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Research article

Is carbon dioxide removal in the Arctic region really feasible?

Walter Leal Filho[a,b], Johannes M. Luetz[c,d,e,*], Maria Alzira Pimenta Dinis[f,g], Julian David Hunt[h], Gustavo J. Nagy[i]

[a] Department of Natural Sciences, Manchester Metropolitan University, Chester Street, Manchester M1 5GD, United Kingdom
[b] European School of Sustainability Science and Research, Hamburg University of Applied Sciences, Germany and Merito University, Wrocklaw, Poland
[c] Graduate Research School, Alphacrucis University College, Brisbane, QLD, 4102, Australia
[d] School of Social Sciences, University of New South Wales, Sydney, NSW, 2052, Australia
[e] School of Law and Society, University of the Sunshine Coast, Maroochydore, QLD, 4556, Australia
[f] Fernando Pessoa Research, Innovation and Development Institute (FP-I3ID), University Fernando Pessoa (UFP), Praça 9 de Abril 349, 4249-004, Porto, Portugal
[g] Marine and Environmental Sciences Centre (MARE), University of Coimbra, Edifício Do Patronato, Rua da Matemática, 49, 3004-517, Coimbra, Portugal
[h] Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, 23955-6900, Saudi Arabia
[i] Instituto de Ciencias Ambientales y Ecología, Facultad de Ciencias, Universidad de La República, Udelar, Montevideo, Uruguay

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ABSTRACT

The Arctic region, warming at nearly four times the global average rate, is both an important carbon sink and a potential source of greenhouse gas emissions, especially due to thawing permafrost. Carbon dioxide removal (CDR) is increasingly recognised as a necessary measure to support global efforts to reduce emissions. This article examines whether, and under what conditions, large-scale CDR deployment in the Arctic is practically feasible. It also discusses the challenges associated with it. We synthesise peer-reviewed evidence on the performance of key CDR approaches relevant to high-latitude environments, including nature-based solutions (NbS), e.g. peatland restoration, blue carbon protection and afforestation, as well as enhanced rock weathering (ERW), ocean alkalinity enhancement (OAE) and direct air carbon capture and storage (DACCS). Across these approaches, the feasibility is constrained by permafrost dynamics, hydrology, ecological sensitivity, energy availability, monitoring and verification, and governance. Whereas some CDR methods offer potential climate benefits, most are characterised by considerable uncertainty and context-dependent trade-offs. None currently demonstrates unequivocal feasibility at scale under Arctic conditions. Beyond these technical and ecological constraints, we identify four clusters of socio-political barriers that further complicate Arctic CDR: governance fragmentation, geopolitical tensions, inadequate regulatory mechanisms, and uneven global deployment. A comparative assessment suggests that peatland restoration and blue carbon protection are the most immediately actionable options, whereas DACCS and OAE would require substantial new infrastructure and energy investment. The study concludes by outlining targeted policy and research priorities to address existing technological, ecological, and governance challenges, and to situate Arctic CDR within broader mitigation strategies without risking over-reliance or mitigation deterrence. The novelty of this paper lies in its analysis of the multiple variables that influence the viability of CDR. Overall, Arctic CDR appears technically possible but remains highly constrained, with its feasibility contingent on meeting stringent operational conditions, robust governance, and continued emissions reductions elsewhere.

1. Introduction

For the purposes of this article, the Arctic is defined as the region north of the Arctic Circle (≈66°33′N), together with adjacent sub-Arctic landscapes where permafrost, tundra and polar marine systems predominate. This operational boundary aligns with conventions used in major Arctic assessments and is used in this paper as the analytical domain for the synthesis herewith provided (AMAP, 2021).

Carbon dioxide removal (CDR) performs three interrelated functions in climate mitigation (IPCC, 2022; Smith et al., 2023): (i) it can

* Corresponding author. Alphacrucis University College (AC), Brisbane Campus, 48 O'Keefe St, Woolloongabba/Brisbane, QLD 4102, Australia.
E-mail addresses: walter.leal2@haw-hamburg.de (W. Leal Filho), johannes.luetz@ac.edu.au (J.M. Luetz), madinis@ufp.edu.pt (M.A.P. Dinis), julian.hunt@kaust.edu.sa (J.D. Hunt), gnagy@fcien.edu.uy (G.J. Nagy).

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accelerate near-term reductions in net greenhouse gas concentrations by removing CO_2 that would otherwise remain in the atmosphere; (ii) it can counterbalance residual emissions at the point when societies reach net zero; and (iii) it can achieve and help sustain net-negative emissions after net zero if deployed at sufficient scale. Each role carries different temporal, technical and governance implications for Arctic deployment. It is noted that there is the risk of mitigation deterrence (moral hazard), meaning the excessive expectation that future CDR will be a substitute for rapid emissions reductions. Arctic CDR proposals should therefore be framed and governed as complements to, not as substitutes for, immediate decarbonisation efforts.

