Te unu a te moana i te hauhā i Aotearoa

Marine carbon dioxide removal in Aotearoa New Zealand

We capture carbon on land for climate change mitigation: What about in the ocean?

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

ROYAL SOCIETY TE APĀRANGI

Ngā ihirangi
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Introduction

Aotearoa New Zealand is increasingly being affected by climate change, a consequence of rising average global temperatures due to human-caused increases in carbon dioxide (CO_2) and other greenhouse gases in the atmosphere (1). To mitigate the extremes of climate change, Aotearoa New Zealand is part of a global effort to reduce the rate of greenhouse gas emissions (largely CO_2) into the atmosphere. Globally, and in Aotearoa New Zealand, there is also increasing focus on taking action to remove greenhouse gases already in the atmosphere.

There are many international agreements and initiatives designed to reduce emissions (discussed elsewhere), but strategies for removal are less well-developed. Most initiatives have focused on terrestrial carbon storage, such as planting more forests to remove CO_2 from the atmosphere or underground storage of CO_2. However, there has been less focus on the potential of the ocean to capture and store CO_2.

While oceans naturally absorb up to 30 percent of the CO_2 emissions caused by human activities (2), there is interest in human-driven methods to increase this uptake. These methods are termed marine Carbon Dioxide Removal (mCDR).

mCDR encompasses a range of techniques, from biological methods involving seaweed cultivation, adding nutrients, and marine ecosystem recovery, to physical or chemical approaches, such as altering ocean alkalinity (3). mCDR techniques are still under development, with research and small-scale trials happening around the world to determine if they successfully remove and store meaningful amounts of CO_2 and what impacts they may have on complex ocean systems. It is important to note, though, that CO_2 removal cannot substitute for emissions reductions; it will never be sufficient on its own to address climate change (4).

It is also not yet clear if mCDR techniques would be feasible in Aotearoa New Zealand; each has unique social, environmental, and economic impacts that need to be understood if they are to become part of our future climate change mitigation strategies.

With this publication, the Royal Society Te Apārangi aims to help people better understand marine carbon dioxide removal techniques, their relevance to New Zealand's unique environment, and the issues associated with these approaches – so communities can make informed decisions about the future of our oceans.

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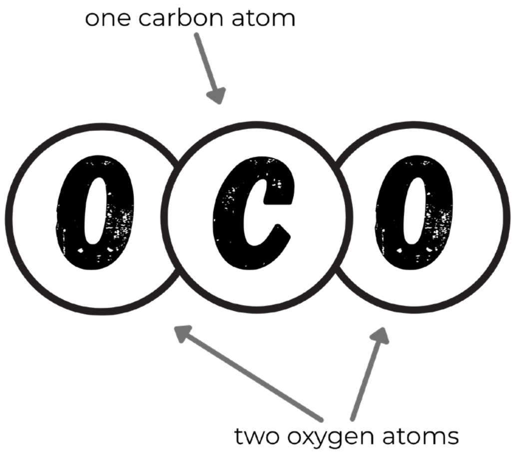
He aha i tika ai kia unuhia te hauhā?

Why should we remove carbon dioxide?

CO_2 is a gas that is naturally present in our atmosphere. It is released into the air through both geological and biological processes (such as volcanic activity, respiration, and organic matter decomposition) (3) and is an essential requirement for processes such as plant photosynthesis and growth.



CO_2 in Earth's atmosphere absorbs heat radiating from the planet's surface and prevents this heat from being emitted into space, instead trapping it in the atmosphere (5,6). This natural process, known as the greenhouse effect (5), maintains Earth's average surface temperature, currently at around 15°C (6).

Human activities such as the burning of fossil fuels (coal, oil, and gas) and deforestation (7) have resulted in an increase in CO_2 from about 280 ppm (parts per million) in pre-industrial times to about 420 ppm in the atmosphere today (8). While atmospheric CO_2 has varied significantly (with average temperatures) over Earth's history, these pre-historical changes occurred over vast geological timescales. The rapid increase in atmospheric CO_2 since the industrial revolution is unprecedented in the last 800,000 years and potentially the last 3 million years (9). This is a problem because CO_2 is a greenhouse gas that has caused global average temperature to rise by 1.2°C or greater since modern records began (10)[1]. This seemingly small increase has already had serious impacts on both humans and the environment that include sea level rise (12) and increased frequency and intensity of severe weather events (eg, storms, heavy rainfall, extreme heat), wildfires and droughts (12). Furthermore, these impacts are forecast to escalate as atmospheric CO_2 concentrations – and global average temperature – continue to climb (13–15).

1. According to the latest 10-year period (11); calculations differ. Individual years have been hotter; NASA reports that 2024 was 1.47°C warmer than pre-industrial averages (10), but temperatures have to be consistently at an elevated level over a 10–20 year period before an average is officially altered (11).

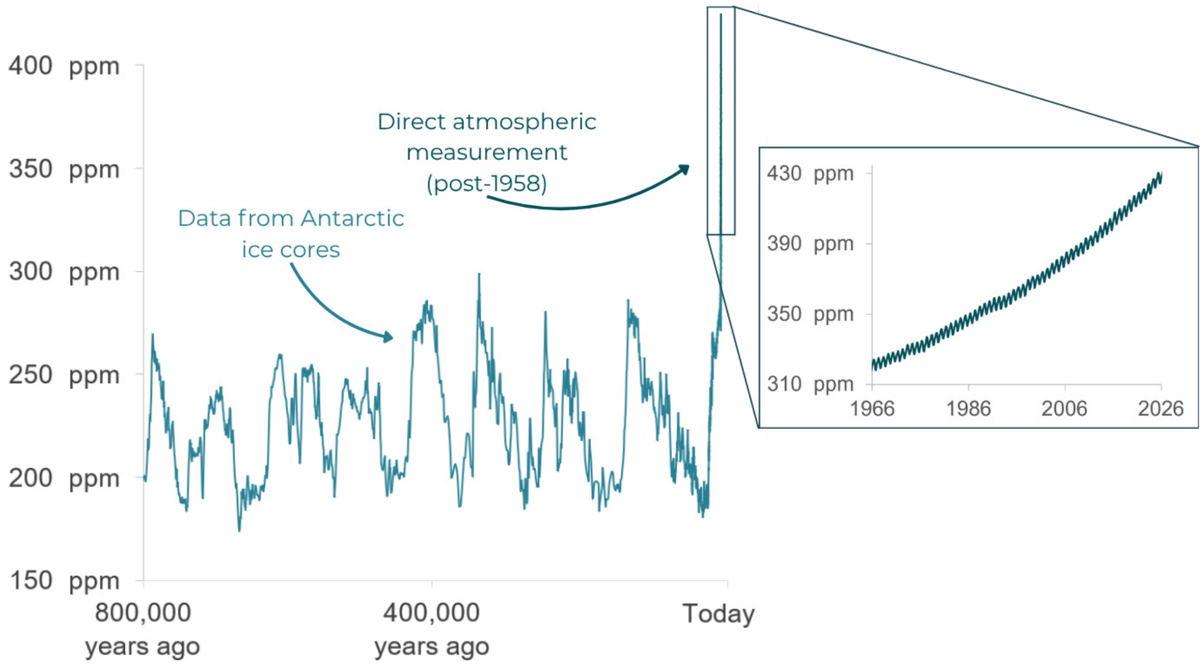


FIGURE 1 | Atmospheric CO_2 has varied naturally over the last 800,000 years (length of ice core records), but it has never been higher than it is today (2,3).

BOX 1 | The Carbon Cycle

The carbon atoms in CO_2 molecules are converted to different forms (captured or 'fixed') by biological, physical and geological processes which result in them being stored (or sequestered) for variable lengths of time before release back into the atmosphere as CO_2. Carbon reservoirs include the atmosphere, the terrestrial biosphere (organisms living on land), the hydrosphere (oceans), and the geosphere (Earth's mantle and crust) (16). Processes that remove CO_2 from the atmosphere are known as carbon sinks, while those that release CO_2 into the atmosphere are sources. This movement of carbon is called the carbon cycle, which occurs at both fast and slow timescales.

- **The slow carbon cycle** operates over thousands to millions of years, primarily through geological processes such as volcanic activity, rock weathering, and the formation and burial of carbonate minerals (17). Most of Earth's carbon is stored in sedimentary rock (18).
- **The fast carbon cycle** (also known as the biological carbon cycle) operates over timescales ranging from minutes to centuries through biological, physical and chemical interactions between the biosphere, atmosphere, and ocean (19).
    - **In the ocean:** Atmosphere-biosphere carbon exchange by plants, algae, and phytoplankton is a major component of the fast carbon cycle (19). When atmospheric CO_2 dissolves in surface waters, these organisms convert the dissolved CO_2 into organic matter via photosynthesis and release some of this carbon back to the atmosphere through respiration and decomposition. When the organisms die, a small proportion of this carbon sinks into the deep ocean and is buried in marine sediments (19). Gas exchange at the ocean surface also occurs via physical mixing and temperature changes.
    - **On land:** Natural or anthropogenic burning and decomposition of organic matter releases CO_2 (16).

The burning of fossil fuels represents the redistribution of carbon from the slow carbon cycle to the fast cycle by a rapid transfer from geological reservoirs (such as coal, oil, and gas) to the atmosphere, and is a human-induced alteration of the natural carbon cycle (4).

