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Meeting Carbon Dioxide Removal Demand in 2030: The Potential of Macroalgae Cultivation and Harvest

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Meeting Carbon Dioxide Removal Demand in 2030: The Potential of Macroalgae Cultivation and Harvest

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1 INTRODUCTION

Modelled mitigation pathways consistent with the ambitious temperature targets of the Paris Agreement include atmospheric carbon dioxide removal (CDR) as part of climate policy (IPCC 2022). Numerous studies have investigated the potential of various – particularly land-based – CDR methods, i.e., the CDR supply side (Smith et al. 2024), but there have been few analyses on how their implementation might be influenced by, or contingent upon climate policy frameworks (Morris et al. 2024). Currently, only a few countries have established incentives for obtaining carbon credits through CDR, i.e. the demand side of removals in compliance markets, and most of the transactions take place in the voluntary market (Lamb et al. 2024 and cdr.fyi, respectively). In this study, we apply a static compliance problem for the year 2030, derived from the countries' emissions reduction targets, as set out in the national determined contributions (NDCs) under the Paris Agreement to analyze regional disparities in CDR demand. We contrast the regional variation in CDR demand with the regional variation in CDR supply, which in case of macroalgae cultivation and harvest results from different nutrient availabilities and marine conditions in national waters. The analysis is hypothetical in the sense that we do not capture the regional specific supply chains involved in macroalgae cultivation and harvesting. Instead, it aims to illustrate regional mismatches of CDR supply and demand, which have so far only been analyzed for terrestrial CDR options (Morris et al. 2024). Despite its hypothetical nature, the study offers valuable insights regarding the incentives for the development of this removal through macroalgae cultivation specifically and marine CDR methods in general.

Macroalgae aquaculture with harvesting is regarded as a prospective marine CDR option (Krause-Jensen and Duarte 2016). The biomass could potentially be used for long-term carbon storage through further processing and utilization, like bioenergy with carbon capture and storage (BECCS) or biochar production (National Academies of Sciences, Engineering, and Medicine 2022; Mathew et al. 2024). Obviously, scaling up the cultivation to a Gt-scale implies the extension to more exposed marine environments. This would require considerable learning-by-doing and the development of appropriate supply-chain logistics, as current technologies have only been established in sheltered coastal waters (e.g. Buck and Buchholz 2004; Goecke et al. 2020). Nevertheless, since the actual carbon storage resulting from utilizing the biomass obtained from macroalgae aquaculture and harvest in national waters could take place on land (i.e., as part of BECCS r biochar), monitoring reporting and verification issues are less complicated compared to in situ open ocean carbon storage via biomass sinking. Yet, at the same time, there would be no conflicts with other land use demands as are often central for terrestrial CDR options. In addition, macroalgae cultivation offers significant co-benefits, particularly in mitigating eutrophication (Froehlich et al. 2019; Ross et al. 2023). Coastal blue carbon projects are generally recognized for providing a range of co-benefits (Merk et al. 2022; Doolan and Hynes 2023). Furthermore, in coastal countries where people are already somewhat familiar with existing macroalgae farms for food production and aquaculture (Froehlich et al. 2017) the local population might be more open to cultivate macroalgae for marine CDR compared to the deployment of novel marine approaches such as ocean alkalinity enhancement (Merk et al. 2023; Nawaz et al. 2023). Especially, as concerns about environmental side-effects seem to be lower compared to fish farming (Budhathoki et al. 2024).

Currently, with a few exceptions, carbon compliance markets do not yet allow for the inclusion of CDRs, and when they do, they are usually limited to land-based measures such as afforestation. In addition, regional climate policies tend to be fragmented, with different instruments and regulations for different sectors, implying that also regionally different frameworks for the inclusion of CDR are developed (Fridahl et al. 2023; Burke and Schenuit 2023). Our focus, however, is not on the development of instruments for the inclusion of CDR, but on examining the potential regional variations in demand for CDR. This demand is driven by each region's climate policy ambition and marginal abatement cost levels. We aim to assess how this demand aligns with regional CDR supply, specifically considering CDR via macroalgae cultivation and harvest. The analysis is supplemented by a modeling framework to investigate the CO_2 price effects and distributional implications of regional marine CDR supply.

2 METHODS

2.1 Potential CDR demand resulting from the Nationally Determined Contributions in 2030

We derive potential CDR demand from the countries' Nationally Determined Contributions (NDCs) for 2030. To comply with their NDCs, each country i must reduce its emissions so that the actual net emissions, E_i, are equal to the target level, A_i. The actual net emissions are calculated from business-as-usual emissions, $\bar{E}_i$, adjusted for the abatement rate, R_i, as follows:

$$E_i = \bar{E}_i \cdot (1 - R_i) \qquad \text{with} \qquad R_i = \frac{\bar{E}_i - A_i}{\bar{E}_i} \tag{1}$$

Each country's compliance cost is given by an abatement cost function, $C_i(E_i)$, which reflects the cost of reducing emissions to meet the target, A_i. The marginal abatement cost, $C'_i(E_i)$, is the derivative of the abatement cost function with respect to negative emissions and represents the country-specific CO_2 price, p_i.

If the cost at which CDR can be supplied in country i, denoted by r_i, is lower than the marginal abatement cost ($r_i < p_i$), it becomes cost-effective to substitute some emissions reductions with CDR. In other words, CDR will only be used if it is cheaper than reducing emissions. The corresponding demand for CDR, CDR_i, aligns with the optimal amount in a social planner scenario with a linear CDR cost function and can be determined by inverting the marginal abatement costs. Consequently, the actual net emissions with CDR are given by the NDC target, A_i, plus the amount of CDR deployed ($E_i^{CDR} = A_i + CDR_i$). This effectively allows for higher emissions because CDR represents negative emissions that offset these additional emissions. The emission abatement rate with CDR, R_i^{CDR}, is calculated as:

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$$R_i^{CDR} = \frac{\bar{E}_i - A_i - CDR_i}{\bar{E}_i} \quad (2)$$

and is smaller than the abatement rate without CDR deployment.

