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Key Points:

- Marine carbon dioxide removal is a rapidly growing sector with the potential to significantly reduce atmospheric carbon dioxide
- Early career ocean professionals have a crucial role to play in shaping the future of the marine carbon dioxide removal sector
- The paper presents early career recommendations to ensure global equity and build capacity

Supporting Information:

Supporting Information may be found in the online version of this article.

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Early Career Recommendations for the Equitable Growth of a Marine Carbon Dioxide Removal Sector

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Abstract In addition to steep carbon emission reductions, all modeled pathways to reach global climate goals require carbon removal. Marine carbon dioxide removal has the potential to play a large role in drawing down legacy anthropogenic emissions due to the scalability and durability of proposed methods. While this field is rapidly expanding, a number of issues remain, including efforts to grow the industry, align projects with equity and justice goals, and ensure development of trusted, unique, durable carbon credits. We, a group of early career ocean professionals (ECOPs), provide an overview of the scale of the field, the aforementioned issues, and then make recommendations to ensure global equity and expand early career capacity in the marine carbon dioxide removal sector. We argue that substantial investment is needed to reduce costs of marine carbon dioxide removal and spur innovation in monitoring, reporting, and verification, but also in the training and development of early career researchers. Careful co-design of marine removal projects by experienced and emerging collaborators, including local communities, can help mitigate perpetuating existing global inequalities. Given the anticipated growth of the marine carbon dioxide removal workforce, ECOPs can contribute their existing interdisciplinary expertise, if they are supported within traditional structures. Those entering the field can leverage skill sets that intersect engineering, policy, community engagement, and business. We maintain that ECOPs will be key leaders in the field, if appropriately engaged, compensated, and empowered.

1. Introduction

Greenhouse gas emissions from human activities are driving adverse changes to Earth's climate at an unprecedented rate, including biodiversity loss, food and water insecurity, and extreme weather events (IPCC, 2023). The ocean's absorption of anthropogenic carbon dioxide (CO_2) from the atmosphere is driving a decrease in ocean pH and carbonate mineral saturation states, a process known as ocean acidification, which endangers marine ecosystems and human communities that depend upon them (Doney et al., 2020). Countries around the world must meet carbon emission reduction targets to retain diverse ecosystems and support equitable societal development

(UNFCCC, 2015). Immediate and substantial emission reductions remain the highest priority action (Ho, 2023; Shutler, 2020). However, carbon dioxide removal (CDR) from the atmosphere is required under almost all pathways to limit warming to 1.5–2°C globally over the coming century (Cross et al., 2023; IPCC, 2023). CDR draws down legacy carbon pollution from the atmosphere and durably stores it in geological, land, or ocean reservoirs (IPCC, 2023). These removals are distinct from carbon capture, utilization, and storage, given the focus on removing legacy carbon pollution, rather than reducing new carbon emissions. This climate change mitigation strategy is rapidly gaining attention, and in some cases investment, from policymakers, private capital, researchers, and environmental organizations (Cohen-Shacham et al., 2016; Seddon et al., 2020) despite questions around efficacy, equity, safety, and operational potential.

Marine CDR (mCDR) in particular is experiencing a surge in research, development, and proposed deployments (Figure 1). The momentum for mCDR is driven by the ocean's natural potential to hold carbon in comparison to other CDR strategies (e.g., land-based techniques). The ocean naturally stores 50 times as much inorganic carbon compared to the preindustrial atmosphere (Friedlingstein et al., 2023), has a vast surface area for air-sea CO_2 equilibration, and has absorbed approximately one-quarter of anthropogenic CO_2 emissions to date (Friedlingstein et al., 2023). Proposed mCDR interventions include stimulation of biological carbon drawdown through ecosystem restoration, nutrient fertilization, macroalgae cultivation, and artificial upwelling and/or downwelling of seawater as well as enhancing inorganic oceanic processes through direct stripping of CO_2 from seawater, and the manipulation of seawater alkalinity to enhance absorption of atmospheric CO_2 (GESAMP, 2019; NASEM, 2022). To support climate change mitigation, mCDR techniques must elicit a CO_2 deficit in the surface ocean to drive net CO_2 removal from the atmosphere, with this removal lasting on timescales of at least 100–1000s of years. Overall, the field has the potential for effective, scalable, and economically viable removal of legacy carbon emissions (Figure 1), as well as mCDR pathway-dependent co-benefits of local ecosystem restoration and ocean acidification mitigation.