A structured literature review was conducted to situate this study within current knowledge on Arctic carbon dynamics and the state of CDR techniques. We synthesised peer-reviewed articles, authoritative reports, including Intergovernmental Panel on Climate Change (IPCC) and National Academies assessments, and recent high-quality reviews that examine.

(i) Arctic terrestrial and marine carbon stocks (peatlands, permafrost and blue carbon);
(ii) the state of development of CDR technologies, i.e., direct air carbon capture and storage (DACCS), enhanced rock weathering (ERW), ocean alkalinity enhancement (OAE), nature-based solutions (NbS); and
(iii) governance and socio-political analyses relevant to Arctic projects.

Key gaps identified in the literature include limited field trials and site-specific data for ERW and OAE in polar conditions; sparse, place-based socio-cultural analyses of Indigenous consent and benefit-sharing in CDR projects; and large uncertainties in permanence and leakage risks where thawing permafrost may alter stored carbon pools.

This article therefore examines under what conditions specific CDR methods are practically and ethically deployable in Arctic settings. We focus on those options most frequently proposed for the region, peatland restoration and coastal blue carbon interventions, afforestation/reforestation, ERW and OAE, and technological approaches such as DACCS and emerging ocean thermal energy conversion (OTEC)–direct air capture (DAC) concepts. For each method, we synthesise evidence on carbon sequestration potential, ecological and climatic risks, logistical constraints, and governance requirements under Arctic conditions, while underscoring that such CDR options can only complement, and not replace, rapid emissions reductions and the protection of existing carbon stocks. Figs. 1 and 2 distil this method-by-method appraisal of Arctic suitability and associated socio-political barriers. In doing so, the article clarifies where Arctic CDR appears plausibly feasible, where it remains speculative or high-risk, and where conventional mitigation should be prioritised.

2. Literature review

The Arctic is warming at a rate significantly faster than the global average, a phenomenon known as Arctic amplification, which is primarily driven by rising atmospheric CO_2 levels and is reinforced by feedback mechanisms such as the Planck, lapse-rate, and surface albedo effects (Zhou et al., 2023). These aspects could inform CDR strategies, but they also introduce considerable uncertainty in predicting outcomes. The Arctic Ocean has a high capacity for CO_2 uptake, due to its cold waters that enhance CO_2 solubility and the expansion of open water areas as sea ice declines. However, actual anthropogenic CO_2 uptake has remained limited. One key factor is the increasing freshwater input, which dilutes total alkalinity and reduces the ocean's buffering capacity (Woosley and Millero, 2020). The role of the Arctic Ocean as a long-term carbon sink remains contested, especially under ice-free conditions, where some models suggest it may not absorb substantial amounts of atmospheric CO_2 (Chen et al., 2016). According to Chen et al. (2016), CO_2 dynamics in the Arctic Ocean vary widely by season and region: ice-covered zones tend to exhibit low partial pressure of CO_2 (pCO_2), driven in part by ice algae activity, while ice-free areas show higher pCO_2 due to rapid air-sea CO_2 exchange.

CDR refers to a range of technologies and methods aimed at capturing and storing CO_2 from the atmosphere to lessen climate change. As global temperatures rise due to more greenhouse gas emissions, CDR has become a vital part of climate strategies that aim to keep warming between 1.5 and 2 °C above pre-industrial levels (IPCC, 2023). CDR methods include NbS, such as afforestation and soil carbon sequestration, as well as technological approaches like DAC and bioenergy with carbon capture and storage (BECCS) (National Academies of Sciences, 2019). Throughout this manuscript, the term direct air carbon capture and storage (DACCS) is used to denote direct air capture systems where the captured CO_2 is intended for durable and verifiable storage, e.g., geological sequestration or mineralisation. The more generic term DAC is reserved for descriptions of capture technologies in a non-storage or hypothetical sense.

Recent studies highlight the growing importance of CDR in achieving climate goals. However, the magnitude of current and future residual emissions, and the implications for required CDR scale, has not received the attention it deserves, despite their obvious impacts. Indeed, the increasing greenhouse gas emissions, mainly from hard-to-abate sectors, will require large-scale CDR deployment (Brad et al., 2024). Strefler et al. (2018) indicate that delays in mitigation and scaling up CDR will shift greater reliance to later in the century, increasing costs and dependence on less mature approaches (see also Fuss et al., 2018). Nonetheless, considerable challenges persist, including high costs, energy demands, and potential ecological impacts (Iyer et al., 2021; Ganti et al., 2024).

