Offshore cultivation of seaweeds to capture CO_2 and alleviate global changes: a feasibility analysis for the Israeli Mediterranean Sea

Álvaro Israel[1], Leor Korzen[1], Assaf Ariel[2], Ruslana Rachel Palatnik[3], Dor Hertzenstein[3], Itamar Avishay[2]

[1] Israel Oceanographic & Limnological Research, Tel Shikmona, Haifa 3109701, Israel

[2] Eco Ocean, Kefar HaNoar Hadassah Neurim, Beit Yanai, 40298, Israel

[3]The Max Stern Yezreel Valley College, Israel; NRERC- Natural Resource and Environmental Research Center, University of Haifa, Israel

The creation of this report was supported by The Ministry of Environmental Protection, Israel

Table of Contents:

תקציר מנהלים

קליטת פחמן דו-חמצני (CO_2) מהאטמוספירה באמצעות טכנולוגיות לקיבוע פחמן דו-חמצני (CDR), לצד הפחתות משמעותיות בפליטות, מרכזית להשגת מדיניות אפס פליטות גזי חממה נטו עד שנת 2050 ולהגבלת העלייה בטמפרטורות העולמיות ל- 1.5° C מעל רמות טרום עידן התעשו.

קיימות מספר אפשרויות CDR שהוצעו על מנת לענות על הצורך בהפחתת פחמן דו חמצני בסדר גודל עולמי, כשאפשרות אחת כזו מתייחסת לקיבוע פחמן דו חמצני באמצעות פוטוסינתזה של מאקרו אצות ימיות. אצות ים גדלות במהירות הודות ליכולת הפוטוסינתטית הייחודית שלהן בשילוב עם שיעורי ספיגת חנקן וזרחן גבוהים. גידול יצרני של אצות ים בעלות ערך כלכלי גבוה יכול גם לספק יתרונות חשובים נוספים ושירותי מערכת אקולוגיים לרבות מזון לבני אדם, מזון לבעלי חיים, חלבונים ומינרלים או מולקולות טבעיות פעילות, ולכן מספקים תמיכה נוספת בצרכי האדם. אף על פי כן, השאלה האם אצות מסוגלות ללכוד פחמן דו חמצני לתקופות ארוכות (100 שנים ויותר) כדי לשמש מנגנון יעיל לוויסות אקלימי שנויה במחלוקת. לפני הקמת מערך ייצור המוני אפקטיבי ובר קיימא המבוסס על אצות המיועד לקיבוע פחמן יש לפתור פערים טכנולוגיים וביולוגיים. יתרה מכך, האם גידול אצות בים הפתוח עשוי להיות אופציה רלוונטית עבור הים התיכון הישראלי (IMS) היא שאלה שהתשובה עליה אינה ידועה לעת עתה. ל-IMS יש מספר רב של מיני אצות הניתנות פוטנציאלית לגידול מסחרי, אולם ההבנה הנוכחית בביולוגיה שלהם (כולל מחזורי חיים הקריטיים לגידולם המסחרי) קלושה. בניגוד לגידול יבשתי, טכנולוגיות לגידול בים הפתוח באופן מקיים ובעל התכנות כלכלית אינן מפותחות היטב. דו"ח זה דן בפוטנציאל הגלובלי של אצות ים על ידי התייחסות לתכונות הספיגה והקיבוע היעיל של פחמן אנאורגני במהלך תהליך הפוטוסינתזה ביחס לפוטנציאל סילוק הפחמן שלהן מהמערכת. הדו"ח בוחן גם פיתוח טכנולוגיות לגידול אצות ימיות שניתן לאמץ ל-IMS, תוך התמקדות בתקציבי הפחמן הכוללים ובטביעות הרגל של אצות מקומיות ומציג את התועלות והאתגרים בשימוש באצות מקומיות ככלי לבלימת שינויי אקלים. הדו"ח מדגים כי כדאיות כלכלית של גידול אצות ים לקיבוע פחמן גדלה מאוד אם האצות משמשות חומר גלם גם למוצרים אחרים בעלי ערך כלכלי. יתר על כן, פיתוח ואימוץ של טכנולוגיות חדשות לקיבוע פחמן דו-חמצני (CDR) תלויים ביסודם במדיניות תמחור פחמן יעילה כתמריץ להפחתת פליטת גזי חממה וכן לעידוד הפיתוח והפריסה של שיטות CDR חדשניות. לבסוף, הדו"ח מדגיש את הצורך הקריטי בהשקעה מוגברת במחקר בסיסי כדי לשפר את ההבנה והיעילות של טכנולוגיות CDR.

1. Abstract

The active removal of carbon dioxide (CO_2) from the atmosphere through Carbon Dioxide Removal (CDR) technologies is, alongside significant emissions reductions, central to achieving net zero by 2050 and limiting the rise in global temperatures to 1.5°C above pre-industrial levels. There are several options at hand to meet the need of C reduction on a global basis, and one such option refers to CDR via photosynthesis of marine macroalgae (seaweeds). Seaweeds grow fast owing their unique photosynthetic capacity combined with high nitrogen and phosphorous uptake rates. High commodity production of seaweeds can also deliver important additional benefits and ecosystem services including human food, animal feed, proteins and minerals, or active natural molecules, therefore giving extra support to human needs. Still, whether seaweeds can trap CO_2 for long periods (100 years and more) to be effective in climate regulation is controversial. Technical and biological gaps need to be resolved before an effective and sustainable, seaweed-based mass production intended for the sequestration of CO_2 is established. Further, whether offshore seaweed cultivation might be an option for the Israeli Mediterranean Sea (IMS) is for now largely unknown. The IMS has a large number of potentially cultivable seaweed species, however, their biology understanding (including life cycles which are critical for their cultivation) is slim. Contrarily to land-based cultivation, technologies for sustainable and economically viable offshore cultivation are well undeveloped. This report elaborates on the global potential of seaweeds by addressing the efficient inorganic carbon uptake and fixation traits during photosynthesis in relation to their carbon sequestration potential. This report also explores developing technologies for offshore seaweed cultivation that could be adopted to the IMS, focusing on total carbon budgets and footprints for seaweeds from the IMS, and presents the values and the challenges in using IMS seaweeds as a tool to curb climate changes. Economic viability of seaweed- based carbon capture

is shown to greatly increase with co-production of seaweed-based valuable commodities. The development and adoption of novel carbon dioxide removal (CDR) technologies are fundamentally reliant on the establishment of carbon taxing, an effective carbon pricing policy for incentivizing the reduction of carbon emissions as well as for encouraging the development and deployment of innovative CDR methods. Finally, the report highlights the critical need for increased investment in basic research to enhance the understanding and efficiency of CDR technologies.

2. Preface

Actively extracting carbon dioxide (CO2) from the atmosphere via Carbon Dioxide Removal (CDR) technologies, coupled with substantial reductions in emissions, is pivotal to attaining net-zero GHG emissions by 2050 and capping the increase in global temperatures to 1.5°C above pre-industrial levels.

This survey was elaborated for the Ministry of Environmental Protection (MEP) as an expert opinion and feasibility analysis concerning offshore cultivation of seaweeds in the Israeli Mediterranean Sea (IMS) as a CDR. Seaweeds, encompassing diverse marine photosynthetic organisms, constitute a significant element of the IMS marine flora. Despite extensive studies of IMS ecosystems in recent decades, the economic potential and ecological roles of seaweeds within these local marine ecosystems remain relatively unexplored.

Israel contributions to seaweed aquaculture have predominantly focused on land-based settings, with minimal exploration in offshore cultivation. Presently, commercial ventures primarily involve the cultivation of two seaweed species — *Gracilaria* and *Ulva* — resulting in processed products marketed both domestically and internationally. While Israel has excelled in land-based seaweed cultivation, instances of macroalgal culture in sea-based settings remain limited, particularly in strictly offshore environments.

The primary aim of this survey is to investigate the potential viability of seaweed aquaculture in the IMS as a Carbon Dioxide Removal (CDR) approach, specifically from an offshore perspective. The survey inspects various essential topics, such as the inorganic carbon system in seawater, marine macroalgae aquaculture, carbon fixation and storage capabilities of seaweeds in deep water environments, environmental impacts, economic analyses, and concluding suggestions.

The profound interest in seaweed cultivation arises from its high productivity, efficient CO_2 uptake, and subsequent conversion into valuable organic biomass. However, the utilization of seaweed farming expressly for CDR purposes remains relatively unexplored, especially in the IMS region and the specific conditions in it, introducing uncertainties regarding its efficacy and ecological impacts.

This survey includes recommendations that focus on environmental objectives alongside economic and fiscal strategies. It underscores the pivotal role of policy and research in advancing seaweed-based carbon sequestration, potentially contributing significantly to broader environmental goals while addressing economic challenges.

The survey was a collaborative effort involving experts: Dr. Álvaro Israel and Dr. Leor Korzen from the Israeli Oceanographic & Limnological Research center provided expertise regarding the Mediterranean Sea and seaweeds; Dr. Ruslana Palatnik and Dor Hertzenstein from The Max Stern Yezreel Valley College and the University of Haifa contributed to the economic analysis and the subsequent assessment of macroalgae as a CDR source. Additionally, Dr. Assaf Ariel and Itamar Avishay from Ecoocean provided insights into environmental implications.

Valuable contributions were added by Mr. Gideon Vennor from Climate Net and Mr. Shalom Zemach.

We extend special thanks to all those who contributed to this work. It is our hope that this survey will prove beneficial in addressing future challenges related to seaweed cultivation and climate change, thereby promoting a better and healthier marine environment.

3. Introduction

Since around 1750, the atmospheric CO_2 concentration has increased by 48% (NASA, 2022) and is unequivocally the result of human-driven activities (Masson-Delmotte et al 2021). Together with other so-called anthropogenic emissions (greenhouse gases), CO_2 has warmed the atmosphere, ocean, and land by accumulating additional energy (i.e., heating) in the Earth's climate system. Reduced food and water security, increased extreme weather events, irreversible losses of terrestrial and marine ecosystems are some of the consequences of climate change (Pörtner et al 2022). Climate change thus stances threats to sustainable development of human societies on Earth.

In response to the threat of climate change, more than 190 countries signed the Paris Agreement in 2015, pledging to take actions to limit global warming in the 21st century to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels (UNFCCC, 2017). Additionally, the foundation for the Paris Agreement and the recent UNFCCC (COP27) held in Sharm El-Sheikh in 2022 have again addressed the threats of climate change and called for the urgent lowering of carbon (C) emissions, hand in hand with the removal of excess C. This requires rapid and dramatic reduction of CO_2 and other greenhouse gas emissions, and reaching net-zero CO_2 emissions in the mid-century. Concomitant with these arguments, the international community has agreed to a

'Blue-Carbon' initiative on C sequestration and storage in deep (oceanic) waters and sediments, which encompasses all marine ecosystems. A recent thorough review presented by Nandhini et al (2022) described a number of options for which C neutrality (i.e. equal amounts of C released vs. C trapped, aimed for 2050) can be reached. They include a number of technologies and modern approaches including CO_2 sequestration by marine algae (Nandhini et al 2022). Blue-Carbon can help paving the way for more sustainable global development and seaweed is one of the options, owing to its multiple benefits and applications (Froehlich et al 2019). As such, 'Carbon Offsetting, a trade-off strategy coined for receiving credit in reducing, avoiding, or sequestering C, has become part of the portfolio of solutions to mitigate C emissions' (Froehlich et al 2019). This approach generally refers to land-based, re- or afforestation and preservation strategies. However, land is limiting, and the increasing worldwide demand for food, feed, and fuel is exerting enormous strain on terrestrial ecosystems. Hence, and quite recently, the interest in a rapidly growing aquatic farming sector of seaweed aquaculture has increased. Indeed, the world Ocean is a major sink for anthropogenic CO_2 emissions, and while still under dispute, the photosynthetic activities of algae can play a major role tackling the rise in atmospheric CO_2 (Raven 2017, Ji and Gao 2021).

Mitigation of atmospheric CO_2 comprise either emission reduction (avoiding emissions at the source) or removal and storage. Article 3.1 - in stating the goal of the Kyoto Protocol – aims at "reducing the overall emissions". However, national emission inventories include emission reduction as well as removal of greenhouse gases through certain sequestration activities. Carbon sequestration activities have in common that they do not avoid the production of CO_2, but lock CO_2 away from the atmosphere for a certain period of time. Removing CO_2 from the atmosphere for sequestration purposes is called Carbon Dioxide Removal (CDR). CDR is defined by IPCC (2022) as any form of CO_2 storage actively induced by humans. As discussed below, the most common CDR approaches are direct CO_2 capture from the air, direct storage in terrestrial or marine reservoirs or usage of natural carbon sequestration systems. Natural processes such as photosynthesis by vegetation, weathering of silicate rock, and absorption by the ocean already remove CO_2 from the atmosphere. However, the accelerated rate of CDR through enhanced natural processes and development of options which capture and sequester or utilize CO_2 is necessary to reach negative net carbon emissions.

4. Typical CO_2 removal options (Carbon Dioxide Removal – CDR)

Having the above background in mind and, as it will be discussed below, large areas of seaweeds cultivation are among the arsenal of options for CO_2 sequestration, with an added value of usable biomass for human benefit in a very wide spectrum (Trevathan-Tackett et al 2015, Buschmann et al 2017, Gao and Beardall 2022). While cultivation of seaweeds only will likely not solve the problem of climate change, indirect valuable benefits must be considered. Nonetheless, more scientific work and technological developments in seaweed aquaculture are needed to make this happen.

Below the most common alternatives routes for CO_2 capture suggested so far:

CO_2 capture from industrial processes

Capturing CO_2 from process streams is possible for a variety of industries at different costs that are inversely related to CO_2 concentration. Existing CO_2 capture is mostly from natural-gas processing, bioethanol production, and hydrogen and ammonia production.

CO_2 capture from power generation

There are mainly three technological routes for CO_2 capture at traditional fossil-fuel power plants: post-combustion, pre-combustion, and oxy-fuel combustion. For all three approaches, CO_2 capture creates an energy penalty, which reduces the overall efficiency of a power plant.

Direct Air Capture (DAC)

DAC systems trap CO_2 directly from the atmosphere through chemical adsorption. CO_2 bonding to aqueous or solid chemical sorbents is used in order to collect CO_2, and subsequent bond breaking to produce a concentrated form of CO_2 that is ready for transport and storage. These technologies have long been used in small systems such as space stations and submarines. DAC facilities are flexible in placement and in theory have unlimited capture capacity. Most importantly, the cost of DAC represents the upper limit of carbon abatement for any industry.