As a subset of early career ocean professionals (ECOPs) from the International Carbon Ocean Network of Early Careers, we recognize that ECOPs have the potential to profoundly impact the field of mCDR. As ECOPs (<10 years of professional experience) we are poised to define the most effective, durable, safe, equitable, and scalable methods of carbon removal if given the opportunity to fill increased demands for interdisciplinary ocean professionals across industry with various levels of education (Figure 1). Moreover, many ECOPs have personally witnessed the effects of climate change and are likely motivated by solutions-based careers. This group developed in a time of increased trans-disciplinary training with a focus on scientific communication, project co-design, and production of culturally relevant scientific materials (Brodie et al., 2022). Due to the ocean's unique biophysical characteristics and climate feedbacks (e.g., transboundary nature, timescales of natural variability, sea ice albedo, ocean overturning circulation, etc.) across short- and long-time scales, mCDR strategies will require a tailored regulatory, co-designed, and capacity-building approach to address societal needs. The mCDR sector encompasses companies, communities, research institutions, policymakers, and investors working on removing atmospheric CO_2 using the ocean. Considerations in mCDR include monitoring, reporting, and verification (Bach et al., 2023, 2024; Boyd et al., 2023, p. 202; Ho et al., 2023), climate and environmental justice (Batres et al., 2021), governance across multiple scales (Lezaun, 2021), the need for legitimacy to avoid mistakes made in other carbon offset markets (e.g., forestry; Greenfield, 2023a, 2003b), feasibility and risks (Boyd & Vivian, 2019), and the moral hazard concern that CDR could undermine emissions abatement efforts (NASEM, 2022). In this article, we, a global group of ECOPs, highlight the potential scale of the mCDR field and provide recommendations (Table 1) to build a durable, sustainable, equitable, and transparent mCDR sector that leverages the unique ECOP perspective.

2. Marine CDR at Scale

Achieving climate goals will require scaling up novel efforts, including mCDR. To meet temperature goals set by the Paris Agreement, 10–15 Gt CO_2 per year must be removed from the atmosphere by the middle of the century, and up to 17 Gt CO_2 per year by the end of the century (Rogelj et al., 2018). Approximately $4B has been dedicated to publicly funded research, development, and demonstration of CDR techniques. Of this $4B, ~$200M has been invested in novel CDR approaches (e.g., bioenergy carbon capture and storage, biochar, direct air carbon capture and storage, or enhanced rock weathering) from 2020 to 2022 (Smith et al., 2023), which equates to removing ~0.6 Gt CO_2 per year. Global commitments for CDR only support an additional 1.5–2.3 Gt CO_2 per year by 2050, leaving an immense gap in our global capacity to remove enough anthropogenic carbon