In the case of international emissions trading, marginal abatement costs are equalized across countries, resulting in a uniform international CO_2 price, p, which ensures that all countries collectively meet their reduction targets. Countries with marginal abatement costs below the international price will sell permits, while those with higher costs will buy permits. CDR demand arises if the CDR supply price is lower than the international CO_2 price. When CDR is deployed, emissions reduction levels decrease, lowering marginal abatement costs and thus reducing the international CO_2 price ($p > p^{CDR}$). Given this price and country-specific CDR costs, regional CDR demand can be determined. The actual net emissions, accounting for emission trading and CDR deployment, are given by:

$$E_i^{CDR} = A_i + CDR_i - P_i \quad (3)$$

where P_i represents the emissions trading volume of country i ($P_i < 0$ for permit buyers, $P_i > 0$ for sellers). The condition for deploying CDR is that the CDR supply price, r_i, is smaller than the adjusted CO_2 price with CDR, p^{CDR}, ensuring CDR remains cost-effective.

To quantify regional CDR demand, the abatement cost curves in the static compliance problem are calibrated with the Dynamic Applied Regional Trade (DART) model based on Rickels et al. (2024). DART is a global and recursive dynamic computable general equilibrium (CGE) model (Klepper et al. 2003; Winkler et al. 2021). The DART model itself is calibrated to the GTAP10 database (Aguiar et al. 2019), using 2014 as the base year. The baseline dynamics are calibrated to the GDP data from IEA (2020) and updated to include renewable energy data from the IEA (2022). Rickels et al. (2024) use DART to derive marginal abatement cost curves (MACCs) for the year 2030 by varying the emissions reduction target for each region from 0% theoretically up to 100% reduction relative to 2014 levels, in 5% increments, while assuming that all other regions fulfilled their NDC targets. These MACCs are then fitted to a cubic abatement cost curve, $C_i(E_i)$, implying a quadratic marginal abatement cost curve, $C'_i(E_i)$, for each region, i. Here, $\bar{E}_i$ represents the 2030 emissions in the business-as-usual scenario without climate policy, E_i denotes the actual emissions, calculated as $\bar{E}_i(1 - R_i)$, and $\bar{Y}_i$ is the GDP in 2030. The cost functions are given by:

$$C_i(E_i) = \alpha_i * (1 - \frac{E_i}{\bar{E}_i})^3 \bar{Y}_i \bar{E}_i \quad (4)$$

$$C'_i(E_i) = \alpha_i * 3 * \left(1 - \frac{E_i}{\bar{E}_i}\right)^2 \bar{Y}_i. \quad (5)$$

The region-specific cost parameters, α_i, are calibrated by minimizing the sum of the difference between the CO_2 price from the DART model, $P^{R_i}_{CO_2^{DART}}$, and the region-specific marginal abatement costs, $C'_i(E_i)$, for the range of R_i values.

The regional CO_2 prices are obtained by using information on the NDCs from Meinshausen et al. (2022). The dataset shows countries' initial NDCs and includes updates up to November 2nd, 2022, distinguishing between low- and high-ambition levels, translating into emissions reductions of 16.22 (SD 4.28) and 23.16 (SD 4.16) percent in 2030 relative to 2020, respectively. In the main analysis, we focus on the high-ambition targets for 2030. Furthermore, business-as-usual CO_2 emissions and business-as-usual GDP for the year 2030 are obtained from the DART model and the projections for all SSPs (Riahi et al. 2017, i.e., SSP1: van Vuuren et al. 2017, SSP2: Fricko et al. 2017, SSP3: Fujimori et al. 2017; Calvin et al. 2017, and SSP5: Kriegler et al. 2017) together with the OECD GDP growth projections (Dellink et al. 2017). In total, we analyzed six scenarios for future GDP and emissions. Table A.1 in Appendix A details the region-specific cost parameter α_i, the mean projected values for GDP and CO_2 BAU emissions, and the emissions reduction targets, A_i.

2.2 Potential CDR supply from macroalgae cultivation and harvest in national waters in 2030

The CDR supply from macroalgae cultivation and harvest in national waters is approximated using the study of Wu et al. (2024). They apply earth system model (ESM) simulations with the University of Victoria Earth System Climate Model version 2.9 (UVic) (Weaver et al. 2001; Keller et al. 2012) which has been adjusted to include an explicit macroalgae component, based on the Nearshore Macroalgae Aquaculture for Carbon Sequestration (N-MACS) model developed by Wu et al. (2024). N-MACS is an idealized generic model for the Phaeophyceae Sacharina (brown algae) where macroalgae growth is controlled by multiple limiting factors (nutrient availability, light, temperature) with a fixed C:N:P stoichiometric molar ratio of 400:20:1. In the model simulations, macroalgae farms are limited to ocean surface zones directly along coasts between 60°S and 60°N, with grid boxes 200 to 400 km wide extending to within 200 nautical miles from sovereign state coasts (Froehlich et al. 2019; Feng et al. 2017). The macroalgae cultivation is assumed to be deployed from 2020 to 2100 and simulations are detailed in Wu et al. (2024).

From the model simulations, we obtain the cumulative macroalgae harvest yields over time and convert them to estimates of potential annual harvest (tCO_2/km^2) for coastal grid cells, which are then assigned to countries' exclusive economic zones (EEZs). Note that various further processing steps are required to transform the CO_2 fixed by net primary production into long-term carbon storage (Ross et al. 2022; Troell et al. 2024), affecting efficiency and complicating monitoring, reporting and verification (MRV). As climate policies expand to more sectors, CO_2 emissions along the supply chain will increasingly be priced, eliminating the need for downstream corrections for life-cycle emissions. CO_2 negative projects will be profitable. However, such complete pricing coverage of CO_2 emissions will not be achieved by 2030. This means, our results for CO_2 removal via macroalgae cultivation, harvest and subsequent storage should be considered an upper limit (Ross et al. 2022; Lian et al. 2023). Removal via macroalgae cultivation presents an additional challenge for MRV even under full CO_2 pricing: It extracts carbon from seawater rather than directly from the atmosphere (Hurd et al., 2022, 2024; Troell et al. 2023, 2024).

