Exploring the intersection of coastal blue carbon and ocean acidification: A synthesis of biogeochemical processes, coastal management strategies, knowledge gaps, and future research opportunities

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ABSTRACT

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Blue carbon ecosystems (BCE) provide carbon storage and sequestration services that deliver global and local outcomes for carbon cycling spanning geologic time. Ocean acidification (OA) is the process of decreasing pH in the ocean that results from the adsorption of anthropogenic carbon dioxide (CO_2) from the atmosphere. The recent focus on quantifying and understanding the mechanisms whereby BCEs capture or release atmospheric CO_2 has spurred interest in also understanding how these systems, both naturally and via management, may contribute to OA mitigation. This report explores the intersection of coastal blue carbon and ocean acidification (i.e., OA-BC nexus). We conducted a joint DFO-NOAA technical meeting to synthesize knowledge of the biogeochemical processes and coastal management strategies that impact the OA-BC nexus, and discuss knowledge gaps, including potential effects of climate change on the nexus, and outline future research opportunities. We focused on BCEs that Canada and USA have in common (i.e., tidal marshes, macroalgal forests, and seagrass beds) and outlined the production, consumption, and exchange of carbon and alkalinity between BCEs and their adjacent estuarine and coastal aquatic ecosystems. An expert assessment of the contribution of BCE management strategies (i.e., conservation, restoration, creation, and enhancement) to enhance OA mitigation locally revealed variable results and knowledge gaps. We concluded that conservation of focal BCEs was the most likely management strategy to positively mitigate local coastal acidification. Numerous natural and human activities affect BCE structure, function, and areal extent, but our predictive understanding of how such changes might affect coastal acidification is rudimentary. More detailed thought experiments are needed to identify ways to collaborate further across the OA-BC nexus. While it may not be possible to merge blue carbon and ocean acidification science entirely, this report provides a starting point to continue working together.

RESUME

Hunter, K.L., Poach, M., Howe, J., Hopkinson, C., Wang, Z.A., Krumhansl, K., Burgers, T., and Meseck, S. 2025. Exploring the intersection of coastal blue carbon and ocean acidification: A synthesis of biogeochemical processes, coastal management strategies, knowledge gaps, and future research opportunities. Can. Tech. Rep. Fish. Aquat. Sci. 3730: vi + 30 p. https://doi.org/10.60825/zx02-r335

Les écosystèmes à carbone bleu (BCE) fournissent des services de stockage et de séquestration du carbone qui ont des répercussions mondiales et locales sur le cycle du carbone à l'échelle géologique. L'acidification des océans (AO) est le processus de diminution du pH dans les océans qui résulte de l'adsorption du dioxyde de carbone (CO_2) anthropique présent dans l'atmosphère. L'intérêt récent pour la quantification et la compréhension des mécanismes par lesquels les BCE capturent ou libèrent le CO2 atmosphérique a suscité un intérêt pour comprendre comment ces systèmes, tant naturellement que par le biais de la gestion, peuvent contribuer à l'atténuation de l'AO. Ce rapport explore l'intersection entre le carbone bleu côtier et l'acidification des océans (c'est-à-dire le lien AO-BC). Nous avons organisé une réunion technique conjointe entre le MPO et la NOAA afin de synthétiser les connaissances relatives aux processus biogéochimiques et aux stratégies de gestion côtière influençant le lien entre l'AO et le BC, de discuter des lacunes dans les connaissances, y compris les effets potentiels du changement climatique sur ce lien, et de définir les possibilités de recherche futures. Nous nous sommes concentrés sur les BCE communs au Canada et aux États-Unis (c'est-à-dire les marais littoraux, les forêts de macroalgues et les herbiers marins) et avons décrit la production, la consommation et l'échange de carbone et d'alcalinité entre les BCE et leurs écosystèmes aquatiques estuariens et côtiers adjacents. Une évaluation d'experts portant sur la contribution des stratégies de gestion des BCE (c'est-à-dire la conservation, la restauration, la création et l'amélioration) à l'atténuation locale de l'AO a révélé des résultats variables et des lacunes dans les connaissances. Nous avons conclu que la conservation des BCE ciblés était la stratégie de gestion la plus susceptible de contribuer à l'atténuation de l'acidification côtière locale. De nombreuses activités naturelles et humaines affectent la structure, la fonction et l'étendue des BCE, mais notre compréhension prédictive de la manière dont ces changements pourraient affecter l'acidification côtière rest rudimentaire. Des expériences de réflexion plus détaillées sont nécessaires pour identifier des moyens de collaboration supplémentaires dans le cadre du lien entre l'acidification des océans et les BCE. Bien qu'il ne soit peut-être pas possible de fusionner entièrement la science du carbone bleu et celle de l'acidification des océans, ce rapport constitue un point de départ pour continuer à travailler ensemble.

TABLES

1 Introduction

Human-derived atmospheric carbon dioxide (CO_2) is absorbed by the ocean where it causes the pH of surface waters to decrease. This phenomenon is referred to as Ocean Acidification (OA). Each year the global ocean absorbs roughly one fourth of atmospheric CO_2 emissions (Friedlingstein et al. 2024), while emissions continue to rise globally (Gruber et al. 2023). Since the industrial revolution, the pH of the surface ocean has decreased by approximately 0.1 pH units, which corresponds to a 30% increase in acidity (Cooley et al. 2022). Consequences of OA on oceans include effects on marine organisms such as reduced growth, survival, and calcification for a wide variety of shell-forming species (Fabry et al. 2008; Pörtner et al. 2008; Doney et al. 2009; Kroeker et al. 2013). Considerable effects of OA on shellfish aquaculture production and economic outputs have already been documented in Northwest USA (Barton et al. 2015; NMFS 2022).

Blue carbon ecosystems (BCEs) are coastal ecosystems where organic carbon (OC) burial and production of dissolved organic carbon (DOC) is substantially greater than most ecosystems of the biosphere. Globally, the existing stock of BCEs offer significant natural carbon storage and sequestration (235-480 Tg C/yr; Macreadie et al. 2021). However, the atmospheric carbon they naturally offset is declining as BCEs continue to disappear globally, thereby reducing the potential for added natural absorptive effects (Nellemann et al. 2010; Macreadie et al. 2021). Though amplifying management strategies such as restoration and enhancement of BCEs may only minimally offset global atmospheric CO_2 emissions (Johannessen and Christian 2023), in combination with natural processes and carbon dynamics driven by BCEs, management strategies may provide localized mitigative effects of coastal acidification (i.e. ocean acidification in coastal areas; Garrard et al. 2014; Wang et al. 2016; Fakhraee et al. 2023). To better understand the local effects of BCE carbon cycling on coastal acidification, knowledge of how BCE processes including exports of carbon and other materials (i.e., outwelling; Teal 1962; Odum 1968; Hopkinson 1988; Wang and Cai 2004,) interact with ocean chemistry and the variability of these interactions is required.

