Memo: Response to Boyd et al. (2022)

Running Tide’s mission is to develop an open ocean carbon dioxide removal (CDR) platform capable of applying the foremost scientific understanding of global carbon cycling to large-scale experimental investigation and execution of carbon removal projects. Our expectation is that the application of our platform will continually evolve as the research community continues to engage with the climate emergency.

This brief acknowledges *Potential negative effects of ocean afforestation on offshore ecosystems* (Boyd et al., 2022), a Perspective Article in *Nature Ecology and Evolution* which, through its citations, addresses Running Tide and one of the carbon removal pathways we are developing within our CDR platform.

As titled, the piece provides a catalog of informed speculation on potential ecosystem perturbations that could arise from the large-scale industrial practice of open ocean macroalgae farming for the purpose of removing atmospheric carbon dioxide. These potential interactions are known to Running Tide and to our partners\(^1\), and have been identified for characterization and study during our ongoing project development and assessment of ecological impacts. Specifically, the authors discuss the following items:

- Impact on endemic surface ocean communities, especially phytoplankton, either through mechanical (interaction with drifters or shading of light) or chemical (nutrient competition) means
- Introduction of hitchhiking species to open ocean surface waters, including those of the macroalgae microbiome
- Addition of dissolved organic matter (DOM), dissolved organic carbon (DOC), and particulate organic carbon (POC) from macroalgae to the surface ocean and the impact of these inputs on baseline carbon and nutrient cycling

Running Tide is in agreement with the authors’ assessment that the degree and severity of each of these interactions is a question of scale and that, in most cases, indications of a potential interaction will be too diffuse to observe with small scale pilot studies. For these

\(^1\) Ocean Visions & Running Tide: First Progress Report
reasons, Running Tide, through consultation with our scientific partners, has converged on the following research program:

- A staged progression of pilot deployments, in which the magnitude, spatial density, and duration of our macroalgal deployments are gradually scaled upwards after careful evaluation of the ecological impacts of the prior smaller-scale deployments
- Observations at each scale of deployment will be used to inform and improve our models predicting the surface transport, biochemical evolution, and sinking of the algal floats
- At each stage of scaling, the model predictions associated with the next phase of deployment will be presented to our scientific partners, who will in turn:
  - Review environmental impact assessments of the next-level deployments
  - Review our estimates of CO$_2$ sequestered by the algal floats
  - Advise Running Tide on designing and conducting experiments aimed at simulating the evolution of the algal floats in the laboratory and monitoring their dispersal and evolution in the field

Running Tide is engaged with a growing list of formal, informal, and prospective scientific collaborators in the form of individuals, research institutions, NGOs, and private entities. Running Tide has partnered with Ocean Visions, a leading nonprofit, who has convened an external, independent Scientific Advisory Board to review and advise on our foundational science, quantification, and approach. We will continue to work with Ocean Visions to grow this Board in a way that reflects the evolving scientific consensus and integrates perspectives on the various components of our carbon removal system. It is within this broad collaborative framework that Running Tide intends to pursue the above described program of research, monitoring, and evaluation.

Discussion of the costs associated with Ocean CDR should be considered within the context of the costs of inaction—i.e., warming, as discussed by the authors, as well as ocean acidification, melting glaciers, rising sea level, increased storms and wildfires, droughts, famines, and the resulting global insecurity. The ecological impacts of Ocean CDR should also be contextualized by the reality that ecosystems of the world are presently unstable, with many arguing that the planet is in the midst of its Sixth Major Extinction. The CO$_2$ problem and resulting climate emergency is a global-scale challenge that threatens all occupants of our planet. The scale of this challenge requires a big tent of solution-seeking individuals and organizations pursuing
diverse and independent pathways for removing atmospheric CO\textsubscript{2}. Running Tide remains engaged with experts and looks forward to the continuing dialog and discovery around Ocean CDR.

Running Tide Discussion of Boyd et al. (2022): Assumptions and Conclusions

The uncertainties of ocean afforestation are real, but they are not unique to the Running Tide approach, nor are they greater than the risks presented by oceanic or terrestrial CDR in general.