Afforestation and Reforestation

Afforestation and Reforestation, an established CDR option, are commonly referenced land management methodologies that involve intentional forest management techniques to sequester and store CO_2 over a prolonged period. Afforestation is the process of foresting land that never contained forests or restoring land that has been deforested over 50 years ago. Reforestation is the process of restoring land to a forested state that has been deforested less than 50 years ago (NRC, 2015). Via photosynthesis trees capture CO_2 from the atmosphere, store the carbon within their trunk, branches, stems, and roots, and then release oxygen back into the atmosphere (Vashum & Jayakumar 2012). One major drawback of afforestation/reforestation is competition over land use with urban development, agriculture, etc. Afforestation/reforestation, soil carbon sequestration, and terrestrial Bioenergy with Carbon Capture and Storage (BECCS) will all be direct land competitors when deciding which CDR option to implement.

Soil Carbon Sequestration

This is a land management technique that aims to increase the quantity of organic and inorganic carbon forms stored within the soil. While soil can be either a source or sink of carbon, techniques such as cover cropping, reduced fallow, and increased perennial crops can improve the soil ability to hold carbon in crop and grazing land (Eagle 2012). Other soils in grasslands, forests, wetlands, and tundra also form part of the overall potential for soil to remove CO_2 from the atmosphere through targeted land management. As a CDR option, soil carbon sequestration is a demonstrated CDR approach with a high degree of variability in outcomes due to ecological system dynamics. Adding to this, the challenge of balancing yield maximization with carbon storage makes soil carbon sequestration a complex option with high levels of uncertainty.

Terrestrial Bioenergy with Carbon Capture and Storage (BECCS).

The BECCS process, like afforestation and reforestation, takes advantage of the CO_2 removal abilities of photosynthesis through the growth of terrestrial biomass. Current biomass resources include forestry, dedicated energy crops, and agriculture and municipal wastes. This biomass is then transformed into an energy product. Biofuels and biomass-generated electricity are energy options provided by BECCS. At the time of energy generation, CO_2 is captured and subsequently concentrated and stored to potentially produce negative emissions. Large amounts of land are required to create the necessary biomass to have a measurable CO_2 reduction effect on the atmosphere. This large land requirement will compete with agriculture, urban growth, and other CDR options. The CO_2 removal potential of BECCS is determined by many factors such as the biomass used, the feedstocks for biomass production, where it was collected, transportation distance, and the methods of converting the biomass into an energy product. These variables may cause BECCS to become carbon positive instead of carbon negative as many of the integrated assessment models assume when using BECCS in their climate target feasibility models.

Aquatic Bioenergy with Carbon Capture and Storage (BECCS)

This is a speculative CDR option stating that absorbs CO_2 via plant growth in the ocean and then uses the harvested aquatic biomass to generate energy with the capture and subsequent storage of

CO_2 (N'yeurt et al 2012). Although a variety of aquatic species might be suitable as a feedstock for Aquatic BECCS, much of the literature addresses aquatic macroalgae, but not only. In this context, aquatic macroalgae refer to a variety of kelps and seaweeds. Ideally, the expansion of such kelp and seaweed ecosystems for Aquatic BECCS would be managed in ways that promote biodiversity, increase primary productivity, as well as, sequester CO_2 from oceans (Nellemann et al 2009, N'yeurt et al 2012). Once seaweed has grown, it can be harvested and processed through a biodigester to generate bioenergy. The resulting CO_2 can be captured and stored to affect a net removal of carbon from the atmosphere (N'yeurt et al 2012).

Carbon utilization options

These options include CO_2 direct geological storage and natural storage in soils ocean and vegetation. Current carbon utilization in the United States has largely been driven by the demand of CO_2 from enhance oil recovery (EOR) operations, in which CO_2 is injected into depleted oil reservoirs to blend with the trapped oil and carry more of it to the production wells. The injected CO_2 either remains underground or is produced and re-injected in a subsequent EOR project. While producing a source of revenue for CO_2 capture activities, EOR also uses infrastructure and knowledge of oil wells that already exist which significantly reduce the costs associated with EOR injection activities.

Carbon storage options

Direct geological storage involves injection of captured CO_2 into deep saline aquifers or depleted oil and gas reservoirs (without EOR), more than 1 km below land surface, for long term storage. The high temperature and pressure in the storage formation keep CO_2 in the supercritical state, which means high density and low viscosity, implying more efficient use of the pore spaces. Direct CO_2 storage is less commercially mature than CO_2 storage via EOR, but has vast potential storage capacity. Ocean storage is a speculative CO_2 storage option in which CO_2 is stored in the ocean. It can be naturally removed from the atmosphere through ocean-atmospheric gas exchange. This process removes large quantities of CO_2 from the atmosphere and stores the gas within the shallow waters of the sunlit zone. This natural process, however, increases the acidity level of the water, which can affect marine organisms. Ocean storage, through anthropogenic means, is a form of storage where compressed CO_2 in the form of liquid, gas, or solid CO_2 is pumped into mid-level ocean depths. Due to the uncertainty with regards to the effects on marine ecosystems, this method has not been deployed widely, nor are there many known pilot programs.

Ocean Fertilization

Another speculative CDR option that claims purposefully introducing specific nutrients into the ocean to stimulate growth of photosynthetic organisms, largely phytoplankton, thus removing CO_2 from the atmosphere via enhanced photosynthesis (NRC 2015, Williamson et al 2012). Three nutrients that are typically thought of as the limiting nutrients for phytoplankton growth: iron, nitrogen, and phosphorous. Ocean fertilization has been implemented in areas of the ocean called desolate zones, also known as high nutrient, low chlorophyll zones which lack a critical nutrient, therefore prohibiting phytoplankton or other aquatic life from growing (NASA 2017b, Williamson et al 2012). Oceans, as a natural sink, allow for CO_2 to be taken from the atmosphere and stored in the ocean both through diffusion and dissolution in ocean water and through photosynthesis by ocean organisms. Considering oceans occupy over 70% of the earth's surface area, a CDR approach that utilizes such a large percentage of the earth's surface sounds promising. However, the introduction of these nutrients inevitably has major ecosystem impacts that could severally inhibit the potential implementation of this approach (Bertram 2008, Denman 2008, NRC 2015, Powell 2008b).

5. The inorganic carbon system in seawater

Current atmospheric CO_2 levels range 400-420 ppm (https://research.noaa.gov, Beer 2022), while 30 years ago concentrations were only ca. 360 ppm (Beer et al 2014, Olivier and Peters 2019). The already tangible changes in global climate will continue as CO_2 will keep raising during the coming years, until, optimistically, current calls for C mitigation will become effective on a worldwide perspective. The oceans are the major reservoir of CO_2 as this gas readily equilibrates with seawater. The surface temperatures and salinities in the Oceans are increasing (Pastor et al 2020), while acidification is already measurable on a global basis. These effects are particularly evident in more naturally sensitive, e.g. the Levant basin of the Mediterranean Sea (Ozer et al 2016), or highly complex and productive e.g. coral reefs, marine ecosystems (Eddy et al 2021).

Seaweeds are photoautotrophs that dominate benthic marine ecosystems and show efficient adaptations to incorporate C (Falkowski & Raven 2013). The dissolution of atmospheric CO_2 initiates the C system in seawater, creating a pool of Dissolved Inorganic Carbon, DIC. It involves equilibria between carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), with CO_2 and HCO_3^- being the C forms utilized in marine photosynthesis (Fig. 1). In seawater, the concentration of CO_2 is in chemical equilibrium with atmospheric CO_2. However, salinity and temperature make seawater-CO_2 generally 20-30% lower than air-CO_2 (Beer 2022, Fig. 1). CO_2 comprises less than 1% of total DIC, while that of HCO_3^- accounts for over 90%. Hence, at an average seawater pH (8.1), HCO_3^- and CO_3^{2-} concentrations are ~120 and ~20 times higher than that of dissolved CO_2 at equilibrium (Beer 2022).

The carbon concentrating mechanisms (CCMs) widely found in seaweeds convert HCO_3^- to CO_2, enhancing the CO_2 concentration to RUBISCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase), the central photosynthetic enzyme (Beer et al 2014, Beer 2022). As a collateral benefit, the high intracellular CO_2 level inhibits photorespiration impeding significant CO_2 reversed back into the seawater medium. In most cases, CCMs involve the active uptake and utilization of HCO_3^- (Beer et al 2021, Beer 2022). For this to occur, HCO_3^- ions are converted to CO_2 by carbonic anhydrase before the CO_2 can be assimilated to organic matter via RUBISCO.

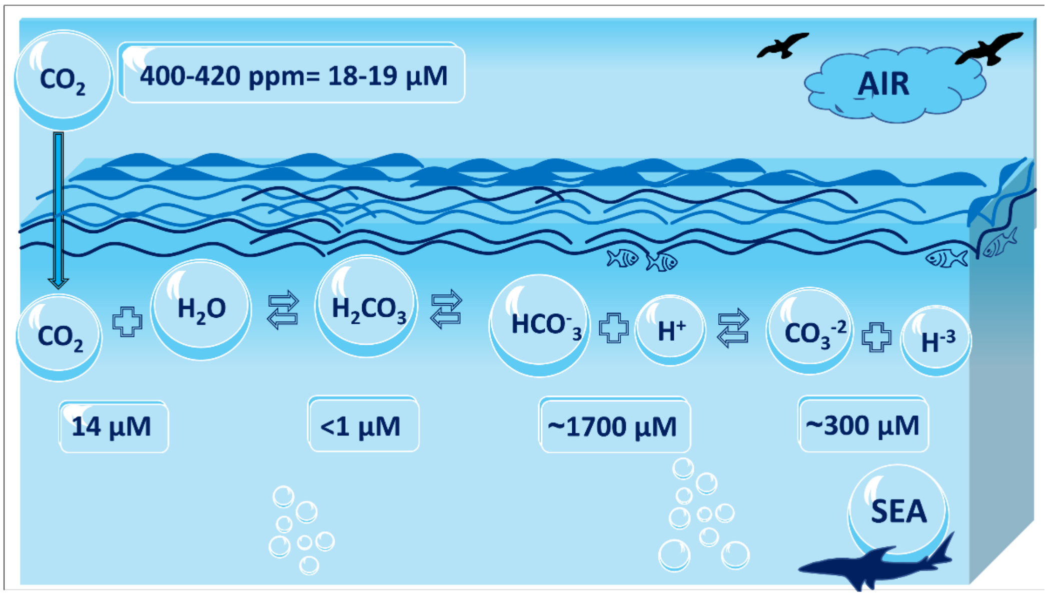

Fig 1. The equilibrium and concentrations of atmospheric- and seawater-CO_2. Salinity and temperature make the equilibrated CO_2 level in seawater roughly 20% lower than in air. CO_2 will hydrate to form carbonic acid (H_2CO_3), which dissociates to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). These reactions are pH dependent. The distribution between C chemical forms at an average seawater pH of 8.1 translates in approximately 120 and 20 times higher HCO_3^- and CO_3^{2-}, respectively, than that of dissolved CO_2 at equilibrium (Beer 2022; Israel & Sphigel 2023).

6. Marine macroalgae, or seaweeds

Seaweeds comprise a diverse group of marine photosynthetic organisms with about 25,000 species described worldwide. There are three different types of seaweeds which are visibly different by their color; red (Rhodophyta), green (Chlorophyta) and brown (Ochrophyta from the Class Phaeophyceae). The marine flora diversity in the Israeli Mediterranean Sea (IMS) is substantial, around 300 species out of an estimated 1,200 species in the entire eastern Mediterranean Sea. While the IMS ecosystems have been studied quite extensively in the last couple of decades, the economic potential and ecological roles of seaweeds to local marine ecosystems are yet to be assessed (Lipkin & Friedlander 1998, Israel & Einav 2017, Badreddine et al 2018). In general, algal communities are abundant with high standing stocks on abrasion platforms and subtidal hard substrates developing during short growing seasons (Figure 1), usually in spring and fall (Einav & Israel 2007). Abrasion platforms are periodically exposed during low tides and, although tidal fluctuations are limited (ca. 30 cm), seaweeds become exposed to extreme conditions of temperature, irradiance and dehydration (Lipkin & Safriel 1971). Over the years, Israel has contributed significantly to the research and development of seaweed aquaculture in land-based settings while only recently offshore cultivation attempts have taken place (Israel et al 2018). Current commercial ventures involve two companies that grow *Gracilaria* and *Ulva* producing a number of processed products that sell both locally and abroad.

The Mediterranean Sea and the Levant basin

The Mediterranean Sea has been exposed to long-term environmental pressures of anthropogenic nature and on-going global changes such as increasing temperatures, salinities and seawater levels (Kress et al 2014). As one moves east, nutrients become depleted and seawater heats up and evaporates, hence, making the eastern Mediterranean Sea (EMEDS) particularly oligotrophic, saltier and hotter than the Western basin. The EMEDS is divided into four sub-basins; the so-called Adriatic, Ionian, Aegean and Levant Seas. The Israeli Mediterranean shoreline is situated in the Levant basin. Here, the bottom is primarily sandy and exposed to the open sea, with biogenic abrasion platforms in some parts (Lipkin & Safriel 1971). The opening of the Suez Canal in 1869 permitted the in-flow of marine organisms from the Red Sea and Indo-Pacific Ocean straight into the Levant basin. These migrations are collectively called the "Lessepsian invasion" (Por 1978, Galil 2007). There is a consensus that the major vector of introduction of seaweeds into the EMEDS is via the Suez Canal (Verlaque & Boudouresque 2005, Zenetos et al 2010, 2012, Romero 2015, Verlaque et al 2015), with additional alien species originating from mariculture and maritime related activities such as ballast waters and hull fouling, for example, seaweeds entering the Western Mediterranean from the Atlantic Ocean, on their way into the Eastern basin (Katsanevakis & Crocetta 2014, Aragay et al 2016, Sghaier et al 2016). Seaweed biodiversity is larger in the Western basin than in the Eastern basin (ca. 60% vs 40% of an approximate 1500 species suggested for the whole MEDS; Hoffman 2014), yet the arrival of alien marine macroalgae is more intense in the EMEDS (Verlaque et al 2015).