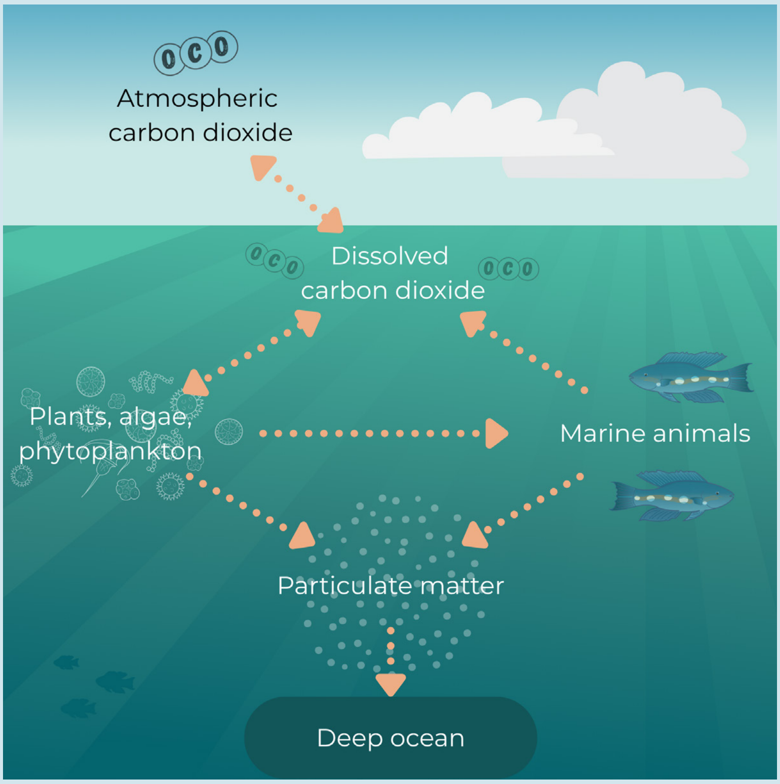


FIGURE 2 | The fast carbon cycle in the ocean involves biological and physical processes.

Te whakamauru i ngā pānga o te huringa āhuarangi
Mitigating the impacts of climate change

Carbon dioxide removal (CDR) is the name for deliberate human actions, technologies, and approaches that remove CO_2 from the atmosphere to durable storage (the carbon is locked away for centuries or longer).

Climate change is increasingly seen as a global emergency (1,4,20,21). Greenhouse gas-induced increases in global temperatures are stressing ecosystems and societies (4). The consequences of climate inaction are likely to be severe and to be felt within our lifetimes, negatively affecting biodiversity, water and food security, the economy, community resilience and safety, indigenous practices, and many other factors critical for human wellbeing for generations to come (4). Urgent and sustained reductions in greenhouse gas emissions are needed to mitigate these impacts (4).

Global and domestic initiatives

Aotearoa New Zealand is a party to the 2015 Paris Agreement (22,23) – a legally binding international treaty with the principal goal of limiting global average warming to below 2°C, with efforts to restrict warming to 1.5°C (22). This means New Zealand is obligated to help reach internationally agreed targets by implementing actions that reduce the country's emissions of CO_2 and other greenhouse gases.

Each of the Paris Agreement's signatory nations communicates the actions they will take to limit emissions – as well as to adapt and build resilience against ongoing climate change – in strategies known as Nationally Determined Contributions, which are updated every five years (22). Aotearoa New Zealand's emissions reduction strategy (24) is complex and incorporates methods ranging from transitioning to renewable energies and implementing the Emissions Trading Scheme; to planting forests for land-based carbon capture; to improving waste management and investing in the development of point-of-emission carbon capture (and storage) technologies (24). These strategies aim to minimise emissions of CO_2 and other greenhouse gases – a stated priority for both national and international emissions targets.

Drastically reducing our carbon emissions, however, is not sufficient on its own to avoid 1.5°C global warming (25). The science which underpins the Paris Agreement's goals indicates that both emissions reduction and carbon removal techniques (22) are necessary to avoid the worst consequences of climate change. Given that global CO_2 emissions are continuing to rise rather than fall (4), effective removal of CO_2 is essential for climate change mitigation (26), despite the difficulty in removing atmospheric CO_2 at a meaningful scale (27).

CO_2 removal

The natural carbon cycle sequesters about half of human-released carbon emissions into terrestrial (land-based) and marine (ocean-based) sinks (8,28). Without these natural processes, the concentration of atmospheric CO_2 would be higher and global temperatures would be hotter due to the greenhouse effect (4).

Natural processes, however, are not sufficient to keep up with emissions. Carbon dioxide removal (CDR) techniques – deliberate human actions, technologies, and approaches that remove CO_2 from the atmosphere to durable storage (4,27) – are increasingly being considered or used to mitigate climate change. However, global CDR interventions currently remove only about five percent of total global emissions (26).

Examples of CDR on land include:

- planting forests to capture carbon naturally through photosynthesis and store it in their wood. Carbon is released again when trees die and decompose or burn (4) (see Box 1).
- using artificial direct carbon capture technologies – often at the emission source, such as a factory or natural gas processing plant – to draw CO_2 from the air, compress it, and pump it underground for storage (4,29) or sequester it within durable materials (eg, cement). This approach has also been applied to geological reservoirs beneath the ocean (eg, offshore Norway (30)) (Figure 10 below).

Terrestrial and geological CO_2 removal techniques are described in detail elsewhere, including these references (4,29,31). From this point on, this report will concentrate on methods for capturing and storing CO_2 in the ocean.

Te unu a te moana i te hauhā
Marine carbon dioxide removal

The ocean is the largest natural sink of carbon (28); it is predicted to have naturally absorbed about 30 percent of all human-caused CO_2 emissions (2).

Marine carbon dioxide removal (mCDR) is the name for interventions that increase CO_2 uptake from the atmosphere into the ocean (32). mCDR encompasses a range of techniques mostly based on enhanced natural processes, including:

- coastal blue carbon
- seaweed aquaculture and afforestation
- ocean nutrient fertilisation
- ocean alkalinity enhancement
- artificial upwelling.

Some of these mCDR techniques may become tools in New Zealand's future strategies, and for Nationally Determined Contributions globally, to meet national and international targets[2].

2. Carbon naturally up-taken by open ocean sinks (excluding coastal waters) is not currently counted towards Nationally Determined Contributions (33).

Marine carbon dioxide removal (mCDR) is the name for interventions that increase CO_2 uptake from the atmosphere into the ocean.

In Aotearoa New Zealand, CO_2 removal initiatives have generally focused on planting trees to uptake and remove carbon from the atmosphere (24); however, the Second Emissions Reduction Plan issued in 2025 and amended in 2026 specifies 'non-forestry removals', which include coastal blue carbon, marine ecosystems, and ocean fertilisation (34). Recent reports from the Intergovernmental Panel on Climate Change have also drawn attention to significant international efforts to research and develop ocean-based carbon removal and storage (4,27).

Despite research and consideration of potential applications, all these techniques have significant uncertainty regarding their:

- efficacy and scalability
- permanence
- costs
- risks and additional side effects.

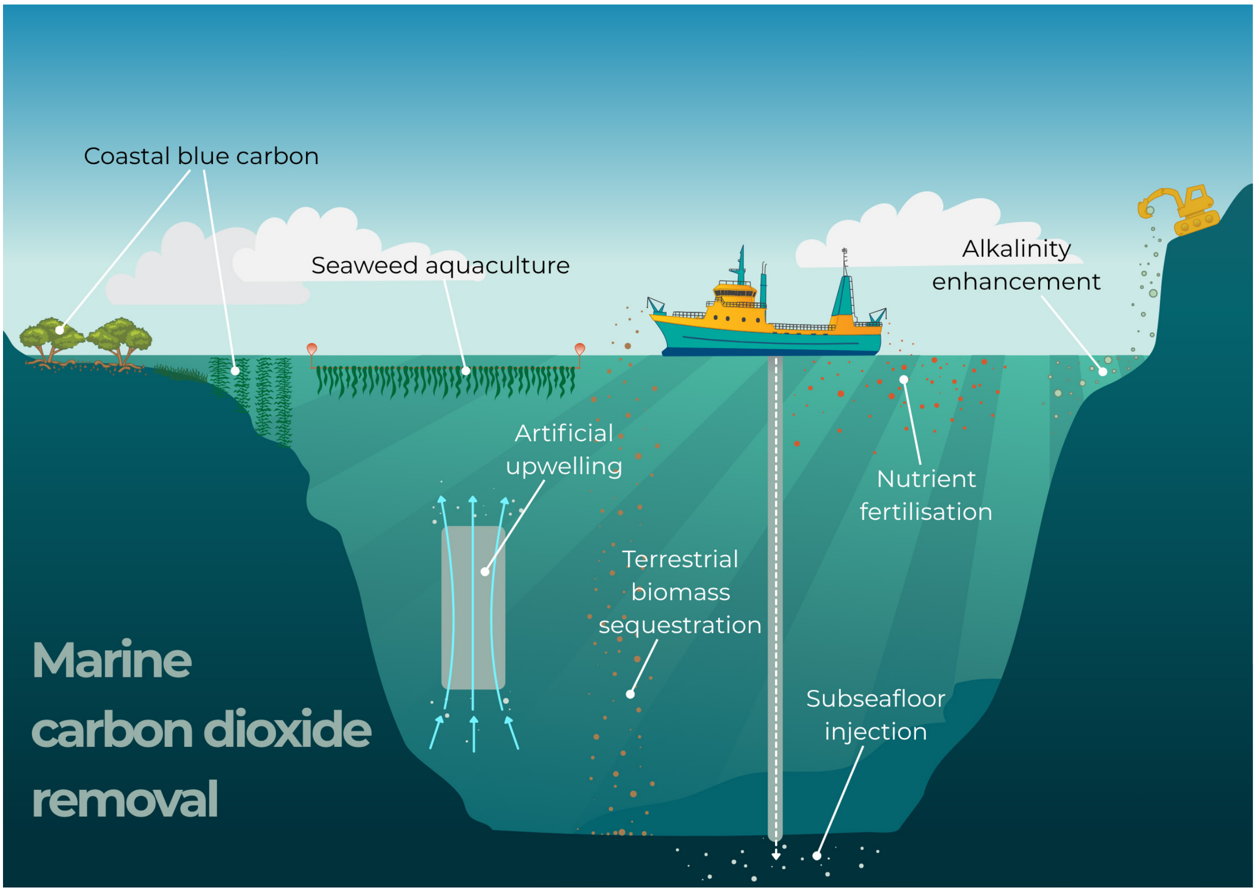


FIGURE 3 | Marine carbon dioxide removal approaches in this publication.

