*Cambridge Prisms: Coastal Futures*

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## Review

**Cite this article:** Jones SF, Arias-Ortiz A, Baldocchi D, Eagle M, Friess DA, Gore C, Noe G, Nolte S, Oikawa P, Paytan A, Raw JL, Roberts BJ, Rogers K, Schutte C, Stagg CL, Thorne KM, Ward EJ, Windham-Myers L and Yando ES (2024). When and where can coastal wetland restoration increase carbon sequestration as a natural climate solution? *Cambridge Prisms: Coastal Futures*, **2**, e13, 1–16 https://doi.org/10.1017/cft.2024.14

Received: 26 April 2024
Revised: 12 July 2024
Accepted: 13 August 2024

**Keywords:**
natural climate solutions; coastal wetlands; ecosystem management; restoration; carbon sequestration

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# When and where can coastal wetland restoration increase carbon sequestration as a natural climate solution?

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## Abstract

Coastal wetlands are hotspots of carbon sequestration, and their conservation and restoration can help to mitigate climate change. However, there remains uncertainty on when and where coastal wetland restoration can most effectively act as natural climate solutions (NCS). Here, we synthesize current understanding to illustrate the requirements for coastal wetland restoration to benefit climate, and discuss potential paths forward that address key uncertainties impeding implementation. To be effective as NCS, coastal wetland restoration projects will accrue climate cooling benefits that would not occur without management action (additionality), will be implementable (feasibility) and will persist over management-relevant timeframes (permanence). Several issues add uncertainty to understanding if these minimum requirements are met. First, coastal wetlands serve as both a landscape source and sink of carbon for other habitats, increasing uncertainty in additionality. Second, coastal wetlands can potentially migrate outside of project footprints as they respond to sea-level rise, increasing uncertainty in permanence. To address these first two issues, a system-wide approach may be necessary, rather than basing cooling benefits only on changes that occur within project boundaries. Third, the need for NCS to function over management-relevant decadal timescales means methane responses may be necessary to include in coastal wetland restoration planning and monitoring. Finally, there is uncertainty on how much data are required to justify restoration action. We summarize the minimum data required to make a binary decision on whether there is a net cooling benefit from a management action, noting that these data are more readily available than the data required to quantify the magnitude of cooling benefits for carbon crediting purposes. By reducing uncertainty, coastal wetland restoration can be implemented at the scale required to significantly contribute to addressing the current climate crisis.

## Impact statement

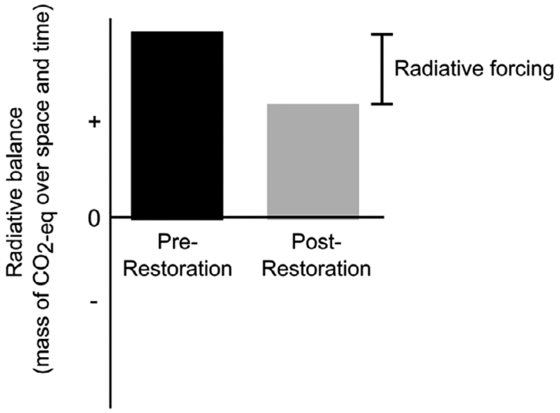
Coastal wetlands, including mangrove forests, tidal marshes and seagrass meadows, can take carbon out of the atmosphere and store it in plant tissue and soil at the highest rates of any ecosystem. Because of this unique feature, coastal wetland restoration can act as a natural climate solution (NCS), helping to mitigate climate change by having a net cooling benefit compared to pre-restoration conditions. However, uncertainty remains in when and where coastal wetland

restoration acts as effective NCS. This manuscript synthesizes the fundamental requirements for restoration to act as effective NCS: additionality, permanence and feasibility. We highlight the minimum data required to understand these requirements, which are less robust than the data needed for carbon crediting or accounting. Many of these data are spatial and widely available. We also highlight future perspectives that may help address uncertainty in restoration as NCS, by taking a landscape-scale approach and incorporating methane emissions. Ultimately, reducing uncertainty in when and where coastal wetland restoration acts as NCS supports the broader effort to mitigate climate change most effectively.