As acknowledged by the authors, “more than 20 marine CDR approaches have been proposed and all have major knowledge gaps centering on major uncertainties around both side effects and the quantification of their efficacy for carbon sequestration.”

These uncertainties are real, but they are by no means unique to Running Tide’s method of Carbon Cycle Enhancement, nor to Ocean CDR in general. Comparable uncertainties exist for terrestrial-based CDR, including direct air capture. However, the unfounded perception that marine ecosystems are more pristine than terrestrial ecosystems has led to the unsubstantiated conclusion that there is greater uncertainty and risk presented by Ocean CDR.

From an anthropocentric perspective, the uncertainty and risk associated with terrestrial CDR is arguably greater than “ocean afforestation”, as terrestrial CDR will more directly impact the human environment, as both the built environment and the surface and subsurface terrestrial landscapes would need to be extensively modified to accommodate the quarter-to-half trillion tons of CO\textsubscript{2} that must be stored over the next half-century under business-as-usual emissions scenarios.\textsuperscript{2}

Open ocean afforestation may accompany CO\textsubscript{2}-induced climate change, regardless of human intervention via Ocean CDR.

Part of the authors’ argument against open-ocean afforestation invokes natural and non-natural analogs for deploying macroalgae to the open ocean, and the resulting deleterious side effects.

\textsuperscript{2} IPCC - Climate Change 2022: Impacts, Adaptation and Vulnerability
Notably, of the six macroalgal dispersal events that they present (Table 1) as analogs for intentional open ocean afforestation with negative side effects, two ("Climate Change Radiative Dispersal" and "Expansion of the Great Atlantic Sargassum Belt [GASB]") actually resulted from or were likely enhanced by CO₂-induced warming. This suggests that significant expansion of macroalgae into the open ocean may occur along with CO₂-induced warming, regardless of whether humans utilize ocean afforestation as a method for Ocean CDR. This raises the possibility that CDR via the controlled release and sinking of macroalgae to the open ocean may reduce the extent to which macroalgae naturally expand into different areas of the ocean as a result of CO₂-induced climate change.

Unlike the controlled approach to open ocean afforestation, macroalgae expanding via "Climate Change Radiative Dispersal" and "GASB" have no mechanism of ballasting for rapid transport (i.e., sinking) from the fast carbon cycle in the upper ocean to the slow carbon cycle in the deep sea and marine sediments, and will likely end up accumulating in the surface ocean and on shorelines (e.g., the accumulation of Sargassum along the eastern margin of Central America over the past decade).

The authors understate the risks of rising levels of fast carbon cycle CO₂, ignoring the effects of ocean acidification, rising sea levels, glacial melting, increased storms/wildfires, droughts, famines, socio-economic instability, economic loss, etc.

Throughout the article, the authors describe the goal of Ocean CDR as solely the act of "limiting warming". In reality, a warming planet is only one of the threats posed by rising levels of CO₂ that Ocean CDR addresses. By removing CO₂ from the coupled upper ocean-atmosphere system, ocean CDR also combats the equally grave threat of ocean acidification (Doney et al. 2009). Additional threats posed by rising CO₂ excluded from the article include the secondary effects of increased magnitude and frequency of storms and wildfires, accelerated glacial melting, rising sea level, increased droughts and famine, and socio-economic instability arising from these factors. Each of these impacts should be considered in an evaluation of the cost of action vs. cost of inaction, with respect to CDR.
The authors overstate uncertainties and risks of resource competition in the open ocean

Global annual net primary production (NPP) in the oceans is estimated at 48.5 Gt of carbon (C), which equates to 177.8 Gt of CO₂ per year, the majority (97%) of which is performed by floating microphytes (Field et al., 1998). Since phytoplankton NPP is generally nutrient-limited in the surface ocean (Moore et al., 2013), the surface ocean can be assumed to be at carrying capacity with respect to NPP. Thus, introduction of macrophytes to this system through Running Tide’s CDR method would displace the nutrient-denominated equivalent of microphyte biomass. However, macrophytes tend to have approximately three-fold higher C:nutrient ratios than microphytes, which allows them to fix more C per unit of limiting nutrient than the microphytes currently dominating oceanic NPP.