The role of BCEs in coastal carbon cycling is driven by complex biogeochemistry including the transport of carbon compounds away from the coast and into the ocean. BCEs influence local and regional ocean chemistry through carbon flux by altering carbon, alkalinity, and nutrient concentrations as well as CO_2 equilibria. For instance, microbial processes within the sediments of tidal marshes, mangroves, and seagrass beds drive the production of dissolved inorganic carbon (DIC) and alkalinity followed by their tidal or lateral exports into adjacent coastal waters (Wang and Cai 2004; Sippo et al. 2016; Wang et al. 2016; Santos et al. 2021). These exports can significantly contribute to the carbonate chemistry in nearby coastal waters and may provide a source of buffering against coastal acidification by enhancing the seawater's capacity to neutralize acidity (Wang et al. 2016). Moreover, BCEs including macroalgal forests can directly affect coastal waters' pH and carbonate chemistry. For example, during photosynthesis, seagrasses and macroalgae absorb CO_2, reducing coastal acidity and potentially providing temporary refuges for marine organisms vulnerable to acidification (Edworthy et al. 2023). However, the extent of these benefits depends on factors such as water residence time, ecosystem health, and external stressors like nutrient runoff or temperature changes. Drivers of OA and the proclivity for BCEs to interact with and potentially mitigate coastal acidification have yet to be thoroughly investigated (Reithmaier et al. 2023; Wang and Cai 2025), but existing studies offer a good foundation for the next steps in research.

Addressing scientific and coastal management concerns requires identifying knowledge gaps and research priorities for the OA-blue carbon (OA-BC) nexus. Future research guided by these priorities could inform best practices and coastal management decisions that aim to reduce the effects of coastal acidification on BCEs. This report summarises a set of structured discussions undertaken by OA and BC experts from Canada and the United States to assess and synthesize the current knowledge at the intersection of OA and BC in coastal environments, focusing on their combined role in mitigating the effects of OA on ocean chemistry and marine ecosystems. Four themes were explored in a technical meeting to arrive at an understanding of knowledge gaps and research questions linked to each theme:

1. BCE processes and their linkage to coastal acidification;
2. BCE management effects on the coastal acidification mitigation potential of BCEs;
3. Other environmental conditions (high temperature, low oxygen) effects on coastal acidification mitigation potential of BCEs; and,
4. Knowledge gaps and research opportunities.

This report presents a review and synthesis of current knowledge, knowledge gaps, and the next steps associated with these themes to provide a foundation for strategic research actions that could expand shared knowledge and potential benefits of BCEs for acidification mitigation in BCEs present in Canada and USA. This report does not examine whether or not coastal acidification dynamics may affect BCE capacity to absorb, store and export carbon.

1.1 Technical Meeting

Fisheries and Oceans Canada (DFO) and the United States National Oceanic and Atmospheric Administration (NOAA) created a formal collaboration on ocean acidification to coordinate efforts in ocean acidification monitoring, research, modelling, and experimentation, and to support data and information sharing between DFO and NOAA’s Ocean Acidification Programs. The DFO-NOAA OA Collaboration funds research of interest to both countries, focusing on transboundary areas where applicable, including the workshop detailed in this report. Results are intended to enhance ocean reporting processes, inform resource managers of the state and extent of ocean acidification, and further develop adaptation tools to inform decisions related to fisheries and ocean management (DFO/NOAA 2017).

In 2024, the DFO-NOAA OA Collaboration Steering Committee proposed a collaborative project to evaluate the current state of knowledge and prospective directions for research at the interface of blue carbon and OA in coastal ecosystems common to both nations (Appendix 1). This project’s main activity was to convene a technical meeting of experts from Canada and USA to: 1) synthesize the state of the science of cycling and/or exchange of organic and inorganic carbon and alkalinity in BCEs that can alter seawater pH; 2) discuss anticipated connections between BCEs and coastal acidification under future climate conditions; and 3) identify gaps in knowledge and collaborative science activities. The technical meeting was organized and delivered in November 2024, with 26 participants attending three consecutive half-day sessions focused on the OA-BC nexus (Appendix 2).

Based on the interests of the DFO-NOAA OA Collaboration, the technical meeting focused on BCEs of relevance to both Canada and the US. Therefore, meeting discussions about the OA-BC nexus focused mainly on tidal marshes, seagrass beds, and macroalgal forests. First, participants shared their knowledge of the connections between BCEs and OA by highlighting how these systems interact within coastal waters to influence carbon cycling, carbon content, pH, and buffering capacity. These discussions aimed to understand how BCE natural carbon cycling and the transfer of carbon offshore affects seawater pH and buffering capacity to either alleviate or exacerbate the effects of coastal acidification. The next discussions explored whether management strategies applied in BCEs may mitigate coastal acidification. Management strategies included conservation, restoration, creation, and enhancement. Following this, discussions explored plausible effects of changing environmental conditions (present and future) on OA-BC processes and the potential to affect any existing mitigation potential of BCEs. Lastly, knowledge gaps and research questions generated throughout the meeting discussions were assembled and reviewed by participants. This technical meeting promoted discussion around potential future research leveraging this combined set of expertise via the DFO-NOAA OA Collaboration or otherwise. The following sections of this report outline the OA-BC nexus meeting discussions in combination with a literature review to arrive at a set of knowledge gaps and next steps for this research community.

2 Ocean Acidification - Blue Carbon Nexus

Initial nexus discussions focused on identifying important biogeochemical processes linking BCEs to coastal acidification. Aquatic environmental processes that either contribute to or remove OC and DIC hydrogen ions (‘acidifying’) and alkalinity (‘de-acidifying’) were discussed. We grouped processes into three categories: sediment transformation, chemical transport/exchange, and within water column transformation (Table 1).

Sediment transformation processes in BCEs relevant to this report mainly involve organic matter production (via photosynthesis) and oxidation (via microbial aerobic and anaerobic respiration). Photosynthesis removes CO_2 from the atmosphere and converts it to OC. Some of this carbon ultimately forms particulate organic carbon (POC) in the sediment and dissolved organic carbon (DOC) in sediment porewater. Aerobic and anaerobic respiration convert OC in the sediment back to CO_2. When these processes occur in waterlogged sediments, the resultant CO_2 will produce DIC in sediment porewater. In addition to DIC, anaerobic respiration, such as sulphate reduction coupled with pyrite formation and storage, produces net gains of alkalinity (Giblin et al. 1990; Wang and Cai 2004). Alkalinity refers to the capacity of water to neutralize acids, primarily due to the presence of carbonate (CO_3^{-2})

ions that act as buffers that resist changes in pH (e.g. sediment transformation processes are known to maintain a neutral pH in tidal marshes).

Water flow and tidal action result in the exchange of carbon and alkalinity from the sediment to the overlying water column which can then be transported to adjacent estuarine and shelf waters (i.e. lateral export) and the open ocean (i.e. offshore export). To date, blue carbon science has mostly focused on atmospheric carbon removal and long-term carbon storage in BCE sediments via burial. Recent studies have extended blue carbon science to consider the transfer of carbon between adjacent systems and its potential storage in the long residence time of oceanic waters (Santos et al. 2021; Wang and Cai 2025). OC export from wetland systems has been a popular topic of interest in the coastal ecosystem community ever since Teal's first carbon budget of a salt marsh (1962). Odum popularized the concept known as outwelling, which hypothesized that OC not stored or metabolized within the marsh itself was exported to adjacent estuarine and shelf waters where it subsidized local fisheries through a detrital food web (Darnell 1967; Odum et al. 1979; Odum 1980). Numerous studies show that tidal wetlands tend to export POC and DOC, while the fate of that material is still debated (Nixon 1980; Hopkinson 1988; Childers et al. 2000; Santos et al. 2021). Only in recent decades have efforts been made toward determining the export of DIC and alkalinity from BCEs (Raymond et al., 2000; Neubauer and Anderson 2003; Raymond and Hopkinson 2003; Wang and Cai 2004; Reithmaier et al. 2023). A series of studies show that DIC lateral export can be significantly larger than DOC regionally and globally (Wang and Cai 2004; Sippo et al. 2016; Wang et al. 2016; Wang et al. 2018, Bogard et al. 2020; Santos et al. 2021; Alongi 2022). BCEs may therefore not maintain alkalinity that is produced via sediment transformation processes as transport processes can move it away from the local system.

