Seafields Solutions, Ltd

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

(The General Application applies to everyone; all applicants should complete this)

Company or organization name

> Seafields Solutions, Ltd

Company or organization location (we welcome applicants from anywhere in the world)

> UK

Name(s) of primary point(s) of contact for this application

> Jaime Cano, Franziska Elmer

Brief company or organization description

> A private company founded in 2021 which aims to aquafarm the floating seaweed Sargassum to sequester carbon, promote ocean productivity and biodiversity, and provide a renewable feedstock to industry for alternatives to fossil fuel products.
> https://www.seafields.eco

1. Project Overview[1]

a. Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

> Seafields will permanently sequester CO_2 in the deep ocean and help avoid emissions while restoring ocean productivity and increasing biodiversity. Our approach consists of growing and harvesting Sargassum seaweed, processing its biomass to extract nutrients and fossil fuel replacing products,

[1] We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

followed by baling and sinking the carbon-rich residual to the deep abyssal plain.

Sargassum inundations have a devastating effect on Caribbean and West African countries, harming tourism, fisherfolk, human health and coastal ecosystems. At the same time, Sargassum can provide a giant feedstock for CDR and can be an important source of CO2 replacing products. In the initial stages of our operation, we will harvest, and both utilize and sink this available feedstock in the Caribbean. At a later stage, aiming to sequester 1 Gt annually, we will grow Sargassum in the open ocean using artificial upwelling pipes as we learn to make them cost efficient.

In the initial stage, we will intercept and harvest wild Sargassum off the islands of the Eastern Caribbean beginning with St Vincent and the Grenadines (where we have obtained a permit). Preventing the beaching of Sargassum on these islands will have beneficial impacts on local economies and ecosystems and will avoid the release of CO2 and methane as Sargassum rots. The Sargassum we harvest will be processed to extract the plant's nutrients and shred its aerocysts (air vesicles). It will then be pressed and wrapped into bales which, for the St Vincent farm, will be transported to the deep abyssal plains just inside the EEZ of Barbados and Martinique/Guadeloupe (See Fig. 6 in Ocean Supplement) where it will sink on its own. Sinking from the initial farm and subsequent Caribbean farms will require national permits. We would also plan to sink in international waters as environmental assessments and regulation allow. Both the amount of carbon sequestered in the biomass during the growth phase, and the amount that remains in the deep sea will be monitored with an array of sensors that will inform our numerical models. Our measurements of avoided greenhouse gas emissions otherwise released during beach decomposition will be based on the methodology developed by our partners at Carbonwave who are applying for verification from Verra.

Our St Vincent "catch and grow" aquafarm will be moored and will be continuously full of Sargassum. The farm will retain a constant standing stock and will be continuously re-stocked with Sargassum intercepted from beaching. Grown and captured biomass will be harvested regularly. Our approach will enable a Sargassum harvest year round with an increased harvest load delivered by the Atlantic currents during the Sargassum season (March-September).

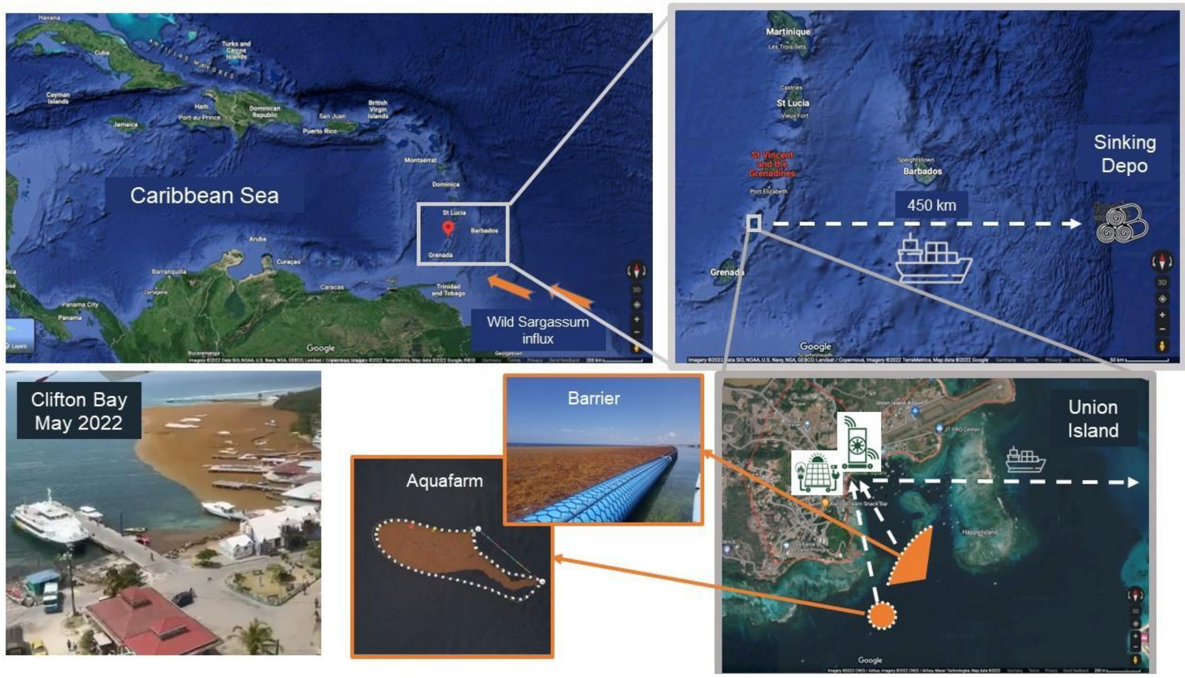

Fig. 1. Example of how an interception barrier, "catch and grow" aquafarm and processing plant could be located in Clifton Harbour, Union Island, St. Vincent and the Grenadines. The left top corner shows the location of St. Vincent and the Grenadines as well as the direction of the wild Sargassum influx. Top right corner shows the distance between St. Vincent and the deep sea depot for our bales in the EEZ of Barbados. Bottom left is a picture from July 2022 showing the masses of Sargassum that arrived in Clifton bay that day, Pinel island is clearly visible as a point of reference. On the right is the satellite view of the bay in which the interception barrier, "catch and grow" aquafarm and processing plant are shown in white, while the Sargassum is shown in yellow. White arrows show how the Sargassum caught either goes to the processing plant and that regularly Sargassum will be harvested from the aquafarm and processed in the plant. Examples of an interception barrier and aquafarm are shown in the bottom middle.

While we aim to replicate "catch and grow" farms and wild harvesting throughout the Caribbean, we will also focus on the means to sequester the needed 1 Gt of additional carbon per annum which can only be accomplished through open ocean farming and the provision of additional nutrients for Sargassum growth from the deeper water column or from nutrient recycling from the harvested Sargassum. We will work on developing a free-floating aquafarming system to grow Sargassum in the subtropical gyres which are currently ocean deserts with very low productivity. An area of 1´200´000 km^2 inside the South Atlantic gyre is suited for activities that avoid shipping routes and migration of whales, our farms will take up only fractions of that space.

To access the needed nutrients for Sargassum growth, we are developing artificial upwelling pipes based on the Stommel pipe principle that uses the density gradient in the ocean and thus does not require external energy. For harvesting, processing, sinking, and monitoring, the same methods developed for the Caribbean operations will be used. As the free floating aquafarms will be located above the abyssal plain (4000 m depth on average), no transport will be needed to the sinking site. Our farm operations and sinking will be undertaken in international waters on large ships or floating platforms. The closest harbor for logistics will be on the island of St. Helena (UK).

Fig. 2 Sketch of our open ocean aquafarms (FOAK)

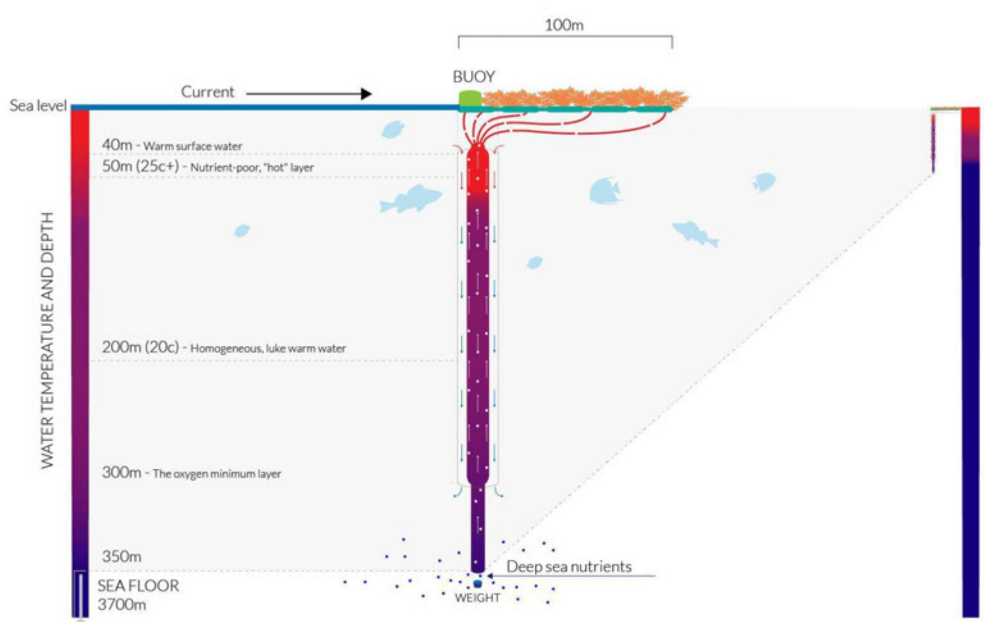

Fig 3 Diagram of our Stommel pipe for upwelling

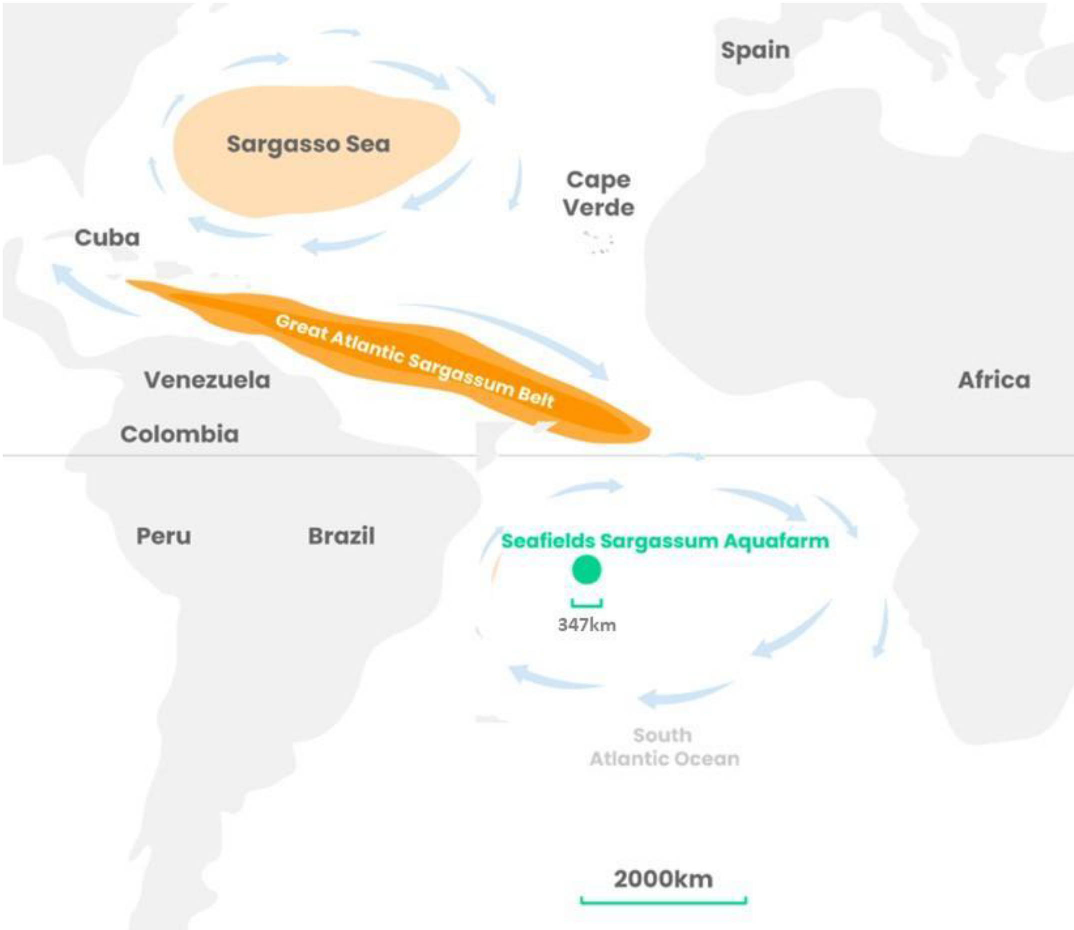

Fig. 4 Atlantic ocean map. In the map, the two areas where Sargassum aggregates naturally are seen (Sargasso Sea, Great Atlantic Sargassum Belt). The two gyres in the Atlantic are shown by circular currents. And the approximate location and size of our farms in the subtropical gyre when we reach Gt scale is shown.

Our 1 Gt approach is different and superior to other biomass sinking approaches for the following reasons:

Sargassum: *Sargassum fluitans* and *natans* are free-floating fast-growing (1-3 weeks) seaweed species which reproduce by fragmentation. Unlike kelp they do not require complicated hatchery/nurseries nor expensive substrate to grow on. In addition, sargassum has a very high carbon to nitrogen ratio (average C:N 34.5 (Lapointe et al. 2021)), making it extremely efficient at sequestering carbon per unit of nitrogen compared to phytoplankton (C:N 6-12).

Space for upscaling: Our approach is not constrained by arable land, coastal space, artificial fertilizer, or freshwater availability. The space available to grow sargassum is 100 times that available for kelp. Our estimates indicate that we would need 94´300km^2 (0.027% of the ocean surface) to grow and harvest enough Sargassum to sequester 1Gt of CO_2 per year.

Open ocean aquafarming: We recently tested the first barrier prototype in St Vincent and we are confident of its ability to contain Sargassum even in difficult seas. We are currently improving the design to increase the surface area inside the barrier. Our monitoring technologies (GPS and drones equipped with sensors) will make the tracking and reallocation of our farms possible even under tough conditions. From our initial trials we don't foresee adverse issues with large marine life entanglement since our structures are flexible, but we will monitor this with underwater cameras in the prototype farms. We are also working on systems to prevent any surface bycatch of smaller marine life.

In situ processing: We will process the Sargassum biomass at sea on vessels for the farms in the gyre and on land close to the harvesting site for the wild harvest in the Caribbean. This avoids energy intensive transportation. We will not need to clean the seaweed with freshwater nor use energy intensive drying processes. At sea the Sargassum will not be dried as bales can be sunk right at the farm. The Sargassum processed on land in the Caribbean will be air dried to avoid decomposition over time and then large amounts (120 t) will be transported to the sinking sites at once. Seafields is the first entity to achieve seaweed negative buoyancy without external mass. Our proprietary method relies on mechanically processing the Sargassum so that the aerocysts that enable sargassum to float are ruptured making the Sargassum negatively buoyant. The biomass can be compacted with a baler. We are experimenting with a number of biodegradable materials to wrap the bales.