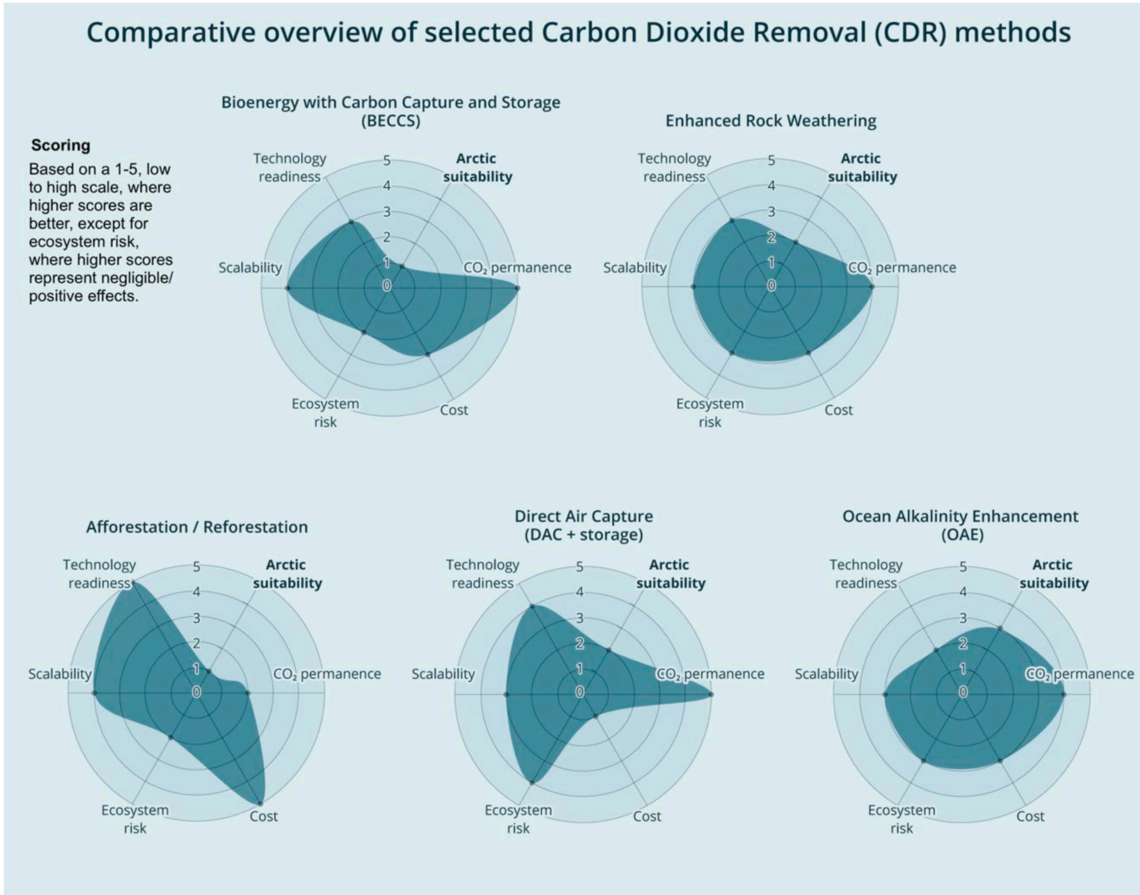
The Arctic region presents both opportunities and risks for CDR. ERW and OAE have been suggested as some of the means via which the Arctic's vast natural systems may be used for CO_2 uptake (Kowalczyk et al., 2024). On the other hand, the fact that Arctic ecosystems are sensitive to large-scale changes requires thorough assessments to avoid unintended consequences. Whereas CDR is potentially a key tool for combating climate change, its implementation requires careful management to make sure it adheres to the principles of sustainability and fairness. This includes the need for studies to improve CDR methods and ensure their integration into broader climate policies.