The IMS witnessed a number of aliens macroalgae proliferating in subtidal areas such as *Codium parvulum* (Israel et al 2010), *Stypopodium schimperi* (Verlaque & Boudouresque 1991, Einav & Israel 2009) and *Galaxaura rugosa (*Hoffman et al 2008), and recently species of *Dictyota* (Delva et al 2023) and *Lobophora* (Vieira et al 2018), and many others which are unaccounted for. Offshore drifts of these species can be intense (Israel et al 2010), with biomass amounts decreasing following relatively short time-periods (e.g. 2-5 years) and invaders integrating thereafter with existing seaweed assemblages. In another example, *Asparagopsis taxiformis,* allegedly introduced into the MEDS in 1831 (Verlaque et al 2015) was hardly noticeable in the Israeli intertidal zone until a decade ago (Nahor et al 2022) and now covers significant areas in both the rocky intertidal and shallow subtidal (Nahor et al 2022). Other genera, such as *Fucus* and *Laminaria* J.V. Lamouroux, as well as the seagrass *Posidonia oceanica*, reported to proliferate in Cyprus (Kletou et al 2018), have never been spotted in the IMS coasts. Worth mentioning is the presence of *Caulerpa racemosa* var. *turbinata* (Durand et al 2002) which bloomed on Turkish, Greek and Cypriot shores (Tsiamis et al 2014) yet never established on the Israeli Mediterranean shores (Einav 1998a,b, Ukabi et al 2013, 2014).

The seaweed flora of Israel

The population biology and biodiversity of seaweeds have been studied irregularly for the IMS. From the estimated 300 species about 60% were reds, 23% greens and 17% browns (Einav & Israel 2008, Israel & Einav 2017). (Fig. 2).

Fig 2. Characteristic seaweed communities from the Israeli Mediterranean Sea. **A**. An assemblage of macroalgae at 10 m depth in Haifa Bay composed of *Jania rubens*, *Padina* spp., *Lobophora schneideri*, *Dictyota* spp. and others (photo credit: G. Rilov). **B**. Intertidal *Volonia utricularis* and *Ulva* spp. **C**. Abrasion platforms in the intertidal covered by *Ulva* species in Hertzlyia, **D**. Populations of *Asparagopsis taxiformis* thriving in intertidal rock pools in Rosh Hanikra. **E**. Algal diversity during high growth season on the intertidal shores of Atlit. (taken from Israel et al 2018).

Only two seaweed taxonomic keys with general descriptions have been published for local seaweeds (Nemlich & Danin 1964, Einav 2007), and one, extensive eco-taxonomic review article (Einav and Israel 2008). For the IMS only one endemic species has been suggested, the brown alga *Cystoseira rayssiae* Ramon (Ramon 2000), while the red algae *Gracilaria* and *Porphyra* as well as many others are all in need of taxonomic confirmation (Israel et al 1999, 2008, Israel & Einav 2017). The largest and the oldest seaweed collection in Israel is to be found at the Botanical Herbarium of The Hebrew University in Jerusalem. Another collection is preserved at the Museum of Natural History, Tel Aviv University, and is based on decades of field collections. A third, newly established seaweed herbarium is found at Israel Oceanographic & Limnological Research, Haifa, with more than 1500 records and about 100 species identified so far.

At present, insufficient knowledge of the physiological tolerance ranges of native and exotic seaweeds, the attributes of their life histories, and the genetic makeup of their populations, hampers the prediction of the impact of invasion and climate change on seaweeds from the IMS (Guy-Haim et al 2016). In this context, explaining the disappearance of species is much more difficult than their appearance as invasive ones. Nevertheless, the resilience capacity within the IMS is worth mentioning. For example, *Halymenia dichotoma* and *Halymenia floresii* had been abundant in the shallow subtidal hard bottoms (Nemlich & Danin 1964), then were unseen for several years, and are now observed thriving again at deeper depths of about 18 m (A. Israel, unpublished observations). A similar phenomenon accounts for species of *Naccaria* and *Scinaia furcellata*, as well as *Pyropia* sp. and species of *Laurencia* (A. Israel, unpublished observations). In contrast, the green seaweed *Halimeda tuna* has virtually disappeared from the intertidal region, at least for the last 10-15 years (A. Israel, unpublished observations). By feeding on coarse seaweeds, Lessepsian herbivorous fishes, typically *Siganus* spp. have contributed (in a yet unquantified degree) to the changes observed in the IMS seaweed population dynamics (Lundberg 1981).

The species composition of the common green seaweed *Ulva* has also shifted over the last couple of decades, from populations then composed of usually three species to populations now composed of six dominant species, including two aliens (Krupnik et al 2017). Years of rapid environmental change in the IMS, particularly rising sea temperatures (Gertman et al 2013, Shaltout & Omstedt 2014, Raveh et al 2015, Ozer et al 2016) combined with local effects of thermal pollution from power plants and brines from desalination plants (Titelboim et al 2016) have all contributed to a gradual environmental shift and an unknown impact on the seaweed populations. There are 86 seaweeds currently regarded as alien in IMS shores (Israel & Einav 2017) and new ones are detected regularly (Hoffman & Wynne 2016). *Ulva ohnoi* is an invasive species originally described from southern and western temperate regions of Japan where it forms green tides (Hiraoka et al 2004). It was first spotted in 2002 from natural habitats in the IMS (Krupnik et al 2017). Probably, earlier records of *U. rigida* and *U. lactuca* from Israel were misidentifications of this species (Einav & Israel 2008). *Ulva ohnoi* is very closely related to, and can interbreed with, *U. fasciata* (Hiraoka et al 2004), which has often been found in Israel (Beer et al 1990). *Ulva* species all grow at high rates in aquaculture tanks (Neori et al 2004, Ashkenazi et al 2017).

Due to the geographic-oceanographic patterns of Lessepsian introductions, newly-introduced species are often reported first in Israel (Nunes et al 2014). A positive aspect of alien species relies on the opportunity to incorporate them into local industries and aquaculture. For example, *Ulva* species may be valuable for the local bioeconomy (Chemodanov et al 2017). The results are especially important given the growing interest in using *Ulva* biomass for various food applications, for example protein (Kazir et al 2018) and starch (Prabhu et al 2019), in bioremediation, or as a source for bioethanol production. Any future industrial-scale cultivation of *Ulva* will rely initially on collections of material from the wild. Given that sustainable food supplies, renewable energy and water treatment are major challenges for the near future, *Ulva* species could be a viable answer to many of these challenges. With respect to the clear impact of invasive marine organisms, which are evidently changing the seaweed diversity of the Levant area, the future contribution of critical natural seaweed resources to the Israeli coast and economy remains to be seen.

Seaweed cultivation in the IMS

In Israel, seaweed cultivation technologies, development and commercialization have all been insufficiently addressed. Perhaps one noticeable exception refers to cultivation approaches of seaweeds using land-based technologies which have with the years been adopted by emerging local seaweed companies (Friedlander & Lipkin 1982, Israel et al 2006, Friedlander 2008). Due to the exposed nature of the IMS coastline, implementing offshore, long-line rope or raft methods as in SE Asia is problematic. Hence, the making of on-land (in tanks and ponds) is preferable, or perhaps the only practical alternative for seaweed culture within the IMS (Neori et al 2017). The commercial maturation of these trials has been limited to few small enterprises, as described below. However, Israeli cultivation technology has been deployed abroad, for instance in South Africa (Amosu et al 2013), Australia (Winberg et al 2011, Lawton et al 2013) and China (Wang et al 2007). With appropriate technological advancements, however, offshore seaweed cultivation as part of Integrated Multi-Trophic Aquaculture (IMTA) approach could play a significant role in the development of the local economy (Fernand et al 2017). IMTA promotes the simultaneous cultivation of valuable marine organisms in a single deployed unit, thus creating effective aquaculture. Elsewhere, outside SE Asia, technologies for massive offshore seaweed culture are limited in scale and include farm concepts for kelp growth, tidal flat farms, floating cultivation, ring cultivation, wind-farm integrated systems, and bottom plantations (Buschmann et al 2017). However, future expansion of biomass production in the open sea will require shifting the cultivation infrastructure to more exposed environments, where operation with current technologies would require complex logistics and high costs.

While Israel has been for years a pioneer in land-based seaweed cultivation (Friedlander 2008, Neori et al 2017), there have been only two reports of macroalgal culture in sea-based settings, yet none in strictly offshore settings. Friedlander and Lipkin (1982) first cultivated a number of polysaccharides producing seaweeds in a shallow field site in south Israel. *Ulva* sp. and *Gracilaria* sp. were more recently tested in nets or single layer lines as reported by Korzen et al (2016) and Chemodanov et al (2017). Korzen et al (2016) reported a series of short-term experiments in which *Ulva rigida* and *Gracilaria bursa-pastoris* were cultivated downstream of fish cages (ca. 3 miles offshore) yielding encouraging perspectives on their nutrient uptake, growth and chemical constituents as related to the nutrients derived from the fish. Chemodanov et al (2017), tested the productivity of *Ulva* sp. during a full year in one-layered reactors set within the proximity of a power plant, a concept that underlined the possibility of long-term cultivation. The generally rough offshore conditions for the IMS as presented above, have precluded further experimental or pilot efforts to cultivate seaweeds in the sea. Nevertheless, the high natural irradiance and relatively warm seawater temperatures year around, in addition to emerging offshore technologies could encourage these types of activities.

Commercialization of seaweeds

During the late 1990s, SeaOr Marine Enterprises Ltd. established a 2-ha pilot, land-based seaweed farm using tanks and ponds in the locality of Michmoret. The company adopted the IMTA approach culturing marine fish, abalone, sea urchins and also bivalves and shrimps, all integrated with the seaweeds *Ulva* sp. and *Gracilaria* sp. and occasionally also *Porphyra.* It leveraged local climate and recycled fish waste products into macroalgal biomass, which was fed to the abalone. It also effectively purified the water sufficiently to allow seawater recycling back to the fishponds and to meet point-source effluent environmental regulations. The farm was a pilot that operated technically well but was too small to be profitable (Neori et al 2017). Under a new management, and for the last 10 years or so, and using the same infrastructure grounds, Seakura Ltd. (www.seakura.co.il) has engaged quite successfully in the cultivation of *Ulva* spp. intended for high-value foods. In recent years, this same company has also produced important amounts of *Gracilaria* sp. biomass for human consumption, and a number of products of both species have been available in local and international markets. Another active seaweed company is Sealaria Ltd. (www.sealaria.co.il), based in the northern Kibbutz Rosh Hanikra. This company produces a few tonnes of fresh *Ulva* sp. and *Gracilaria* sp. intended for cosmetics and for veterinarian products based on hydrogels extracted from these seaweeds.

7. Marine macroalgae aquaculture – potential in the IMS

The aim of this report is to argue whether seaweed aquaculture in the IMS can be a promising CDR approach specifically under an offshore perspective. The broad interest in seaweed cultivation relies in the high productivity of many species, their efficient uptake of seawater-CO_2 and subsequent conversion into valuable organic biomass. As such, several strategies have emerged to try to enhance the rate of C sequestration and storage in the ocean by protecting, restoring, or enhancing productivity of wild marine plants, macroalgae, and phytoplankton. Large-scale farming of seaweed has been put forward as a potential CDR strategy. A variety of approaches to seaweed farming for the express purpose of CDR have been proposed, including the purposeful transport of seaweed biomass to the deep ocean where it can remain for long periods, and the use of seaweed to produce lower emission products such as biofuel. Such approaches remain largely untested, and their efficacy and ecological impacts remain uncertain.

How much Carbon can seaweeds fix and store?

Seaweed net primary production (NPP) results from their capacity to fix and store C over time, and is generally expressed per unit area. All seaweeds combined contribute with 5-10% of the global NPP. Primary production is strongly coupled to climatic variables, peaks at temperate latitudes, and is dominated by "forests" of large brown seaweeds, the so-called kelps (Hurd et al 2022; Pessarrodona et al 2022). Seaweed forests exhibit exceptionally high per-area production rates with a global range of 656 and 1711 g C m^{-2} y^{-1} in the subtidal and intertidal, respectively, up to 10 times higher than coastal phytoplankton in temperate and polar seas (Pessarrodona et al 2022). Hence, it is quite clear that seaweed NPP is a strong driver of production in the coastal ocean and should be integrated in oceanic carbon cycle estimates, which so far has not. Duarte et al (2022) recently presented global estimates of the extent and production of macroalgal forests. From a global perspective, it has been estimated that an area of ca. 48 million km^2 is suitable for seaweed farming given known ecological constraints such as nutrients and temperature; yet most of this area is largely unfarmed. Hence, there is huge potential for seaweed farming worldwide. However, it must be recognized that the expansion of macroalgal farming to an extent where it can make significant contributions to CO_2 mitigation will require extensive areas of cultivation and significant technological and ecological developments (Ortega et al 2019, Ross et al 2022). Within its industry, seaweed could create a C-neutral aquaculture sector with just 14-25% of current seaweed production, which corresponds to ca. 0.001% of the above mention suitable area. At a much larger scale, seaweed culturing will be extremely unlikely to offset global agriculture, in part due to production growth and cost constraints. Seaweed farming can provide other benefits to coastlines affected by eutrophic, hypoxic, and/or acidic conditions. Seaweed offsetting is not the sole solution to climate change; but provides an invaluable new tool for a more sustainable future.