Within water column transformations include photosynthesis and respiration, OC photooxidation, outgassing/degassing of CO_2, and alkalinity consumption. These processes can affect seawater buffering capacity by consuming or producing CO_2 and alkalinity, thereby changing the DIC to total alkalinity ratio (DIC:TA) within the coastal ecosystem (Hirsh et al. 2020; Young et al. 2022). All submerged aquatic plants will remove CO_2 directly from the water during daylight hours resulting in a localized decrease in DIC and concomitant increase in pH. The opposite trend will occur during the night when plants only respire. POC and DOC are also produced by submerged macrophytes and are released into the water column where it can be exported to adjacent nearshore ecosystems or offshore to the shelf or deep sea (Filbee-Dexter et al. 2024a). The DOC and POC produced within macroalgal and seagrass communities or from lateral export can be converted to CO_2 through respiration or photooxidation. Whereas sediment transformation processes produce alkalinity, oxidation processes in the water column will consume that alkalinity (Middelburg et al. 2020). Overall, knowledge gaps for transformation of carbon within the water column remain large.

Technical meeting participants indicated that the probability of BCEs reversing OA on a global scale was low, and also that it would be challenging to distinguish between anthropogenic carbon and natural carbon within BCEs; however, BCEs could mitigate OA on a local scale. As the magnitude and even direction of OC and IC pathways vary from one coastal system to another, the local, small-scale dynamics may outweigh any larger-scale effect of BCE effects on OA. For salt marshes, their effect on coastal acidification will depend on the amount of OC and IC carbon and alkalinity exported, the amount of OC remineralized offshore, and the amount of DIC exported that is returned to the atmosphere, especially in shelves supersaturated already with CO_2. While sufficient data exist that quantify BCE carbon export and transport from a few coastal marshes, data from most BCEs is limited and only a handful of models assess lateral fluxes (Filbee-Dexter et al. 2024a). In discussions on carbon export from the sediment, the DIC:TA was mentioned as a useful parameter to understand the effect of lateral export on coastal acidification. The contribution of organic alkalinity was also discussed. Alkalinity from organic acids, referred to as organic alkalinity, is not well quantified and may be an important contributor to exported alkalinity. For marsh and seagrass systems that export alkalinity, the DIC:TA will determine if the BCE has a mitigating or exacerbating effect on coastal acidification. Seagrasses and macroalgae directly affect water column CO_2 through photosynthesis and respiration. Mitigating effects on coastal acidification can be expected in systems where net production exceeds respiration. Exporting POC and DOC from macroalgae to nearshore seagrass beds, salt marshes, bare sediments, and the shelf/open ocean was also emphasized as a key process that will have an effect on OA. Consideration of how carbon stored as POC moves through a system (i.e., the fate of sloughed debris) to affect DIC:TA locally and estimating how much biomass from BCEs is ultimately buried both locally and offshore is key to estimating the overall effect of macrophytes on OA.

Based on current knowledge and best professional judgment, participants were asked to rank (low, medium, high) the potential for each aquatic environmental process to reduce coastal acidification in different BCEs (Table 1). We created this table to summarize expert opinion on whether there was potential for any of these processes to affect OA within each BCE type. There is such high variability among BCE sites that it is not possible to summarize positive or negative effects at this time.

Table 1. Potential for primary carbon cycling pathways and processes to affect coastal acidification in four types of blue carbon ecosystems ranked by expert opinion as high, medium or low. The effect of each pathway or process may be a net positive or negative depending on variability within each blue carbon ecosystem site and type. ND = No data.

Blue Carbon Ecosystem	Sediment Transformations			Chemical Export/Transport		Within Water Column Transformations				
	Organic Production	Aerobic Oxidation	Anaerobic Oxidation	Lateral Export	Offshore Export	Photo-Synthesis	Respira-tion	Photo-Oxidation	Out-gassing	Alkalinity consumption
Salt marsh	High	Low	High	High	Low	Low	Low	Low	ND	ND
Seagrass	High	High	Low/ Medium	Medium	Medium	High	High	Low	ND	ND
Macro-algae (high energy)	Low	Low	Low	High	High	High	High	Low	ND	ND
Macro-algae (low energy)	Medium	Medium	Medium	Medium	Medium	High	High	Low	ND	ND

2.1 Knowledge and methodological gaps relating to Ocean Acidification - Blue Carbon processes

Closing gaps in the carbon budget of BCEs, especially carbon and alkalinity flux and their fate, is critical to assess the overall potential of BCEs to mitigate coastal acidification. Various ecosystem components (e.g., grasses, sediment microbial community, phytoplankton, etc.) can alter the local carbon system differently, depending on their dominant biogeochemical processes (e.g., primary production, respiration, iron or sulphate reduction, etc.), yet the specific effect of these processes on the buffering capacity of aquatic systems associated with the various BCEs remains unclear. More research and data are needed on the lateral flux of DIC and alkalinity, especially the contribution of organic alkalinity as these dynamics could affect seawater buffering capacities significantly. Another critical knowledge gap lies in determining chemical stability and sensitivity of BCEs, i.e. how labile, semi-labile, or refractory the OC is in these systems, as molecular structure and interactions with minerals in BCEs remain poorly understood. Spivak et al. (2019) suggested that to understand OC decomposition dynamics, study is needed of both daily and seasonal carbon cycles to more accurately determine the signals and capacities of each BCE biological component over both short- and long-term scales.

There are a number of challenges that further complicate our understanding of carbon processes and dynamics of BCEs:

- Methodological challenges: Elements that can reduce complication include 1) use of measurement standards that can quantify various carbon pools to highlight inconsistent results across study approaches, 2) comparative studies of various sampling and analytical methods to offer insights into discrepancies and inform best practices for these studies, and 3) consideration of sampling regimes as short-term sampling may not provide reliable extrapolation for system-wide data, emphasizing a need for longer-term and high-frequency sampling.
- Measurement scale: Existing bias of measurement scales, particularly over seasonal and annual cycles, needs further exploration. Carbon isotopes ^{14}C and ^{13}C may help unravel various OC and IC sources, transport pathways, and sinks in coastal waters (see e.g., Raymond and Hopkinson 2003). Limited accessibility to high-frequency tools also hinders the integration of marsh processes, while the effect of measurement scales, particularly over seasonal and annual cycles, needs further exploration. The quantification of CO_2 air-sea fluxes in tidal wetlands is incomplete as we lack knowledge of the effect of swamp and marsh plant canopies. For example, the surface area of water exposed to the atmosphere swells 2-5X when water rises out of tidal creeks and bays and spreads out onto wetland sediment platforms (Wang et al. 2018).
- Anthropogenic influences on marine ecosystems: Quantifying the uptake of anthropogenic carbon within BCEs and differentiating its source remains a challenge. Simplifying the analysis through modelling and scenario-building may help clarify interactions between anthropogenic signals and wetland carbon exports. Moreover, the potential export of anthropogenic carbon from wetlands to the shelf and its historical trends are debated, with recent research suggesting minimal long-term increases. Understanding these dynamics is critical to understanding the effects of blue carbon on coastal acidification, especially when multiple changes, such as rising temperatures, freshwater fluxes, and sea-level rise, are occurring on biogeochemical processes within BCEs at the same time. Considering the ^{14}C signal of CO_2 emitted from fossil fuel combustion, the use of natural abundance radioisotopes may help us better define anthropogenic carbon contributed to BCEs (Bauer et al. 1998; 2001).
- Research collaboration: Collaboration between the ocean acidification and blue carbon research communities could enhance our understanding of marine carbon dioxide removal (mCDR) and alkalinity exports. While not the focus of this report, important knowledge gaps include how coastal acidification affects kelp and seagrass growth and the differences in carbon and alkalinity exports between intermittently submerged ecosystems (e.g., salt marshes, mangroves) and always-submerged systems (e.g., kelp forests, seagrasses). Mesocosm studies that quantify exports of DIC and alkalinity could foster collaboration and improve the quantification of ecosystem exports.

