCC criteria of ‘real’, ‘measurable’, ‘permanent’, ‘unique’ and ‘additional’ (Gold Standard, 2021). Compliance markets, such as California's cap-and-trade program, are established by regional, national, or international governing bodies (Marland et al., 2017). Voluntary markets operate outside of compliance markets, and allow corporations or individuals to offset "personal" GHG emissions (Joppa et al., 2021). Gold Standard (GS), Verified Carbon Standard (VCS), and the Clean Development Mechanism (CDM) are the most widely known verification bodies that facilitate the issuance of C credits.

We adhered to the guidelines of GS and VCS to calculate verification costs. According to these guidelines, producers must draft a project methodology. This document outlines the scientific precedent supporting the proposed project and is reviewed by experts in the associated field (Gold

Standard, 2017; VCS, 2021). Drafting a methodology and navigating the review process costs \$150,000. Next, project developers must submit a "Project Design" document that outlines the specifics of the proposed CDR operation (i.e., how does the proposed project follow an approved methodology?). The GS Project Design review fee is \$1,500. These costs were assumed in year 0 and, just as with the initial investment in cap-ex and regulatory fees (I_0), were not discounted.

GS requires an annual third-party audit to certify the quantity of credits claimed by the producer. Two audit costs were associated with each year's crop of kelp. First, there was a fixed "performance review" fee that ranges in price from \$10,000 year^{-1} for simple projects, such as point source carbon capture and storage, to \$100,000 year^{-1} for more complex projects, such as those that fall into the category of Land use and Forestry (LUF). We assumed the upper-end of the range for an annual fee of \$100,000 given the complexity of verifying kelp aquaculture CDR (NASEM, 2021). Next, GS charges a \$0.30 credit^{-1} issuance fee. CDR projects are often required to reserve a portion of credits within a "buffer pool" to account for MRV uncertainty and potentially lost C (Matzek et al., 2015). Accurately quantifying the amount of CO_2 removed not just from the oceanic C pool, but from the atmosphere, may be challenging due to the discrepancy between the timing of photosynthetic uptake of dissolved inorganic carbon (DIC) by kelp and the time required for re-equilibration of CO_2 between the atmosphere and the C replete surface waters within and adjacent to the farm (Hurd et al., 2022). If the waters carrying a DIC deficit are subducted prior to the drawdown of atmospheric CO_2, producers may not be able to take credit for the total amount of potential C removed by kelp. Furthermore, the artificial growth of large quantities of kelp may compete for nutrients with phytoplankton, decreasing natural NPP and thus C export and sequestration (Frieder et al., 2022; Gallagher et al., 2022). Finally, some portion of kelp derived particulate organic carbon (POC) that is deposited in the deep sea will ultimately be remineralized and, depending on deposition location, returned to the atmosphere before the 100-year mark (Siegel et al., 2021). Due to these potentially large uncertainties, we assumed 15% of credits, after all C accounting and deductions within submodels (2) and (3), respectively, would be reserved within a buffer pool.

2.6 Bio-techno-economic model analyses

We primarily focused on the levelized cost of producing C credits (LCOC; \$ tCO_2eq^{-1}) to evaluate the performance of kelp CDR. First, LCOC was calculated for the 1,000-acre baseline farm. We also quantified the levelized cost of C capture by kelp (LCOK; \$ t^{-1} kelp CO_2eq) prior to sequestration and thus without transport, sinking, or verification costs. LCOK was calculated by dividing the discounted sum of expenses, less sinking and verification, by the discounted sum of net C credits (after all emissions and buffer pool discounts) produced over the same 30-year horizon. To assess the effects of scaling, we then adjusted the farm size from 500 - 1,500 acres in 100 acre increments and calculated a corresponding LCOC and LCOK for each farm size. All expenses were then aggregated over the 30-year design life by line-item to provide a categorical cost breakdown of LCOC for the 1,000-acre baseline farm. We then quantified the annual impact (in tCO_2eq $year^{-1}$; the functional unit) of the primary categories within the LCA, as well as the required buffer pool, on the net quantity of C credits produced annually. To evaluate the emissions profile of the baseline kelp BTEM in the context of macroalgae LCA literature, we also calculated the CO_2eq impact of the farm from cradle to farm-gate. Excluding the emissions from biomass transport and sinking, we quantified the tCO_2eq emitted per ton of dry weight kelp produced.

To assess the relative impact of key variables on LCOC, we performed a sensitivity analysis using the 1,000-acre baseline scenario. First, we increased and decreased, in 10% increments, a comprehensive set of 21 variables within the BTEM to a range of +/- 40% and calculated a corresponding LCOC after each change (**Table S5; Figure S3**). Of the comprehensive list of variables selected, the 6 parameters that generated the greatest change in LCOC with changes in the baseline assumption were selected for visualization.

To develop a roadmap towards potential cost reductions and identify R&D priorities, we then conducted an "optimization" analysis. We identified a range of values from literature reviews and expert consultations for 18 key parameters within submodels (1) - (4) and iteratively changed the assumption for each parameter to the maximum or minimum value within the observed range that decreased LCOC. These changes represent potential "line of sight" improvements that exist within the current framework of kelp cultivation in emerging farming regions (i.e., North America, South America, and Europe). We performed this analysis looking at both LCOC (\$ tCO_2eq^{-1}) and "additionality rate" (AR; %). Additionality is the net effect that CDR projects have on atmospheric CO_2 concentrations (Barata et al., 2016). AR was thus calculated as the ratio of net C credits produced (tCO_2eq after all emissions and buffer pool deductions) to the gross quantity of CO_2eq

sequestered each year in kelp biomass. The metric gives an estimate of the efficiency of the farm as a CDR technology. With each parameter optimization, we recorded the subsequent change in both LCOC and AR (**Table S6**). All changes were then combined to arrive at a parameter set that minimized LCOC and maximized AR.

To explore the future scaling potential of this emerging technology, we then evaluated the impact of top-down "learning rates" on the optimized LCOC. Learning rate (LR) refers to the reduction in unit production costs for technologies as a result of a doubling in scale (Faber et al., 2022; Rubin et al., 2015). In the case of energy technologies, this would mean the % reduction in unit costs ($ kWh^{-1}) with each doubling of total installed capacity. For kelp CDR, the LR is the unforeseen unit cost reduction ($ tCO_2eq^{-1}) that is driven by doubling the size of the farm. For the majority of energy technologies, such as natural gas and solar photovoltaics (PV), production costs have declined with increases in installed capacity due to economies of scale, R&D, and "learning by doing" (LBD) (Kavlak et al., 2018; McDonald & Schrattenholzer, 2001). Given that kelp CDR remains in concept stages (NASEM, 2021), we would be unable to accurately predict future unforeseen cost reductions as a result of empirically derived LRs from historic production data. Therefore, we calculated the effect of a range of LRs realized for other technologies on the optimized LCOC. We doubled the footprint of the 1,000-acre optimized BTEM until a levelized sequestration cost of $100 tCO_2eq^{-1} was reached. With each doubling, we reduced LCOC by either 5%, 10%, 15%, or 20%. For comparison, the LR for PV between 1959 - 2011 was 23%, the highest for all energy technologies during that period (Rubin et al., 2015).

3. Results

At the scale of our baseline 1,000 acre farm, production costs (LCOC) were $17,048 tCO_2eq^{-1}. Across the range of simulated farm sizes (500 - 1,500 acres), LCOC decreased from $21,988 to $15,517 tCO_2eq^{-1} (**Figure 3**). The costs of capturing and sequestering a single ton of CO_2eq (i.e., sinking kelp) were consistently between $500 - $13,500 more (depending on farm scale) than those for only capturing a ton of CO_2eq within kelp (excluding verification and sinking costs), reflecting the additional costs and emissions associated with biomass transport to the sink site and third party verification of C credits (**Figure 3**). When examining the breakdown of LCOC, labor and fixed overhead costs made up the greatest portion of expenses at $4,299 and $3,449

tCO_2eq^{-1}, respectively (**Figure 4**). Fixed costs were primarily driven by the requirements of installing 40, 11-ton drag embedment anchors for a total of ~$6.2 million in year 0. Contracted vessels (not including barges and tugboats for biomass transport) and seeded twine were the next most substantial contributors to costs at $2,717 and $2,654 tCO_2eq^{-1}, respectively.

The baseline farm contained 359,140 m of grow-line. With yields of 12.5 kg WW m^{-1}, 4,489 tons (WW) of kelp were produced annually. Based on the conversion factors within submodel (2), 628 tCO_2eq were transported to the sink site, deposited below the sequestration horizon (>1,000 m) using reclaimed concrete, and sequestered each year. After deducting the project emissions calculated in Submodel (3), and the 15% buffer pool from Submodel (4), the baseline farm only issued 244 C credits (tCO_2eq) annually, a 384 tCO_2eq discount from the full potential of the operation (**Figure 5**). Therefore, the additionality rate (AR) of the project was 39%. In other words, 61% of the CO_2eq sequestered within kelp biomass was negated by the emissions resulting from the operation. Excluding the emissions from transportation to the sink site, the baseline farm produced 0.45 tCO_2eq per ton of harvested kelp biomass (DW). The operations of the nursery resulted in the largest annual deduction from the CO_2eq sequestration budget, -115 tCO_2eq, followed by the annualized upstream GHG impacts of the materials within the cultivation structure (-92 tCO_2eq), biomass transport and sinking emissions (-70 tCO_2eq), and contracted vessel fuel (-64 tCO_2eq). The vast majority of nursery CO_2eq emissions stemmed from electricity usage, nearly 90%, a product of sourcing energy from a standard U.S. electricity mix generated primarily from hydrocarbon based fuels, such as natural gas. The baseline farm sequestered 7,266 tCO_2eq over the 30-year lifetime of the project, an average of 0.6 tCO_2eq sequestered ha^{-1} $year^{-1}$. Therefore, to achieve Gt scale annual sequestration, the baseline farm would need to cover ~16.6 million km^2.

The assumptions within submodel (2) (moisture content, tissue C content, and yield) were by far the most influential factors in the sensitivity analysis. A 40% decrease in either the % kelp dry weight or the C content of kelp dry matter resulted in a ~$55,000 increase in LCOC (**Figure 6**). The required biomass transport distance (km), the duration of the nursery grow-out period (days), and the harvest labor requirements (FTE person hours per ton of harvested biomass) were the next most sensitive parameters (**Figure 6**). A 40% increase or decrease in these variables resulted in 15 - 25% changes in levelized sequestration costs.

The line of sight optimization pathways towards cost reduction and additionality rate (AR) increase were broken down into five categories: (1) Nursery, (2) Ocean cultivation, (3) Kelp biology, (4) Biomass transport, and (5) Verification. By combining all 18 line of sight improvements to the baseline farm, LCOC fell from \$17,048 to \$1,257 tCO_2eq^{-1} (**Figure 7; Table S6**), a ~14 factor reduction in levelized costs. Changing the assumptions for harvest labor requirements (FTE hours per ton of harvested kelp), the size of the spools within the nursery (m of twine per spool), and the kelp WW:DW ratio to the optimal values identified in the literature led to the largest reductions in LCOC: -\$3,787, -\$1,929, and -\$1,904 tCO_2eq^{-1}, respectively. Reducing the nursery grow-out duration (days) and the emissions from the nursery energy supply (kg CO_2eq per kWh) were the next two most impactful changes resulting in \$1,823 and \$1,679 reductions in LCOC, respectively (**Figure 7**). Only 12 of the 18 parameters impacted the AR of the baseline farm. Changing these 12 parameters to the optimum value identified in the literature increased AR from 39% to 91%, and generated a ~7 factor increase in the quantity of credits issued each year (**Figure 8; Table S6**). Decreasing the buffer pool from 15% to 2% led to a 12% increase in AR, the most significant improvement. Increasing the C content of the kelp dry matter and sourcing the nursery electricity from renewables (i.e., a reduction in kg CO_2eq per kWh) resulted in 8% and 7% increases in AR, respectively, the next two most impactful changes. Notably, increasing the capacity of the PVC spools within the nursery to each hold 642 m of twine (up from the baseline assumption of 132 m) led to a 5% increase in AR.