## Coastal wetlands as natural climate solutions

Climate change is causing cascading impacts to human and natural systems globally, and all possible mitigation and adaptation actions will be needed to keep warming below critical thresholds over the next decade (United Nations Framework Commission on Climate Change (UNFCCC), 2015; Intergovernmental Panel on Climate Change (IPCC), 2022; Diffenbaugh and Barnes, 2023). For coastal landscapes, sea-level rise is among the greatest drivers of change, impacting coastal communities through increased flooding and salinization risks (Intergovernmental Panel on Climate Change (IPCC), 2021; Sweet et al., 2022). Natural climate solutions (NCS), or those actions that mitigate climate change using ecosystem management, can remove greenhouse gases from the atmosphere, complementing efforts to reduce fossil fuel emissions (Fargione et al., 2018; Macreadie et al., 2021; United Nations Environment Programme (UNEP) and International Union for Conservation of Nature (IUCN), 2021). Although we explicitly focus on NCS as actions that remove greenhouse gases here (without concurrent negative impacts; Ellis et al., 2024), restoration of coastal ecosystems comes with a host of additional co-benefits (Hagger et al., 2022; Krauss et al., 2022a; Rogers et al., 2023b; Novick et al., 2024).

Coastal wetlands, including mangrove forests, tidal marshes and seagrass meadows (among all other tidal wetlands; Adame et al., 2024), are highly productive 'blue carbon' ecosystems connecting terrestrial and marine realms globally. These ecosystems are unique in their ability to mitigate climate change as they continually absorb and store carbon from the atmosphere, leading to a climate cooling benefit (Figure 1; Neubauer, 2021) that grows over time if they continue to add carbon within the



**Net ecosystem carbon balance**:
the net rate of carbon inputs and losses for an ecosystem (Chapin et al. 2006, 2009)

**Radiative balance**:
the net effect of an ecosystem's carbon balance on Earth's energy budget (Neubauer 2021)

**Radiative forcing**:
the net effect of a change in radiative balance due to an external perturbation or action (Ramaswamy et al. 2001, Neubauer 2021)

**Cooling benefit**:
the amount of net negative radiative forcing (cooling) due to an external perturbation or action (Neubauer & Megonigal 2015, Neubauer 2021)

**Restoration**:
the process of assisting the recovery of an ecosystem's structural and/or functional characteristics after degradation, damage, or destruction (Gann et al. 2019)

**Additionality**:
the cooling benefit due to a specific management action, such as restoration (Mason et al. 2022, Glass et al. 2024)

**Permanence**:
the capacity for cooling benefits to persist over time (Glass et al. 2024)

**Feasibility**:
the capacity for restoration to be successfully carried out (Lovelock et al. 2022c)

**Figure 1.** Key terms as defined in this manuscript. Conceptual comparison is of the radiative balance of a coastal wetland in pre-restored (black) and post-restored (gray) states (modified from Neubauer, 2021). In this example, the pre-restored and post-restored states both have positive radiative balances, adding energy to Earth's energy budget. After restoration, there is a change in radiative balance (i.e., a radiative forcing); restoration action led to a reduction in radiative balance. Because the radiative forcing is negative, this example indicates a cooling benefit from restoration actions; the project has additionality.

accommodation space created by sea-level rise (Rogers et al., 2019a; Buffington et al., 2021). Present day coastal wetlands initiated development when relative sea-level rise decelerated sufficiently for coastal wetlands to maintain their position within the tidal frame; the timing of this development varies globally due to differences in glacio-isostatic adjustment of coastlines (Woodroffe, 2019). Global distribution of blue carbon ecosystems is variable as well and largely determined by climate constraints (McKenzie et al., 2020; Jia et al., 2023; Worthington et al., 2024); these ecosystem types vary in how they store and cycle carbon to mitigate climate change.

