Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics

Authors: Aurora M. Ricart[1]*, Dorte Krause-Jensen[2,3], Kasper Hancke[4], Nichole N. Price[1], Pere Masque[5,6,7], Carlos M. Duarte[8]

Affiliations:

[1]Bigelow Laboratory for Ocean Sciences; East Boothbay, Maine, United States.
[2]Arctic Research Centre, Aarhus University, Aarhus, Denmark.
[3]Department of Bioscience, Aarhus University, Silkeborg, Denmark.
[4]Norwegian Institute for Water Research (NIVA), Oslo, Norway.
[5]Institute of Environmental Science and Technology (ICTA) and Physics Department, Universitat Autònoma de Barcelona, Bellaterra, Spain.
[6]School of Science and Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, Western Australia, Australia.
[7]International Atomic Energy Agency, Principality of Monaco, Monaco.
[8]Red Sea Research Center (RSRC) and Computational Bioscience Research Center (CBRC), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia.

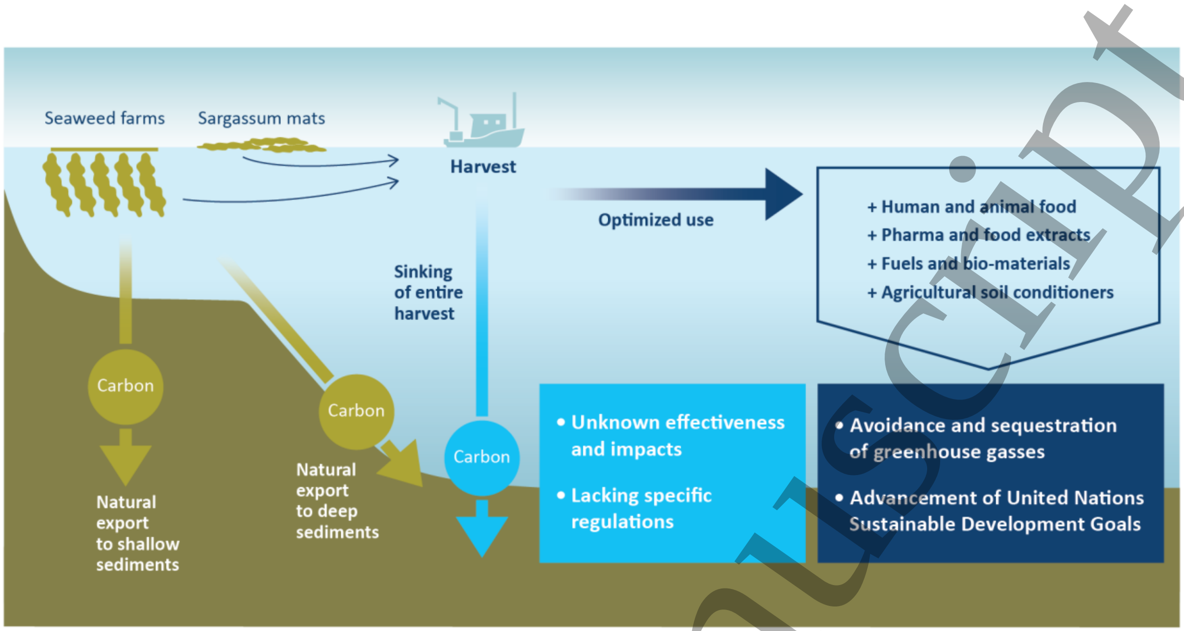
*Corresponding author. aricart@bigelow.org

Preface/Abstract: Sinking vast amounts of seaweed in the deep ocean is currently being proposed as a promising ocean carbon dioxide removal strategy as well as a natural-based solution to mitigate climate change. Still, marketable carbon offsets through large-scale seaweed sinking in the deep ocean lack documentation and could involve unintended environmental and social consequences. Managing the risks requires a number of urgent actions.

The window to meet the goals of the Paris Agreement, measured as remaining cumulative greenhouse gas (GHG) emissions to avoid trespassing the 1.5-2°C threshold of atmospheric warming, is narrow and rapidly closing, leading to calls to urgently activate all options. It is imperative to reduce emissions while implementing vetted carbon dioxide removal (CDR) strategies to remove excess carbon dioxide (at the gigaton scale) from the atmosphere. However, most direct air carbon capture technologies are still in their infancy and are operational at insufficient scale and/or involve too steep financial or environmental costs. Many corporations and nations, committed to achieving carbon neutrality, are in search of investable carbon credits derived from nature-based CDR strategies. Ocean CDR, especially related to the expansion of Blue Carbon habitats (i.e., coastal and marine vegetated habitats), are in the spotlight.