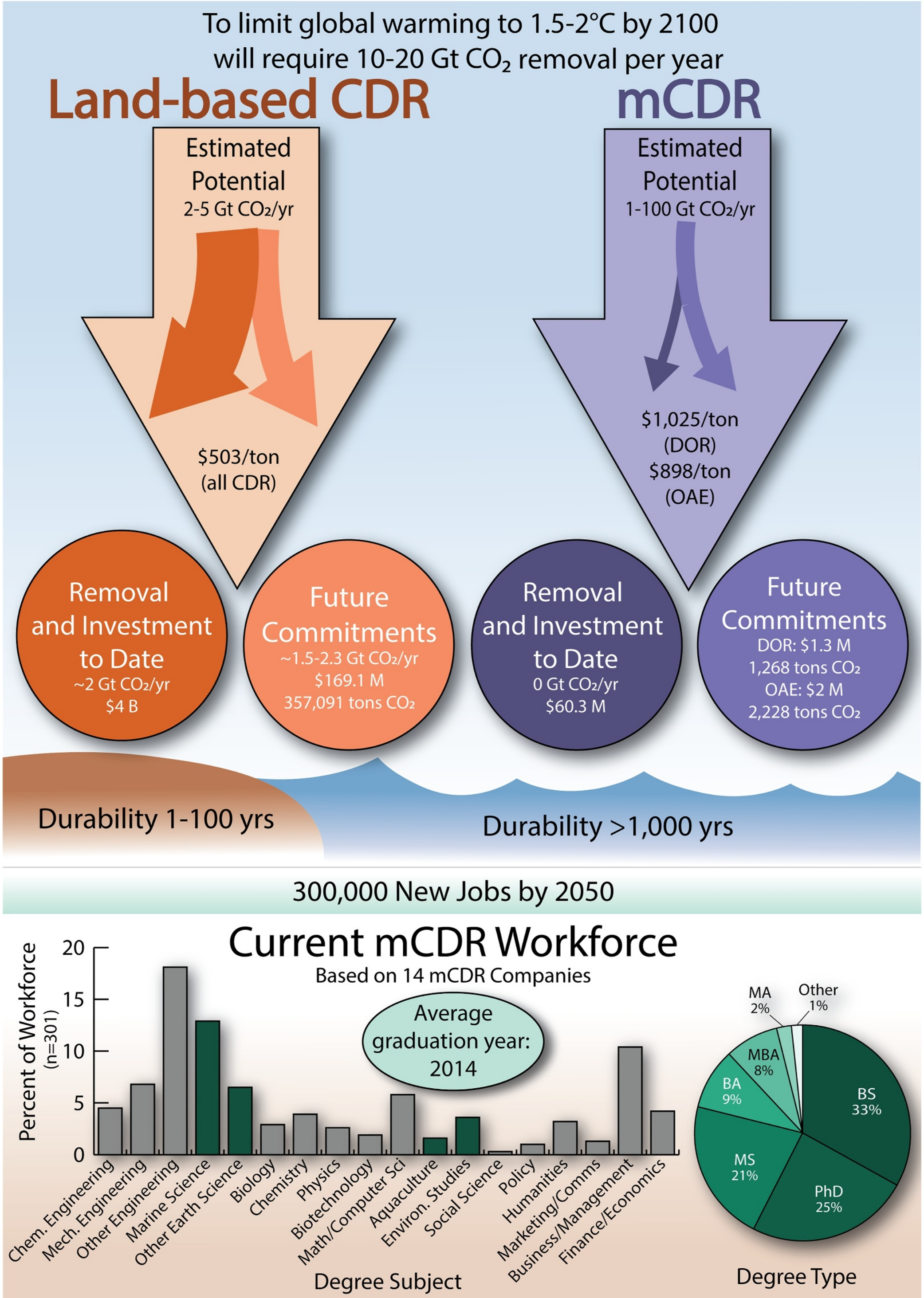

Figure 1. (a) Projected total required carbon dioxide removal (CDR) capacity (Gt/yr) by 2050 to limit global warming to 1.5–2°C by 2100 (Cross et al., 2023; IPCC, 2023) broken into estimated potential of land-based CDR and marine CDR (mCDR). Values of estimated potential for land-based CDR are the low and medium risk scenarios from Deprez et al. (2024) and the large ranges for mCDR are from Smith et al. (2023). Reported durability comes from direct ocean removal (DOR; also known as direct ocean capture) and ocean alkalinity enhancement (OAE; Bach et al., 2019), and reforestation or afforestation (Anderegg et al., 2020; Griscom et al., 2017). (b) Bar chart of employee education background, and (c) pie chart of highest reported degree from non-comprehensive snapshot of current mCDR sector workforce based on 14 mCDR companies (seven based in the US, three in the UK, two in Canada, one in the Netherlands, and one in Mexico; $N = 301$ total employees; Table S1 in Supporting Information S1). Projected future mCDR workforce from Larsen et al. (2020). Abbreviations are as follows: Doctor of Philosophy (PhD), Bachelor of Science (BS), Master of Science (MS), Bachelor of Arts (BA), Masters in Business Administration (MBA), Master of Arts (MA).