We assume that macroalgae cultivation starts in the year 2025 and that harvesting rates of the fifth deployment year can be used to derive the potential CDR supply in the year 2030. This assumption reflects our long-term scenario in which macroalgae cultivation and harvesting are strategically planned and optimized as part of a long-term CDR strategy. In contrast, we also

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consider a short-term scenario, where harvesting rates from the first year of deployment are used to determine the CDR supply, representing a more immediate strategy. The carbon sequestration efficiency of N-MACS exhibits region-specific variation of nutrient availability, water temperature, and solar radiation levels on simulated macroalgae growth. These controlling factors result in notable variations in removal efficiency across regions. Figure 1 shows the regional differences in efficiency for the fifth deployment year.

Cost estimates for macroalgae-based CDR are typically provided as broad ranges, such as 25 to 125 USD/tCO_2 or 50 to 150 USD/tCO_2 (Cross et al. 2023; National Academies of Sciences, Engineering, and Medicine 2022). Detailed information about a potential supply chain of macroalgae cultivation, harvest, and storage, including information about regional labor and capital costs are missing. Furthermore, it is not detailed whether the cost estimates were derived under biochar-based storage or bioenergy with carbon capture and storage (BECCS). Biochar-based storage is estimated to potentially even result in negative costs (i.e. the revenues of biochar supply already exceed the production costs, making additional revenues from carbon credits unnecessary). In contrast, BECCS is estimated to have costs (net of electricity revenues) ranging between 60 and 160 USD/tCO_2 (Hepburn et al. 2019). It is unclear, whether the lower estimate of 25 USD/tCO_2 in Cross et al. (2023) is based on the assumption of a biochar storage design that includes additional revenues from biochar supply, or whether it reflects regionally low labor costs. Moreover, it is uncertain to what extent these cost estimates already account for economies of scale or incorporate potential price effects. The former may lead to low-cost estimates and the latter may lead to high-cost estimates. For instance, increased biochar supply could lower selling prices and thus revenues, while growing demand for carbon storage as part of BECCS might increase storage costs.