BOX 2 | Carbon in the ocean

The ocean continuously uptakes, redistributes, and releases CO_2 through several key processes called pumps (17).

How does CO_2 enter and exit the ocean?

CO_2 enters the ocean primarily via air-sea gas exchange as part of what is called the solubility pump (17,35). Where the partial pressure[3] of CO_2 in the atmosphere is greater than in surface water, CO_2 dissolves into the ocean. Conversely, CO_2 will be released into the atmosphere if partial pressure in the water is greater than in the air. Sea temperatures can also have an impact on this air-sea flux since colder waters can uptake more CO_2 than warmer waters, so changes in water temperatures affect gas exchange between the ocean and atmosphere (17,36).

3. Partial pressure is the pressure that a specific gas would exert if it occupied the same given volume alone at the same temperature.

How does CO_2 move around the ocean?

After entering the ocean, CO_2 is redistributed by several interconnected pumps:

- **Biological pump:** Phytoplankton (tiny, photosynthetic marine organisms) take up CO_2 via photosynthesis in surface waters and convert it into organic matter. Much of this carbon is transferred through the food web as the phytoplankton are consumed by other organisms, but a portion eventually sinks to the deep ocean via gravity as particulate matter (which includes marine snow[4], faecal pellets, and carcasses) (36).
- **Carbonate (counter) pump:** Many marine organisms produce shells or skeletons of calcium carbonate ($CaCO_3$) by combining dissolved carbonate ions with calcium, which causes an increase in surface ocean CO_2. When these organisms die, however, they sink, taking organic carbon with them, and either dissolve or are buried in sediments (sequestering it) (17,35).
- **Physical pump:** This refers to physical processes, such as the circulation of ocean currents and wind-driven mixing, which distribute CO_2 through the water column. In high-latitude regions, CO_2 is carried down into the deep ocean by the sinking of dense, cold water (comprised of fresh water and sea ice melt), while upwelling zones bring deep, CO_2-rich waters back to the surface (16,17).

4. Marine snow is a transfer of organic matter by particles sinking from the ocean surface. The particles look like snow, with a fluffy white appearance. The 'snowflakes' are composed of decaying animal and plant matter as well as inorganic material such as sand and dust. Particles aggregate and grow as they fall; some are consumed by animals or microbes as they fall and the rest collect on the seafloor (37).

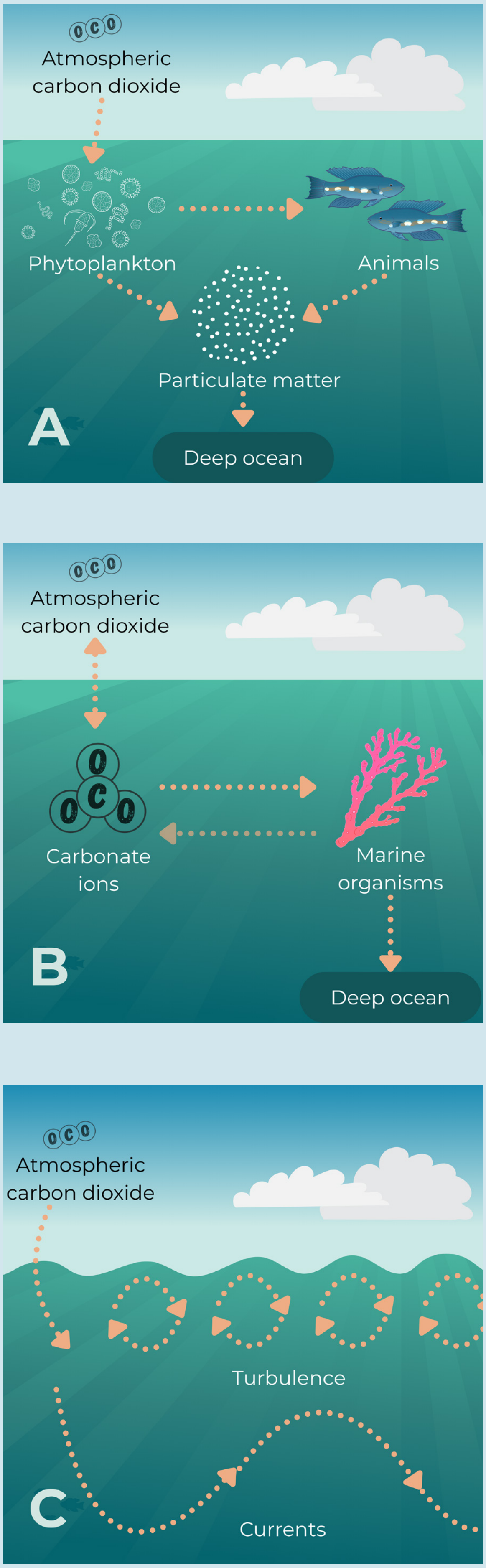


FIGURE 4 | Carbon, taken up at the ocean surface, moves through the water via the (A) biological pump, (B) carbonate (counter) pump, and (C) physical pump.

Te hauhā kahurangi ā-tai
Coastal blue carbon

Coastal blue carbon involves the enhanced storage of carbon in natural vegetation in coastal environments. Marine CO_2 uptake can be improved through better management of coastal wetlands, mangroves, macroalgae (seaweeds), and seagrass beds to protect existing blue carbon[5] sinks. This can be achieved by allowing ecosystems to recover, actively restoring them, or artificially expanding them to further enhance their carbon uptake, most of which is sequestered in the sediment beneath the plants.

Coastal blue carbon ecosystems cover up to 185 million hectares globally. This is only about 0.5 percent of the seafloor, but may be responsible for more than 50 percent of CO_2 burial in the ocean (38). Unfortunately, about half of global coastal mangrove, seagrass and saltmarsh ecosystems have been lost (38,39) and much of what remains grows outside protected marine areas (38). One publication estimates that restoration of tidal marshes, seagrasses, and mangroves could lead to carbon sequestration equal to about three percent of global emissions[6] (38). Restoration of coastal mangroves is predicted to have the greatest carbon benefit (31). Mangroves are also protective against flooding and provide resilience against other effects of climate change (40–42). Protecting mangroves is more cost efficient than replacing them with protections such as sea walls[7] (40). Highly productive macroalgal ecosystems are estimated to contribute 3–4 percent of the global ocean carbon sink capacity (45,46).

5. In this paper we use 'blue carbon' to refer to carbon captured by coastal ecosystems, such as mangroves, seagrasses and saltmarshes (32).

6. Based on 2019–2020 global emissions (38).

7. Coastal wetlands, however, will fail to keep up with sea level rise if the rate of rise increases from a current rate of about 4.5 millimetres per year to 7 millimetres (43,44).

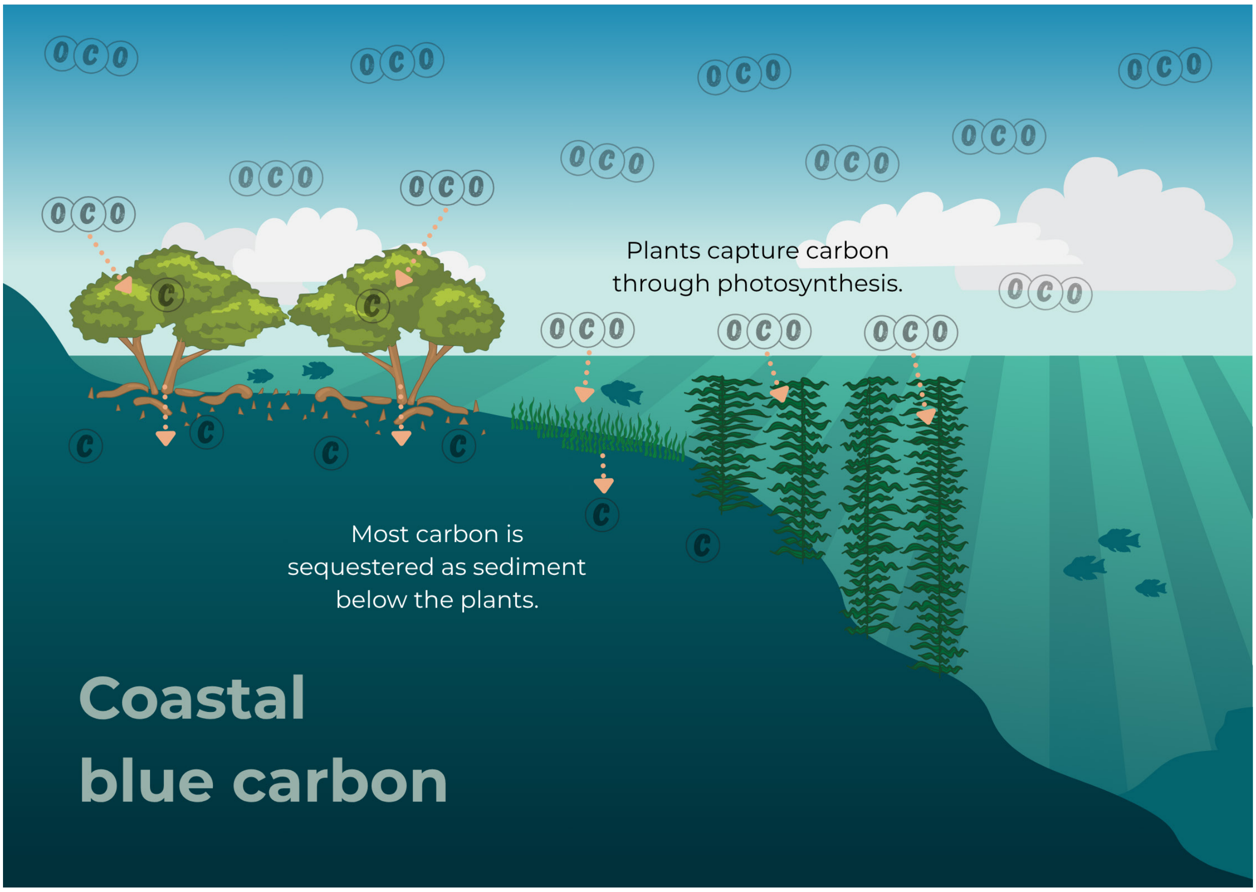


FIGURE 5 | In coastal blue carbon, carbon is captured and stored by photosynthesising seaweed and plants growing along the coast.