Table 1
Table of Recommendations for Building Early Career Capacity to Address Rapid Growth in the Global mCDR Sector to Ensure Equitable, Durable, and Safe Solutions

Global Equity	
Invest in knowledge sharing and ocean observing capacity across mCDR fields worldwide.	(a) Global Ocean Acidification Observation Network (GOA-ON) in a box kit for developing carbonate chemistry observing capacity and associated hands-on training (http://doi.org/10.5281/zenodo.13855458) (b) NOAA Ocean Acidification Program, the International Atomic Energy Agency's Ocean Acidification International Coordination Center, and The Ocean Foundation capacity building programs (GOA-ON Pier2Peer and trainings) (c) Partnership for Observation of the Global Ocean (POGO) Scientific Committee on Oceanic Research (SCOR) Fellowship program (https://pogo-ocean.org/capacity-development/pogo-scor-fellowship-program/)
Ensure a diverse number of ECOPs are active participants in the development of mCDR codes of conduct that allow for accountable scaled testing.	(a) No current example for mCDR field
Interdisciplinary training courses that incorporate equity training, co-development, and traditional knowledge.	(a) Indigenous Canada free online course through Coursera by the University of Alberta (Canada) (b) Master of Indigenous Governance degree program from the Canadian Institute for Indigenous Governance at the University of Victoria (Canada)
Increased funding of projects to co-design mCDR projects, including those with ECOP leads.	(a) NOAA Ocean Acidification Program Regional Vulnerability Assessments focus on co-design and community input
Address systemic barriers of retention.	(a) Implement strict harassment policies and reporting structures, especially for field work (b) Funding organizations provide a no-time limit policy for reporting and cessation of funding to PIs who harass colleagues and students (c) Make sure employees are aware of reporting structures in more formal organizations
Enable ECOP leadership in global, national, and regional organization, including mentorship structures, to empower ECOPs to participate fully.	(a) Participation and development of GOA-ON International Carbon Ocean Network for Early Career (ICONEC) Community (http://www.goa-on.org/iconec/iconec.php) (b) ECOP nodes for the UN Ocean Decade (https://www.ecopdecade.org/)
Ensure ECOP representation on various mCDR working groups, panels, and speaking opportunities.	(a) Generation of integrated Scientific Steering Committees with multiple Early Career Members who have equal weight and title to all other members
Capacity building	
Develop cross-disciplinary university mCDR hubs.	(a) Yale Center for Natural Carbon Capture (https://naturalcarboncapture.yale.edu/) (b) Dalhousie University's Office of Commercialization and Industry Engagement (https://www.dal.ca/dept/research-services/OCIE.html)
Develop best practices for contracting and consulting models to allow academic and government researchers to guide industry mCDR activities while protecting their scientific integrity and intellectual property	(a) Contracting and consulting from Isometric (https://science.isometric.com/) and Carbon Direct (https://www.carbon-direct.com/)
Establish research fellowships and internships within the mCDR industry.	(a) Mid-Atlantic Coastal Acidification Network Workforce Development Fellowship (https://midacan.org/news/f/macan-workforce-development-fellowship-request-for-proposals)
Address compensation gaps between academic, government, and industry positions.	(a) Federal-level graduate scholarship values have not increased since 2003, with postdoctoral fellowships only modestly increasing (https://www.supportourscience.ca).
Support the development of mCDR areas of opportunity for public, centralized experiments and data sharing.	(a) Bedford Basin (Halifax, Canada)
Acknowledge the need for expertise across all ocean science fields to evaluate mCDR approaches.	(a) Novel hiring processes to evaluate non-traditional skillsets and diverse background
Generate mentorship structures across all levels of ECOP experience in mCDR in academia and industry.	(a) Ocean Carbon and Biogeochemistry postdoc exchange and mentoring program (https://www.us-ocb.org/science-support/early-career/)
Offer leadership training opportunities for ECOPs to understand organization structures and leadership styles.	(a) Offer in-house, or financially support formalized leadership training