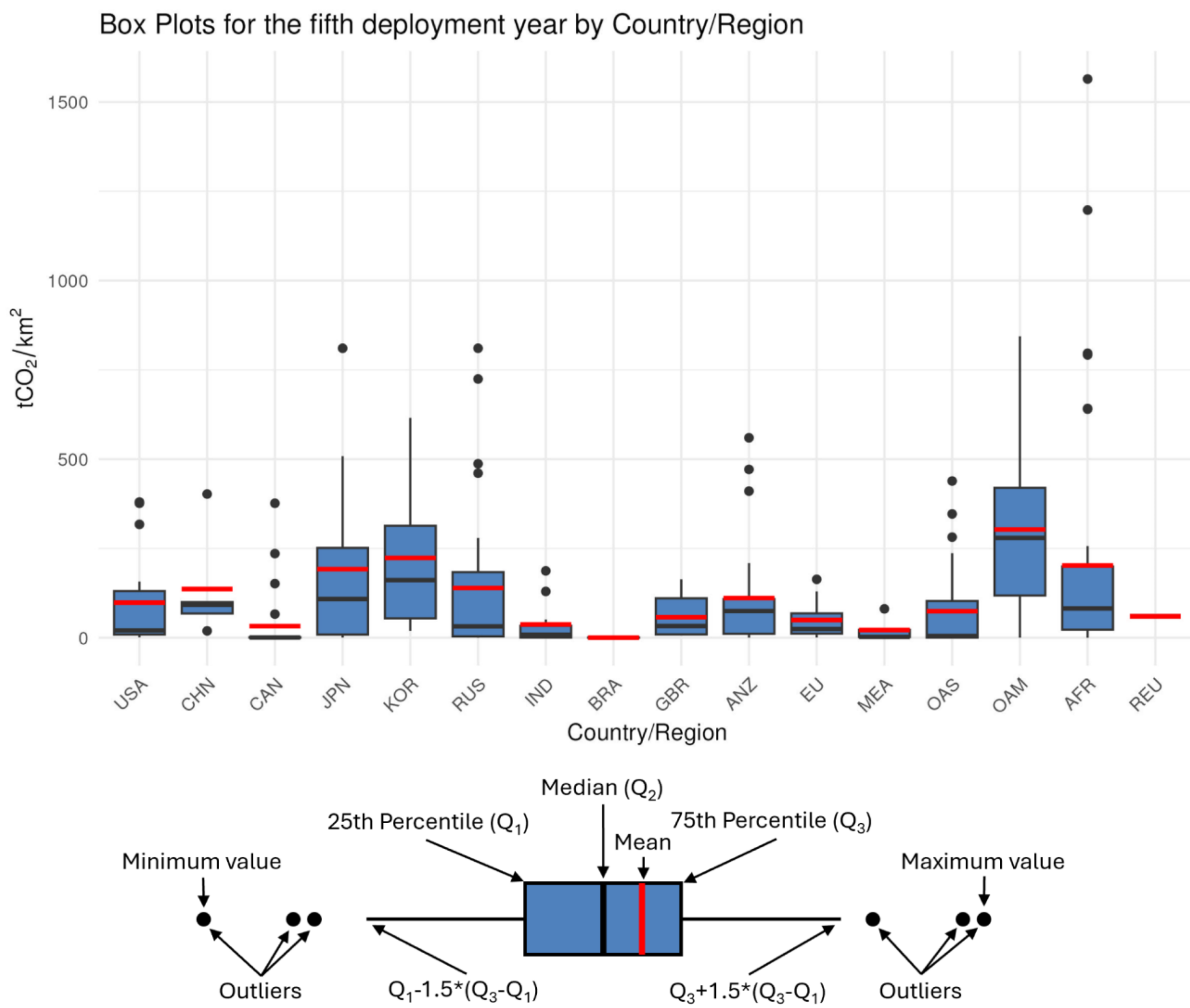

Figure 1 Regional variation in potential CDR supply through macroalgae cultivation and harvest. The box plots illustrate the carbon sequestration yields of macroalgae aquaculture in national waters, measured in metric tons of CO_2 per square kilometer (tCO_2/km^2) across various countries and regions. The CDR capacity represents the carbon securely stored within the harvested macroalgae biomass. The data, derived from the University of Victoria ESM (version 2.9), corresponds to the fifth year of macroalgae cultivation deployment, with each data point reflecting a pixel of horizontal resolution, measuring 3.6° longitude by 1.8° latitude. The analyzed pixels extend up to 200 nautical miles from coastlines, aligning with the boundaries of Exclusive Economic Zones (EEZs). USA: United States, CHN: China, CAN: Canada, JPN: Japan, KOR: South Korea, RUS: Russia, IND: India, BRA: Brazil, GBR: United Kingdom/Ireland, ANZ: Australia/New Zealand, EU: European Union, MEA: Middle East, OAS: Other Asia, OAM: Other Americans, AFR: Africa, REU: Rest of Europe.

Given these uncertainties, we simply consider three cost scenarios, allowing carbon credits from macroalgae cultivation, harvesting, and storage at 50 USD/tCO_2 (low cost), 100 USD/tCO_2 (medium cost), and 150 USD/tCO_2 (high cost) (denoted in 2020 USD). Since we consider macroalgae cultivation with harvest, we assume that permanent storage is achieved either via biochar or BECCS. We, thus, implicitly assume the net-accounting method (Rickels et al. 2010), i.e. the CO_2 in the harvested biomass in a given year can be accounted for.

Using the area-specific tCO_2/km^2 estimates, we can calculate the required area of a country's EEZ to satisfy regional CDR demand. We only have information about the carbon sequestration efficiency for a subset of coastal boxes due to the coarse resolution of UVic. Accordingly, we assume that the carbon sequestration rate at the 75th percentile of the regional efficiencies (Figure 1) can be realized. This assumption accounts for potential spatial limitations. Parts of the EEZ might already be occupied by other usages or marine protected areas or might be less economically attractive due to difficulties to access and operate in more remote locations. To account for these limitations, we censor the highest (model-based) carbon sequestration rates and assume that the 75th percentile provides a better proxy for realistic sequestration efficiencies.

We extend the analysis by exploring the potential impacts of exogenous CDR scenarios on CO_2 prices and cost-reduction dynamics within national and international climate policy frameworks. This provides insights into the cost thresholds at which certain CDR methods become cost-competitive and thus start to supply CO_2 credits (Rickels et al. 2012). This framework is implemented in the *CDRex* model which allows users to implement their own assumptions on regional marine CDR potentials and to obtain information about the corresponding market reactions. The *CDRex* model is detailed in Appendix B.

3 RESULTS

Without international emissions trading, the average aggregated demand for CDR in the compliance year 2030 is 1064 $MtCO_2$ (SD 375), 353 $MtCO_2$ (SD 171), 124 $MtCO_2$ (SD 11), for the low, medium, and high-cost scenarios, respectively (Table 1). Under the low-cost scenario, the EU29 exhibits the highest demand at 333 $MtCO_2$ (SD 232). For the medium-cost scenario, Japan has the highest demand at 109 $MtCO_2$ (SD 97). In the high-cost scenario, only three countries maintain any demand for CDR, with Brazil showing the highest demand at 69 $MtCO_2$ (SD 44). The variation in CDR demand across cost scenarios reflects the steepness of the marginal abatement cost curves. For example, Japan's marginal abatement cost curve is steeper than that of the EU29. In the low-cost scenario, the demand in the EU is larger due to its larger BAU emissions compared to Japan; with increasing costs (i.e. switching to the medium-cost scenario), the EU29's CDR demand declines more sharply than Japan's, making Japan the country with the largest demand in this scenario. This example is shown in Figure C.1 in Appendix C.

Country/Region	Unit cost 50 USD/tCO_2 Mean (SD) MtCO_2	Unit cost 100 USD/tCO_2 Mean (SD) MtCO_2	Unit cost 150 USD/tCO_2 Mean (SD) MtCO_2
EU29 (EU)	333 (232)	79 (123)	0
Japan (JPN)	238 (119)	110 (97)	37 (59)
United States (USA)	180 (252)	0	0
Brazil (BRA)	158 (62)	106 (56)	69 (44)
Canada (CAN)	120 (46)	58 (40)	19 (26)
South Korea (KOR)	19 (47)	0	0
Aus+New Zeal. (ANZ)	15 (24)	0	0
Russia (RUS)	0	0	0
GB+Irel. (GBR)	0	0	0
China (CHN)	0	0	0
India (IND)	0	0	0
Middle East (MEA)	0	0	0
Other Asia (OAS)	0	0	0
Other Americ. (OAM)	0	0	0
Africa (AFR)	0	0	0
Rest of Europe (REU)	0	0	0
Sum	1064 (375)	353 (171)	124 (11)
With international emissions trading	0	0	0

Table 1 Average demand for CDR depending on CDR unit costs in the year 2030. The costs are denoted in 2020 USD.

The uncertainty in the demand for CDR arises from the uncertainty regarding the development of GDP and CO_2 BAU emissions. When GDP and CO_2 BAU emissions increase strongly, aggregated demand (without international emissions trading) could rise to 2197 MtCO_2 for the low-cost CDR scenario in the year 2030. On the other hand, with lower growth in GDP and CO_2 BAU emissions, there would be zero demand for CDR in the high-cost CDR scenario in the year 2030. The minimum and maximum values for CDR demand are shown in Table C.1 in Appendix C. The derived CDR demand estimates show that CDR is limited to countries and regions with relatively high GDP per capita and thus relatively high abatement costs, while abatement costs are still very low in regions with lower GDP per capita and especially in developing regions. This disparity is evident in the wide variation of national CO_2 prices (i.e., marginal abatement costs) across regions (Table C.2 in Appendix C).