Some intertidal and economically important fleshy macroalgae in the IMS show enhanced photosynthesis and growth rates when exposed to increased concentrations of CO_2 (Israel and Hophy 2002; Zemach Shamir et al. 2021). However, some do not, or their response is positive in a few weeks timeframe and then levels off, and most were not tested in the long run (Israel and Hophy 2002). Seaweeds, nonetheless, have experimentally shown remarkable resilience to the pH drop associated with increased CO_2 of anthropogenic origin (Gao et al. 2020; Peña et al. 2021). Seaweed farming has been suggested to be capable of CO_2 mitigation by trapping 1500 t CO_2 km^{-2} y^{-1} (Duarte et al. 2017). Because macroalgal farming capabilities will likely differ between geographical regions and species, studies should be targeted over a wide range of latitudes and conditions and integrated accordingly thereafter. Further, current estimates might significantly underestimate the CO_2 sequestration capacity of farmed macroalgae (Duarte et al. 2017, 2022). For example, the sea-farming of the edible kelp *Laminaria* has been shown to capture more than 7500 t of CO_2 km^{-2} in 7 months, assuming that the carbon content of the dry biomass is 25% (Duarte et al. 2017). Seaweeds can play a significant role in increasing the marine carbon sink since macroalgal thalli and their debris can be transformed into ‘recalcitrant’ (refractory) particulate (RPOC) and dissolved organic carbon (RDOC) (Duarte et al. 2017, Chen et al. 2020), which cannot be mineralized by other marine organism and can then be stored for millennia (Jiao et al. 2010). During the growth of macroalgae, for instance, *Saccharina* kelp, part of their thalli can be torn off by water motion (Zhang et al. 2012), and the algal debris can be transported, via ocean currents and sinking to deep regions of the open ocean. This phenomenon has been evidenced by macroalgal eDNA detected on the seafloor at 4000 m depth (Ortega et al. 2019). While the contribution to RPOC and RDOC from macroalgae may differ between different taxa, about 1.6% of the biomass production by the green tide alga, *Ulva* sp. remains as RDOC after bacteria-mediated mineralization (Chen et al. 2020). Naturally grown and commercially farmed macroalgae contribute to pools of blue carbon in the oceans, though the proportion of recalcitrant carbon in their biomass is subject to debate (e.g., Hill et al. 2015; Trevathan-Tackett et al. 2015). Discrepancies arise as values for recalcitrant carbon in seaweed biomass will depend on the cellular composition, particularly cell wall components with different degradation rates that differ between species (Trevathan-Tackett et al. 2015). Further complications about the fate of biomass arise from differences in *in situ* decomposition capacity and biogeochemical activity in different regions. All these components are difficult to assess, making the real contribution of seaweeds far more complex.

The role of exudates, dissolved organic carbon in the final C budget

Organic exudates can be quite a significant portion when establishing net C uptake into fresh seaweed biomass. Previous studies have largely overlooked the role of lost particle organic carbon (POC) and excreted dissolved organic carbon (DOC) from seaweed cultivation in C sequestration, that is, long-term C storage in the oceanic sediments and the water (Gao and Beardall 2022; Gao et al. 2022). Seaweed-derived DOC is found throughout coastal ecosystems and supports multiple food web linkages. It significantly regulates carbon pools in green tides (Li et al. 2022). DOC release rates by seaweeds have been reported in the range of 0–266.44 for Chlorophyta, 0– 89.92

for Ochrophyta, and 0–41.28 μmol C g dry weight^{-1} h^{-1} for Rhodophyta (Hurd et al. 2022). In nature, rates of DOC release increased under environmental factors such as desiccation, high irradiance, non-optimal temperatures, altered salinity, and elevated dissolved CO_2 concentrations. The impact of DOC release by seaweeds on future ocean scenarios (ocean acidification, seawater warming, altered irradiance) and the role of seaweed-derived DOC in carbon sequestration models is largely missing (Paine et al. 2021). Nonetheless, from a global perspective, one can expect that biomass measurements and the C components (in the range of 20-30%) can still give estimates of seaweed Ci sequestration capacity.

Can seaweed farming alleviate climate changes?

As mentioned, realistically seaweeds will likely not solve the problem of climate change, neither any other specific technology. Rather a combination of approaches working synergistically on a worldwide perspective could eventually act effectively to diminish the problem. However, seaweeds can offer an extra value in view of their enormous economic and environmental additional benefits. Marine macroalgae can transform C into organic matter via photosynthesis, sequestering the CO_2 in seawater at harvest time. However, scaling up offshore cultivation for the only purpose of C sequestration is problematic and suffers from various technological, social, and most importantly, research gaps to allow accurate estimations of C sequestration rates (Ross et al. 2022). Still, seaweeds can act as effective carbon sinks because their biomass is larger, and their turnover times are relatively longer, than those of other marine photosynthetic organisms, for example, phytoplankton. One should not underestimate, nonetheless, the potential of microalgae since optimistically these organisms could consume a significant portion of seawater CO_2. However, seaweeds can potentially make effective contributions to CO_2 mitigation because a large number of species have cell wall structures and composition that can store carbon over the long term by becoming a carbon donor to other ecosystems (Thau Lym et al. 2022; Trevathan-Tackett et al. 2015) and by converting the biomass into a range of bioenergy products from biogas to liquid and solid biofuels. These attributes may become part of the C-offsetting or C-trade by reducing CO_2 release indirectly. We realize that the problem with seaweeds being considered effective organisms for C sequestration is their short turnover time. Life cycles and major accumulation of C in seaweeds are relatively limited compared to trees, nonetheless, much CO_2 can be accumulated in a short time owing to their high productive capacity. Hence, seaweeds are more effective as a recycling resource for fuel in which CO_2 accumulation and retention occur over a much longer time. For example, it has been estimated that *Sargassum* sp. turnover time in the Sargasso Sea is 10 to 100 years (Hurd et al. 2022). Not all seaweeds have short turnover times, and some show potential for long-term C sequestration because they contain very recalcitrant compounds and are likely to break down slowly in sediments (Trevathan-Tackett et al. 2015; Hurd et al. 2022). For the IMS, the extent of climate change affecting various ecosystems was discussed in the past and included forecasts of the ecological functioning in marine environments (Sternberg et al. 2015; Rilov 2016). In reality for the IMS there are hitherto no evaluations of the role of seaweeds as potential CO_2 scavengers, much less offering a potential solution to alleviate climate changes through seaweed culture.

Advantages, gaps, and expected limitations of seaweed cultivation – the case of the green seaweed Ulva for the IMS

Seaweed aquaculture accounts for 53.1% of global mariculture production and grows fast at an average of 6.2% y^{-1}, calculated between 2000-2018 (FAO 2020). One seaweed widely investigated and ubiquitous throughout the world's oceans is the green alga *Ulva*. This seaweed possesses high photosynthetic capacity which translates into exceptionally high productivity, it can be grow in many geographic areas year around and offers an immense range of nutritional benefits. Species of *Ulva* have been extensively analyzed for their value as food, feed, food ingredients (e.g., protein, carbohydrates, pigments, antioxidants), chemical constituents, and medicinal properties (Mantri et al. 2020; Prabhu et al. 2020). One should keep in mind that tank cultivation requires high power inputs and the use of expensive materials and equipment and, if not operated effectively, is in most cases too costly and inappropriate for commercial-scale production of seaweeds. However, it has been shown that on-land-based tank cultivation produces the highest biomass yields per m^2 of water surface. Furthermore, it offers several additional advantages, such as adequate control over the cultivation parameters, which allows for manipulative cultivation and simple operation during harvest periods.

These features have been underlined during the years also in Israel and there is a solid starting point to offshore cultivation implementation. Indeed, *Ulva* has been cultivated using land- and sea-based technologies year around (Chemodanov et al. 2017; Korzen et al. 2015; Neori et al. 2020; Steinhagen et al. 2021). Cultivation of *Ulva* species has largely been limited to coastal nearshore areas (cages, nets) and on-shore tanks, basins, or (paddle wheel) pond-based (in- and outdoors) cultivation methods. In land-based ponds yields of *Ulva* may range between 36 -110 kg wet weight m^{-2} y^{-1} largely depending on seasonality (Qarri and Israel 2020). However, offshore settings have proven to be more complicated to handle, and biomass harvest is generally lower in the 2-20 t dry weight $hect^{-1}$ y^{-1} range, which translates into 1-3 t C ha^{-1} y^{-1} (Chemodanov et al. 2017). The most effective cultivation systems encourage yielding more seaweed biomass per m^{-2} than land plants; 25-40 t dry weight ha^{-1} y^{-1}, compared to 2.1, 4.1and 5.1 t dry weight ha^{-1} y^{-1} for soybean, wheat, and maize, respectively (Shpigel et al. 2015). As for nitrogen uptake capacity, which is driven concomitantly with C uptake, *Ulva* assimilation rates ranges between 1.1–5.5 kg

N m^{-2} y^{-1} (Neori et al. 2019, Shpigel et al. 2017). Further arguments underlying *Ulva* as the most promising marine crop are as follows:

(1) worldwide distribution allowing for ease of collection of intertidal eco-types.

(2) fast growth reaching doubling its biomass daily under optimal conditions.

(3) large areal yield throughout the year, whether in a sessile or free-floating system.

(4) easy reproduction (vegetative and sexual) to build stocks for up-scaled cultivation.

(5) a proven source of sustainable feedstock (fresh or dry) for human consumption, animal feed, and a reliable source of high-value by-products (nutraceutical and cosmetic industries), as well as potential biomass for biodegradable (bioplastic) packaging as an alternative to plastic and other biodegradable synthetic polymers.

(6) plasticity in biochemical composition, with numerous documented bioactive metabolites (primary and secondary) exhibiting antimicrobial, antiviral, antioxidant, anti-inflammatory, and anticancer activities.

(7) the ability of microbiome engineering to trigger growth and enhanced production of specific algal constituents.

(8) excellent efficiency as an ecological biofilter for ecosystem services, supporting the sustainability of the growing industry of land- and sea-based fish farming, preventing eutrophication in coastal waters.

(9) *Ulva* is genome-sequenced and the only macroalgae which can be transformed for genetic modifications.

(10) ideal model for clarifying fundamental aspects of seaweed biology such as growth, metabolism, and seaweed-bacteria interactions.

Relevant areas for seaweed cultivation in the IMS

The potential marine sites for offshore seaweed cultivation in the IMS advocated by the Min of the Interior and Min of Agriculture are depicted in Fig 3. Ideally, a large are in the deep sea is planned for seaweed cultivation, and theoretically areas dedicated to fish farms in cages could serve as a platform to establish future IMTA. The potential economic benefit in terms of maximal seaweed biomass production and C sequestration capacity are discussed further below ("Economic Analyses").

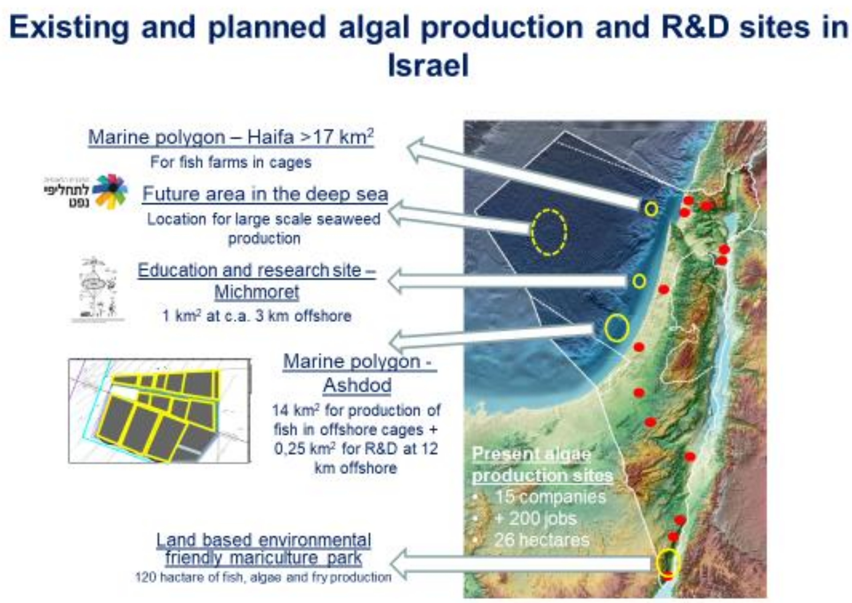

Fig 3. A representation of dedicated polygons for marine aquaculture within the EEZ of Israel, including potential sites thought for seaweed cultivation (source Ministry of Agriculture, Israel).

Technical feasibilities

Full quantitative understanding of C sequestration by seaweeds requires additional experimental supporting evidence. Calculations of C uptake potential by seaweeds are still largely based on assumptions and extrapolations. This is a general drawback not only when considering seaweeds from the IMS, rather is valid on a global perspective. Therefore, a sea-based seaweed cultivation farm in the IMS also faces several biological technical constrains. These limitations have been mentioned previously in this report with the main bottle-neck residing in the establishment of a fit sea-based infrastructure that will need thorough planning and engineering assessments. The designated marine areas within the EEZ need further evaluation and investments are expected to be high. One option to reduce costs and to solve mooring constrains is by taking advantage of current marine structures, or those planned for the future, such as fish farms. These options can be highly advantageous and can make seaweed farms deployment much faster. Also, seaweed cultivation at the proximity of fish farms can offer great benefits for the environment as excess nutrient can be incorporated into the seaweed tissues while enhancing seaweed growth. In order to establish an offshore seaweed platform there is a need to maintain a "seed nursery" and additional gear related to cultivation itself. This platform can be installed on land or at close proximity to the seaweed farm itself.

8. Environmental impacts

In this section we indicate the potential impacts that seaweed cultivation practices might have on marine coastal ecosystems. In spite of the huge benefits seaweeds offer there are potential environmental disadvantages and dangers to the ecosystem when engaging in large-scale seaweed cultivation. However, since the authentic degree of specific changes in the environment are uncertain, risk ratings are cautious. Risk-reduction strategies are presented to reduce the risk of seaweed farming. While small-size farming ventures are currently considered "low risk", a development of the sector to be included in "large-scale" farming will necessarily require an improved knowledge of scale-dependent modifications to maintain ecological risks low in relation to the advantages that seaweed farming initiatives can provide. The most concerning aspects to be affected by seaweed cultivation include (1) disease acceleration, (2) community genetic modifications, and (3) significant variations in the local physicochemical characteristics of the ecosystem. Since there is so much ambiguity about the authentic degree of specific changes in the environment right now, risk ratings are cautious.

Risk-reduction strategies are presented to reduce the risk of seaweed farming. As mentioned above, seaweed farming has several well-established environmental benefits, including improving water quality by reducing nutrient levels (nitrogen and phosphorus), removing organic particulates, and increasing dissolved oxygen. This can help mitigate eutrophication (Liu et al., 2019; Wei et al., 2017) as well as enhance carbon cycling by increasing carbon flux from air to sea that may contribute to long-term carbon sequestration (Jiang et al., 2013; Li et al., 2018). However, several variable and detrimental environmental impacts require further study. These are the most common aspects that are identified as potential environmental threats derived from seaweed aquaculture:

(1) Biodiversity Impacts: Seaweed farms may alter pH, sediment composition, organic content, and water flow with variable effects on local flora and fauna (Han et al., 2020; Xie et al., 2017). Effects on biodiversity are mixed - some species like grazing fish benefit from artificial habitat, while others like benthic invertebrates and seagrass can suffer habitat disruption from farming infrastructure (Bergman et al., 2001; Hehre & Meeuwig, 2015). While farms provide structure and food that may enhance invertebrates, fish, and marine mammals, it may also restrict movements or cause entanglements of megafauna (Markowitz et al., 2004; Watsoncapps and Mann, 2005).