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Table 1
Continued

Develop hierarchical roadmaps and codes of interaction to explicitly outline both informal and formal chains of command.	(a) Offer in-house explicit onboarding documents that outline organization dependent structures
Develop online learning and networking platforms to enhance mCDR access.	(a) Live webinar series including the Open Air Collective (https://openaircollective.com/) (b) Forums including the CDR Google Groups (https://groups.google.com/g/CarbonDioxideRemoval), Frontier's carbon removal knowledge gaps database (https://gaps.frontierclimate.com/), Ocean Visions roadmaps (https://www2.oceanvisions.org/roadmaps), and freely available resources including the CDR Primer (https://cdrprimer.org/) (c) OceanTeacher Global Academy Regional and Specialized Training Centers (https://classroom.oceanteacher.org/) (d) Airminers CDR course that offers self-guided or cohort learning on CDR fundamentals (https://bootup.airminers.com/)
Expand education on academic-industry specific challenges including intellectual property, technology transfer, and startup basics.	(a) Master of Engineering in Technology Commercialization at Northwestern University (U.S.) (b) Stanford Technology Ventures Program (U.S.)

Note. Examples are provided where appropriate and available but may not be specific to mCDR. These recommendations were generated from the author team to address barriers the collective group has experienced or observed in the sector. The order of these recommendations does not connote prioritization and they should be considered within the cultural context of a region noting that all suggestions are novel mechanisms to increase participation of ECOPs in the equitable growth of the mCDR sector. Therefore, these recommendations will challenge the status quo across many cultures.

from the atmosphere (Smith et al., 2023). Land-based CDR methods are the focus of those commitments. However, a recent study focused on sustainable land-based CDR budgets notes that the land can only remove up to 2–5 Gt per year if land-based CDR methods are to pose little risk to ecosystems and other Sustainable Development Goals (Figure 1; Deprez et al., 2024). Therefore, mCDR is a critical element in the global CDR portfolio in order to achieve CDR targets (Figure 1).

The ocean reservoir has the potential to play a large role in closing the required CDR capacity gap (Figure 1; Smith et al., 2023), which has spurred investment from both the private and public spheres. The number of mCDR companies and the scale of mCDR projects have increased rapidly in recent years (GESAMP, 2023). In 2023, the U.S. National Oceanic and Atmospheric Administration (NOAA), on behalf of the National Oceanographic Partnership Program, committed \$24.3M to support mCDR research. In the same year, the US Department of Energy's (DOE) Advanced Research Projects Agency-Energy contributed \$36M to foster the development of mCDR technologies and support monitoring, reporting, and verification. A consortium of philanthropic partners recently announced a \$250M fund for the Ocean Resilience and Climate Alliance, of which mCDR is a key pillar. Frontier Climate has committed to purchasing \$925M of permanent carbon removal between 2022 and 2030 including direct ocean removal/capture and ocean alkalinity enhancement. Frontier is the only advance market commitment, meaning they will contract to purchase or subsidize a product that is still being developed in the CDR space, and their purchasing is accessible to the public. As of December 2024, Frontier had contracted \$169.1M, equivalent to ~357K tons of CO_2 removal. Of this, only a small fraction has been contracted for mCDR techniques, including \$1.3M (~1,200 tons of CO_2) for direct ocean removal/capture and \$2M (~2,200 tons of CO_2) for ocean alkalinity enhancement (Frontier's Carbon Removal Portfolio, 2024; Figure 1). Recognizing that these current investments are centralized within more economically developed regions (e.g., United States, Canada, and the European Union), there is a strong need to increase research investment across the world and encourage equitable development of mCDR infrastructure and knowledge.

Many mCDR approaches are still in early development stages and will require significant investment to scale and reduce costs. This early stage of mCDR technological and methodological development makes the current cost per ton of CO_2 for mCDR technologies greater than the average for conventional, land-based approaches. For instance, Frontier's pricing of direct ocean removal/capture (\$1025/ton) and ocean alkalinity enhancement (\$898/ton) have higher cost estimates than the average of all CDR techniques (oceans included, \$503/ton; Figure 1). Despite higher costs, initial durability estimates of some mCDR techniques (e.g., >1,000 years for ocean alkalinity enhancement; Bach et al., 2019) show improved long-term CO_2 removal compared to land-based techniques (e.g., 1–100 years for reforestation or afforestation; Griscom et al., 2017; Anderegg et al., 2020). Monitoring, reporting, and verification of mCDR techniques also present an additional costly challenge due to the complexity of monitoring dynamic ocean environments. A larger workforce of experienced personnel can drive innovation to ensure mCDR is durable, accountable, culturally sensitive; reduces environmental impact on the land and ocean ecosystems; and limits operational safety risks.