3 Blue Carbon Ecosystem Management Strategies and Mitigation of Ocean Acidification

Ecosystem services provided by BCEs, including storage and sequestration of CO_2, are recognized as being globally important and are a focus of conservation and management efforts (Costanza et al. 1997; 2021). There are numerous management strategies that can be employed in BCEs to enhance carbon sequestration, alkalinity production and/or export, and remove carbon dioxide from the water column and potentially decrease local acidity. Here, we consider conservation, restoration, creation and enhancement.

Blue carbon ecosystem processes described in Section 2 reflect the natural state of systems that have supported human activity over millennia. Under industrialization, coastlines have shifted from natural states under coastal development, and as new problems like OA emerge. For tidal marshes along the eastern coast of North America, there are very few areas untouched by the mosquito-ditching campaigns of the 1930s (Corman et al. 2012). Today, coastal activities, including shoreline armouring (e.g., seawalls, breakwaters) to evade erosion, contribute to altered natural coastal processes (Dugan et al. 2008; 2012; 2018). Locating, mapping, and studying reference sites (i.e., site is as natural as possible) is a preferred approach for understanding a baseline of BCE processes that intersect with ocean chemistry. As reference sites are often impacted by human activity (Atkinson et al. 2016), it is important to study and understand whether management strategies promote deacidifying processes in degraded BCEs and in areas where site-level protections may limit human-derived consequences in coastal areas. However, a lack of data on BCE degradation affects natural site biogeochemistry makes it hard to evaluate how BCE management mitigates coastal acidification. It remains worthwhile to investigate how certain BCE management strategies may fare in terms of mitigation, particularly as global carbon emissions are not being sufficiently abated, thus ever-increasing the OA risks in coastal environments.

The technical meeting explored how different management strategies might affect coastal acidification in different BCEs. Management strategies have not been applied consistently across BCEs, resulting in more knowledge in some BCEs and significant gaps in others. In summary, participants assessed the overall effect of each management strategy's capacity to mitigate coastal acidification in specific BCEs (Table 2).

Table 2. Synthesis of participant expert knowledge on the effects of various blue carbon ecosystem management strategies in mitigating coastal acidification in tidal marshes, and macroalgae forests (high and low energy) and seagrass beds. All rankings are based on current knowledge and assessment of relative success of each strategy.

	Tidal marshes	Macroalgae Forests		Seagrass
		High energy	Low energy	
Conservation	Highly variable	Positive	Positive	Positive
Restoration	Positive	Neutral	Neutral	Positive
Creation	Negative	Unknown	Unknown	Positive
Enhancement	Positive	Unknown	Unknown	Unknown

3.1 Conservation

Coastal vegetation in BCEs maintains high carbon stocks and long-term carbon storage. Conservation of BCEs protects natural function and prevents large carbon fluxes derived from other management strategies (e.g., creation (section 3.3), enhancement (section 3.4)). As a BCE management strategy, conservation is cost-effective as it can reduce direct human pressures and support natural processes that have formed over millennia. When lost from BCEs, their capacity for carbon sequestration and storage can take decades to recover. The effects of conservation of BCEs on coastal acidification is expected to be very localized with possible benefits from mitigated pH for protected areas depending on the species present and the related management objectives. Some stronger mitigation effects may be possible, especially in highly variable systems that may link to offshore transport of acidic or acidifying compounds.

The effect of conservation as a strategy to mitigate coastal acidification was not consistent across BCEs. Tidal marshes were deemed too variable to generalize about conservation effects on coastal acidification, but there was overwhelming agreement that protecting marshes is necessary to avoid their further decline. High variability in tidal marsh processes and functioning results in a need to explore individual sites to understand the OA-BC nexus at the local level. More consistent knowledge is available for macroalgae BCEs, yet the benefits of these systems on coastal acidification are also local. Conservation (and also restoration) can increase kelp biomass and productivity (Filbee-Dexter et al. 2024b), which leads to higher coastal buffering capacity. Rickart et al. (2021a) provided evidence of alleviation of low pH over extended periods in kelp beds with a tendency for stronger effects at higher latitudes. Similar responses in seagrass beds have been observed or are anticipated in unstudied areas based on modelling efforts (Koweek et al. 2018; Ricart et al. 2021a,b).

3.2 Restoration

The intended outcome of coastal ecological restoration is to restore natural function, improve biodiversity, reduce coastal erosion, and protect against storm surges and flooding. Restoring BCE ecosystems is broadly seen as vital for maintaining their capacity to sequester carbon and improving overall coastal resilience (Howard et al. 2017; 2023). Restoration can also prevent additional carbon dioxide losses from soil/sediment to the atmosphere and enhance an ecosystem’s ability to take up carbon dioxide from the atmosphere (Leavitt et al. 2021). Restoration may involve replanting seagrasses in areas where they have been lost or degraded and rehabilitating salt marshes through reintroducing tidal flow or removing obstacles. Challenges for restoration include very large gaps in BCE mapping and uncertainty around where highly impacted candidate restoration sites are located.

Restoration in macroalgal forests has had limited success and is not yet scalable; therefore, conservation remains the most effective mitigation strategy for these systems. Management of local inputs in coastal systems (e.g., run-off) can increase kelp biomass and productivity in high-energy, kelp-dominant areas (Miller and Shears 2023; Miller et al. 2024). In low-energy areas, acute nutrient inputs can lead to algal blooms, reducing macroalgal biomass and productivity and creating anoxia/hypoxia. In those areas, managing point source inputs can result in the natural recovery of systems and higher restoration success. More generally, restoration in macroalgal systems would benefit from access to models to help with site selection, especially to maximize kelp growth. Restoring kelp through techniques such as sea urchin removals can increase recovery (e.g. Miller and Shears 2023), and could lead to some measurable deacidifying effects at high restoration success (Hirsh et al. 2020; Young et al. 2022). Overall, participants assessed macroalgal systems as having a positive effect on coastal acidification (Table 2), highlighting the need for continuing research these methods.

Seagrasses play an important role in coastal carbon deposition (Oreska et al. 2017). As with other coastal habitats, considerable effects of human activity on seagrass has also resulted in broad scale efforts over space and time to restore seagrasses. Several studies have shown the potential of restoration to reinstate the ecosystem service of carbon capture and sequestration in seagrass meadows (McGlathery et al. 2012; Rezek et al. 2019; Orth et al. 2020). For example, restoration can enhance particle deposition and prevention of particle resuspension which are key environmental modifications in seagrass meadows that occur via sustained changes in the direction of waves and speed of currents (Hansen et al. 2012). While there is ongoing study to understand benefits of seagrass restoration as an coastal acidification mitigation tool, local effects may be net positive with possible variable effects over time (Table 2).