In particular, seaweed farming has entered the family of Blue Carbon options with large expectations due to its scalability, and the multiple socioeconomic benefits that can be derived generating revenue at artisanal to industrial scales. Farmed seaweeds, as well as natural macroalgal beds, can export a fraction of the carbon fixed during growth to adjacent environments (Fieler *et al* 2021) where a portion of this carbon, either as entire thali or fragments, may occasionally sink to the deep ocean, and thus become removed from the short-term carbon cycle and sequestered (Krause-Jensen and Duarte 2016, Queirós *et al* 2019). Harvested seaweeds are used for human consumption and animal feed. This cannot be considered for carbon sequestration in the long-term, but can replace foodstuffs with higher carbon footprints, and potentially reduce enteric methane emissions from ruminants (Vijn *et al* 2020). Seaweeds can also deliver high-value molecules for pharma and food industries, replace carbon intensive commodities like chemical fertilizers and synthetic plastics, or generate biochar and biofuels (Duarte *et al* 2021). Each of these emerging markets may represent meaningful GHG emissions avoidance or sequestration opportunities elsewhere in extant supply chains (Fig. 1). The best path to activate the promise of seaweed farming likely is to develop it both as a CDR strategy and utilization technology of low carbon footprint. However, motivated by quick investment returns from carbon credits and the desire to act quickly, some are eager to purposefully sink the entirety of the harvested biomass of seaweed, both farmed and wild, into the deep ocean (i.e., below 2000m for maximized efficiency based on Baker *et al* 2022).

We reflect on risks stemming from scientific knowledge gaps and the lack of governance related to large-scale seaweed sinking, and consider ethical concerns.



All pathways need life cycle analysis to account for total greenhouse gasses.

Fig. 1. Conceptual diagram of the pathways for seaweed as a CDR strategy. Seaweed from farms and *Sargassum* mats can naturally export carbon, where a fraction sinks into shallow and deep sediments. Harvested seaweed can be allocated for assisted sinking in deep sediments. However, scientific evidence on its effectiveness as a CDR strategy is lacking and it needs development of specific regulations to be implemented. Alternatively, uses of harvested seaweed can be optimized as a CDR strategy and utilization technology of low carbon footprint which also will help advance numerous UN SDGs.

Seaweed carbon as an emerging opportunity

Traditional natural Blue Carbon habitats (seagrass, saltmarshes, mangroves) are the focus of conservation and restoration projects for gaining carbon credits. However, these habitats are restricted to a narrow belt along the shore and occupy <0.2% of the ocean surface (Duarte *et al* 2013). Seaweed aquaculture represents a more scalable opportunity (Duarte *et al* 2017), since the areas suitable for seaweed cultivation can extend far offshore (Froehlich *et al* 2019) within precautionary limits that avoid unintended consequences on the environment (Duarte *et al* 2021). Additionally, floating *Sargassum*, which recently has been observed expanding across the tropical Atlantic Ocean causing unprecedented landings of nuisance macroalgal mats in different continents (Fidai *et al* 2020), is also attracting attention in the carbon crediting context (Bach *et al* 2021).

Hence, the deliberate sinking of seaweed in the deep-sea has been proposed as a climate mitigation strategy to capitalize on the scalability of seaweed farming, including the growing masses of floating *Sargassum* (National Academies of Sciences Engineering and Medicine 2021), and is garnering media, scientific, philanthropic, and commercial attention. Coupled with a roaring demand for carbon credits linked to the wave of carbon neutrality pledges in the private sector, many entrepreneurs and private companies are emerging that offer rapid solutions at scale from sinking seaweed in the deep sea (Fig. 2).

The seaweed sinking strategy appears very attractive at first blush: a natural, but manipulatable solution that reduces atmospheric carbon dioxide levels, is easily measurable and can be valorized (\$/ton of CO_2-equivalent or \$/kg of seaweed sunk), with expected increases in the value of carbon. The increasing uncertainty surrounding terrestrial carbon capture options due to space limitations, wildfires and other catastrophic events that release captured GHGs further points to farming and sinking seaweed as an appealing alternative to investors. It has all the ingredients for success, and so, the seaweed sinking market has already emerged. The current discussion on CDR strategies is being capitalized on by Western countries, and the US and UK are at the forefront regarding the number of the companies offering seaweed sinking options for carbon removal (Fig. 2). Most of them have large institutional investors behind.