Entanglement in fishing gear and mooring lines is a significant threat to oceanic megafauna, potentially causing fatalities among various species including sharks, rays, mammals, turtles, and large fish. The risks associated with entanglement increase due to limited visibility, smaller tension anchorages and lines making escape difficult for these animals. The slow growth and reproductive rates of many oceanic megafauna species make entanglement-related accidents and deaths critical environmental issues. The location of seaweed cultivation plays a crucial role in avoiding adverse impacts on megafauna, although the specific reactions of different species remain uncertain. While seaweed farming might offer improved foraging opportunities for some species, the mismanagement of these practices could heighten the risk of entanglement, particularly in deeper offshore locations where larger marine animals are more commonly found. The scale of cultivation — small to medium versus large-scale operations — also influences the risk, with larger-scale operations posing a higher risk due to increased infrastructure.

(2) Light penetration: At large scales, seaweed farming can reduce light penetration and therefore primary productivity in the water column (Shi et al., 2011). This can be of particular concern in shallow waters. Cultivated seaweed environments, specifically grown at optimal depths for Photosynthetically Active Radiation (PAR), can face challenges from excessive or inadequate light, leading to photo-oxidative stress or insufficient photosynthetic efficacy, respectively. This altered light environment can affect autotrophic life forms like pelagic phytoplankton and benthic macroalgae. Seaweed farming in specific regions has been observed to reduce primary production, influencing the aquatic food chain and benthic food webs (Bhuyan, 2023).

(3) Nutrient budget: Seaweed farms absorb nutrients like nitrogen and phosphorus, which provides some environmental benefits but risks depleting nutrients below levels required to sustain natural marine productivity if expanded substantially (Aldridge et al., 2012; Lüning and Pang, 2003). By absorbing access nutrients farms may reduce phytoplankton productivity but also provide habitat for protist grazers and influence viral mortality, causing complex trophic interactions (Clasen and

Shurin, 2015; Zhao et al., 2016). Poorly managed seaweed farms can enable blooms of pest macroalgae, with multiple cases documented worldwide (Huo et al., 2016; Liu et al., 2010). Benthic effects relate to enrichment combined with altered physical factors, requiring habitat monitoring (Zhang et al., 2009), assessing and mitigating any negative interactions will be important.

(4) Effects on carbon budget: Large-scale cultivation of seaweed presents an opportunity to sequester significant amounts of carbon. Extensive seaweed cultivation on CO_2 capture might be minimal in freely moving open water bodies, yet substantial quantities of photosynthetic products released could potentially raise regional pH levels. Although seaweed ecosystems significantly contribute to organic carbon in aquatic habitats, the specific effects of cultivation on carbon cycling remain uncertain, necessitating further investigation.

(5) Flow dynamics: Seaweed cultivation systems significantly impact fluid flow and nutrient dynamics in marine ecosystems. Floating seaweed alters water flow patterns, affecting currents and nutrient transport, potentially limiting growth in certain areas. These changes, stemming from extensive cultivation, can influence bottom and pelagic ecosystems. Moreover, manmade nitrogen sources like those from mariculture may further contribute to regional nitrogen imbalances. To mitigate these impacts, careful consideration of seaweed farm locations is crucial to maintain ecosystem resilience. Co-locating cultivation in areas with high levels of nitrogen supply, like fish farms, can assist in regional nutrient cleanup. Overall, while seaweed farming offers environmental benefits, its expansion necessitates thoughtful planning and management strategies to mitigate potential ecological disruptions and maintain the health of marine ecosystems.

(6) Organic matter release: The expansion of seaweed farming introduces the release of dissolved organic matter (DOM) and particulate organic matter (POM) into marine ecosystems, impacting

various ecological processes. Seaweed play a crucial role in providing organic matter to marine areas, with their exudations containing carbohydrates that contribute to the dissolved organic carbon (DOC) pool in marine waters. These exudates, although a part of the refractory DOC pool, may still have short-term effects on light absorption and could influence nearby microbial communities. The microbial utilization of carbohydrate-rich exudates may impact microbial communities in the "microbial loop," altering local microbial compositions. While the impact of these changes might be negligible in small to medium farming initiatives due to naturally occurring bioactive substances, the potential ecological repercussions of large-scale ventures remain uncertain. The quantity and fate of DOM and POM from seaweed cultivation, its transportation, and its implications on marine habitats, including sediment oxygenation, hypoxia, and nutrient fluxes, necessitate further detailed investigation. To mitigate these impacts, comprehensive studies are needed to determine the precise volumes and environmental factors governing the release of DOM and POM from seaweed cultivation. Understanding the potential ecological consequences, especially in depositional zones, would aid in the development of effective management strategies for large-scale seaweed farming initiatives (Bhuyan,2023).

(7) Habitat Alteration: Seaweed infrastructure alters water flow, light, sedimentation, and organic loading, negatively impacting benthic habitats through reduced diversity, organic enrichment, and community shifts (Fan et al., 2009; Zhang et al., 2009; Zhou, 2012). However, farms also create new habitats, providing structure and food for various fauna (Walls et al., 2016). The release of particulate and dissolved organics from farms can stimulate bacterioplankton growth but also enrich sediments locally (Hulatt et al., 2009; Wada et al., 2007; Zhang et al., 2011; Zhou, 2012).

(8) Disease Management and Biosecurity: The expansion of seaweed farming also presents environmental challenges in the form of disease outbreaks and the introduction of invasive species.

Open water cultivation is vulnerable to pathogens, made worse by genetic bottlenecks in farmed stock (Valero et al., 2017). Disease susceptibility due to genetic loss and vulnerability to stressors like rising water temperatures threaten cultivated seaweed. Invasive species, introduced through aquaculture activities, pose ecological and economic risks by altering marine ecosystems. Biosecurity measures including quarantine, diagnostics, breeding, and planning are critical to control diseases (Cottier-Cook et al., 2016; Gachon et al., 2010). Preventing introductions of non-native species is also a priority (Cook et al., 2014). Mitigation strategies involve managing vectors like biofouling, cultivating native seaweeds, and monitoring operations to reduce the risk of introducing exotic species. Additionally, efforts to understand and control diseases affecting seaweed, and vigilance in preventing the spread of invasive species, are crucial to safeguarding marine ecosystems (Bhuyan, 2023).

(9) Pollutants: The expansion of seaweed farming involves the addition of artificial materials, mainly synthetic ropes and other non-degradable elements. Mismanagement or loss of these materials could contribute to ocean pollution, adding to existing environmental concerns like the rising quantity of plastics in aquatic systems.

In conclusion, seaweed farming provides important ecosystem services but may also alter marine habitats and food webs substantially if not properly managed. Overall, while some environmental benefits of seaweed aquaculture are well-supported empirically, outcomes are often context-dependent. More research is needed to clarify species-specific and regional impacts. Of special note are the potential risks of scaling up seaweed cultivation (Spillias et al.,2023). Developers must consider appropriate scales and sites to balance production and sustainability through monitoring, research, and mitigation measures.

9. Economic analyses of seaweed-based CDR

During the last decades, the high biomass production rates and high content of valuable organic compounds led to the increase in consumer demand for seaweed products and commercial interest in their production in general (Hochman and Palatnik, 2022). Seaweed farms bring benefits beyond the immediate value of their crop (Hochman and Palatnik, 2022). Advancements in science and technologies led to the diversification of macroalgae applications to food and beverages (Torres et al 2019), pharmaceuticals (Golberg et al 2020), wastewater treatment (Wang et al 2020), biorefining (Prabhu et al 2020, Seghetta et al 2016), dietary supplements (Peñalver et al 2020), cosmetics (Pereira 2018), animal feed (deMorais & Costa 2007), and other intermediate factors of production (Janarthanan & Kumar 2018).

The potential of seaweed aquaculture for C-sequestration has recently garnered global interest. The theoretical possibility of large-scale seaweed cultivation for C-sequestration is substantial, with Froehlich et al. (2019) identifying up to 48 million km^2 of oceans as suitable for this purpose, constituting approximately 11% of the total ocean area. Accordingly, Ross et al (2022) calculated a theoretical maximum annual C-sequestration from seaweed aquaculture at 72 billion tonnes of CO_2, almost twice the global annual emissions (based on a theoretical maximum CO_2 sequestration of 1,500T CO_2 per km^2 proposed by Duarte et al 2017). Smith et al (2023) offer a more conservative estimate suggesting that seaweed-based CDR could mitigate about 1 Gt CO_2 per year, accounting for 2-3% of global annual GHG emissions, across an area of 400,000 km^2 (Ross et al 2022). China has already dedicated 1500 km^2 to seaweed cultivation (Gao et al 2022). Europe, with about 240 firms engaged in seaweed cultivation and processing, including C-sequestration, is also making strides in this field particularly in Norway, Ireland, the UK, Sweden, Portugal, and France (Investors Memo Europe, 2021; https://www.seaweedeurope.com/wpcontent/uploads/2021/10/S4E-InvestorMemo-MainReport-16OCTOBER2021.pdf). The USA and China are noted as global leaders in this sector (Hochman and Palatnik, 2022). The number of firms in the industry reflects an interest from governments, venture capitalists, and big tech, and the sheer number of ways in which seaweed-based CDR might be done.

Costs of seaweed-based CDR - An ideal CDR technique should store C in a way that is easily monitored and verified, it should be able to work on a large scale, and its costs should be low. Empirical evidence on C capture from macroalgae is scarce, with few studies estimating the costs of the seaweed industry globally (e.g. Valderrama et al 2015, van der Burg et al 2016, Kite-Powel et al 2022) and in Israel (Chemodanov et al 2017, Korzen et al 2015, Golberg et al 2021). These studies provide insights into the financial feasibility of establishing large-scale seaweed farms.

Table 1: Seaweed farm production cost estimates from the literature. (DW = dry weight)

Date	**Seaweed species**	**Location**	**Farm scale (hectares)**	**Yield (kg DW m^{-2} y^{-1})**	**Production Cost (2021 $ per DW tonne)**	**Source**
1985	*Saccharina*	USA	5300	2.2	225	Feinberg & Hock, (1985)
2009	*Kappaphycus*	Mexico	<1	5.4	900	Valderrama et al., (2015)
2009	*Kappaphycus*	Indonesia	1	1.1	400	Valderrama et al., (2015)
2016	*Saccharina*	North Sea	4,000	2	2,000	van den Burg, van Duijn, Bartelings, van Krimpen, & Poelman, (2016)
2019	*Macrocystis*	Chile	10	1.9	610	Camus, Infante, & Buschmann, (2019)

2020	*Saccharina*	Sweden	2	0.35	10,000	Hasselstroem et al., (2020)
2022	*Saccharina*	Cool temperate	1000	5	300	Kite-Powel et al., (2022)
		Tropical		5	200	

In Table 1, an analysis of current technologies indicates that the production costs for macroalgae fluctuate between $200 and $10,000 per dry ton, with an average cost approximating $400. The C composition of a dry ton of macroalgae is approximately 25%, as delineated by Duarte et al (2017). Consequently, this translates into a cost of $1,600 per ton of C for seaweed-based CDR, derived by dividing the mean production cost by the C content per ton (i.e., $400/0.25). This cost metric substantially exceeds the estimated benefits of C mitigation, as captured by the social cost of C, which recent analyses by Renert et al (2022) suggest ranges between $100 and $400 per ton of C. This discrepancy highlights a significant economic challenge in the viability of seaweed-based CDR under current technological and market conditions. However, it is important to note that co-production strategies involving seaweeds for CDR alongside the generation of seaweed-based commodities present a potentially economically viable pathway. Such co-production not only aligns with economic feasibility but also offers co-benefits that contribute to sustainable development objectives. Considering this, the subsequent section of this report is dedicated to a detailed analysis of algae-based CDR in Israel. This analysis considers the dual utilization of seaweeds, both for CDR purposes and the production of dry macroalgae for the food industry.

Estimation of seaweed-based CDR for Israel - To estimate the maximum seaweed CDR potential for Israel we multiply the theoretical maximum CO_2 sequestration of 1500 t of CO_2 per km^2 a year (Duarte et al 2017) by the area of economic waters in the Mediterranean Sea suitable for aquaculture ranging between 100 to 555 km^2 (Fig. 3). The calculation suggests a potential capture of up to 832,500 t CO_2 annually at currently available technologies comprising about 1% of the CO_2 emissions of Israel in 2022 (Israel PRTR Pollutant Release and Transfer. https://www.gov.il/en/departments/news/prtr_2022#:~:text=Greenhouse%20gas%20emissions-,National%20inventory,81.8%20million%20tons%20of%20CO2e.

The methodology of the economic evaluation is adapted based on Palatnik et al (2023). The framework in Eq. 1 allows the revenue and cost functions to decline over time due to dynamic processes of learning especially relevant in the case of novel technologies such as CDR. If potential revenues increase over time and costs of cultivation and/or processing decline, production will increase. The investor in the project maximizes the present discounted value of expected lifetime profits:

$$Eq.1:\ \max_{qt} \pi = -I + \int_0^T \left(a * p_t * q_t - \frac{vc_t^{1+\theta} * q_t}{(\sum Q_t)^\wedge \gamma} - x + (1-a) p_t^{co2} * q_t * \beta_{co2}\right) * e^{-rt}\, dt \ + \frac{I*\delta}{(1+r)^T}$$

Table 2: Definition of parameters in the profit function

parameter	meaning
r	interest rate
p	Selling price
VC	variable cost
t	Project duration in years
I	Total initial investment
a	Seaweed sales percentage
x	The cost of the CDR technology

βco2	Quantity carbon sequestration
q	Quantity
p^{co2}	carbon price
γ	Learning elasticity
δ	One less depreciation rate
θ	Real annual growth rate of variable costs

The values of the key parameters including the ranges for sensitivity analysis are presented in

Table *3*.