The restoration of BCEs, particularly in tidal marshes, can dramatically alter the redox chemistry of the system thereby influencing microbial processes, nutrient cycling, and carbon dynamics. By reintroducing tidal flows and restoring natural flooding and draining cycles, BCE restoration can support more favourable conditions for specific redox processes, such as denitrification, sulphur reduction, or methane production. Where restoration occurs by removing barriers for tidal inundation to restore a non-tidal freshwater wetland into a tidal system and the former freshwater system is restored to a saline state, the lateral flux of alkalinity should increase and methane emissions should decrease (Portnoy 1999; Kroeger et al., 2017; Arias-Ortiz et al. 2021). Restoration of tidal hydrology to freshwater wetlands restores sulphate influx and increases flushing frequency. Change in sulphate supply drives the contribution of sulphate reduction to increased alkalinity production and reduced methanogenesis. Tidal impoundments typically have lower sulphate reduction rates than wetlands with tidal hydrology. This can result in the export of acidity as a result of a high DIC:TA. It also can have a high DOC/DIC export ratio, with the potential for estuarine oxidation. Where restoration of tidal hydrology to drained former salt marshes is undertaken, large releases of acid can occur, for which the rate and duration depend on the total area and flushing rate (e.g. Ollerhead et al. 2024). Alkalinity and DIC exports might also increase, but this remains unknown. Furthermore, the effects of additional sediment on the system and its chemistry are poorly understood.

From a coastal acidification mitigation perspective, since restoration starts from disturbed sites, it is challenging to understand whether improvements to BCEs result in similar coastal acidification conditions as the original system. There is also a lack of data from original systems to indicate restoration success. Despite these setbacks, restoration can influence coastal acidification mitigation, with variable effects across BCE types.

3.3 Creation

Blue carbon ecosystem creation may be initiated through various management mechanisms, including developing habitat off-sets, revitalizing a known former site (beyond restoration techniques), and creating a habitat for a specific conservation or management objective. Steps toward building a BCE begin with an initial non-steady state requiring significant assessment of siting, construction effects, and likelihood of a functioning system post-creation. BCE creation supports the accretion of organic sediments via carbon sequestration and is likely higher than older natural systems at first (Childers et al. 1993). Similar to restoration, creating new BCEs, particularly tidal marshes, influences carbon processes, including microbial processes, nutrient cycling, and carbon dynamics, mainly by introducing tidal flows and natural flooding and draining cycles. However, their geomorphology and choice of sediment used in the initial creation of the site affect the naturalness achieved in any particular tidal marsh project. BCE creation can enhance ecological functions, such as water quality improvement, nutrient removal, and carbon sequestration, but they can also introduce trade-offs, such as increased methane emissions. Understanding and managing these redox processes is key to maximizing the ecological benefits and coastal acidfication mitigation of creation projects across BCE types.

In tidal marshes, the time scales to reach natural wetland productivity rates, carbon burial, and other carbon cycle processes are highly variable. The consensus from the technical meeting was that marsh habitat creation has a negative effect on coastal acidification mitigation related to the release of carbon from construction. A central issue for creating new tidal marshes is achieving an elevation that functions with natural tidal cycles to facilitate vegetation plantings and recruitment. Mimicking sediment characteristics is also very difficult as not all dredge material used in projects is created equal, and functional sediment-driven processes are characteristic of stable systems. For example, olivine sediments contain trace metals, and understanding its effects on carbon cycling is not trivial (see 3.4 enhancement). In addition, complex processes and functions mean that site selection for marsh creation is challenging, and where undertaken, the time for functioning is demonstrably long (Callaway 2005).

Growing macroalgae involves challenges with site selection, especially for kelp, as sites must be suitable for currents and nutrients (e.g. Thomas et al. 2019). Overall, creating new macroalgae habitats and farming macroalgae can have a short-term positive effect on coastal acidification and may benefit long-term carbon storage. Macroalgal aquaculture may also have negative local effects, including local nutrient depletions and accumulations of POC leading to anoxia. However, co-culturing macroalgae with shellfish may ameliorate some coastal acidification effects and algae produced on farms can be used in other industrial systems as offsets (Price et al. 2024).

3.4 Enhancement

Blue carbon ecosystem alkalinity enhancement (i.e., manipulation) refers to methods aimed at increasing the alkalinity of these environments, which can have important implications for biological and ecosystem processes and the broader issue of ocean acidification. Investments in enhancement are progressing without a clear understanding of their effect on carbon cycling in coastal environments.

Tidal marshes, particularly those with substantial vegetation, act as natural buffers to ocean acidification by capturing and storing carbon (as OC) and releasing alkalinity. Alkalinity manipulation might involve adding alkaline substances (like crushed shells, lime, or other carbonate-rich materials) into the marsh to increase the water's ability to buffer against ocean acidification. This may help to directly reduce the harmful effects of increased CO_2 concentrations in the surrounding waters. Increased alkalinity can promote better conditions for some marsh plants and may increase their overall carbon sequestration potential (e.g., Tutiyasarn et al. 2025).

Tidal marshes are home to a diverse community of microbes that play key roles in nutrient cycling, such as nitrogen and sulphur cycling. Enhanced alkalinity may influence the microbial community by altering the water and sediment pH. The impact of this on carbon cycling in these communities will depend on the specific microbial species present, as changes in pH could either support or inhibit certain microbial functions. There are, therefore, potential risks and feedbacks from enhancement activities. Manipulating alkalinity through artificial means (e.g., adding lime or other chemicals) must be carefully managed to avoid unintended ecological consequences, such as altering the ecosystem's natural balance and to avoid disrupting natural nutrient cycles, harm specific species, or change the physical properties of the soil and water in ways that negatively affect biodiversity. These interventions must be approached cautiously, as improper management may have unintended adverse effects on the marsh ecosystem.

In summary, conservation, restoration, creation, and enhancement of BCEs are intended to support natural mechanisms in coastal marine environments. The mixture of engineered and natural solutions presents various options to affect carbon cycling in BCEs and, in some cases, coastal acidification. Based on expert knowledge, the effect of BCEs on coastal acidification mitigation through implementing these strategies is inconsistent. However, positive effects are known or anticipated (Table 2). While the success of creating new systems is likely limited, conservation, restoration, and enhancement are generally considered beneficial where knowledge permits. Effects, in some cases, can take a very long time relative to management needs, or there may be negative feedback that becomes clear only after implementation (i.e., restoration of drained marshes). Apparent knowledge gaps emerged for some BCEs concerning effects from enhancement activities. These knowledge gaps are expected to continue to grow as alkalinity enhancement activities and marine carbon dioxide removal projects increase without sufficient scientific investments to understand their effects on BCEs.

4 Changing Environments

Blue carbon ecosystems are vulnerable to the changing climate through many pathways, including rising sea levels, increasing episodic events that result in changing water flows, and changes in ocean temperature, salinity, and acidity. Changes in these physical drivers could affect the health and functioning of these ecosystems, limiting their ability to store carbon and support biodiversity. Among these, the effects of ocean acidification on the de-acidifying potential of BCEs are poorly understood. The technical meeting discussions combined published knowledge with expert knowledge to identify knowledge gaps associated with the effects on coastal acidification mitigation in BCEs.