Pros and cons

Co-benefits: Co-benefits of coastal blue carbon on top of carbon sequestration include improved water quality, biodiversity conservation, ecological restoration, eco-tourism opportunities, improved coastal protection from storm surges, and improved customary and recreational fishing sustainability (38).

Access: Coastal ecosystems are easier to access than the open ocean for monitoring and verification of interventions.

Competition for resources: Coastal blue carbon projects must compete with other uses of the coastline, including fishing, recreation, agriculture, infrastructure, and transport.

Long-term investment needed: For mCDR via coastal blue carbon to be successful, ecosystem protections need to be sustained long-term. If coastal environments are allowed to degrade, most sequestered carbon would likely be released back into the atmosphere (4,47). For example, some approaches are vulnerable to extreme weather, such as typhoons or cyclones (48) and coastal blue carbon efforts would have to plan to restore storm damage. To achieve lasting benefits from variable systems, international coastal blue carbon guidelines require commitments of 25 to 100 years (49). Rising sea levels also need to be taken into account for long-term viability (50).

International research and applications

Vietnam is often cited as a success story of coastal restoration. The mangrove forests and seagrass meadows that were devastated by bombing in the Vietnam War have been undergoing restoration (both through planting and natural regrowth) since 1978 (42,48). Although carbon capture was not the main motivator for recovery efforts, the Mekong mangrove restoration area was estimated, in 2013, to absorb about three times more carbon than Vietnam emitted (51).

Mangrove forests are the most well-studied coastal blue carbon ecosystem. However, there are still many gaps in our knowledge of other ecosystems and more research is needed to better understand opportunities and risks related to coastal mCDR.

Existing international coastal blue carbon initiatives include:

- Tidal Wetland and Seagrass Restoration[8]: a global carbon storage programme which includes creating, restoring, and maintaining tidal wetlands (49,52).
- Agriculture and Forestry Carbon Benefit Assessment[9]: a global programme to empower communities to capture carbon through forestry, including growing and protecting mangroves (49,53). Community-driven mangrove conservation initiatives are taking place in Kenya (54,55) and Madagascar (56).
- Tidal Restoration of Blue Carbon Ecosystems[10]: an Australian Carbon Credit Units scheme (57) which incentivises regions to re-establish and protect wetlands that have been drained. Early projects include protecting river flood plains (58) and rewilding farmland in Queensland (59–61).

Research and applications in Aotearoa New Zealand

In Aotearoa New Zealand, research into blue carbon projects is in its early stages. A report commissioned by The Nature Conservancy Aotearoa New Zealand and the Ministry for the Environment recently looked into opportunities and barriers (49). Key recommendations included: the development of a national blue carbon road map or strategy; further consideration of barriers and opportunities for Māori; clear guidance for carbon rights; and an enabling environment for voluntary markets (49).

Māori engagement will be critical where restoration efforts focus on coastal ecosystems because of iwi ownership, kaitiakitanga (guardianship), and customary rights and interests over coastal land (49,62).

Active research across Aotearoa New Zealand includes:

- Moanaanuanu estuary, near the Whangamatā Harbour: researchers found that deforestation within an estuary led

8. Verra VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1.
9. Plan Vivo PM001 Agriculture and Forestry Carbon Benefit Assessment Methodology.
10. T-Restor Tidal Restoration of Blue Carbon Ecosystems Method.

to a decline in sediment carbon stocks (63). Coastal areas that are dominated by mangrove growth store more organic carbon than regions with other marine plants (63).

- Tairua estuary, in the Coromandel: researchers have highlighted the importance of unvegetated habitats as significant carbon sinks, with important transfer of carbon between different habitats such as saltmarsh, seagrass, mangroves, and unvegetated sediments (64).
- North Island saltmarshes: researchers are currently working on quantifying the carbon sequestration potential of saltmarshes by analysing soil cores across three different sites (65).
- Fiordland: research is underway to understand how fluctuations in the capacity of fiords to store carbon are influenced by freshwater input and climate change (66), given that such environments are important globally and locally as carbon repositories (67,68).

Te ahumoana rimurimu me te whakarimurimu
Seaweed aquaculture and afforestation

In mCDR, seaweed aquaculture (farming) means growing seaweed for the purpose of removing carbon from seawater and storing it in living tissue (69), followed by the deliberate deposition of this organic material in the deep sea.

Seaweeds (macroalgae) sequester CO_2 via photosynthesis, the process by which plants and algae convert light energy into chemical energy and plant biomass by absorbing CO_2 and releasing oxygen. This causes the amount of CO_2 in the water around the plant to decrease (70), so the water can then absorb more CO_2 from the atmosphere via gas exchange at the surface.

The promotion of ocean afforestation (planting) using existing systems, such as the Great Atlantic Sargassum Belt or offshore seaweed farms and seeding buoys, was suggested as an early viable mCDR approach by entrepreneurs and scientists (71). Rehabilitation and reforestation of natural kelp forests could also contribute to carbon removal (72) (these efforts are often included under the definition of coastal blue carbon).

Experts have since raised various limitations and considerations regarding seaweed aquaculture, detailed below. More research is needed to understand the complex processes and wide-ranging effects of cultivating seaweeds for carbon dioxide removal.

Pros and cons

High efficiency: Seaweeds are fast growing, highly productive, widely distributed in different aquatic habitats across the globe, and can grow on ropes or other structures that make farming easy (73–75).

Co-benefits: Seaweed biomass is important in mitigating coastal ocean acidification and supporting healthy ecosystems. Farmed seaweed delivers social and economic benefits to communities, ie, seaweed can be partially harvested for food, and for products such as textiles, pharmaceuticals, and bioplastics (76,77). A recent study also found that seaweed farms enhance alkalinity in the sediment below them, which can improve long-term carbon storage (78) (see alkalinity enhancement section).

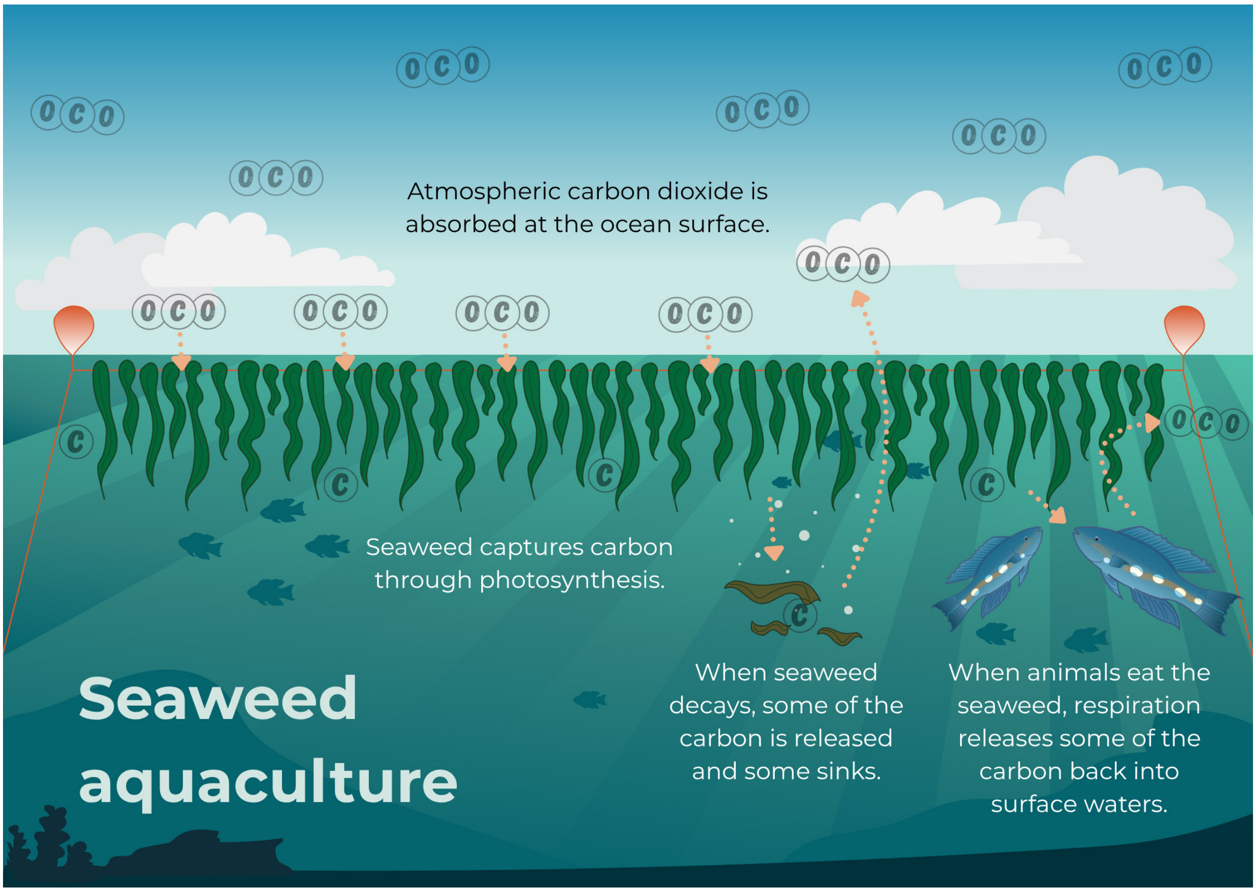


FIGURE 6 | Seaweed aquaculture is an mCDR technique because it boosts CO_2 capture at the ocean surface.