The learning rate (LR) analysis indicated that significant cost reductions would have to accompany increases in project scale for kelp CDR to serve as an effective climate change mitigation technology. Even when starting with the optimized LCOC of \$1,257 tCO_2eq^{-1}, the magnitude of the chosen LR had a large impact on the ocean area required to achieve the cost target of <\$100 CO_2eq^{-1}. For example, assuming a relatively high learning rate of 20%, the optimized farm reached a LCOC of <\$100 tCO_2eq^{-1} at a scale of 16,589 km^2 (**Figure 9**). However, with a LR of only 5%, the optimized farm required 4.6×10^{15} km^2 to reach a levelized sequestration cost of <\$100 tCO_2eq^{-1} (**Figure 9**). Based on the sequestration rate of the optimized farm, 410 $tCO_2eq\ km^{-2}$, the project would need ~2.4 million km^2 to achieve Gt scale sequestration (1 Gt of CO_2eq sequestered $year^{-1}$).

4. Discussion

Significant commercial and research interest has recently flowed to the concept of growing and then sinking large quantities of kelp as a means of sequestering CO_2 (Hurd et al., 2022 *and supporting information therein*). Kelp CDR may have potential advantages over both "nature based" and "engineered" solutions (NASEM, 2021). Given that growers control production across the full value chain, select the macroalgae species ultimately destined for the seafloor, and determine the timing and location of biomass sinking, MRV of kelp CDR may eventually overcome some of the challenges that blue carbon approaches aiming to enhance natural C stocks, such as ecosystem restoration, face (Ortega et al., 2019). Furthermore, kelp aquaculture can provide numerous co-benefits to both ecosystems and coastal communities (Duarte et al., 2021; Theuerkauf et al., 2022). However, these tradeoffs remain to be resolved, and the results of our model are interpreted through a strictly techno-economic approach. It should be underscored that there are still fundamental, unanswered questions regarding the environmental and economic feasibility of kelp CDR that ought to be explored alongside discussions of potentially hazardous spillover effects, the durability of kelp C storage, relevant biogeochemical constraints and uncertainties, and overall environmental impact.

We took a hyper-realistic approach to estimating the costs and additionality of kelp aquaculture CDR and our results suggest that leveraging kelp farming as a means of selling C credits, under current assumptions, would generate production costs at the upper end of the range for CDR technologies, \$17,048 tCO_2eq^{-1}. In the absence of optimization, the method would likely be cost and space prohibitive (Fuss et al., 2018). To achieve Gt-scale CO_2 removal would require \$1.7 x 10^{13} in annual investment, ~20% of global GDP[2], and a farming area of ~16.6 million km^2, ~1.5x the size of the U.S. exclusive economic zone (EEZ). However, we also identified optimization pathways that capture the "line of sight" improvements required to both cost effectively scale and decarbonize kelp cultivation. The combined effects of the optimization analysis led to a ~14 factor decrease in levelized costs, \$1,257 vs. \$17,048 CO_2eq^{-1} (**Figure 7**), as well as a 7 factor increase in the annual quantity of CO_2eq sequestered over the 30-year lifespan of the 1,000 acre (404.5 ha) project.

Our analysis highlights the challenges of not only generating verifiable kelp C credits, but also cultivating macroalgae at a large scale in deep water (>100 m) exposed sites. To reduce costs,

[2] https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

the sector will need to de-risk alternative cultivation system designs, develop innovative seeding and harvesting methods, optimize selective breeding in conjunction with nursery production, and decarbonize kelp aquaculture at all points of the production process, i.e., from the nursery to the sink site. Ocean cultivation labor, seeded twine, vessel contracting, and mooring installation were the main drivers of expenses within the model (**Figure 4**). The energy required to produce seeded twine within the nursery, manufacture the materials within the cultivation structure, and transport biomass to the sink site were the largest sources of CO_2eq emissions and led to substantial reductions in the annual quantity of available C credits (**Figure 5**). Model outputs were most sensitive to changes in yield (kg m^{-1}), the conversion from WW to DW, and kelp C content (**Figure 6**). We also observed that resolving MRV uncertainty can dramatically increase the net quantity of C credits produced each year, as demonstrated by the effect that a 15% buffer pool had on the C budget within the BTEM. The extent to which kelp CDR is able to overcome these R&D, regulatory, and MRV challenges, and accelerate towards an optimized \$1,257 tCO_2eq^{-1} cost target and beyond (i.e., \$100 tCO_2eq^{-1}), will ultimately determine the future potential of this emerging technology.

The "high-volume, low-value" (Hasselström et al., 2020) application of kelp for CDR necessitates cultivation system designs that maximize available growing area while minimizing cap-ex and anchor installation costs. Our design process highlighted the challenges of balancing the quantity of available cultivation substrate with the aspect ratio of, and thus the loads on, the structure at large scales. The intent of the baseline model was to apply existing approaches to deep water sites in fully exposed conditions. Most farms in Maine, the study region, are sited in sheltered areas (<13 m depth) and consist of single culture lines with a mooring at each end (Flavin et al., 2013; Grebe et al., 2019; St-Gelais et al., 2022). This design was expanded and modified to be an array of multiple grow-lines with 4 m spacing, suitable for deep-water, exposed conditions. The system was specified such that the grow-lines were held in tension with a 4-point, spread mooring system connected to a header rope (**Figure 2**). The configuration consisted of mooring floats, anchor chain and surface floats every 12 m to maintain a nominal cultivation line grow depth of 2 m. However, even with pretensioning, the structure still required the use of 42,000 surface floats across all 1,000 acres to support the kelp as it grew (**Table S1**). In addition to the biomass, these floats are subjected to surface currents and winter storm waves, increasing structural loads and thus cap-ex and embedded emissions.

The usable grow-area was increased by using high-efficiency drag embedment anchors to enable a minimal 3:1 mooring scope and a 10:1 ratio of permit length to width (**Figure 2**). However, we were still only able to fit ~89 km of grow-line within each km^2 of lease area. In a recent techno-economic analysis of macroalgae CDR, DeAngelo et al. (2022) assumed a grow-line quantity of ~666 km per km^{-2} of lease area, and estimated a C sequestration cost of ~$500 tCO_2eq^{-1}. The difference in grow-line density is partially a result of increased line spacing and the increased fraction of permit area required for the mooring scope at the exposed, deep-water sites considered here. The discrepancy in estimates is further driven by greater yields, the most sensitive parameter within our analysis (**Figure 6**). If farms are able to move into larger, contiguous offshore lease sites, such as the recently established U.S. Aquaculture Opportunity Areas (Morris Jr, 2021; Riley, 2021), operators will be forced to contend with the design challenges noted here. Furthermore, the installation requirements of industrial scale anchors are a significant financial hurdle. The baseline farm required an initial construction investment (mooring installation alone) of ~$6.2 million, a value that made up nearly 12% of total levelized costs despite occurring only once (**Figure 4**).

These constraints suggest that the industry should continue to explore lower-cost mooring systems (including installation costs) and de-risk alternative farm and lease configurations that make more efficient use of ocean space. The latter could include reducing mooring scope, e.g. (Moscicki et al., 2022), utilizing more vertical space in the water column, e.g. (Bak et al., 2018; van Oirschot et al., 2017), and decreasing horizontal line spacing. Expanding cultivation line diameter or using non-rope components (e.g., pipe) with larger dimensions may also increase yield for each meter of growth and address marine mammal entanglement prevention criteria. Flotation could also be incorporated with these larger cultivation components. Cost-sharing with other offshore ocean users, such as wind energy producers (Buck et al., 2010; Schupp et al., 2021) could reduce fixed permitting and siting costs, which make up 5% of the LCOC. Techniques used to calculate the dynamic loads on farm "c" and any future design iterations, including the calculations of the velocity reduction through the farm, represent an area of uncertainty, especially since the cap-ex associated with the 40 anchors is substantial. Validation efforts with in-situ measurements, additional tank tests, and other computational techniques, especially at the farm scales considered here, would provide more confidence in the load carrying requirements for the cultivation system, and could allow designers to reduce the required uncertainty factors when specifying structural components.

The next generation of kelp farm designs must also optimize labor requirements, as there will likely be tradeoffs between minimizing cap-ex and efficient seeding, maintenance, and harvest practices. Reducing the harvest labor requirements (FTE hours per ton of harvested biomass) to the lowest value identified in the literature (Correa et al., 2016) resulted in a \$3,787 reduction in levelized sequestration costs (**Figure 7**). Furthermore, optimizing all three production steps led to a combined 7.8% increase in AR and avoided ~57 tCO_2eq of annual emissions (**Figure 8**). The reduction in person hours necessitated fewer vessel trips to the farm site, and thus less fuel usage. Therefore, the harvest practices currently utilized by growers in emerging farming regions will pose a bottleneck, both from a cost and emissions standpoint, as farms expand into larger offshore sites. Identifying methods to automate these steps should be an immediate priority (Zhang et al., 2017). Improved cultivation systems, spray-on seeding of adult sporophytes at sea (Kerrison et al., 2018), and innovative harvest practices designed specifically to transport kelp biomass long distances may drive labor cost reductions.

The timing of harvest may be optimized specifically for kelp CDR. Producers typically remove food-grade plants from the farm site in the early spring, before the onset of fouling organisms and epibionts. However, kelp CDR operators may be able to continue the grow-out process well into the summer, thereby potentially increasing total biomass (of both kelp and fouling organisms also made of organic C) and avoiding competition with harvesting vessels contracted for other kelp uses. Utilizing kelp aquaculture infrastructure outside of the typical farming season could provide seasonal employment opportunities as well as reduce the cost of renting vessels that would otherwise be in high-demand. While the notion of an extended growing season has intriguing potential benefits, there remain large ecological unknowns regarding the epibiont, infaunal and meifaunal communities that may associate in unexpected ways with offshore kelp and farm structures at this scale. Natural analogs demonstrate that large macroalgae rafts are important habitats as well as vectors for the spread of invasive species (Avila et al., 2020; Fraser et al., 2011). At sea transportation to sinking sites and inadequate containment during sinking may promote the movement of invasive species and the dislocation and demise of many marine organisms other than kelp. Large scale farms may also serve as fish aggregating devices (FADs) or as unexpected nursery habitat for marine species, similar to the ecological function of sargassum, that would be disrupted by annual harvest and removal of biomass (Rothäusler et al. 2012). These critical ecological issues should be studied

The sensitivities within the BTEM dictate that both the biomass yield and biomolecular composition of cultivated kelp will ultimately exert the largest impact on the economic viability of macroalgae CDR. Even with innovative farm designs that maximize 3D ocean space and more efficient labor practices, producers will likely need to leverage selective breeding techniques to increase growth rates and C content, while also reducing moisture content (Augyte et al., 2020; Umanzor et al., 2021; Zhao et al., 2016). Based on the hypothetical sensitivity analysis, a 40% increase in either kelp dry matter or C content resulted in a 50% decrease in levelized sequestration costs (**Figure 6**). With yields of 12.5 kg WW m^{-1} (Stekoll et al., 2021), the farm produced ~1.5 t DW ha^{-1} $year^{-1}$, well below the MARINER programmatic target of 25 t DW ha^{-1} $year^{-1}$ (ARPA-E, 2017). In a common garden experiment of 100 unique parental kelp crosses in Maine USA, Umanzor et al. (2021) observed a 50 factor difference in yield between the fastest and slowest growing replicates. The results of their study underscore the phenotypic variation that can occur within a population derived from genetically similar sources of kelp broodstock, the heritability of these traits, and thus the relatively rapid improvements that can be achieved within only a few seasons of selection (Umanzor et al., 2021). Froehlich et al. (2019) estimated that, with yields of 32 DW t ha^{-1}, the costs of kelp CDR in the North Sea would be between \$1,219 - \$1,924 tCO_2eq^{-1} (Froehlich et al., 2019). When compared to our estimates of both yield (1.5 t ha^{-1} $year^{-1}$) and cost (\$17,048 tCO_2eq^{-1}), it is clear that selecting for optimal biomolecular composition and fast growth will be a powerful tool in reducing the levelized sequestration costs of kelp CDR.