3. Methods

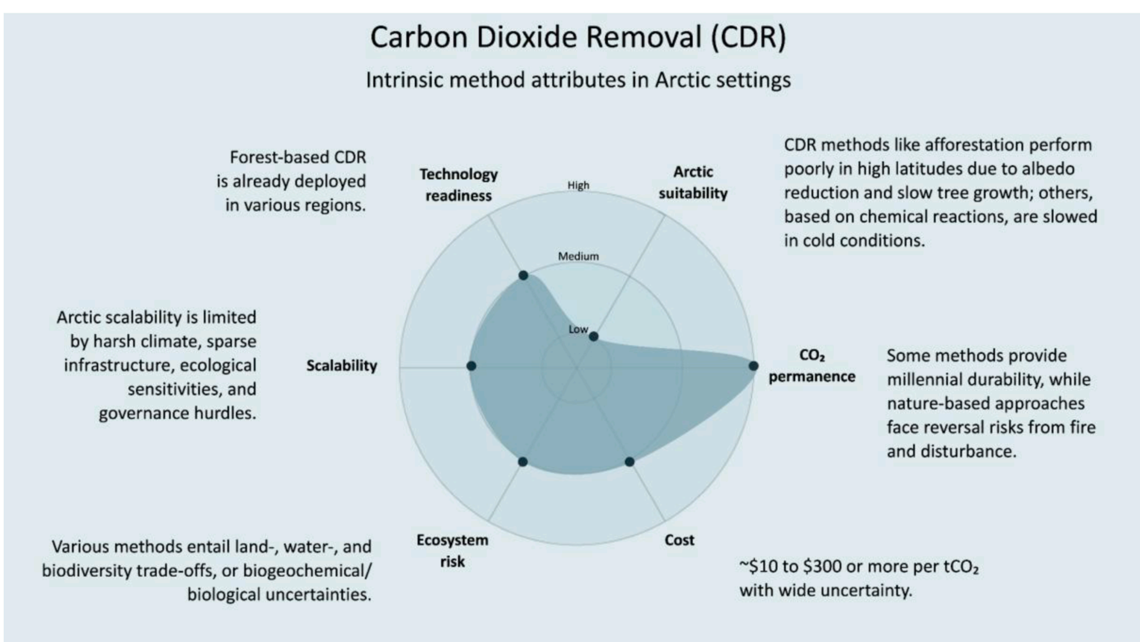
This study investigates the practicality of CDR in the Arctic using a combined approach. A structured literature search was conducted using Web of Science, Scopus and Google Scholar for publications spanning 2000–2025. Searches used strings combining “Arctic” with “carbon dioxide removal”, “CDR”, “DACCS”, “direct air capture”, “enhanced rock weathering”, “ocean alkalinity enhancement”, “afforestation”, “peatland restoration” and “blue carbon”. We included peer-reviewed articles, authoritative reports, and high-quality reviews in English. Titles and abstracts were screened for relevance and full texts were read and synthesised thematically. When quantitative estimates were reported, e.g. carbon potential or cost ranges, we present them as ranges with associated citation and caveats about uncertainty. The synthesis emphasises Arctic-specific evidence where available; where data are sparse, we identify priorities for targeted field trials and monitoring. Lastly, an assessment of the challenges of implementing CDR against the potential carbon benefits is made.

4. Results and discussion: approaches to CDR

The potential to implement CDR in the Arctic relies on a complex mix of factors, from the region's unique environmental context to the behaviour of its carbon systems and the limits of current technology. When exploring the existing possibilities, three central aspects stand out.



(a)



(b)

Fig. 1. Comparative overview of selected carbon dioxide removal (CDR) methods and indicative performance across Arctic-relevant dimensions. *(a) Graphical abstract* showing method-specific radar charts (BECCS, enhanced rock weathering, afforestation/reforestation, direct air capture with storage, and ocean alkalinity enhancement). Scores are on a 1–5 scale (higher is better), except ecosystem risk, where higher scores indicate lower risk/benign effects. *(b) Stylised conceptual radar chart* summarising intrinsic Arctic-suitability attributes, i.e., technology readiness, Arctic suitability, scalability, ecosystem risk, indicative cost band and CO_2 permanence, across the CDR methods evaluated in this article (see Table 1). The shaded area represents a qualitative synthesis, not numerical averages, and is intended to be interpreted together with the method-specific discussion in Sections 4.1–4.3.
(Source: authors)

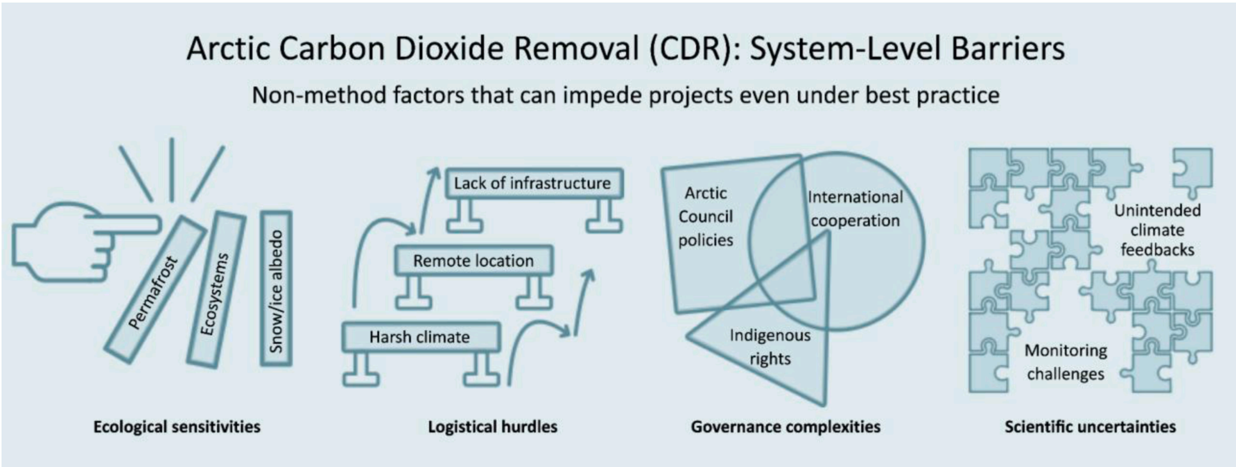


Fig. 2. – Conceptual illustration of system-level, non-method-specific barriers that can impede Arctic CDR deployment. The four clusters, i.e., ecological sensitivities, logistical hurdles, governance complexities, and scientific uncertainties, are illustrative across the CDR methods summarised in Table 1. Additional barriers and nuances are discussed in the text.
(Source: authors)

First, NbS, particularly peatland restoration, coastal blue carbon interventions, and afforestation/reforestation, aim to protect and enhance existing Arctic carbon sinks but also entail ecological risks and substantial logistical constraints. Second, technological approaches promise broader scalability but demand significant investment and imply notable trade-offs. Third, the socio-political landscape is shaped by fragmented governance, international tensions, and persistent concerns around justice and accountability. Understanding how these elements interact is central to evaluating whether CDR can serve as a viable climate tool in the Arctic.