Difficult to monitor; uncertainty of long-term carbon storage: Carbon sequestration by growing seaweed is not as simple as it sounds; the biological processes involve both capture and release of carbon. Carbon is captured through photosynthesis by living seaweeds and released during degradation of dead ones (seaweeds have short life spans). It is difficult to track how the carbon that seaweed fixes moves through the marine environment, and the duration of seaweed biomass storage (79). Seaweed must also be considered from an ecosystem perspective rather than in isolation; seaweed is consumed by animals and the carbon from its tissues is metabolised and integrated into animal tissue or released as waste or during respiration. Seaweed, unlike trees on land, does not have a lot of dead biomass (ie, wood) that goes uneaten.

To be considered a viable mCDR technique, seaweed biomass needs to sink to a depth below 1000 metres or be buried in marine sediment, effectively removing the carbon it contains from the atmosphere (69). In wild seaweed beds, it is estimated that nine percent of absorbed carbon is exported to the deep sea, but only one percent is buried in the seafloor (46). The rest is recycled back to CO_2 by grazing and respiration, and so does not contribute to emissions reduction targets (46). Long-term seaweed farms, however, have been demonstrated to accumulate substantial carbon burial in the sediment below (80). Deliberate sinking of large amounts of seaweed (known as seaweed dumping) has been proposed as a way of increasing the likelihood of long-term carbon sequestration in the deep ocean (81). Extensive analyses of the relationship between seaweed life cycles and marine carbon flux under a variety of farming scenarios will be necessary to fully evaluate the utility of this technique (74,79,81,82).

Use of fossil fuels: Current seaweed farming practices rely heavily on fossil fuels (eg, transportation and processing). At present, this carbon release is likely to outweigh any carbon sequestration potential (69,79).

Potential side effects: Mass cultivation (farming) of seaweed will likely affect marine ecosystems at the sea surface and in the deep sea (3), though ecological effects require further investigation (83). For example, seaweed farms could block light, smother deep-sea environments, and use up important nutrients that reduce photosynthesis and CO_2 uptake by phytoplankton (84). This reduction in phytoplankton may alter food chains and limit energy transfer to fish and marine mammals (84).

Concerns have been raised (71,73,79,84,85) about the viability and practicalities of ocean afforestation and related techniques, with questions about atmospheric re-equilibration timescales, efficacy and verification of macroalgae-associated carbon sequestration, ecosystem impacts, and operational scalability (such as farm sizes).

International research and applications

The Global Seaweed Project (Oceans 2050) aims to 'harness the power of seaweed farming to mitigate climate change and restore ocean health' (86).

Researchers participating in Project Tanah Air in Singapore aim to 'advance Blue Carbon sequestration and seaweed bioremediation to aid sustainable agriculture practices to combat marine pollution, soil degradation, and climate change in Southeast Asia' (87).

Research and applications in Aotearoa New Zealand

Seaweed aquaculture is the subject of several research projects that assess its suitability for mCDR in Aotearoa New Zealand and researchers are developing protocols to quantify carbon removal.

Seaweed Sector Framework: There has been an extensive literature review of how seaweed could be used in mCDR in Aotearoa New Zealand (88); the results suggest that targeted expansion of seaweed aquaculture could contribute to climate change mitigation (70).

The Quantifying Kelp Blue Carbon project: Researchers are working in the Cook Strait to estimate natural carbon sequestration by kelp and quantify its potential role in offsetting carbon emissions (72). Difficulties with correlating kelp biomarker concentrations (environmental DNA) to carbon content in marine sediments suggest that assessments of the effectiveness of kelp in carbon sequestration require additional research (89)[11].

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11. Recent research offshore Norway has shown success with a similar approach (90).

Te whakahaumako i ngā taiaro moana
Ocean nutrient fertilisation

Ocean nutrient fertilisation is an mCDR technique that aims to sequester carbon by encouraging the growth of phytoplankton (91,92). First, a limiting nutrient[12] is added to surface waters to increase phytoplankton growth. More phytoplankton leads to higher rates of photosynthesis, which removes dissolved CO_2 and increases the transfer of carbon from the atmosphere to the surface ocean. When the phytoplankton die, some of this additional organic carbon sinks and is sequestered in the deep ocean (91,92). This mCDR technique effectively boosts the efficiency of the natural biological carbon pump.

12. A limiting nutrient is a crucial component required for an organism's growth. Many components are necessary for growth, but a limiting nutrient is the most scarce on the list, so its availability limits growth. When the concentration of a limiting nutrient is increased, growth also increases. If concentrations are increased significantly, then the nutrient may cease to be limiting because some other nutrient becomes most in-demand.

Natural events that deposit nutrients on the ocean surface, such as volcanic eruptions or ash from wildfires, have provided evidence for iron fertilisation of phytoplankton (93), and ice core studies confirm that it has happened in pre-history (94). Research in the 1990s–2000s showed that iron concentrations limit phytoplankton growth in certain ocean regions where other nutrients are readily available, such as the Southern Ocean (95,96). New Zealand researchers played important roles in this foundational work (95,96).

Pros and cons

Limited evidence of carbon sequestration: Trial iron addition experiments in high nutrient, low phytoplankton oceanic areas confirmed that phytoplankton productivity and biomass are enhanced when iron is added to surface waters (95). Indeed, some iron addition experiments resulted in large blooms exceeding 1000 km^2 that were visible in satellite images (97).

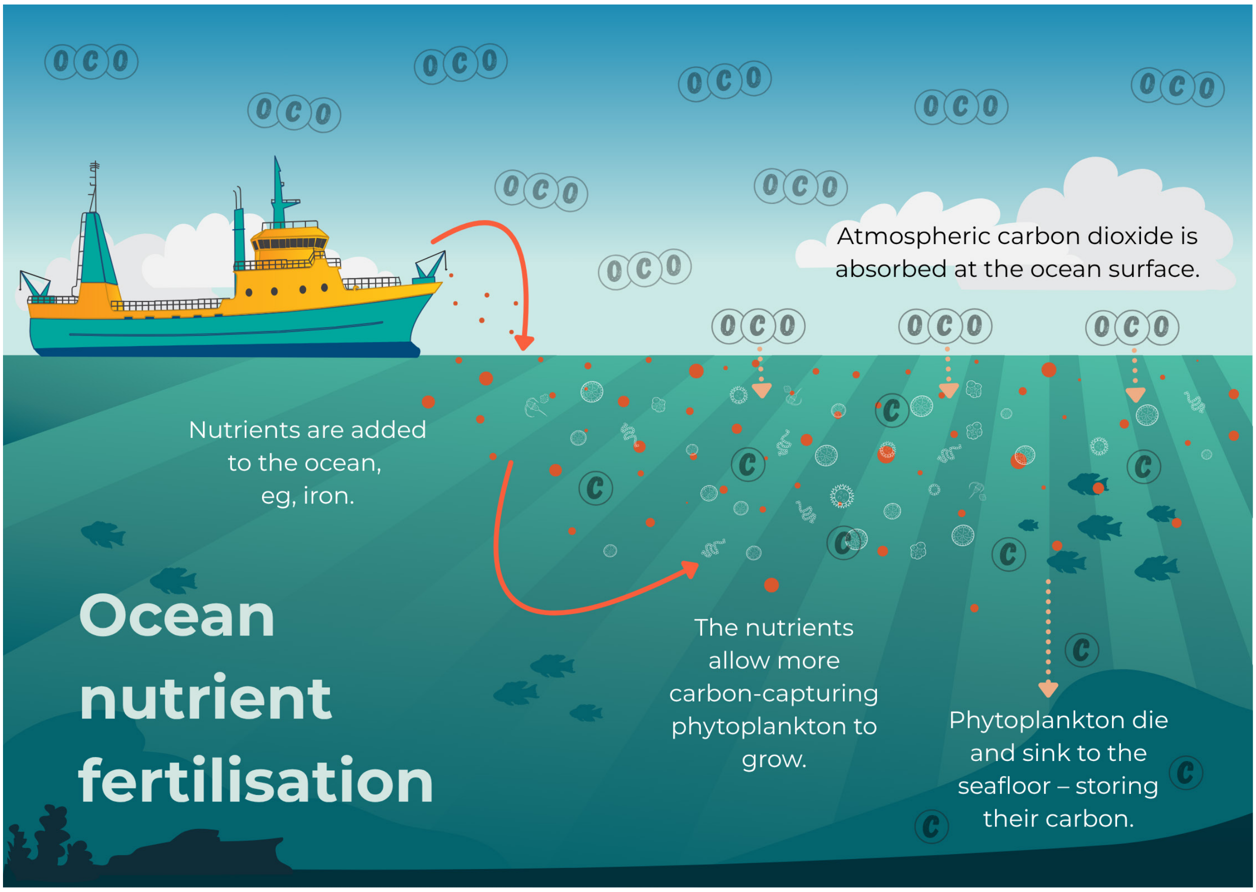

FIGURE 7 | Ocean nutrient fertilisation increases CO_2 capture by encouraging phytoplankton growth.

However, larger and longer field campaigns are needed to understand the scalability of iron and nutrient fertilisation as a viable mCDR method (97), as there is currently limited evidence of significant carbon sinking to a depth where it can be considered sequestered.

Harmful species: Most iron addition experiments found that the composition of phytoplankton changed after iron was added to the surface ocean, with larger species becoming more abundant over small cyanobacteria species, potentially impacting the food web and creating harmful algal blooms (92). One of these larger species, *Pseudo-nitzschia*, produces a harmful neurotoxin called domoic acid, so if iron addition enhanced growth of this species it could also increase the presence of this toxin (98).

Chemical side effects: There are also concerns that the decomposition of the sinking organic matter resulting from iron fertilisation could result in deoxygenation, acidification, and production of other greenhouse gases (such as nitrous oxide) in deeper waters (3). These effects have been modelled (99) but are yet to be confirmed in field trials.

