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AIR-SEA CARBON DIOXIDE EQUILIBRIUM: WILL IT BE POSSIBLE TO USE SEaweEDS FOR CARBON REMOVAL OFFSETS?

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SEAWEEDS FOR CARBON REMOVAL OFFSETS?

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Abstract

To limit global warming below 2°C by 2100, we must drastically reduce greenhouse gas emissions and additionally remove ~100–900 Gt CO₂ from the atmosphere (Carbon Dioxide Removal, CDR) to compensate for unavoidable emissions. Seaweeds (marine macroalgae) naturally grow in coastal regions worldwide where they are crucial for primary production and carbon cycling. They are being considered as a biological method for CDR via substantially expanding the current scale of seaweed aquaculture, and for use in carbon trading schemes as offsets. To use seaweeds in carbon trading schemes requires verification that seaweed photosynthesis that fixes CO₂ into organic carbon results in CDR, along with the safe and secure storage of the carbon removed from the atmosphere for more than 100 years (sequestration). Although there is much ongoing research into the magnitude of seaweed carbon storage pools (e.g. as living biomass, and particulate and dissolved organic carbon in sediments and the deep ocean), these pools do not equate to CDR unless the amount of CO₂ removed from the atmosphere as a result of seaweed primary production can be quantified and verified. The draw-down of atmospheric CO₂ into seawater is via air-sea CO₂ equilibrium which operates on time scales of weeks or years depending upon the ecosystem considered. Here, we explain why quantifying air-sea CO₂ equilibrium and linking this process to seaweed carbon storage pools is the critical step needed to verify CDR by discrete seaweed beds and aquaculture systems prior to their use in carbon trading.

Introduction

Since the industrial revolution, humans have released carbon, that was stored on geological timescales as gas, oil and coal, into the atmosphere. The resulting increase in atmospheric CO₂ from pre-industrial levels of ~280 ppm to current values of 417 ppm is causing ongoing warming of the atmosphere and ocean, terrestrial and marine heatwaves, and altered weather patterns: the cumulative effects of these rapid environmental changes are altering natural systems and challenging human societies across the globe to adapt (Bindoff, 2019; Smale et al., 2019; Smith et al., 2022).

In order to keep warming below 2°C, CO₂ emissions must be drastically reduced, but also 100–1000 Gt CO₂ must be removed from the atmosphere over the present century (IPCC, 2018; 1 Gt CO₂ = a billion tonnes of carbon dioxide). Carbon Dioxide Removal (CDR) is defined as anthropogenic activities removing carbon dioxide (CO₂) **from the atmosphere** and durably storing it in geological, terrestrial, or ocean reservoirs, or in products (van Diemen R., 2022). Carbon sequestration can be defined as the storage of carbon-containing molecules for more than 100 years outside the atmosphere: sequestered carbon must be stored in a safe, reliable and verifiable way (GESAMP 2019). Ideally, carbon sequestration would permanently lock-up CO₂ so that it does not re-enter the atmosphere in the future (Smith et al. 2023). Various strategies are being proposed for CDR. Ocean-based CDR includes ocean alkalinity enhancement (Renforth and Henderson 2017) and the expansion of coastal seaweed beds including via aquaculture in order to increase the scale of seaweed primary production (Ross et al. 2023).

Seaweeds are highly productive coastal primary producers of temperate rocky shores worldwide where they form substantial biomass in natural beds, provide energy to higher trophic levels and create a habitat for invertebrates and fish (Hurd et al. 2014, Pessarrodona et al. 2022 a, b). They have been proposed as a biological method of CDR, and for eventual use in carbon trading as carbon removal offsets (Coleman et al. 2022, Cooley et al. 2022, Ross et al. 2023, S1): indeed some companies and NGOs are already selling on the voluntary carbon market seaweed carbon from aquaculture as offsets (S2, S3, S4). Ongoing projects include enhancing the scale of natural seaweed beds by restoring beds that have been negatively affected by climate change and local anthropogenic activities, and expanding the scale of seaweed aquaculture including in the open ocean (Duarte et al. 2017, Froehlich et al. 2019, Filbee-Dexter et al. 2022). Numerous start-up companies and NGOs are trialing growing seaweeds, particularly kelps (order Laminariales), in various aquaculture systems in the coastal and open oceans (S1-S7). An underlying assumption in all these trials is that the areal expansion of seaweed production will remove globally relevant amounts of atmospheric CO₂ and result in secure storage on time scales relevant to sequestration.

Demonstrating the long-term CDR and carbon sequestration by seaweeds is currently confounded by the lack of adoption of a clear definition of the term “carbon sequestration”. We use biogeochemical definitions of CDR and secure C-storage for more than 100 years (see above): these definitions require that two processes are coupled in a quantifiable way i.e. the removal of atmospheric carbon dioxide and the subsequent storage of the resulting organic carbon on long time scales. However, in the literature, carbon sequestration is variously considered as synonymous with net primary production (NPP), carbon fixation, carbon standing stock/biomass, carbon sink, or break-down products of seaweed carbon that are buried in sediments (e.g., Chung et al., 2011, Chung et al., 2017, Duarte et al., 2017,

Sondak et al., 2017, Filbee-Dexter and Wernberg 2020, Eager et al. 2023, UNEP 2023).

Although each of these processes is important to assess carbon stocks, storage pools, fluxes and budgets in seaweed systems, and export to other systems, none are equivalent to CDR nor carbon sequestration as defined above.

Forensic Carbon Accounting (FCA) is a framework to assess the contribution of seaweed to CDR and carbon sequestration and was developed to assist scientists, NGOs and companies interested in assessing the potential of seaweeds for carbon offsets and credits (see the checklist in Table 2, Hurd et al. 2022). Ensuring that carbon offset/credit schemes are legitimate is critically important to ensure the integrity of carbon credits so that they can be used in carbon trading, i.e. the removal of atmospheric CO₂ by seaweeds and its secure storage must be subject to a monitoring, reporting and verification (MRV) process (Cadman and Hales 2022). The FCA framework includes biological metrics such as photosynthesis, standing stocks, export of seaweed production to other systems including nearshore sediments and the deep ocean (Hurd et al., 2022). It also incorporates an Earth system analysis because the carbon cycles of the atmosphere and oceans are linked on global scale. There is much ongoing research to determine the contributions of seaweed carbon to various storage pools, particularly in the context of ‘Blue Carbon’, including as living biomass, particulate and dissolved organic carbon (POC, DOC), and sedimentary seaweed carbon (e.g. Pedersen et al. 2020, 2021, Gao et al. 2022, Li et al 2022, Perkins et al 2022, Erliana et al. 2023). Here we build on Hurd et al. (2022) by detailing why it is critical to link these carbon pools with air-sea CO₂ exchange in order to verify CDR by seaweeds.

Seaweed carbon storage pools

Seaweeds contribute to a range of oceanic carbon storage pools including living biomass, as well as POC, DOC and dissolved CO₂ which are released into the water column (Fig. 1a). As seaweeds are short-lived with rapid turnover-times, they do not store carbon as living biomass on time-scales relevant to sequestration (Hurd et al. 2022; Fig. 1a). Seaweed beds do not create soil, which is the largest pool of sequestered carbon on land. A proportion of seaweed carbon is, however, exported (often laterally – termed out-welling) to other systems including where it may be stored on various times-scales including in deep oceanic sediments (Fig. 1 a; Filbee-Dexter et al. in revision; Ould and Caldwell 2022). As POC and DOC are transported via ocean currents beyond continental shelves (200 m isobath, Filbee-Dexter et al. in revision), a range of processes will regulate the fate of seaweed carbon including remineralization to CO₂ by heterotrophic bacteria and photochemical oxidation (Fig. 1 a; Filbee-Dexter et al. in revision).

POC ranges in size from tiny particles (100 µm and larger detritus) to large pieces of detached seaweed blade, holdfasts, stipes or even entire detached seaweeds (Pedersen et al. 2020, 2021). It is an extremely important carbon-flux that supports higher trophic levels, being consumed within the seaweed bed by mobile and sessile herbivorous invertebrates (e.g. urchins, amphipods, isopods, snails, abalone, Fig. 1a). A proportion of POC is exported to adjacent systems where it may also be consumed (Filbee-Dexter et al., 2020) or broken down into various biochemical components some of which may reside in sediments on long time scales (Pedersen et al., 2021). The fate of kelp biomass will depend various environmental factors that affect the rate at which it decomposes and the specific biochemicals the biomass is degraded to. Factors include temperature and whether or not the local environment is

aerobic or anaerobic (Pedersen et al., 2021). In field studies of the kelp *Laminaria* *hyperborean*, break-down times were between 150-300 days, with aerobic conditions leading to the complete degradation of the biomass into various substances including mannitol and polyphenols (both constituents of DOC), whereas under anaerobic conditions around 20-30% of kelp material did not breakdown and was stored in the sediment (Pedersen et al 2021). As larger pieces of POC transit offshore, they do so with a range of invertebrates and bacteria that will result in its decomposition on various timescales (Boyd et al., 2022).

Living seaweeds release substantial amounts of DOC which is defined as “any organic carbon particles that pass through a filter pore size 0.22–0.7 μm (GF/F filters)” (Paine et al., 2021; Sondergaard & Middelboe, 1995; Fig. 1). The release rate varies seasonally, with species and location (Paine et al., 2021, 2023). DOC is a generic term for a wide range of molecules of various sizes and labilities. Labile DOC may be consumed almost immediately by bacteria in the water column. Recalcitrant and refractory DOC have much longer time scales of degradation and are the most likely form of DOC in long-term carbon storage pools: They are exported offshore to other systems including shelf seas and the deep ocean where DOC from various sources is considered an important carbon store on sequestration-relevant time scales (see Paine et al. 2021). Similar to POC, the composition of DOC will alter as it moves offshore and downwards. For example, the photochemical breakdown of DOC will likely increase in the optically brighter open oceans compared to turbid coastal waters (Wada et al. 2015). The contribution of seaweed carbon to the DOC pool is unknown and we have little understanding of its transit time and fate offshore (Paine et al., 2021).