In the absence of selective breeding, exogenous oceanographic factors at offshore sites may prevent economically viable kelp growth rates. Dense canopies of surface cultured kelp attenuate flow within the farm, depleting nutrients and potentially leading to decreased growth (Frieder et al., 2022). However, the greater line spacing required for open-ocean sites and the smaller fraction of the water column occupied by the biomass due to the greater water depth may result in less flow attenuation than in dense farms at protected sites. Ambient Winter surface nutrient (specifically Nitrate) conditions in offshore regions may be limiting to the extent that farmers would be unable to replicate the yields (i.e., 12 kg m^{-1} WW) from nearshore and coastal sites (Rebuck & Townsend, 2014; Wu et al., *in review*). Maximizing kelp growth is an exercise in both site selection and production optimization. Line spacing, depth, and seeding and harvest timing must all be balanced

(Broch et al., 2013; Bruhn et al., 2016; Peteiro & Freire, 2013). However, if kelp aquaculture is forced to move into more oligotrophic offshore areas due to competition with other users for coastal space (van den Burg et al., 2020), *in situ* measurement of growth rates will be required to accurately assess the potential of large scale cultivation. The increased line spacing (4m) required by the exposed deep water baseline site may mitigate potential nutrient depletion issues, as the grow-line only occupies ~5% of the water column. Laboratory and nearshore common garden experiments must be complemented by pilot and commercial scale demonstrations to validate projected yields.

In addition to providing the necessary platform for selective breeding, improved nursery practices could have the complementary benefits of reduced operating expenses coupled with decarbonization. Optimizing the nursery assumptions within the BTEM resulted in an aggregate 35% reduction in levelized costs, as well as a 15% increase in AR (**Figure 7**). At a scale of 1,000 acres, the facility emitted ~112 tCO_2eq $year^{-1}$ from the direct consumption of electricity, and another ~2.7 tCO_2eq $year^{-1}$ from the upstream manufacturing of equipment (**Table S4**). Reducing the sporophyte grow-out duration from 44 to 33 days resulted in a 27 ton decrease in annual CO_2eq emissions and a ~$1,800 decrease in levelized costs (**Figure 7**). Sourcing the nursery electricity exclusively from renewables led to an additional ~85 ton decrease in annual CO_2eq emissions and a $1,679 reduction in LCOC (**Figure 7**), despite the fact that nursery electricity costs alone comprised less than 1% of total expenses (Coleman et al., 2022). Across all 18 parameters, the second largest reduction in LCOC within the optimization analysis came from maximizing the size of the PVC spools: a $1,929 decrease in LCOC and a 5% increase in AR (**Figure 7**). Increasing spool size or sourcing electricity strictly from renewables would be a relatively low-technology risk pathway for nursery operators in the near term. However, identifying methods to reduce the duration of the sporophyte grow-out period would require further study of optimal light, nutrient, flow regimes, and production strategies (Camus & Buschmann, 2017).

Improved and de-risked gametophyte culture could reduce the amount of time that kelps are held on spools within tanks (Alver, 2019), which would have knock-on effects for both the cost structure and emissions profile of land-based nursery facilities. Despite inconsistent success in the field, spools seeded with gametophytes (as opposed to spores) would only require a 14 - 21 day grow-out period in illuminated and temperature controlled tanks (Forbord et al., 2020). This timeline represents a substantial reduction from the baseline grow-out length of 44 days (Coleman et al., 2022). Furthermore, maintaining gametophyte stocks optimized for yield, C content, and moisture content would allow growers to eventually access free-floating sporophyte culture and direct seeding of grow-lines at sea (Alver et al., 2018). The process of tumble culturing free-floating kelps within large flasks has been shown to reduce space requirements by nearly 99% (Kerrison et al., 2018), and eliminate the need for PVC spools and twine entirely. It must be noted, however, that gametophyte culture would require maintaining vegetative stocks year-round, leading to potentially unforeseen energy demands or labor increases. Based on the relationships we observed between nursery emissions and costs within the BTEM, we argue that these tradeoffs should be explored within a comprehensive framework. Similarly, utilizing larger, flow-through systems might lead to a reduction in direct energy consumption if ambient light or more efficient chillers could be employed at larger scales (Greene et al., 2020; Su et al., 2017). Small-scale recirculating systems allow for redundancy and thus built-in biosecurity measures. Shifting to larger, flow-through tanks would allow nurseries to maximize space, but could also increase the risk of catastrophic product loss. Further research of the potential economic risks and benefits of these pathways is needed before such systems could be employed commercially.

As technologies mature, the application of learning rates (LRs) can help uncover the impact of unforeseen cost reductions that are typically driven by learning by doing, investment in R&D, and economies of scale. The optimized BTEM represents a best-case view of the costs of kelp CDR based on "line of sight" improvements that exist within current kelp cultivation systems. However, selective breeding, optimized gametophyte culture, improved offshore farm designs, and future technologies that lead to decarbonization of supply chains represent pathways of cost reduction with potential unforeseen consequences best captured by the application of learning rates (**Figure 7**). A "top-down" LR analysis (Faber et al., 2022; Thomassen et al., 2020), such as the one presented here (**Figure 9**), can allow researchers and policy makers to back into a relevant commercial scale or specific LR required to achieve financial viability for an early stage technology (Héder, 2017). As kelp CDR matures, applying empirical LRs calculated from historic production data to discrete techno-economic mechanisms would allow stakeholders to more accurately predict how reductions in e.g., per unit labor costs, cap-ex, or raw material costs may impact total levelized sequestration costs (Thomassen et al., 2020). A relevant application of this concept would be to quantify the effect that increases in farm size would have on the emissions profile of the operation (kg CO_2eq emitted per unit of kelp harvested), and thus the true additionality of kelp CDR (Faber et al., 2022). The lack of historical production data for kelp farming in emerging regions (i.e., outside of the Pacific Rim), as well as the low technology readiness level of kelp farming specifically for CDR, pose a challenge to accurate cost and climate potential forecasting (Wender et al., 2014). As the kelp aquaculture industry expands in North America, Europe, and South America, the growing body of economic and lifecycle benchmarking data should be utilized to resolve these uncertainties (Engle et al., 2020; Thomas et al., 2021).

While the majority of our analysis focuses on strategies to reduce the direct costs and emissions footprint of kelp cultivation, it is clear that inaccurate Monitoring, Reporting, and Verification (MRV) will be a strong bottleneck to future scaling. There is considerable uncertainty concerning the rate at which the uptake of DIC by kelp will impact atmospheric CO_2 concentrations, the fate of kelp derived POC after deep-sea deposition, and the durability of storing remineralized CO_2 in the deep ocean (Bach et al., 2021; Boyd et al., 2022; Gallagher et al., 2022; Hurd et al., 2022). The lag in re-equilibration between the ocean and atmosphere after DIC uptake by kelps may not lead to a strict 1:1 ratio of CO_2 sequestered within kelps to the quantity removed from the atmosphere (Bach et al., 2021; Hurd et al., 2022). Using a 1:1 ratio, we demonstrated that a 17 factor reduction in costs (\$1,257 vs. \$17,048 tCO_2eq^{-1}) was possible if production could be optimized (**Figure 7**). However, if the ratio of sequestered CO_2 within kelp to atmospheric CO_2 removal drops to 50%, the cost (even under optimized conditions) doubles (\$2,731 tCO_2eq^{-1}). Furthermore, the accuracy with which models and *in situ* measurements are able to track the fate of kelp POC and any remineralized C within the deep sea (Siegel et al., 2021) will determine the magnitude of the required buffer pool (Matzek et al., 2015). Under optimized assumptions, the AR of the farm was 91% (**Figure 8**). However, if the uncertainty factor regarding the quantity of deposited CO_2 that re-enters the atmosphere before the 100 year target is 25%, then the buffer pool must be increased to 25% and the AR of the optimized farm drops from 91% to 74%. Developing accurate MRV protocols should be prioritized to the same extent as reducing the costs of CDR given the influence C accounting will have on the bottom line of future projects.

Ultimately, negative emissions technologies must be rigorously assessed on their net benefits and risks to both society and ecosystems, and kelp CDR is not immune. While outside the scope of the present analysis, Boyd et al. (2022) discuss the potential impacts that large-scale kelp cultivation and subsequent deep-sea deposition could have on open-ocean ecosystems. Introducing a new species to regions of the ocean that underpin food systems, the blue economy (FAO, 2020), and global net primary productivity (Kwiatkowski et al., 2020) is inherently risky. Kelps may compete with local planktonic communities for limited nutrients, such as N and P, and light, leading to a decline in NPP and the efficiency of the biological carbon pump (Frieder et al., 2022). The increased oxygen demand at the sea floor of kelp deposition sites could also reduce sediment aerobic depth with trickle down effects on the understudied benthos (Wu et al., *in review*). The space required for kelp CDR to effectively draw down atmospheric CO_2 could not only pose a major bottleneck to scaling, but also displace and compete with other ocean users. Based on the optimized BTEM, ~2.4 million km^2 would be needed to sequester a Gt of CO_2 $year^{-1}$, an area that is nearly 1,500 times greater than the current space occupied by global macroalgae aquaculture (Duarte et al., 2017). Identifying a sustainable role for kelp CDR at both a climate relevant and globally responsible scale will be a challenge for regulators, policy makers, industry members, NGOs, and other ocean stakeholders moving forward. Relying on research that is transparent regarding costs, risks, and spillover effects will help guide that decision making in an effective and equitable manner.

5. Conclusion

We quantified the levelized costs of intentionally sinking cultivated kelp in the deep-ocean to capture and sequester atmospheric CO_2. Our site specific baseline approach sheds light on the challenges of cost effectively scaling the production of verified kelp C credits, as well as farming macroalgae at large scales in exposed offshore sites. We estimated that, according to the baseline model, the unit costs of kelp CDR would be \$17,048 tCO_2eq^{-1}, with a spatial sequestration rate of 0.6 tCO_2eq ha^{-1} $year^{-1}$. Labor, mooring installation, contracted vessels, and seeded twine made up the largest portions of costs. Nursery production, the manufacturing of materials within the cultivation structure, and biomass transport to the "sink site" were the largest sources of emissions and contributed to an additionality rate (AR) of only 39%. However, we also calculated an "optimized" sequestration cost of 1,257 tCO_2eq^{-1}, with an associated AR of 91%, demonstrating that with "line of sight" process improvement and decarbonization, unit costs and emissions could be reduced by orders of magnitude. To reach this hypothetical cost floor, our analysis points towards six key R&D needs: (1) de-risk alternative farm and mooring designs that maximize space and minimize cap-ex, (2) automate the seeding and harvest process, (3) leverage selectively bred kelp strains to maximize C content and yield, (4) assess the cost tradeoffs of gametophyte culture coupled with redesigned nursery protocols, (5) decarbonize equipment supply chains, nursery production, and ocean cultivation by employing low GHG impact materials, sourcing electricity from renewable sources, and increasing labor efficiency, and (6) resolve MRV uncertainty to reduce the buffer pool and maximize net C budgets.

Author contributions

SC, DB, TD, DF, AS, and EL contributed to the conceptualization of the work. TD, MM, and DF conducted the cultivation structure design, engineering, and dynamic modeling. SC developed the bio-techno-economic model with input from all authors. SC, KC, TD, and MM led figure and table production. SC wrote the initial draft of the manuscript. DB, DF, AS, EL and TD provided manuscript edits and comments on model analyses. All authors contributed to the article and approved the submitted version.

Conflict of interest

Tobias Dewhurst and Michael MacNicoll are employed by Kelson Marine Co. David Fredriksson is employed by Ocean Environmental LLC. Eric Laufer is employed by Conscience Bay Research, LLC. All authors declare no other competing interests.

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Tables

Table 1. Summary of costs included within the Initial Investment (I_0) in the baseline BTEM. *I* was further broken down into "Cap-ex" and "One-time lease regulatory, and design fees". Values for capital expenditures (Cap-ex) are shown before financing.