Biological side effects: Ocean nutrient fertilisation may also lead to an imbalance of other nutrients in the water. The enhanced phytoplankton growth due to iron addition will take up more macronutrients such as silicate and nitrate in surface waters (91). These macronutrients may subsequently limit phytoplankton growth, regardless of iron availability, which has led to suggestions that this may minimise phytoplankton response to iron addition (91). This removal of macronutrients can also have a negative effect downstream, known as 'nutrient robbing'. Modelling of large-scale fertilisation finds there is a risk of productivity loss downstream as macronutrients that are usually transported to other regions are instead used up in the area of the iron fertilisation (100).

Cost: Ocean nutrient fertilisation is likely to be very expensive, especially for methods other than iron fertilisation, such as nitrogen or phosphorus (99).

Use of fossil fuels: Currently, most marine vessels rely heavily on fossil fuels (eg, for transportation). At present, it is unclear if the carbon release from ocean nutrient fertilisation will outweigh any carbon sequestration potential.

International research and applications

Ocean iron fertilisation has historically been a controversial idea, due to the risks outlined above (101,102). In 2008, the London Convention and Protocol, which regulates marine dumping activities on the high seas, stated that iron fertilisation projects should only be allowed if carried out for 'legitimate scientific research' (103). More recently, amendments to the London Protocol have been proposed to regulate ocean iron fertilisation, labelling it as a marine geoengineering[13] technique (108). However, the annex relating to ocean iron fertilisation has only been ratified by nine nations to date (it needs 37 to come into effect) and Aotearoa New Zealand is not a signatory (103,109).

Research and applications in Aotearoa New Zealand

Aotearoa New Zealand was the first country to conduct an *in situ* (in the field) iron fertilisation experiment in the Southern Ocean (110). This work proved the connection between iron limitation on phytoplankton production and CO_2 capture (94). Numerous countries have undertaken similar experiments in a range of different oceanic regions, with a variety of ecosystem responses and carbon sequestration outcomes (96,110,111). Despite the recognition of issues regarding the effectiveness and potential impacts of ocean iron fertilisation (102), it is being actively promoted as a potential mCDR solution (97,104).

13. Geoengineering is human-driven alteration of the climate, typically intended to counteract climate change and cool the planet (104). By some definitions, all carbon dioxide removal techniques – such as those described in this report – are classified as low-risk geoengineering (99,105).
Geoengineering is a topic of debate in climate science, politics, and the public (31,106,107); some scientists have called for international agreements banning geoengineering (101).
Deploying geoengineering techniques at effective scale is likely to be very expensive (though relatively affordable compared to the costs of climate change), logistically difficult, of questionable effectiveness, and may have severe side effects (101,107). Benefits of the technologies include rapid deployment for some of the high-risk, high-reward inventions. Lower risk CDR techniques such as afforestation on land and coastal regions will take longer to have a smaller impact and most are reversible (31).

Te whakapiki i te waipāhuatanga o te moana
Ocean alkalinity enhancement

Ocean alkalinity enhancement is an mCDR technique that captures CO_2 by altering the natural chemistry of seawater. Ocean alkalinity is a measure of the ability to neutralise acids in seawater, and increasing alkalinity converts dissolved CO_2 to bicarbonate which is stable in seawater.

Ocean alkalinity is part of the slow carbon cycle and has regulated the ocean's capacity to absorb CO_2 from the atmosphere via the weathering of rocks on land over geological timescales. Over tens of thousands of years, rocks release alkaline minerals into rivers and streams which empty into the ocean. The minerals react with water and consume hydrogen ions (H^+), raising alkalinity and pH (112). This process converts CO_2 to bicarbonate (HCO_3^-) and so lowers the CO_2 concentration in surface water and increases the transfer of CO_2 from the atmosphere to the ocean.

To enhance ocean alkalinity, naturally alkaline substances (silicate rocks, such as olivine and basalt, or carbonate rocks, such as limestone) could be mined, pulverised, and deposited as a fine dust in the surface ocean, on the seafloor or on coastal beaches. Alkalinity can also be enhanced via addition of liquid containing dissolved minerals to the ocean and by electro-chemical reactions that remove acid from seawater (113). These methods would increase the ocean's ability to sequester carbon by enhancing its chemical capacity to absorb and store atmospheric CO_2 (112).

Pros and cons

Long-term storage: Ocean alkalinity enhancement does not depend upon biological mechanisms and has lower risk of ecosystem impacts than other mCDR techniques described here (114). Bicarbonate is a stable form of dissolved inorganic carbon that can remain in the ocean for millennia with little risk of rapid re-release, giving this technique an advantage in terms of long-term carbon sequestration (112).

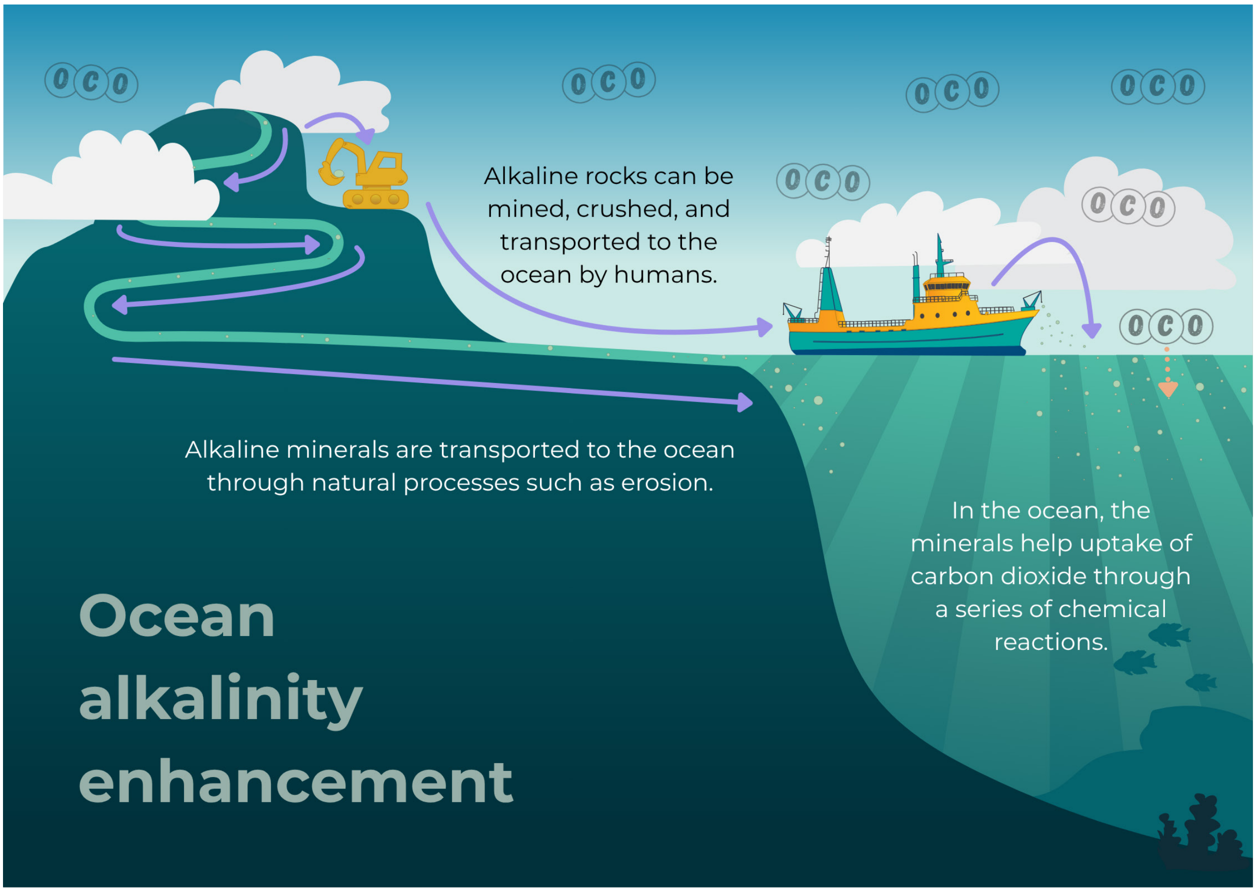

FIGURE 8 | Ocean alkalinity enhancement involves altering the chemistry of the ocean to increase its ability to uptake CO_2.

Co-benefits: Ocean alkalinity enhancement could mitigate ocean acidification and its negative ecological effects (such as dissolving calcium carbonate shells (115)), at least locally where the technique is employed (116).

Potential toxicity to and disruption of sea life: Minerals used in alkalinity enhancement may leach trace metals, such as nickel, into the water leading to toxicity to sea life (and people consuming it) (113). Other minerals may stimulate growth of some types of phytoplankton over others and change the balance of the ecosystem (112). This risk can be managed by avoiding trace metal-rich minerals or by favouring liquid alkalinity.

Potential disruption to land-based ecosystems: Mining and other forms of extraction and crushing of rocks disturb land-based ecosystems and associated biodiversity, and usually involve the use of fossil fuels in their extraction and processing (117).

Direct study needed: Most research on ocean alkalinity enhancement has been based on modelling (112,116) (although there have recently been some *in situ* deployments of alkalinity in North American waters, see below). Alkalinity is difficult to monitor because the background alkalinity in the ocean is already high. However, coastal and open ocean research findings are starting to emerge.

International research and applications

The Ocean Alkalinity Enhancement Pelagic Impact Intercomparison Project aims to develop and implement a standardised ocean alkalinity enhancement experiment with plankton communities (118). The study will be conducted worldwide to evaluate the impacts and scalability of ocean alkalinity enhancement in marine systems.

The LOC-NESS (Locking Ocean Carbon in the Northeast Shelf and Slope) project was an early mCDR field trial that has been monitoring the impacts of ocean alkalinity enhancement (using sodium hydroxide) in the North Atlantic (119–121). Engagement with Indigenous communities and commercial stakeholders helped with field site selection and constructive guidance on project design (122). The trial has been declared a success by the team, who noted that measured results correlated closely with modelling (123). Preliminary results suggest that marine life is relatively tolerant to elevated pH and alkalinity, but further investigation is needed to determine long-term effects (124).