Temperature generally has an important role in BCEs, as it drives production, reaction rates, internal redox chemistry, and anoxia, and can increase physiological stress. As organic matter releases CO_2 as it degrades, any temperature increase creates a potential for increased interactions and changes in BCE biogeochemistry and/or atmospheric exchange. What happens to degraded carbon is not well known across BCEs. However, hypotheses supported by seasonal evidence from tidal marshes suggest that as respiration increases with temperature, there is an increase in DOC and excess carbon is exported (Wang et al. 2016; Tamborski et al. 2021). Gradual adaptation of BCE vegetation to warmer conditions may result in faster rates of various BCE functions (plants/microbes) including overall productivity of BCEs and the potential for increased net ecosystem production. For example, increased temperature increases degradation rates of macroalgal POC, which can reduce export and burial potential. This potentially leads to lower sequestration rates (Filbee-Dexter et al. 2022). For coastal areas, anoxic conditions related to temperature are trending upward in some regions (e.g., Crawford and Peňa, 2013), and may be more frequent as ocean conditions change (e.g., Peňa et al. 2019). Plant and animal distributions (native or invasive) are responsive to temperature and oxygen change which will have different implications for their overall interaction with OA. In conditions where OA exposure is inevitable, changes in the presence of sensitive species can be anticipated (Haigh et al. 2015). Acute change such as marine heat waves or deoxygenations events are more likely to have negative effects. Seagrasses and macroalgae show sensitivity to strong shifts in temperature especially in shallower locations (Starko et al. 2025). Although highly variable across groups and species of subtidal plants, this sensitivity to temperature is partly attributed to how they absorb CO_2 (e.g., smaller or filamentous species have more passive diffusion making them more sensitive), meaning that short, stressful events may favour less sensitive species and facilitate (relatively) rapid species replacement. Very little is known about the effects of anoxia on BCEs. More information is needed to understand the related effects of temperature and oxygen changes (acute and gradual) on carbon export or overall contribution to carbon cycling and/or any potential effects on OA.

Together, changes in water flows brought about through extreme storm events and sea level rise (SLR) may directly affect BCEs through their potential effect on carbon flux and ecosystem loss (Murray et al. 2022). Changes in flooding dynamics, including possible permanent loss of vegetated coastal areas and/or effects on stored carbon (sediment), especially for tidal marshes where vertical accretion is slower than gradual inundation, will be key effects from sea level rise on BCE-driven biogeochemistry and carbon cycling (Lovelock et al. 2017). As sea level and tides control the export of carbon from marshes, radical changes in carbon flux of unknown magnitude, export, and transport can all be anticipated where permanent inundation occurs, particularly for tidal marshes (Guimond et al. 2020). Moreover, there is a lot of interannual variability in flux, and measurements of pore water and tidal water consistently differ (Song et al. 2023), meaning that there are large unknowns about whether sea level change or tides plays a more important role in overall flux. In contrast, immediate extreme storm event effects on BCEs include coastal erosion (i.e., BCE loss), heavy wrack deposition on tidal marshes, and macroalgal losses or increased sloughing. More about how significant biomass movement affects carbon flux in these systems must be understood. Coastal erosion is associated with changes in water flow (SLR driven or hydrological changes) which affects tidal marshes export, susceptibility to loss of sediment dynamics (i.e. load/deposition), and internal redox chemistry.

Associated with SLR and hydrological change is the effect on salinity. Changes in salinity result in modifications to tidal marsh communities, loss of habitat, and changes in internal redox chemistry, each having incompletely described or understood interconnections with carbon chemistry and resulting flux from these BCEs. Increasing freshwater inputs may have negative consequences for BCEs. Hydrological changes driven by river regulation for hydropower have been shown to reduce BCE extent (e.g., eelgrass beds, Hudson Bay, Canada; Davis et al. 2024), related to turbidity effects of increased water flow on light availability.

Finally, the direct effect of ocean acidification must also be considered to understand overall atmospheric carbon-driven stressors on BCE's capacity to mitigate OA. To correctly consider how OA affects BCEs, the OA signal (i.e., anthropogenically driven change) must be detectable. For global OA, signal variability is high and often offshore, away from coastal areas where BCEs are located (Doo et al. 2020). While there is low variability in OA in the open ocean, coastal areas are far more challenging to resolve because of the naturally high inshore variability of the carbonate system and other inputs that contribute or add to that variation (e.g., human development). Despite these uncertainties, the increase in oceanic deposition of CO_2 via the atmosphere could have repercussions for coastal zones. Under OA the available buffering load delivered to the coastal system by tides would be expected to decrease with time, therefore, these systems may exhibit an increased range in daily pH over decadal timescales.

Ocean acidification increases the availability of bicarbonate in the system. Seagrasses and algae use bicarbonate in the water column for their daily functions, growth, and reproduction. For seagrasses, acidification has been shown to relieve CO_2 limitation and heat stress (Zimmerman et al. 2017; Zayas-Santiago et al. 2020), thereby creating an environment that is better for growth (Saderne et al. 2019). While in these instances OA may be considered beneficial, high uncertainty remains over whether this apparent advantage will result in an overall benefit for these BCEs as other processes and possible feedback have not been fully considered (Zimmerman 2021). In the case of tidal marshes, it is difficult to suggest what impacts OA may have. Marsh processes naturally result in near-neutral pH. How various carbon species or plant species respond to realistic exposures to waters with lower pH needs further exploration where vulnerability to such exposure merits investigation.

5 Summary of Knowledge Gaps

The technical meeting demonstrated that there is a large number of knowledge gaps within each of the areas of discussion. Here, we present a high-level summary of knowledge gaps consistently mentioned throughout discussions (Table 3). Detailed knowledge gaps that apply to BCE processes, mitigation strategies, and climate stressors are described within the text of each relevant section of this document.

Discussions highlighted the processes that could ultimately impact coastal acidification while acknowledging significant uncertainty in the coupled carbon budget of BCEs and their adjacent aquatic systems (tidal creeks, bays, sounds, etc). Much of this uncertainty results from the site-specific behaviour of individual BCEs. Even within individual systems, we lack the spatial and temporal breadth of data needed to quantify impacts over time and space.

We summarized that BCE management strategies' (conservation, restoration, creation, enhancement) ability to potentially benefit OA mitigation was accompanied with broad uncertainty of effects across all strategies. Evaluating OA mitigation in BCEs requires robust quantification of the drivers and mechanisms that control the fate of carbon export and transport and biogeochemical cycles to determine DIC:TA. The fate of carbon also determines the possibility for within-system feedback. Carbon chemistry is different across and within BCEs attributed to variations in sediment, with mitigation strategies potentially further affecting BCE chemistry via the introduction of materials with unknown outcomes for the system. Though neutral or positive outcomes may occur there remains considerable uncertainty on the likelihood of contributing broadly to OA mitigation. It is more likely, where effective, that mitigation of OA in BCEs may be more critical at the site-specific scale than any aggregate effect on global carbon mitigation.

Knowledge gaps associated with the changing climate applied similarly to all BCEs. For example, it is unclear whether there will be increased net ecosystem production (NEP) under warming in any BCE. The effect of OA on BCEs and possible feedback was not explored as richly in discussions, but participants agreed that there is high uncertainty with possible effects, in part because OA is affected by coastal systems (not only BCEs) and ocean circulation that contribute to high inshore OA variability. There are large risks associated with SLR for tidal marshes, but the magnitude of changes in flux under SLR is not understood. For subtidal BCEs, anoxia is a factor that is concerning and associated with increases in temperature. However, the uncertainty of modelled oxygen and temperature change in coastal regions is high, especially where model grids are large and/or not resolved to the coastline. Thus, little is known about the threat of anoxia on BCEs.

Table 3. Summary of high-level knowledge gaps identified by technical meeting topic and blue carbon ecosystem.