At the regional scale, hydrogeomorphic setting (i.e., landscape configuration) constrains the occurrence of blue carbon ecosystem types and their ability to store carbon. Hydrogeomorphic setting influences the dominance of water forcings (e.g., wind, wave, tide; Boyd et al., 1992), sediment availability and deposition (Hupp et al., 2019), connectivity to other habitats (Noe et al., 2016; Woo et al., 2022), and freshwater availability and timing important for sulfate concentrations and methane production (Poffenbarger et al., 2011; Knox et al., 2021). As one example, intermittently connected lakes and lagoons (ICOLLs) or temporarily open/closed estuaries (TOCEs), are coastal wetlands that can undergo state shifts in salinity and water level that drive changes in ecosystem parameters like macrophyte community extent and composition (Riddin and Adams, 2008), presenting specific challenges in quantifying dynamic climate benefits.

Accounting for the temporal evolution of coastal wetlands can be challenging for practitioners, researchers and policy-makers alike (Neubauer and Megonigal, 2015; Neubauer, 2021; Abernethy and Jackson, 2022). Continuous and effectively permanent soil carbon sequestration, a particularly important aspect of coastal wetlands as blue carbon ecosystems, is a long-term additive process (Chmura et al., 2003; Mcleod et al., 2011). In the context of NCS, however, decadal timescales are of primary interest to assist in meeting climate commitments as soon as possible (United Nations Framework Commission on Climate Change (UNFCCC), 2015; United Nations Environment Programme (UNEP) and International Union for Conservation of Nature (IUCN), 2021). Greenhouse gas fluxes and herbaceous biomass can respond rapidly to management actions in coastal wetlands (Wang et al., 2021; Woo et al., 2022), and carbon sequestration rates and woody biomass can also recover within decades in certain situations (Marbà et al., 2015; Osland et al., 2020; Eagle et al., 2022; Rogers et al., 2023a). Regardless, losing millennia of stored carbon simply cannot be regained over short timescales by restoration; preservation of existing carbon stocks and functioning ecosystems is therefore key (Drexler et al., 2009; Arias-Ortiz et al., 2021a).

Given historical degradation and land conversion of coastal wetlands globally (Friess et al., 2019; Turschwell et al., 2021; Campbell et al., 2022), under-recognized but tractable opportunities exist to use restoration as NCS to recover carbon sequestration functionality (Macreadie et al., 2017; United Nations Environment Programme (UNEP) and International Union for Conservation of Nature (IUCN), 2021; Krauss et al., 2022b; Lovelock et al., 2022a). Hydrologic impoundment is a leading cause of stress and degradation for intertidal coastal ecosystems (Montague et al., 1987; Warren et al., 2002; Lewis et al., 2016; Chambers et al., 2019). Reconnecting degraded wetlands to their watersheds is therefore a common restoration technique, with documented success in halting oxidative loss of carbon stores or otherwise shifting carbon cycling for a climate cooling benefit (Kroeger et al., 2017; Dittmann et al., 2019; Cormier et al., 2022; Eagle et al., 2022; Windham-Myers et al., 2023). Sediment augmentation is also commonly used to increase resilience to relative sea-level rise in coastal wetlands that have deteriorated from increased flooding stress (Stagg and Mendelssohn, 2010; Yuan et al., 2022; Fard et al., 2024), leading to enhanced longevity of carbon sequestration compared to no-action alternatives. Additionally, improving water quality (e.g., eutrophication) and other threats (Turschwell et al., 2021) before introducing large numbers of foundation species may be critical for seagrass restoration success (van Katwijk et al., 2016).

Regardless of restoration approach, coastal wetlands have been identified as particularly impactful habitats for restoration actions as NCS because of (a) their high rates of carbon sequestration and high densities of carbon storage over centuries to millennia (Bridgham et al., 2006; Mcleod et al., 2011; Poulter et al., 2022); (b) the potential for management actions that have meaningful impacts on carbon budgets of degraded habitats, leading to climate cooling benefits; and (c) the potential for interventions to have additional social and environmental co-benefits (Lovelock and Duarte, 2019). Given that opportunities for restoration are distributed unevenly across continental scales (e.g., Holmquist et al., 2023) and resources for restoration activity are limited, there remains a lack of clarity on where coastal wetland restoration is maximally effective as NCS, and under which circumstances action is warranted.