4.1. Nature-based solutions — peatlands, blue carbon and afforestation

Arctic peatlands and coastal blue carbon ecosystems store substantial amounts of organic carbon accumulated over millennia. NbS, such as afforestation and reforestation (A/R) and the restoration of peatlands and blue carbon ecosystems, present both additional opportunities and challenges. Conservation and restoration, e.g., rewetting peatlands, protection of coastal sediments, reduce near-term CO_2 emissions and deliver biodiversity and cultural co-benefits when led by local communities and aligned with traditional ecological knowledge (IPCC, 2022; NOAA, 2023; The Arctic Institute, 2024). However, permanence is uncertain owing to permafrost thaw, fire risk and hydrological change. Rewetting programmes must be carefully designed to avoid increases in methane emissions and to ensure net climate benefits. A/R provide cost-effective carbon sinks, support microclimate regulation, protect permafrost, and reduce soil erosion, thereby contributing to climate management goals, while enhancing ecosystem resilience, improving wildlife habitats, and supporting local livelihoods (IPCC, 2022; The Arctic Institute, 2024; Macias-Fauria et al., 2020). Afforestation at high latitudes is contested because changes to surface albedo and soil thermal regimes may offset carbon gains and so, site-specific assessments are required before any tree planting initiatives are approved. This is because Arctic soils are vulnerable to cultivation for forestry or agriculture, and the penetration of tree roots can release stored CO_2 into the atmosphere (Kristensen et al., 2024). Another review on the Canadian northern boreal and southern Arctic regions emphasises the need to reconcile uncertainties in biogeochemical and biogeophysical changes following afforestation and the limitations of current assessment methodologies before concluding about the climate benefits of afforestation (Bradley Dsouza et al., 2025).

Coastal blue carbon ecosystems, such as salt marshes, seagrass meadows, and brown macroalgae, sequester and store carbon in sediments, protect the coast from erosion and support biodiversity and water quality, and have the potential to deliver climate change mitigation and co-benefits (Krause-Jensen et al., 2022).

Arctic peatland restoration (APR) offers benefits when native habitats are preserved, due to the massive carbon stocks that have accumulated over millennia (Loisel and Gallego-Sala, 2022). Some advantages of APR are: (i) the large amounts of carbon accumulated over millennia; (ii) their rewetting can reduce methane and CO_2 emissions from peat oxidation and drainage; (iii) the potential regeneration of unique ecosystems and hydrology. Nevertheless, CDR faces several challenges and constraints. Its implementation requires the consent and active participation of Indigenous peoples, along with respect for their values, land-use rights, and traditional ecological knowledge (IPCC, 2022; The Arctic Institute, 2024). Stored carbon is vulnerable to: (i) the Arctic's ecological fragility (Kreplin et al., 2021); (ii) limited land availability (Kreplin et al., 2021); (iii) rapid warming, permafrost thaw, and hydrological shifts (Jahn et al., 2010); (iv) low temperatures and short growing seasons that hinder biomass growth (Abbott et al., 2016); (v) difficulties in measuring carbon sequestration and ensuring permanence (Abbott et al., 2016; Wieder et al., 2019); (vi) disturbance from fires (Yang, 2022) or altered drainage patterns (Kreplin et al., 2021); and (vii) potential large-scale emissions from future warming (McGuire et al., 2009; Prater et al., 2020). APR must stay nature-based, avoid extractive approaches, and limit social pressure. Large projects require financial support, shared knowledge, and strong policies (IPCC, 2022; NOAA, 2023; Science Daily, 2025).

Comparative feasibility and key uncertainties indicate a medium to high feasibility for protection and restoration, as existing stock protection measures can be implemented relatively quickly and provide multiple co-benefits. However, key uncertainties remain regarding the permanence of these measures under warming conditions, potential methane-related trade-offs, and the need for sociocultural consent. Priority actions should therefore focus on protecting existing stocks, funding long-term monitoring programs, and integrating Free, Prior, and Informed Consent (FPIC) processes into planning and implementation.