Blue Carbon Ecosystem	Blue Carbon process linkages to OA	Mitigation strategies	Climate stressors
Tidal Marshes	•Understand + predictive modelling of system variability (temporal, spatial) •Fluxes of DIC, TA, DIC:TA •Export of alkalinity and carbon, and effects on carbon chemistry •Effect of DIC:TA on buffering capacity •Carbon budget of the system •Fate of carbon exported	•Effect of mitigation on DIC:TA •Effects of enhancement on biogeochemical cycles not well understood. •Restoration/creation introduce materials with unknown outcome for system	•Magnitude of changes in flux under SLR •Net Ecosystem Production under warming •Effect of OA on system and possible feedbacks
Macroalgae (high and low energy	•Understand + predictive modelling of system variability (temporal, spatial) •Fluxes of DIC, TA, DIC:TA •Carbon budget of the system •Fate of carbon production •Export of alkalinity and carbon, and effects on carbon chemistry •Do these systems present negative feedbacks?	•Clarify effects of increased macroalgae productivity in protected areas or restored/enhanced sites on OA mitigation.	•Anoxia •Net Ecosystem Production under warming •Effect of OA on system and possible feedbacks
Seagrass	•Understanding system heterogeneity/variability (temporal, spatial) •Carbon budget of the system •Fate of carbon production •Export of alkalinity and carbon, and effects on carbon chemistry •Carbon alkalinity fluxes from seagrass sediments •How to measure/define export in open systems •Do these systems present negative feedbacks?	•Effects of enhancement on biogeochemical cycles not well understood. •Restoration/creation introduce materials with unknown outcome for system	•Anoxia •Net Ecosystem Production under warming •Effect of OA on system and possible feedbacks

6 Future Opportunities and Next Steps

On the last day of the technical meeting, a short discussion on future opportunities and next steps brought key suggestions for further consideration by the OA and blue carbon research communities and DFO-NOAA OA Collaboration coordinators.

6.1 Future Research and Alignment Across Fields of Study

6.1.1 Synthesis studies

Research and the increasing global interests in BCEs as carbon sinks have revealed a need to provide better estimates of lateral/aquatic carbon exports from tidal wetlands to the marine bicarbonate pool to resolve whether land-to-ocean fluxes contribute to long-term sequestration in the ocean. New studies aimed at synthesizing carbon flux from land to ocean and quantifying unknown related carbon fluxes have the potential to attribute a much greater magnitude of CO_2 removal to tidal wetlands and thereby influence creditable carbon markets (see CMS 2022).

Reithmaier et al. (2023) investigated whether mangroves (n = 38) and saltmarshes (n = 8) might buffer coastal waters against acidification and re-examine their potential to sequester atmospheric CO_2. These authors compiled TA and DIC contents in porewater and surface water (measured during time series and spatial surveys) at mangrove- and saltmarsh-dominated systems worldwide. They also upscaled compiled TA and DIC outwelling rates globally to evaluate whether intertidal wetlands export more TA or DIC and to update mangrove and saltmarsh carbon budgets. While this synthesis paper showed overall acidification from pore water outflow with high DIC:TA ratios at a local scale, the limited availability of pore water measurements makes this conclusion somewhat speculative. Research to compile data from individual BCE studies that have examined DIC and TA concentrations in the water is needed to undertake more synthesis studies and address uncertainties generated by current data gaps. Synthesis also identifies other data gaps that are useful in different experiments and simulations.

6.1.2 Model development

Process models can simulate and/or predict BCE function and flux. Individual model domains have been developed for specific research interests but are not necessarily linked to OA. Models could be developed to synthesize BCE observations and use them to simulate conditions when blue carbon systems are not present or altered as experiments to generate hypotheses and research questions. One specific exercise could be to expand on existing efforts that aim to describe carbon budgets on a regional basis but focus the parametrization of models on BCEs to address local BCE effects on carbon budgets and OA. Other efforts could concentrate on modelling exercises to identify areas for BCE growth and run model experiments under changing environmental conditions to inform future suitable BCE areas. Global Earth system models can provide important insight into coastal and ocean carbon dynamics, however, they tend to ignore the dynamic chemical processes and transformations associated with BCE's (Ward et al. 2020). Ward et al. (2020) recommend approaches to incorporate these processes into Earth system models to improve predictions of coastal-ocean interactions.

6.1.3 Comparative and integrative studies

Discussions of expanding the understanding of how BCEs affect alkalinity led to suggestions for comparative and/or integrative studies with some focus on investigating how to align methods and measurement across fields of study.

- Comparative studies of BCEs could synthesize and/or study lateral flux to determine and understand alkalinity's absolute and relative importance in BCEs.
- Investigation of how alkalinity or DIC:TA affects degradation and/or deposition as this is a key area of overlap for both fields of study
  - Degradation (POC, DOC) and carbon deposition are highly important to sequestration and sedimentation estimates.
  - Carbon compounds/species (DIC) in the water column that drives acidification may affect carbon degradation and deposition with unknown effects on sequestration and/or sedimentation. This uncertainty highlights the importance of determining DIC export/flux (thus, synthesis and model studies are required).
- Communities have been operating separately, so there aren't tangential measurements happening, and few are broadly transferable yet.
  - The difference in measurements currently relied on for both fields of study has implications for the alignment of research. The BC community studies buried carbon and measures annual carbon cycles. The latter links to OA measurements, but related data time scales are inconsistent.
    - Blue carbon researchers are estimating annual carbon cycling, but the measured BCE indicators (e.g., DOC) tend to operate on very long timescales. Thus, recorded observations represent decades or centuries of carbon reservoirs at study sites. Other options to capture more contemporaneous carbon processes are challenging to sample and measure (e.g., POC moves during storms, and there are no standardized sampling devices)
    - DIC flux is a key link across fields of study.
- Integrative studies could examine the various methodologies used to evaluate carbon sequestration in particular systems and develop a decision map to help researchers determine methods and measurements conducive to resolving carbon flux in specific BCEs (see Pessarrodona et al., 2023).
- Compile methods and measurement research (e.g. Bansal et al. 2023; Hopkinson et al. 2025) to explore application to the OA-BC nexus.
- Collaboration between the blue carbon and OA research communities could enhance understanding of marine carbon dioxide removal (mCDR) and blue carbon systems, especially around alkalinity export quantification.

6.2 Follow-up Workshop

It was suggested for the OA and BC communities to come together again to explore components of their work identified in this first technical meeting that would benefit from better alignment. This could take the form of a multi-day workshop to share a number of cross-cutting approaches including: field and lab methods (e.g., sample preservation), measurement techniques and scale, data analyses, and consideration of essential variables and best methods for BCE systems (e.g., develop a decision tree to assist researchers). Such a workshop would address a clear literature gap by producing a review paper on the best way to integrate field and laboratory methods across Blue Carbon and OA fields of expertise.

7 Conclusion

Blue carbon ecosystems are noted as important ecosystems that contribute to global and regional outcomes for carbon cycling that span geologic time. In this report, we synthesize the current understanding of the effects and potential of blue carbon systems to mitigate OA via natural process and/or management action, explored how changing climate may influence the BC-OA interaction, outlined key knowledge gaps, and discussed future opportunities for scientific research on the nexus of coastal acidification and blue carbon ecosystems. Technical meeting discussions revealed a number of assumptions of both the blue carbon and OA technical fields. More detailed thought experiments are needed to identify ways to collaborate further. While it may not be possible to merge blue carbon and ocean chemistry entirely, this report provides a starting point to continue working together.

The workshop arrived at the following main conclusions about the state of knowledge of the OA-BC nexus:

- Overwhelmingly, the OA-BC nexus operates at very local scales in the BCEs explored in this report.
- BCEs might provide some buffering capacity to coastal systems but is dependent on relatively unstudied lateral and offshore transport processes.
- BCE carbon budgets need to include carbon export/flux and local fate.
- Alkalinity budgets should be determined in conjunction with carbon and include the contribution of organic alkalinity.
- The magnitude of coastal acidification mitigation provided by various BCE management strategies is unclear; Conservation was assessed as having an overall positive effect on mitigating local coastal acidification.
- Ocean acidification could potentially change the coastal buffering contribution of BCEs.