Ultimately, to be effective as NCS, coastal wetland restoration projects must accrue climate cooling benefits that would not occur without management action (Figure 1). Here, we synthesize current understanding to 1) illustrate the fundamental requirements for coastal wetland restoration to be an effective NCS, addressing uncertainty in where restoration maximizes climate benefits, and 2) discuss potential paths forward to overcome current implementation barriers, addressing uncertainty in when restoration action is warranted.

## Requirements for coastal wetland restoration as an effective natural climate solution

Three fundamental criteria determine the effectiveness of restoration actions as NCS: additionality, feasibility and permanence (Table 1). Below, we discuss requirements in an ecological sense, rather than within the context of a particular carbon finance or accounting framework. Due to their potential to influence site-specific climate benefits, local-scale factors are also considered.

### *Additionality*

Coastal wetland restoration is effective as NCS when actions ‘add’ carbon to the landscape, reducing atmospheric greenhouse gas concentrations and leading to a cooling benefit compared to initial degraded conditions (Figure 1). Maximal cooling benefits occur where the difference in pre-restoration and post-restoration climate impact is large. For example, highly degraded pre-restoration sites with large carbon emissions being converted to productive post-restoration sites with large carbon sequestration maximizes additionality. This cooling benefit can be achieved through restoring areas back to their original ecosystem type (e.g., conversion of shrimp ponds back to mangrove forests; Sidik et al., 2019), enhancing or rehabilitating function within an ecosystem type (e.g., restoring hydrology to impounded marshes, Eagle et al., 2022), or creating

**Table 1.** The fundamental requirements for coastal wetland restoration to be effective as NCS: additionality, feasibility and permanence

| Requirements | Values that maximize climate benefit | Minimum data required to quantify |
|---|---|---|
| Additionality | Current pre–restoration conditions contribute to substantial climate warming (large positive radiative balance)<br>Expected post–restoration conditions contribute to substantial climate cooling (large negative radiative balance), or contribute to substantially less climate warming in comparison to pre–restoration conditions<br>Large area of degraded, restorable habitat is available in the region<br>Potential for biomass carbon gain is high, particularly of woody plant species | Regional land use/land cover maps at a sufficient resolution and specificity to allow area calculations for each land use/land cover class<br>Regional carbon radiative balance or emissions/removal factor estimates by land use/land cover classes |
| Feasibility | Funding is secured and appropriate in scale<br>Land tenure is secured, clearly communicated and respected<br>Local communities are part of the project team and will gain access to co–benefits of restoration for NCS<br>Governance is effective in the region<br>Pre–restoration biophysical conditions are amenable to regional restoration practices/culture | Regional land ownership/tenure maps at a sufficient resolution to allow project planning<br>Estimates of restoration cost per area restored given regional restoration culture and available financial incentives<br>Local reports of existing communication and collaboration among local communities to understand end–user involvement and investment |
| Permanence | High capacity for resilience through allochthonous processes (e.g., large sediment supply)<br>High capacity for resilience through autochthonous processes (e.g., high rates of root production)<br>Upslope and/or upstream accommodation space is available and accessible for wetland migration<br>Low risk of short–term perturbations | Regional estimates of coastal wetland resilience to relative sea–level rise<br>Regional topography maps, including anthropogenic alterations to topography that influence hydrology, at a sufficient resolution to allow project planning<br>Local reports from communities on equitable distribution of restoration co–benefits |

*Note*: Specific values of these requirements can maximize the cooling benefit of coastal wetland restoration. There are relatively straightforward minimum data needed to quantify if the fundamental requirements are met to address the question, ‘Does this management action lead to a net climate benefit?’

new/novel habitat. Large areas available in degraded condition that can be converted through management action to an enhanced condition equates to large potential cooling benefits. Small estuarine systems therefore may not have the same potential as large deltas/bays (unless aggregated as regional systems; Duarte de Paula Costa et al., 2022), because habitat size (i.e., degraded land that can be restored) was originally small. Beyond size considerations, often ignored but potentially important biophysical changes can occur after restoration, leading to net cooling benefits without changing carbon cycling directly (e.g., changes in albedo, latent/sensible heat flux, roughness; Graf et al., 2023; Zhu et al., 2024).