3. Ensuring Equity

Centering equity and justice goals in the development and deployment of mCDR will help ensure approaches are sustainable, accessible, and safe for communities. The uneven distribution of benefits and knowledge related to proposed mCDR interventions worsens global inequities (Boettcher et al., 2023; Loomis et al., 2022). Particularly in less economically developed regions, defined as those countries home to the majority of the world's young and resource-poor populations (e.g., formerly colonized countries in Africa, Latin America, the Middle East, India, and parts of Asia; Braff & Nelson, 2022; Odeh, 2010; UNCTAD, 2024), efforts to address the climate crisis compete with other development priorities (Marquardt et al., 2023). Less economically developed regions lack well-funded scientific initiatives due to resource shortages, leading to a deficiency of ocean carbon measurements (Bakker et al., 2016; Lauvset et al., 2022), putting vulnerable communities at a disadvantage (Marquardt et al., 2023). This inequity results in twice as much available knowledge about emerging climate change impacts in more economically developed regions compared to less economically developed ones (Callaghan et al., 2021). Due to a combination of socio-economic challenges and scientific capacity, mCDR research in many countries and territories is not likely to occur at the same pace and scale as in more economically developed regions (Reidpath & Allotey, 2019), defined as countries or regions with developed economies (e.g., the US, Canada, the European Union, and parts of Asia; Braff & Nelson, 2022; Odeh, 2010; UNCTAD, 2024). Reliance on support from external industry and research institutes for climate solutions in less economically developed regions can have a disproportionate impact on marginalized groups, such as Indigenous communities, as imposed mitigations may not fully consider the diverse effects on communities (Nawaz & Lezaun, 2024; Rodrigues, 2021). Such effects may also uniquely exacerbate local climate-related hazards, power imbalances, and political rivalries (Dunne & Quiroz, 2023; Marquardt et al., 2023). Marine CDR initiatives should prioritize local needs, value local knowledge and technologies, and foster local ownership to strengthen social dialogue and empower communities (Duke et al., 2023; Vogel et al., 2022), which will provide a path to long-term success and more robust scaling. The complexity of accountable mCDR requires scientific examination by the larger research community. Community developed products such as the Code of Conduct for mCDR Research (Boettcher et al., 2023), and the Guide to Best Practices for Ocean Alkalinity Enhancement Research (Oschlies et al., 2023) offer critical guidance for future research in mCDR, yet geographically diverse voices remain underrepresented in these initiatives.

As regulatory structures in more economically developed regions present obstacles to scaling mCDR research, industry expansion may transfer risks to vulnerable communities. If pilot projects expand to focus on ocean regions of potentially high efficacy (Cross et al., 2023), there might be a mismatch with socio-cultural context and community values, or a lack of mCDR regulations (Cooley, Leonard, et al., 2023). Without clear implementation pathways, regulations and oversight, there is a risk of over-exploitation of more lenient national laws, which can lead to, marine resource depletion, environmental degradation, and harm to vulnerable communities (Samaniego et al., 2023). Additionally, foreign experts are often utilized to run such projects, which can limit job opportunities for local researchers and reduce the integration of place-based knowledge in projects (Kiggundu, 1989). Advocating for nations to embrace explicit regulatory and inclusion protocols might address these disparities and advance responsible management of mCDR activities. "Climate solutions" have previously served as tools to propagate colonialism and the exploitation of peoples and marine resources of less economically developed regions (Text S1 in Supporting Information S1), with promises of mCDR and ecosystem co-benefits (McAfee, 1999). Strong regulations should consider the rights and priorities of Indigenous people as outlined in the UN Declaration on the Rights of Indigenous Peoples (UNDRIP, 2007), maintain socio-cultural uses, protect marine biodiversity, prioritize environmental sustainability over profit (Boettcher et al., 2021), and provide technical training opportunities for the local community to participate in the growing economy. Mitigating local environmental impacts is an essential component of responsible mCDR activities, for if not managed carefully the intervention may have detrimental effects on marine ecosystems, including damage or loss of subsistence and commercial harvests (Boettcher et al., 2023).