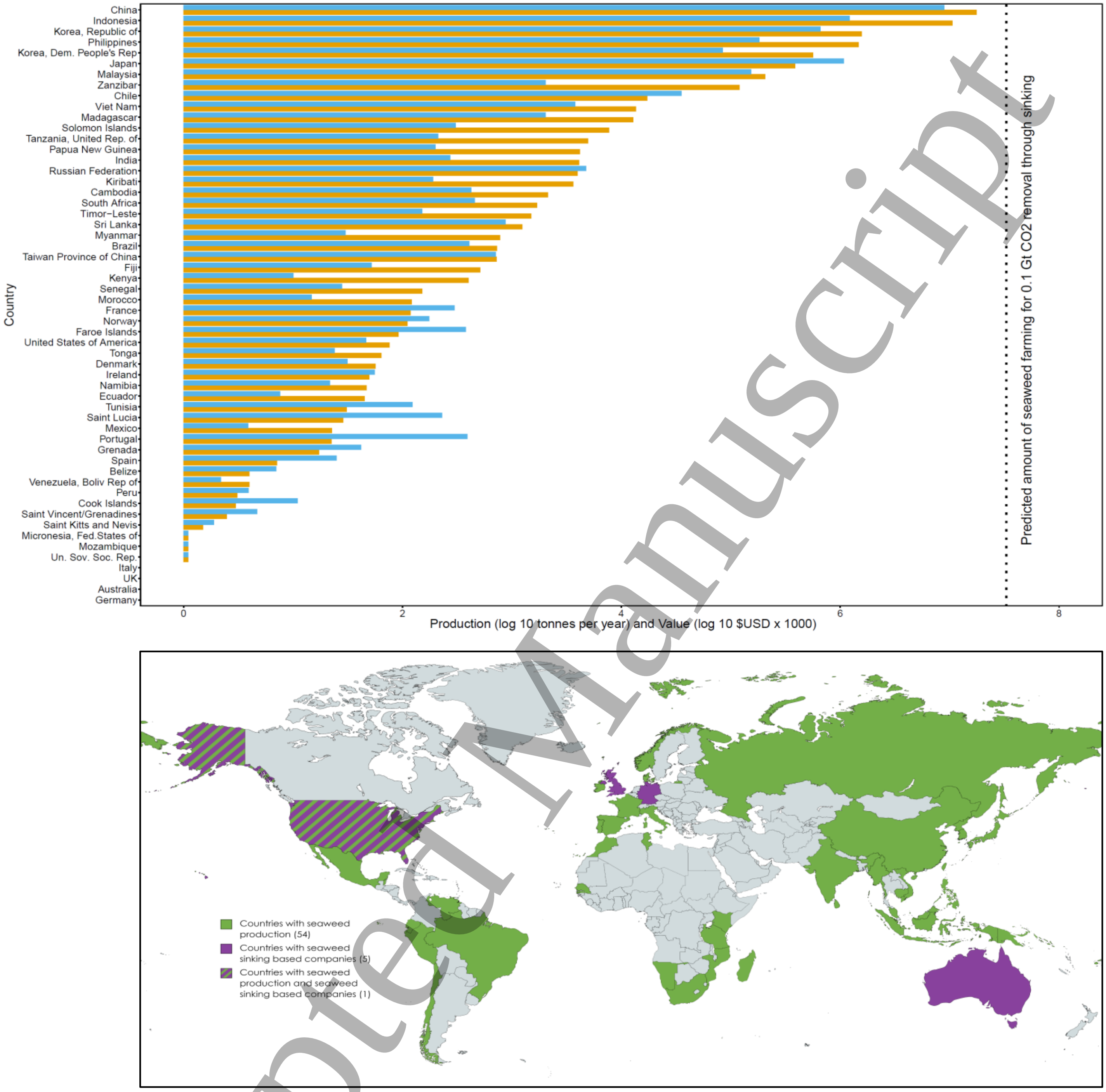


Fig. 2. Location of global seaweed aquaculture production and private companies offering seaweed sinking for carbon neutrality. Data for global seaweed production comes from FAO 2021 https://www.fao.org/fishery/statistics-query/en/aquaculture/ and is presented in two ways: fresh biomass (yellow bars) and economic value (blue bars). Yellow bars represent average production per year in the last five years (2015-2019) in tonnes of fresh weight using a logarithmic transformation. Blue bars represent average value per year in the last five years (2014-2019) in USD x 1000 using a logarithmic transformation. The vertical dotted line represents the amount of annual seaweed production required for the removal of 0.1 Gt of carbon dioxide (CO2), see details in main text. The subplot map highlights the number of countries (n=54) with seaweed production reported to FAO in the last five years (2015-2019) and the number of countries (n=6) with registered private companies or startups offering seaweed sinking for carbon benefits as of 21st of December 2021. For the latter, information comes from a search in CDR project databases (carbonplan.org, airminers.org, Stripe Negative Emissions Purchase, Microsoft