Nitrogen (N) is typically the limiting nutrient for NPP in surface waters, although phosphorus (P) and iron (Fe) can be co-limiting at some times and locations. Regardless, the C:N, C:P, and C:Fe ratios of macrophytes are all approximately three-fold higher than those of microphytes (Martiny et al., 2013; Bach et al., 2021; Wang et al., 2018), which means that macroalgae will sequester three times more C than the microalgae that they are replacing. Therefore, only 0.5 GT of CO₂-equivalent microphyte NPP would need to be displaced by macrophyte NPP per year in order to achieve annual CO₂ removal at the 1-Gt scale, which translates to displacing about 0.28% per year of total marine NPP (0.5 Gt CO₂ microphyte NPP/177.8 Gt CO₂ total NPP).

Assuming a three-month transport time for macroalgae before sinking, 1-Gt scale CDR could be achieved by displacing microphytes throughout 0.07% of the oceanic area of the Earth (362 x 106 km²), or approximately 253,400 km² (0.0007 x 362 x 106 km²). This represents only 0.15% of the area of the Pacific Ocean (253,400 km²/162 x 106 km²).

This relatively small impact on the surface ocean could be further mitigated by spreading out deployments at multiple sites, potentially in different oceans. This low density of macroalgal biomass in the surface ocean is corroborated by the authors’ modeling (Fig 1 C,D), in which they predict <1 float per 100 km² after 120 and 240 days.
On the lack of precedent for “ocean afforestation” as a form of Ocean CDR

Contrary to the authors’ assertions, there are indeed natural precedents for CDR by open ocean afforestation.

One example is the expansion of floating Sargassum in the Sargasso Sea of the North Atlantic Ocean across the (sub)tropical North Atlantic from West Africa to South America and across the Caribbean Sea, forming the “Great Atlantic Sargassum Belt” (GASB; Gower et al., 2013; Wang et al., 2019). This 2011 event has been considered by many, including some of the authors of the present article, as a natural analog for assessing impacts of open-ocean cultivation of floating macrophytes for CDR (Bach et al., 2021).

Notably, although both ecological and social impacts of the GASB analog have been observed (Wang et al., 2019; Baker et al., 2018; Gower et al., 2013), these impacts have not been shown to be severe, especially compared with the predicted impacts of unmitigated CO$_2$-induced climate change.

On the role of OAE in altering pelagic ecosystems by favoring calcifying organisms

Rising atmospheric CO$_2$ (the “no-action” baseline) is presently harming marine calcifiers by causing ocean acidification, which reduces the saturation state of seawater with respect to calcium carbonate.

CDR by ocean alkalinity enhancement (OAE), as well as by other methods, will reverse the chemical and biological effects of CO$_2$-induced ocean acidification, with the aim of returning the saturation state of surface seawater to levels that existed prior to the Industrial Revolution, when humans began extracting and combusting fossil fuels at scales that could impact atmospheric pCO$_2$ and seawater pH.

On the effects of dissolved organic carbon (DOC) release by macroalgae

The authors are correct in stating that macroalgae release DOC to seawater, especially when nutrients are limiting. This means that sequestered CO$_2$ embodied in the released DOC will not be transported with the sinking algal biomass to the deep ocean and/or marine sediments.
However, Running Tide’s method of carbon accounting only counts carbon that is stored within the tissue of the sinking macroalgae, not the DOC released by the macroalgae into the surface ocean. Importantly, the production of DOC by the macroalgal will not lead to competition for nutrients with phytoplankton because most of the DOC produced by the macroalgae, and the incorporated nutrients, will be remineralized in the surface ocean back to a form that is available for phytoplankton (Bauer et al., 2013). Any recalcitrant DOC (Hansell, 2013) that is not remineralized should function as a long-term carbon sink.