Table 3: Values of the key parameters

Parameter	Value	Remarks	Source
General			
Yield wet weight in kg m^{-2}	5	Range 3-10 kg wet weight m^{-2}	Kite-Powell et al., 2022, Chemodanov et al. 2017
The size of the area in km^2	100	Size ranges 100-555 km^2 total mariculture area	Min of Agriculture, Israel
Scale conversion for area	1mil	a million square meters in a 1 square kilometer	
Project duration in years	20	Range between 3 and 30 years	
Real interest rate	4%	Range between 0% and 10%	
Costs			
Total investment (fixed costs)	$ 32 mil	Range between $ 0 and 32 million	Van den Burg et al., (2016) Golberg et al., (2021)
Cost of planting material per meter	$ 1.5	dollars planting cost per meter (range between 0.4 dollar and 4 dollars)	Van den Burg et al., (2016)
Total labor cost	$ 3.27 mil	Between 40-180 workers for eight hours of work a day for 365 days a year at a salary of $28 an hour	Van den Burg et al., (2016) Golberg et al., (2021)
Transportation	$ 2.29mil	Range between 0.1 of the original cost up to double cost	Golberg et al., (2021)
Growth rate of variable cost per year	0.5%	Range between 0.1% and 1%	Golberg et al., (2021)

Elasticity of learning in algae technology	5%	Range between 0% and 70%	Palatnik et al., (2023)
Depreciation	80%	By the end of the project	Palatnik et al., (2023)
Revenues			
Selling price per kg of dry seaweed	$7	range 4-11$	US seaweed prices 2023 https://www.selinawamucii.com/insights/prices/united-states-of-america/seaweed/
Dry weight seaweed value in $ kg^{-1}	$10.5	equation (the price is per kilo)	
Conversion from wet to dry material	0.3	conversion factor	Duarte et al. 2017
Carbon pricing	$200	$ per tonne of CO_2 range 100-400	Renet et al., (2022)
Carbon content coefficient	0.3	conversion number	Duarte et al. 2017
Tone of carbon km^{-2}	450	A tonne of CO_2 km^{-2} range 350-1500	Duarte et al. 2017

As the costs of sequestration are not available at this point, the strategy of this report is to estimate the maximum cost of C-sequestration that will allow the process of seaweed-based C sink to be economically efficient.

Results - First, we apply the modeling framework to the mean values of all the parameters in Table ***3***. The resulting cost per ton of dry weight of seaweed is $ 334.27. If only 5% of seaweed production is devoted to direct consumption, the net present value (NPV) of the profit in Eq. 1 is negative. However, increasing the share of dry seaweed to 10% results positive NPV stressing the importance of co-production for economic feasibility of the process (Fig 4.).

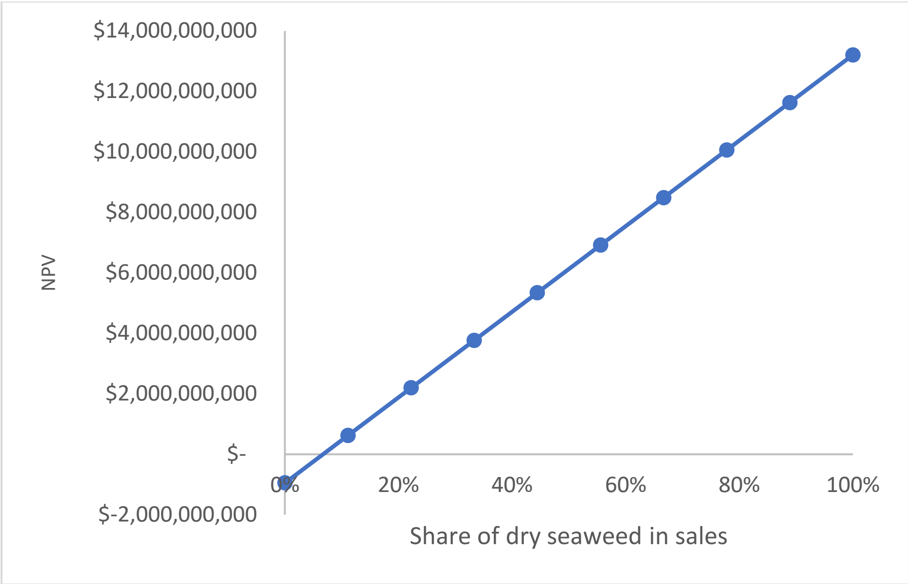

Fig 4. NPV as a function of the share of dry seaweed in sales

The size of the area devoted to seaweed cultivation has a positive impact on the profitability of the process due to learning modeled explicitly in the cost function (Fig 5.).

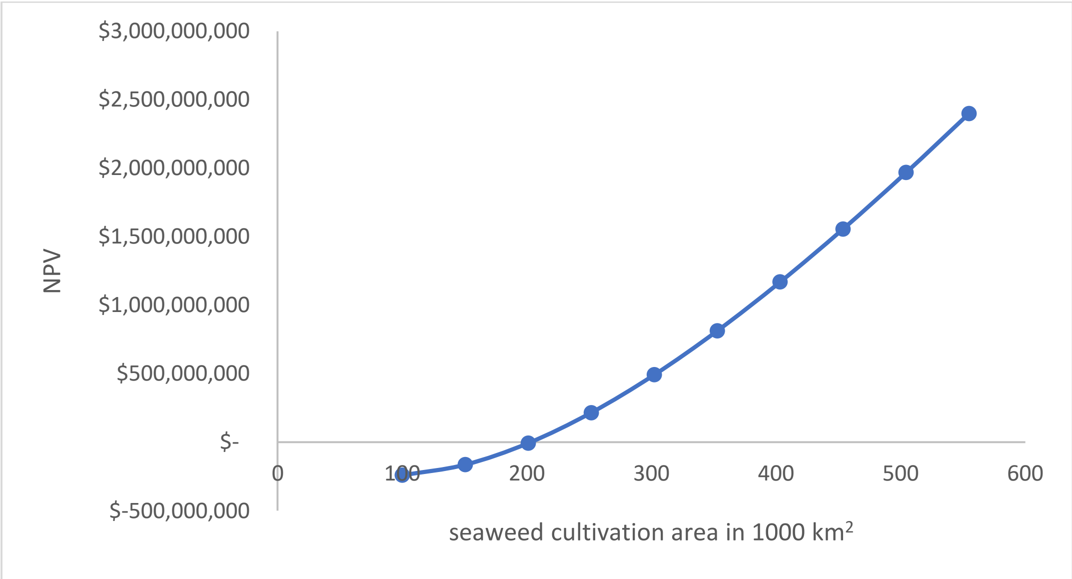

Fig 5. NPV as a function of seaweed cultivation area in thousand square kilometers

Figure 3 elucidates the relationship between the scale of seaweed production and the corresponding cost per ton. It demonstrates a clear correlation wherein an increase in the scale of seaweed farms is associated with enhanced production outputs. This increment in production concurrently facilitates a 'learning by doing' effect, which is instrumental in driving a reduction in the cost per unit of seaweed produced. The projection within this figure suggests that, with the expansion of production scale, the costs could potentially decline to levels that are commensurate with the social cost of carbon. Such a trend indicates the possibility of rendering seaweed-based CDR economically efficient, positioning it as a viable component within the array of strategies aimed at achieving Net Zero policies in Israel.

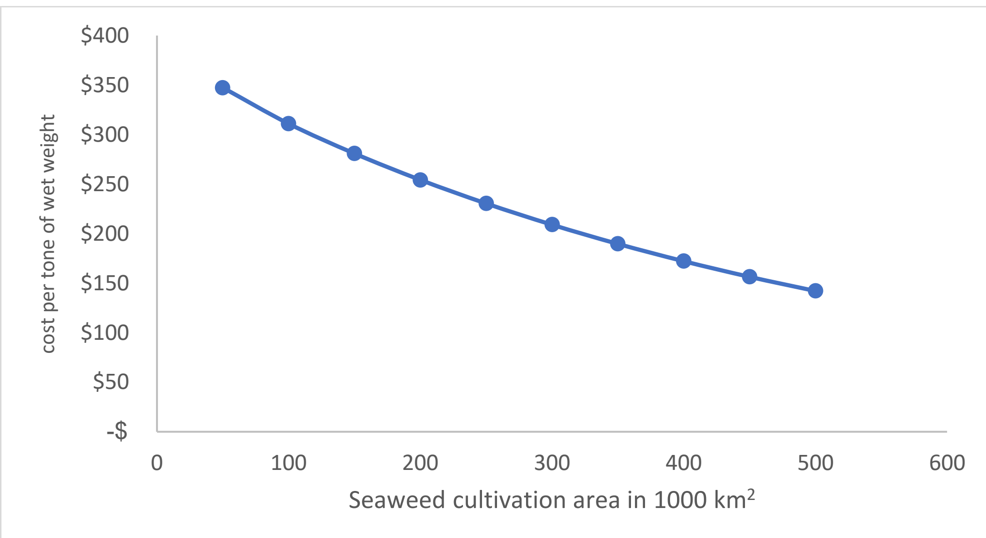

Fig 6. The effect of the change in the size of the area on the cost per ton of wet weight of seaweed

In the concluding segment of our analysis, we investigate the economic dynamics of substitutability between the carbon content and the market price of seaweed. Notably, there is an observable variation in both the carbon content and the market price across different seaweed species. To comprehensively assess this relationship, we fix the NPV at a neutral profitability (zero). Fig allows to methodically explore the necessary escalation in seaweed prices that would offset any diminution in carbon content.

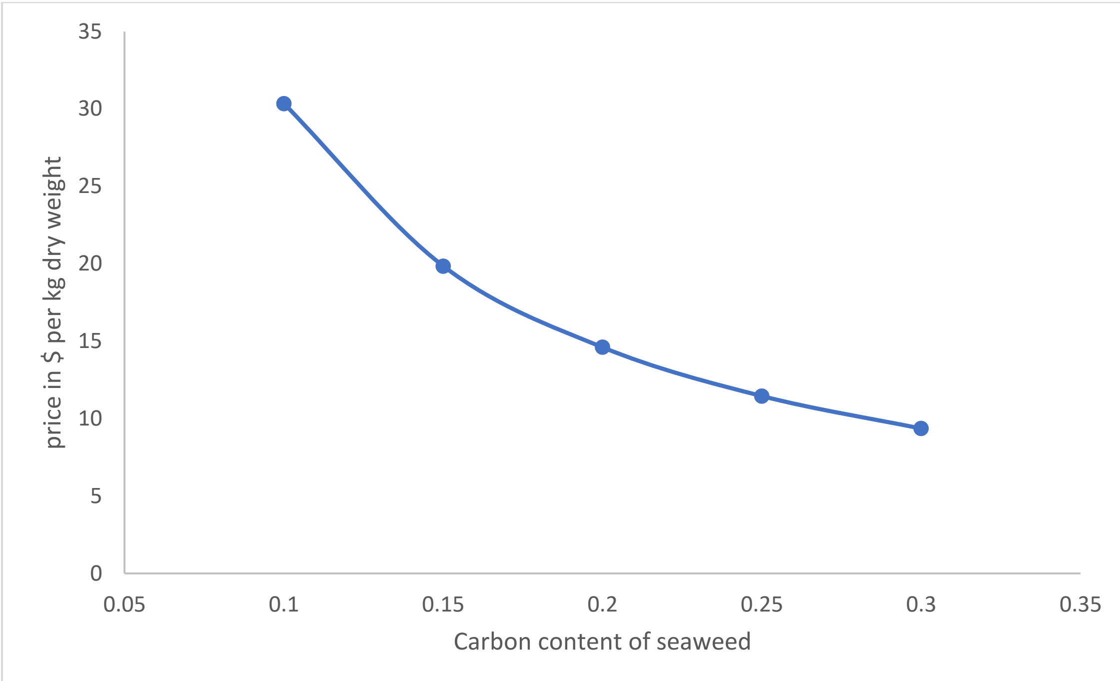

Fig 7: The change in carbon content on seaweed price (for npv 0).

Fig aims to elucidate the price elasticity in relation to the carbon content among various seaweed species, providing insights into the economic implications of variances in carbon sequestration capabilities within the context of commercial seaweed production. Such an analysis is pivotal in understanding the financial adjustments required to maintain economic viability in the face of fluctuating carbon yields in different seaweed species.

Discussion of the insights of economic assessment - The commercial interest in algae production has surged due to its high biomass growth rates and organic compound content. The use of macroalgae has diversified into numerous sectors, including food, pharmaceuticals, and biorefining. Seaweed aquaculture's potential for carbon sequestration is significant, with theoretical estimates suggesting a substantial capacity for global CO_2 mitigation. However, more conservative estimates suggest a mitigation potential of about 1 $GtCO_2$ per year, equating to 2-3% of global annual GHG emissions. The estimation of seaweed-based CDR potential in Israel can reach about 1% of annual emissions. Therefore, CDR should be considered not as a tool for carbon mitigation but rather as a complementary policy for Net Zero pledges.

Notable progress in seaweed cultivation is seen globally, with China, Europe, and the USA leading in cultivation and research. This indicates a growing interest and investment in seaweed-based CDR.

The production cost of macroalgae varies significantly, with the cost of seaweed-based CDR currently much higher than the social cost of carbon. This poses an economic challenge to its viability as a CDR method. The report shows that co-producing seaweed for CDR and seaweed-based commodities (like food) could be economically viable and sustainable, offering a solution to the cost challenge. The cost per ton of seaweed production decreases with the increase in the scale of farms, suggesting that learning could make seaweed-based CDR more cost-efficient and align it with Net Zero policy strategies. The analysis of the substitutability between the carbon content in seaweed and its price revealed that price adjustments might be necessary to compensate for variations in carbon content across different seaweed species.

In summary, while seaweed-based CDR presents a significant potential for carbon mitigation and sustainable development, its economic viability hinges on factors such as production scale cost management, species-specific characteristics, and the integration of CDR with other commercial uses of seaweed.

10. Conclusions and suggestions

- In the last few years, the CO_2 scrubbing capacities of seaweeds have been the focus of attention by the general community, encouraged by their recognition for their added values. A substantial number of arguments and theoretical assessments have been published only between 2018-2023 to address **the potential use of seaweeds for climate solutions**. Interestingly, valuable assessments were also carried out much earlier (Chung et al. 2011) when global change threats were still on the verge.
- Developing technologies for various offshore environmental conditions are needed. From past experimental and feasibility work done by Israeli scientists we suggest that the best potential seaweed candidates for further work are *Ulva* and *Gracilaria.*
- Economical/technical comparisons **between land-based and marine-based** seaweed cultivation under various scenarios should be evaluated and considered. As the demands grow, land-based seaweed aquaculture in Israel can develop on extensive abandoned fish farms along the Carmel coast, or in desert locations along the Arava area. Furthermore, with appropriate advances in infrastructure and engineering, offshore cultivation may take place within the Exclusive Economic Zone (EEZ) set for the IMS.