Carbon Removal Request for Proposals) and Google (words: “seaweed sinking deep ocean carbon dioxide removal”).

Potential risks and lack of scientific evidence

Currently, science cannot discern the impacts of large-scale seaweed sinking in the ocean for marine life or the carbon cycle. The ecological carrying capacity of both large-scale offshore farming and large-scale sinking is unresolved. The consequences for primary productivity in the upper ocean and associated food webs (e.g., from diverting nutrients into large scale production of seaweed), as well as the impacts of large seaweed biomass to deep-sea biological communities (e.g., from oxygen depletion), are largely unknown (National Academies of Sciences Engineering and Medicine 2021, Campbell *et al* 2019). Moreover, not all seaweed ecosystems, farmed or wild, may sequester carbon (Gallagher *et al* 2022) and it is not known with confidence how much and for how long sunk seaweed will store carbon in the deep ocean, and what will be the turnover rate, which likely will depend on the location (Siegel *et al* 2021).

The scientific community, in a clear example of producing demand-driven research, is in the process of identifying the best approaches to test the reliability and impacts of sinking seaweed. This is an essential step forward. Here, we alert that the race to sink seaweed in the ocean is outpacing the rate of progress of the essential science to assess risks, surging past even perfunctory evaluation of the environmental impacts and social benefits. This lack of scientific evidence and of peer-reviewed procedures to verify success of the practice, however, has not prevented the private sector from currently offering carbon removal from sinking seaweed as an attractive marketable product where millions $USD have already been invested.

Lack of governance regarding large-scale seaweed sinking

Seaweed farming is a multibillion-dollar industry (Fig. 2) and the fastest-growing aquaculture sector worldwide. For the most part, seaweed cultivation activities in territorial waters are regulated in the same way as shellfish farming (Billing *et al* 2021, Wood *et al* 2017), and there are no explicit regulations regarding sinking seaweed in the deep ocean at any national or international level, although there are international policy instruments that may apply: The United Nations Convention on the Law of the Sea (UNCLOS), the Convention on Biological Diversity (CBD), and the London Convention (1972) and its modernization under the London Protocol (1996). Under the London Protocol, all dumping into the ocean is prohibited, except for acceptable wastes, including organic material of natural origin. But, if the objective of farmed seaweed is to sink it for financial gain through carbon credits, should the valued biomass be considered waste? Specific regulations designating harvested biomass status are required, particularly if negative environmental and social impacts are anticipated. Further, in-depth, third-party environmental impact assessments will be crucial. Similarly, accreditors of carbon credits should enforce reliable verification processes and hold companies accountable for the accuracy and precision of estimations of carbon removal.

Commensurate with emergent scientific evidence, urgently needed is a plural oversight approach that embraces and coordinates the diversity of actors: governments, managers, civil society (as consumers and final beneficiaries) and the private sector. All of these play a vital role in climate action governance.

Ethical considerations

The disposal of a valuable, nutritional and biomaterial resource in the deep ocean in a world suffering from hunger and a sustainability crisis needs careful ethical consideration. The agriculture capacity to meet demands from the growing human population for food and materials is forecasted to become limited (Duarte *et al* 2009). Seaweed cultivation, for centuries a common practice in East Asia, has recently gained increased attention globally for its great potential to meet these challenges (Duarte *et al* 2021). Seaweed farming has the capacity to meet multiple goals contributing to advance a number of the United Nations Sustainable Development Goals (UN SDGs). These include zero hunger (SDG2), good health and well-being (SDG3), affordable and clean energy (SDG7), climate action (SDG13) and life below water (SDG14); which provide integrative benefits contributing to additional SDGs (Duarte *et al* 2021). Despite its sustainability potential, social license for the seaweed aquaculture sector hinders its growth (Billing *et al* 2021). Sinking seaweed for a poorly documented climate benefit will likely be met with increasing social opposition.