Conditions amenable to quick recovery of carbon storage pools, reduction in greenhouse gas emissions, and/or enhanced carbon sequestration rates are key to maximizing additionality in coastal wetland restoration. While most carbon is stored in coastal wetland soils over the long-term, biomass pools often develop more rapidly and can be the first sign of additionality from restoration (Rogers et al., 2023a). Habitat types with large woody vegetation (characteristic of mangrove and tidal forests) contain substantially more biomass carbon than habitat types with herbaceous vegetation (characteristic of tidal marshes and seagrasses) (Adame et al., 2024), and can amass considerable additionality over 15–25 years after restoration (Osland et al., 2020; Rogers et al., 2023a). Restored sites that have the potential for large gains in biomass carbon after management action may therefore maximize additionality over decadal scales (e.g., Sasmito et al., 2019). This additional vegetation biomass can be constrained by regional scale factors (e.g., Rovai et al., 2021 for mangroves). The accommodation space for carbon burial in an estuary also varies regionally, based largely on geologic ‘maturation’ stage (Owers et al., 2022; Rogers et al., 2022). Regionally variable sediment availability for allochthonous carbon burial and freshwater availability to support autochthonous production can drive the potential for adding carbon to the landscape as well (e.g., Thorne et al., 2022) (see the discussion on allochthonous carbon in Section ‘Coastal wetlands as cross-ecosystem linkages’). Additionality after restoration may not follow a linear increase, instead showing rapid initial responses (e.g., for carbon accumulation; Burden et al., 2019). For effective cooling, additionality and general carbon cycling after restoration do not need to match remnant ecosystems; there needs to be enhanced function compared to the initial/alternative degraded state.

### Feasibility

Coastal wetland restoration is effective as NCS when actions are feasible to implement. Pinpointing areas on the landscape where restoration actions will have the largest benefits to climate mitigation is inconsequential if the actions themselves cannot be completed. Feasibility is largely set by conditions external to the restoration site, including regional socioeconomic and governance constraints that influence human decision-making (Friess et al., 2019; Stewart-Sinclair et al., 2020). Restoration can take considerable infrastructure and funding to implement; this funding must be in place or accessible in the region for action to commence, and may use a variety of financial instruments (Friess et al., 2022). Regional and local land tenure is an additional crucial consideration for effective restoration (Lovelock and Brown, 2019; Lovelock et al., 2022c; Bell-James et al., 2023), as additional co-benefits should be delivered to local communities and stakeholders, who are often direct (and historical) users of coastal ecosystems (Wylie et al., 2016; Dencer-Brown et al., 2022). Existing policies and regulations can vary in scope and purpose across jurisdictional lines, making a complex web that may impede effective coastal management, including restoration activities (Herr et al., 2019). To maximize feasibility, external conditions will support restoration action through available funding, appropriate land tenure, and effective governance (Stewart-Sinclair et al., 2020; Macreadie et al., 2022; Windham-Myers et al., 2023).

**Table 2.** A non-exhaustive list of example methods and applicable case studies for restoration of coastal wetlands that may lead to climate cooling benefits