Sargassum growth: We are following a two-step approach to provide nutrients to the Sargassum. Upwelling pipes will provide nutrients from deeper waters while the mechanical system we will use to process the Sargassum will include extraction technology to liberate most of the nutrients which will be returned to the aquafarm. We will perform laboratory studies to determine how these extracted nutrients enhance Sargassum's growth.

Additionality: Our open-ocean approach provides durable net removal of carbon from the atmosphere since the carbon sequestered by the Sargassum growing in our aquafarms irrigated by artificial upwelling wouldn´t have grown otherwise and is therefore additional carbon removed from the atmosphere. We will also estimate the average carbon export driven by phytoplankton in the oligotrophic subtropical gyre areas from the scientific literature and subtract this from total carbon removed.

During the initial activities in the Caribbean (This Project in TEA) additionality is achieved by capturing wild Sargassum that would have beached and grown it in "catch and grow" aquafarms. Newly grown Sargassum roughly accounts for ⅙ of the carbon that will be removed permanently in the Caribbean operations. The other ⅚ will avoid the release of the carbon stored in the naturally grown Sargassum back to the atmosphere. To determine Sargassum´s beaching potential we will employ ocean current models combined with satellite data and drift trajectory calculations in collaboration with SAM Tools.

Upwelling pipes: Our upwelling pipes are based on the Stommel "salt fountain" principle (Stommel 1956, Maruyama et al. 2004 and 2011). Cold, low-salinity, high-nutrient deep water (400 m) rises, accelerated by an equivalent downwelling counterflow of warm, high-salinity, low-nutrient surface water. Floating feeder pipes ensure further warming of the upwelled water on the surface and effective channeling to the Sargassum fields. One key differentiating feature of this upwelling technique is that the water reaching the surface is warmed, so we are avoiding water sinking again and the negative climate feedbacks of cold water reaching the surface (described in Oschlies et al 2010). The extra dissolved inorganic carbon (DIC) brought up will be absorbed by the macroalgae with its higher than Redfield C:N ratio. In addition, because it is a double counter pipe, the down-welled oxygen-rich waters avoid the formation of oxygen depleted areas below our farms. Modeling of the upwelling flow rates (in collaboration with GEOMAR, https://www.geomar.de/) has shown that flow rates that can be achieved by this method are comparable to those of wave pumps. We are now modeling the pipes and will test a first small scale prototype by mid 2023.

Products: Part of our harvest will be transformed into bioethanol and other carbon storing products in close collaboration with our partner, Carbonwave (https://carbonwave.com/), one of the world's largest processors of sargassum. We are currently researching the best fermentation pathway to achieve optimum yields (C-CAUSE project funded by SPRIN-D, https://www.sprind.org/en/challenges/carbon-to-value/). The ethanol will then be used by the chemical industry (including BASF, https://www.basf.com/global/en.html), from whom we are receiving support to produce long-lived plastic alternatives that will store carbon for decades. The aim is that Seafields' pipes will be fabricated from Sargassum derived plastic. We are also investigating the production of biogas through anaerobic digestion. This source of energy will potentially fuel our future offshore operations.

The processing of our biomass into bales releases liquid from the Sargassum that can be processed into biostimulant. This is a product that is already sold on the market by Carbonwave and we can supply them with this liquid for biostimulant production. This step does not lower the carbon content of the Sargassum and therefore does not impact the amount of CO_2 sequestered.

Rapid sinking: After the nutrients and other useful components of the Sargassum are extracted, the remaining biomass will be compressed into dense, carbon-rich negatively buoyant bales for stacked storage on selected sites of the deep sea abyssal plain. We have proven that the sinking of baled Sargassum biomass occurs rapidly; in its 7-hour descent (0.23 m/s) to reach a depth of 4,000m remineralization is avoided.

Monitoring: Compared to other sinking biomass approaches (e.g. phytoplankton or loose seaweed biomass), the amount of carbon sequestered in our bales is easy to monitor by weight and carbon content. To monitor atmospheric CO_2 uptake at the ocean surface we will use pCO_2 sensors. As tested in Mexico and St. Vincent, we will use drones to monitor and calculate the area covered by Sargassum. The deep-sea deposit will be equipped with cameras and oxygen sensors to assess macro and micro benthos consumption. All this will give us a precise indication of the fate of the biomass in the deep sea. More details on our monitoring approach are below.

Permanence: As we will sink tightly compressed bales the amount of space for bacterial remineralization will be significantly reduced. From preliminary lab experiments we expect the remineralization rates of the carbon-rich biomass in the deep sea to be negligible. The small percentage of remineralized CO_2 that does occur, would take 20-2700 years (median 600 yrs, average 900 years) to reach the surface of the ocean. Until then it is locked away (Siegel et al 2021).

Co-benefits: We expect positive impacts on the marine ecosystem coastally (avoided beaching), at the surface and in the deep sea. Seaweed cultivation contributes to several Sustainable Developmental Goals and it counteracts ocean acidification locally (Duarte et al 2017 and 2022). Also, Sargassum is a rich habitat for diverse species (Huffard et al 2014 and Martin 2016). Our preliminary observations confirm that recreating the Sargassum ecosystem in biologically empty parts of the ocean will attract diverse crustaceans and act as a fish nursery as well as feeding ground for commercially important fish species. Because our bales will not be rapidly remineralized, they will act as new substrate for the abyssal fauna to thrive.

Socio-economic benefits: Domesticating Sargassum in aquafarms will provide a stable source of raw material to the handful of small and medium-sized companies developing products from irregular but devastating influxes of Sargassum in the Caribbean. To date, lack of large scale rapid Sargassum collection (within 12 hours of beaching) has meant that these companies have been unable to scale-up operations to the degree needed to absorb the huge amount of Sargassum landing on Caribbean beaches. Our operations will fuel a robust Sargassum processing industry which will in turn protect coastal ecosystems from damage, avoid CO_2 emissions from Sargassum beach landings and improve the tourism economy of Caribbean Island nations.

References:

Duarte, Carlos M., et al. "Can seaweed farming play a role in climate change mitigation and adaptation?." *Frontiers in Marine Science* 4 (2017): 100.

Duarte, Carlos M., Annette Bruhn, and Dorte Krause-Jensen. "A seaweed aquaculture imperative to meet global sustainability targets." *Nature Sustainability* 5.3 (2022): 185-193.

Huffard, C. L., et al. "Pelagic Sargassum community change over a 40-year period: temporal and spatial variability." *Marine Biology* 161.12 (2014): 2735-2751.

Lapointe, B. E., et al. "Nutrient content and stoichiometry of pelagic Sargassum reflects increasing nitrogen availability in the Atlantic Basin." *Nature communications* 12.1 (2021): 1-10.

Martin, Lindsay Margaret. *Pelagic Sargassum and its associated mobile fauna in the Caribbean, Gulf of Mexico, and Sargasso Sea*. Diss. 2016.

Maruyama, Shigenao, et al. "Artificial upwelling of deep seawater using the perpetual salt fountain for cultivation of ocean desert." *Journal of oceanography* 60.3 (2004): 563-568.

Maruyama, Shigenao, et al. "Evidences of increasing primary production in the ocean by Stommel's perpetual salt fountain." *Deep Sea Research Part I: Oceanographic Research Papers* 58.5 (2011): 567-574.

Oschlies, Andreas, et al. "Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice." *Geophysical Research Letters* 37.4 (2010).

Stommel, H. M., Arons, A. B., Blanchard, D. 1956. An oceanographic curiosity: the perpetual salt fountain. Deep-Sea Res. 3: 152-53

Siegel, D. A., et al. "Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies." *Environmental Research Letters* 16.10 (2021): 104003.

b. What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

TRL4-6 for the Sargassum aquafarming infrastructure (the free floating and stationary farm).

We built a pilot farm barrier in St. Vincent in May 2022 and tested it for 3 weeks. The farm barrier can carry up to 500 kg (140 m^2) of Sargassum. It works well as a free floating farm as long as the current is aligned with the wind direction.

Our first barrier construction will need improvement to increase the stability under crosswind conditions when the farm barrier is used as a free floating farm.

We are currently working with a local group in St. Vincent which is implementing the planned optimisations. We plan to test the new construction early 2023.

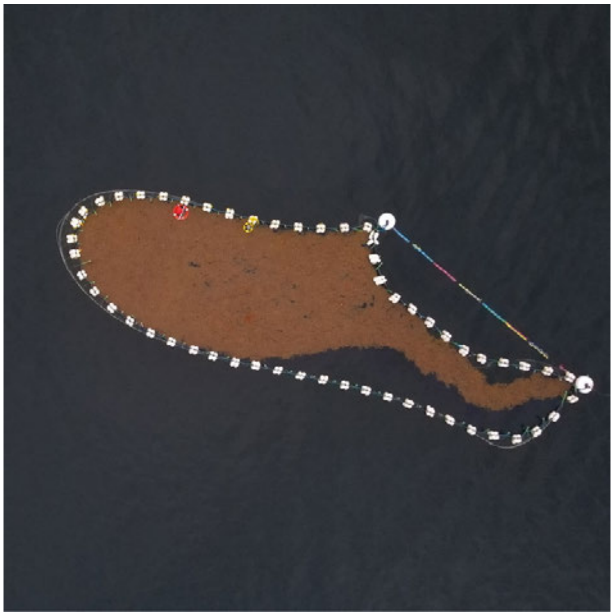

Fig. 5 Picture of our free floating barrier during tests in St. Vincent in May 2022.

TRL9 for sargassum harvest

Several companies have commercialized Sargassum interference via barriers and harvest along these barriers. We have done bycatch assessment for the alganova barrier and harvesting system (http://www.algeanova.com/en/) and the DESMI barrier and harvesting system (https://www.desmi.com/media/1dahsaxa/desmi_seaweed_uk.pdf). RanMarine (https://www.ranmarine.io/) is constructing a larger version of their WasteShark called MegaShark for Sargassum collection. Their WasteShark can be used for biomass removal and we have been in close contact with them to plan the potential use of their MegaSharks in our farms. We are in close and regular contact with SOS Carbon which developed two successful Sargassum harvesting methods (https://soscarbon.com/). The final decision on which system we will work with will depend on the environment we are operating in (close to shore versus open ocean), harvesting capacities, energy use and cost. While some of these solutions are only suited for relatively calm waters, others can be used in the open ocean.

TRL6 for the processing, baling and sinking of biomass

Processing of Sargassum via shredder and screw press is done at large scale at our partner company Carbonwave, which can process several tons of Sargassum per day and has used this method at TRL9 since spring 2021. We baled processed Sargassum in a manual baling machine and created bales of an average density of 311.7 kg/m^3 that sank at an average speed of 0.23 m/s. These numbers are based on 3 bales produced for a pilot test. For our deep sea environmental impact assessment (Bermuda 2023) we will acquire a hydraulic baler that can produce even more compacted bales and do so at a faster rate than via the manual baling machine.

TRL3 for the artificial upwelling pipes

The upwelling Pipes have been modeled with positive results from two different institutions (Geomar and a Phd student Tom Newton working in conjunction with Wim Van Rees from MIT through the Ocean Visions foundation) with similar results using different methods of estimating flow rates. The design for the pipes is now being configured to optimize the highest flow rates within commercially viable constraints. We are aiming at producing a 1/15th scale pipe to test in a disused mine shaft with large tanks at either end to control and mimic the oceans differing factors such as temperature and saline profiles across depth that would be very hard to measure in the ocean. Following the analysis of these results a full scale prototype would be conducted.

TRL6 for the monitoring of the aquafarms.

In September 2021, May 2022 and July 2022 we undertook multispectral drone monitoring trials to determine the size, density and health of the Sargassum patches. We are currently working with the drone company VisionFly to use pCO2 and albedo sensors on the drones.

c. What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

Key performance parameter	Current observed value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Energy cost of processing per ton of carbon	353 kWh/ton	54 kWh/ton	When we operate at NOAK level we don't need to dry the Sargassum as we can sink right below the farm.
Transport of biomass to sinking site	450 km	0 km	At NOAK we will operate above the abyssal plain and can sink at site
Sargassum doubling rate	0.05 per day	0.05-0.09 per day	Some improvements in doubling rate might be possible as we learn more about ideal growth conditions for Sargassum. Selection of specific strain or genetic modification could also lead to higher C:N ratios.
Upwelling rates per pipe	360 m^3/h	360 m^3/h	The modeling of the upwelling pipes has shown that the upwelling rate can only be increased significantly if the diameter of the pipe is increased.

			At 1.2 m diameter our upwelling pipe is currently at the max diameter that is commercially viable. The commerical viability of much larger pipes that could upwell 1000 m^3/h in undergoing feasibility studies and there is much work still to be done to get to upwelling rates higher than 360 m^3/h.
Nitrogen retrieved from Sargassum to fertilize our operations	104 mmol Nitrate (1.456 g) per ton of Sargassum This is 0.08% of the nitrogen contained in the ton of Sargassum	60% of the nitrogen contained in a ton of Sargassum	Our partner Carbonwave is testing a leach bed extraction method that would extract a higher percentage of the nutrients from the Sargassum than the screw press process.
Carbon:Nitrogen molar ratio of Sargassum	33	33-50	Some improvements in the C:N ratio might be possible as we learn more about ideal growth conditions for Sargassum. Selection of specific strain or genetic modification could also lead to higher C:N ratios.

d. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

Franziska Elmer is the scientific project manager of Seafields. She has a PhD in Marine Ecology and has researched Sargassum since 2018. As a host of the Sargassum Podcast, officer of the Association of Marine Laboratories of the Caribbean and Island Innovation Ambassador she has an extensive network in the Caribbean. During the last year she has gained extensive field expertise on aquafarming sargassum. She has also developed key personal relationships both in Mexico and in St Vincent, which enables a smooth implementation of the operations planned.

Nicola Schwehm is Seafields environmental engineer. His background is in automatization, robotics and renewable energy systems. Through his active participation in all 2021-22 operations he has gained experience in the field assembling and modifying the barrier prototype, deploying scientific monitoring equipment, programming, and operating the multispectral drone.

Mar Fernández Méndez is Seafields lead scientific advisor. She currently leads a Helmholtz Young Investigator group at the Alfred Wegener Institute for Polar and Marine Research. Her extensive expertise in carbon and nutrient cycling in the ocean provides Seafields with the information required to guide their operations and ensure transparency and an accurate implementation of monitoring. She has also acquired public research funding to explore the potential of sargassum for Ocean CDR (https://sea4society.cdrmare.de/en/) and leads the C-CAUSE consortium funded by SPRIN-D (https://www.sprind.org/en/challenges/carbon-to-value/)

Don Comrie has spent close to 30 years in translational science and intellectual property focused biopharma and biology systems. He has been awarded US and International patents in computational neuroscience.

Dave Brookes is an expert in Deepwater and Subsea Engineering with Project Engineering and Management of complex offshore and onshore projects with over 50 years industry experience. He champions leadership in Technology Development in Deepwater, Subsea Robotics and Fluid Flow Engineering. Through his professional affiliations and industry related network, he draws cooperation and sharing of Deepwater and Subsea Technology through leading international organizations, conferences and technology exchange agreements.