- Accurate assessments of how much CO_2 seaweeds can trap and retain in the long run need further work. Several open questions require attention before a seaweed-based platform for climate change remediation is implemented, and further socio-economic analysis, clear regulations, and policy incentives are necessary; the following some of the relevant ones:

(1) Cultivation up-scale; this includes some aspects such as developing cultivation technologies that are sustainable, economically viable, and effective not only in trapping CO_2 but also keeping it away for a long time. There is still one big challenge for the IMS: the technological development of seaweed farms that will be sustainable under the frequent harsh offshore conditions. Production costs are also a significant aspect, and while model calculations are encouraging (for example, US$ 200-300 per dry tonne of *Saccharina latissima*; Kite-Powell et al. 2022), they still need field validation for all seaweed candidates within the IMS.

(2) Full quantitative understanding of C sequestration; calculations of C uptake potential by seaweeds are largely based on assumptions and extrapolations (Dudgeon and Kübler 2020; FAO 2020). Quantifying the NPP of different seaweed groups and specific target species across their global extent remains a key barrier to reliably resolving the contribution of seaweed to oceanic carbon cycles (Pessarrodona et al. 2022). There is a need to produce accurate experimental data when seaweeds are cultivated in a specific biogeographic area, in the long run, covering seasonality and for a variety of species.

(3) Long-term (at least 100 years) sequestration of CO_2; estimations of seaweed organic matter deposition at depth or in sediments have been made, and theoretical solutions have been discussed.

- The prevailing harsh natural conditions within the IMS with its exposed coastline and various usage conflicts have largely discouraged the development of seaweed cultivation projects in the sea. The economic potential of the EEZ has been fully recognized in the last decade, triggering the possibility of aquaculture activities including seaweed cultivation. Producing sustainable algal biomass offshore for commodities and bioenergy is promising because of its sustainability, but is an extremely challenging endeavor. Although the concept of Ocean Farms has been introduced decades ago, current commercial seaweed cultivation is mostly practiced in protected, near shore areas. In most cases offshore cultivation means the movement of farm installations from near shore, sheltered environments and facilities to more exposed environments, where frequent harvests may have additional logistical and cost implications. New original ideas for the physical cultivation technology, nutrient supply and biomass processing, such as in biorefineries, will be needed (Neori and Guttman 2017, Kazir et al. 2018, Prabhu et al. 2019). Key aspects when evaluating the potential value of seaweeds in Israel include also solidifying past taxonomic identifications and long-term records and descriptions of local seaweeds, both particularly troublesome for the Levant basin.

Following the economic assessments, these additional recommendations are proposed:

1. The economic viability of seaweed cultivation greatly increase with **co-production** of valuable products combined with carbon capture.
2. Implementation of C pricing policy: The development and adoption of novel CDR technologies are fundamentally reliant on the establishment of an effective C pricing policy. Such a policy framework is essential not only for incentivizing the reduction of C emissions but also for encouraging the development and deployment of innovative CDR methods.
3. Utilization of C taxing in current economic climate: Considering the prevailing economic crisis, the implementation of a C tax could serve dual objectives. It would not only foster environmental sustainability by pricing C emissions appropriately but also contribute positively to fiscal policy

needs by generating revenue. This dual benefit makes it a compelling policy tool in the current economic scenario.

4. Investment in basic research and learning potential: There is a critical need for increased investment in basic research to enhance the understanding and efficiency of CDR technologies. Additionally, harnessing the potential of 'learning by doing' through ongoing development and deployment can lead to cost reductions and improvements in technology over time. Such investment is crucial for advancing the scalability and economic viability of CDR solutions.

These recommendations emphasize the integration of environmental objectives with economic and fiscal strategies, highlighting the role of policy and research in advancing the field of CDR, particularly in the context of seaweed-based C sequestration. Implementing these measures could significantly contribute to achieving broader environmental goals while addressing economic challenges.

Finally, as described below, microalgae as feedstock for CDR is also worth exploring. Brilliant Planet, a London-based company, has operations in Morocco and Oman aiming at pumping seawater into big ponds in coastal deserts, growing algae with it, drying the algae out and burying it. Charm Industrial, based in San Francisco, raised $100m in June 2023 for a system which turns biomass into a sort of C-rich oil and pumps it into geological storage.

11. A brief evaluation of microalgae offshore cultivation potential in the IMS

We have judged pertinent to also present in this report emerging technologies and alternatives related to the cultivation of microalgae, or phytoplankton. Approaching microalgae should also be part of a broad-spectrum evaluation of whether other groups within the algal sector can offer substantial benefits on C-sequestration. One suggested model is depicted in Fig. 8.

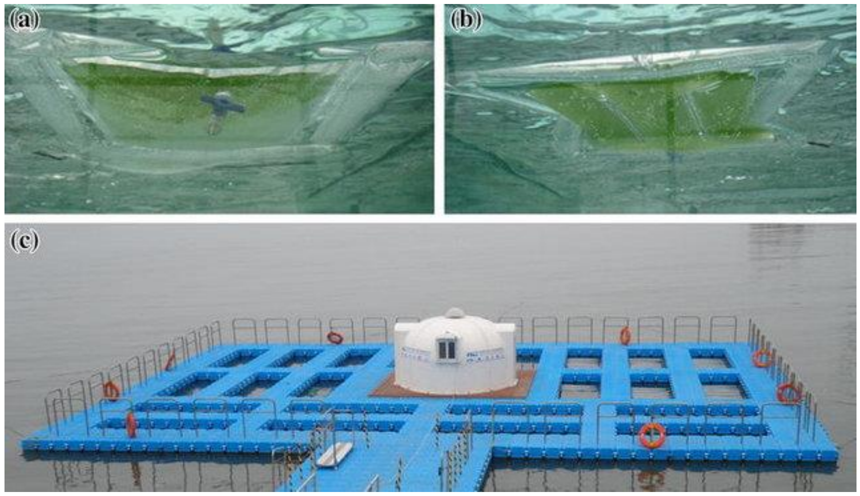

Fig 8. Photographs of prototype floating PhotoBioReactors (PBRs) for microalgal culture offshore. Control (a) and the PBR with C-2 partitions (b) and the ocean test bed where cultivation experiments were performed (c). Taken from Bioprocess and Biosystems Engineering (DOI:10.1007/s00449-016-1552-6).

Similar to macroalgae, the wide application of microalgae in health foods, nutritional feeds, aquaculture, pharmaceutical extracts, and biofuel production is appealing to the general economy. These traits of microalgae can be an added value to C-sequestration in the context of global change attenuation. Commercial-scale cultivation of microalgae offshore also still faces two major constrains which are technological challenges and economic feasibility, with sustainable infrastructures lower cost and energy consumption. Developing floating PBRs to be utilized in offshore open water areas can diminish the cost effects of onshore land utilization. Additional benefits may include regulated temperature, proximity to sunlight and nutrient supplies, and integrated ocean renewable energy, and is timely to explore the potential of floating PBRs for microalgae cultivation in the offshore region. The design of floating PBRs has the opportunity to adopt hydrodynamical design by utilizing the external force from ocean waves to generate internal liquid sloshing for improving the mixing of cultivation medium. Offshore-based microalgae cultivation is considerably new as part of blue economy and mariculture in general, and direct potential benefits include C capture and utilization, hydrogen production, and ocean thermal energy. Various challenges in biological, economic and environmental issues, installation and maintenance, as well as destructive hydrodynamic loads need to be assessed.

12. References

Aldridge, J., van der Molen, J., Forster, R. (2012) Wider ecological implications of macroalgae cultivation. *The Crown Estate* 95.

Aminu MD et al V (2017) A review of developments in carbon dioxide storage. *Applied Energy* 208.

Ashkenazi DY, Israel A, Abelson A (2018) A novel two-stage seaweed integrated multi-trophic aquaculture. *Reviews Aquaculture* DOI: 10.1111/raq 12238.

Ashkenazi DY, et al (2022) Enrichment of nutritional compounds in seaweeds via abiotic stressors in integrated aquaculture. *Innovative Food Science & Emerging Technologies* https://doi.org/10.1016/j.ifset.2022.103067.

Bäckstrand K, Kuyper JW (2017) The democratic legitimacy of orchestration: the UNFCCC, non-state actors, and transnational climate governance. *Environment Politics* 26, 764–788.

Beck, S. & Mahony, M. The IPCC and the new map of science and politics (2018) *WIREs Climate Change* 9, e547.

Beer S, Bjork M, Beardall J (2014) *Photosynthesis in the Marine Environment*. Wiley-Blackwell, Oxford, UK. pp. 203.

Beer S, Björk M, Beardall J (2021) *Carbon dioxide vs. bicarbonate utilisation*. In: Gao HAD, Beardall J (eds) Research methods of environmental physiology in aquatic sciences. Singapore, Springer. pp. 153–164.

Beer S (2022) Photosynthetic traits of the ubiquitous and prolific macroalga *Ulva* (Chlorophyta): a review. *European Journal of Phycology* DOI: 10.1080/09670262.2022.2150894.

Bergman, K.C., Svensson, S., Ohman, M.C. (2001) Influence of algal farming on fish assemblages. *Marine Pollution Bulletin*, 42(12), 1379–1389. https://doi.org/10.1016/s0025-326x(01)00168-0

Bhuyan, M.S. (2023) Ecological risks associated with seaweed cultivation and identifying risk minimization approaches. *Algal Research*, 69. https://doi.org/10.1016/j.algal.2022.102967

Borchers M et al (2022) Scoping carbon dioxide removal options for Germany – What is their potential contribution to Net-Zero CO_2? *Front Clim* 4:810343. doi: 10.3389/fclim.2022.810343

Bhattacharyya SS et al (2022) Soil carbon sequestration – An interplay between soil microbial community and soil organic matter dynamics. *Sci. Total Environ.* 815.

Burns W, Nicholson S (2017) Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *J. Environ. Stud. Sci.* 7, 527–534.

Chemodanov A et al (2017) Net primary productivity, biofuel production and CO_2 emissions reduction potential of *Ulva* sp. (Chlorophyta) biomass in a coastal area of the Eastern Mediterranean. *Ener Conv Man* 148: 1497-1507.

Chen J et al (2020) DOC dynamics and bacterial community succession during long-term degradation of *Ulva prolifera* and their implications for the legacy effect of green tides on refractory DOC pool in seawater. *Water Res* 185:116268.

Chung IK et al (2011) Using marine macroalgae for carbon sequestration: a critical appraisal. *J Appl Phycol* DOI 10.1007/s10811-010-9604-9.

Clasen, J.L., Shurin, J.B. (2015) Kelp forest size alters microbial community structure and function on Vancouver Island, Canada. *Ecology*, 96(3), 862–872.

Cook, E.J., Payne, R., Macleod, A. (2014) Marine Biosecurity Planning-Identification of Best Practice: A Review. *Scotland: Scottish Natural Heritage*.

Cooley SR et al (2023) Sociotechnical Considerations about Ocean Carbon Dioxide Removal. *Ann. Rev. Mar. Sci.* 15, 41–66.

Cottier-Cook, E.J., Nagabhatla, N., Badis, Y., et al. (2016) Safeguarding the Future of the Global Seaweed Aquaculture Industry. *United Nations University (INWEH) and Scottish Association for Marine Science Policy Brief.* http://inweh.unu.edu/safeguardingthe-future-of-the-global-seaweed-aquaculture-industry-policy-brief/

Council NR (2015) *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. (The National Academies Press, 2015). doi:10.17226/18805

Delva S et al (2023) Tracing the introduction of *Dictyota acutiloba* (Dictyotales, Phaeophyceae) in the Mediterranean Sea, with a reassessment of its geographical distribution. *Eur J Phycol* https://doi.org/10.1080/09670262.2023.2214184

Drechsler Z et al (1993) The relationship of arginine groups to photosynthetic HCO_3^- uptake in *Ulva* sp. mediated by a putative 675 anion exchanger. *Planta* 191: 34–40.

Duarte CM et al (2017) Can seaweed farming play a role in climate change mitigation and adaptation? *Front Mar Sci* 4, 100.

Duarte CM et al (2022) Global estimates of the extent and production of macroalgal forests. *Glob Ecol Biogeo* 31, 1422– 1439. https://doi.org/10.1111/geb.13515.

Dudgeon S, Kübler JE (2020) A multistressor model of carbon acquisition regulation for macroalgae in a changing climate. *Limnol Oceanogr* doi:10.1002/lno.11470.

Eddy TD et al (2021) Global decline in capacity of coral reefs to provide ecosystem services. *One Earth*. https://doi.org/10.1016/j.oneear.2021.08.016.

Erans M et al (2022) Direct air capture: process technology, techno-economic and socio-political challenges. *Energy Environ. Sci.* 15, 1360–1405.

EU (2022) Communication from the Commission to the European parliament, the Council, the European economic and social committee and the committee of the regions. pp. 17.

Fan, X., Wei, H., Yuan, Y., Zhao, L. (2009) Vertical structure of tidal current in a typically coastal raft-culture area. *Cont. Shelf Res.*, 29(20), 2345–2357.

FAO (2020) The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome, DOI:10.4060/ca9229en.

Falkowski PG, Raven JA (2013) Aquatic photosynthesis. New Jersey: Princeton University Press.

Froehlich HE et al (2019) Blue growth potential to mitigate climate change through seaweed offsetting. *Curr Biol 29,* 3087.

Gachon, C.M., Sime-Ngando, T., Strittmatter, M., et al. (2010) Algal diseases: spotlight on a black box. *Trends Plant Sci.*, 15, 633–640. doi: 10.1016/j.tplants.2010.08.005

Gao K, Beardall J (2022) Using macroalgae to address UN sustainable development goals through CO_2 remediation and improvement of the aquaculture environment. *App Phycol* DOI: 10.1080/26388081.2022.2025617.

Gao G et al (2022) The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. *Environ Res Lett* https://doi.org/10.1088/1748-9326/ac3fd9.

Golberg A et al (2021) "Hybrid solar-seaweed biorefinery for co-production of biochemicals, biofuels, electricity, and water: Thermodynamics, life cycle assessment, and cost-benefit analysis." *Energy Conversion and Management* 246: 114679.

