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Global ocean spatial suitability for macroalgae offshore cultivation and sinking

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Abstract

Macroalgae offshore cultivation and sinking is considered a potentially practical approach for ocean-based carbon dioxide removal. However, several considerations need to be resolved to assess the effectiveness and sustainability of this approach. Currently, several studies focus on the area required for climate-relevant carbon sequestration through macroalgae cultivation and sinking without considering realistic, global spatial limitations. This study uses a spatially-explicit suitability assessment model for optimised open-ocean afforestation and sinking site designation. By applying specific maritime, ecological and industrial constraints, two maps are produced: a) suitable areas for macroalgae offshore cultivation and sinking, and b) suitable areas for macroalgae sinking only (for sequestration purposes). These data provide a more realistic approach to quantifying the ocean surface (including the corresponding depths) required for macroalgae offshore cultivation and sinking within a spatially sustainable framework. The resulting maps estimate the respective suitability areas within the EEZs of the world countries. A total area suitable for macroalgae offshore cultivation and sinking is calculated at 10.8M km^2, whereas sinking-only areas account for 32.8M km^2 of the offshore ocean. The implications of spatial suitability patterns at global and national levels are discussed. We suggest that the concept of '*grow nearshore, sink offshore*' should be explored as an alternative to offshore cultivation.

Keywords: macroalgae; ocean afforestation; carbon dioxide removal; suitability; spatial planning; mariculture; carbon sequestration

Introduction

Current international climate agreements require a rapid and extensive restriction of carbon dioxide (CO_2) emissions so that the global average temperature rise is kept below 1.5°C by the year 2100 (IPCC, 2022; UNFCCC, 2015). Several approaches for reducing atmospheric CO2 levels have been proposed to achieve this ambitious goal. These approaches include a) energy efficiency, b) diversification of energy resources (renewables), and c) limiting fossil fuel consumption (Hassan et al., 2022; IPCC, 2022), as well as more aggressive strategies, focusing on CO_2 removal (hereafter Carbon Dioxide Removal, CDR) (Duarte et al., 2017; IPCC, 2022). Industrial-type CDR strategies (aka 'carbon capture and storage', CCS) mainly refer to extracting CO_2 at the emission spots or directly from the atmosphere and storing it in the subsurface as pressurised liquid (Leung et al., 2014). Additionally, nature-based CDR solutions, such as: enhancing carbon absorption by restoring or expanding natural habitats such as forests, wetlands, mangroves, seagrasses, and macroalgae, have also been proposed or implemented (Chung et al., 2013; Fujita et al.,

2023; Gao et al., 2022; Kuwae et al., 2022; O'Dell et al., 2023; Smith and Torn, 2013). Recently, particular interest has focused on CDR through the geoengineering approach of ocean afforestation, also called macroalgae open-ocean mariculture and sinking (MOS) (Wu et al., 2023). The MOS approach aims at inducing a sustained, artificial deficit in oceanic CO_2 so that the ocean responds by absorbing more CO_2 from the atmosphere. To achieve this CO_2 deficit in the ocean, large-scale, massive cultivation of macroalgae is required. Macroalgae build biomass by consuming nutrients and absorbing CO_2 for photosynthesis, and thus when cultivated over vast areas it is suggested that they could accelerate the carbon pump in the ocean (Krause-Jensen et al., 2018; Siegel et al., 2021). The basis of MOS is not only to cultivate macroalgae but also to remove their biomass on time and quickly from the ocean surface and isolate it on the deep seafloor where carbon remineralisation can take place over extended time-scales (Krause-Jensen and Duarte, 2016; Siegel et al., 2021; Wu et al., 2023) and thus avoiding the dissolved carbon to re-enter the upper parts of the ocean and subsequently the atmosphere. Effective MOS-CDR operation requires large, open-ocean areas where macroalgae can grow and get directly sunk in the deep sea once a sufficient biomass level is reached.