In addition to the natural fluxes of seaweed carbon beyond the continental shelf, there is considerable interest in enhancing these process by growing seaweeds on artificial structures

in the open ocean termed ‘ocean macroalgal afforestation’ and sinking resulting biomass to the deep ocean (Fig. 1b, N’Yeurt et al. 2012, Ocean Visions and Monterey Bay Aquarium Research Institute 2022; Ross et al. 2022, Arzeno-Saltero et al. 2023, S1, S7). As seaweeds sink, a range of processes (as above) will affect their degradation and the amount of biomass that reaches the deep ocean floor (Fig. 1b). Once below the permanent pycnocline (~ 500 m) the seaweed carbon is out of contact with the atmosphere for more than 100 years. In some respects, FCA for these aquaculture systems should be more straightforward as they are mono-cultures (compared to highly diverse natural seaweed communities) with relatively few natural herbivores; so, some biological processes will be easier to assess. Nevertheless, to quantify the amount of atmospheric CO₂ that sunken seaweed biomass has removed requires measurement of air-sea CO₂ equilibrium.

Air-sea CO₂ equilibration

The key concept in understanding the role of seaweeds in CDR is the air-sea CO₂ exchange (Fig. 2). CO₂ enters (influx) and leaves (efflux) seawater as a gas, and it is the difference in the partial pressure of CO₂ in air and water that drives the movement of CO₂. If the partial pressure in air is greater than water, there will be a net influx of CO₂, and vice-versa if the partial pressure in water is higher than in air. The chemistry of CO₂ in seawater is much more complex than that of other gases such as O₂ and N₂. When it enters the ocean, CO₂ does not simply dissolve, but it reacts with the water molecule which starts a series of chemical reactions, characterizing the seawater carbonate system (Fig. 2). Bicarbonate (HCO₃⁻) is the predominant form of dissolved inorganic carbon (DIC) in the ocean with a concentration of ~1913 μmol kg⁻¹ compared to ~16 μmol kg⁻¹ for CO₂ (illustrative example, see legend of Fig. 3). The series of reactions in the seawater carbonate system are reversible and act to buffer

seawater and maintain seawater pH. However, the carbonate system reactions are very slow, leading to an air-sea equilibration time about 20 times longer for CO₂ than oxygen. The consequence is that the timescale for CO₂ to equilibrate with seawater is weeks in the coastal ocean, months and years in the open ocean and several years in some systems such as the Arctic (Jones et al. 2014, Bach et al. 2023). These timescales are modified by local physical (e.g. bubble injection), chemical (e.g. slicks and surfactants) and biological (e.g. photosynthesis and respiration) conditions which will vary in each seaweed system (see Fig. 3 in Hurd et al. 2022 and references therein).

When considering CDR by seaweeds, it is important to recognize that CO₂ is in constant flux between the air and sea: whether or not CO₂ enters or exits seawater, and the rate of this process, is essential in the assessment of CDR by seaweeds. However, this two-way movement of CO₂ to and from seawater has been overlooked in some conceptual figures of seaweed carbon sequestration potential (e.g. Coleman et al., 2022, Gao et al., 2022, Krause-Jensen & Duarte, 2016, UNEP, 2023). For example, Fig. 2 in Krause-Jensen and Duarte (2016), shows CO₂ entering the ocean as a result of natural seaweed biomass sinking to the deep ocean, implying a direct link between sinking seaweeds, CDR and carbon sequestration. However, these processes are not directly linked as we illustrate below.

Quantifying CDR by seaweeds

The vast majority of seaweeds remove inorganic carbon (CO₂ or HCO₃⁻) from seawater and not the atmosphere (Fig. 3). This photosynthetic uptake of CO₂ results in a deficit of CO₂ in the seawater within the seaweed bed and, in a second step, CO₂ enters seawater from the atmosphere, a process referred to as CO₂ equilibration (Fig. 3 a-c). The timescale of

photosynthetic CO₂ uptake by seaweeds is seconds, whereas the timescale for equilibration is weeks to years. Therefore, although seaweeds have removed CO₂ from seawater, it will take weeks to years for full equilibration depending on the system (Bach et al. 2021, 2023).

The temporal mismatch between seaweed photosynthesis and CO₂ equilibrium means that knowledge of photosynthetic rates and the size of the various seaweed carbon storage pools does not equate to either CDR or carbon sequestration. To verify CDR, the critical step is to evaluate the air-sea CO₂ equilibration (Bach et al. 2023). This can be calculated from the residence time of the seawater in the seaweed bed, and the time needed for equilibration (e.g. Bach et al 2021). The simplest seaweed system to measure would be a large, dense and shallow seaweed bed or farm (on scales of km²) that have slow seawater flows and little exchange or mixing of seawater within the bed with that surrounding it. In this scenario, the seawater within the bed may be resident for sufficient time (weeks) for CO₂ equilibration to occur, noting that most seaweeds have a requirement for at least moderate water flow for healthy growth (Hurd, 2000). If the seaweed biomass (or part thereof) can then be securely stored for 100 years or more, this could result in CDR and be quantified and verified.

If the seaweed bed is in wave-exposed site, which are typically beneficial for seaweed healthy seaweed growth (Hurd 2000), then the seawater that bears the CO₂-deficit will move rapidly to new locations with currents, along shore drift, tides and waves – such that the equilibration needed for CDR will not occur in the surface waters above the seaweed bed where the CO₂ was taken up by photosynthesis (Fig. 3e). If seawater moves along the shoreline for several weeks, and continues to stay in an autotrophic system, then it may be possible to track the water and quantify CDR (Fig. 3f1). If, however, the seawater moves over heterotrophic systems such as an oyster or mussel bed, then the water with the CO₂

deficit will mix with high-CO₂ water and there will be less net CDR, and in some extreme cases (heterotrophic water column end-member) there may be a net release of CO₂ (Fig. 3f2). In some marine systems, particularly the open ocean, the seawater bearing the CO₂ deficit can subduct such that it is not in contact with the atmosphere for a time sufficiently long for equilibration and CDR (Fig. 3 f3; Orr and Sarmiento 1992, Bach et al. 2021).

Measuring CDR by seaweeds

The critical step in measuring and verifying CDR by seaweeds is to track the parcel of water from which seaweeds removed the CO₂ to quantify CO₂ drawdown into the ocean, and verify that the CO₂ was removed by the seaweed bed or farm for which carbon removal offsets are being claimed. This is technically challenging but can be achieved by incorporating physical oceanographers and modelers into programs to assess CDR by seaweeds (see Van Dam et al. 2021, Berger et al. 2023). A few studies have recognized the need to measure air-sea CO₂ equilibrium by following the seawater which bears the CO₂ deficit (Orr and Sarmiento 1992, Watanabe et al. 2020, Bach et al. 2021, 2023, Berger et al. 2023). The required methods, and their critical importance for measuring CDR, are exemplified for seagrass systems by Van Dam et al. (2021), who found that four of six seagrass beds studied were net CO₂ sinks whereas two beds were net sources of CO₂ for the atmosphere. Such methods will need to be applied to each seaweed system being considered for carbon credits or offsets.

Some of the complexities highlighted here for seaweeds are less problematic when measuring air-sea CO₂ equilibration by caused by phytoplankton photosynthesis. Phytoplankton are ubiquitous throughout the euphotic zone of the global ocean and are mainly passive drifters

that move with the water mass (Basterretxea et al. 2020). For these two reasons, equilibrium is more likely to occur following phytoplankton carbon fixation than in seaweed systems where the seaweeds, in discrete beds or farms, are attached to a substratum and the water moves away from where the CO₂ was photosynthetically fixed. Thus, there is a pronounced decoupling between seaweed C fixation and the water body that carries the 'memory' of that fixation which then must equilibrate with atmospheric CO₂. The only naturally-occurring free-drifting pelagic seaweeds are *Sargassum* spp of the Sargasso Sea; they also comprise the recently-formed (> decade ago) Great Atlantic Sargassum Belt (GASB) which comprises a patchy floating seaweed system. Within the free-drifting GASB, the seawater from which the CO₂ was photosynthetically fixed has a residence time in the upper ocean, before the waters subduct to depth, which is 3-18 fold too fast relative to the equilibration time for atmospheric CO₂. Hence, equilibration will be inefficient with only 6-33% of potential CDR being achieved (Bach et al. 2021).

Summary

Seaweeds are critically important to the health of coastal systems and provide substantial services to humanity. Important work is ongoing to restore seaweed beds already damaged by climate change (Wernberg et al. 2011, Smale et al. 2019). Seaweeds also have tremendous aquaculture potential for human food and animal feeds, novel nutraceuticals and pharmaceuticals (e.g. Wells et al. 2017, Bleakley and Hays 2017, Yu et al. 2018). For example, they produce bioactive chemicals that are well-known to improve soil qualities and agriculture that will have climate benefits in soil enhancing soil carbon (e.g. Roberts et al. 2015, Cole et al. 2017). The red seaweed genus *Asparagopsis* produces the chemical bromoform that, when fed to sheep and cows, shows promising signs of reducing methane

emissions; there is evidence that chemical properties of brown seaweeds also play a similar role (Choi et al. 2021, Alvarez-Hess et al. 2023, De Bhowmick and Hayes 2023). Seaweed biomass may therefore be useful to help offset climate change in ways that have a disproportionate influence for the amount of seaweed biomass used, and for which offsets are more easily verifiable. Ongoing work to understand the role that seaweeds play in the coastal and open ocean carbon cycle, including the size of various storage pools, is extremely important to enable predictions of how oceanic carbon cycles will change in the future, as temperature rises and levels of dissolved CO₂ increase causing ocean acidification (Pessarrodona et al. 2018, Gao et al. 2022).