Han, T., Shi, R., Qi, Z., Huang, H., Wu, F., Gong, X. (2020) Biogenic acidification of Portuguese oyster *Magallana angulata* mariculture can be mediated through introducing brown seaweed *Sargassum hemiphyllum*. *AQUACULTURE*, 520.

Hanssen SV et al (2022) Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. *GCB Bioenergy* 14, 307–321.

Hehre, E.J., Meeuwig, J.J. (2015) Differential Response of Fish Assemblages to Coral Reef-Based Seaweed Farming. *PLoS ONE*, 10(3). https://doi.org/10.1371/journal.pone.0118838

Hill R et al (2015) Can macroalgae contribute to blue carbon? An Australian perspective. *Limnol Oceanogr* 60: 1689–1706.

Hochman Gal, Palatnik RR (2022) The economics of aquatic plants: the case of algae and duckweed. *Annual Review of Resource Economics* 14: 555-577.

Hong WY (2022) A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO2 emissions future. *Carbon Capture Sci. Technol.* 3, 100044.

Hulatt, C.J., Thomas, D.N., Bowers, D.G., Norman, L., Zhang, C. (2009) Exudation and decomposition of Chromophoric Dissolved Organic Matter (CDOM) from some temperate macroalgae. *Estuar. Coast. Shelf Sci.*, 84, 147–153. doi: 10.1016/j.ecss.2009.06.014.

Huo, Y., Han, H., Hua, L., Wei, Z., Yu, K., Shi, H., et al. (2016) Tracing the origin of green macroalgal blooms based on the large scale spatio-temporal distribution of *Ulva* microscopic propagules and settled mature *Ulva* vegetative thalli in coastal regions of the Yellow Sea, China. *Harmful Algae*, 59, 91–99.

Hurd CL et al (2009) Testing the effects of ocean acidification on algal metabolism: considerations for experimental designs. *J Phycol* 45, 1236–1251.

Hurd CL et al (2020) Ocean acidification as a multiple driver: how interactions between changing seawater carbonate parameters affect marine life. *Mar Fresh Res* 71, 263–274 https://doi.org/10.1071/MF19267.

Hurd CL et al (2022) Forensic carbon accounting: assessing the role of seaweeds for carbon sequestration. *J Phycol* https://doi.org/10.1111/jpy.13249.

Israel A, Hophy M (2002) Growth, photosynthetic properties and Rubisco activities and amounts of marine macroalgae grown under current and elevated seawater CO_2 concentrations. *Glob Change Biol* 8:1-10.

Israel A, Shpigel M (2023) Photosynthetic CO_2 uptake by *Ulva* (Chlorophyta) as a potential contribution to global warming containment. *Journal of Applied Phycology* https://doi.org/10.1007/s10811-023-02929-w

Jeswani HK, Saharudin DM, Azapagic A (2022) Environmental sustainability of negative emissions technologies: A review. *Sustain. Prod. Consum.* 33, 608–635.

Ji Y, Gao KS (2021) Effects of climate change factors on marine macroalgae: A review. *Adv Mar Biol* 88:91–136.

Jiang, Z.J., Fang, J.G., Mao, Y.Z., Han, T.T., Wang, G.H. (2013) Influence of Seaweed Aquaculture on Marine Inorganic Carbon Dynamics and Sea-air CO2 Flux. *Journal of the World Aquaculture Society*, 44(1), 133–140.

Jiao NZ et al (2010) Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nat Rev Microbiol* 8:593–599.

Kite-Powell HL et al (2022) Estimating production cost for large-scale seaweed farms. *Appl Phycol* 3:435-445, DOI: 10.1080/26388081.2022.2111271.

Korzen L, Abelson A, Israel A (2015) Using an offshore Integrated Multi-Trophic Aquaculture system for enhanced production of carbohydrate-rich seaweed biomass. *J Appl Phycol* 28:1835-1845.

Li, H., Zhang, Y., Liang, Y., Chen, J., Zhu, Y., Zhao, Y. (2018) Impacts of maricultural activities on characteristics of dissolved organic carbon and nutrients in a typical raft-culture area of the

Yellow Sea, North China. *Marine Pollution Bulletin*, 137, 456–464. https://doi.org/10.1016/j.marpolbul.2018.10.048.

Li H et al (2022) Green tides significantly alter the molecular composition and properties of coastal DOC and perform dissolved carbon sequestration. Environ Sci Technol https://doi.org/10.1021/acs.est.2c05684.

Liu, D., Keesing, J.K., Dong, Z., Zhen, Y., Di, B., Shi, Y., et al. (2010) Recurrence of the world's largest green-tide in 2009 in Yellow Sea, China: *Porphyra yezoensis* aquaculture rafts confirmed as nursery for macroalgal blooms. *Marine Pollution Bulletin*, 60(9), 1423–1432. https://doi.org/10.1016/j.marpolbul.2010.05.015.

Liu, Z., Luo, H., Wu, Y., Ren, H., Yang, Y. (2019) Large-scale cultivation of *Gracilaria lemaneiformis* in Nan'ao Island of Shantou and its effects on the aquatic environment and phytoplankton. *Journal of Fishery Sciences of China*, 26(1), 99–107.

Lüning, K., Pang, S. (2003) Mass cultivation of seaweeds: current aspects and approaches. *J. Appl. Phycol.*, 15(2), 115–119.

Markowitz, T.M., Harlin, A.D., Würsig, B., McFadden, C.J. (2004) Dusky dolphin foraging habitat: overlap with aquaculture in New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 14, 133–149. doi: 10.1002/aqc.602.

Masson-Delmotte V et al (2021) IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://hdl.handle.net/10204/12710.

McLaughlin H et al (2023) Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world. *Renew. Sustain. Energy Rev.* 177, 113215.

Madejski, P et al (2022) Methods and Techniques for CO_2 Capture : Review of Potential. *Energies* 15, 887.

Mantri VA et al (2020) Concise review of green algal genus *Ulva* Linnaeus. *J Appl Phycol* https://doi.org/10.1007/s10811-020-02148-7.

Nahor O, Luzzatto-Knaan T, Israel Á. (2022) A new genetic lineage of *Asparagopsis taxiformis* (Rhodophyta) in the Mediterranean Sea: as the DNA barcoding indicates a recent Lessepsian introduction. *Frontiers in Marine Science* https://DOI:10.3389/fmars.2022.873817

Nandhini R, Sivaprakash B, Rajamohan N, Vo D-VN (2022) Carbon-free hydrogen and bioenergy production through integrated carbon capture and storage technology for achieving sustainable and circular economy– A review. *Fuel* https://doi.org/10.1016/j.fuel.2022.126984.

Neori A et al (2019) Israeli-developed models of marine integrated multi trophic aquaculture (IMTA). In: Jithendran KP, Saraswathy R, Balasubramanian CP, Kumaraguru Vasagam KP, Jayasankar V, Raghavan R, Alavandi SV, Vijayan KK (eds) BRAQCON 2019: World Brackishwater Aquaculture Conference. J Coastal Res. Special Issue pp 11–20.

Neori A et al (2020) The suitability of *Ulva fasciata*, *Ulva compressa* and H*ypnea musciformis* for production in an outdoors spray cultivation system, with respect to biomass yield and protein content. J Appl Phycol https://doi.org/10.1007/s10811-020-02130-3.

Olivier JGJ and Peters JAHW (2019) Trends in global CO_2 and total greenhouse gas emissions: 2019 report. PBL Netherlands Environmental Assessment Agency, The Hague.

Ortega A et al (2019) Important contribution of macroalgae to oceanic carbon sequestration. Nature Geosci 12:748–754. https://doi.org/10.1038/s41561-019-0421-8.

Ozer T et al (2016) Interannual thermohaline (1979-2014) and nutrient (2002-2014) dynamics in the Levantine surface and intermediate water masses, SE Mediterranean Sea. Glob Plan Chan 1-8. doi:10.1016/j.gloplacha.

Paine ER et al (2021) Rate and fate of dissolved organic carbon release by seaweeds: a missing link in the coastal ocean carbon cycle. J. Phycol. 57:1375–1391. DOI: 10.1111/jpy.13198.

Palatnik RR et al (2023). Algae-based two-stage supply chain with co-products. *Ecological Economics*, *207*, 107781.

Pastor F, Valiente JA, Khodayar S (2020) A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote Sens* 12:2687. https://doi.org/10.3390/rs12172687.

Peña V et al (2021) Major loss of coralline algal diversity in response to ocean acidification. Glob Chang Biol https://doi.org/10.1111/gcb.15757.

Pessarrodona A et al (2022) Global seaweed productivity. Sci Adv 8, eabn2465.

Pörtner H et al (2022) *IPCC, 2022: summary for policymakers.* In: Climate change 2022: Impacts, adaptation, and vulnerability: contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, NY, US, pp. 3-33.

Prabhu M et al (2020) Integrated biorefinery process for sustainable fractionation of *Ulva ohnoi* (Chlorophyta): process optimization and revenue analysis. J Appl Phycol https://doi.org/10.1007/s10811-020-02044-0.

Qarri A, Israel A (2020) Seasonal biomass production, fermentable saccharification and potential ethanol yields in the marine macroalga *Ulva* sp. (Chlorophyta). Renew Ener 145:2101-2107.

Rennert K et al (2022). Comprehensive evidence implies a higher social cost of CO_2. *Nature, 610(7933), 687-692.*

Rennert K et al (2022) Comprehensive evidence implies a higher social cost of CO2. *Nature,* 610(7933), 687-692.

Raven JA (2017) The possible roles of algae in restricting the increase in atmospheric CO_2 and global temperature. *European Journal of Phycology 52:*506–522.

Rilov G (2016) Multi-species collapses at the warm edge of a warming sea. Sci Rep 6, 36897; doi: 10.1038/srep36897.

Ross F, Tarbuck P, Macreadie PI (2022) Seaweed afforestation at large-scales exclusively for carbon sequestration: critical assessment of risks, viability and state of knowledge. Front Mar Sci. https://doi.org/10.3389/fmars.2022.1015612.

Shi, J., Wei, H., Zhao, L., Yuan, Y., Fang, J., Zhang, J. (2011) A physical–biological coupled aquaculture model for a suspended aquaculture area of China. *Aquaculture*, 318(3–4), 412–424.

Shpigel M et al (2017) *Ulva lactuca* from an Integrated Multi-Trophic Aquaculture (IMTA) biofilter system as a protein supplement in gilthead seabream (*Sparus aurata*) diet. Aquaculture https://doi.org/10.1016/j.aquaculture.2017.08.006.

Smith SM et al (2023) The State of Carbon Dioxide Removal - 1st Edition. The State of Carbon Dioxide Removal. doi:10.17605/OSF.IO/W3B4Z

Spillias, S., Kelly, R., Cottrell, R.S., O'Brien, K.R., Im, R-Y., Kim, J.Y., Lei, C., Leung, R.W.S., Matsuba, M., Albano Reis, J., Sato, Y., Sempert, K., McDonald-Madden, E. (2023) The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustain Transform*, 2(2). https://doi.org/10.1371/journal.pstr.0000042.

Sternberg M et al (2015) Impacts of climate change on biodiversity in Israel: an expert assessment approach. Reg Environ Change 15: 895-906.

Steinhagen S et al (2021) Sustainable large-scale aquaculture of the northern hemisphere sea lettuce, *Ulva fenestrata*, in an off-shore seafarm. J Mar Sci Eng. https://doi.org/10.3390/jmse9060615.

Thrasher B et al (2022) NASA Global Daily Downscaled Projections, CMIP6. *Sci. Data* 9, 262

Trevathan-Tackett SM et al (2015) Comparison of marine macrophytes for their contributions to blue carbon sequestration. *Ecology* 96:3043–3057.

Valero, M., Guillemin, M.L., Destombe, C., Jacquemin, B., Gachon, C.M.M., Badis, Y., Buschmann, A.H., Camos, C., Faugeron, S. (2017) Perspectives on domestication research for sustainable seaweed aquaculture. *Perspective in psychology,* 4(1), 33–46.

Wada, S., Aoki, M.N., Tsuchiya, Y., Sato, T., Shinagawa, H., Hama, T. (2007) Quantitative and qualitative analyses of dissolved organic matter released from *Ecklonia cava Kjellman*, in Oura Bay, Shimoda, Izu Peninsula, Japan. *J. Exp. Mar. Biol. Ecol.*, 349(2), 344–358.

Walls, A.M., Kennedy, R., Fitzgerald, R.D., Blight, A.J., Johnson, M.P., Edwards, M.D. (2016) Potential novel habitat created by holdfasts from cultivated *Laminaria digitata*: assessing the macroinvertebrate assemblages. *Aquacult. Environ. Interact.*, 8, 157–169.

Watsoncapps, J., Mann, J. (2005) The effects of aquaculture on bottlenose dolphin (*Tursiops sp.*) ranging in Shark Bay, Western Australia. *Biol. Conserv.*, 124, 519–526. doi: 10.1016/j.biocon.2005.03.001.

Wei, Z.L., You, J.G., Wu, H.L., Yang, F.F., Long, L.J., Liu, Q., et al. (2017) Bioremediation using *Gracilaria lemaneiformis* to manage the nitrogen and phosphorous balance in an integrated multi-trophic aquaculture system in Yantian Bay, China. *Marine Pollution Bulletin*, 121(1–2), 313–319. https://doi.org/10.1016/j.marpolbul.2017.04.034.

Xie, X., He, Z., Hu, X., Yin, H., Liu, X., Yang, Y. (2017) Large-scale seaweed cultivation diverges water and sediment microbial communities in the coast of Nan'ao island, South China Sea. *Sci. Total Environ.*, 598, 97–108.

Yong WTL et al (2022) Seaweed: A potential climate change solution. Renewable Sustainable Energy Rev. https://doi.org/10.1016/j.rser.2022.112222.

Zemach-Shamir S et al (2021) Cultivating marine macroalgae in CO_2-enriched seawater: a bio-economic approach. *Aquaculture* https://doi.org/10.1016/j.aquaculture.2021.737042.

Zhang, J., Hansen, P.K., Fang, J., Wang, W., Jiang, Z. (2009) Assessment of the local environmental impact of intensive marine shellfish and seaweed farming-application of the MOM system in the Sungo Bay, China. *Aquaculture*, 287(3–4), 304–310.

Zhang JH et al (2012) Growth and loss of mariculture kelp *Saccharina japonica* in Sungo Bay, China. *J Appl Phycol* 24:1209–1216.