In recent human history, we have seen other examples of natural food resources being deviated to climate-related actions with negative consequences for communities that depend on them. The sudden interest in sinking seaweed, that otherwise is usable and has market value, mirrors the biofuel race a few decades ago, where the price of flour increased due to competing demands of crops for biofuel. Developing seaweed farming, both as a CDR strategy and an industry for resource production and use in parallel, could have a positive social impact by enhancing both the blue economy and the green shift, and possibly avoid negative social consequences. But the framework should be to achieve UN SDGs goals as a whole, not solely climate action (Duarte *et al* 2021).

A call to action

Managing the risks from the growing drive toward sinking seaweed as a CDR strategy requires a number of urgent actions.

-Advance the scientific understanding of sinking seaweed as a CDR strategy (scope and duration) and the associated ecological impacts. The development of comprehensive estimates of regionally specific carrying capacity for large-scale seaweed farming and informed assessments of where seaweed sinking trials are best executed, are critical elements to inform regulations.

-Generate robust estimates of the spatial area necessary to grow enough seaweed to sink in a way that is climatically effective, as well as estimates of area availability. A recent exercise in this sense (National Academies of Sciences Engineering and Medicine 2021) suggests a required farming area of 7.3 million hectares for CDR-worthy gigaton levels (0.1 Gt carbon dioxide sequestered per year = seaweed production of 0.033 PgC yr^{-1}), which would require the entire current global annual aquaculture production (Fig. 2) to be sunk. Estimates for carbon neutrality suggest even larger areas and seaweed production (Gao *et al* 2022a). However, the uncertainty around these estimates is very large, and layered seaweed cultivation systems are in development that would modify these estimates.

-Craft sustainability and ethical standards for large-scale natural nuisance or farmed seaweed sinking including socioeconomic and climate benefits that consider all applicable UN SDGs.

-Develop and vet reproducible and species-specific methodologies to verify carbon credits from seaweed sinking that considers various current farming practices. Aside from sinking the entire crop, seaweed farming presents other opportunities for CDR through pathways not currently accounted for (Fig. 1). For instance, consideration for carbon sequestration purposes should be given to non-edible parts of the seaweed which are currently culled and dumped during harvest as they are difficult to commercialize (e.g., holdfasts, biofouled fronds, excess product). Similarly, sediments underneath farms could also be accumulating and storing carbon. Gaining carbon credits from these pathways represents an unrealized, existing opportunity at no change in current activities and their impacts that needs to be explored.

-Synthesize life cycle assessments (LCAs) to account for total GHG emissions. These ‘sinking of farmed seaweed’ LCAs need to be juxtaposed against the same assessments for sinking nuisance seaweed and against farmed seaweed biomass utilization strategies that avoid or sequester GHGs elsewhere in food, feed, plastic, or fuel supply chains to fully understand trade-offs and determine the most cost-effective CDR strategies.

-Consider all potential options that seaweeds offer as a natural-based solution to reduce CO2 emissions. From integrating all seaweed uses (e.g., food, biofuel) and their specific temporal scale of carbon sequestration in estimates of carbon neutrality, to considering the role of all carbon pathways from seaweed cultivation, including lost particle organic carbon and excreted dissolved organic carbon, which are usually overlooked (Gao *et al* 2022b, Duarte *et al* 2021).

In conclusion, the urgency to find solutions that help stem climate change does not justify the deliberate sinking of seaweed in the deep ocean without properly assessing the consequences. Investment is best spent on advancing practical knowledge, not on unfounded promises of carbon sequestration.

References

Bach L T, Tamsitt V, Gower J, Hurd C L, Raven J A and Boyd P W 2021 Testing the climate intervention potential of ocean afforestation using the Great Atlantic *Sargassum* Belt *Nat. Commun.* **12** 1–10 Online: http://dx.doi.org/10.1038/s41467-021-22837-2

Baker C A, Martin A P, Yool A and Popova E 2022 Biological Carbon Pump Sequestration Efficiency in the North Atlantic: A Leaky or a Long-Term Sink? *Global Biogeochem. Cycles* **36**

Billing S L, Rostan J, Tett P and Macleod A 2021 Is social license to operate relevant for seaweed cultivation in Europe? *Aquaculture* **534** 736203 Online: https://doi.org/10.1016/j.aquaculture.2020.736203

Campbell I, Macleod A, Sahlmann C, Neves L, Funderud J, Øverland M, Hughes A D and Stanley M 2019 The environmental risks associated with the development of seaweed farming in Europe - prioritizing key knowledge gaps *Front. Mar. Sci.* **6**