Although the MOS concept is still in its infancy, it seems to be gaining more attention due to the effectiveness of macroalgae in absorbing more CO_2 compared to other 'blue carbon' resources and the potential scalability of existing macroalgae farming industry (Coleman et al., 2022; Froehlich et al., 2019; Krause-Jensen and Duarte, 2016; Lehahn et al., 2016; Ross et al., 2022). Several recent studies tried to estimate how much space is necessary for effective CDR through MOS operation. Arzeno-Soltero et al., (2023) estimated that 1M km^2 of MOS area is required to cultivate various taxa at oceanic areas with optimal nutrient concentration to absorb 1 $GtCyear^{-1}$, which is relevant for CDR purposes. Wu et al., (2023) suggested a global MOS area of 70M km^2 is required for removing *ca.* 13 $GtCyear^{-1}$, using idealised offshore areas that are not bounded by strict spatial criteria. However, these studies do not answer the question: how much area in the global ocean is suitable for MOS operations? Froehlich et al., (2019) estimated that *ca.* 48M km^2 was suitable for macroalgae aquaculture using sea surface temperature and nutrient availability for building a suitability model. To our knowledge, no study combines suitable areas for cultivating macroalgae and for MOS operations.

In practice, MOS planning requires the identification of suitable offshore areas where: a) MOS can be operated and monitored in a sustainable way, ensuring its CDR efficiency is not affected by operational CO_2 emissions, b) it does not overlap with other activities (*e.g.:* shipping, submarine infrastructures), and c) it does not overlap with ecologically significant areas (such as marine protected areas and hydrothermal vents) and d) is located in open-ocean areas with sufficient nutrient concentrations and adequate depth. This study aims to provide a spatially explicit suitability assessment for MOS and sink-only areas of the global ocean. These areas can be used as a base map for MOS planning and for obtaining more realistic approximations about CDR metrics such as biomass production and CO_2 absorption over different time scales and CDR scenarios. Spatial layers were processed to produce a global map of MOS- and sink-suitable areas and to calculate the percentage of these areas within national jurisdictions (Exclusive Economic zones, EEZ). In addition, the potential MOS-CDR efficiency of selected countries is discussed along with various scenarios focusing on the feasibility of MOS in achieving the 2100 climate goals. The sink-only suitability map is a novel dataset that addresses the multidisciplinary aspects and synergistic effects of various geospatial components that could be complementary to MOS approach.

Methodology

The global geospatial layers used in this study (Table 1) were based on a detailed set of criteria for MOS area selection, as suggested in a recent report by Ocean Visions (2022). The global datasets were initially divided into potential and unsuitable areas depending on their role in MOS, and data processing was based on a similar concept applied in spatial multi-criteria evaluation (Barillé et al., 2020). Datasets of the potential areas were transformed to represent suitability scores. The most critical factors for MOS potential areas include a) bathymetry, b) distance to the nearest port and c) nutrient (nitrogen-phosphorus ratio, N:P hereafter) availability. In addition, potential areas were identified either for MOS or Sink operations. Potential MOS areas should satisfy all three criteria. In contrast, potential sinking areas should satisfy only the bathymetry and distance to port criteria, given that macroalgae could be grown nearshore and transported in these areas.

Table 1: Geospatial layers applied in this study as MOS/Sink suitability criteria.

Area type	Variable	Model	Score threshold	Source
POTENTIAL	GEBCO bathymetry (m)	Gaussian distribution (μ= 2500 m, σ=1000 m)	0.75	https://www.gebco.net/data_and_products
	Distance to nearest port (km)	Gaussian distribution (μ= 300 m, σ=600 m)	0.75	https://globalfishingwatch.org
	N:P ratio	Gaussian distribution (μ= 30 , σ=20)	0.5	Froehlich et al. (2019)
EXCLUDED	Marine Protected Areas	Binary	-	UNEP-WCMC (2019), http://wcmc.io/WDPA_Manual
	Hydrothermal vents	Binary (Buffer: 10 km)	-	http://vents-data.interridge.org
	Submarine cables	Binary (Buffer: 1 km)	-	https://hub.arcgis.com/maps
	Major shipping lanes	Binary (Buffer: 10 km)	-	Benden, P. (2022), https://doi.org/10.5281/zenodo.6361763
	Important Marine Mammal Areas	Binary (Buffer: 10 km)	-	IUCN MMPATF (2018) www.marinemammalhabitat.org