Nearby, in Halifax Harbour, a startup company works with university collaborators to model and run an ocean alkalinity enhancement field trial (125). The site uses a magnesium hydroxide solution to add alkalinity (126), and the team studies carbon capture and potential broader impacts to the ecosystem (126–128). In 2025, the startup was issued the first carbon credits for ocean alkalinity enhancement for removing an estimated 625.6 tonnes of CO_2 from the atmosphere (129–131). However, researchers who analysed the whole life cycle of the work found that, under today's conditions, the intervention would affect little-to-no net carbon removal (and may emit net carbon), given the use of fossil fuels in the supply chain (132). They said the technique could be helpful in the future with a decarbonised energy system and careful site selection (132).

Recent coastal studies in Australia and the United States tested whether the alkalinity can be tracked, providing proof-of-concept data for small-scale release (133,134).

Research and applications in Aotearoa New Zealand

Under the programme 'Catching Marine Carbon: Testing Ocean Solutions for Climate Mitigation using Natural Analogues', researchers in Aotearoa New Zealand will undertake laboratory experiments, field surveys, and modelling to better understand the effect that ocean alkalinity enhancement, combined with direct air capture, may have on native species (135).

Researchers are also testing natural analogues for ocean alkalinity enhancement in Hawke's Bay to measure and verify carbon removal, assess environmental risk, and consider the social and regulatory frameworks that would be required before the intervention could be considered as part of national climate strategy (135). Further work on land in the area – a collaboration between researchers and Ngāti Pūkenga which trials the use of ground rocks for carbon capture on farmland (136) – may also affect the ocean via river and groundwater leaching.

To date, like most mCDR methods, ocean alkalinity enhancement is not being considered for large-scale deployment in Aotearoa New Zealand waters without further research.

Te tō ake i ngā wai o raro
Artificial upwelling

Upwelling occurs naturally when cold, nutrient-rich water rises from the deep ocean to the surface (3,35). This process is driven by wind patterns, currents, and the Earth's rotation, and typically occurs along coastlines. Upwelling brings nutrients to the surface and naturally fertilises surface waters, stimulating the growth of phytoplankton and subsequent absorption of atmospheric CO_2 through photosynthesis (3,35).

Artificial upwelling replicates and enhances nature by mechanically transferring deep water to the surface using wave-driven or pump-assisted vertical pipes. The process aims to enhance phytoplankton productivity in surface waters, and associated carbon uptake and export via the biological carbon pump (137).

Pros and cons

Limited trials: Small-scale studies of artificial upwelling in semi-enclosed bodies of water have shown promise for increasing phytoplankton concentrations (3). However, large-scale studies have yet to be conducted successfully in the open ocean.

Logistically difficult: There are significant engineering and logistical challenges to operating in the open ocean. These projects require artificial upwelling structures to withstand strong currents and storms, long deployment periods, and biofouling, while overcoming complicating factors such as running energy requirements and maintenance (3).

Uncertain composition: In addition to the largely unknown ecological effects of pumping cold water to the sea surface, this upwelled water is likely to be older than surface waters and therefore rich in dissolved CO_2 (137), which could lead to the release of carbon back into the atmosphere and offset any sequestration gains.

Research and applications

Recent studies (138–140) suggest that artificial upwelling is likely to be ineffective as an mCDR technique because it is an oversimplification of complex ocean processes.

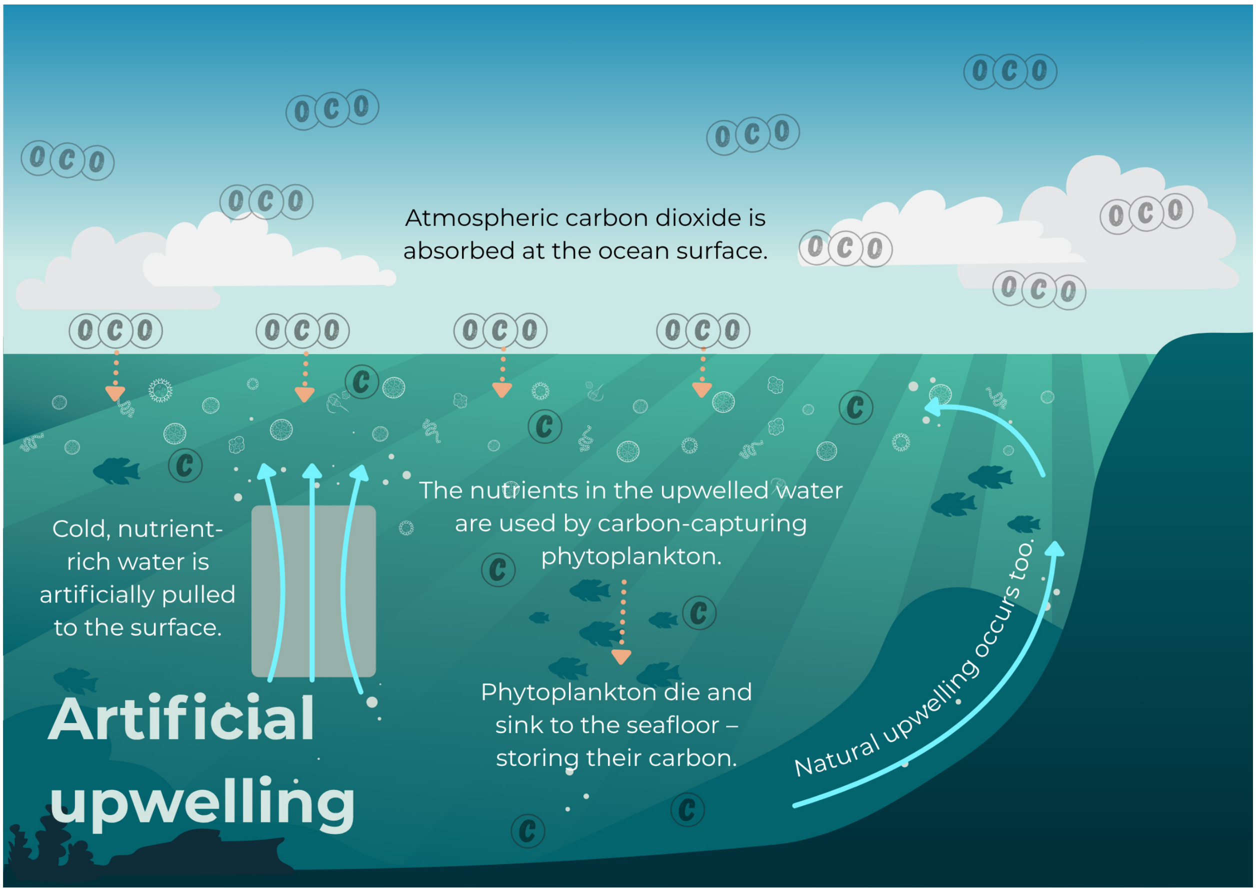

FIGURE 9 | Artificial upwelling involves pumping nutrient-rich water from the bottom of the ocean to the surface to stimulate phytoplankton growth.

Ētahi atu tikanga
Other techniques

Several other mCDR techniques are also being explored globally (141,142), either as stand-alone approaches or in conjunction with other techniques, though these have so far received less attention, and their potential ecological impacts have not been thoroughly investigated. Two examples are:

- **Terrestrial biomass sequestration** involves sinking organic matter (such as woodchips, crop residues, or hay) into the deep ocean (143). This approach aims to sequester carbon by isolating slowly decomposing biomass at depth, where its carbon would be less likely to return to the atmosphere. A test deployment of this technique involved the dumping of wood chips off the coast of Iceland (143), which drew significant controversy regarding the lack of oversight and verification, ultimately leading to the demise of the company responsible (144).
- **Subseafloor injection** entails pumping captured liquid CO_2 into disused oil and gas reservoirs or seabed basalt rock layers (3,145). These sites can potentially store carbon securely for millennia and allow for long-term monitoring of storage integrity. Norway has been a leader in this field since the late 1990s, with various depleted oil and gas reservoirs and drill sites used for subsea carbon capture and storage (146). Such methods can also be employed on land.