**On the direct/indirect ecological effects of open ocean afforestation**

Cultivating macrophytes in the open ocean for CDR would potentially impact the surface, interior, and benthic environments of the ocean. The surface environment would be modified by increased shading associated with the floating macrophytes, increased three-dimensional substrate, increased food availability, increased pH associated with enhanced photosynthetic activity by the macrophytes, and increased albedo.

The increased three-dimensional structure and food availability would also increase diversity and abundance in these waters—a benefit, if this increase supported ecosystem productivity and resilience. The increased floating substrate may also increase the connectivity of biogeographically isolated regions of the surface ocean, increasing the dispersal and range of different species. This could be viewed as a negative if, for example, it allowed non-native species to invade previously isolated regions, or a positive if it allowed species to more easily shift their geographic range to accommodate the effects of climate change. The increased seawater pH associated with the increased carbon-fixation per unit of limiting nutrients by the macrophytes, compared with the microphytes that they are displacing, would be viewed as a positive as it would partially offset CO$_2$-induced ocean acidification.

The interior ocean would not be materially modified by the metabolic byproducts of microbial decomposition of the sinking biomass because the sinking rates for macroalgae after removal of their pneumatocysts is estimated at 2500 m/d (Baker et al., 2018), resulting in a residence time on the order of days. However, the sinking biomass would generate a spatially contiguous (albeit rapidly moving) three-dimensional structure that may increase the ecological connectivity of the various ocean layers. The increased three-dimensional structure and food in the ocean interior may support increased diversity and abundance in this zone, as well as...
facilitate transport of organisms to deeper waters, which may be viewed positively or negatively, depending on ecosystem impacts.

The benthic environment would be similarly impacted by the elevated diversity and abundance associated with increased structure and food on the ocean floor, which again could be viewed either positively or negatively, depending on ecosystem impacts. Although some of the sunken biomass would be decomposed by microbes, thereby recycling the associated CO$_2$ and nutrients back to the oceans, it is estimated that this process would take on the order of a thousand years (DeVries and Holzer, 2019) and is thus not relevant to the timescales of CDR. Furthermore, sinking of macrophytes in zones of high sedimentation rate (e.g., > 1 cm/yr), such as alluvial fans, in the path of turbidity flows (i.e., submarine landslides that are constantly occurring along the continental slope and rise), submerged deltas, and carbonate producing environments, should slow the rate of microbial degradation of this biomass on the seafloor.

**On the impact of open ocean afforestation on albedo and light penetration**

Cultivation of macrophytes in the surface ocean would increase the Earth’s albedo because macrophytes reflect more short-wave radiation than seawater (Fogarty et al., 2018).

It is estimated that 1 km$^2$ of surface macrophytes reduces radiative forcing of the Earth by 0.0295 peta-J/y (1800 peta-J/y/6100 km$^2$; Bach et al., 2021). Assuming that 1 Mt of CO$_2$ sequestration causes a 100 peta-J/y reduction in radiative forcing (Myhre et al., 1998), the 253,400 km$^2$ area of macrophyte coverage corresponding to 1 Gt of CO$_2$ drawdown would have the additional benefit of reducing radiative forcing by 7,475 peta-J/y (253,400 km$^2$ x 0.0295 peta-J/y)—equivalent to additional CDR of 75 Mt CO$_2$/y (7,475 peta-J/y x 1 Mt CO$_2$/100 peta-J/y). The resulting increase in albedo would therefore be viewed positively, in contrast to the authors’ view. They believe this increase in albedo associated with open ocean afforestation—and the resulting mitigation of CO$_2$-induced global warming—to be negative. Running Tide disagrees with this opinion, as one of the primary goals of CDR is the mitigation of CO$_2$-induced global warming.

Increased shading may reduce rates of photosynthesis deeper in the water column, a potential negative impact. However, the shading would also provide cover for pelagic organisms that could not otherwise avoid predation in the open ocean, thereby increasing abundance and diversity—a potential positive if this increases ecosystem productivity and/or resilience. But,
again, due to the small percentage of the global surface ocean that would be impacted by even a Gt-scale deployment of macroalgae (0.07%, as discussed above), these impacts of shading would be correspondingly limited.
References


References (cont.)