Richard Wills is a large-scale organic farmer with a background in creative 3D design and 20 years experience in developing sustainable farming practices and problem solving.

John Auckland is the Director of Communication and Investments. Founder of crowdfunding marketing agency TribeFirst (supported over 100 companies with successful equity crowdfunding campaigns, raising over £65m); Founder of seed stage impact fund, GreenTribe; and Virgin Startup's resident crowdfunding trainer.

Randall Purcell is the governance and regulatory expert, with 25 years at the World Bank and United Nations in Senior and Technical Advisor roles. Randall's expertise is on climate mitigation and adaptation strategies for both land and oceans, with a focus on project development for the Global Environment Facility (International Waters Focal Point) and Green Climate Fund.

Jaime Cano is the Director of Commercial and Business Development Operations and outreach investors and potential partners. Founder of international Consulting firm (Consulting Suma), Co-Founder of Remote Work Solutions start up (HQinSpace) and Partner of a VFX & 3D Animation Studio (Morgana Studios). He brings 23 plus years in Global ICT (including submarine cables), UX design & development with a wide startups experience.

We are looking to recruit another experienced offshore engineer.

e. Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	Role in the Project	Level of Commitment
Alfred Wegener Institute Helmholtz Institute for Polar and Marine Research (AWI)	Close scientific collaboration. Joint field trials, lending scientific equipment, coordinator of SPRIN-D grant, scientific advisor on aqua farming Dr. Bela H.	High

	Buck.	
GEOMAR Helmholtz Center for Ocean Research Kiel	Partner on SPRIN-D grant modelling artificial upwelling pipes. Scientific advisor on artificial upwelling Dr. Ulf Riebesel.	High
Universidad Nacional Autonoma de Mexico (UNAM)	Close scientific collaboration with the Unidad de Sistemas Arrecifales de Puerto Morelos. Use of their mesocosm laboratory, facilities and permit to collect Sargassum, scientific advisor on Sargassum Dr Brigitta van Tussenbroek	High
INES Solutions	Independent Organization to conduct Environmental Impact Assessment of the Deep Sea sinking trial for Seafields	High
Bermuda Institute for Ocean Science (BIOS)	Initiating collaboration or the first deep sea sinking trial in 2023. Director Will Curry and scientists Dr. Bates and Dr. Johnson.	Medium
Senckenberg am Meer	Scientific advisor on deep sea macrofauna Dr. Pedro Martinez.	Medium
Jacobs University	Scientific advisor on ocean ecosystems, collaborations with industry and deep sea environmental impact assessment Dr. Laurenz Thomsen.	Medium
Carbonwave	Close collaboration. Use of their warehouse, work area, machinery and Sargassum collecting permit, advisors on processing of Sargassum for product development.	High
Ocean Visions	We were selected to be part of the Ocean Visions XPRIZE launchpad and Ocean Visions provides us with resources and opportunities to catalyze our progress. Through them we have access to 3 scientific advisors: Dr. Matt Long, National Center for Atmospheric Research (NCAR) Dr. Wim van Rees, Massachusetts Institute of Technology (MIT) Tanja Brodie Rudolph, Stellenbosch University	High

	Our lead scientific advisor Mar Fernández Méndez is part of the Ocean Visions Macroalgae Sinking working group	
SOS Carbon	A Sargassum based CDR company which we have close relations with and plan to collaborate on scientific assessments. Have developed two harvesting methods which we may employ at stages of our development.	High
RanMarine	Provider of harvesting aqua drones that we plan to use for wild Sargassum harvest and for harvest inside our aquafarms.	Medium
Kelson Marine	Engineering company that provided us with the first design of the floating aquafarm and ran some numerical models for us.	Medium
H2Offshore	Engineering company we subcontracted to do the structural analysis of the artificial upwelling pipes.	Medium
VisionFly	In September 2021, May 2022 and July 2022, we worked with VisionFly to develop multispectral drone monitoring techniques to determine the size, density and health of the Sargassum patches. We are currently working with VisionFly to fit albedo sensors on drones and measure Sargassums radiative forcing.	High
Justcarbon	Token-based carbon market through which we will partly sell our carbon credits.	High
CO2Balance	Verification and certification partner with whom we are developing a methodology for carbon sequestration with our CDR option.	High
University of Oldenburg	We are currently in contact with Dr. Mariana Ribas Ribas to deploy her pCO2 monitoring catamaran and air-flux exchange mooring in one of our	Low

	aquafarms to quantify the air-ocean CO2 flux.	

f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

> The development phase of our first project began in September 2021 and first CDR delivery will occur in September 2024 (3 years), delivery of the credits should be completed by september 2026. We do not plan on decommissioning infrastructure after July 2026. if they are economically viable.

g. When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

> CDR from the project in the Caribbean ("this project" in TEA) will start in September 2024. 18 tons of CDR will be sequestered between September 2024 and December 2024. This is the mid-low season of wild Sargassum arriving (Johns et al. 2020) and we will be mainly dependent on daily growth in our stationary farm. 501 tons of CO2 will be sequestered during 2025.
>
> CDR from the FOAK will start in January 2027
>
> There is no foreseen end date to our CDR operations
>
> Reference
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> Johns, Elizabeth M., et al. "The establishment of a pelagic Sargassum population in the tropical Atlantic: biological consequences of a basin-scale long distance dispersal event." *Progress in Oceanography* 182 (2020): 102269.

h. Please estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)
2023	0
2024	18 tons
2025	501 tons (this project TEA, first operations in St Vincent)
2026	4´509 tons (9 facilities to harvest wild Sargassum with stationary farm and

	processing in the Eastern Caribbean)
2027	36´310 tons (72 total facilities for harvest of wild Sargassum with stationary farm in Eastern Caribbean (36´072 t) , 1 FOAK farm Q1-Q4 (68 t), 5 NOAK Q3-G4 (170t))
2028	291,296 tons (576 total facilities for harvest of wild Sargassum with stationary farm in Eastern Caribbean (288´576 t), 40 NOAK farms (2´720 t)
2029	310´336 tons (576 total facilities for harvest of wild Sargassum with stationary farm in Eastern Caribbean (288´576 t), 320 NOAK farms (21´760 t)
2030	462´656 tons (576 total facilities for harvest of wild Sargassum with stationary farm in Eastern Caribbean (288´576 t), 2560 NOAK farms (174´080 t)

i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	**Target completion date** (eg Q4 2024)
1	Processed Sargassum bales that are negatively buoyant	Q3 2021
2	Working protocol for drone monitoring of Sargassum biomass.	Q3 2021
3	Carbon loss in beached Sargassum quantified	Q3 2021
4	Free floating barrier that retains Sargassum designed and tested	Q2 2022
5	Non collapsing free floating barrier designed and tested	Q1 2023
6	Small scale model of upwelling pipe produced and tested	Q3 2023
7	Growth rate of Sargassum in near coastal drift of free floating barrier determined	Q2 2023
8	Stationary barrier for Sargassum retention and growth developed and tested	Q4 2023
9	Start of Sargassum harvest and aquaculture in St Vincent and the Grenadines. - Industry is supplied with fresh Sargassum biomass - LCA data collection for stationary farm completed	Q2 2024
10	Growth rate of Sargassum in across Atlantic drift determined - LCA data collection for free floating farm completed	Q4 2024
11	Environmental impact assessment of deep sea completed	Q1 2025 with intermediate results in Q3 2024

12	Methodology for carbon credits accredited by verifier.	Q3 2024
13	Sargassum harvest and aquaculture in St. Vincent including sinking of biomass for carbon credits.	Start in Q4 2024 if intermediate results of Environmental impact assessment give green light
14	Test of full scale upwelling pipe completed	Q2 2026
15	Installation Sargassum aquafarming in South Atlantic gyre	Q4 2026
16	Fully functional FOAK farm. Start of harvest.	Q1 2027

j. What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly (if applicable).

Seafields Ltd. applies an identification, qualification, and maturation model to select the appropriate intellectual protection. We have a number of projects in development from TRL3 to TRL9. Once a project advances it is screened to establish novelty. After the value of the claim is estimated, a decision is made about whether to patent it or treat it as a trade secret. Several inventions (approximately a half a dozen) have graduated to the development phase that should be completed in the next 18 months. Seafields has registered trademarks and copyrights in US and Europe.

k. How are you going to finance this project?

The first US $1,17m was financed by founding team members, friends, family and angel investors. We also received an investment from the band Coldplay, who selected us as one of their 15 good causes for the recent Music of the Spheres world tour. On top of their investment we and the other good causes are due a share of 10% of the tour profits – we don't know what percentage and how much profit they will make, but for perspective their last tour made over US $1bn profit.

We are in the final stages of closing our Seed round from an institutional investor that's dedicated to carbon removal technologies. They will invest US $1.68m in total and support us through a crowdfunding round in November for an additional US $2m. We will need to raise US $16,8m in Summer/Fall of 2023 once we have achieved technical proof of concept. If we are successful with proving each of the technology elements we will essentially be credit generating so will be able to advance sell credits (and be on your offtake track). However, we anticipate much of the US $16,8m will be raised via an equity investment into Seafields Solutions Ltd, and have already had discussions with investors interested in investing at this stage.

In collaboration with international research institutions like AWI and our partner company Carbonwave, we have raised around US $0.6m to study the potential of Sargassum for Ocean CDR at a global scale (sea4soCiety-CDRmare project funded by the German Ministry of Education and Research) and to develop and test the first aquafarm prototype and the processing steps to ethanol for long-lived engineering plastics (C-CAUSE project funded by SPRIN-D).

We are also establishing a not-for-profit foundation to support the long-term independent scientific monitoring and assessment of the potential ecosystem impacts of our operations both at the ocean's surface and at the seafloor. It is imperative that we are science led which will inform politics and the legal aspect of our marine activities. The scientific knowledge produced will be open source.

l. Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

We have had a promising conversation with Toyota and are in the active discussion phase. We are also actively discussing bringing out a range of NFTs with the digital platform JustCarbon (https://www.justcarbon.com/#/) that are linked to the project, which will deliver credits in the future. Both conversations are in the early stages.

m. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

We can extract some valuable resources from the Sargassum before we bale it ready for sinking. This includes alginates, nutrients such as phosphates and nitrates. We are working in partnership with Carbonwave, which specialize in turning Sargassum into products, and will take most of what we can provide them as it enhances confidence in their supply and allows the opening of new markets.

In addition, the C-CAUSE project funded by SPRIN-D, from which we are essential partners (https://www.sprind.org/en/challenges/carbon-to-value/https://www.sprind.org/en/) has the official support from BASF to transform the bioethanol produced by fermentation from Sargassum into long-lived engineering plastics to substitute fossil fuel plastics and avoid emissions.

n. Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	Mitigation Strategy
Environmental impact	The assessment of the environmental impact of ocean CDR is challenging. Our aquafarms can affect the environment both at the surface of the ocean as well as at the abyssal plain where the biomass is stored. We are committed to conducting rigorous environmental impact assessments and are part of a broad coalition of partners supporting each other, learning, and sharing information on ocean CDR generally and biomass sinking in particular (eg. Ocean Visions, CDRmare, OceanCDR.net). For our initial environmental assessment, we will sink 30 bales off-shore Bermuda in early 2023 in collaboration with BIOS (http://www.bios.edu/#!/who-we-are). A lander with a camera, pH, temperature and oxygen sensors will be deployed and retrieved with an

	ROV 12 months later to analyze the data and the carbon content of the bales retrieved. The surrounding areas will be analyzed and compared with a control area. This rigorous assessment of deep sea deposits will follow the recommendations of the Ocean Visions Macroalgae Sinking Working Group and will be conducted by independent researchers. Sinking Sargassum for carbon credits will not start until results of the assessment are completed (expected early to mid 2024 for first results). When commercial operations are in full gear, continuous monitoring of deep sea deposits will be undertaken in collaboration with our research partners (AWI, Senckenberg. et.al.) The abyssal plains comprise 50% of the earth surface and only a tiny part of this will be impacted. Since our bales contain processed compacted Sargassum, we expect negligible decomposition rates.
Impacts of scale up on marine ecosystem and ocean biogeochemical cycles	To comprehensively assess the impacts of large-scale aquafarming in the open ocean on the marine ecosystem and ocean biogeochemical cycles, we will use (in collaboration with external independent scientists) Earth System Models. As we scale up during our trials, we will obtain the data necessary to parameterize those models correctly and be able to predict future large-scale consequences.
Lack of growth of Sargassum while contained	No one has managed to domesticate Sargassum for aquaculture. We have learned a great deal during our initial trials about designing and deploying a free-floating, self-opening barrier that will effectively contain Sargassum and will not collapse with changing wind and current conditions. Our first barrier prototype contained Sargassum remarkably well and we encountered no impacts on marine life during short, off-shore deployments. For the second prototype we have developed a proprietary design that will enable Sargassum aquafarming in the open ocean. This design will be tested to determine if it avoids collapse with changing wind and current conditions in Q1 2023. In Q2 2023 we will conduct a 5 day drift of the barrier with Sargassum to determine if and how fast Sargassum grows inside of it. In Q1 of 2023 we will design a stationary barrier that we will test and modify in Q2-4 2023.
Deployment and maintenance of artificial upwelling pipes	Artificial upwelling pipes have been proposed as a technology to irrigate surface waters since the early 1950s. We are learning from the challenges of previous attempts to deploy them, and have cast a wide net for talent from research institutions and the oil and gas industry to develop a system that works. We are confident of designing and constructing a modular counter pipe that can free-float between 50-400 m depth, bringing deep nutrient-rich waters to the surface. Initial modeling calculations by our contractors and confirmed by our engineers, show that upwelling rates of 0.1 m^3/s are feasible with a 1 m diameter pipe with 20-50 inner pipes. We are also in contact with

	companies developing technologies to avoid biofouling in the ocean, including ocean thermal energy conversion approaches that close a pipe for some time so that it becomes anoxic.
Monitoring Reporting and Verification	Our science team has extensive experience in monitoring climate change impacts in the carbon and nutrient cycles in the open ocean. They are aware of the challenges that ocean CDR MRV pose (e.g. accuracy of pCO2 measurements, taking into account the dilution of the signal, etc.) and are developing novel tools to improve the resolution for large scale operations. Using a combination of water and air sensors, we will monitor the air-ocean CO2 influx.
Governance and regulation	Our trials are taking place in the EEZ of St Vincent and the Grenadines and Mexico at the moment, with local partners which guide us through the request for permits for our activities. As we start upscaling and moving to international waters, we will need to ensure that our activities conform to UNLCOS (and the emerging Biodiversity Beyond Jurisdiction requirements), the London Protocol, the Biodiversity Convention, other international laws and the emerging Ocean CDR Code of Conduct being developed with Woods Hole, the American Geophysical Union and others. Our team has expertise in laying and recovering telecommunication cables around the world as well as extensive government and UN relationships, and we are confident of successfully navigating these issues. We are drafting a document together with environmental and marine law expert, Tanya Brodie Rudolph of the University of Capetown (lent to us by Ocean Visions), to track and ensure that we abide by the current and emerging legal and regulatory frameworks.