The essential step that needs to be incorporated into all studies aimed to at quantifying and verifying CDR and carbon sequestration by seaweeds is air-sea CO₂ equilibrium. Figure 4 highlights the fates of both the parcel of water bearing the CO₂ deficit and seaweed biomass. There is no doubt that seaweeds form long term carbon storage pools in ocean sediments on time scales of 100 years or more, although their contribution on a global scale is extremely small (< 1%, 55 Tg C yr⁻¹) compared to 99 % from oceanic phytoplankton via the biological pump (5-15 Pg C yr⁻¹; Boyd et al. 2019; Pessarrodona et al. 2023, Filbee-Dexter et al. in review). However, for any seaweed system (natural bed, seaweed farm) under consideration for carbon credits and/or offsets, two steps are required to monitor, report and verify CDR (Fig. 4): 1. The parcel of seawater that bears the CO₂ deficit resulting from seaweed photosynthesis must be tracked over long time scales (weeks to months) to quantify the amount of atmospheric CO₂ that enters seawater; at the very least, an assessment of the risk involved in not knowing the full equilibration time must be undertaken (Bach et al. 2023), and 2. The amount of the organic carbon from the same seaweed system that enters long term storage (> 100 years; as POC, DOC) must be quantified. Our view is that the difficulty of

linking these two steps for individual seaweed beds and farms currently precludes the use of seaweeds in carbon trading schemes.

Figure legends

Figure 1. Seaweed carbon storage pools. (a). Most seaweeds store carbon as living biomass for < 10 years. (1) Carbon from living and decaying seaweeds can be recycled within the seaweed bed via herbivory, autotrophic and heterotrophic respiration, and release of particulate and dissolved organic carbon (DOC, POC). (2) Living and decaying seaweeds also contribute POC and DOC to adjacent systems via lateral transport. This transport may be within coastal systems or beyond the continental shelf to the deep ocean. As POC and DOC are transported offshore, they are broken down into carbon-containing molecules via various processes including photochemical oxidation (zig-zag arrow) and heterotrophic respiration. (b). Schematic of an offshore seaweed aquaculture system in which (1) seaweeds are grown in the photic zone, and (2) the resultant biomass is sunk below the permanent pycnocline (500 m) to the deep ocean. (3) Seaweeds that have been sunk below the permanent pycnocline are out of contact with the atmosphere, and seaweed carbon and breakdown products will not return to the atmosphere for more than 100 years.

Figure 2. In its gaseous form, carbon dioxide (CO_2) is exchanged between seawater and the atmosphere. The rate and magnitude CO_2 flux into and out of the surface ocean is driven by the partial pressure of CO_2 , and other processes (see text). CO_2 dissolves slowly in seawater compared to other gases such as O_2 , and once dissolved it reacts with water (H_2O) and is subject to a series of chemical reactions. The combined effects of the relative insolubility of

CO₂ and the slow reactions times of the seawater carbonate system lead to the timeframe of equilibration between atmosphere and air of weeks (coastal ocean) to months and year (open ocean). Illustrative values of the concentration of CO₂ and HCO₃⁻ were calculated using the following set of variables: *p*CO₂ (417 μatm), total alkalinity (2290 μmol kg⁻¹), salinity of 35 and a temperature of 15°C.

Figure 3. Air-sea CO₂ equilibrium and the fate of the water parcel which bears the CO₂-deficit that resulted from seaweed net photosynthesis. Air-sea CO₂ exchange is indicated on the upper left hand side of each figure, but this process occurs across all water bodies illustrated. (a) Carbon dioxide (CO₂) in the atmosphere enters or leaves seawater (CO_{2(g)}) as a gas. It dissolves into seawater (CO_{2(aq)}) which is a component of the seawater carbonate system (see Fig. 2). (b) Seaweeds remove CO₂ and bicarbonate (HCO₃⁻) from seawater on time-scales of seconds, which (c) results in a CO₂ deficit in the seawater within the seaweed bed (grey shading). (d) The seawater bearing the CO₂ deficit moves away from the seaweed bed. For simplicity, it moves to the right of the picture (indicated by the arrow) and is replenished with new seawater (dashed line) from which seaweeds to remove dissolved inorganic carbon. (e). The seawater bearing the CO₂ deficit has moved completely away from the seaweed bed from where the CO₂ was photosynthetically fixed. We now consider three fates for the seawater bearing the CO₂ deficit: In (f1), the seawater has moved in another autotrophic (vegetated) system. In (f2), it has moved into a heterotrophic (e.g. an oyster bed) system. In both cases (f1 and f2), the seawater bearing the CO₂ deficit mixes with water in the new systems which will affect the direction and magnitude of air-sea equilibrium. In (f3), the seawater bearing the CO₂ deficit has moved offshore, and subducted below another water parcel such that it is no longer in contact with the atmosphere.

Subduction is most common in the open ocean where CO₂ equilibration times are months to year, and can result in incomplete CO₂ equilibration (see text).

Figure 4. Schematic linking the two processes that are critical to assess whether discrete seaweed beds (or seaweed farms) can be used in carbon trading schemes as offsets or credits. Air-sea CO₂ equilibrium is illustrated on the top left hand side but this process occurs in all water bodies illustrated. Black text and lines depict the various ways in which the seawater that bears the CO₂-deficit may move away from the seaweed bed in which the CO₂ was photosynthetically fixed. To assess CO₂ equilibrium, the water parcel must be followed for weeks in natural coastal systems (illustrated here), whereas in the open ocean (ocean macroalgal afforestation) the time scale of tracking the water is months to years. In the coastal system illustrated, the seawater may move along shore staying within a large kelp bed (i.e. an autotrophic system, see Fig. 3 f1) for several weeks. It may also move along shore but over a heterotrophic system (see Fig. 3 f2), or offshore where the seawater will be mixed with other water bodies with different partial pressures of CO_{2(g)}. The seawater may also subduct below a less-dense water mass, resulting in incomplete equilibration (see Fig. 3 f3). The white arrows and text illustrate the processes involved in assessing carbon storage pools for seaweed carbon that has moved across the continental shelf. Some proportions of DOC and POC from seaweeds will break down and re-enter the atmosphere as CO₂. An estimated 16% of seaweed POC will transit the continental shelf (200 m isobath) and be stored in deep ocean sediments (Filbee-Dexter et al. in revision). A proportion of recalcitrant DOC that is resistant to degradation may be stored in the deep ocean but this has not been quantified to date. If seaweeds are grown offshore at large spatial scales in ocean macroalgal afforestation (Fig. 1 and S1, S7) and the resulting biomass sunk below the permanent pycnocline, then the

biomass will reside on the ocean floor, out of contact with the atmosphere for more than 100 years.

References

Alvarez-Hess, P. S., Jacobs, J. L., Kinley, R. D., Roque, B. M., Neachtain, A. S. O., Chandra, S., & Williams, S. R. O. (2023). Twice daily feeding of canola oil steeped with *Asparagopsis armata* reduced methane emissions of lactating dairy cows. *Animal Feed Science and Technology*, 297. <https://doi.org/10.1016/j.anifeedsci.2023.115579>.

Arzeno-Soltero, I.B., Saenz , B.T., Frieder, C.A., Long, M.C., DeAngelo J, Davis S.J. & Davis K.A. (2023). Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. *Communications Earth & Environment* <https://doi.org/10.1038/s43247-023-00833-2>

Bach, L. T., Ho, D. T., Boyd, P. W., & Tyka, M. D. (2023). Toward a consensus framework to evaluate air–sea CO₂ equilibration for marine CO₂ removal. *Limnology and Oceanography Letters*. <https://doi.org/10.1002/lol2.10330>.

Bach, L. T., Tamsitt, V., Gower, J., Hurd, C. L., Raven, J. A., & Boyd, P. W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications*, 12(1). <https://doi.org/10.1038/s41467-021-22837-2>.

Basterretxea, G., Font-Muñoz, J. S., & Tuval, I. (2020). Phytoplankton Orientation in a Turbulent Ocean: A Microscale Perspective. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00185>.