In the regions with low abatement costs, CDR is not yet economically competitive, even under the low-cost scenario. For example, for high ambitions NDCs, the marginal CO_2 price in China, Russia, and India remains well below 10 USD/tCO_2, meaning that CDR would need to be delivered at a similarly low cost to be viable (see Table C.2). With international emissions trading, these regions increase their emission abatement and supply permits to high CO_2-price regions like the EU, Great Britain, Japan, Canada, or the United States. Marginal abatement costs then equalize globally at the permit price of 15 USD/tCO_2 (SD 7) (for NDCs with high ambition). Thus, CDR supply would be substituted by emissions abatement.

Without international emissions trading, we can calculate what share of a country's or region's EEZ would be needed for macroalgae cultivation and harvesting to meet the national CDR demand (Table 2). Several regions with favorable conditions for macroalgae farming (see Figure 1) are not engaging in this method since there is no local CDR demand. Examples are Other Asia or Africa and/or regions with potentially existing infrastructure for macroalgae harvest like China (not reflected in our cost scenarios).

Furthermore, the calculation shows that in regions with local CDR demand, a short-term macroalgae cultivation and harvesting strategy, i.e. starting not before 2030, would in most regions not be sufficient to meet CDR demand. That is because, even if the required share of the EEZ is less than 100%, various further restrictions and considerations will considerably limit the feasible area. Moreover, countries will not devote their entire EEZ to macroalgae cultivation but only a (small) fraction. These constraints significantly reduce the number of scenarios in which macroalgae cultivation and harvest could fully satisfy regional CDR demand. However, it is also very unlikely that the entire CDR demand would have to be satisfied by one CDR method alone. Instead, these results should be interpreted as highlighting regional disparities between CDR demand and supply. Importantly, the findings also suggest that a long-term (marine) CDR strategy, initiated well before the compliance date, could make a meaningful contribution to meeting CDR demand in regions such as Australia and New Zealand, South Korea, Japan, and the United States.

Country/Region	Unit cost 50 USD/tCO_2 Percent		Unit cost 100 USD/tCO_2 Percent		Unit cost 150 USD/tCO_2 Percent	
	short (1 y)	long (5 y)	short (1 y)	long (5 y)	short (1 y)	long (5 y)
EU29	>100	68	94	16	0	0
Japan	>100	23	61	10	20	4
United States	>100	16	0	0	0	0
Brazil	>100	>100	>100	>100	>100	>100
Canada	>100	>100	>100	>100	>100	>100
South Korea	72	14	0	0	0	0
Aus.+NZ	31	1	0	0	0	0
Russia	0	0	0	0	0	0
GB + Ireland	0	0	0	0	0	0
China	0	0	0	0	0	0
India	0	0	0	0	0	0
Middle East	0	0	0	0	0	0
Other Asia	0	0	0	0	0	0
Other Americans	0	0	0	0	0	0
Africa	0	0	0	0	0	0
Rest of Europe	0	0	0	0	0	0

Table 2 Proportion (percent) of EEZ required for macroalgae harvest and cultivation to meet CDR demand in the year 2030. The costs are denoted in 2020 USD.

4 DISCUSSION AND CONCLUSION

General equilibrium models are a common tool to quantify the marginal abatement cost (which is the basis for the calibration of our model), national and international CO_2 prices, and distributional implications (Böhringer et al. 2021; Morris et al. 2024; Rickels et al. 2024). Morris et al. (2024)

show how international trade in CDR offsets leverages comparative advantages of land-based CDR methods, thereby reducing the overall cost of climate change mitigation. However, they also show that trade in CDR does not really take off before considerable emissions reductions are achieved. This is because cutting emissions is generally more cost-effective than CDR, with CDR trade becoming viable only as countries approach zero emissions. This result is confirmed by our study, finding no CDR deployment via macroalgae harvesting and cultivation under international emissions trading in 2030.

Currently, international emissions reduction trading is limited, and CDR offset trading is just about to start under the Paris Agreement (UNFCCC 2024). Typically, general equilibrium models do not capture the frictions and the fragmentation of national climate policies. EU climate policy can, for example, be described by a three-pillar system, with the first pillar covering energy and industry emissions, the second pillar covering emissions from households, transport and agriculture, and the third pillar covering land-use-related emissions and removals through afforestation (Fridahl et al. 2023). Marginal abatement costs vary between these pillars, affecting the demand for CDR, which is currently only included in the third pillar (land-use, land-use change, and forestry (LULUCF)) (Fridahl et al. 2023).

This exemplifies that our analysis underestimates the efficiency losses even in the case without international emissions trading. We assume a uniform CO_2 price per country, but also national climate policies are fragmented. This inefficiency likely increases the potential demand for CDR in specific segments of national climate policies. Accordingly, demand for CDR (already) starts before 2030 and removal targets for the LULUCF sector already exist (Fridahl et al. 2023). As CDR supply via afforestation and other land-based options might face shortages, we investigate the supply potential of a specific marine CDR method, macroalgae cultivation and harvest with subsequent use of the biomass for BECCS or biochar production. In such a fragmented climate policy setting, macroalgae-based CDR could already contribute to meeting a small fraction of CDR demand in 2030.