Unsuitable areas

The following global datasets were used to exclude sensitive areas. Marine Protected Areas (MPAs) were applied without any buffer as they already contain appropriate buffer zones. The operation of MOS sites may involve increased ship traffic for management purposes, potentially resulting in marine mammal disturbance. Sustainable, ecologically-informed, large-scale MOS planning should further exclude areas important for marine mammals (e.g.: migration corridors, and reproduction sites) (Ocean Visions, 2022). Hydrothermal vents host fragile and complex ecosystems which rely on particular types of microbial communities. These communities should not be disturbed or altered by potential interactions during macroalgae remineralisation (Ocean Visions, 2022). As macroalgae accumulations start to decompose, they may develop their microbial communities, which are expected to interact with local benthos (Campbell et al., 2019; Harbour et al., 2021). MOS sites should not overlap with major shipping lanes (DeAngelo et al., 2023; Ocean Visions, 2022) and should be sufficiently distant from submarine

installations such as cables or pipelines (Ocean Visions, 2022). Here, we applied a 1 km buffer distance from submarine cables only, considering that open-ocean pipelines are limited and could be considered during fine-tuning of the MOS designation. Depths shallower than 1000 m and deeper than 5000 m were also excluded (see next paragraph).

Suitable areas

Once all exclusion areas were applied to potential areas, two types of suitability areas resulted: a) MOS-suitable areas, where sufficiently deep areas exist within sustainable proximity to ports and open-ocean nutrient availability is at acceptable levels for macroalgae mariculture and sinking, and b) Sink-suitable areas where open-ocean mariculture is not advised due to nutrient limitations, but these areas could be targeted for macroalgae sinking only, due to their proximity to nearest ports and appropriate sequestration depths.

The main concept of MOS projects assumes that cultivation and sinking occur at the same location. In this way, the transport of cultivated biomass is avoided since it can be directly and quickly sunk and deposited on the seafloor below (Ross et al., 2022; Wu et al., 2023). This practice is supposed to lower the MOS costs and minimise the project's carbon footprint. Thus, the GEBCO bathymetry grid was used for selecting areas with appropriate depths for MOS operations. Coleman et al. (2022) suggested 1000 meters as an upper depth limit (sequestration horizon), as dissolved carbon (a by-product of macroalgae mineralisation) may be leaked to the upper ocean layers if the deposition is not sufficiently deep. Wu et al. (2023) proposed that a seafloor deeper than 3000 meters was required to ensure that mineralised carbon will not re-enter the atmosphere in the next 100 years. However, areas deeper than 3000 m are located further offshore, requiring more time and cost (and thus having a larger footprint) for MOS deployment and monitoring. According to Siegel et al. (2021) the different basins of the global ocean hold specific ocean-ventilation times (time required by deep water to reach the top layer), meaning that MOS-suitable depth should vary across the global ocean. According to findings from Siegel et al., (2021), most carbon sequestered at depths of 1500-3500 m should not reach the atmosphere for the next few centuries. Thus, a Gaussian distribution function was fitted to GEBCO bathymetry to highlight areas in the 1500-3500 m range and assign lower scores to areas beyond this range (Table 1; Supplementary material, Fig. S1). This bathymetry range is suggested as optimal for either MOS or Sink operations, as shallower areas may pose a risk due to carbon leakage in the long term, and deeper areas could render CDR operations inefficient. The proximity of potential MOS/Sink areas to the shore is important not only for nutrient availability but also for optimizing the necessary logistics required for project implementation. Combining information from the economic feasibility studies of (Coleman et al., 2022; DeAngelo et al., 2023; Lehahn et al., 2016) a one-way distance to the nearest port of 1000 km was considered as maximum acceptable. A vessel suitable for such operations with an average speed of 15 knots, containing 100k metric tons of fresh seaweed biomass would need approximately 72 h to cover a 2000 km distance (two-way) which results in a 2-20% reduction in CO_2 efficiency due to emissions from fuel consumption (Bach et al., 2021; Lehahn et al., 2016). Therefore, an empirical Gaussian distribution function was applied to the Distance2port dataset (Table 1; Supplementary material, Fig.S1) in order to assign high scores to areas closest to nearest ports, while introducing rapid score decrease with increasing distance beyond the 1000 km fuzzy boundary. The function was applied to distances corresponding to areas with a depth greater than the depth of sequestration horizon (1000 m).

The N:P ratio in the surface water is a significant criterion for establishing an offshore ocean afforestation area. Different macroalgae species have their own optimal ratios, but 30:1 has been proposed as an average, with the range between 10:1 and 60:1 describing the overall variability of nutrient preferences (Harrison and Hurd, 2001; Froehlich et al., 2019). In this study, we applied an empirical Gaussian function, with the highest scores assigned to a 30:1 nutrient ratio (Supplementary material, Fig.S1). The global potential area, resulting from the sum of thresholded data, was thinned according to the ecological and industrial activity criteria shown in Table 1. Bathymetry and distance to port were thresholded using a cut-off score of 0.75, and for nutrient ratio, a 0.5 score was used for selecting a more comprehensive range of optimal areas. These threshold values ensure that only areas with the most favorable/sustainable conditions are considered for further analyses.