- 421 Berger, M., Kwiatkowski, L., Ho, D. T., & Bopp, L. (2023). Ocean dynamics and biological
422 feedbacks limit the potential of macroalgae carbon dioxide removal. *Environmental*
423 *Research Letters*, 18(2). <https://doi.org/10.1088/1748-9326/acb06e>.
- 424 Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R.,
425 Hilmi, N., Jiao, N., Karim, M. S., Levin, L., O'Donoghue, S., Purca Cuicapusa, S. R.,
426 Rinkevich, B., Suga, T., Tagliabue, A., & Williamson, P. (2019). Changing Ocean,
427 Marine Ecosystems, and Dependent Communities. In C. Intergovernmental Panel on
428 Climate (Ed.), *The Ocean and Cryosphere in a Changing Climate: Special Report of*
429 *the Intergovernmental Panel on Climate Change* (pp. 447-588). Cambridge
430 University Press. <https://doi.org/DOI:10.1017/9781009157964.007>.
- 431 Bleakley, S., & Hayes, M. (2017). Algal Proteins: Extraction, Application, and Challenges
432 Concerning Production. *Foods*, 6(5). <https://doi.org/10.3390/foods6050033>.
- 433 Boyd, P. W., Bach, L. T., Hurd, C. L., Paine, E., Raven, J. A., & Tamsitt, V. (2022). Potential
434 negative effects of ocean afforestation on offshore ecosystems. *Nature Ecology*
435 *& Evolution*, 6(6), 675-683. <https://doi.org/10.1038/s41559-022-01722-1>.
- 436 Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., & Weber, T. (2019). Multi-faceted
437 particle pumps drive carbon sequestration in the ocean. *Nature*, 568(7752), 327-335.
438 <https://doi.org/10.1038/s41586-019-1098-2>.
- 439 Cadman, T., & Hales, R. (2022). COP26 and a Framework for Future Global Agreements on
440 Carbon Market Integrity. *The International Journal of Social Quality*, 12(1), 76-99.
441 <https://doi.org/10.3167/ijsq.2022.120105>.
- 442 Choi, Y., Lee, S. J., Kim, H. S., Eom, J. S., Jo, S. U., Guan, L. L., Seo, J., Kim, H., Lee, S. S.,
443 & Lee, S. S. (2021). Effects of seaweed extracts on in vitro rumen fermentation
444 characteristics, methane production, and microbial abundance. *Scientific Reports*,
445 11(1), 24092. <https://doi.org/10.1038/s41598-021-03356-y>.

- 446 Chung, I. K., Beardall, J., Mehta, S., Sahoo, D., & Stojkovic, S. (2011). Using marine
447 macroalgae for carbon sequestration: a critical appraisal. *Journal of Applied*
448 *Phycology*, 23(5), 877-886. <https://doi.org/10.1007/s10811-010-9604-9>.
- 449 Chung, I. K., Sondak, C. F. A., & Beardall, J. (2017). The future of seaweed aquaculture in a
450 rapidly changing world. *European Journal of Phycology*, 52(4), 495-505.
451 <https://doi.org/10.1080/09670262.2017.1359678>.
- 452 Cole, A. J., Paul, N. A., de Nys, R., & Roberts, D. A. (2017). Good for sewage treatment and
453 good for agriculture: Algal based compost and biochar. *J Environ Manage*, 200, 105-
454 113. <https://doi.org/10.1016/j.jenvman.2017.05.082>.
- 455 Coleman, S., Dewhurst, T., Fredriksson, D. W., St. Gelais, A. T., Cole, K. L., MacNicoll, M.,
456 Laufer, E., & Brady, D. C. (2022). Quantifying baseline costs and cataloging potential
457 optimization strategies for kelp aquaculture carbon dioxide removal. *Frontiers in*
458 *Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.966304>.
- 459 Cooley, S. R., Klinsky, S., Morrow, D. R., & Satterfield, T. (2022). Sociotechnical
460 Considerations About Ocean Carbon Dioxide Removal. *Ann Rev Mar Sci*, 15, 41-66.
461 <https://doi.org/10.1146/annurev-marine-032122-113850>.
- 462 De Bhowmick, G., & Hayes, M. (2023). Potential of Seaweeds to Mitigate Production of
463 Greenhouse Gases during Production of Ruminant Proteins. *Glob Chall*, 7(5),
464 2200145. <https://doi.org/10.1002/gch2.202200145>.
- 465 Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can Seaweed
466 Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in*
467 *Marine Science*, 4. <https://doi.org/10.3389/fmars.2017.00100>.
- 468 Eger, A. M., Marzinelli, E. M., Beas-Luna, R., Blain, C. O., Blamey, L. K., Byrnes, J. E. K.,
469 Carnell, P. E., Choi, C. G., Hessing-Lewis, M., Kim, K. Y., Kumagai, N. H., Lorda,
470 J., Moore, P., Nakamura, Y., Perez-Matus, A., Pontier, O., Smale, D., Steinberg, P.

- 471 D., & Verges, A. (2023). The value of ecosystem services in global marine kelp
472 forests. *Nat Commun*, 14(1), 1894. <https://doi.org/10.1038/s41467-023-37385-0>.
- 473 Erlania, Bellgrove A., Macreadie P.I, Young M.A., Holland O.J., Clark, Z., Ierodiaconou D.,
474 Carvalho R.C., Kennedy D. & Miller A.D. (2023) Patterns and drivers of macroalgal
475 'blue carbon' transport and deposition in near-shore coastal environments. *Science of*
476 *the Total Environment* 890: 164430
- 477 Filbee-Dexter, K., Feehan, C. J., Smale, D. A., Krumhansl, K. A., Augustine, S., de
478 Bettignies, F., Burrows, M. T., Byrnes, J. E. K., Campbell, J., Davoult, D., Dunton, K.
479 H., Franco, J. N., Garrido, I., Grace, S. P., Hancke, K., Johnson, L. E., Konar, B.,
480 Moore, P. J., Norderhaug, K. M., . . . Wernberg, T. (2022). Kelp carbon sink potential
481 decreases with warming due to accelerating decomposition. *PLoS Biol*, 20(8),
482 e3001702. <https://doi.org/10.1371/journal.pbio.3001702>.
- 483 Filbee-Dexter, K., Pedersen, M. F., Fredriksen, S., Norderhaug, K. M., Rinde, E., Kristiansen,
484 T., Albretsen, J., & Wernberg, T. (2020). Carbon export is facilitated by sea urchins
485 transforming kelp detritus. *Oecologia*, 192(1), 213-225.
486 <https://doi.org/10.1007/s00442-019-04571-1>.
- 487 Filbee-Dexter, K., & Wernberg, T. (2020). Substantial blue carbon in overlooked Australian
488 kelp forests. *Scientific Reports*, 10(1). <https://doi.org/10.1038/s41598-020-69258-7>.
- 489 Filbee-Dexter, K., Pessarrodona, A., Pedersen, M.F., Wernberg T., Duarte, C.M., Assis J.,
490 Bekkby, T., Burrows, M.T., Carlson D.F., Gattuso, J.-P., Gundersen, H., Hancke, K.,
491 Krumhansl, K.A., Kuwae T., Middelburg, J.K., Moore, P.J., Queirós, A.M., Smale,
492 D.A., Sousa Pinto, I., Suzuki, N., Krause-Jensen, D. (In revision). Carbon export
493 from seaweed forests to deep ocean sinks. *Nature Geoscience*.

- 494 Froehlich, H. E., Afflerbach, J. C., Frazier, M., & Halpern, B. S. (2019). Blue Growth
495 Potential to Mitigate Climate Change through Seaweed Offsetting [Article]. *Current*
496 *biology*, 29(18), 3087-3093.e3083. <https://doi.org/10.1016/j.cub.2019.07.041>
- 497 Gao, G., Gao, L., Jiang, M., Jian, A., & He, L. (2022). The potential of seaweed cultivation to
498 achieve carbon neutrality and mitigate deoxygenation and eutrophication.
499 *Environmental Research Letters*, 17(1), 014018. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/ac3fd9)
500 [9326/ac3fd9](https://doi.org/10.1088/1748-9326/ac3fd9).
- 501 GESAMP. (2019). *High level review of a wide range of proposed marine geoengineering*
502 *techniques*. (Vol. 98). International Maritime Organisation, London, UK, 144.
- 503 Hurd, C. L. (2000). Water motion, marine macroalgal physiology, and production. *Journal of*
504 *Phycology*, 36(3), 453-472. <https://doi.org/10.1046/j.1529-8817.2000.99139.x>.
- 505 Hurd, C. L., Harrison, P. J., Bischof, K., & Lobban, C. S. (2014). Seaweed Ecology and
506 Physiology. In (pp. 551). Cambridge, UK: Cambridge University Press.
- 507 Hurd, C. L., Law, C. S., Bach, L. T., Britton, D., Hovenden, M., Paine, E. R., Raven, J. A.,
508 Tamsitt, V., & Boyd, P. W. (2022). Forensic carbon accounting: Assessing the role of
509 seaweeds for carbon sequestration. *Journal of Phycology*, 58(3), 347-363.
510 <https://doi.org/10.1111/jpy.13249>.
- 511 IPCC. (2018). *Summary for Policymakers*. In: Masson-Delmotte V., Zhai P., Pörtner H.-O.,
512 Roberts D., Skea J., Shukla P. R., Pirani A., Moufouma-Okia W., Péan C., Pidcock
513 R., Connors S., Matthews J. B. R., Chen Y., Zhou X., Gomis M. I., Lonnoy E.,
514 Maycock T., Tignor M. & Waterfield T. (Eds.), *Global warming of 1.5°C. An IPCC*
515 *Special Report on the impacts of global warming of 1.5°C above pre-industrial levels*
516 *and related global greenhouse gas emission pathways, in the context of strengthening*
517 *the global response to the threat of climate change, sustainable development, and*