2. Durability

a. Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

We will sink shredded and baled Sargassum to the abyssal plain. Any biomass that is not remineralized and is stored at that depth (>4000 m) will be sequestered permanently for much longer than 1000 years. A small percentage of the sunk biomass will be remineralized, to date there is no data available to indicate exactly how large this percentage will be. However, recently, it has been found that the immense hydrostatic pressure in the deep sea has an inhibitory effect on the metabolism of the bulk

deep-sea heterotrophic prokaryotic community, leading to substantial lower heterotrophic prokaryotic activity in the deep-sea than previously assumed (Amano et al 2022). Furthermore, on the Sargasso Sea floor, four times more Sargassum is found than at the surface (Baker et al. 2018), indicating a potential slow remineralization rate. The small percentage of remineralized CO_2 that does occur, would take 20-2700 years (median 600 yrs, average 900 years) to reach the surface of the ocean. Until then it is locked away (Siegel et al 2021).

In partnership with AWI, we conducted laboratory-based sargassum decomposition experiments that measured the depletion of oxygen. Our results (not yet published) show that Sargassum processed for nutrient recovery decomposes slower than fresh Sargassum, which will lead to less remineralization of our bales compared to Sargassum that sinks naturally. This, together with the fact that on tightly compressed bales the amount of space for bacterial remineralization will be significantly reduced, suggests there will be negligible remineralization rates of the carbon stored in the bales in the deep sea.

References

Amano, Chie, et al. "Impact of hydrostatic pressure on organic carbon cycling of the deep-sea microbiome." *bioRxiv* (2022).

Baker, Philip, et al. "Potential contribution of surface-dwelling Sargassum algae to deep-sea ecosystems in the southern North Atlantic." *Deep Sea Research Part II: Topical Studies in Oceanography* 148 (2018): 21-34.

Siegel, D. A., et al. "Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies." *Environmental Research Letters* 16.10 (2021): 104003.

b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

See 2 a) which explains the risk of remineralization and the uncertainties about the underlying biological processes. As the abyssal plain (4000 m deep) is essentially untouched by human activities, we do not foresee any socioeconomic risk.

3. Gross Removal & Life Cycle Analysis (LCA)

a. How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO_2 here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	501 in 2025 (This is the project costed out in "this project TEA")
Describe how you calculated that value	We expect to harvest an average of 7.5 tons of Sargassum a day or a total of 2737.5 tons of Sargassum in 2025 0.183 tons of CO_2 are sequestered in 1 ton of Sargassum: 5.9 t of wet Sargassum = 1 t of dry Sargassum Carbon content of dry Sargassum = 30 % Weight of Carbon = 12 g/mol Weight of CO_2 = 44 g/mol Carbon content of wet Sargassum = (1 t Dry Sargassum·0.3 t C/t dry Sargassum)/(5.9 t Wet Sargassum / Dry Sargassum)= 0.050 t C /t wet Sargassum CO_2"content" of wet Sargassum = (0.050 t C /t wet Sargassum ·43.991 g CO2/mol)/(12.011 g C/mol) = 0.1831 t CO_2/ t wet Sargassum

b. How many tonnes of CO_2 have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

500 kg captured, 0 kg stored

c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO_2 utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do not include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

In the St Vincent project phase ("this project" in TEA), some of the processed Sargassum will be directly harvested wild Sargassum that would have otherwise beached. Carbonwave is currently in the process of having their methodology approved by Verra and in it they calculated that avoidance of beaching leads to avoided greenhouse gas emissions of 0.259 tons CO2 equivalents per ton of Sargassum. This is 0.076 tons of CO2 higher than the CO2 sequestered during Sargassum growth. Therefore for each ton we sink that was prevented from beaching, 0.076 tons of avoided emissions result.

For our open ocean farming, the change in albedo due to Sargassum growing in the open ocean will lead to a cooling effect. The increase of albedo due to Sargassum has not been determined but would likely be on the upper end or above the 0.01-0.07 range measured for seagrasses (Bach et al. 2021, Fogarty et al. 2018). This cooling can be translated into CO2 offsets using a conversion rate of 2.5-4.3 kg/m² per 0.01 change in surface albedo (Akbari et al. 2009, Akbari et al. 2012). We hope to measure the albedo of Sargassum and seawater in 2023 to get a more precise number than what is published in Bach et al. 2021 and to include this in our carbon accreditation method.

References:

Akbari, Hashem, Surabi Menon, and Arthur Rosenfeld. "Global cooling: increasing world-wide urban albedos to offset CO2." *Climatic change* 94.3 (2009): 275-286.

Akbari, Hashem, H. Damon Matthews, and Donny Seto. "The long-term effect of increasing the albedo of urban areas." *Environmental Research Letters* 7.2 (2012): 024004.

Bach, Lennart T., et al. "Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt." *Nature communications* 12.1 (2021): 1-10.

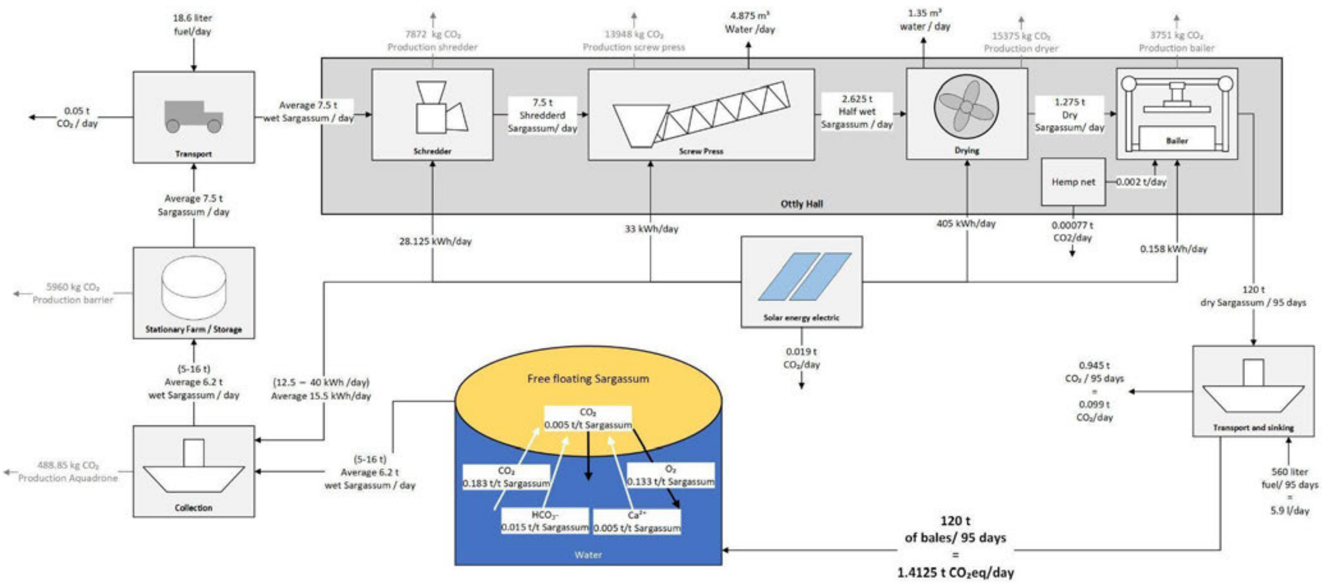
Fogarty, M. C., et al. "The influence of a sandy substrate, seagrass, or highly turbid water on albedo and surface heat flux." *Journal of Geophysical Research: Oceans* 123.1 (2018): 53-73.

d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions described below this table)*	44.7 t CO2 in 2025
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	0.09
Net CDR over the project timeline *(gross CDR - gross project emissions)*	456.3 t CO2 in 2025

e. Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA). Some notes:

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO_2 equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
  - Review the diagram below from the CDR Primer, Charm's application from 2020 for a simple example, or CarbonCure's for a more complex example
  - See University of Michigan's Global CO_2 Initiative resource guide
- If you've had a third-party LCA performed, please link to it.



f. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

Our boundary includes all the processes that occur between algae taking up carbon until the sinking of algae. The diagram includes processes that feed into this boundary, e.g. the production of equipment or the gas exchanges between the ocean and the algae. It does not include gas exchanges between the ocean and the atmosphere as that does not feed directly into our boundary. However, we plan to measure this gas exchange as it is important to understand in which timescales dissolved inorganic carbon removal from the ocean translates into CO2 removal from the atmosphere.

g. Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. Climeworks' LCA paper.

Below is the LCA for “this project” in the TEA. As project life time we took 1 year in which 501 gross tons of CO_2 will be captured (2025). Please see *PFD -StreamTable - 2270 t CO2 per yr GYRE FARMS* for the process flow diagram of the FOAK farm and *LCA 2270t CO2 per year GYRE FARM* for the life cycle assessment of the FOAK farm. These were done for the phase 1 XPRIZE submission last February. These were 3rd party verified by Elias Azzi who is an specialist in LCA from KTH, Royal Institute of Technology.

Process Step	**CO_2(eq) emissions over the project lifetime (metric tonnes)**	**Describe how you calculated that number. Include references where appropriate.**
CO2 emitted during calcification process	9.58 t CO_2eq emitted per year	CO_2 emitted during the calcification process. Certain epiphytes (mainly bryozoans) that attach to the Sargassum produce calcium carbonate ($CaCO_3$). In this process CO_2 is emitted (Bach et al. (2021)). In September 2021 we measured PIC/POC ratio on 51 Sargassum samples from Mexico and found it to be 0.043±0.049, much lower than the value reported by Bach et al. (2021) that was based on data from 1985 in the Sargasso Sea. The older the Sargassum plant is, the more epiphytes are attached to it. As the growth rate in the Sargasso Sea is much slower (3-20 weeks doubling time) than in coastal areas (1- 3 weeks doubling time), there is likely a larger percentage of very old Sargassum that has a lot of epiphyte cover and therefore the value in the Bach et al. (2021) paper was higher than our measurement. We aim to upwell enough nutrients to get to a doubling rate of 14 days, and therefore our epiphyte load will likely be similar to the one in Mexico. Using the same formula as Bach et al. (2021) we found that the average CO2 released by carbonisation happening inside epiphytes is equal to 2.9% of the CO2 captured by the algae through photosynthesis. Reference: Bach, Lennart T., et al. "Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt." *Nature communications* 12.1 (2021): 1-10.
CaCO3 sunk as part of the Sargassum	9.58 tons of CO_2eq **sequestered** per year	$CaCO_3$ is attached to the surface of the Sargassum that sinks. This $CaCO_3$ is produced by epiphytes as described above. The paper describing this process (Bach et al. 2021) does not account for the $CaCO_3$ sequestered but it should be accounted for. During the process, 2HCO_3 atoms are on the input side, while 1 C atom is released as CO_2 and the other C is incorporated into the $CaCO_3$. Therefore the two should balance each other out. The processing of the harvested Sargassum

		does not detach the $CaCO_3$ from the Sargassum (visually inspected) and therefore we assume that all of that $CaCO_3$ is sunk to the deep sea storage. In the process flow diagram this value is included in the total amount of CO_2eq sequestered in the bales
Harvest of Sargassum	0.18 tons of CO_2eq emitted per year	RanMarine Megashark harvester uses 2.5 kWh per ton of Sargassum harvested. Daily harvest 6.2 tons = 6.2 hours = 15.5 kWh 40 g of CO_2eq released per kWh of solar energy Source: https://www.nrel.gov/docs/fy13osti/56487.pdf Daily harvest releases 620 g of CO_2eq
Transport of Sargassum to processing site	33 tons of CO_2eq emitted per year	7.5 tons transported 40 km by truck once a day According to figure 3 in https://www.transportenvironment.org/wp-content/uploads/2021/10/202108_truck_CO2_report_final.pdf A small truck (4 UD) emits 307.2 g CO2 per t-km A daily transport would therefore release 0.092 t of CO_2
Shredding of Sargassum	0.27 tons of CO_2eq emitted per year	According to specification sheet of DT-1575SR from Delitek http://www.delitek.nl/systems-solutions/shredders/dt-1575sr-shredder/ 1.5 m3 capacity 7.5 kW Assumptions: 1.5 m3 = 0.5 tons of shredded wet Sargassum 1.5 m3 can be shredded in 15 min 2 tons per hour -> 3.75 kWh per ton of Wet Sargassum 28.125 kWh per day (7.5 ton of wet Sargassum) 40 g of CO_2eq released per kWh of solar energy Source: https://www.nrel.gov/docs/fy13osti/56487.pdf 1.125 kg of CO_2eq released per day
Screw Press	0.31 tons of CO_2eq emitted per year	CP-4 screw press was tested with Sargassum and can process 285 pounds per hour. Specification sheet says 150-500 pounds. According to specifications sheet of CP-12 from Vincent

		Corp. https://vincentcorp.com/wp-content/uploads/CP_VP_Screw_Press_1M-08_13_0.pdf 4000-16000 pounds per hour = 7600-9120 pounds per hour of Sargassum = 3447- 4136 kg 20 HP motor = 15 kW Assumptions: 3.4 t per hour 4.4 kW per ton of wet Sargassum 33 kW per day (7.5 tons of Sargassum) 40 g of CO_2eq released per kWh of solar energy Source: https://www.nrel.gov/docs/fy13osti/56487.pdf 1.32 kg CO_2eq per day
Drying	3.89 tons of CO_2eq emitted per year	Sargassum is 17% dry weight and 83% water. 1 ton of Sargassum therefore has 830 L of water in it, the screw press removes 650 L of water (information provided by Carbonwave) The drying process must remove 180L of water. This will be done by laying the Sargassum out in a hall and letting it air dry. To dry the Sargassum, we will use electrical energy to move air and not to generate heat. This way a heating capacity of 84 kW can be achieved with the input of electric energy of 30 kW. To remove 180 l of water, a heating capacity of 151.2 kWh is needed, therefore 54 kWh of energy is needed to dry 1 ton of wet Sargassum. 405 kWh per day (7.5 tons of wet Sargassum) 40 g of CO_2eq released per kWh of solar energy Source: https://www.nrel.gov/docs/fy13osti/56487.pdf 16.2 kg CO_2eq per day
Bailing	0.0015 tons of CO_2eq emitted per year	According to specifications of DT-1500MC https://delitek.no/Products/DT-1500MC 1.5 m3 capacity 1.8 kW Assumptions

		1.2 tons of dry Sargassum per 1.5 m3 = 7 tons of wet Sargassum (5.9 tons of wet Sargassum = 1 ton of dry Sargassum) 1 Bale per 15 min, 5 min of energy use. Hourly 20 min on. 0.021 kWh per ton of wet Sargassum 0.158 kWh per day (7.5 tons of wet Sargassum) 40 g of CO_2eq released per kWh of solar energy Source: https://www.nrel.gov/docs/fy13osti/56487.pdf 6.32 g CO_2eq per day
Hemp net for bailing	0.279 tons of CO_2eq emitted per year	0.364 kg CO_2eq/kg Hemp Source:https://renewable-carbon.eu/publications/product/carbon-footprint-and-sustainability-of-different-natural-fibres-for-biocomposites-and-insulation-material-%e2%88%92-full-version-update-2019/ Surface area of bale 7.86 m² 1 m² = 0.25 kg of hemp 2 kg of hemp per bale 0.28 kg of hemp per ton of wet Sargassum 0.05 kg of hemp per ton of CO2 sequestered 2.1 kg of hemp per day 0.7644 kg CO_2eq per day
CO2 sequestered through sinking of the hemp net	0.249 tons of CO_2eq **sequestered** per year	0.325 kg CO_2eq/ kg of Hemp Source: Elias Azzi gave us this value from official LCA tables for our XPRIZE LCA 2.1 kg of hemp per day 0.68 kg of CO_2eq sequestered per day In the process flow diagram this value is included in the total amount of CO_2eq sequestered in the bales
Transport of bales to sinking site	2.39 tons of CO_2eq emitted per year	Calculated using http://www.sustainablefreight.com.au/tools-and-programs/emission-calculators/ship-type-carbon-emissions-calculator Ship type: General Cargo 0-4999 t Distance 450 km Weight 120 t dry Sargassum Emissions 945 kg of CO_2eq Transport will happen every 95 days