4.2. Technological carbon dioxide removal methods

Efforts to implement CDR in the Arctic face both logistical and political barriers. Sanctions and geopolitical tensions, particularly in the Russian Arctic, limit cooperation and access (Samarina et al., 2023). The high costs associated with infrastructure and technology deployment in such a remote and hostile environment pose significant challenges in terms of feasibility (Tsvetkova and Middleton, 2023). Different CDR technologies, such as ERW (Eufrasio et al., 2022) and DACCS (Strefler et al., 2021), technically deployable but energy-intensive and expensive, have been proposed. Arctic deployment would require secure low-carbon energy supply (Asibor et al., 2022), reliable logistics for CO_2 transport (Tsvetkova and Middleton, 2023) and demonstrably secure storage pathways, e.g., geological sequestration that meets long-term liability and monitoring requirements (Cherepovitsyna, 2025). Feasibility in the Arctic is therefore Low–Medium unless these energy and storage conditions are satisfied.

There are also challenges related to energy requirements for CDR. Some of them are.

i) *High Direct Energy Intensity.* DAC and other engineered CDR techniques need much of direct energy consumed to work with fan operations, sorbent regeneration, and gas compression and face the local energy demand (Han et al., 2025).
ii) *Non-Electric Thermal Requirements.* Various CDR processes, e.g., solvent regeneration in DAC, biomass pyrolysis for biochar, require high temperature heat for its power generation, and are not efficiently produced cleanly in the Arctic's cold conditions Luckow et al. (2010).
iii) *Small and Carbon-Intensive Grids.* Some remote Arctic villages use diesel generators, or fuel-fired, high consumption microgrids for power. CDR energy-driven power output eliminates net removal benefits and raises local pollution (Das and Cañizares, 2019).
iv) *Renewable energy is intermittent in nature.* There is some solar, wind, and hydro potential; however harsh operating conditions, seasonal darkness (polar night), and infrastructure issues lead to difficult and expensive supply of renewable power at stable and high-capacity (Zsiborács et al., 2019).

Overall, the high energy cost per ton is one of the reasons why the technology may take a long time to be widely adopted.

ERW typically involves spreading finely crushed silicate minerals with differing reaction kinetics. Common examples include olivine, wollastonite, and basalt (Beerling et al., 2025), which can accelerate mineral carbonation. ERW is promising due to its relatively fast reaction rates and lower costs compared with other silicate-based CDR approaches (Shi et al., 2025), such as *in situ* mineral carbonation (e.g., CO_2 injection into basaltic or ultramafic silicate rocks; Matter et al., 2016), *ex situ* mineral carbonation (e.g., industrial carbonation of mined silicate minerals; Sanna et al., 2014), and marine or coastal silicate dissolution (e.g., silicate addition to ocean or coastal systems; Renforth and Henderson, 2017). Still, ERW effectiveness and environmental impacts in Arctic settings remain poorly understood and require further study and testing. In Arctic conditions, reaction kinetics may be slower because of low temperatures and reduced moisture availability. The ecological impacts of large-scale spreading and the embodied emissions from rock extraction and grinding require explicit evaluation. Then, feasibility is currently low and requires staged field trials. Thus, accurate quantification of carbon dynamics in the Arctic is critical in this context. This includes monitoring greenhouse gas fluxes, soil organic carbon storage, and the impacts of permafrost thawing (Hugelius, 2012; López-Blanco et al., 2025). Improving observational networks and integrating advanced models can help reduce uncertainties and guide effective CDR strategies (López-Blanco et al., 2025; Sitch et al., 2007).

OAE increases seawater buffering capacity and can promote CO_2 uptake (Fennel et al., 2023). In the Arctic, sea-ice seasonality, distinct circulation patterns and ecological sensitivities create unique risks. Accordingly, careful small-scale experiments and monitoring are necessary before any scale-up.

A further strategy which may be deployed is OTEC, which uses the difference in temperature between the surface and the ocean waters (Aresti et al., 2023). In the Arctic, OTEC can use the cold air from the Arctic atmosphere (from −20 to −60 °C) and warmer water (0 °C) to run a Rankine thermoelectric power plant with ammonia, to generate electricity. The electricity can then be used to run CDR processes, and the atmospheric air can be mixed with the water to adsorb CO_2 directly from the air. Also, deep liquid CO_2 storage could be considered. Below 300 m depth, CO_2 liquifies due to the high pressure. This liquid CO_2 can be stored in the deep Arctic Ocean in a lake, large bags or tanks (Zhao et al., 2024). The primary benefit of the deep Arctic lies in its slow-moving currents. However, if there is a CO_2 leakage, the CO_2 will be trapped between the surface ice and the ocean, resulting in a significant environmental impact.

Fig. 1 presents the graphical abstract with approach-specific profiles (Fig. 1a) and summarises method-by-method attributes relevant to Arctic deployment, e.g., logistical difficulty, ecological risk, and qualitative cost band (Fig. 1b). These qualitative assessments are illustrative and intended to guide discussion rather than provide precise rankings. They should be interpreted together with the method-specific text in this section.