Initial investment (*I*)		
	Cap-ex	
Item	Cost per 100-acre plot	Cost basis for 1,000-acre baseline
Anchors and tackle (lot)	$380,975	$3,809,751
Mooring and grow-line (lot)	$257,168	$257,167,547
Floats and connector lines (lot)	$179,376	$1,793,760
Total		*$262,771,058*
	One-time lease, regulatory, and design fees	
Item	Unit cost	Total 1,000-acre baseline cost
Mooring installation ($ anchor^{-1})	$155,266	$6,210,626
Lease application ($ 100-acre plot^{-1})	$2,000	$20,000
Engineering and siting fees ($)	$300,000	$300,000
NEPA process and Marine mammal monitoring ($)	$2,447,500	$2,447,500
Total		*$8,978,126*

Table 2. Summary of costs included within Ocean Cultivation Costs (*OC*) in the baseline BTEM. *OC* was further decomposed into Fixed Costs (*FC*) and Operating Expenses (*OE*).

Ocean cultivation costs (*OC*)

Fixed costs (FC)

Item	Assumption	1,000-acre baseline annual cost
Interest	5 of cap-ex%	\$265,904
Lease rent	\$100 acre^{-1}	\$100,000
Misc. fixed costs	5% of annualized cap-ex	\$22,475
Total		*\$388,379*

Operating expenses (OE)

Item	Unit cost	1,000-acre baseline quantity	Annual total
Seed string (\$ m^{-1})	\$0.91	678,775	\$617,414
Vessel contracting (lot; *not including transport*)	\$652,183	1	\$652,183
Biomass transportation to sink site (lot)	\$69,851	1	\$69,851
Seeding labor (lot)	\$134,678	1	\$134,678
Maintenance labor (lot)	\$201,208	1	\$201,208
Harvest labor (lot)	\$695,834	1	\$695,834
Consumables and expendable supplies (lot)	\$5,000	10	\$50,000
Total annual op-ex			*\$2,421,168*

Figures

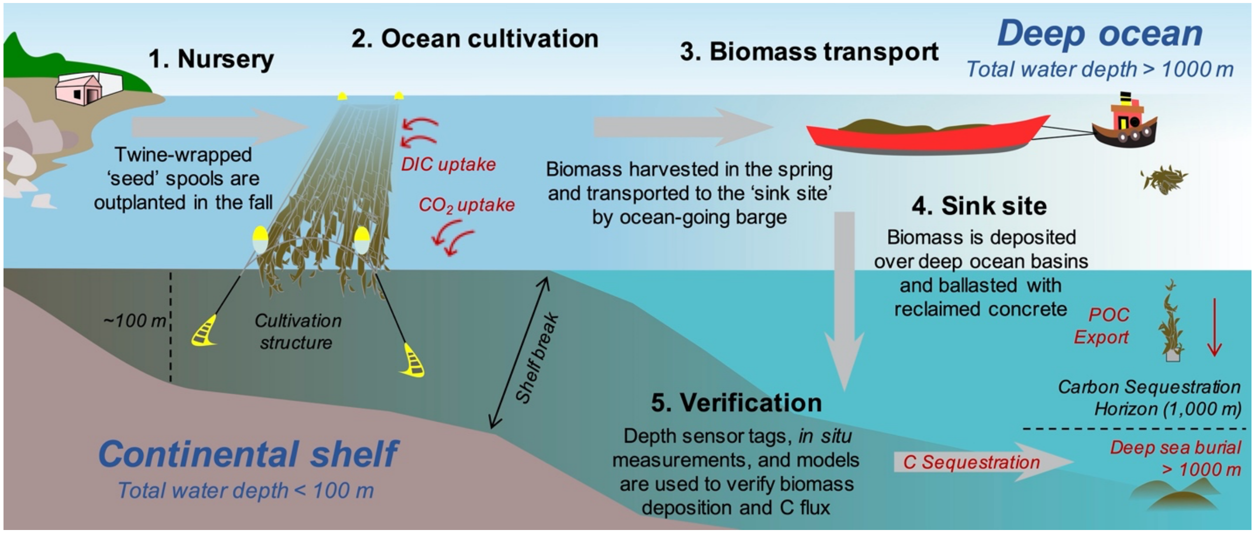

Figure 1. Conceptual diagram of offshore macroalgae cultivation in the Gulf of Maine and intentional deep-ocean sinking as a method of carbon dioxide removal (CDR). Juvenile sporophytes are grown within a land based nursery during the summer and then outplanted on twine-wrapped PVC "spools" in the fall. The cultivation site is located ~20km from the Maine coastline. As kelp uptake dissolved inorganic carbon (DIC) to build tissue, the DIC deficient seawater equilibrates with the atmosphere and draws down atmospheric CO_2 into the oceanic C pool. In the spring, kelp biomass is harvested and then transported ~350 km using ocean-going barges to the deep-ocean "sink site" located at the edge of the continental shelf. Biomass is ballasted using reclaimed concrete and deposited below the Carbon Sequestration Horizon (1,000 m). Lastly, a combination of *in situ* measurements and modeling is used to verify the quantity of CO_2eq sequestered.

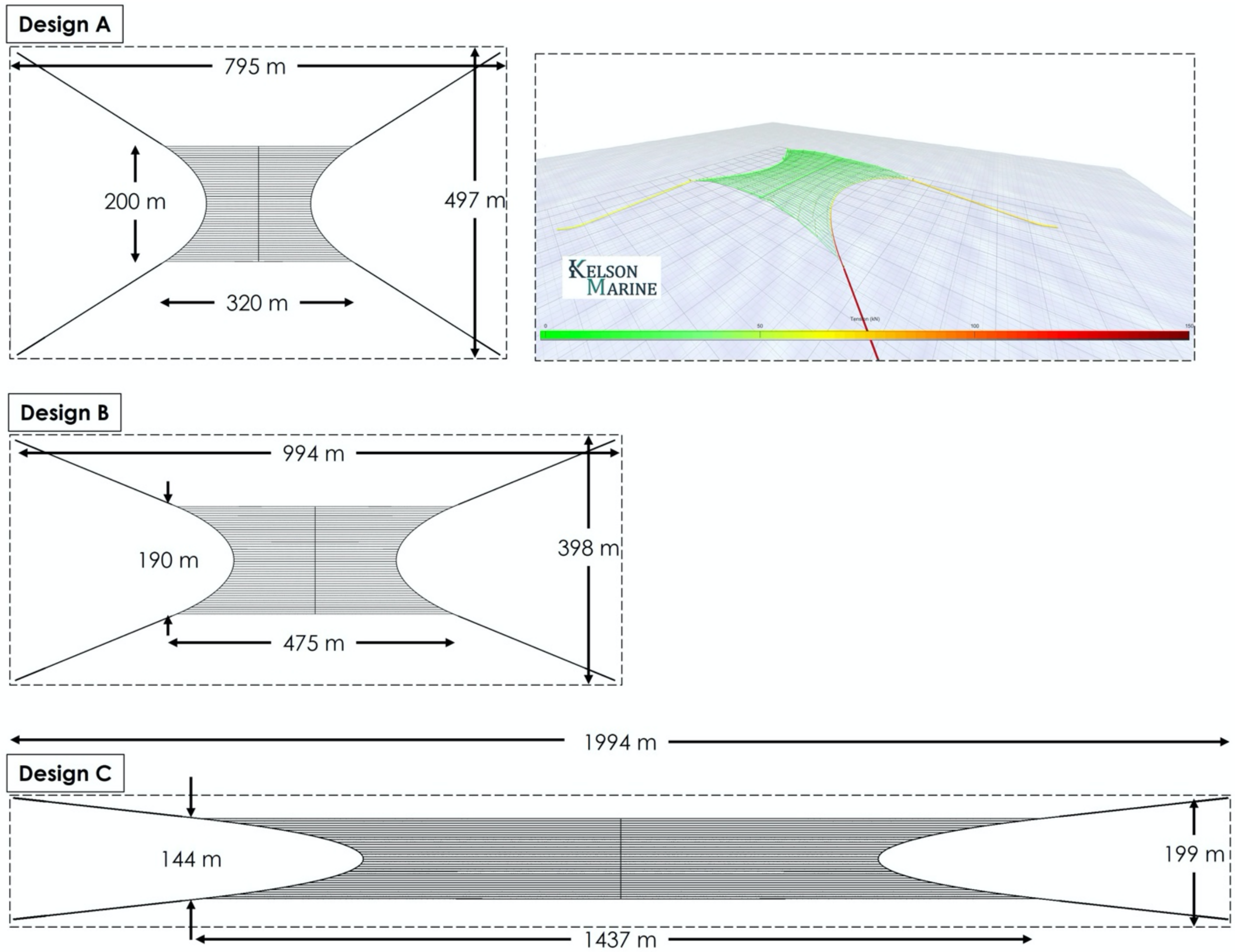

Figure 2. Overhead view of the three candidate modular cultivation structure designs. Designs differed by aspect ratio (length vs width). Design "C", with an aspect ratio of 10:1 was ultimately chosen as it provided the most available growing substrate within the allotted 100 acre lease footprint. Inset: Simulation of Design “A” showing tensions in structural lines in 1-year storm conditions.

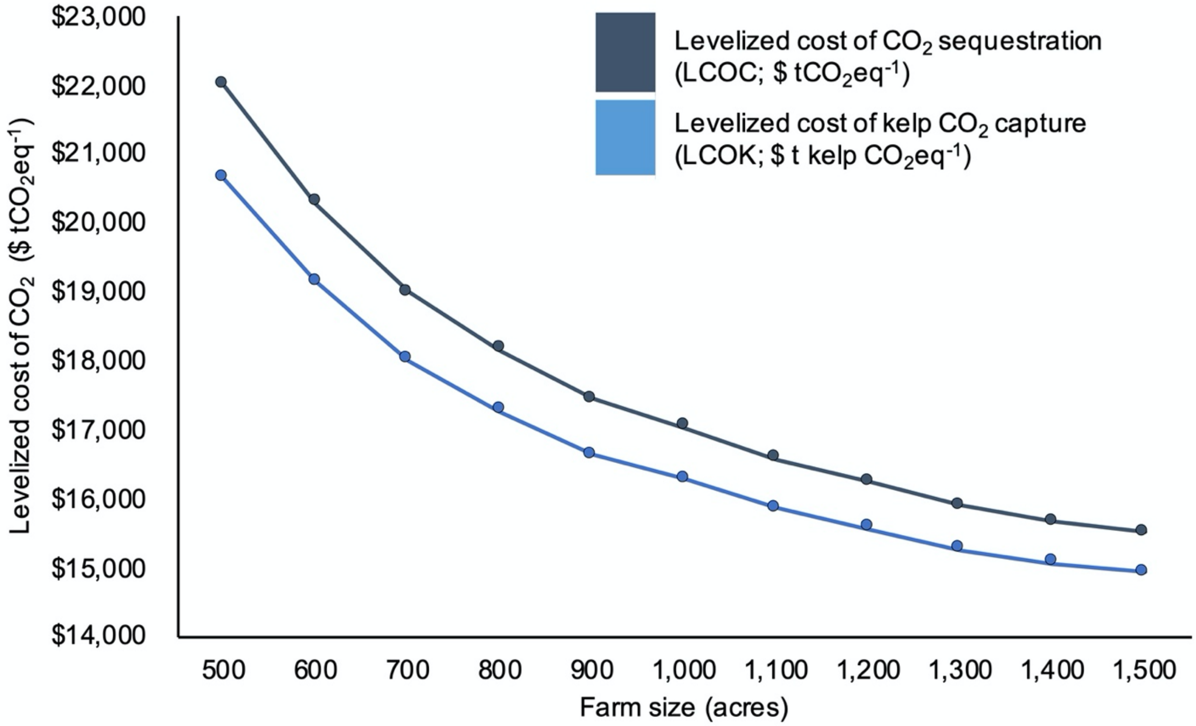

Figure 3. Levelized cost of sequestering a single ton of CO_2eq (\$ tCO_2eq^{-1}; LCOC; *dark blue line*) and levelized cost of capturing a single ton of CO_2eq within kelp biomass prior to transport, verification, and permanent sequestration (\$ tCO_2eq^{-1}; LCOK; *light blue line*) as a function of farm size (acres).