Duarte C M, Bruhn A and Krause-Jensen D 2021 A seaweed aquaculture imperative to meet global sustainability targets *Nat. Sustain.*

Duarte C M, Holmer M, Olsen Y, Soto D, Marbà N, Guiu J, Black K and Karakassis I 2009 Will the oceans help feed humanity? *Bioscience* **59** 967–76

Duarte C M, Losada I, Hendriks I, Mazarrasa I and Marbà N 2013 The role of coastal plant communities for climate change mitigation and adaptation *Nat. Clim. Chang.* **3** 961–8 Online: http://www.nature.com/doifinder/10.1038/nclimate1970

Duarte C M, Wu J, Xiao X, Bruhn A and Krause-Jensen D 2017 Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* **4** 100 Online: http://journal.frontiersin.org/article/10.3389/fmars.2017.00100/full

Fidai Y A, Dash J, Tompkins E L and Tonon T 2020 A systematic review of floating and beach landing records of Sargassum beyond the Sargasso Sea *Environ. Res. Commun.* **2**

Fieler R, Greenacre M, Matsson S, Neves L, Forbord S and Hancke K 2021 Erosion dynamics of cultivated kelp, *Saccharina latissima*, and implications for environmental management and carbon sequestration *Front. Mar. Sci.* **8** 1–16

Froehlich H E, Afflerbach J C, Frazier M and Halpern B S 2019 Blue growth potential to mitigate climate change through seaweed offsetting *Curr. Biol.* **29** 3087-3093.e3 Online: https://doi.org/10.1016/j.cub.2019.07.041

Gallagher J B, Shelamoff V and Layton C 2022 Seaweed ecosystems may not mitigate CO2 emissions *ICES J. Mar. Sci.* **79** 585–92

Gao G, Beardall J, Jin P, Gao L, Xie S and Gao K 2022a A review of existing and potential blue carbon contributions to climate change mitigation in the Anthropocene *J. Appl. Ecol.* 1–14

Gao G, Gao L, Jiang M, Jian A and He L 2022b The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication *Environ. Res. Lett.* **17**

Krause-Jensen D and Duarte C M 2016 Substantial role of macroalgae in marine carbon sequestration *Nat. Geosci.* **9** 737–42

National Academies of Sciences Engineering and Medicine 2021 *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (Washington, DC: The National Academies Press)

Queirós A M, Stephens N, Widdicombe S, Tait K, McCoy S J, Ingels J, Rühl S, Airs R, Beesley A, Carnovale G, Cazenave P, Dashfield S, Hua E, Jones M, Lindeque P, McNeill C L, Nunes J, Parry H, Pascoe C, Widdicombe C, Smyth T, Atkinson A, Krause-Jensen D and Somerfield P J 2019 Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean *Ecol. Monogr.* **89**

Siegel D A, DeVries T, Doney S C and Bell T 2021 Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies *Environ. Res. Lett.* **16** 104003

Vijn S, Compart D P, Dutta N, Foukis A, Hess M, Hristov A N, Kalscheur K F, Kebreab E, Nuzhdin S V., Price N N, Sun Y, Tricarico J M, Turzillo A, Weisbjerg M R, Yarish C and Kurt T D 2020 Key considerations for the use of seaweed to reduce enteric methane emissions from cattle *Front. Vet. Sci.* **7** 1–9

Wood D, Capuzzo E, Kirby D, Mooney-McAuley K and Kerrison P 2017 UK macroalgae aquaculture: What are the key environmental and licensing considerations? *Mar. Policy* **83** 29–39 Online: http://dx.doi.org/10.1016/j.marpol.2017.05.021

Data availability statement: All data supporting this study is publicly available and data sources can be found in the main text and references.

Competing interests: Authors declare that they have no competing interests.

Acknowledgments: This work originated in a research workshop at the International Atomic Energy Agency (IAEA) in Monaco, November 2021, organized by the Oceans 2050 Seaweed Project. The IAEA is grateful for the support provided to its Marine Laboratories by the Government of the Principality of Monaco. AMR and NP were supported by the World Wild Fund (WWF) with support from Earth Bezos Fund. DKJ was supported by the European Union H2020 (FutureMARES, contract #869300). KH was supported by the Norwegian Institute for Water Research (NIVA).

Author contributions: All authors contributed to conceptualization and investigation. AMR led the writing of the original draft and all co-authors contributed to review and editing.