We suggest that the potential for OA mitigation is highest in natural BCEs that are part of conservation efforts. Other management strategies may provide some compensation should the rate of BCE alteration and removal from coastlines continue at the current pace. While tidal marsh restoration is unlikely to significantly mitigate ocean acidification, it remains a valuable component of broader marsh management efforts.

While the effects of climate stressors on BCEs is relatively well studied, the interaction of a changing environment, including OA, on the nexus of BC and OA is quite understudied. We combined these unknowns with a number of knowledge gaps and research opportunities associated with natural processes and BCE management strategies to arrive at some guiding ideas to consider in future work. This would include proposing studies focusing on monitoring, experimental research, and developing models to predict the outcomes of blue carbon restoration on OA.

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10 Appendices

10. 1 Appendix 1

TERMS OF REFERENCE

DFO-NOAA Collaboration OA-BC Nexus Project Technical Meeting
Date: November 13-15, 2024
Location: Virtual - MS Teams **Time:** 8:30 - 2:00 Pacific Time

Meeting Co-Champions:
Karen Hunter, Climate Change Science, National Capital Region, Fisheries and Oceans Canada
Matthew Poach, Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration

Meeting Support/Rapporteurs:
Jahnelle Howe, Doctoral Candidate at the Graduate Center, City University of New York
Alexandra Puritz, Ocean Acidification Action Program, National Oceanic and Atmospheric Administration
Christine Stortini, Climate Change Science, National Capital Region, Fisheries and Oceans Canada

Invited Speakers: Dr. Nick Ward, PNNL and Dr. Paul Snelgrove UMUN

Participants: National experts (Canada, USA), DFO and NOAA staff with expertise in blue carbon, ocean acidification, and their carbon cycling connections.

CONTEXT

In 2024, the DFO-NOAA Collaboration on Ocean Acidification proposed a collaborative project to evaluate the current state of knowledge and prospective directions for research at the interface of blue carbon and ocean acidification (OA) in transboundary coastal ecosystems. This project includes a technical meeting that is designed to promote discussion amongst blue carbon and OA experts to address what is known about the connections and/or series of connections between blue carbon and OA in current and future climate conditions and to identify gaps in knowledge and science activities associated with these themes:

1) What do we know about the connections between blue carbon systems and ocean acidification in coastal environments?
2) How do mitigation strategies (i.e., restoration, manipulation) promote carbon capture and deacidifying processes?
3) How do climate-driven multi-stressors affect blue carbon and ocean acidification processes?
4) Knowledge gaps and future science activities.

These questions will be addressed across three sessions over three ½ days of virtual discussions.

Session 1. The blue carbon - ocean acidification nexus: what do we know about the connections between blue carbon systems and ocean acidification in coastal environments?

Presently, there remains considerable uncertainty regarding the carbon budgeting of coastal ecosystems and the lateral exchange of carbon with neighbouring ocean environments. Further, research communities focused on coastal blue carbon (coastal habitat management and restoration) and coastal acidification have typically worked separately. However, recent studies have indicated that restoration of some wetland environments can enhance the alkalinity flux into associated bays and estuaries, potentially mitigating coastal ocean acidification (OA), enhancing carbon capture, and promoting carbon export to neighbouring shelf-slope environments. Uncertainties are significant for carbon cycling, potential ocean acidification mitigation, and biological co-benefits in these nearshore and shelf/slope environments, including unknowns about the export of blue carbon from coastal wetlands and how those exports are modified via carbon cycling (remain in the ocean, become atmospheric).

Outcome: Identifying research pathways on how blue carbon affects ocean acidification processes in coastal ecosystems.

Discussion questions:

a) What are the processes that link blue carbon and ocean acidification in coastal ecosystems?
a) What is the magnitude of the nexus between the two?
b) How do these processes affect coastal acidification?

Session 2. Mitigation strategies and Multi-stressor effects

Investments in scientific research and mitigation efforts (manipulation and restoration) are progressing without a clear understanding of the effect of available strategies and those being developed and tested in natural settings on carbon cycling in coastal environments. The effects of current and future climate-related stressors (e.g., sea level rise, temperature), warming, and deoxygenation on the de-acidification potential of blue carbon systems have not been thoroughly investigated.

I. ***Do mitigation strategies (i.e., restoration, manipulation) promote deacidifying processes?***

Discussion questions:

a) What are the strategies that are being employed to buffer OA?
b) How do these strategies affect coastal acidification?

Outcome: Generate an understanding of mitigation strategies that buffer coastal acidification and/or its effects.

II. ***How do climate-driven multi-stressors blue carbon and ocean acidification processes?***

Discussion questions:

a) How do multi-stressors disrupt passive/"natural" processes and active/" human-guided" mitigation activities that contribute to carbon capture and 'de-acidification' and possibly affect the nexus?
b) Where are projections available for multi-stressors, and what is anticipated as stressors change?

Outcome: A clear understanding of the climate-driven multi-stressors acting on the connections between blue carbon storage and OA with consideration of current and future conditions.

Session 3: Knowledge Gaps and Future Science Activities on the OA-BC Nexus

a) What research topics important to the OA-BC interface have not been addressed to date by research investments engaged by either DFO or NOAA?
b) Have important research areas not been addressed because they may have fallen through the cracks between these two topic areas?

Outcomes: (1) Identify and summarize information and data gaps. (2) Suggested future research avenues.

Expected publications and follow-on goals

A technical meeting report. Opportunity to inform research direction for DFO and NOAA in this area of science programming.

10.2 Appendix 2 Participant name and affiliation

Participant name	Affiliation
Simone Alin	National Oceanic and Atmospheric Administration
Wei-Jun Cai	University of Delaware
David Capelle	Fisheries and Oceans Canada
Tonya Burgers	Expert Panel, Fisheries and Oceans Canada, Arctic Region
Meagan Eagle	U.S. Geological Survey
Dwight Gledhill	National Oceanic and Atmospheric Administration
Helen Gurney-Smith	Fisheries and Oceans Canada, Maritimes Region
Charles Hopkinson	Expert Panel, University of Georgia
Jahnelle Howe	City University of New York
Christopher Hunt	National Oceanic and Atmospheric Administration
Karen Hunter	Co-Chair, Fisheries and Oceans Canada, Pacific Region
Thomas Hurst	National Oceanic and Atmospheric Administration
Sophia Johannessen	Fisheries and Oceans Canada, Pacific Region
Kira Krumhansl	Expert Panel, Fisheries and Oceans Canada, Maritimes Region
Zou Zou Kuzyk	University of Saskatchewan
Marie Claude Lamarche	Fisheries and Oceans Canada, National Capital Region
John O'Brien	Fisheries and Oceans Canada, Arctic Region
Jie Yuen Ong	Fisheries and Oceans Canada, National Capital Region
Shannon Meseck	Expert Panel National Oceanic and Atmospheric Administration
Matthew Poach	Co-Chair, National Oceanic and Atmospheric Administration
Alexandra Puritz	National Oceanic and Atmospheric Administration
Daniel Small	Fisheries and Oceans Canada, Quebec Region
Paul Snelgrove	Invited Speaker, Memorial University
Christine Stortini	Fisheries and Oceans Canada, National Capital Region
Zhaohui Aleck Wang	Expert Panel, Woods Hole Oceanographic Institution