Our calculations show that even under idealized conditions, macroalgae-based CDR can only provide a small contribution to CDR supply in most regions. In the case of high CDR demand, i.e. low CDR cost, the EU would theoretically need to devote about 70 percent of its EEZ to macroalgae cultivation and harvesting to provide the required biomass alone, not even considering the various CO_2 losses along the processing supply chain (Ross et al. 2022; Lian et al. 2023). Furthermore, our approach to CDR supply via macroalgae cultivation and harvest is also rather stylized with respect to the cost scenarios as we assume globally uniform carbon removal costs, not reflecting differences in for example labor cost but also experiences with macroalgae farming. Froehlich et al. (2019) report considerable regional cost variation due to different cultivation and harvest designs, as well as regional disparities in labor costs. Their analysis also suggests that initial costs could far exceed those considered in our high-cost scenario. Similarly, DeAngelo et al. (2023) demonstrate that seaweed production costs can vary significantly by region, with the lowest-cost areas, including the equatorial Pacific, Gulf of Alaska, and southeastern edge of South America, achieving costs as low as 190 USD per ton of dry weight (tDW) of seaweed under ambient nutrient conditions. In contrast, less favourable regions may face costs exceeding 7,000 USD per tDW. The study emphasizes that factors such as nutrient availability, capital, labour and operational costs drive these regional differences, suggesting that targeted implementation in naturally and economically favourable regions would maximize cost efficiency. For example, Coleman et al. (2022) estimate that the costs of using kelp aquaculture to achieve CDR could initially range from 1,257 to 17,048 USD/tCO_2. On the other hand, Kite-Powell et al. (2022), using a techno-economic model, show that large-scale seaweed farms (>1000 hectares) in waters up to 200 km offshore can achieve farm gate production costs ranging from 200 to 300 USD (in 2021 USD) per dry tonne of biomass. However, at farm sites with near shore support facilities and under optimal conditions, production costs could drop as low as 100 USD per dry tonne or less. While dry biomass cannot be equated with carbon storage (Ross et al. 2022; Lian et al. 2023; Troell et al. 2024), various CDR methods are estimated to have actually very low or even negative removal costs as is the case for certain biochar production settings (Hepburn et al. 2019). We show that in certain markets, competitiveness would be achieved when costs are below 162 USD/tCO_2 (Canada), 152 USD/tCO_2 (Japan), and 125 USD/tCO_2 (UK). Unsurprisingly, Japan allows the supply of CDR in its emissions trading system which was launched in 2023 (the green transformation emissions trading system, GX-ETS). Direct air carbon capture and storage (DACCS), BECCS, and coastal blue carbon methods are eligible as removal credits (Chen 2024). We would like to stress again that our estimates assume a country-wide efficient emissions trading system, while in reality, climate policy and carbon markets are fragmented. This means that macroalgae cultivation and harvesting biomass for BECCS or biochar production could already be cost-competitive at higher cost per tCO_2. This is particularly true if there are price effects for land-based biomass and food as a result of increasing demand for biomass for CDR (Morris et al. 2024).

Further limitations arise from our simulation of CDR supply from macroalgae cultivation and harvest. The Macroalgae Aquaculture for Carbon Sequestration framework implemented in the UVic Earth system model includes several feedback mechanisms related to nutrient availability and marine food webs. However, in nearshore regions, such as those used in our current study, nutrient limitations may not pose significant challenges for large-scale macroalgae cultivation, as estuarine and coastal waters are typically eutrophic. Still, significant uncertainties persist concerning impacts both within and outside the target area. These include canopy shading effects on ambient phytoplankton, nutrient redistribution, and air-sea carbon buffering processes (Berger et al. 2023; Paine et al. 2023; Troell et al. 2023, 2024; Wu et al. 2023, 2024). The applied UVic macroalgae model includes canopy shading (light competition) alongside nutrient competition, thus accounting for this feedback on phytoplankton growth that also indirectly affects their nutrient uptake. Nevertheless, further studies are required to identify and quantify biophysical constraints, such as macroalgae loss rates resulting from infestation, disease, grazing, and wave erosion (Gallagher et al. 2022; Arzeno-Soltero et al. 2023; DeAngelo et al. 2023). Furthermore, the effectiveness of this CDR method should be evaluated not only based on its carbon sequestration efficiency but also based on other metrics, including side-effects and co-benefits (Oschlies et al. 2017; Bach et al. 2021, 2024; Boyd et al. 2022, 2024; Gallagher et al. 2022; Ross et al. 2023; Smetacek et al. 2024; Troell et al. 2024).

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Given future net-zero and even net-negative CO_2 emissions targets, dynamic efficiency considerations suggest that CDR should be included into climate policy early on to induce learning-by-doing effects. This could potentially be achieved by procuring CDR credits already before 2030 (Rickels et al. 2022). Ganti et al. (2024) also support this argument for a forward-looking approach to climate policy in their assessment of total CDR in mitigation scenarios, distinguishing between conventional and novel methods. They show that more than 80% of the net greenhouse gas reductions (between 2020 and global net zero CO_2) are likely to come from emission reductions, but also that CDR methods other than afforestation will become an important part of medium- and long-term climate policy, thus requiring early investment and technological development.

Notwithstanding these limitations in the quantitative interpretability of the results, our analysis highlights the regional disparities between CDR supply and demand, providing insights into the optimal integration of CDR into climate policy. The results indicate that near-term demand for CDR is primarily driven by fragmented, inefficient climate policies. In a scenario with full international emissions trading, emissions reductions would still satisfy this demand and substitute for early CDR deployment. However, given the reservations against international emissions trading, considerable CDR demand will already arise in regions with ambitious climate targets and high abatement costs, such as Canada, Japan, UK, and the European Union in the year 2030. Marine CDR methods like macroalgae cultivation and harvest could provide a small, but relevant contribution to meeting this demand. However, given the lead time required to provide reasonable carbon sequestration efficiencies, anticipatory climate policy would start incentivizing the scale-up of such methods already now and banking early removal credits for later.

DATA AVAILABILITY STATEMENT AND ACKNOWLEDGEMENTS

The CDRex model framework is available in the following GitHub repository at: https://github.com/lfsiebert/CDRex. This repository includes the CDRex Excel Application, which implements the model calibration described in Appendix A of this paper. The repository also provides input datasets used for modelling regional carbon dioxide removal (CDR) potentials, and related market responses. Additionally, a comprehensive README file is included, offering detailed application instructions for configuring the tool, running simulations, and reproducing the results presented in this study.