It has to be noted that the actual surface of suitable areas should still be less than calculated in this study, since detailed fine-tuning may exclude areas: a) with steep seafloor or areas where sinking is not advised due to geo-hazards (Ocean Visions, 2022) and b) where there is potential conflict between MOS with other maritime activities.

Results

Global and EEZ-scale coverage

According to the spatial suitability model developed in this study, the total surface area of the global ocean which is suitable for MOS is 10.8M km^2 (Fig 1). Many of the global MOS-suitable areas are located in sub-arctic and temperate zones. On the other hand, the global ocean area, which is sink-suitable (*i.e.,* sinking only), is significantly larger, covering 32.8M km^2 approximately (Fig 1). Considering that global efforts towards CDR are expected to rely mainly on national-level initiatives (Froehlich et al., 2019), the amount of MOS- and Sink-suitable areas within the national EEZs was calculated (Table 2). The total MOS-suitable area within the national EEZs is *ca.* 4.8M km^2. Most countries with the largest MOS-suitable surface area in absolute numbers are in sub-arctic and temperate zones. At the same time, there are also a few tropical countries located along the western coast of Africa (Mauritania), the Caribbean Sea (Cuba, Jamaica) and the eastern and western coasts of South America (Brazil, Chile, Ecuador). Norway has the largest surface of MOS-suitable area (593616 km^2) in its EEZ, followed by Denmark (453805 km^2) and the US (390911 km^2). The total Sink-suitable area falling within the national EEZs is *ca.* 18.4M km^2. The countries with the most significant Sink-suitable areas within their EEZ are located worldwide, with more than half covering
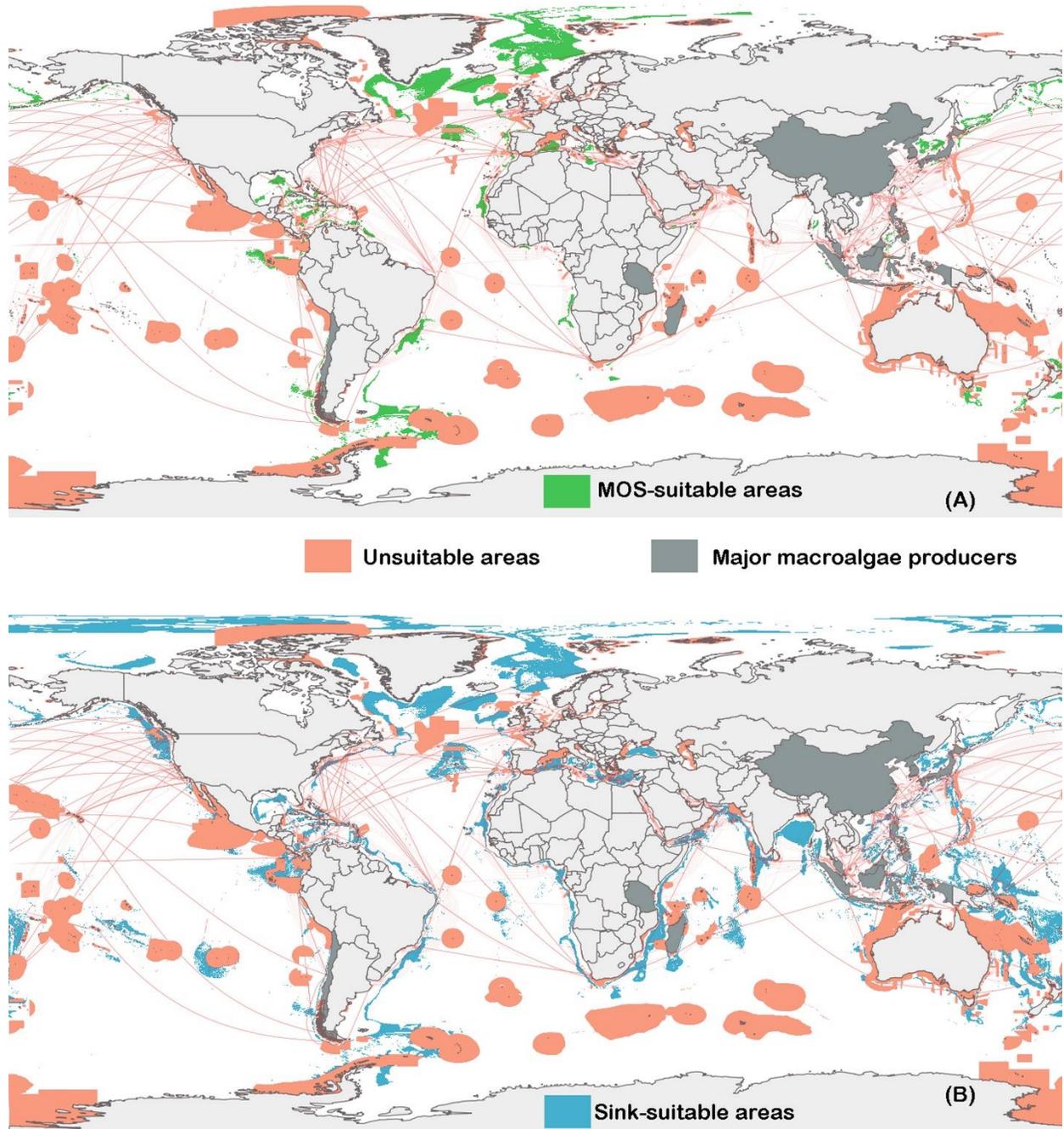
Figure 1. Global suitability map for: (A) Macroalgae offshore cultivation and sinking (MOS) and (B) sinking-only.