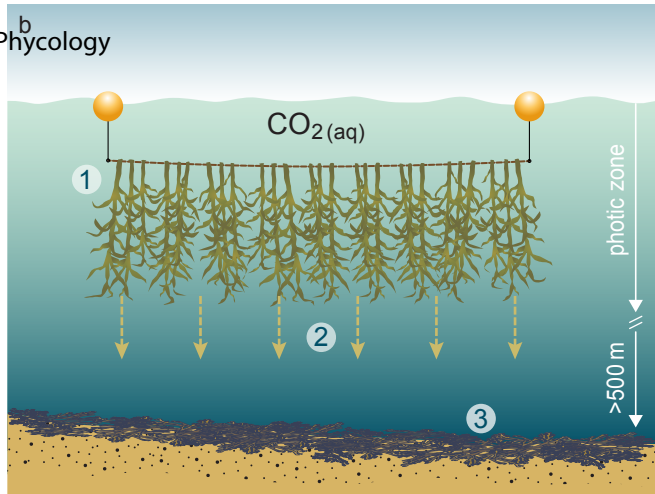
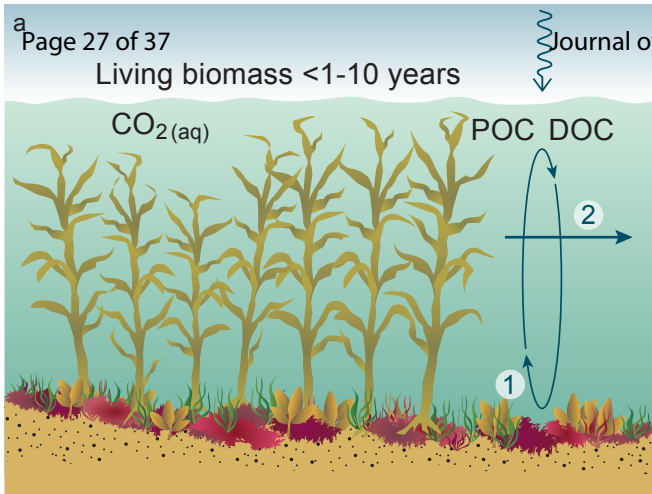
- 518 *efforts to eradicate poverty*, pp. 32. Geneva: Intergovernmental Panel on Climate
519 Change.
- 520 Jones, D. C., Ito, T., Takano, Y., & Hsu, W.-C. (2014). Spatial and seasonal variability of the
521 air-sea equilibration timescale of carbon dioxide. *Global Biogeochemical Cycles*,
522 28(11), 1163-1178. <https://doi.org/10.1002/2014gb004813>.
- 523 Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon
524 sequestration. *Nature Geoscience*, 9(10), 737-742. <https://doi.org/10.1038/ngeo2790>.
- 525 Li, H., Zhang, Z., Xiong, T., Tang, K., He, C., Shi, Q., Jiao, N., & Zhang, Y. (2022). Carbon
526 Sequestration in the Form of Recalcitrant Dissolved Organic Carbon in a Seaweed
527 (Kelp) Farming Environment. *Environ Sci Technol*, 56(12), 9112-9122.
528 <https://doi.org/10.1021/acs.est.2c01535>.
- 529 N'Yeurt, A. d. R., Chynoweth, D. P., Capron, M. E., Stewart, J. R., & Hasan, M. A. (2012).
530 Negative carbon via Ocean Afforestation. *Process Safety and Environmental*
531 *Protection*, 90(6), 467-474. <https://doi.org/https://doi.org/10.1016/j.psep.2012.10.008>.
- 532 Ocean Visions and Monterey Bay Aquarium Research Institute (2022). Answering Critical
533 Questions About Sinking Macroalgae for Carbon Dioxide Removal: A Research
534 Framework to Investigate Sequestration Efficacy and Environmental Impacts.
535 Available online at: oceanvisions.org/seaweedresearch
- 536 Orr, J. C., & Sarmiento, J. L. (1992). Potential of marine macroalgae as a sink for CO₂:
537 Constraints from a 3-D general circulation model of the global ocean. *Water, Air,*
538 *& Soil Pollution*, 64(1-2), 405-421. <https://doi.org/10.1007/bf00477113>.
- 539 Ould, E., & Caldwell, G. S. (2022). The potential of seaweed for carbon capture. *CABI*
540 *Reviews*, 2022. <https://doi.org/10.1079/cabireviews202217009>.
- 541 Paine, E. R., Brewer, E. A., Schmid, M., Diaz-Pulido, G., Boyd, P. W., & Hurd, C. L. (2023).
542 Strong seasonal patterns of DOC release by a temperate seaweed community:

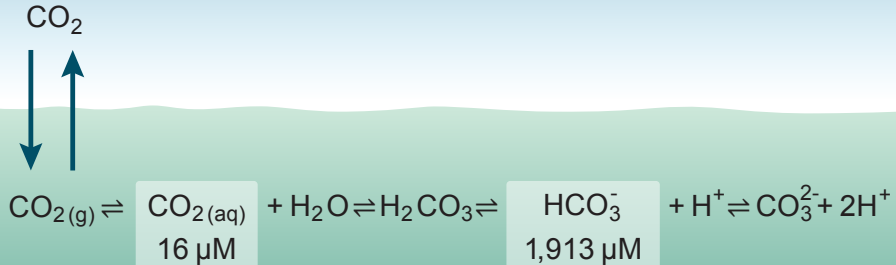
- 543 Implications for the coastal ocean carbon cycle. *Journal of Phycology*.
544 <https://doi.org/10.1111/jpy.13352>.
- 545 Paine, E. R., Schmid, M., Boyd, P. W., Diaz-Pulido, G., & Hurd, C. L. (2021). Rate and fate
546 of dissolved organic carbon release by seaweeds: A missing link in the coastal ocean
547 carbon cycle. *Journal of Phycology*. <https://doi.org/10.1111/jpy.13198>.
- 548 Pedersen, M. F., Filbee-Dexter, K., Frisk, N. L., Sárossy, Z., & Wernberg, T. (2021). Carbon
549 sequestration potential increased by incomplete anaerobic decomposition of kelp
550 detritus. *Marine Ecology Progress Series*, 660, 53-67.
551 <https://doi.org/10.3354/meps13613>.
- 552 Pedersen, M. F., Filbee-Dexter, K., Norderhaug, K. M., Fredriksen, S., Frisk, N. L., Fagerli,
553 C. W., & Wernberg, T. (2020). Detrital carbon production and export in high latitude
554 kelp forests. *Oecologia*, 192(1), 227-239. [https://doi.org/10.1007/s00442-019-04573-](https://doi.org/10.1007/s00442-019-04573-z)
555 [z](https://doi.org/10.1007/s00442-019-04573-z).
- 556 Perkins, A. K., Santos, I. R., Rose, A. L., Schulz, K. G., Grossart, H.-P., Eyre, B. D., Kelaher,
557 B. P., & Oakes, J. M. (2022). Production of dissolved carbon and alkalinity during
558 macroalgal wrack degradation on beaches: a mesocosm experiment with implications
559 for blue carbon. *Biogeochemistry*, 160(2), 159-175. [https://doi.org/10.1007/s10533-](https://doi.org/10.1007/s10533-022-00946-4)
560 [022-00946-4](https://doi.org/10.1007/s10533-022-00946-4).
- 561 Pessarrodona, A., Franco-Santos, R.M., Wright L.S., Vanderklift M.A., Pidgeon E.,
562 Wernberg, T. Filbee-Dexter, K. (2023). Carbon sequestration and climate change
563 mitigation using macroalgae: a state of knowledge review. *Biol. Rev.* doi:
564 10.1111/brv.12990
- 565
- 566 Pessarrodona, A., Assis, J., Filbee-Dexter, K., Burrows, M. T., Gattuso, J. P., Duarte, C. M.,
567 Krause-Jensen, D., Moore, P. J., Smale, D. A., & Wernberg, T. (2022). Global