		120 t dry Sargassum = 708 tons of wet Sargassum 1.33 kg of CO_2eq per ton of wet Sargassum 9.95 kg of CO_2eq per day
Production of harvesting aquadrones	0.03259 t of CO_2eq emitted per year	Production of 2 aquadrones uses 14 kg of aluminum 60 kg of stainless steel 200 kg of fiber mat, rovings and resin Life time of drone is 15 years (communicated by RanMarine) CO_2eq intensity estimates: Aluminum 8.14 CO_2eq/kg material. Source: XPRIZE Stainless steel 6.15 kg CO_2eq/kg material. Source: XPRIZE Carbon fiber mat 0.02945 kg CO_2eq/kg material. Source: https://www.compositesworld.com/articles/building-confidence-in-recycled-carbon-fiber Emissions for each material Aluminum: 113.96 kg CO_2eq Steel: 369 kg CO_2eq Fibermat: 5.89 kg CO_2eq Total: 488.85 kg CO_2eq (15 years life time)
Production of processing equipment (shredder, screwpress, dryer, baler)	4.09 t of CO_2eq emitted per year	Production of 1 shredder 1´280 kg of stainless steel → 7´872 kg CO_2eq Life time 10 years Production of 1 screw press 2´268 kg of steel→ 13´948 kg CO_2eq Life time 10 years Production of 1 baler 610 kg of stainless steel → 3´751.5 kg CO_2eq Life time 10 years Production of 1 dryer 2´500 kg of steel → 15´375 kg CO_2eq for

		production Life time 10 years CO_2eq intensity estimates: Stainless steel 6.15 kg CO_2eq/kg material. Source: XPRIZE Emissions for production 40´946.5 kg of CO_2eq (10 years life time) Yearly CO2 sequester rate: 330 t 10 year sequester rate: 3300 t
Production of barriers for beaching prevention and for farm	0.596 t of CO_2eq emitted per year	Recycled HDPE for floats: 6´500 kg 10 years life time 85% recycled PET for net: 1´378 kg 5 years life time CO_2eq intensity estimates: HDPE: 0.265 kg CO_2eq per kg material Source: Elias Azzi gave us this value from official LCA tables for the XPRIZE LCA PET: 1.538 kg CO_2eq per kg material. Source https://winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf Emissions for each material: HDPE: 1´722.5 kg CO_2eq PET: 2´119 kg CO_2eq Total: 5´960.5 kg CO_2eq (10 years life time)

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see Charm's bio-oil sequestration protocol for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

Compared to other sinking biomass approaches (e.g. phytoplankton or loose seaweed biomass), the amount of carbon sequestered in our bales is easy to monitor by weight and carbon content. We will determine the mean weight of the bales produced with our baler including standard deviation, and regular samples will be taken for carbon content analysis. To monitor atmospheric CO_2 uptake at the ocean surface of our farms we will use pCO_2 sensors attached to buoys within our farms. We will use numerical models to quantify the sea-air exchange of CO2 as the water parcels travel away from our farm. In addition, we will monitor temperature, salinity, pH, current speed, and oxygen in situ with our fully equipped CTD (Conductivity-Temperature-Depth Probe) as well as DIC and alkalinity. These measurements will be continuous with a minimal measurement frequency of 30 min. Regular measurements of particulate organic carbon content in the Sargassum biomass will be used to calculate the carbon stored in the total aquafarm biomass. As tested in Mexico and St. Vincent, we will use drones to monitor and calculate the area covered by Sargassum. Our methodology includes quantifying the part of the carbon taken up that is excreted as dissolved organic carbon (DOC) in the water column. The carbon content of Sargassum is on average 5% of wet biomass and natural sargassum mats have an average density of 3.34 kg per m^2 (Wang et al. 2018). The deep-sea deposit will be equipped with cameras and oxygen sensors to assess macro and micro benthos consumption of the bales. All this will give us a precise indication of the fate of the biomass in the deep sea. We are undertaking a sinking trial with 30 bales at the beginning of 2023 off-shore Bermuda to conduct a rigorous third-party environmental impact assessment as well as measure remineralization rates. These investigations are being led by deep sea specialists from Senckenberg am Meer, Jacobs University, Alfred Wegener Institute ("AWI"), and Integrated Environmental Solutions (INES).

References:

Wang, Mengqiu, et al. "Remote sensing of Sargassum biomass, nutrients, and pigments." *Geophysical Research Letters* 45.22 (2018): 12-359.

b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

Remineralization rates of Sargassum will be estimated by measuring the oxygen concentration inside and around some of our bales with deep sea oxygen sensors. Oxygen consumption is a proxy for carbon remineralization. Furthermore, footage from cameras mounted on landers with a bale inside will give insights on the type of community that might establish on the bales and volume/consistency changes of the bales. An ROV will visit the deposits of bales once every two years to take footage and take a few subsamples of the bales and the surrounding sediments back to the surface. In collaboration with scientists the carbon trophic transfer and the microbial community composition in and around the bales will also be determined. All of these measurements help us determine if Sargassum is being remineralized and at what rate.

c. This tool diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:

- In the first column, list the quantification components from the Quantification Tool relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
- In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
- See this post for details on Frontier's MRV approach and a sample uncertainty discount calculation and this Supplier Measurement & Verification Q&A document for additional guidance.

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Macroalgae harvest	The harvest rate depends on the growth rate in our farms. In neritic waters the doubling rate of Sargassum varies between 8-23 days which reflects a daily growth rate of 3-11% per day (Hanisak and Samuel 1987, Lapointe et al., 2014, Lapointe, 1986, Howard and Menzies, 1969). Our estimates were done with a 5% growth rate per day or a doubling in 14 days. The net CDR over a certain time frame would be 40% smaller if the doubling rate is 23 days and 120% larger if the doubling rate is 8 days. This affects mainly our predictions on how long it takes to sequester a certain amount of CO2. The weight of the algae harvested will be accurately determined with a scale (0.1 % accuracy e.g. https://www.abqindustrial.net/store/dillon-awt05-506312-edx-1t-inchred-inch-edxtreme-dynamometer-with-2-shackles-2-500-lbf-p-396-op-815_9799.html?gclid=Cj0KCQjwnP-ZBhDiARIsAH3FSRf_LI_QK52vxEfZ_4SUms7g9twyHunJigXpEQtQKWIvUadeMIFSCSEaAugBEALw_wcB) and the particulate organic and inorganic carbon content of the biomass will be measured using an elemental analyzer in some subsamples taken before sinking. Our POC analysis have been performed at the laboratory facilities of GEOMAR and AWI with a precision of 1 ug/mg dry weight (0.3% accuracy). The combined accuracy is 0.43% (multiplication operation). We will weigh 10% of the produced bales during each operational day and take 14 subsamples of the biomass after processing (extracting the nutrients) for carbon content per processing plant set up

	every week to calculate the amount of carbon stored in the bales before sinking. The standard deviation of these measurements will give us insights on the consistency of the weight of the bales and %C measurement. We hope that the baling machine is constant enough that we only have to discount 1% due to not weighting each bale. Otherwise we will weigh each bale in order to get a 0.43% accuracy of the amount of Carbon sunk to the deep sea. Therefore we estimate the impact of this component on the net CDR to be 1% References: Hanisak, M. Dennis, and Mary A. Samuel. "Growth rates in culture of several species of Sargassum from Florida, USA." *Twelfth International Seaweed Symposium*. Springer, Dordrecht, 1987. Howard, K. L., and R. J. Menzies. "Distribution and productions of Sargassum in the waters off the Carolina coast." (1969). Lapointe, Brian E., et al. "Ryther revisited: nutrient excretions by fishes enhance productivity of pelagic Sargassum in the western North Atlantic Ocean." *Journal of Experimental Marine Biology and Ecology* 458 (2014): 46-56. Lapointe, Brian E. "Phosphorus-limited photosynthesis and growth of Sargassum natans and Sargassum fluitans (Phaeophyceae) in the western North Atlantic." *Deep Sea Research Part A. Oceanographic Research Papers* 33.3 (1986): 391-399.
Leakage	We estimate that the fraction of biomass not sunk to depth will be very minimal as the biomass is compressed and held together in bales and made negatively buoyant. Pieces that break free from the bale will be negatively buoyant and sink. We estimate the impact of this component on the net CDR to be < 0.1%.
Surface competition effect	Bach et al. (2021) calculated that 31-32% of the net CDR should be discounted from Sargassum growth due to the amount of phytoplankton that could grow naturally with the nutrients taken up by Sargassum. This is based on a very simplified model that doesn't take into account the nutrient recycling taking place in Sargassum mats that includes fauna and bacteria. For our FOAK project this impact will be negligible for several reasons. 1. We choose a site with low natural nutrient levels and therefore low phytoplankton levels.

	2. We assumed that the Sargassum will only use 86% of the upwelled Nitrogen, while the other 14% are available for phytoplankton and might even lead to more phytoplankton in our farms than naturally occuring in that part of the ocean. We will perform simulations of our upwelling activities using an Earth System model with a biogeochemical ocean package in which the C:N ratio is flexible to estimate which percentage of the nutrients used by our aquafarms would be missing somewhere else and in which time scales. 3. We work towards recovering most of the nutrients in our harvested Sargassum to return it back to our aquafarms. These nutrients would have otherwise been sunk to the deep sea and not available for phytoplankton nor sargassum. For now we go with the conservative estimate that any nutrients we upwell are not able to provide food to phytoplankton later on where that water would have naturally upwelled. Bach et al. assumes 31-32% of the CDR done has to be deducted. Assume that we are able to recover 60% of the nutrients in the Sargassum and return it to the farm and only need to upwelling 40% of the nutrients needed via upwelling, then 12% (40% of 31.5%) of our CDR needs to be deducted due to competition with phytoplankton. For our first farm design, most of the Sargassum grew wild with naturally available nutrients. The rest is grown near the coast where human induced eutrophication is often a problem. These extra nutrients which in theory Sargassum is taking away from the phytoplankton or benthic algae are excess nutrients that would not be there in a system without anthropogenic influence. Sargassum presence therefore helps to restore the natural nutrient level, aiding slow growing benthic species such as corals to compete against algae. The impact of this component is more difficult to estimate than the two above, to our best knowledge it will be <0.1 % for the Caribbean operations (This project in TEA). Reference: Bach, Lennart T., et al. "Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt." *Nature communications* 12.1 (2021): 1-10.
Air-Sea gas exchange	Our approach to quantify the air-ocean pCO2 flux is to combine an array of in situ measurements using pCO2 sensors and chambers on buoys, as well as temperature, wind and mixed layer depth measurements that will then inform numerical models. As our farms are moving, the air-sea exchange rate will not be stable but change based on location. Furthermore air-sea exchange rates vary between seasons (Jones et al. 2014).

	The wild Sargassum harvested in the Eastern Caribbean will have traveled last through an area where the time needed for air-sea equilibrium is up to 1 month and previously passed areas where this time is up to 4 months (Bach et al. 2021, Jones et al. 2014). The mixed layer residence time is 0.5-1 month in the area passed just before the Eastern Caribbean and 0-1 month in the area before that (Bach et al. 2021, Jones et al. 2014), which leads to the residence time being between ⅓ to 1 x the time needed for full air-sea exchange. As the air-sea exchange happens linear to the concentration difference of the gas, much more is exchanged at the beginning when this difference is larger. The amount of CO2 exchanged overall follows a natural log scale. Therefore only 8.4% of the gas will not be exchanged if the parcel of water loses contact with the atmosphere after ⅓ of the time needed for full air-sea exchange. This exchange will happen at a later time (on a scale of 1s to 100s of years) but for simplicity we assume that 0-8.4% have to be deducted from the CDR due to insufficient air-sea exchange. The Sargassum grown in the subtropical gyre will be in an area with residence time of 1.5-2.3 months and air-sea exchange rate of 2-7 months which leads to the residence time being 0.2-0.6 of the air exchange time (Jones et al. 2014). 1-22.4% of the gas will not have been exchanged within this time frame and would have to be deducted from the CDR. Due to the fact that sargassum warms the water around it, we expect the mixed layer depth to decrease dramatically within the aquafarms, enabling a faster exchange with the atmosphere during the time the water parcel resides in the aquafarm. Reference: Bach, Lennart T., et al. "Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt." *Nature communications* 12.1 (2021): 1-10. Jones, Daniel C., et al. "Spatial and seasonal variability of the air‐sea equilibration timescale of carbon dioxide." *Global Biogeochemical Cycles* 28.11 (2014): 1163-1178.
Materials	We estimated the embodied emissions of any materials consumed during operation in the cradle-to-grave life cycle assessment (LCA) of the material input. Emissions / removal ratio for materials including consumed materials (Hemp net) and materials to build machines is

	0.01. We therefore estimate this at 1%
Energy	We estimated the emissions of energy consumed during operation in the cradle-to-grave life cycle assessment (LCA) of the material input. Emissions / removal ratio for energy including fuel used for transport and solar energy used for processing is 0.08. We therefore estimate this at 8%
Deep water recirculation	The (carbon) plan website recommends that carbon management takes a conservative assumption that all sunk biomass is remineralized. If the remineralization was instant then 30% of the carbon would still be sequestered after 1000 years (Figure 2 BATS station, 4000 m depth in Siegel et al. 2021). A 70% loss after 1000 years would therefore be the worst case scenario. BATS station is in the Sargasso Sea which has slightly higher sequestration time than our two planned sinking sites (EEZ Barbados or Guadeloupe/Martinique and South Atlantic Gyre) (Fig. 3F in Siegel et al. 2021). We therefore used the BATS site data to make estimates for our sinking sites as they are very comparable. Sargassum has been found intact on the seafloor so we know that instant remineralization does not occur. In the Sargasso Sea, about 0.4 g C m2 yr-1 or roughly 10% of the total particulate organic matter (POM) in the deep-sea carbon pool originates from Sargassum (Rowe and Staresinic, 1979). There, the Sargassum biomass in the deep sea (0.07-3.75 g/m^2) was about 4 times higher than at the surface (0.024 – 0.84 g/m^2), while in the Gulf of Mexico, Sargassum was the most common natural ocean-produced material found in otter trawl surveys of the seafloor (>200 m - ~3000 m depth) (Wei et al. 2012). Camera surveys of the deep sea benthos have found Sargassum clumps of varying sizes and varying degrees of degradation (Rowe and Menzies 1969; 1968; Roper and Brundage 1972), while sediment corers came up with leaves of Sargassum and high concentration of decomposing Sargassum in the sediment (Baker et al. 2018; Grassle and Morse-Porteous 1987). Sargassum clumps were generally well preserved, which indicated either a steady sedimentation rate that replaces degraded materials, or a very slow degradation rate. Both explanations are plausible based on biochemical data, however, the first is more likely as macrofauna are known to feed on Sargassum and presence and traces of them have been found around Sargassum in the deep sea (Baker et al. 2018). Respiration rate measurements done by AWI showed that the processed Sargassum, from which some nutrients have been removed, decomposes slower than fresh Sargassum.