Another potential, albeit unexplored, solution to combine efforts to reduce sea level rise with glacial barriers (Hunt and Byers, 2019) and provide CDR is to inject cold air beneath ice shelves. Related Arctic geoengineering proposals include attempts to modify Arctic–Atlantic circulation to alter heat exchange and ice conditions (Hunt et al., 2020). The cold air would contribute to freezing water, increasing the ice shelf, extending its life and contributing to lower sea levels, while the CO_2 in the air would be absorbed by the ocean. However, recent rare borehole temperature measurements from East Antarctica show that basal thermal conditions can diverge markedly from prior model predictions, highlighting substantial uncertainties in the subsurface state of polar ice sheets and the challenges this poses for engineered glacier interventions (Talalay et al., 2025). Future work will need to investigate the viability of this option.

Comparative feasibility and key uncertainties suggest that DACCS is the most technically mature option, although it is costly and energy-intensive. Then, ERW and OAE offer potential advantages in terms of permanence, but their performance in cold environments remains highly uncertain. Priority actions should therefore include funding-controlled field experiments, quantifying embodied energy and life-cycle emissions, and assessing ecological impacts under Arctic conditions.

4.3. *Comparative feasibility and economics*

Several publications demonstrate wide cost ranges across CDR options and substantial uncertainty for Arctic deployment. DACCS is frequently reported as among the costliest per tCO_2 removed (van der Spek et al., 2025; Küng et al., 2023), while NbS often have lower short-term cost per tCO_2 but higher permanence risk. ERW and OAE cost estimates depend strongly on transport, grinding (ERW) and monitoring/regulatory expenses and therefore remain highly context dependent. Because the available cost estimates are region- and technology-specific, we refrain from presenting new numeric estimates and instead direct readers to the cited reviews for detailed ranges (Ho et al., 2023; Liu et al., 2025). Priority research needs are high-resolution, site-specific techno-economic assessments and life-cycle analyses that explicitly account for Arctic logistical constraints.

Table 1 presents a comparative summary of the principal CDR methods considered for Arctic deployment, with the advantages, major disadvantages and specific constraints that matter in Arctic settings, e.g., logistics, ecology, governance. Representative references point to key reviews or studies relevant to each method.

4.4. *Socio-political barriers to Arctic CDR deployment*

Notably, efforts to deploy CDR approaches in the Arctic face a confluence of socio-political barriers, as summarised in Fig. 2, particularly related to governance, geopolitics, regulatory uncertainty, and

Table 1
Summary of carbon dioxide removal methods for Arctic settings.

Method	Advantages	Disadvantages	Arctic-specific constraints	References
Peatland restoration	Large carbon stocks; co-benefits	Methane risk; permanence uncertainty	Permafrost thaw; need for FPIC	Hugelius (2012); López-Blanco et al. (2025)
Blue carbon protection	Sedimentary carbon sinks; coastal protection	Limited areal extent in Arctic	Ice-cover seasonality; monitoring challenges	Krause-Jensen et al. (2022)
Afforestation	Potential carbon uptake	Albedo impacts; soil disturbance	Short growing season; risk of net warming	Kristensen et al. (2024); Bradley Dsouza et al. (2025)
ERW (silicates)	Long-term mineral storage potential	Grinding/ transport embodied energy; uncertain reaction rates	Slow kinetics in cold; ecological impacts	Kowalczyk et al. (2024); Beerling et al. (2025); Shi et al. (2025)
OAE (ocean alkalinity)	Potential for large-scale uptake	Marine chemistry/ ecosystem impacts; governance	Ice cover; circulation; leakage risks	Kowalczyk et al. (2024)
DACCS	Technically deployable; centralised control	High energy and cost; infrastructure needs	Need for low-carbon power & secure storage; transport/ logistics	(National Academies of Sciences, 2019); Ganti et al. (2024)

equity. Fig. 2 maps technical, ecological, logistical, and socio-political barriers and highlights four socio-political subcomponents: governance fragmentation; geopolitical tensions; inadequate regulatory mechanisms; and uneven global deployment and benefit-sharing. Each component is annotated with short examples drawn from the text.

There are many challenges to CDR in the Arctic Region. Some of them are.

i) *Extreme Environmental and Logistical Hurdles.* The Arctic's isolation, harsh weather, seasonal darkness, and limited infrastructure pose unprecedented challenges, hazards, and costs for deploying and maintaining any CDR technology. Sea ice makes marine operations even more complicated (Das and Cañizares, 2019; Tsvetkova and Middleton, 2023).

ii) *Ecosystem Sensitivity and Risks.* Arctic ecosystems are fragile and uniquely adapted. Strategies such as ocean alkalinity enhancement or large-scale afforestation could disrupt food webs, change albedo (reflectivity), and threaten biodiversity, with impacts that are poorly understood and potentially irreversible (Fennel et al., 2023; Krause-Jensen et al., 2022; Kristensen et al., 2024).

iii) *Scale and Permanence Limitations.* Methods designed for long-lasting storage are hampered by the area's vast, deep, and seasonally isolated oceans. For instance, ensuring CO_2 remains sequestered in marine sediments or that enhanced weathering operates effectively in frozen soils is scientifically uncertain. The natural carbon cycles are also sluggish (Hugelius, 2012; Streck et al., 2025).

iv) *Governance and Ethical Concerns.* The Arctic is an area that involves multiple nations and Indigenous communities with sovereign rights. The deployment of CDR presents profound ethical challenges, such as consent, equity—with potential transboundary impacts—as well as implications for transboundary development. A comprehensive, inclusive legal and governance framework for this sort of geoengineering is almost non-existent. As a result, substantial political and social issues remain unresolved (Brad et al., 2024; Gao and Guo, 2025; Smieszek et al., 2021).