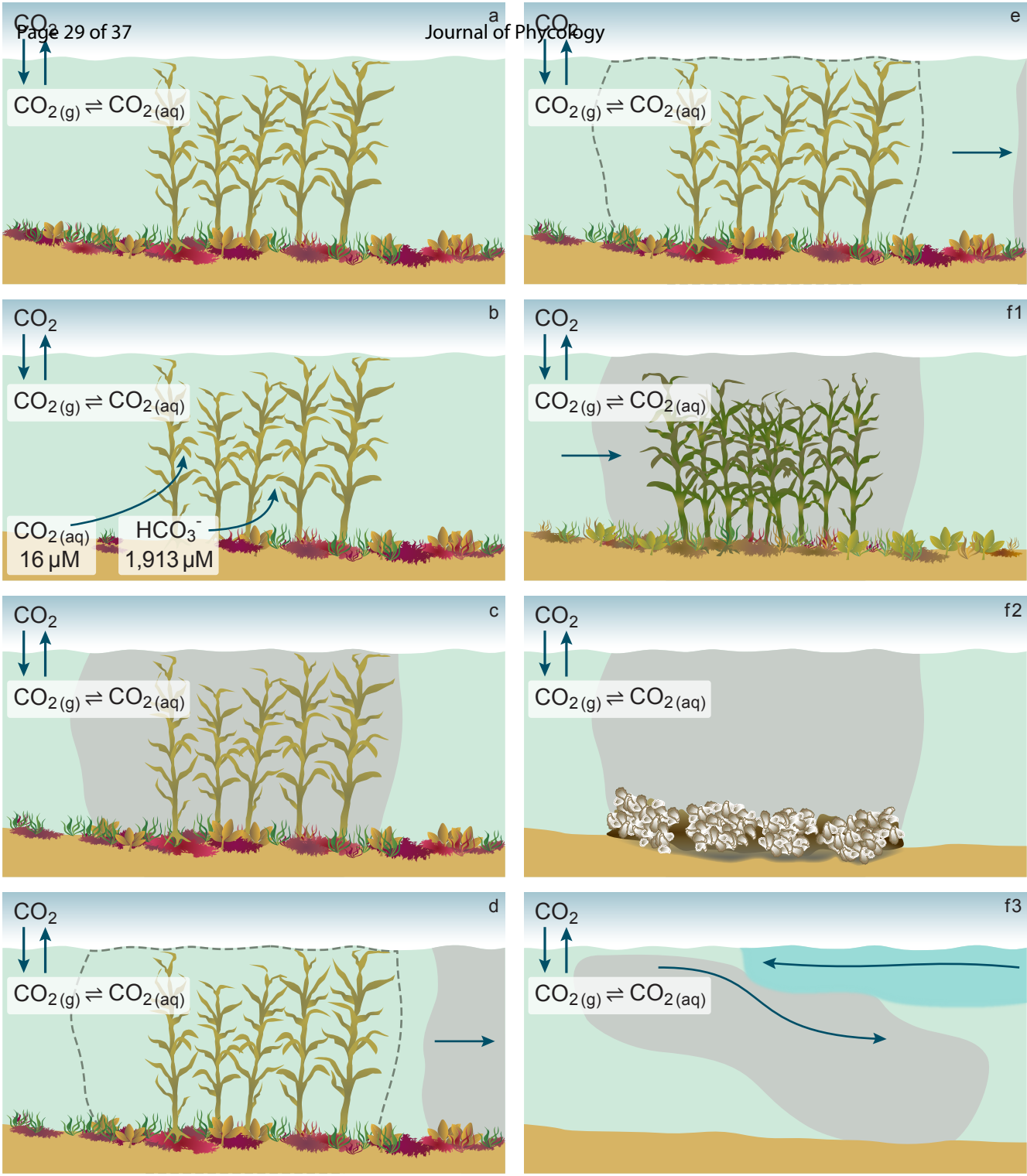
- 568 seaweed productivity. *Sci Adv*, 8(37), eabn2465.
569 <https://doi.org/10.1126/sciadv.abn2465>.
- 570 Pessarrodona, A., Filbee-Dexter, K., Krumhansl, K. A., Pedersen, M. F., Moore, P. J., &
571 Wernberg, T. (2022). A global dataset of seaweed net primary productivity. *Sci Data*,
572 9(1), 484. <https://doi.org/10.1038/s41597-022-01554-5>.
- 573 Pessarrodona, A., Moore, P. J., Sayer, M. D. J., & Smale, D. A. (2018). Carbon assimilation
574 and transfer through kelp forests in the NE Atlantic is diminished under a warmer
575 ocean climate. *Glob Chang Biol*, 24(9), 4386-4398.
576 <https://doi.org/10.1111/gcb.14303>.
- 577 Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration.
578 *Reviews of Geophysics*, 55(3), 636-674. <https://doi.org/10.1002/2016rg000533>.
- 579 Roberts, D. A., Paul, N. A., Dworjanyn, S. A., Bird, M. I., & de Nys, R. (2015). Biochar from
580 commercially cultivated seaweed for soil amelioration. *Sci Rep*, 5, 9665.
581 <https://doi.org/10.1038/srep09665>.
- 582 Ross, F. W. R., Boyd, P. W., Filbee-Dexter, K., Watanabe, K., Ortega, A., Krause-Jensen, D.,
583 Lovelock, C., Sondak, C. F. A., Bach, L. T., Duarte, C. M., Serrano, O., Beardall, J.,
584 Tarbuck, P., & Macreadie, P. I. (2023). Potential role of seaweeds in climate change
585 mitigation [Review]. *Science of the Total Environment*, 885, Article 163699.
586 <https://doi.org/10.1016/j.scitotenv.2023.163699>.
- 587 Smale, D. A., Wernberg, T., Oliver, E. C. J., Thomsen, M., Harvey, B. P., Straub, S. C.,
588 Burrows, M. T., Alexander, L. V., Benthuyssen, J. A., Donat, M. G., Feng, M.,
589 Hobday, A. J., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Sen
590 Gupta, A., Payne, B. L., & Moore, P. J. (2019). Marine heatwaves threaten global
591 biodiversity and the provision of ecosystem services. *Nature Climate Change*, 9(4),
592 306-312. <https://doi.org/10.1038/s41558-019-0412-1>.

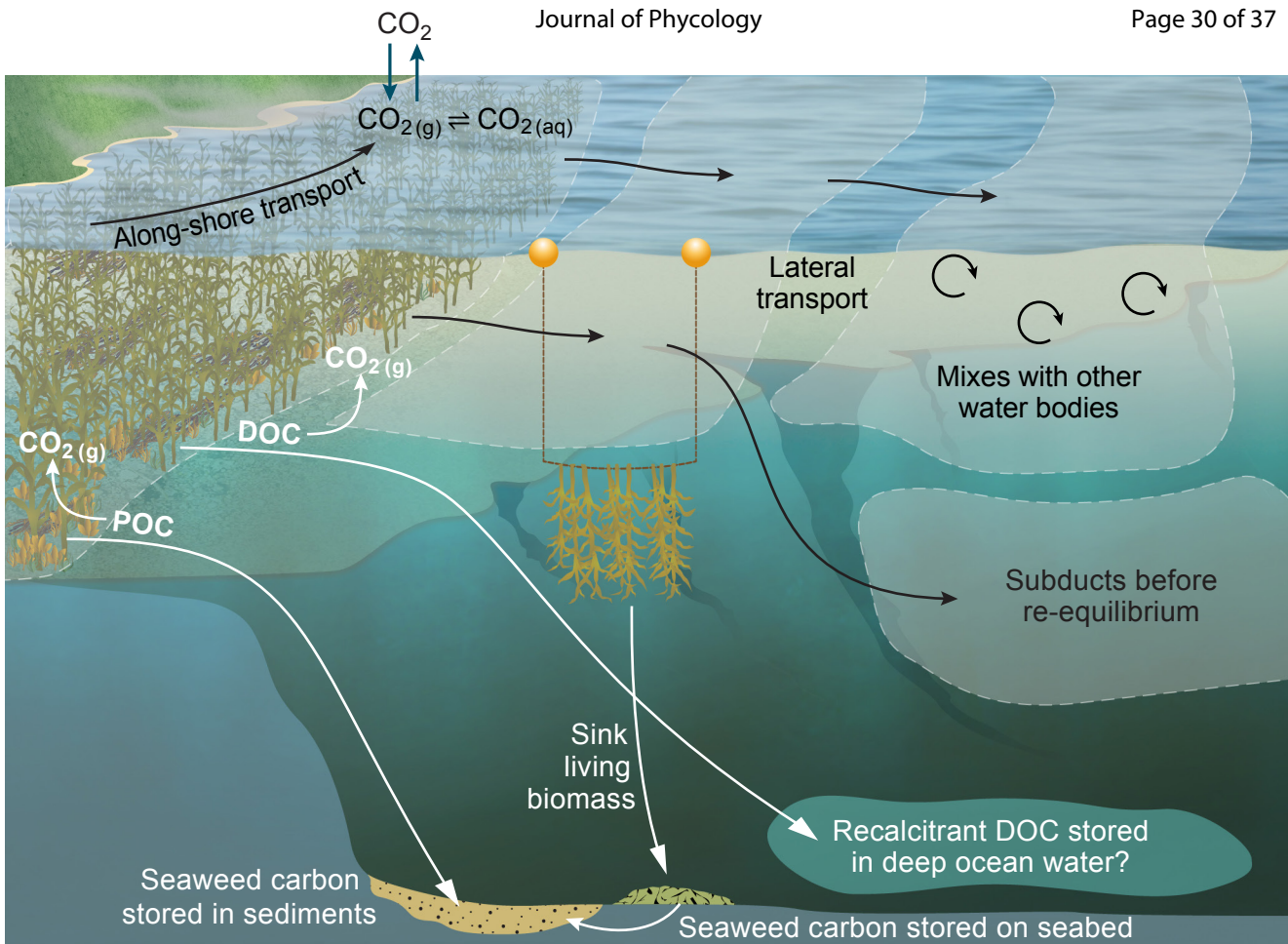
- 593 Smith, K. E., Burrows, M. T., Hobday, A. J., King, N. G., Moore, P. J., Sen Gupta, A.,
594 Thomsen, M. S., Wernberg, T., & Smale, D. A. (2022). Biological Impacts of Marine
595 Heatwaves. *Annual Review of Marine Science*, 15(1), 119-145.
596 <https://doi.org/10.1146/annurev-marine-032122-121437>.
- 597 Smith, S. M., Geden, O., Nemet, G. F., Gidden, M. J., Lamb, W. F., Powis, C., Bellamy, R.,
598 Callaghan, M. W., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J.,
599 Lück, S., Mohan, A., Müller-Hansen, F., Peters, G. P., Pratama, Y., . . . Minx, J. C.
600 (2023). *The State of Carbon Dioxide Removal - 1st Edition*.
601 <http://dx.doi.org/10.17605/OSF.IO/W3B4Z>.
- 602 Sondak, C. F. A., Ang, P. O., Beardall, J., Bellgrove, A., Boo, S. M., Gerung, G. S., Hepburn,
603 C. D., Hong, D. D., Hu, Z., Kawai, H., Largo, D., Lee, J. A., Lim, P.-E., Mayakun, J.,
604 Nelson, W. A., Oak, J. H., Phang, S.-M., Sahoo, D., Peerapornpis, Y., . . . Chung, I.
605 K. (2017). Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs).
606 *Journal of Applied Phycology*, 29(5), 2363-2373. [https://doi.org/10.1007/s10811-016-](https://doi.org/10.1007/s10811-016-1022-1)
607 [1022-1](https://doi.org/10.1007/s10811-016-1022-1).
- 608 Sondergaard, M., & Middelboe, M. (1995). A cross-system analysis of labile dissolved
609 organic carbon. *Marine Ecology Progress Series*, 118, 283–294.
- 610 UNEP. (2023). *Seaweed Farming: Assessment on the Potential of Sustainable Upscaling for*
611 *Climate, Communities and the Planet*. <https://wedocs.unep.org/20.500.11822/42642>.
- 612 Van Dam, B., Polsenaere, P., Barreras-Apodaca, A., Lopes, C., Sanchez-Mejia, Z., Tokoro,
613 T., Kuwae, T., Loza, L. G., Rutgersson, A., Fourqurean, J., & Thomas, H. (2021).
614 Global Trends in Air-Water CO₂ Exchange Over Seagrass Meadows Revealed by
615 Atmospheric Eddy Covariance. *Global Biogeochemical Cycles*, 35(4).
616 <https://doi.org/10.1029/2020gb006848>.