	Furthermore we plan to compact and bale the Sargassum which reduces the surface area exposed to fauna and bacteria greatly compared to naturally sunk Sargassum. Assuming that naturally sunk Sargassum is scattered on a single layer and is exposed both at the top and bottom to fauna and bacteria, a ton of Sargassum would have ~1240 m^2 of area exposed (in house measurement), while a baled ton would only have ~7 m^2 of area exposed. We therefore assume that the baling decreased the remineralization rate by 177 times. As the remineralization rate of natural sinking Sargasssum is unknown we cannot make confident estimates of the remineralization rate of our bales yet. However, by 2024 when we retrieve the first bales from our sinking trial off Bermuda, we will be able to calculate this more accurately. Siegel et al. 2021 shows that a small amount (5%) of the remineralized carbon can recirculate to the atmosphere rather quickly in about 20 years. As it is very likely that parts of our bales will remineralize in 980 years time, we have to assume that we have some carbon lost due to deep water recirculation. In the below example we assume that 10% is remineralized within 1000 years, 1% per 100 years. According to Figure 2 BATS station, 4000 m depth in Siegel et al. 2021: 70% of the 2% released in year 0-200 will be recirculated before year 1000. = 1.4% 60% of the 2% released in year 201-400 will be recirculated = 1.2% 50% of the 1% released in year 401-500 will be recirculated = 0.5% 40% of the 1 % released in year 501-600 will be recirculated= 0.4% 30% of the 1% released in year 601-700 will be recirculated= 0.3% 20% of the 1% released in year 701-800 will be recirculated= 0.2% 10% of the 2% released in year 801-1000 will be recirculated= 0.2% = total of 4.2% of carbon re-emitted to the atmosphere. We do not know if the assumed 1% remineralization rate per 100 years is an accurate assumption, as we do not yet have data on this from the deep sea, it could be highly overestimated or underestimated, however we wanted to show an example of how remineralization and recirculation can work together. We will sink our bales in Q1 of 2023 and measure remineralization after 1 year which will help us to estimate remineralization rate in the first 100 years.

References:

Baker, Philip, et al. "Potential contribution of surface-dwelling Sargassum algae to deep-sea ecosystems in the southern North Atlantic." *Deep Sea Research Part II: Topical Studies in Oceanography* 148 (2018): 21-34.

Grassle, J. Frederick, and Linda S. Morse-Porteous. "Macrofaunal colonization of disturbed deep-sea environments and the structure of deep-sea benthic communities." *Deep Sea Research Part A. Oceanographic Research Papers* 34.12 (1987): 1911-1950.

Rowe, Gilbert T., and Nick Staresinic. "Sources of organic matter to the deep-sea benthos." *Ambio Special Report* (1979): 19-23.

Rowe, Gilbert T., and Robert J. Menzies. "Zonation of large benthic invertebrates in the deep-sea off the Carolinas." *Deep Sea Research and Oceanographic Abstracts*. Vol. 16. No. 5. Elsevier, 1969.

Roper, Clyde FE, and Walter Brundage. "Cirrate octopods with associated deep-sea organisms: new biological data based on deep benthic photographs (Cephalopoda)." (1972).

Siegel, D. A., et al. "Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies." *Environmental Research Letters* 16.10 (2021): 104003.

Wei, Chih-Lin, et al. "Anthropogenic “Litter” and macrophyte detritus in the deep Northern Gulf of Mexico." *Marine pollution bulletin* 64.5 (2012): 966-973.

d. Based on your responses to 4(c), what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

Macroalgae harvest:		1.0%
Leakage:		<0.1%
Surface competition effect:	This project farm	<0.1%
	FOAK, NOAK	12.0%*
Air-Sea exchange:	This project farm:	0-8.4%*
	FOAK, NOAK:	1-22.4%*
Materials:		1.0%**
Energy:		8.0%**
Deep water recirculation:		4.2%*
Total “this project”		**11.4-19.8% = 3.4%-11.8% additional to the LCA**

	uncertainty discount of 7.4% used for cost analysis below
Total FOAK, NOAK	**24.3-45.7%**

*High uncertainties
**Already included in LCA

e. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

> Our project will work towards reducing the major uncertainties faced by our CDR pathway: air-sea gas exchange, deep water recirculation, and surface competition effect. The planned deep sea environmental assessment will determine if and how fast Sargassum is being remineralized. We hope to gain insights on the air-sea gas exchange by monitoring the pCO2, DIC and alkalinity levels of the water within and outside our farms as well as pCO2 in the atmosphere just above our farms. We are also collecting fine scale temperature depth transects to determine the mix layer depth as well as temperature of the surface water which together with the wind data we collect can help us to model the gas exchange happening in our mats. We will work with an experienced Earth System Modeler (Matt Long from NCAR) to develop a numeric model that estimates how the gas exchange progresses once the water parcels move away from our farm. Furthermore, we will assess the phytoplankton diversity and abundance inside and outside our farm to determine if there is a reduction or increase due to our aquafarming activities. We will also devote a good amount of time in 2023 measuring Sargassum growth rates in our floating farm while it traverses different environments in order to better estimate growth and harvest rates.

f. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

> We are working with one of the most respected firms in the UK for developing projects, CO2 Balance. We would either work with Gold Standard or Verra, and are in discussions with JustCarbon, which is in the early stages of introducing a new, dedicated pathway for verifying blue carbon projects, which will leverage Web3 technologies to make the process more efficient, and achieve verification sooner.
>
> We are fortunate to have Adrian Rimmer as a founding Seafields shareholder. A climate markets veteran, Adrian ran the Gold Standard as CEO for five years (amongst other high-profile roles). Adrian is guiding us to ensure our project moves quickly on its verification journey, supported by Dr Mar Fernandez-Mendez, our lead scientist, who is ensuring we adhere to the highest science-based standards.

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a. What is the levelized price per net metric tonne of CO_2 removed for the project you're proposing Frontier purchase from? This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

$246/ton This does include the uncertainty discount from 4d

b. Please break out the components of this levelized price per metric tonne.

Component	Levelized price of net CDR for this project ($/tonne)
Capex	316 USD
Opex (excluding measurement)	409 USD
Quantification of net removal (field measurements, modeling, etc.)[2]	30 USD
Third party verification and registry fees (if applicable)	5 USD
Income from beach prevention service and biostimulant sales	0 to 1´051 USD
Margin	-514 to + 537 USD
Total	246 USD

c. Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified in 1(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of $100/tonne?

[2] This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

Parameter with high impact on cost	Current value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Pipe cost (due to manufacturing efficiency)	1,600,000 USD	80´000 USD	The first assembly will be built by hand -made by a speciality engineering shop with a cost structure from the oil gas drilling industry. Depending on the number made and the method of manufacturing Seafields could see a reduction more than 95% by the 10,000th unit. Increased diameters could greatly increase efficiency. However, the number of companies capable of 10 m diameter tubes are very select and all are from aerospace and defense with experience in very expensive materials and metals.
Aquafarm barrier cost (due to manufacturing efficiency)	232,5 USD per m	111 USD per m (XPRIZE submission estimate for Mt farm)	Manufacturing efficiency will increase and lead to a decrease in price First barrier is bespoke in Europe. Much of the manufacturing cost reduction will be driven by the deep sea fish cages being deployed by Norway (eg. Sintef) and China.
Harvest costs (due on size of harvesting vessel)	400 USD/ton (based on TEA spreadsheet)	12 USD/ton (based on cost assumptions done at Mt scale for XPRIZE when cargo ships are used for harvest and processing)	Currently the harvesting set up (500 m barrier and 2 aquadrones) is quite cost intensive due to the small scale. However it has an added benefit of beach protection from Sargassum which hotels currently pay thousands of dollars for (https://www.nationalgeographic.com/travel/article/can-science-solve-the-seaweed-problem-on-mexican-beaches), so the current costs do not need to be beared by Seafields alone. Once we work in the free floating aqua farms, no additional barrier is needed for harvesting. Furthermore, RanMarine is working on larger models of their aquadrones that will be more cost efficient. Later on we can also move to harvest from larger vessels that are both harvest and processing vessels.

d. What aspects of your cost analysis are you least confident in?

> The cost of building the upwelling pipes. Since we are still in the modeling and testing phase, the design of the pipes might change, leading to dramatic changes in cost per unit. Also, new technologies (eg 3D printing with sargassum derived materials) might also drop the price considerably.
>
> Importation and setup equipment into the Caribbean can be challenging. Customs, duty, use of foreign experts can be tricky and last minute, Best estimates were applied but until processing is contracted Seafields could experience last minute cost. It should be noted Seafields has excellent relations with St. Vincent's government. Our staff is international with extensive experience in working successfully with host countries.

e. How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

> Seafields models were within 3% to 5% of the TEA results. It was prepared blind.

f. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

> Novel off-shore infrastructure construction machinery (eg. 3D printing to produce our upwelling pipes in modules that can be assembled in situ).

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a. Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

> Currently, our key external stakeholders are scientists, researchers and people in the marine business and oceans policy community, and companies and NGOs involved in Sargassum collection and processing in the Caribbean, including Carbonwave (www.CarbonWave.com), the second largest processor of Sargassum, with a processing plants in Mexico and a research facility in Puerto Rico, in which some Seafields founders have an ownership share. We are also engaged with local communities and governments in our areas of testing (see below). As we mature and operationalize, we expect to more deeply engage with local communities, coastal governments, carbon and Sargassum purchasers (including the digital carbon purchase platform JustCarbon- www.JustCarbon.com - in which Seafield's founders are also shareholders).
>
> We identify stakeholders at conferences (presenters, networking) through the teams personal and professional network (see below for examples of networks we belong to). We also monitor scientific publications, newspaper articles, newsletters of relevant organizations and NGOs, winners of accelerator events and prices, as well as social media posts and learn of new stakeholders through these channels. We use google alerts for weekly updates on news articles in our field and follow hashtags that are relevant to us on social media.
>
> Seafields is part of a broad coalition of scientists and practitioners working with guidance from Ocean Visions, a collaborative research incubator for ocean CDR, which is sponsoring us to compete for the XPRIZE. We are an active member of a number of Ocean Visions Working Groups, and especially active on the macroalgae Sinking Working Group exploring the full range of implications for environmental MRV.
>
> We have constituted a Scientific Advisory Committee composed of preeminent experts in the fields of marine chemistry, biology and ecosystems attached to leading research organizations and universities around the world, including GEOMAR Helmholtz Center for ocean research Kiel, MIT, Woods Hole, University of Greenwich, Universidad nacional Autonoma de Mexico, NCAR, and the Alfred Wegener Institute for Polar and Marine Research.
>
> We have also formally enlisted a group of high level advisors from the United Nations (UNDP), government (Kenya), business (World Ocean Council, Wood. Plc), civil society (Climate Champions, Sustainable Seas) and the research community to help guide us on both commercial and social and environmental justice considerations.
>
> The names of our Science and Seafields advisors can be found on our website (https://www.seafields.eco/)

b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's community engagement and governance approach as an example and Arnestein's Ladder of Citizen Participation for a framework on community input.*

At the ground level, we are consulting with the relevant government bodies involved (Ministries of Environment, Fisheries, etc) as well as local business and civil society relevant to the environment and fisheries. For our Caribbean operations we will employ local staff for logistics, harvesting, processing and administration. This will generate jobs on many Eastern Caribbean islands. For our demonstration farm, we will have an on-shore logistical support system in St Helena and South Africa which will employ local staff. Since Seafields is a UK-based company we expect the relationships with St. Helena to be a good one. For our scale-up towards 1Gt, we envision that on-shore facilities in Africa will provide the bulk of production and logistical support needed.

Our scientific project manager is also the executive producer and co-host of the The Sargassum Podcast https://www.youtube.com/channel/UCZreM59YNCzlmC7Zdra2PXg. As such she has interviewed over 50 stakeholders involved in the challenges and opportunities around Sargassum. The knowledge she gains through these conversations guides us on the views and aspirations of stakeholders, and the knowledge shared through the podcast will continue to enhance interaction and exchange.

We engage regularly with marine scientists and marine engineers through our scientific advisors and the advisors we are paired with as part of the Ocean Visions launchpad. We plan to attend and present at several scientific conferences including the 2023 Ocean Visions biannual summit and Caribbean focussed scientific conferences such as the AMLC or GCFI. Our scientific project leader is an officer of the Association of Marine Laboratories of the Caribbean and uses that association to interact with marine scientists from the Caribbean. In addition, our scientific advisors currently supervise Masters Students from Cape Verde, where the upwelling pipe tests will take place.

We are active members of the United Nations Global Compact Safe Seaweed Coalition, the sustainability focused World Ocean Council, and the US based Carbon Business Council. We have been actively engaged in the UNFCCC COP 26, where we launched. This year we were invited to speak at the Frontier Ocean conference in Halifax and the UN Ocean Conference in Lisbon, and will have speaking roles at the October Ocean Sustainability discussions of the World Ocean Council as well as at COP 27 in Egypt.

Finally, we have been invited as guests on several podcasts (.e.g Carbon market Nori, This is CDR, SPRIN-D Podcast, The Ocean Embassy) and, in addition to the above, have given talks on ocean CDR and Sargassum at a number of scientific and non-scientific conferences and events (e.g. Seaweed around the clock, Seagriculture 2022, UK Environment, Open Air this is CDR).

c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

From the podcast interviews and engagements with Caribbean stakeholders we gained extensive insights on the impacts of Sargassum on communities, economies and ecosystems and we've learned from entrepreneurs about the various challenges they face in valorizing Sargassum.

Our engagement in the macroalgae sinking working group from Ocean Visions continues to give us detailed insights on the rigor scientists agree on that is required for deep sea environmental impact assessment.

Ocean Visions contracted communication experts to evaluate various approaches on messaging around ocean CDR and shared with us that messages delivered by scientists as well as those that tell personal journeys are best perceived by CDR skeptics as well as policy makers and ocean leaders.

Overall, we are continually surprised and heartened by the enthusiasm for our mission from laypeople and experts alike, and find that an active programme of public and private engagement, grounded in science, will sustain support and lead us to achieve our objectives

d. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

As ocean CDR and interest in biomass sequestration grows in the scientific, commercial and policy communities, we envision our engagements across the board to significantly increase. We are particularly interested in expanding our research and large marine business partnerships in order to tackle implementation of our farms at 1 Gt scale. Toward this end, we are already adding experts in these sectors, as well as in biodiversity and food security, to our Seafields Advisors group.

7. Environmental Justice[3]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

Our primary Environmental Justice consideration is to contribute to transformative economic empowerment and food security in the Caribbean, Subsaharan Africa and elsewhere in the Global South. Our long-term 1 Gt sequestration plan envisions the creation of sustainable ocean platforms that support Sargassum growth and CO_2 retirement as well as an abundance of sea life for processing, enhancing food security and promoting livelihoods. While our operations will be far from the coast, and therefore interfere very little with other ocean uses, we will consult the voices of coastal communities and integrate them in decisions that could impact them. We will of course work closely with the ocean fisheries and marine biodiversity communities on proper environmental stewardship.