the tropical and subtropical regions. It is essential to highlight the sinking-area capacity of the top 10 macroalgae farming countries (Table 3). With a combined surface area of *ca.* 2.2 M km^2, they occupy more than half of the area of the top 20 countries with the largest MOS-suitable area. Indonesia is by far the

country with the largest Sink-suitable area (764836 km^2) in its EEZ, followed by Japan (518978 km^2) and the Philippines (266236 km^2).

Table 2. Top 20 countries with a) largest MOS-suitable surface area within their EEZ; b) largest Sink-suitable surface area within their EEZ. Overseas territories included joint regimes excluded (Flanders Marine Institute, 2019).

MOS-suitable			Sink-suitable		
Country	**%EEZ**	**Area (km^2)**	**Country**	**%EEZ**	**Area (km^2)**
Norway	29.3	593616	United States	9.6	1161030
Denmark	17.2	453805	India	40.4	939682
United States	3.2	390911	Indonesia	12.7	764836
Brazil	7.6	280475	Fiji	58.2	751233
New Zealand	4.2	279127	Papua New Guinea	30.4	728481
Russia	2.8	218676	France	7.5	714829
Iceland	26.5	202439	Denmark	25.3	667855
Ecuador	14.6	157295	Micronesia	21.4	644198
Chile	4.2	153848	New Zealand	9.5	636722
Portugal	8.8	151705	Norway	29.3	593616
Japan	3.6	144965	Brazil	15.6	572435
Ireland	30.4	129691	Japan	12.8	518978
Australia	1.1	101683	Australia	5.7	515953
Mauritania	52.6	91013	Solomon Islands	28.4	455214
Canada	1.6	90653	Portugal	25.9	447682
Spain	8.0	80832	Canada	7.4	427085
Jamaica	29.3	75312	Russia	4.5	351066
South Korea	20.3	70471	Ecuador	28.9	311678
Algeria	52.3	68673	Vanuatu	47.0	293170
Cuba	18.6	65479	Mozambique	47.5	268892
Total		*3800669*	*Total*		*11764635*

Table 3: Sinking area capacity of top-10 major producers of cultivated macroalgae (Cai, 2021) within their EEZ. Overseas territories included, joint regimes excluded (Flanders Marine Institute, 2019).