In essence, governance in the Arctic remains significantly fragmented, involving diverse stakeholders, i.e., state actors, the Arctic Council, Indigenous organisations, non-governmental organisations (NGOs), and industry, whose interests often diverge significantly at the local level. This diversity of priorities complicates the development and implementation of coherent policy frameworks for CDR (Gao and Guo, 2025). Second, enduring geopolitical tensions among Arctic states, historically rooted in contested sovereignty claims and competing strategic security interests, undermine the trust and cooperation required for shared oversight and data-sharing in large-scale CDR deployment (Smieszek et al., 2021). Third, inadequate regulatory mechanisms imply that uncoordinated or premature deployment of CDR initiatives might proceed without sufficient foresight and/or environmental safeguards, especially concerning permanence, monitoring, and the long-term integrity of ecosystems (Obydenkova, 2024). Because permanence is critical to the enduring effectiveness of carbon removal, enforceable policies are needed to ensure that methods with limited storage durability are not treated as equivalent to permanent removals. Doing so could distort carbon accounting and disproportionately shift mitigation burdens onto future generations (Streck et al., 2025). Finally, uneven global deployment of CDR risks reinforcing socioeconomic inequities: Arctic-based removal may be used to offset emissions from distant regions, without delivering meaningful benefits to local communities or ensuring their representation in decision-making processes (Obydenkova, 2024). Collectively, these factors highlight the urgent need for future-oriented, multi-actor governance that strengthens regulatory oversight, ensures fair decision-making, supports international cooperation, and is attuned to the Arctic's complex, fast-changing, and precarious geopolitical and ecological landscape (Gao and Guo, 2025; Obydenkova, 2024; Smieszek et al., 2021; Brad et al., 2024).

FPIC of Indigenous peoples and transparent benefit-sharing mechanisms must be fundamental prerequisites for any CDR activity. Priority actions should focus on establishing multilateral governance frameworks, implementing enforceable monitoring and permanence guarantees, and ensuring meaningful participation and benefit-sharing with Indigenous communities.

5. Conclusions - the way ahead

Our synthesis indicates that Arctic CDR cannot be labelled universally ‘feasible’ or ‘infeasible’. Feasibility is method-specific and conditional on energy, storage, and governance contexts. NbS, through peatland conservation and blue carbon protection, as examples, are among the most readily implementable options in the near term if they are led by local communities and coupled with robust monitoring to reduce permanence risks. ERW and OAE merit-controlled field experiments to evaluate reaction rates and ecosystem impacts in cold conditions and are not ready for large-scale deployment. DACCS is technically possible but economically costly and requires reliable low-carbon energy supply and demonstrably secure storage pathways, therefore being feasible only under constrained circumstances. Policy recommendations should thus focus on the following priorities.

- *Protect and restore key carbon sinks.* Governments and funders should prioritise conservation of Arctic peatlands and blue carbon habitats because these actions are low-risk, deliver co-benefits, and reduce immediate emissions risk.
- *Fund participatory field trials.* Support multidisciplinary, community-led pilot trials for ERW and OAE with independent environmental monitoring and staged governance oversight.

- *Condition DACCS deployment*. Any DACCS deployment in the Arctic must be demonstrably powered by low-carbon electricity and guarantee secure, long-term CO_2 storage through legally enforceable mechanisms before scale-up.
- *Strengthen governance and consent.* Establish multilateral frameworks that require FPIC of Indigenous peoples, transparent benefit-sharing and independent oversight panels.

These recommendations aim to balance precaution with the need to advance the field: testing promising approaches in a staged manner while simultaneously protecting existing carbon stocks and community rights. It is hoped that they may support further work in this strategically important area. Future studies should examine, in greater detail, the specific characteristics of each CDR technology, assess their feasibility, and investigate the socio-economic aspects associated with their implementation under real-world conditions.

CRediT authorship contribution statement

Walter Leal Filho: Writing – review & editing, Writing – original draft, Conceptualization. **Johannes M. Luetz:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition. **Maria Alzira Pimenta Dinis:** Writing – review & editing, Writing – original draft. **Julian David Hunt:** Writing – review & editing, Writing – original draft. **Gustavo J. Nagy:** Writing – review & editing, Writing – original draft.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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