Many ECOPs have increasingly pursued interdisciplinary training in a globalized scientific community and therefore are acutely aware of global ocean science inequities. With proper support and empowerment, ECOPs could help steer the direction of the field to ensure global equity is a part of the research and decision-making framework. Table 1 summarizes our high-level recommendations with relevant examples on how to enable a framework where ECOPs can inform the equitable growth of the mCDR field. These recommendations are described in a narrative form here. We recommend expanding co-design and community engagement training initiatives to equip ECOPs worldwide with the skills needed to foster more equitable and inclusive interventions (Table 1; Satterthwaite et al., 2022). Funding for these training activities must derive from a multitude of partners, including governmental, philanthropic, and industry funding to make a meaningful impact. Ocean scientists need to understand the importance of integrating local perspectives and valuing the experiences of communities affected by mCDR initiatives. These training programs and opportunities may include experiences in interdisciplinary knowledge transfer between disciplines, organizations, and sectors (e.g., Hsiao et al., 2018; Killion et al., 2018). We also stress it is critically important for these trainings to include and enforce strict harassment policies, with strong repercussions for offenders, especially during field-based work. Harassment in ocean science still prevents the full participation of women and marginalized groups (St Clair, 2021) despite efforts to issue best practice guidelines (Kelly et al., 2021). With proper safeguards in place, training can lead to projects co-led by experienced and emerging collaborators worldwide who may hold differing opinions on ethical principles for climate mitigation efforts (Beck & Krueger, 2016). Importantly, these efforts should include a range of invested partners from concept to deployment to avoid the pitfalls of "parachute science" (Stefanoudis et al., 2021). Researchers should recognize the opportunity in obligatory data sharing and methods transparency (i.e., open source) and ECOPs should be provided the opportunity, via workshops and training focused on capacity building and directed funding initiatives, to share research findings. These ECOP led co-design efforts will enable a more representative study of mCDR approaches, providing insight into community needs, potential ecosystem co-benefits and impacts, as well as considering the need to scale from local pilot projects to Gt scale removals while supporting and informing defined regulations.

4. Capacity Building

The overall CDR field has immense potential for economic growth and job creation, and mCDR is a critical piece in this expansion (Figure 1). The construction, engineering, and equipment manufacturing associated with building CDR facilities alone could create at least 300,000 new jobs by 2050 in the US (Larsen et al., 2020). If the field scales as projected, diversity of skill sets in the mCDR field is critical to build an inclusive, supportive, and highly collaborative work culture. A diverse workforce can help facilitate the deployment of trustworthy and transparent science-based approaches (Cooley, Klinsky, et al., 2023). The early mCDR sector shows promise in bringing together these varied skill sets (Figure 1). We strongly encourage broad outreach into interdisciplinary scientific fields, which will enable the fundamental research that requires robust sector-wide coordination and will require unprecedented speed, and accountability. More specifically, we stress that equitable growth of the field requires engagement of political and socio-economic experts to address human, nature, and ecosystem-related needs, which may be an additional area for ECOPs to step into.

There is a great opportunity to position the mCDR industry as a central partner in capacity building worldwide. Coupling mCDR industry needs with training outcomes for ECOPs will help deliver equitable, durable, and safe mCDR solutions (Table 1; Cooley, Klinsky, et al., 2023). Interdisciplinary education programs that combine marine science with engineering, policy, community engagement, skilled trades, and business will equip students and professionals with skills to confront the intricate challenges of mCDR from multiple perspectives. This approach removes the burden from individuals to seek out piecemeal training opportunities.

Establishing research and educational hubs within universities will fuel implementation of capacity building initiatives. These hubs would serve as focal points for industry-academia collaboration, allowing the mCDR industry to provide real-world opportunities to talented pools of students and ECOPs. These partnerships would also provide a competitive advantage to ECOPs looking to enter the mCDR sector at the beginning of their careers (Text S2 in Supporting Information S1; Table 1). Partnerships could facilitate the establishment of research fellowships and internships in the mCDR sector, accelerating training for students and ECOPs within the industry. Finally, they would create a direct pipeline for knowledge transfer between academic research and industry applications. However, it is important to note that these opportunities are still disproportionately available to students attending institutions in more economically developed regions, highlighting the need for more equitable distribution of such initiatives globally.