Country	Sink-suitable area (km^2)	Farmed seaweed production (tons.yr^{-1})
Indonesia	764836	9918067
Japan	518978	345507
Philippines	266236	1500026
Madagascar	205733	8865
Chile	183013	21672
China	23894	20122041
Tanzania	102591	106069
South Korea	70952	1812732
North Korea	52128	603000
Malaysia	41923	188110
Total	*2230284*	*34626088*

Discussion

MOS and sinking-only spatial extents

The resulting global suitability maps for MOS estimated in this study was 10.8M km^2, a smaller surface than suggested previously. Wu et al. (2023) tested a global model which provided a potential MOS area of 69.6×10^6 km^2 ($\sim$ 19.7 % of the world ocean), while Lehahn et al. (2016) estimated an area of 35×10^6 km^2 ($\sim$ 10 % of the world ocean). Froehlich et al. (2019) calculated an area of $\sim 48 \times 10^6$ km^2 suitable for ocean macroalgae aquaculture based on nutrient availability and temperature but did not relate it to the sinking process. Adding constraints such as distance to the port, depth, wave energy, shipping traffic, and marine protected areas, Spillias et al. (2023) obtained a smaller estimation of $\sim 6.5 \times 10^6$ km^2. The MOS suitability maps obtained in this study combined simple nutrient availability criteria for growing macroalgae with additional physical, ecological and industrial constraints related to the sinking process. The discrepancy with the MOS estimations from previous studies is mainly due to the setting of strict sinking criteria for optimal depth range (~1500-3500 m) and maximum sustainable distance (<1000 km) from the nearest port. These two limitations are crucial for increasing the cost- and time-effectiveness of MOS operations by reducing the total transit time required (for development and monitoring) and, hence, the carbon footprint of the MOS project itself. Depositing macroalgae on the seafloor in the depth range used in this study reduces the risk of CO_2 leakage back to the surface (Siegel et al., 2021). The global extent of sink-suitable area estimated in this study is 32.8M km^2. This is a new type of dataset that is expected to provide a new dimension in the discussion about open-ocean afforestation and sinking for CDR purposes.

Carbon estimations

The resulting global maps could be utilised for spatially restricting economic and biogeochemical models for MOS operations, allowing more realistic estimations/extrapolations of carbon removal to be obtained. Additionally, the resulting suitability maps are expected to contribute to the marine spatial planning of MOS activities by a) exploiting the carbon removal and sequestration potential of particular areas and b) minimizing the costs and effort required for MOS site selection and MOS operation/monitoring (Ross et al., 2022). Arzeno-Soltero et al. (2023) calculated that a 1M km^2 area (corresponding to 1Gt of fresh macroalgae biomass) with optimal nutrient availability should be cultivated intensively (5 cycles.year^{-1}) for capturing 1 Gt CO_2.yr^{-1}, whereas Ross et al. (2022) estimated an area of 0.4M km^2 for 1 GtCO_2 fixation. Both estimates fall in the lower level of CO_2 quantity that must be removed by 2100 to keep global temperatures lower than 1.5°C (Bach et al., 2021). Upscaling the results from Bach et al. (2021), who considered various uncertainties, a 3M km^2 cultivation area (with 3 cycles.year^{-1}) is required for capturing a climate-effective amount of CO_2 by the end of the century. Considering the above estimations and that international climate goals require at least 5 GtCO_2.yr^{-1} to be removed from the atmosphere by midcentury (Arzeno-Soltero et al., 2023), it is understood that the entire MOS-suitable area within the national EEZs should become operational. Although such a scenario is not realistic for the near future, this study showed significant MOS potential areas within the countries' EEZs. The vast MOS-suitable areas in Canada, the USA, Japan, Russia and Australia occupy less than 5% of their EEZ surface (Table 2), allowing them to pioneer the MOS-CDR development due to spatial opportunities. Considering only the sinking process for the top 10 major producers of cultivated macroalgae, Indonesia has the most significant potential with 0.76 M km^2. These countries are further highlighted by (Liu et al., 2023) as having the greatest nearshore area (without considering sinking in the deep sea) suitable for macroalgae farming. MOS/sink-only areas could be seen as a new type of valuable resource that could influence carbon policy and decision making at both national and trans-national levels. At national level, the presented suitability maps could assist countries in defining their specific net-zero strategies, whereas new economic relationships could be developed between different countries on the base of voluntary carbon offset markets (Froehlich et al., 2019; Ross et al., 2022), as suitable areas tend to be disproportionally distributed in some parts of the globe.