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APPENDIX

Appendix A: Static 2030 emissions reduction compliance problem

The static compliance problem depends on area-specific abatement cost curves as defined in equation (4). To quantify the CDR demand, we use the calibration of Rickels et al. (2024), determining the region-specific parameter values α_i and information on GDP, business-as-usual CO_2.

Country/Region	α_i	GDP in 2030 ($\bar{Y}_i$) Mean (SD) Bn USD (2020)	CO_2-BAU Emissions ($\bar{E}_i$) Mean (SD) $MtCO_2$	Emissions reduction target (A_i) $MtCO_2$
EU29	0.0124	18112.9420 (650.06)	2853.454 (317.03)	1889.662744
Japan	0.0398	5603.6517 (221.34)	1152.798 (163.75)	662.941756
United States	0.0060	26423.6407 (1,303.28)	5084.859 (530.09)	3598.065408
Brazil	0.1505	1959.7821 (150.08)	535.808 (76.13)	303.323878
Canada	0.1224	2042.0458 (80.55)	576.664 (60.04)	331.864569
South Korea	0.0541	2262.2154 (105.27)	685.867 (146.36)	445.438607
Aus.+NZ.	0.0512	2048.1317 (110.38)	474.165 (57.04)	307.062564
Russia	0.0814	2039.7576 (216.16)	1807.208 (87.88)	1947.623448
GB+Irel.	0.0726	3865.3361 (191.79)	391.898 (43.47)	260.653804
China	0.0030	27350.3953 (3,667.23)	13590.564 (757.59)	14212.430715

India	0.0127	4798.9398 (373.47)	3194.141 (378.84)	4347.408689
Middle East	0.0476	4438.0359 (441.47)	3224.038 (176.72)	3684.672592
Other Asia	0.0167	6977.8519 (571.98)	3272.359 (238.55)	3212.900465
Other Americ.	0.0377	4596.5309 (317.08)	1315.593 (120.00)	1471.806871
Africa	0.0337	3960.1042 (430.21)	1763.011 (66.09)	1921.549007
Rest of Europe	0.2331	451.0352 (33.90)	390.086 (25.44)	367.992949

Table A.1 Parameters and values of the static 2030 emissions reductions compliance problem.

Appendix B: Derivation and Description of the CDRex model

To include the option of CDR, we allow the possibility to include for every country an exogenous amount of credits, CDR_i. The difference between a country's net emissions ($E_i = (1 - R_i)\bar{E}_i$) and the number of emission allowances it holds must not exceed its CDR adjusted emission cap,

$$(1 - R_i)\,\bar{E}_i - P_i \leq A_i + CDR_i. \tag{B.1}$$

The objective of each country is to minimize the total cost of achieving the exogenously set emission target A_i. The total costs are given by the sum of abatement and permit trading costs (or trading benefits if a country is a net seller of permits, $P_i < 0$). In addition, every country faces an exogenous cost F_i for its CDR_i. Therefore, each country solves the following optimization problem,

$$\min_{E_i, P_i} C_i = C_i(E_i) + p^{CDR}\,P_i - F_i(CDR_i), \tag{B.2}$$

subject to equations (B.1), where p^{CDR} represents the price for permits under CDR. Without international emissions trading, (B.1) simplifies to $(1 - R_i)\,\bar{E}_i \leq A_i + CDR_i$ which can be solved for a given exogenous amount of CDR_i, such that the corresponding solution, R_i^{CDRex}, indicates the abatement cost with the inclusion of CDR.

With international emissions trading, the solution to the above stated static optimization problem yields the well-known efficiency rule, which is not affected by the introduction of CDR,

$$C'_i(E_i^*) = p. \tag{B.3}$$

Condition (B.3) demands that marginal abatement costs in each country have to equal the price for emission permits p (assuming an interior solution). The market allocates the permits efficiently. Converting condition (B.3) shows that the optimal rate of reduction R_i^* is a function of the carbon credit price.

Together with the overall compliance condition,

$$\sum_i^n \bar{E}_i - \sum_i^n R_i^*(p^{CDR*})\, \bar{E}_i = \sum_i^n A_i + \sum_i^n CDR_i\,, \qquad (B.4)$$

which states that the sum of all countries' net emissions equals the sum of all countries' emissions caps and CDR. The optimal rate of emissions reduction can be expressed as a function of the carbon credit price, $R_i^*(p^{CDR*})$. Using the functional forms defined in (4) and (5), the solution for the permit price is given by

$$p^{CDR} = \left(\frac{\sum_{i=1}^n \bar{E}_i - A_i - CDR_i}{\sum_{i=1}^n \bar{E}_i \sqrt{(3\alpha_i \bar{Y}_i)^{-1}}}\right)^2, \qquad (B.5)$$

which then determines via (B.3) the country-specific emissions levels and trading positions.

Equation (B.5) shows that CDR affects the permit price negatively ($p^{CDR} < p$). As the global CDR adjusted emission cap ($\sum_{i=1}^n A_i + CDR_i$) approaches the global business-as-usual emissions ($\sum_{i=1}^n \bar{E}_i$), the permit price goes to zero.

This model framework, using the calibration detailed in Appendix A, is implemented in the Excel application *CDRex*, that can be found in the following GitHub repository at: https://github.com/lfsiebert/CDRex

Appendix C: Additional Results

Figure C.1 shows that the emissions covered by the marginal abatement cost curve (MACC) of Japan are smaller, i.e. its BAU emissions are lower, compared to the EU. Accordingly, under the low-cost scenario, the demand in the EU29 is larger. However, with the MACC of EU29 for the medium-cost scenario, the intersection with the MACC of the EU29 would already be left to the target (i.e. the required emissions reductions to meet the NDCs) and hence no CDR is demanded in this scenario. In Japan, the MACC is steeper and hence the reduction in CDR is not as strong when moving to the left.