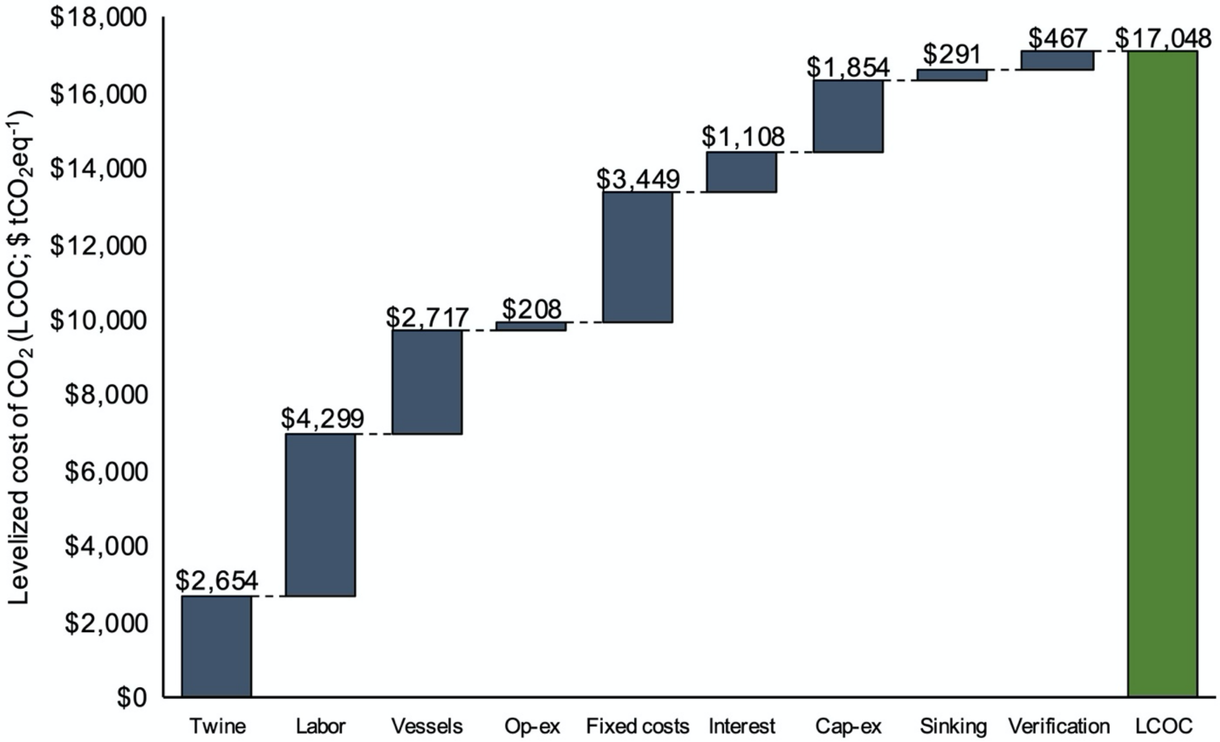

Figure 4. Breakdown of annual expenses within the baseline BTEM for LCOC ($ tCO_2eq^{-1}). The category "Vessels" includes only the contracted vessels required for typical farm operations. The category "Sinking" captures the cost of biomass transport to the "sink" site for CDR. The value above the dark blue bars represents the contribution of the specific line item, while the value above the green bar displays the total LCOC.

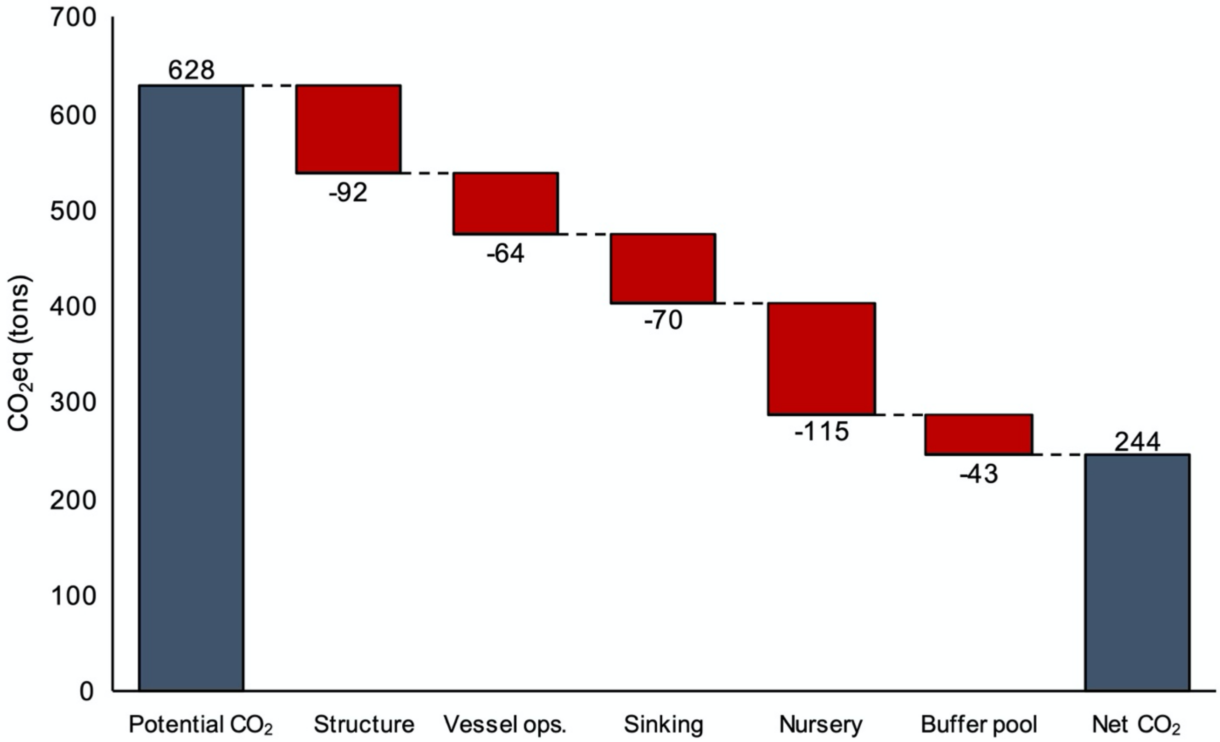

Figure 5. Deductions from the annual quantity of CO_2eq sequestered each year within kelp biomass ("Potential CO_2") as a result of annual emissions from farm components ("Structure"), contracted vessel fuel consumption ("Vessel ops."), biomass transport and sinking ("Sinking"), "Nursery equipment and energy ("Nursery"), and the "Buffer pool". The emissions represented by "Vessel ops." does not include the fuel required to transport harvested biomass to the "sink" site. The category "Sinking" accounts for biomass transport emissions.

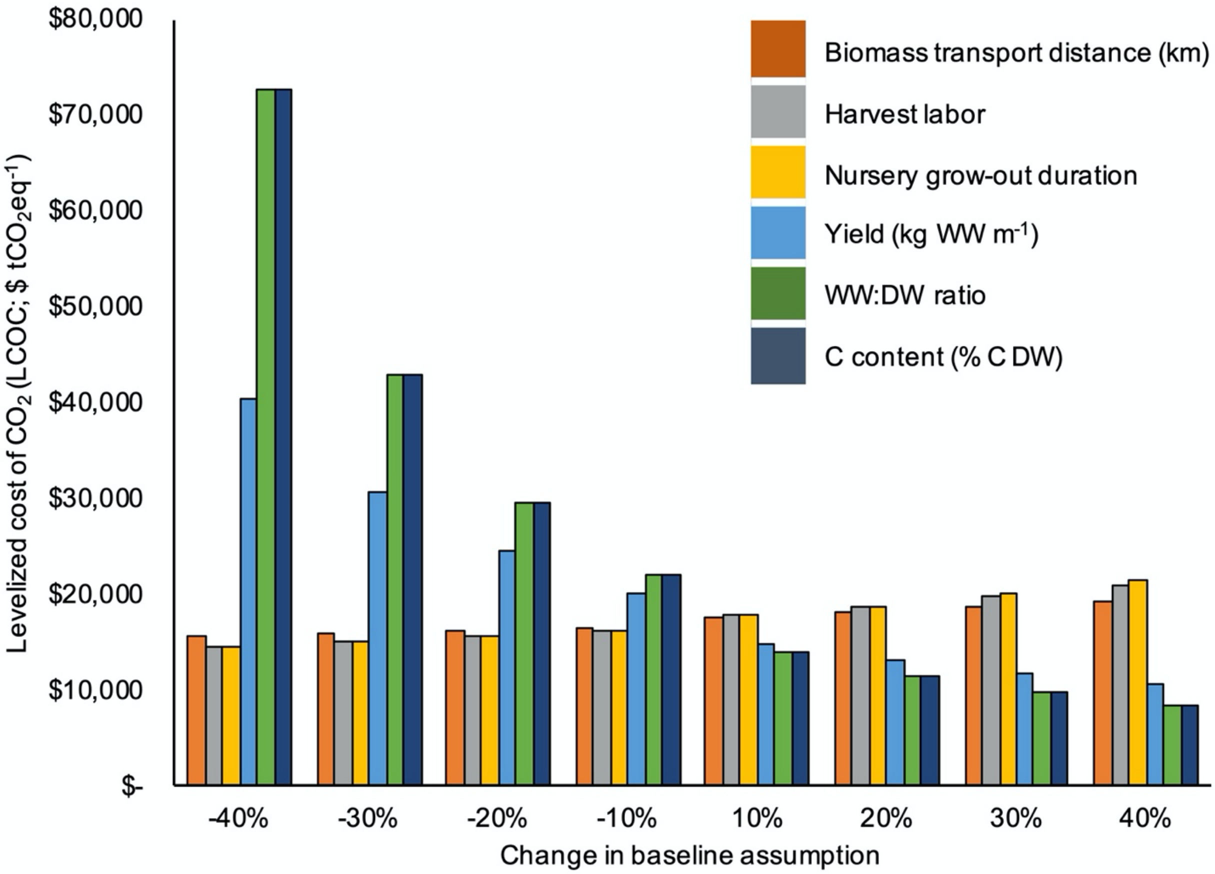

Figure 6. Results of a sensitivity analysis in which the required biomass transport distance (km), harvest labor requirements (FTE hours per ton of harvested biomass), nursery grow-out duration (days), yield (kg m^{-1}), kelp WW:DW ratio (% WW), and kelp C content (% DW) were all all changed in 10% increments to a range of +/- 40%. Parameters were changed individually so as to assess the relative importance of each assumption.