[3] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

See above

8. Legal and Regulatory Compliance

a. What legal opinions, if any, have you received regarding deployment of your solution?

We are working to ensure that our activities conform to the United Nations Law of the Sea (UNCLOS), the emerging Biodiversity Beyond Jurisdiction legislation, the London Protocol, the Biodiversity Convention, other international laws and an expected Ocean CDR Code of Conduct being developed with Woods Hole, the American Geophysical Union and others. We are drafting a document together with world renowned environmental and marine law expert, Tanya Brodie Rudolph (provided to us by Ocean Visions), to track and ensure that we abide by current and emerging legal and regulatory frameworks.

b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

Obtained: permit to test farm in St Vincent and the Grenadines
Working under partner´s permits for Sargassum collection in Mexico

Working on obtaining permit for drifting of our farm into St. Lucia EEZ for the 5-10 day drift test
Working on obtaining permit for sinking of Sargassum in Bermuda EEZ for Environmental Impact Assessment

Will need to obtain permits for sinking of Sargassum in Guadeloupe EEZ or Barbados EEZ for sinking of Sargassum collected in St Vincent and the Grenadines during our early farm operations.
Will need to obtain permits for Sargassum collection in the waters of St. Vincent and the Grenadines and other Eastern Caribbean states.
Discussing permitting to work off-shore of St Helena and Capo Verde

c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

See above

d. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

See above

e. Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

We are receiving UK R&D tax credits. However, we don't believe this conflicts with advance market purchases since this is a form of state aid that's not specific to the activities we are completing around verification and carbon removal.

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

Proposed CDR over the project lifetime (tonnes) *(should be net volume after taking into account the uncertainty discount proposed in 4(c))*	2´032 tons of CO2
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	September 2026
Levelized Price ($/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	246 $/metric tonne CO_2 Wherever possible we will work in places where fresh Sargassum is already collected from the beach by hotels and we can take fresh Sargassum from them free of cost (Carbonwave business model that works in Mexico) or we will install a beach prevention unit (barrier) and charge hotels fully or partially the cost of prevented beaching. The cost dedicated to beach prevention in our TEA is 488USD per ton of CO_2. The water extracted from the screw press can be turned into biostimulant, a product that is currently sold with profit by our partner Carbonwave. They are happy to take the biostimulant we produce and sell it. We would receive around 562 USD from biostimulant production per ton of

	Sargassum if we could sell all of it to them. Both of these income streams are potential and not locked in. However we believe that we can get a part of that income secured and therefore can offer Frontier our sequestered carbon at a price way below the cost in the TEA. Please see our confidential supplement labelled “the Big picture” for more information.

Application Supplement: Biomass

(Only fill out this supplement if it applies to you)

Feedstock and Physical Footprint

1. What type(s) of biomass does your project rely on?

Our project will grow and harvest *Sargassum fluitans* and *natans,* free-floating fast-growing seaweed species which reproduce by fragmentation. Unlike kelp, they do not require complicated hatchery/nurseries nor expensive substrate to grow on. Our own research and the research of others has demonstrated a doubling rate of 8-23 days in mesocosms in the laboratory. In addition, Sargassum has a very high carbon to nitrogen ratio (average C:N 34.5 Lapointe et al. 2021), making it extremely efficient at sequestering carbon per unit of nitrogen compared to phytoplankton (C:N 6-12).

2. How is the biomass grown (e.g., kelp) or sourced (e.g., waste corn stover)? Do you have supply agreements established?

For our first aquafarm design (This Project in TEA) that does not have extra fertilization from artificial upwelling pipes, we will regularly obtain seed biomass from Sargassum mats that would otherwise beach and decompose so that the Sargassum we grow is additional to what happens in nature. The natural and human enhanced nutrient flux around the island of St Vincent should be able to support a 1-3 week doubling rate. When huge amounts of wild Sargassum are threatening to beach at the island or closer by landmassess in the Caribbean, we will also harvest it, process it and sink it.

For our later aquafarm design with artificial upwelling pipes (FOAK), the additional upwelling of nutrients will lead to additional growth that would not be possible otherwise in the oligotrophic subtropical gyre. A seed population will be harvested from the Great Atlantic Sargassum Belt and brought there.

Sargassum is found across the subtropical Atlantic and no supply agreement is needed, however for this Project we will obtain a collection permit of the country where collection will occur (e.g. St Vincent and the Grenadines). The Sargassum will be grown in stationary (This project) or free floating aqua farms (FOAK). Our recent tests of a pilot aquafarm barrier demonstrated that it effectively contains Sargassum even in difficult seas. We are currently improving the design to increase the surface area inside the barrier under cross wind conditions. Our monitoring technologies (GPS and drones equipped with sensors) can track and relocate our farms even under tough conditions.

3. Describe the logistics of collecting your waste biomass, including transport. How much carbon emissions are associated with these logistics, and how much does it cost? How do you envision this to evolve with scale?

Since 2011, several solutions for collection of Sargassum at sea have been developed to address the inundations in the Caribbean and West Africa. We are in contact with several companies and are evaluating which of these collection methods would work in the open ocean and be most energy and cost efficient. Most solutions posited are for small boats (<6 meters) or even smaller aquadrones or devices that can be attached to the barrier. For the St Vincent project (This project in TEA) we are in contact with the company RanMarine to provide us 2 Megashark aquadrones for harvesting Sargassum in the wild and in our aquafarms. Then the wet biomass will be transported a short distance (up to 40 km) to the processing facility on land. Transport will either occur via trucks or boats. The CO_2 emissions of the harvest and transport are equal to 6.6% of the CO_2 sequestered. The costs for this part of the operation is 488 USD per ton.

As we scale up the FOAK offshore farm to multiple NOAK farms, we will be able to also scale up the harvesting and processing vessels, potentially to the size of a container ship. As we scale up we envision linking several aquafarms together and then the vessel can stay with a farm complex, which would result in significant CO_2 emissions savings compared to fielding many small harvesting vessels. Our farms will drift the 4000 m abyssal plain in the southern Atlantic inside the gyre, we therefore do not need to transport the baled sargassum to the deep sea depos. Based on the research we are currently pursuing, we are developing ways to transform part of the harvested Sargassum into engineering bioplastics to build the aquafarming infrastructure with it, as well as producing biogas from anaerobic digestion of the sargassum biomass in situ that could fuel our vessels. This will all contribute to lower even more the operations-related emissions.

4. Please fill out the table below regarding your feedstock's physical footprint. If you don't know (e.g. you procure your biomass from a seller who doesn't communicate their land use), indicate that in the table.

	Area of land or sea (km^2) in 2022	**Competing/existing project area use (if applicable)**
Feedstock cultivation	0,007318 km^2 of sea per FOAK farm. Area taken up by aquafarm and standing stock as well as daily growth of Sargassum within it.	None. We will locate the farm in the south Atlantic subtropical gyre which is not frequented by shipping and where natural nutrient levels are low and therefore very little phytoplankton grows. This makes it not attractive for fisheries.
	0.007161 km^2 of sea for stationary farm(s) in St. Vincent and the Grenadines and 500 m of barrier with a band of Sargassum several meters deep for wild harvest (e.g. 0.005	We will work with the local community and government to find locations for the stationary farms that are not competing with other uses. Same for the Sargassum barriers, which are seen as a positive addition

	km2). This is for the "this project" stage costed out in the TEA.	by the local communities due to beaching prevention during Sargassum season.
Processing	0.0002 km^2 of sea per FOAK farm. Area taken up by the processing and harvesting ship. 0.01 km^2 of land for the "this project" stage costed out in the TEA.	None. We will locate the farm in an area that is not frequented by shipping and where natural nutrient levels are low and therefore very little phytoplankton grows. This makes it not attractive for fisheries. We will work with the local community and government to find locations for the processing facility that do not compete with other uses (eg. Unused Hall in Ottley Hall Marina, St. Vincent).
Long-term Storage	0.000531 km^2 of abyssal plain per FOAK farm per year. 531 m^3 of sargassum will be sunk per year. 0.00225 km^2 of abyssal plain per year for "this project" farm. 2250 m^3 of sargassum will be sunk per year. Area was calculated assuming that these are bales that are 1 m high and none of them are stacked. However the final area might be much lower since the bales will probably be stacked.	None. The abyssal plain is currently not used by humans. We will make sure to avoid sinking in known hydrothermal activity areas along the Mid Atlantic Ridge.

Capacity

5. How much CDR is feasible globally per year using the biomass you identified in question 1 above? Please include a reference to support this potential capacity.

227´890 km^2 are suited for Sargassum growth naturally according to the present temperature and nutrient concentrations (Gouvêa et al. 2020). If that entire area was covered in Sargassum at a density

of 3.34 kg/m^2 (Wang et al 2018) and has a growth rate of 14 days doubling rate, this would lead to 2.4 Gt of CO_2 sequestered per year, more conservative than the calculations of Gouvêa et al. (2020).

We plan to grow Sargassum using artificial upwelling in areas currently not suited for its growth, thus expanding the suitable area for growth. We identified an area inside the south atlantic gyre that is not traversed by major shipping routes, it is 1,200,000 km^2 large and if completely filled with Sargassum could sequester 12.7 Gt of CO_2 per year. This is of course a maximum estimate and we plan to upscale to about 1 Gt of CO_2.

References

Gouvêa, Lidiane P., et al. "Golden carbon of Sargassum forests revealed as an opportunity for climate change mitigation." *Science of The Total Environment* 729 (2020): 138745.

Wang, Mengqiu, et al. "Remote sensing of Sargassum biomass, nutrients, and pigments." *Geophysical Research Letters* 45.22 (2018): 12-359.

Additionality and Ecosystem Impacts

6. What are applications/sectors your biomass feedstock could be used for other than CDR? (i.e., what is the counterfactual fate of the biomass feedstock)

Sargassum can be used for alginates, activated carbon, energy production, fertilizer, growth medium for mushrooms, compost, feed for animals, fucoidan, bioactive secondary metabolites, paper/cardboard, biodegradable single use plates, soap, shoes, and clay bricks (Desrochers et al. 2020). Despite the many uses for Sargassum, currently most of the Sargassum biomass collected ends up in landfills. There are locations (e.g. St. Johns, USVI) where they struggle to find the space on their island for the large landfill needed for Sargassum. The only industrial scale valorization of Sargassum processes is currently using up to 60 t a day (https://d1softballnews.com/the-potential-of-sargassum-when-the-great-problem-of-the-caribbean-becomes-a-raw-material-future-america/).
Further large scale applications have not yet emerged due to limited knowledge on how to turn these specific Sargassum species into products and the high variability of Sargassum feedstock available (in time, quantity and quality). Sargassum also has biosorption properties binding toxic metals affecting food related products, as well as high ash content leading to low energy yields for biofuels (Amador-Castro et al 2021). Carbon sequestration of beach avoided Sargassum in the Caribbean has been shown to be cost effective (Gray et al. 2021) however has not yet been put in practise due to the high costs for environmental impact assessments and accreditation by verfiers (pers. communications by authors of the above paper). Many governments (Guadeloupe/Martinique, USVI) are interested in exploring the possibility of sinking Sargassum to the deep sea since they are lacking the space on land to process or store the seaweed. Thus, permitting should not be a hurdle but they insist on rigorous environmental impact assessments. The development of bioethanol for long-term engineering plastic from Sargassum (currently investigated in the C-CAUSE project funded by SPRIN-D and supported by BASF) could nucleate a value chain that would feed the chemical industry with this renewable

feedstock. Globally the chemical industry will require 2Gt of biomass feedstock to substitute fossil fuel derived products.

7. There are many potential uses for waste biomass, including avoiding emissions and various other approaches to CDR. What are the merits and advantages of your proposed approach in comparison to the alternatives?

Our approach includes other uses prior to sinking Sargassum for CDR. During processing of our bales, 65% of the wet weight of the biomass is extracted as liquid that can be used as biostimulant to enhance plant growth on land and substitute fossil-fuel derived fertilizers.

Together with our partners Carbonwave and BASF, we are developing a process that produces bio ethanol from Sargassum fermentation for engineering plastic (C-CAUSE Project funded by SPRIN-D). As the bioplastic is 100% algae derived, it could potentially be sunk at the end of its lifetime. We do not see competition between other uses and CDR due to the scale that Sargassum could be farmed in the open ocean. Instead we are looking for ways to combine as many uses as possible with our sinking Sargassum CDR approach.

As we scale up to 1 Gt of CO_2 sequestration per year, we will produce so much Sargassum that turning all of it into products would oversaturate the market for some of those products (eg. biostimulant). Once open ocean sargassum aquafarming is running, our business model will probably have diverse incomes depending on how the different markets evolve (eg. feedstock for bioethanol vs feedstock for biostimulant and CDR). There is plenty of space to grow enough Sargassum for CDR and enough for other uses. What percentage of the produced biomass of Sargassum will go to each pathway will depend on the price in the market.

8. We recognize that both biomass production (i.e., growing kelp) and biomass storage (i.e., sinking in the ocean) can have complex interactions with ecological, social, and economic systems. What are the specific, potential negative impacts (or important unknowns) you have identified, and what are your specific plans for mitigating those impacts (or resolving the unknowns)?

Ocean Visions identified the following potential negative impacts: Large-scale algae cultivation operations could lead to enhanced diseases and parasites, alternation of population genetics, introduction of non native species into new environments, release of large quantities of halocarbons and other trace gasses, changes in light and nutrient availability, enhanced in epiphytic calcifiers and additional noise pollution from vessels and machinery (Campbell et al 2019).

Sargassum is a native free-floating macroalgae growing naturally across large areas of the subtropical Atlantic, we are therefore not introducing a non-native species and do not foresee enhanced diseases and parasites due to the size of the farms.

Some seaweeds produce halocarbons which are potent greenhouse gasses. In natural sargassum this has not been observed (Mithoo-Singh et al. , 2017). We will perform some laboratory incubations to check whether our Sargassum species emit short-lived halocarbons under the conditions we are growing it.

Regarding the calcification feedback, our preliminary results show that this effect was exaggerated by Bach et al. (2021) and our PIC:POC ratios are well below what they assume in their back of the envelope calculations. Therefore, as shown in the LCA table, we don't expect this to be a feedback of major concern. Regardless, we will measure the amount of PIC produced by epiphytic calcifiers and deduct the CO_2 released by them from our captured CO_2 as seen in our LCA.

For the initial aquafarms (This project in TEA) close to St Vincent, the barriers that intercept the wild sargassum about to beach will be held to the seafloor with moorings. Our harvesting activities will be dynamic and fast avoiding the sargassum to accumulate at the barriers preventing light from penetrating the coastal waters and damaging seagrass or other coastal ecosystems. We will locate our "catch and grow farms" above seafloor that does not contain seagrasses or coral reefs to avoid negative effects of them on the benthos. By preventing sargassum stranding and decomposing on the beach and creating brown tides we are avoiding several environmental impacts to coastal ecosystems as described in Van Tussenbroek et al. (2017).