As the mCDR industry grows, higher salaries, career progression, rapid hiring, and excitement over climate solutions offer new paths for ECOPs in the private sphere. As current markets do not offer high-value initial public offerings, limited industry re-investment poses a challenge in retaining skilled researchers in academic and government roles. Even established faculty and researchers are leaving academia for industry opportunities due to the chance to shape industry protocols and contribute to climate solutions. Retaining both established researchers and ECOPs in academia and government is crucial for ongoing advancements in mCDR research, maintaining capabilities for ocean observing, and supporting complex ocean modeling essential to mCDR evaluation. Additionally, higher compensation in the private sphere encourages students or workers with fewer resources to flee low-paid sectors or institutions, making workforce diversification much harder in those fields. Competitive compensation structures are vital for staffing experts in mCDR across industry and academia (e.g., stagnant student and postdoctoral salaries; Laframboise et al., 2023). Increased funding for academic research positions, recognition of the societal importance of comprehensive mCDR studies, and support for ECOPs' career development is essential (both within and outside academia). Developing pathways for compensation in academic-industry collaborations that protect scientific integrity and intellectual property, such as cooperative agreements, contracting, and consulting, can provide opportunities for researchers to contribute to mCDR industry activities while retaining their academic or government status. By narrowing the compensation gap, both industry and academia benefit from the expertise of established ocean professionals and ECOPs dedicated to investigating fundamental aspects of marine carbon cycling and mCDR.

Systemic barriers in traditional institutional structures (Battilana et al., 2022) often prevent ECOPs from reaching their full potential. Global, national, and regional organizations that engage in mCDR, or ocean science at large, often offer only entry level positions to ECOPs without further offerings of leadership training nor upward mobility, which de-emphasizes the full scope of their lived experience (e.g., intersectionality and climate activism; Council et al., 2020; Farber, 2020). This structure is in line with traditional bias against young leaders despite their ability and potential (Daldrop et al., 2023), which can compound with historically oppressed identities (Wanelik et al., 2019). These leadership structures are currently upheld in mCDR private sector positions (e.g., director, c-suite executive, or vice-presidential roles average graduation year of 2007; $N = 35$; Table S1 in Supporting Information S1). Even if leadership positions, or fast-tracked positions, are offered to ECOPs given their potential, the implicit conditioning of privileged groups can trigger defensive reactions when their sense of normalcy is challenged (i.e., threat rigidity), hindering progress toward social equity (Goodman, 2011; Phillips & Lowery, 2020) and minimizing ECOP's ability to effect change. While a full list of recommendations to grow the capacity of ECOPs and expand opportunities for those entering the field are discussed in Table 1, we also call attention to critical recommendations to empower ECOPs to reach their full potential. Organizations should offer emerging ECOP leaders fellowship opportunities that showcase a variety of leadership styles to further develop their people and project management abilities. Opportunities aimed at cultivating young leaders should proactively establish safeguards to prevent and address any inadvertent harm to ECOPs. Organizations should craft transparent terms of reference for all members that outline often unspoken chains of command (Table 1). For those ECOPs who hold leadership training and experience from non-traditional avenues, we encourage senior member of organizations to recognize such experience by elevating ECOPs into leadership positions for this emerging field and remaining staunch advocates for these younger counterparts with leadership qualities (Table 1).

5. Conclusions

Funding for mCDR continues to increase, reflecting the ocean's potential to play a very large role in the global CDR portfolio. Recommendations to ensure global equity range from expanded global carbon observations to increased funding for co-designed projects, especially those led by ECOPs. To build capacity, we recommend increased and institutionalized interdisciplinary training, especially in the social and economic fields. For reasons outlined above such as trans-disciplinary training and strong intrinsic motivation, ECOPs are a critically important group shaping the mCDR field, yet systemic barriers in traditional structures may prevent them from realizing their full potential, particuarly impacting academic and government spheres. Diverse perspectives are crucial to effectively address environmental and societal questions. For equitable growth of mCDR, the sector must integrate scientists from differing levels, collaborating equally and merging creative thinking with scientific analysis to develop better solutions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No unique data were produced or reused in this study.

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