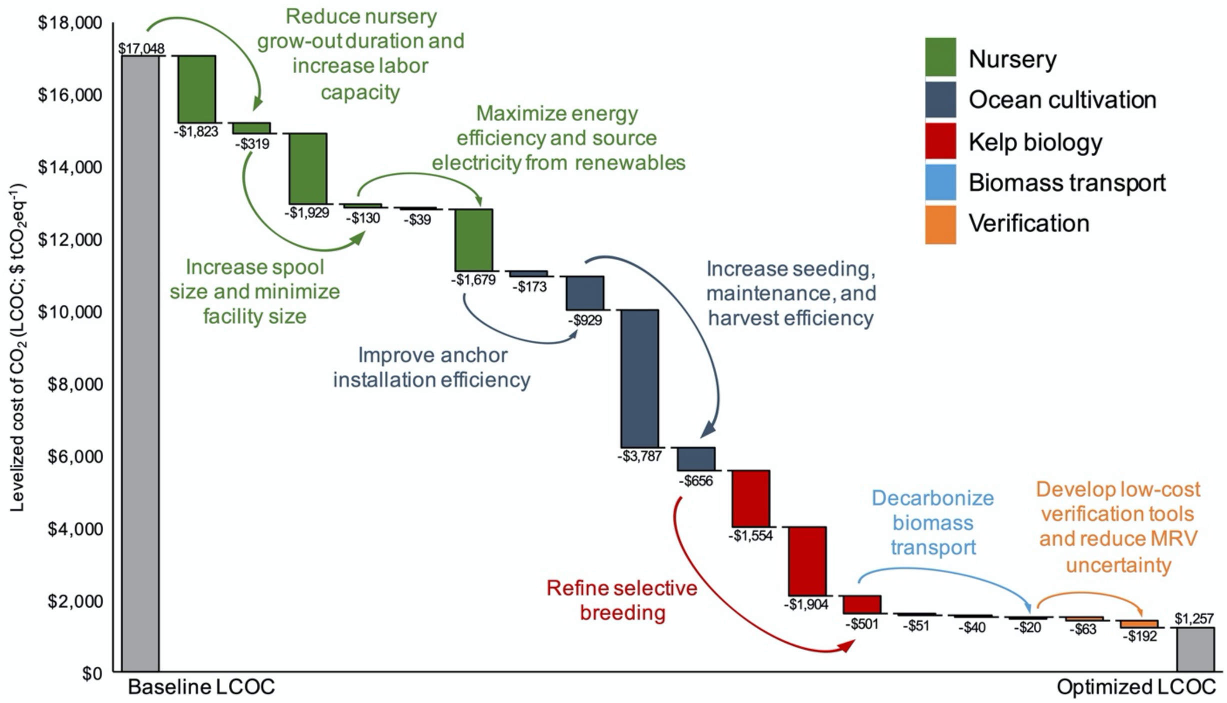

Figure 7. Optimization analysis in which the values for 18 key parameters were sequentially changed to either the minimum or maximum value identified in literature reviews that improved (lowered) levelized sequestration costs ($ tCO_2eq^{-1}). The changes were then combined to calculate an "optimized" LCOC as a result of process improvement and cost reductions (*gray column*). Colors correspond to the 5 areas of potential improvements: nursery production (*green*), ocean cultivation (*dark blue*), kelp biology (*red*), biomass transport (*light blue*), and verification (*orange*).

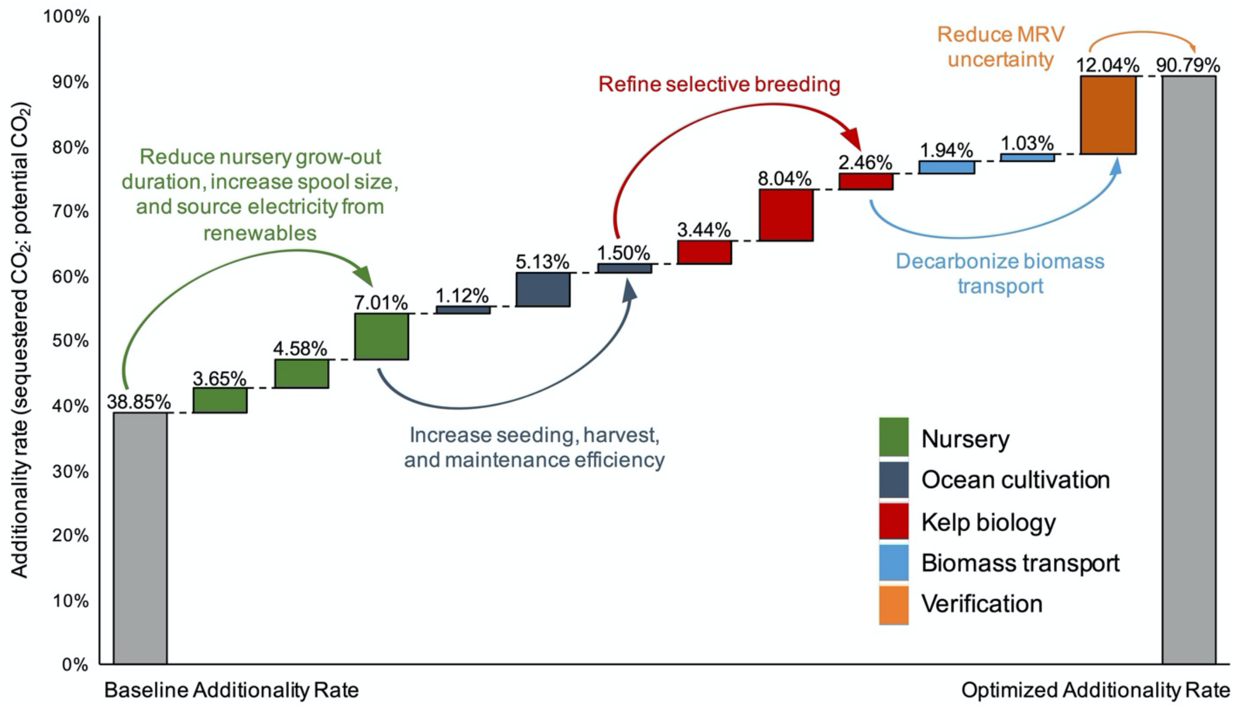

Figure 8. Optimization analysis in which the values for 12 key parameters were sequentially changed to either the minimum or maximum value identified in literature reviews that improved (increased) the additionality rate (AR) of the baseline farm (ratio of annual C credits produced: tCO_2eq sequestered annually, expressed as a %). The changes were then combined to calculate an "optimized" AR as a result of process improvement (*gray column*). Colors correspond to the 5 areas of potential improvements: nursery production (*green*), ocean cultivation (*dark blue*), kelp biology (*red*), biomass transport (*light blue*), and verification (*orange*).

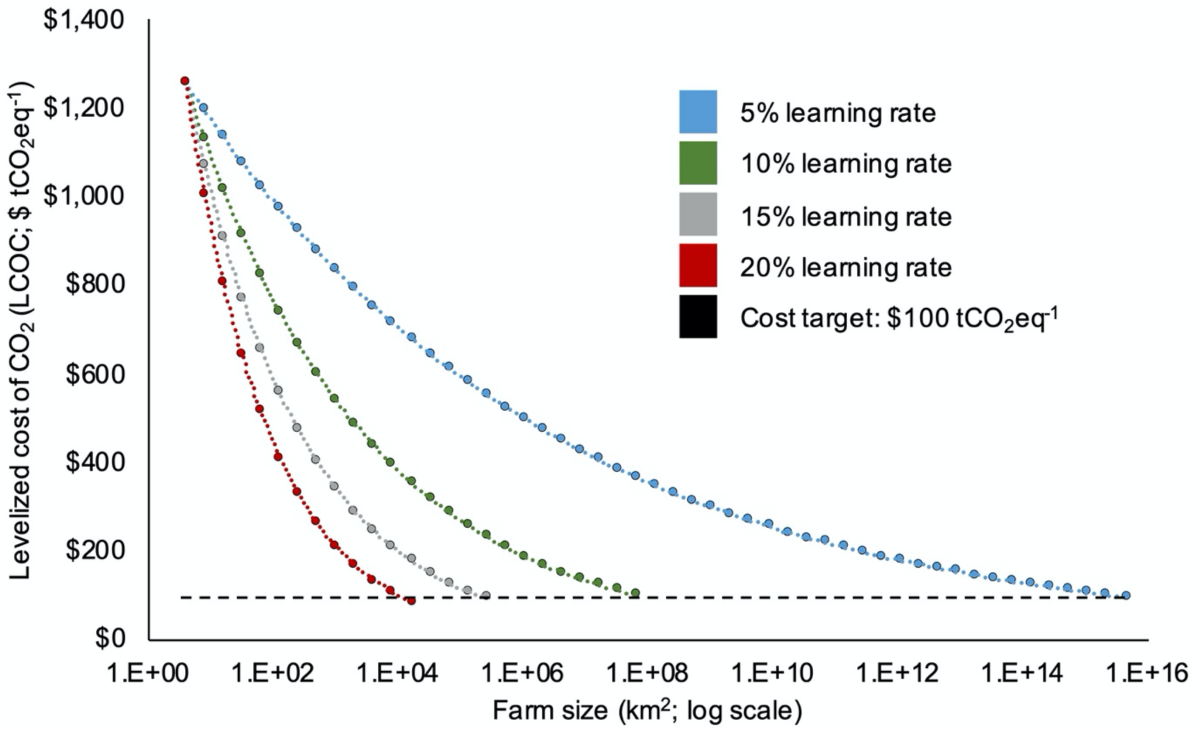

Figure 9. Levelized cost of CO_2 (LCOC; \$ tCO_2eq^{-1}) as a function of farm size (km^2) under four learning rate (LR) scenarios: 5%, 10%, 15%, and 20% reductions in cost with each doubling of scale. The horizontal dashed line denotes a hypothetical cost target of \$100 tCO_2eq^{-1}. The "optimized" bio-techno-economic model (\$1,257 tCO_2eq^{-1}) was used as the starting point in this analysis.

Supplementary figures:

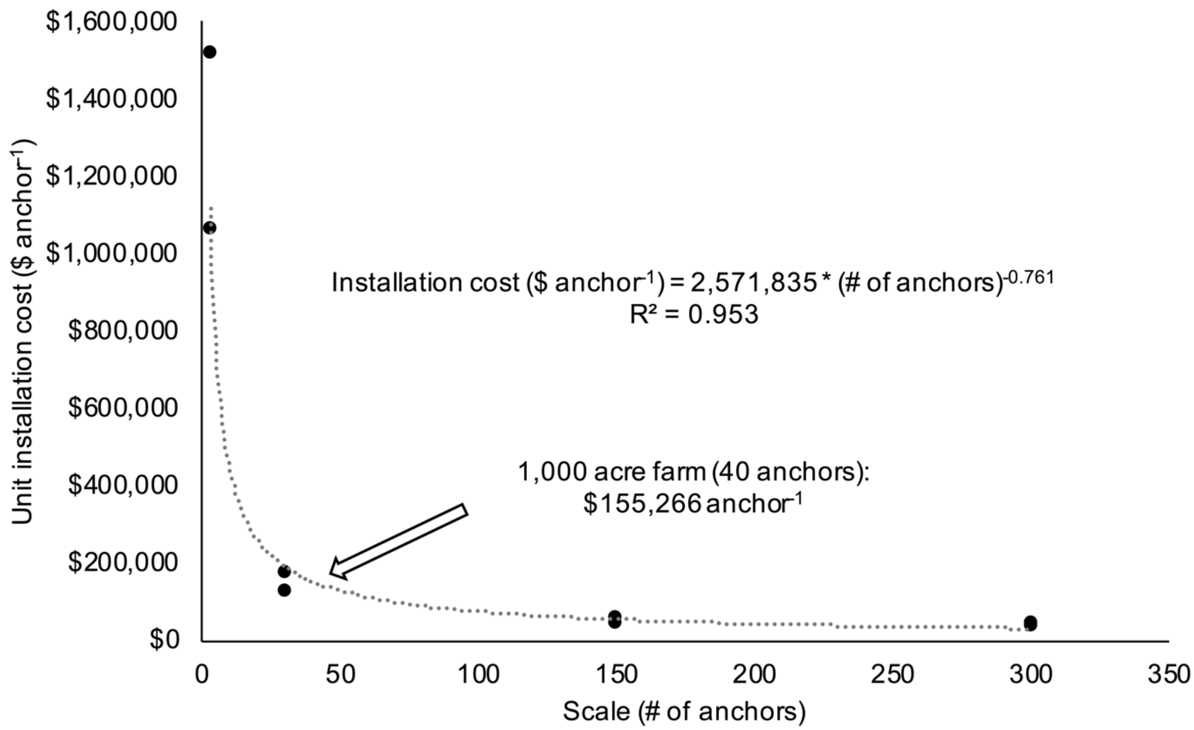

Figure S1. Unit anchor installation costs ($ anchor^{-1}) as a function of farm scale (# of anchors). The cost formula was derived from Jenne et al., 2015 and is displayed. At a scale of 40 anchors (the baseline farm scale), installation costs were estimated at $155,266 anchor^{-1}.