Based on the observations of natural Sargassum mats dominated by the same two species that we are planning to cultivate, Sargassum is a habitat to diverse marine species. We know from our contacts with local fishermen and the literature that Sargassum mats are a productive fish nursery habitat and that several crustacean species can be found living in them. We are also quantifying the bycatch from different harvesting methods in collaboration with UNAM and will make sure we take measures to reduce this to almost zero.

We will actively work towards keeping noise pollution to a minimum, for example by using electric aquadrones instead of diesel boats for collection.

Also, the use of a barrier could lead to entanglement of marine megafauna. Our free floating and flexible barrier makes this unlikely and we continue monitoring this as we test.

As we upwell deep water, there is the risk of potential CO2 outgassing (Pan et al., 2016). However, sargassum uses up more carbon per unit of nitrogen (C:N ratio higher than Redfield) than is supplied by the upwelled water and likely will use up all the carbon that is upwelled leading to no outgassing of CO2. We will monitor the pCO2 levels of the water and the air both at day and night to identify any outgassing events and if these happen will discontinue upwelling or find a way to upwell that does not lead to outgassing. Other potential negative effects of artificial upwelling such as the ones described in Oschleis et al. 2010 do not apply to our approach since the water we bring to the surface is warmed on its way up. In addition, through the Stommel counter pipe we are downwelling oxygen rich water to 350 m depth avoiding the formation of anoxic zones below our farms.

Both in our anchored and in our free-floating farms as well as in our deep sea depos we will monitor the basic parameters to assess the potential negative impacts. For the water column biogeochemistry we will monitor pCO2, pH, temperature, salinity, light, oxygen, nitrate and Chlorophyll a fluorescence. For this we count with a CTD with a suit of sensors and Hobo-loggers for light and temperature. In addition we have underwater cameras attached to the barrier to visually monitor the animals approaching the barrier, to assess risk of entanglement. In the deep sea we will visually monitor 1 bale per deposition site for 6 years (retrieving information every two years) and the oxygen concentrations surrounding the bale at the same temporal resolution. We will invite independent research scientists to take samples both at the surface and in the deep sea to assess the more detailed parameters such as the macro and micro flora and fauna associated with our farms, as well as the potential release of other gasses (eg. methane, halocarbons) either in situ or in lab experiments.

All these in situ data will be used to parameterize local models to predict downstream effects of our farms. We are also collaborating with AWI and NCAR to estimate the potential of large scale implementation of Sargassum aquafarms for CDR as well as estimating the real nutrient reallocation effect that could be caused by artificial upwelling using the eVic earth System Model from Wu et al. 2022. This recent study already showed that open ocean macroalgae farms combined with artificial upwelling could contribute to sequestering 5Gt per year.

References

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Mithoo-Singh, Paramjeet Kaur, et al. "Halocarbon emissions by selected tropical seaweeds: species-specific and compound-specific responses under changing pH." *PeerJ* 5 (2017): e2918.

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Van Tussenbroek, Brigitta I., et al. "Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities." *Marine pollution bulletin* 122.1-2 (2017): 272-281.

Application Supplement: Ocean

(Only fill out this supplement if it applies to you)

Physical Footprint

1. Describe the geography of your deployment, its relationship to coastlines, shipping channels, other human or animal activity, etc.

> The deployment of the first moored standing stock and the prevention of beachings is planned in St. Vincent and the Grenadines with sinking in the EEZ of Barbados or Guadeloupe (Fig. 6). This model can be expanded to other islands in the Eastern Caribbean. Due to its location and the direction of the currents passing by the Eastern Caribbean, it is strategically placed to catch Sargassum and prevent it from entering the wider Caribbean area and beaches. Furthermore there are areas with sufficient depth within the EEZ of Eastern Caribbean nations.
>
> During our first trial on St. Vincent, we familiarized ourselves with the island, interacted with stakeholders and identified partners. We also learned about possible challenges such as fishing areas, boat traffic and currents. Approvals for further trials have been obtained by the government of St. Vincent and work is continuing.
>
> For the open ocean operations (FOAK), our free-floating barriers will be placed in the oligotrophic South Atlantic Gyre; its rotating currents will keep our free floating farms in a limited area. Large areas of the gyre have little shipping traffic, while the entire gyre has sufficient depth to sink Sargassum to the abyssal plain. Furthermore it is not frequented by whales on their migration routes (Fig. 7).

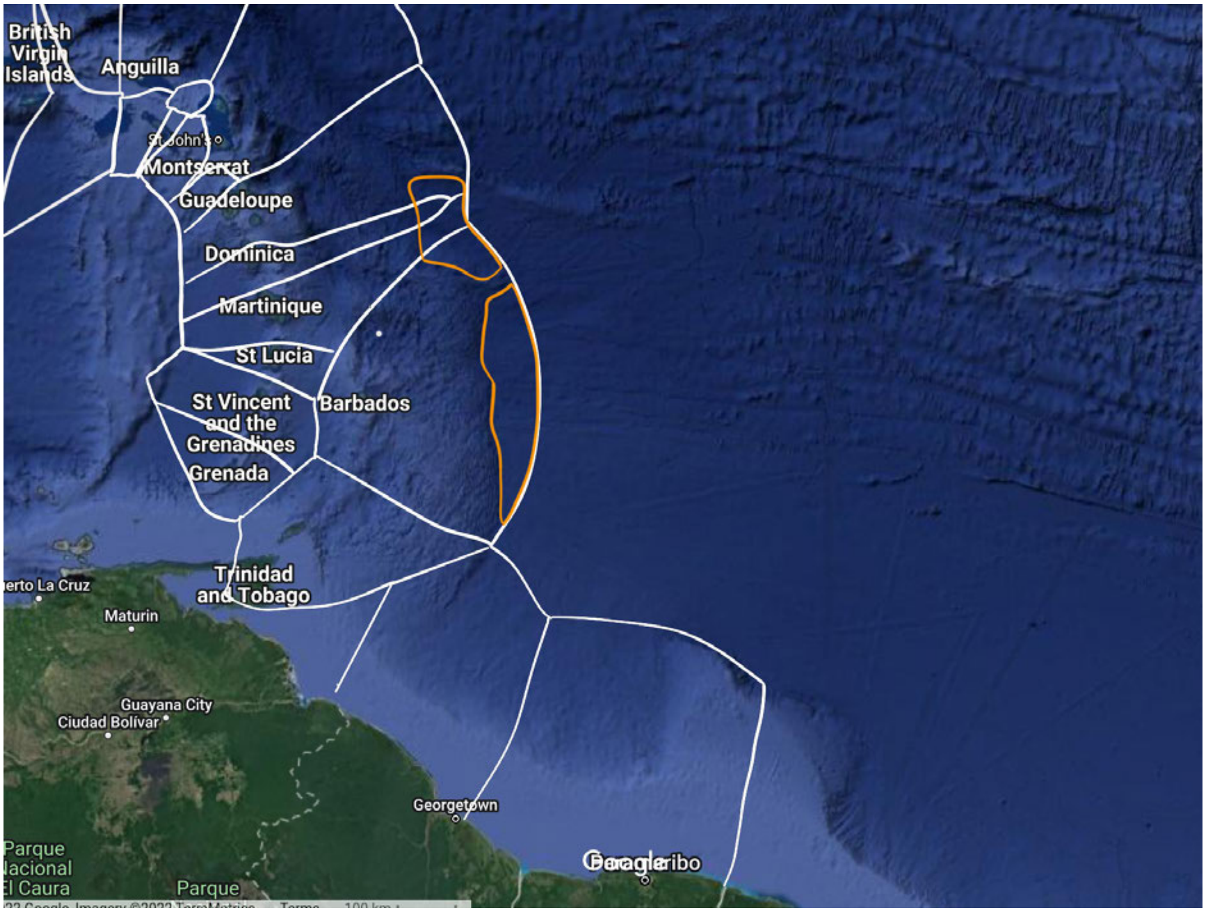

Fig. 6 Eastern Caribbean and Northern South America. Exclusive Economic Zones (EEZ) are outlined in white. Area suited for sinking Sargassum to the abyssal plain in the Barbados and the Guadeloupe and Martinique EEZ are outlined in orange.

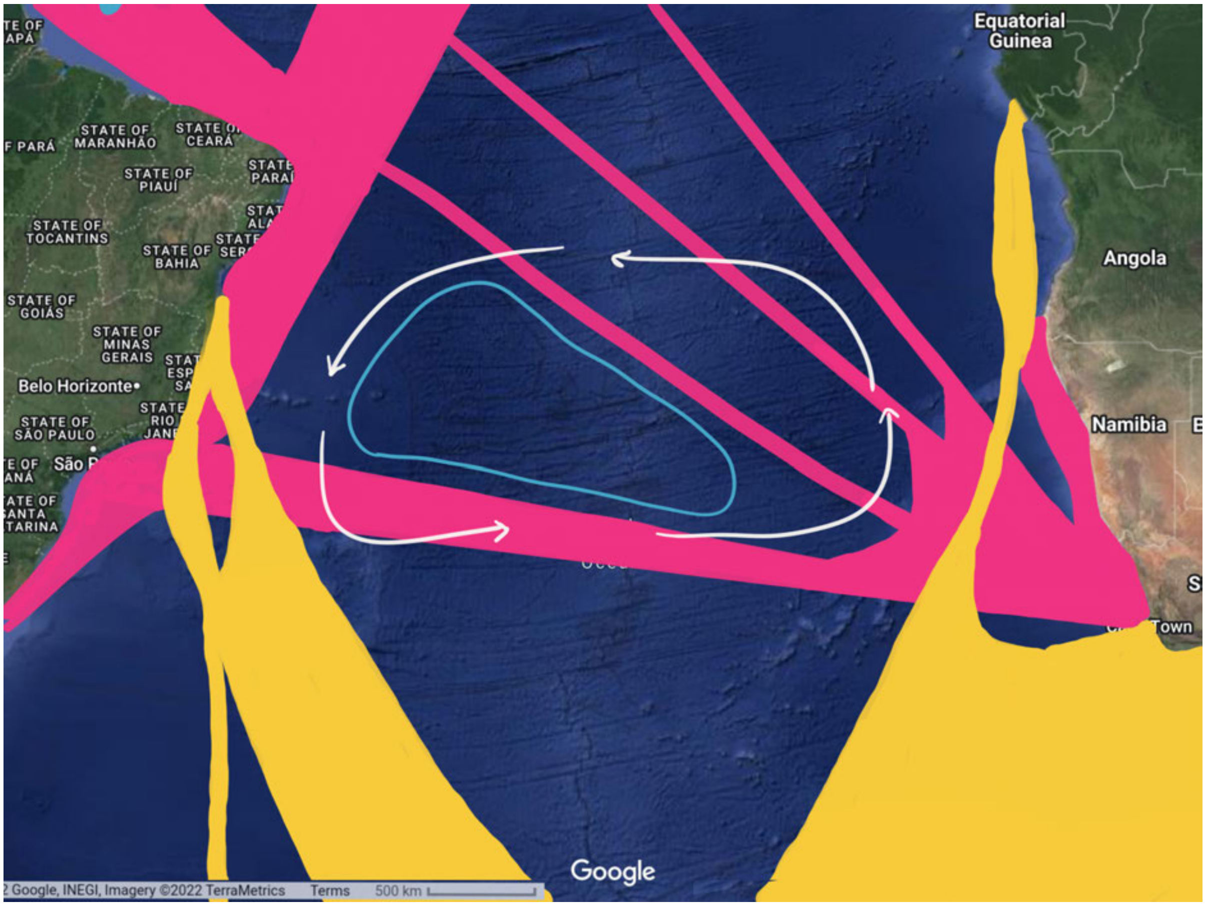

Fig. 7 South Atlantic Gyre. Currency surrounding the gyre are shown in white, major shipping routes are in pink, whale migration in yellow. area of deployment of farm is outlined in blue.

2. Please describe your physical footprint in detail. Consider surface area, depth, expected interaction with ocean currents and upwelling/downwelling processes, etc.
    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

N/A

3. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO_2/yr. Please project your footprint at that scale, considering the same attributes you did above (we recognize this has significant uncertainty, feel free to provide ranges and a brief description).
    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

100 Mt of CO_2 per year corresponds to harvesting 546 Mt of Sargassum per year, which is a daily harvest of about 1.5 Mt tons. This needs a standing stock of 30 Mt tons which together with the daily harvest takes up 9431 km2 at 3.34 kg/m^2 (3340 metric tons per km^2).

Potential to Scale

4. Building large systems on or in the ocean is hard. What are your core engineering challenges and constraints (not covered already within 1(n)? Is there any historical precedent for the work you propose?

Deploying and maintaining free-floating barriers in the ocean is full of challenges. We are currently working towards redesigning the free-floating barrier system so that it doesn't collapse when wind and current go in opposite directions. This first prototype is very successful in containing sargassum and avoiding entanglement with marine life (data from 3 weeks of deployment).

To scale up sargassum aquafarms the main engineering challenge is to design a Stommel pipe that provides enough nutrient rich water to the surface and has a manufacturing cost of no more than 1.6m USD for the FOAK. We are investigating the performance of different configurations and materials through modeling. In collaboration with GEOMAR we will construct and deploy the first prototype (1/15 scale) in a pool system. Once the principle has been proven and the upwelling rates predicted by the model are confirmed, we will move ahead to perform the feasibility study for the construction of the 400m counter pipe.

Maruyama et al. (2011) tried to construct and test a similar pipe, however they had a flexible single pipe which led to very low upwelling rates. We are working to improve this by putting several inner pipes that enhance heat transfer and therefore the upwelling rate. We are confident that we can obtain 360 m^3/h and we are working to enhance this to 1000 m^3/h. For the construction and deployment we need to think outside of the box and use novel technologies such as 3D printing to build the pipe in a modular way so that it can be transported and assembled in situ.

Another big challenge that we foresee is biofouling. We are in contact with a startup that claims to have developed a new coating that is non-toxic to marine life and prevents biofouling. We are also learning from the OTEC industry who use a more pragmatic approach by closing one pipe and letting it become anoxic so that everything in there dies.

Maintaining the location of a free floating farm complex will depend upon how the gyre holds the farm together and how we link each Sargassum field. We will be tracking and monitoring weather and currents from satellite data to most efficiently relocate farms when necessary.

Reference:

Maruyama, Shigenao, et al. "Evidences of increasing primary production in the ocean by Stommel's perpetual salt fountain." *Deep Sea Research Part I: Oceanographic Research Papers* 58.5 (2011): 567-574.

Externalities and Ecosystem Impacts

5. What are potential negative impacts of your approach on ocean ecosystems?

> See answer to question 8 in Biomass supplement
>
> In general we do not expect harmful ecosystem impacts that would be worse than not acting to solve the climate crisis. We need to remove CO2 from the atmosphere, because if we don´t, the deep sea will become anoxic and the upper ocean will lose its productivity due to enhanced thermal stratification. Our vision to green the ocean deserts will contribute to heal the ocean and make it more productive and biodiverse.

6. How will you mitigate the potential for negative ecosystem impacts (e.g., eutrophication and alkalinity/pH)? How will you quantify and monitor the impact of your solution on ocean ecosystems and organisms?

> See answer to question 8 in biomass section.
>
> We work closely with independent scientific institutions and we will follow their recommendations on this respect.