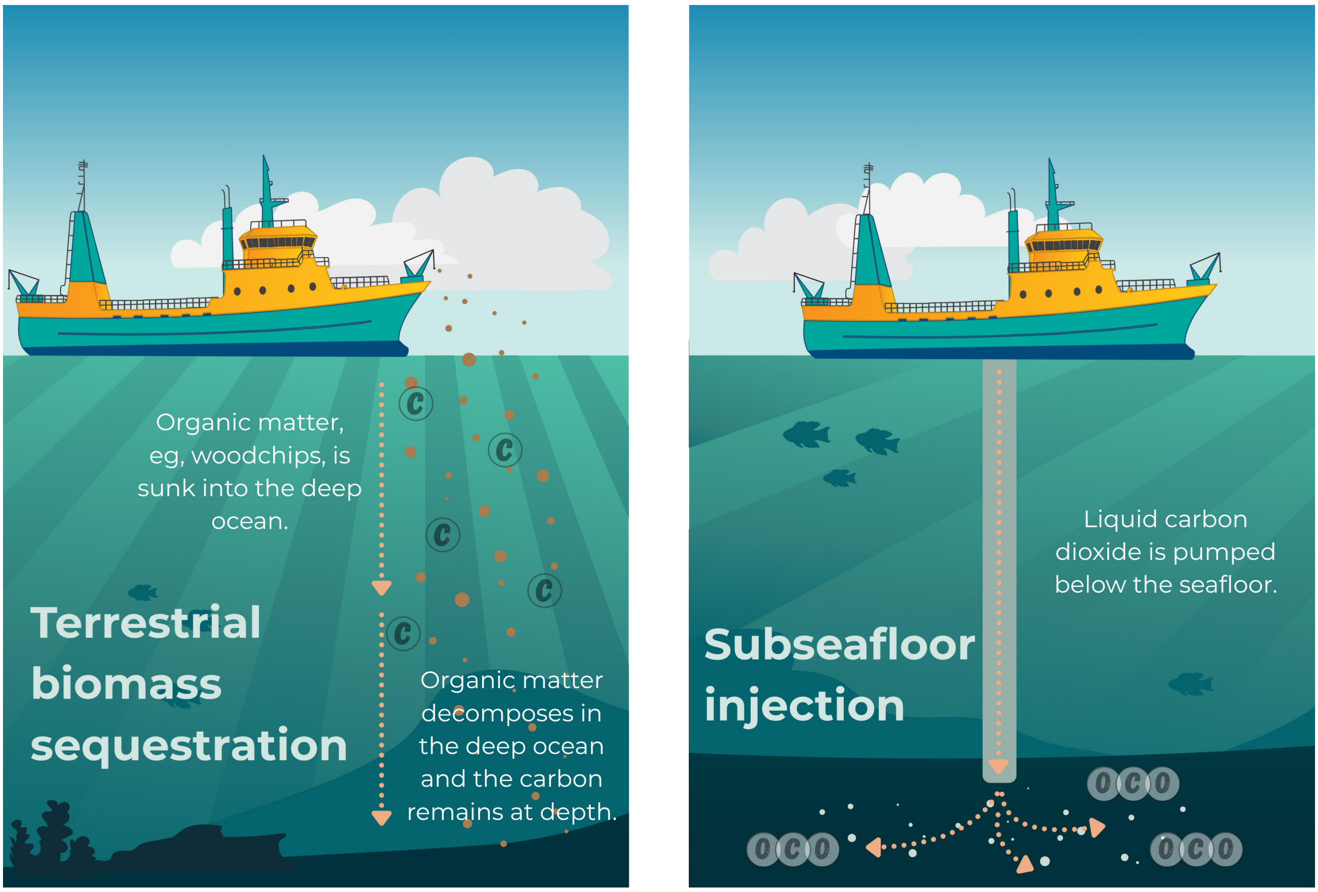

FIGURE 10 | Terrestrial biomass sequestration (left) and subseafloor injection (right) are two more mCDR methods.

Te unu a te moana i te hauhā i Aotearoa
Marine carbon dioxide removal in Aotearoa New Zealand

As of 2026, Aotearoa New Zealand's activities to remove CO_2 from the atmosphere focus heavily on forestry (sequestering in the terrestrial carbon sink) (24). New Zealand's Second Emissions Reduction Plan (2026–2030), however, highlights the potential of mCDR methods, which are identified as nature-based solutions (34).

In Aotearoa New Zealand, many communities have a strong cultural connection to the ocean, including Māori and Pacific communities. Te Tiriti o Waitangi will be an important consideration for any development of mCDR in Aotearoa New Zealand, regardless of scale (147). Our oceans are valued as a source of food, and habitat for taonga (treasured) and precious native species. They are used for a wide variety of customary and commercial uses, and are valued sites for recreation and tourism.

mCDR could present economic opportunities for coastal settlements, particularly if local communities are involved as partners, leaders or investors in project design and development, research, and monitoring (148–151). Positive outcomes could include job creation and community resilience (150). Economic risks could also arise if projects fail or damage the marine environment, directly affecting livelihoods associated with tourism, aquaculture, and fishing, or if economic benefits are not equitably distributed among the communities involved (148,150).

Despite the cultural and economic importance of our oceans, there is currently minimal regulation for mCDR activities (32). Aotearoa New Zealand, together with our Pacific neighbours, will need to establish appropriate regulations and governance that respond to and protect our unique environments and cultures ahead of any adoption of mCDR. Any potential mCDR technique would require more research, effective monitoring and verification, and in-depth societal discussions before considering large-scale use (141).

Currently, mCDR is a collection of developing technologies that are not yet ready for large-scale deployment.

Further investigation of mCDR should span technical feasibility, carbon sequestration potential, and ecological suitability and risks. Quantification of carbon removal rates must also be weighed against the full lifecycle of any technique, including carbon released during production, transport, and monitoring (32). Furthermore, research could consider how new technologies align with te ao Māori (see below) and diverse community values, legal frameworks, and community aspirations (62,152).

Te unu a te moana i te hauhā me te ao Māori
Marine carbon dioxide removal and te ao Māori

While our oceans and coastal environment are important to all of Aotearoa New Zealand, Māori have particular interests in respect of these environments. As the indigenous people of Aotearoa New Zealand, Māori have a deep, evolving relationship with land, sea, and sky (152,153). This relationship is founded in whakapapa (genealogy), kaitiakitanga, and a worldview that sees people and the environment as intrinsically connected (153). The moana (ocean) is not a mere resource for Māori, but a living being, an ancestor.

Mātauranga (knowledge and experience) of the ocean has been collated over millennia of existence in Aotearoa and across Polynesia (152,154,155). mCDR initiatives stand to benefit by gaining the support and guidance of local communities (32,152). Any mCDR intervention that alters the chemistry, biology, or physical state of the ocean could be seen as an intrusion upon a tupuna (ancestor) raising fundamental questions about consent, respect, and the exercise of tino rangatiratanga (sovereignty, self-determination). If mCDR projects do not include Māori participation and benefit sharing, initiatives could risk repeating historical patterns of exclusion and dispossession, leading to confrontation and legal challenge (62).

It is important for mCDR initiatives in Aotearoa New Zealand to consider Te Tiriti o Waitangi principles of partnership, participation and protection (62,147,156). This means early, meaningful engagement with iwi and hapū (62), and respect and provision for Māori rights and interests – including customary marine title and access to mahinga kai (customary gathering of seafood) (62) – and the co-development of mCDR research and monitoring frameworks (32,62).

Māori rights are also protected by the United Nations Declaration on the Rights of Indigenous Peoples (157), which supports the need for Māori to give free, prior and informed consent for projects affecting their rohe moana (customary domains). Such consent requires full information, adequate time for deliberation, and genuine power to say 'no' (157) or to shape outcomes in alignment with their mātauranga, tikanga (protocols), and aspirations.

Māori also have intergenerational kaitiakitanga over the environment for present and future generations (62,158,159) and have a strong interest in rigorous assessment of potential mCDR interventions' impacts and efficacy (32).

mCDR interventions, especially at a large scale, carry scientific uncertainties and potential for unintended consequences. If used irresponsibly or with insufficient risk analysis, mCDR could lead to changes in nutrient flows, disruption of food webs, or chemical imbalances in the moana. Such risks could threaten mahinga kai, taonga species (treasured species), and the mauri (life sustaining quality) of the ocean along with the significant commercial Māori interests in seafood.

On the other hand, if iwi and hapū are involved from the outset, local mCDR projects could support Māori interests in the protection of coastal and marine environments. Successful interventions, such as coastal blue carbon, would help protect oceans and beaches from the adverse effects of climate change such as sea level rise, acidification, warming, and loss of fishing stock and biodiversity. This would align with Māori aspirations to sustain healthy ecosystems for future generations.

Māori-centric approaches can be both innovative and deeply sustainable (88). Done with care and with the leadership or partnership of Māori, mCDR could support Māori kaitiakitanga and innovation in the face of climate change. Done poorly, it could deepen inequities and harm the interconnected fabric of people and ocean. As Aotearoa considers these new frontiers, including Māori voices and values in decision-making is key to a sustainable, resilient future.

He aha kei tua?
What's next?

The widespread negative effects of human-caused climate change are worsening (27) and, according to the Intergovernmental Panel on Climate Change, CO_2 levels are on track to exceed the Paris Agreement's goal of limiting warming to 1.5°C (27).

Carbon emissions need to reduce to constrain global warming (4), but some hard-to-reduce emissions such as those arising from cement production, aviation fuel, and other industries are expected to take a long time to drop. The Intergovernmental Panel on Climate Change states that CDR will be necessary to reach net zero greenhouse gas emissions (27). In this context, marine carbon dioxide removal may be a future tool to help reduce atmospheric carbon levels. However, the scientific basis for this approach is still being established (3,32). For all of the techniques discussed in this report, further research, and robust measurement and verification (which are very difficult in open ocean environments and need to include all emissions across the lifecycle of each technique), are needed to verify whether they can make a significant contribution to reducing atmospheric CO_2.

A 2026 independent report on the state of carbon dioxide removal (CDR), authored by a group of influential researchers (26), advocated for decisive action on CO_2 removal. It declared that:

- Greenhouse gas emission reductions and CDR are both required to meet global targets.
- Current country carbon pledges are not enough to meet the agreed targets.
- Conventional CDR techniques (mostly involving forests and soils) make up 99.9 percent of current CO_2 removals, but are not enough. Novel approaches, such as mCDR, would need to advance rapidly (but still undergo robust validation) to make a difference.
- CDR interventions need to be diversified, not concentrated to a few well-funded initiatives and locations.
- 2026–2030 is a crucial time to deploy CDR interventions in order to limit the greatest impacts of climate change (26).

In Aotearoa New Zealand, we will need to consider whether any of these approaches will be appropriate for our unique cultural and environmental context (32). Achieving this will require research, inclusive engagement with communities, and partnership with and leadership by Māori to understand the direct and indirect implications of mCDR (62,160).

As new carbon removal initiatives appear, we will need to have informed national discussions about mCDR, including consideration of the governance and regulation of potential approaches (32,101,148,152,160–169).

mCDR techniques have unique social, environmental, and economic consequences – some beneficial and some detrimental – and it is important that our communities are able to make informed decisions about whether these approaches could or should contribute to our climate response in Aotearoa New Zealand.

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- Cliff Law also receives funding from MBIE for a Smart Idea on Ocean Alkalinity Enhancement.
- Tim Naish chairs the Joint Scientific Committee of the World Climate Research Programme.

Claude AI (Sonnet 4.6) was used during proofing; suggestions were approved and incorporated by humans. AI was not used for research, writing, or figure development.

Ngā tohutoro
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