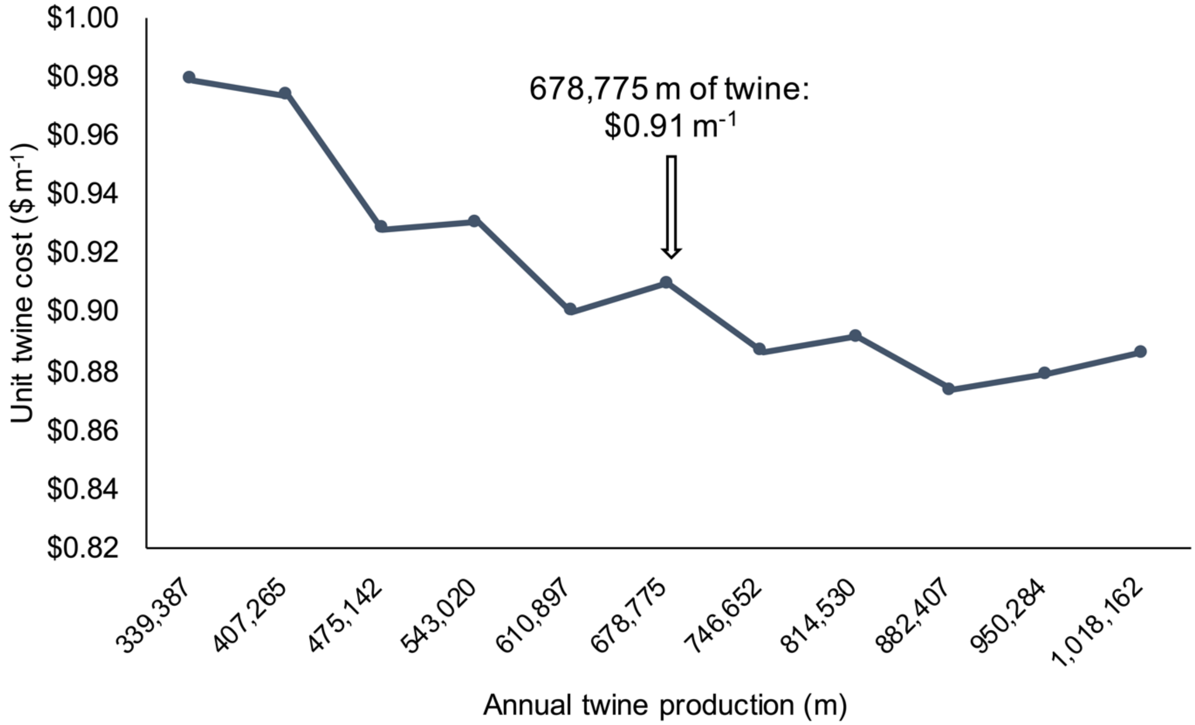

Figure S2. Unit cost of seeded twine ($ m^{-1}) used within the baseline bio-techno-economic model (BTEM) derived from Coleman et al., 2022. At the baseline scale, 678,775 m of twine would be required annually at a cost of \$0.91 m^{-1}.

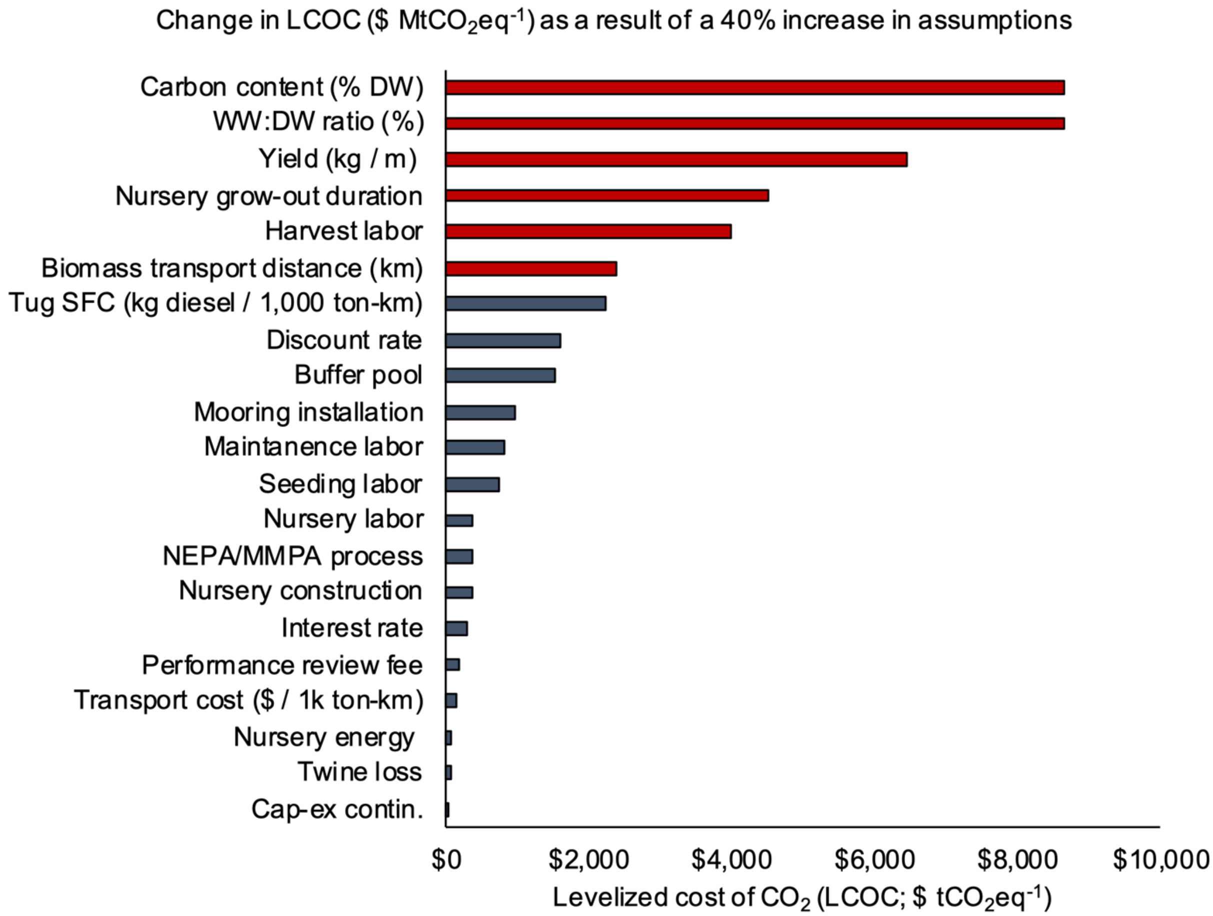

Figure S3. Full sensitivity analysis results. The absolute change in levelized costs of CO_2eq sequestration ($ tCO_2eq^{-1}: absolute value) as a result of a 40% increase in baseline assumptions is displayed. The 6 variables for which the greatest change was observed are in red, and were chosen for visualization (**Figure 6**). Raw data for the figure can be found in **Table S5**.

Kelp ballasting for deep ocean deposition

1. Overview

This section describes a methodology to ballast farmed sugar kelp for deep ocean deposition. It considers hydrostatic characteristics of both the farmed kelp and the ballast material. In this application, recycled concrete is examined as the ballast material. Recycled concrete is readily available and is considered here to be a raw material since it has been through the salvage process as part of its previous role, most likely in the construction industry.

2. Methodology

a. *Hydrostatics of farmed kelp*

The hydrostatics of farmed kelp is characterized by its weight and buoyancy forces. In this application, weight of the kelp is defined as the material out of the water that is wet, but not dripping (Fredriksson et al., 2020) such that

$$wt_{kelp} = y_{kelp} g = \rho_{kelp} g \nabla_{kelp}. \qquad (1)$$

In equation (1), wt_{kelp} is normalized per m of kelp growth as N/m. Yield (y_{kelp}) is defined as harvested biomass (kg/m), ρ_{kelp} is the kelp mass density (kg/m), g is the acceleration constant (m/s^2) and ∇_{kelp} is the displaced volume per m. Buoyancy force per m of kelp growth is defined as

$$Fb_{kelp} = \rho_{sw} g \nabla_{kelp}, \qquad (2)$$

with ρ_{sw} as the mass density of seawater taken here at 1025 kg/m^3. The wet weight of the kelp is the difference between equation (1) and (2). Yield and mass density were estimated to be 12.5 kg/m and 1054 kg/m^3 from kelp grown at a Maine site and harvested in May 2019 (St. Gelais et al., 2022). The weight of the kelp was calculated to be 122.6 N/m with equation (1), from which the volume (∇_{kelp}) was determined to be 1.186 (10^{-3}) m^3 knowing ρ_{kelp}. Using equation (2), the buoyancy force was found equal to 119.3 N. Therefore, the recycled concrete ballast would contribute to the wet weight of the kelp estimated at 3.34 N.

3. Recycled concrete as the ballast material for sinking

The amount of recycled concrete needed per meter to ballast the submerged kelp was estimated to have a wet weight 3 times that of the submerged kelp equal to 10.0 N per m. This would induce sinkage quickly removing any entrained pockets of buoyancy (e.g. air bubbles). The hydrostatics of the recycled concrete applies equations (1) and (2) but with the mass density (ρ_{conc}) nominally at 2400 kg/m^3. Therefore, with a wet weight of 10.0 N, the volume of concrete needed would be 0.000741 m^3 (741 cm^3) weighing 17.46 N per meter of grow line.

Potential concept for disposal

One potential concept for disposal is to size the recycled concrete weight for a predetermined section of grow line (Figure 1). For example, if the grow line is 100 meters long, a concrete weight of 1746 N (dry) would be required. In water, however, the concrete would have a wet weight of 995 N. The drag of the kelp line could be determined with numerical modeling techniques and therefore the power requirements for the tow vessel determined for a specified transit speed. Temporary floats for transit would be used to support the concrete float and for the tail end of the streamer if buoyancy support is needed. A terminal velocity calculation could be done for the disposal process by adjusting the wet weight and drag of the ballast and the length of the kelp line.

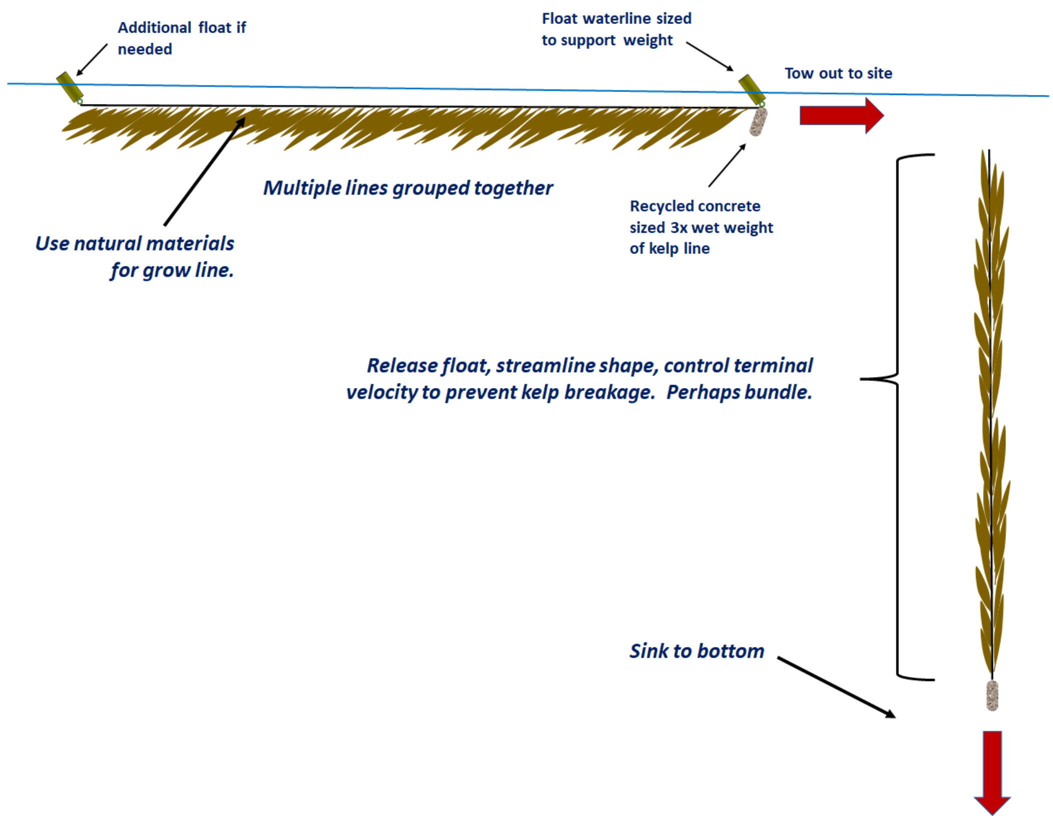

Figure 1. An example of how a weight of recycled concrete could be used in the ocean disposal

process.