- van Diemen R., M. J. R. B., Möller V., Fluglestvedt J. S., Masson-Delmotte V., Méndez C.,
Reisinger A. & Semenov S., (2022). *Annex I: Glossary* (Climate Change 2022:
Mitigation of Climate Change. Contribution of Working Group III to the Sixth
Assessment Report of the Intergovernmental Panel on Climate Change, Issue.
Wada, S., Omori, Y., Kayamyo, Y., Tashiro, Y., & Hama, T. (2015). Photoreactivity of
dissolved organic matter from macroalgae. *Regional Studies in Marine Science*, 2, 12-
18. <https://doi.org/10.1016/j.rsma.2015.08.018>.
Watanabe, K., Yoshida, G., Hori, M., Umezawa, Y., Moki, H., & Kuwae, T. (2020).
Macroalgal metabolism and lateral carbon flows can create significant carbon sinks.
Biogeosciences, 17(9), 2425-2440. <https://doi.org/10.5194/bg-17-2425-2020>.
Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., Smith,
A. G., Camire, M. E., & Brawley, S. H. (2017). Algae as nutritional and functional
food sources: revisiting our understanding. *Journal of Applied Phycology*, 29(2), 949-
982. <https://doi.org/10.1007/s10811-016-0974-5>.
Wernberg, T., Russell, B. D., Thomsen, M. S., Gurgel, C. F. D., Bradshaw, C. J.,
Poloczanska, E. S., & Connell, S. D. (2011). Seaweed communities in retreat from
ocean warming. *Current biology*, 21(21), 1828-1832.
Yu, Y., Shen, M., Song, Q., & Xie, J. (2018). Biological activities and pharmaceutical
applications of polysaccharide from natural resources: A review. *Carbohydr Polym*,
183, 91-101. <https://doi.org/10.1016/j.carbpol.2017.12.009>.

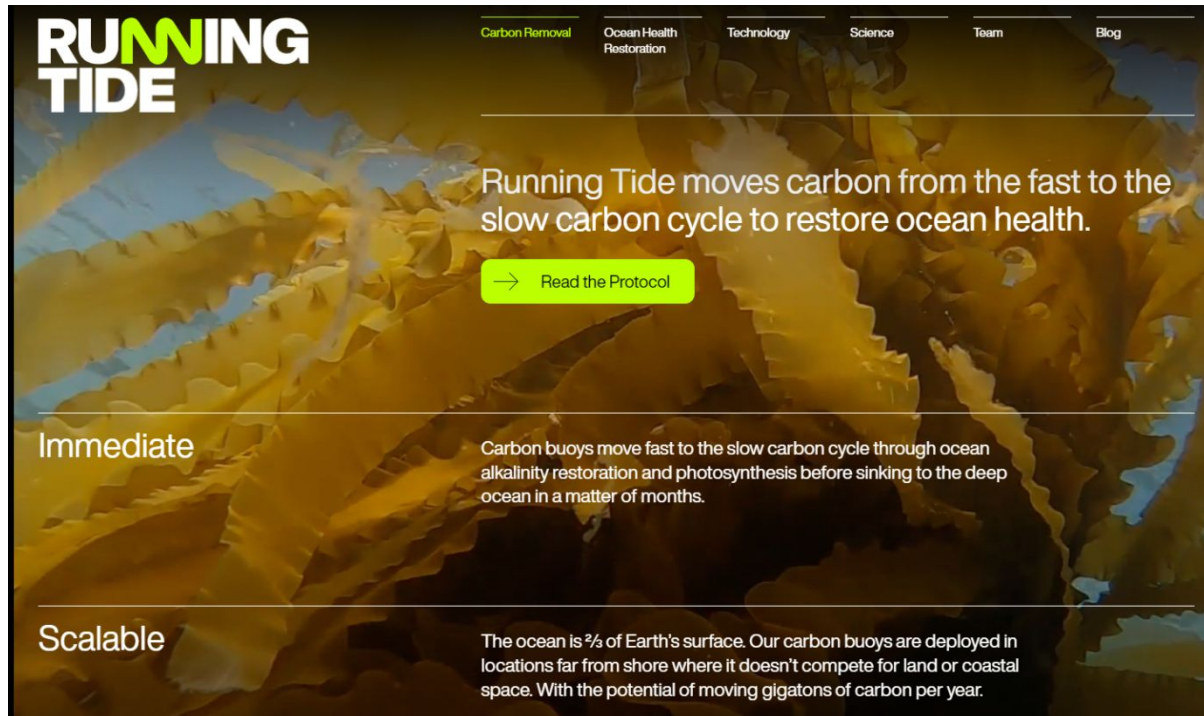








S1. Running Tide. <https://www.runningtide.com/carbonremoval>. Seeks to grow seaweeds on buoys that are subsequently released to sink the biomass to the deep ocean, for carbon sequestration and CDR, and for use in carbon markets. Web site accessed 15 June 2023.



Carbon markets are in the midst of a crisis of trust, paralyzing progress around the urgent climate action we so desperately need. This reinforces the importance of building social license and confidence in new carbon removal solutions, such as those conducted in the ocean, against the backdrop of an emerging — but not yet mature — industry.

In addition to this lack of trust, there is an absence of established governance structures and effective regulatory frameworks that provide guardrails for those working in this space. As these standards are advocated for and developed at an industry level, those conducting this work within natural systems must be crystal clear about the standards we hold ourselves to, and that inform our ethical decision-making – from initial research, to eventual deployments and ongoing monitoring. Smaller scale, low-risk research and carbon removal activities following well-documented protocols can be used to efficiently develop, test, refine, and operationalize effective governance structures that are designed for real-world application, ensuring the creation of practical and actionable standards — without delaying critical climate action.

S2. Green Ocean Seaweed Farming. <https://www.greenoceanfarming.com/ocean-carbon-bonds.php> Selling Green Ocean Carbon Bonds, stating that £300 (Sterling) spent on Green Ocean Carbon Bonds will offset a household carbon footprint for one year. Web site accessed 15 June 2023.

Green Ocean Carbon Bonds

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S3. Carbon Kapture. <https://carbonkapture.com/>. Public can sponsor a seaweed ‘rope’ for a monthly donation of £2, £5 or £10. Corporate rates available for businesses. States that each metre of rope will capture 1.8 kg CO₂. Purchaser receives certification stating how much carbon they have captured. Web site accessed 15 June 2023.





The Power Of One


Small personal actions can add up to a surprisingly significant impact. Climate-conscious individuals around the world are growing seaweed with Carbon Kapture to help create real-time community impact.


Sponsor a rope today for yourself, or as a wonderful gift for someone.


Each metre of rope will capture approx 1.8kg of CO₂

Buy Now 




Buy Now 






01

Get your personalised certificate showing the approximate weight of Seaweed you will grow and CO₂ you will capture.




02

You will receive a what3words reference showing exactly where your rope is floating




03

Quarterly video updates explaining the type of seaweed being grown and general progress




04

The weight of your seaweed when harvested and the amount of biochar produced



05

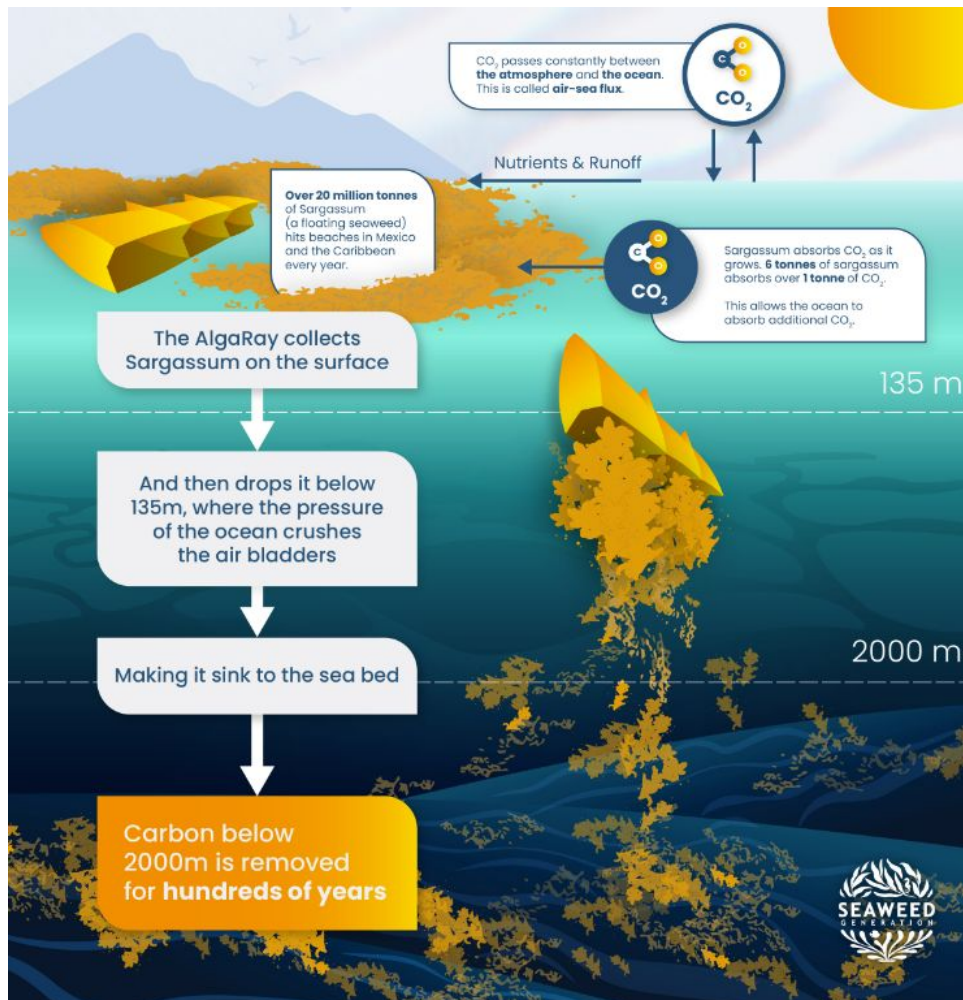
A what3words reference to the field it ends up in, and where it will remain forever more!