Implications on MOS feasibility assessment

The typical MOS concept is based on '*grow and sink offshore',* which is challenged by various technical feasibility aspects. One of the biggest challenges of MOS is related to the logistics and energy required for building and keeping MOS operations running. As large-scale, open-ocean areas are required for effective CDR through MOS, the sustainability of such operations is questionable, given their large carbon footprint (Ross et al., 2022). In addition, the cultivation of macroalgae at different oceanic conditions (temperature, salinity, nutrients) and the effect of various environmental factors (e.g., storms) would cause the biomass (and hence CO_2 absorption) to diverge substantially between MOS areas. On the other hand, the potential of sink-suitable areas within sustainable distance from ports assists in rethinking the operational design of MOS. Thus, the '*grow nearshore, sink offshore'* concept may be explored as an alternative to MOS, particularly for countries such as Indonesia, the second macroalgae producer in the world, with the largest sink-suitable area. It is therefore suggested that macroalgae cultivation could take place in nearshore areas, and wet biomass should then be transported to adjacent sink-suitable areas for deposition. This

practice would not require vast and complex offshore installations and would not be subjected to harsh ocean conditions, a strong constraint for offshore aquaculture (Buck and Grote, 2018; Buck and Langan, 2017). Additionally, growing macroalgae nearshore, would improve water quality of coastal areas by absorbing excess nutrients entering from land (Froehlich et al., 2019; Weerakkody et al., 2023). The main downturn is the environmental footprint resulting from the continuous transport of wet biomass to sinking sites. It needs to be more accurately assessed considering that it could be mitigated by relying on 'green' fuels (*e.g.,* ethanol) for shipping (Lehahn et al., 2016).

The fact that the top ten macroalgae-producing countries occupy large open-ocean areas suitable for sinking-only (Table 3), further emphasizes the potential of these countries in leading global initiatives on '*grow nearshore, sink offshore*' operations. The growing demand for macroalgae products, drives a subsequent need for upscaling the macroalgae farming industry (Froehlich et al., 2019; Lehahn et al., 2016; Liu et al., 2023; Ross et al., 2022; Spillias et al., 2023). However, countries outside the tropics, with large suitable space availability have a negligible macroalgae farming development due to various socio-economic reasons (Liu et al., 2023). Incorporating macroalgae farming for ocean-based CDR along with the use for bioenergy/bio-products production could potentially accelerate the upscaling of current farms globally (Froehlich et al., 2019; Lehahn et al., 2016).

MOS uncertainties

This study highlights the substantial opportunities for ocean-based CDR by identifying significant MOS and sinking-only areas in the global ocean and within countries' EEZs. However, spatial planning is only one aspect of establishing such operations, and several legal, economic and ecological uncertainties must be accounted for. Large-scale MOS is currently lacking a detailed legal framework that regulates multiple user interactions in the open ocean (O'Dell et al., 2023) and ensures compliance with the London (1972) Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (IMO, n.d.). Macroalgae cultivation and sinking are currently subject of feasibility scrutiny, particularly in terms of economic viability as such operations involve huge costs and associated effort. Detailed economic estimates from (DeAngelo et al., 2023) and (Froehlich et al., 2019) place ocean afforestation costs towards the upper range of costs required for terrestrial afforestation. However, upscaling the macroalgae farming sector for large-scale carbon offsetting and production of biofuels could lower the overall costs (Froehlich et al., 2019). Monitoring the CDR efficiency of ocean afforestation includes the challenging tasks of verifying *additionality* and *permanence* (Pessarrodona et al., 2023; Ross et al., 2022). Additionality refers to the amount of carbon removed from the ocean due to MOS implementation. At the same time, permanence is the amount of MOS-captured carbon that is securely sequestered for sufficient timescales. Last but not least, important environmental and ecological uncertainties need to be resolved and quantified to prioritize further MOS research (Campbell et al., 2019). Both macroalgae cultivation and sinking are expected to influence in various ways the upper ocean layers and deep sea habitats, respectively. Open ocean macroalgae cultivation is associated with massive nutrient consumption, leading to competition with phytoplankton. This may cause a decrease in carbon that could be otherwise fixed by phytoplankton (Bach et al., 2021; Ross et al., 2022). Furthermore, macroalgae may host calcifying organisms that reduce seawater alkalinity and subsequently the capacity of the ocean to absorb CO_2 (Ross et al., 2022; Wu et al., 2023). Additional uncertainties and complications are related to the fate of macroalgae and carbon after sinking and their impact on deep sea habitats. Thick accumulations of macroalgae on the seafloor could create new hypoxic zones (Ross et al., 2022; Wu et al., 2023) however

the exact influence on benthic fauna remains quite unclear. Therefore, continuing simulations and real-world experiments are required to better constrain the overall benefits of MOS operations.

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Supplementary material

Figure S1: Gaussian function applied to: (A) GEBCO bathymetry, (B) Distance to port and (C) nutrient ratio N:P.