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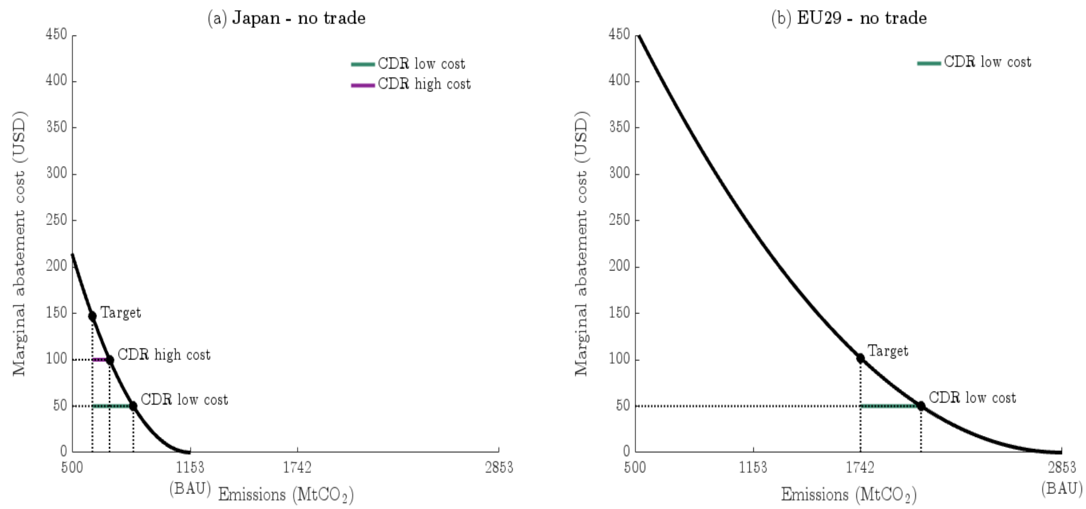

Figure C.1 CDR demand in Japan and EU29 under SSP5 with high ambition NDCs, shown for two cost scenarios: low-cost (50 USD/tCO_2) and medium-cost (100 USD/tCO_2), without international emissions reduction trading.

Country/Region	Unit cost 50 USD/tCO_2 Min—Max MtCO_2	Unit cost 100 USD/tCO_2 Min—Max MtCO_2	Unit cost 150 USD/tCO_2 Min—Max MtCO_2
EU29	3.71—603.97	0—253.06	0—0
Japan	92.09—422.82	0—260.75	0—136.39
United States	0—586.24	0—0	0—0
Brazil	51.92—241.39	9.17—181.15	0—134.93
Canada	52.93—179.22	0.86—112.05	0—60.51
South Korea	0—114.11	0—0	0—0
Aus.+ NZ	0—48.84	0—0	0—0
Russia	0—0	0—0	0—0
GB + Ireland	0—0	0—0	0—0
China	0—0	0—0	0—0

India	0—0	0—0	0—0
Middle East	0—0	0—0	0—0
Other Asia	0—0	0—0	0—0
Other Americans	0—0	0—0	0—0
Africa	0—0	0—0	0—0
Rest of Europe (nonETS)	0—0	0—0	0—0
Sum	200.64—2196.57	10.03—807.02	0.00—331.84
With international emissions trading	0—0	0—0	0—0

Table C.1 Maximum and minimum CDR demand in dependence of CDR unit cost in the year 2030. The costs are denoted in 2020 USD.

Country/Region	NDCs with low ambition Mean (SD) USD/tCO_2	NDCs with high ambition Mean (SD) USD/tCO_2
EU29	101.51 (36.03)	101.51 (36.03)
Japan	127.97 (45.53)	151.67 (46.24)
United States	49.18 (21.74)	55.81 (22.61)
Brazil	70.80 (46.27)	250.49 (78.25)
Canada	131.44 (40.77)	162.06 (42.44)
South Korea	66.69 (34.58)	66.69 (34.58)
Aus. + NZ	51.72 (18.97)	51.72 (18.97)
Russia	1.12 (1.68)	1.12 (1.68)
GB + Ireland	124.92 (43.88)	124.92 (43.88)

China	2.64 (2.75)	6.38 (4.21)
India	0.00 (0.00)	0.59 (1.46)
Middle East	0.00 (0.00)	5.71 (4.82)
Other Asia	0.01 (0.03)	16.21 (7.74)
Other Americans	1.15 (2.82)	7.69 (10.22)
Africa	0.00 (0.00)	10.80 (3.91)
Rest of Europe (nonETS)	5.40 (4.38)	7.43 (4.95)
With international emissions trading	7.26 (4.16)	15.17 (6.86)

Table C.2 CO_2 prices for compliance with the country's NDCs (in 2020 USD).

Country/Region	Share of EEZ	Unit cost 50 USD/tCO_2 Percent		Unit cost 100 USD/tCO_2 Percent		Unit cost 150 USD/tCO_2 Percent	
		short (1 y)	long (5 y)	short (1 y)	long (5 y)	short (1 y)	long (5 y)
EU29	0.10	2.06	11.98	8.65	50.25	0	0
Japan	0.22	12.97	66.17	28.11	>100 [11.01]	84.47	8.31
United States	0.09	9.46	50.25	0	0	0	0
Brazil	0.06	0.02	0.05	0.03	0.07	0.05	0.11
Canada	0.18	7.34	40.00	15.12	82.32	47.20	0.86
South Korea	0.89	88.80	>100 [7.18]	0	0	0	0
Aus+NZ	0.15	73.58	>100 [6.37]	0	0	0	0

Russia	0.17	0	0	0	0	0	0
GB + Ireland	0.25	0	0	0	0	0	0
China	0.53	0	0	0	0	0	0
India	0.37	0	0	0	0	0	0
Middle East	0.43	0	0	0	0	0	0
Other Asia	0.07	0	0	0	0	0	0
Other America.	0.34	0	0	0	0	0	0
Africa	0.26	0	0	0	0	0	0
Rest of Europe	0.09	0	0	0	0	0	0

Table C.3 Share of national demands for CDR being met by the (most) productive cells in the macroalgae data. In squared brackets: Share of the EEZ area needed to meet 100% of national demand. The cost scenarios are denoted in 2020 USD.

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