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Table S1- Cultivation structure

Item	Unit	Unit Cost	Cost with contingency	Lifespan (years)	Quantity (1,000 acre total)	Cost basis	Annual depreciation
Anchor-Chain	$ m^{-1}	$65	$67	10	2,200	$147,610	$14,761
Anchor-Line	$ m^{-1}	$68	$70	10	9,440	$662,078	$66,208
Header	$ m^{-1}	$8	$8	10	12,052	$99,321	$9,932
Transverse	$ m^{-1}	$4	$4	10	1,428	$5,416	$542
Longline	$ m^{-1}	$5	$5	10	359,140	$1,804,861	$180,486
Tether-Float	$ m^{-1}	$20	$21	20	42,000	$878,179	$43,909
Tether-Line	$ m^{-1}	$6	$7	20	126,000	$829,676	$41,484
nodeFloat	Each	$2,095	$2,148	20	40	$85,905	$4,295
Anchor	Each	$77,417	$79,352	50	40	$3,174,077	$63,482
Connecting hardware	Lot	$47,616	$48,806	20	10	$488,064	$24,403
Total cap-ex						*$8,175,186*	*$449,501*

Table S2 - Labor requirements

Task	Unit	Value	Source
Seeding	FTE hours / km grow-line	15.2	van Djik and van der Schoot (2015)
Seeding	FTE hours / km grow-line	0.12	Zuniga-Jara et al. (2016)
Seeding	FTE hours / km grow-line	29.55	Hasselstrom et al. (2021)
Baseline assumption (average)	*FTE hours / km grow-line*	*15*	
Harvest	FTE hours / ton kelp (WW)	17.06	Bak et al. (2018)
Harvest	FTE hours / ton kelp (WW)	0.74	Correa et al. (2016)
Harvest	FTE hours / ton kelp (WW)	3.76	van Djik and van der Schoot (2015)
Harvest	FTE hours / ton kelp (WW)	7.58	Zuniga-Jara et al. (2016)
Harvest	FTE hours / ton kelp (WW)	2.08	Hasslestrom et al. (2021)
Baseline assumption (average)		*6*	
Maintenance	FTE hours / km grow-line	42.4	van Djik and van der Schoot (2015)
Maintenance	FTE hours / km grow-line	2.42	Hasslestrom et al. (2021)
Baseline assumption (average)		*22*	

Table S3 - Raw biological data

% dry weight	Source	C content	Source
11.30%	Gevaert et al. (2001): https://doi.org/10.1017/S0025315401004532	31.63%	Bruhn et al. (2019): https://doi.org/10.1007/s10811-019-01827-4
13.50%	Marinho et al. (2015): https://doi.org/10.1007/s10811-015-0546-0	28.00%	Gevaert et al. (2001): https://doi.org/10.1017/S0025315401004532
22.50%	Marinho et al. (2015): https://doi.org/10.1007/s10811-015-0546-0	32.50%	Bruhn et al. (2016): https://doi.org/10.3354/aei00200
11.70%	Marinho et al. (2015): https://doi.org/10.1007/s10811-015-0546-0	30.00%	Bruhn et al. (2016): https://doi.org/10.3354/aei00200
19.00%	Marinho et al. (2015): https://doi.org/10.1007/s10811-015-0546-0	33.40%	Bruhn et al. (2016): https://doi.org/10.3354/aei00200
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17.00%	Bruhn et al. (2016): https://doi.org/10.3354/aei00200	15.30%	Bruhn et al. (2016): https://doi.org/10.3354/aei00200
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10.50%	Handa et al. (2013): https://doi.org/10.1016/j.aquaculture.2013.08.006	30.70%	Sharma et al. (2018): https://doi.org/10.1016/j.algal.2018.03.012
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14.11%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5	24.80%	Grebe et al. (2021): https://doi.org/10.1111/jwas.12814
14.73%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5	26.00%	Grebe et al. (2021): https://doi.org/10.1111/jwas.12814
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13.48%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
12.54%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
15.67%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
13.79%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
15.05%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
12.85%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
13.17%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
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12.54%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
13.17%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
9.09%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
12.85%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
14.11%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
11.29%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
8.78%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
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15.67%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
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14.42%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
16.93%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
13.79%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
17.55%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
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24.00%	Grebe et al. (2021): https://doi.org/10.1111/jwas.12814
23.00%	Grebe et al. (2021): https://doi.org/10.1111/jwas.12814
26.80%	Kim et al. (2015): doi: 10.3354/meps11331
29.10%	Kim et al. (2015): doi: 10.3354/meps11331
29.90%	Kim et al. (2015): doi: 10.3354/meps11331
31.70%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
30.20%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
30.00%	Visch et al. (2020): https://doi.org/10.1007/s10811-020-02201-5
28.59%	**Average**
4.02%	**Standard deviation**

13.33%	***Average***
3.17%	**Standard deviation**

Table S4. Life Cycle Assessment (LCA) assumptions

Cultivation structure

Item	*Unit*	*Lifespan*	*Quantity*	*kg per unit*	*Total annual kg*	*Unit GWP*	*Annual kg CO2*
Anchor-Chain	m	10	2,200.0	42.4	9,328.0	1.8	17,151.0
Anchor-Line	m	10	9,440.0	2.9	2,699.8	2.1	5,642.7
Header	m	10	12,052.0	0.6	735.2	2.7	1,960.2
Transverse	m	10	1,428.0	0.3	40.0	2.7	106.6
Longline	m	10	359,140.0	0.3	10,055.9	2.7	26,811.8
Tether-Float	Each	20	42,000.0	7.7	16,107.0	1.2	19,328.4
Tether-Line	m	20	126,000.0	0.3	1,701.0	2.1	3,555.1
nodeFloat	Each	20	40.0	130.0	260.0	3.7	956.8
Anchor	Each	50	40.0	11,119.0	8,895.2	1.8	16,355.2
Total							*91,867.7*

Mooring installation

Value	*Assumption*
13.0	Number of trips
520.0	Total kms
18.5	Speed (km / h)
28.1	Total cruising hours
341.0	Fuel consumption (l / hour)
9,574.5	Total install fuel (l)
7,966.0	Total install fuel (kg)
3.2	kgCO2 / kg diesel
25,539.0	Total install CO2

Vessel operations

Assumption	*Value*
Seeding days	26.9
Harvest days	40.2
Maintenance days	139.2
Total km per trip	40.0

Seeding km	1,077.4
Harvest km	1,609.7
Maintenance km	5,566.7
Total ann. km	8,253.8
Fuel (L / km)	2.9
Seeding fuel (L)	3,124.5
Harvest fuel (L)	4,668.0
Maintenance fuel (L)	16,143.3
Annual fuel (l)	23,935.9
Annual fuel (kg)	19,914.7
kgCO2 / kg diesel	3.2
Seeding emissions (kg CO2)	8,334.3
Harvest emissions (kg CO2)	12,451.5
Maintenance emissions (kg CO2)	43,060.6
Total vessel CO2	*63,846.4*

Transport

Assumption	*Value*
Tug transport hours	78.6
Outbound (hours)	39.3
Inbound (hours)	39.3
Tug hp	2,000.0
Total ton - km (outbound)	1,795,035.1
Tug specific fuel consumption (kg fuel / 1000 ton-km)	8.1
Total fuel consumption (kg; outbound)	14,539.8
Total fuel consumption (kg; inbound)	7,269.9
Total kg fuel	21,809.7
kgCO2 / kg diesel	3.2
Total kg CO2	*69,921.8*

Nursery

Components

Item	*Useful life*	*Unit*	*Quantity or amount*	*kg or L per unit*	*Total annual kg or L*	*Per unit impact (GWP)*	*Annual impact (kg CO2)*
Half strength PES	1	L	134.5	134.5	134.5	0.0	2.0
Seed Twine	1	m	678,774.6	0.0	678.8	2.1	1,418.6

Carboys	10	Each	4.0	2.3	0.9	2.4	2.2
Filters	1	Each	1.0	1.7	1.7	5.3	8.8
PVC spools	12	m	1,544.1	2.6	335.8	3.8	1,269.5
Total							*2,701.0*

Energy

Category	*Daily total kWh*	*Annual total kWh*	*Annual total kg CO2*
Seawater pumping and aeration	169.5	15,589.6	6,463.5
Grow-lights	522.9	48,106.8	19,945.4
Seawater chiller	451.4	41,528.7	17,218.0
UV sterilizer	36.1	3,323.0	1,377.8
Facility HVAC	189.6	17,443.2	7,232.1
Facility lighting	1,548.3	142,447.4	59,059.5
Facility lab equipment	37.1	3,414.7	1,415.7
Total	*2,954.9*	*271,853.3*	*112,712.0*

LCA SUMMARY

Gen. summary

Category	Annual CO2 (kg)	Annual CO2 (tons)
Mooring	91,867.7	91.9
Vessel ops.	63,846.4	63.8
Sinking	69,921.8	69.9
Nursery equipment	2,701.0	2.7
Nursery energy	*112,712.0*	*112.7*

Table S6. Optimization analysis variables, ranges, and sources

Parameter	**Unit**	**Baseline assumption**	**Optimized assumption**	**Change in LCOC**	**Change in AR**	**Source**
Nursery grow-out	Days	44	33	-$1,823	4%	Coleman et al.
Nursery labor	m twine per FTE employee	44,149	72,000	-$319	0%	Coleman et al.
Nursery energy cost	$ kWh^{-1}	$0.16	$0.07	-$39	5%	Coleman et al.
Spool size	m of twine per spool	132	643	-$1,929	0%	Coleman et al.
Nursery construction	$ m^{-2}	$2,048	$1,229	-$130	0%	Coleman et al.
Nursery electricity emissions	kg CO2 per kWh	0.410	0.006	-$1,679	7%	Pehl et al. (2017)
Mooring installation	$ / anchor	$155,266.00	$136,769.00	-$173	0%	Jenne et al. (2015); Vryhof
Seeding labor	hours per km grow-line	15.00	0.12	-$929	1%	Zuniga-Jara et al. (2016)
Harvest labor	hours per ton kelp (wet weight)	6.20	0.74	-$3,787	5%	Correa et al. (2016)
Maintenance labor	hours per km grow-line	22.41	2.42	-$656	2%	Hasselstrom et al. (2021)
Yield	kg m^{-1}	12.5	17.0	-$1,554	3%	Design process

WW:DW ratio	unitless	0.13	0.23	-$1,904	8%	Marinho et al. (2015)
Carbon content	unitless	0.29	0.36	-$501	2%	Augyte et al. (2017)
Transport cost	$ / 1,000 ton-km	$0.04	$0.01	-$51	0%	Diesel fuel price 1.9 vs. 3.7
Fuel C content	kgCO2eq per kg fuel	3.206	1.913	-$40	2%	Herdzik et al. (2021)
Tug SFC	kg fuel / 1,000 ton-km	8.10	4.94	-$20	1%	Teodorović and Janić (2017)
Performance review	$	$100,000	$10,000	-$63	0%	Gold standard (2021)
Buffer pool	%	15%	2%	-$192	12%	Gold standard (2021)