06

Satisfaction that you've made an immediate positive impact on climate change

S4. Seaweed Generation. <https://www.seaweedgeneration.com/>. The aim goal is to collect and sink existing pelagic *Sargassum* to the deep ocean (> 2,000 m) for carbon sequestration, and to grow *Sargassum* 'sustainably and cheaply'. Donations of \$40-\$400 are welcomed to remove 100-1,000 kg seaweed to the deep ocean, which are claimed to offset personal carbon use. Web site accessed 16 June 2023.



Be part of the solution

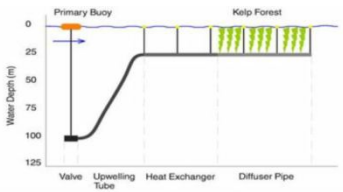
All of us are contributing to climate change. The good news is, you can join the fight right now by contributing to carbon dioxide removal, and helping us to develop our technology. How much can you help?

Silver	Gold	Diamond
100 kg	250 kg	1,000 kg
Price \$40	Price \$100	Price \$400
This would offset about 18 days of meals for the average person (including growth, production, and transportation costs).	This would offset about 650 miles of driving, for the average car that gets 24 miles per gallon.	Flying 6,000 miles, which is about two trips between Boston and London, uses 1,000 kg (or 1 tonne) of CO ₂ per passenger.
Contribute	Contribute	Contribute

Did you know? The average person emits 12,000 to 18,000 kg of carbon dioxide per year!

S5. Climate Foundation. <https://www.climatefoundation.org/>. Growing seaweeds at scale using marine permaculture and artificial upwelling for carbon sequestration, and a range of other seaweed-based products. ‘Thousands to millions’ of modular platforms (each of a hectare scale) will be installed across the tropical and sub-tropical waters. Web site accessed 15 June 2023.

Floating, open-ocean kelp ecosystems placed in the oceanic deserts around the world could sequester atmospheric carbon and attract and grow fish, filtering out their waste and recycling nutrients. The kelp could be harvested to be used as biofuel, fertilizer, livestock feed, superfood and countless biomass applications and high-value extract. After high-value extraction at sea in the harvester bio-refinery, the kelp could be sunk to deep anoxic environments, locking 90% of the sequestered carbon away for millennia.



The diagram illustrates a vertical cross-section of a kelp forest system. On the left, a vertical axis represents 'Water Depth (m)' from 0 to 125. A 'Primary Buoy' is shown at the surface (0m). A 'Valve' is located at approximately 25m depth. Below the valve, an 'Upwelling Tube' extends down to about 100m. A 'Heat Exchanger' is positioned between the upwelling tube and the diffuser pipe. A 'Diffuser Pipe' extends from the heat exchanger down to the bottom. On the right, a 'Kelp Forest' is shown growing from the bottom up to the surface. The kelp is represented by green vertical lines.

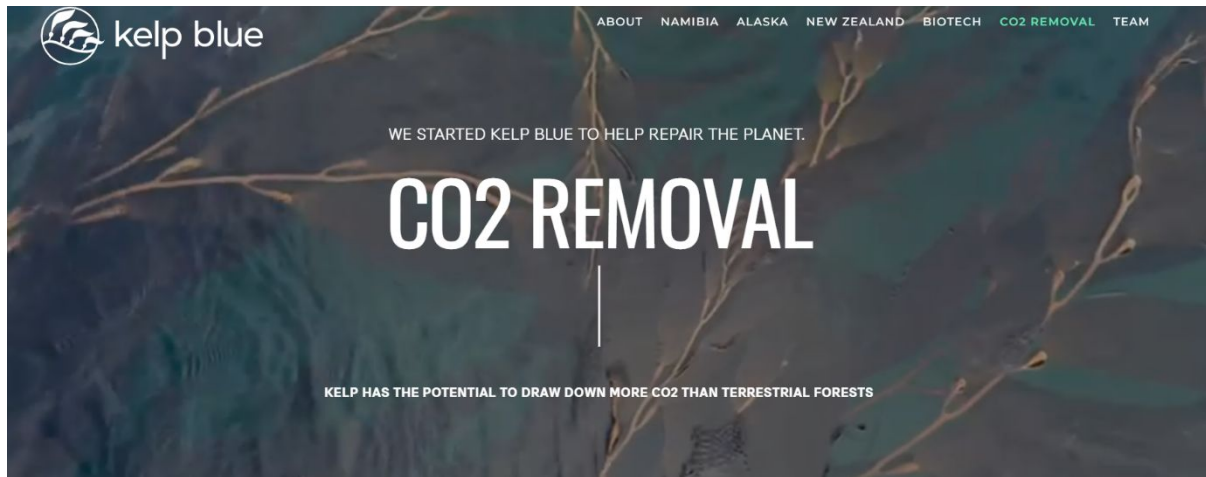
The large-scale regeneration and open-ocean cultivation of kelp forests will provide food, fuel and fertilizer for the 9 billion humans that are likely to inhabit the planet by 2040, while drawing down carbon dioxide from the atmosphere and leaving space on land for all those other uses.


To see what we are doing about it, click here <http://www.climatefoundation.org/marine-permaculture.html>

MP platforms are designed to be modular and will generate income at hectare scale. Such designs enable a distributed scaling model whereby hectare-scale platforms can be built thousands to millions of times across tropical and subtropical waters. Importantly, Marine Permaculture platforms can pay for themselves through seaweed production while drawing down carbon from the mixed layer to the middle and deep ocean, providing scaling opportunities independent of carbon pricing



S6. Kelp Blue. <https://kelp.blue/co2-removal/> Seeks to 're-wild' the oceans by growing *Macrocystis pyrifera* at scale for carbon dioxide removal and carbon sequestration. The harvested biomass will be used in biotechnological solutions to improving soil health <https://biotech.kelp.blue/>. Web site accessed 15 June and 21 July 2023.



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At Kelp Blue, we're optimists and know action is possible. By planting large scale Giant Kelp Forests, we can both restore the natural ocean wilderness, while capturing excess CO₂ from the atmosphere.

HOW DOES KELP STORE AND PERMANENTLY SEQUESTER CO₂?

Giant Kelp (*Macrocystis pyrifera*) is one of the fastest growing organisms on the planet and with optimal conditions can grow up to 60 cm (2 ft) in a day and reach lengths of up to 45 meters (150ft). Kelp is a type of brown seaweed and like land-based plants, uses the process of photosynthesis to grow. In this process, kelp absorbs sunlight, CO₂, and nutrients to store in its tissues like its blades, stipes, and fronds. The amount of carbon stored in the kelp's biomass is expressed as Net Primary Productivity (NPP).

As Kelp grows, it continuously releases organic material, some of which is minuscule and dissolves in water, called Dissolved Organic Carbon (DOC), and some larger material not able to dissolve in water.

DOC released by the kelp is immediately consumed by microbes or is transported out to sea where it sinks to the bottom of the ocean floor. Because the bottom of the ocean is unlikely to be disturbed and has very little human contact, the risk of the carbon being released is effectively zero, it can therefore be considered "permanently sequestered".

Any part of the kelp that breaks off and in size is larger than a pinhead is called Particulate Organic Carbon (POC). This could be the fronds that the kelp continuously sheds.

These fronds have gas bladders called pneumatocysts and gives them the ability to drift- sometimes thousands of kilometers. Eventually the kelp's gas-filled bladders burst, and the kelp detritus sinks to deeper waters or gets buried in ocean sediments. One study concluded that natural seaweed ecosystems already sequester approximately 173 million metric ton of carbon annually. This study also estimates that 43% of the kelp forests' carbon will be exported from the ecosystem in these two forms, DOC and POC and that approximately 9-11% of the Net Primary Productivity of kelp forests will be stored permanently in the ocean's deeper layers and sediments.

S7. Ocean Visions. <https://oceanvisions.org/our-programs/macroalgaeresearchframework/>. A NGO that “catalyzes innovation at the intersection of the ocean and climate crises”. One mitigation strategy they are investigating is growing seaweeds at massive scale in the open ocean and sinking them for carbon dioxide removal (CDR). Web site accessed 14 July 2023.



A Framework for Global Research