| Restoration method | Description | Case study citations |
|---|---|---|
| (Un)Managed realignment | A type of hydrologic restoration. Breaching coastal embankments that were installed to convert historical wetlands to other land uses, either intentionally (managed) or unintentionally (unmanaged). | Masselink et al., 2017; Hudson and Kenworthy, 2021; Mossman et al., 2022 |
| Regulated tidal exchange | A type of hydrologic restoration. Increasing tidal flow through engineered structures or managing estuary mouths in a controlled fashion. | Kroeger et al., 2017; Hudson and Kenworthy, 2021; Claasens et al., 2022; Cormier et al., 2022; Eagle et al., 2022 |
| Subsidence reversal | A type of hydrologic restoration. Rewetting historical wetlands that have been converted to other drained land uses to halt and reverse subsidence processes. | Miller and Fujii, 2011; Windham–Myers et al., 2023 |
| Re–seeding | A type of biotic restoration. Collecting and deploying seeds/propagules to restore foundation plant species populations. | Broome et al., 1988; Orth et al., 2012; Gamble et al., 2021; Sinclair et al., 2021 |
| Re–planting | A type of biotic restoration. Collecting and transplanting shoots/seedlings to restore foundation plant species populations. | Broome et al., 1988; O'Brien and Zedler, 2006; Zamith and Scarano, 2010; Gamble et al., 2021; Sinclair et al., 2021; van Bijsterveldt et al., 2022 |
| Sediment augmentation/placement | A type of geophysical restoration. Applying sediment to increase the elevation capital of a coastal wetland. When placement is from dredged material, can be called beneficial use. | Ray, 2007; Manning et al., 2021; Fard et al., 2024 |

(Broome et al., 1988; O'Brien and Zedler, 2006; Ray, 2007; Zamith and Scarano, 2010; Miller and Fujii, 2011; Orth et al., 2012; Kroeger et al., 2017; Masselink et al., 2017; Gamble et al., 2021; Hudson and Kenworthy, 2021; Manning et al., 2021; Sinclair et al., 2021; Claasens et al., 2022; Cormier et al., 2022; Eagle et al., 2022; Mossman et al., 2022; van Bijsterveldt et al., 2022; Windham-Myers et al., 2023; Fard et al., 2024)

Maximizing feasibility also includes ensuring internal site conditions are amenable to region-specific restoration culture and practice. Pre-restoration land use can influence post-restoration vegetation and water quality recovery, through impacts on elevation and initial plant community composition (Janousek et al., 2020). Restoration activities can also fail when restoration practice does not align with local site conditions. For instance, planting mangrove propagules on mudflats for rehabilitation can have low survival rates if species are used that are unlikely to naturally establish at available elevations (Wodehouse and Rayment, 2019; Lovelock et al., 2022c). Further, the cultural practice of restoration itself, including methods, goals, and rationale, may vary by region (e.g., Hudson and Kenworthy, 2021; Lovelock et al., 2022b) (Table 2). Feasible restoration actions mesh with the regional context of restoration practice and are therefore context specific; creating shared goals across diverse stakeholders can underpin feasibility and successful implementation in this regard (Surgeon Rogers et al., 2019).

## Permanence

Coastal wetland restoration is effective as NCS when cooling benefits are 'permanent' over management-relevant timescales. These timescales should be explicitly defined. Here, we propose decades are the appropriate permanence timescale, to align with 2050 emissions reduction targets (United Nations Framework Commission on Climate Change (UNFCCC), 2015; Intergovernmental Panel on Climate Change (IPCC), 2022). Permanence over management-relevant timescales occurs when restored sites are resilient to relative sea-level rise over the next several decades. Regional controls on sediment type and availability influence the capacity for wetland vertical accretion of allochthonous material, and therefore resilience (Rovai et al., 2018; Gorham et al., 2021; Breithaupt and Steinmuller, 2022). Resilient restoration will balance rates of relative sea-level rise and sediment supply to be successful; restoration at low elevation sites where sediment supply is low risks failure as vegetation may be rapidly overwhelmed by rising sea levels or erosion from wave action. However, where sediment supply is ample, restoration at lower elevations may still be successful as rapid gains in elevation and carbon addition from root biomass may occur (Liu et al., 2021; Mossman et al., 2022). Permanence can also occur where autochthonous production is high, particularly in more biogenic/organogenic settings (Krauss et al., 2017; Cahoon et al., 2021; Windham-Myers et al., 2023). Restored coastal wetlands do not need to depend on vertical processes alone for decadal-scale permanence. Where geomorphic development has led to available accommodation space and land use is amenable, lateral migration into upland or upstream habitats can allow continued cooling benefits of coastal wetland restoration activity even where vertical elevation-building processes are expected to be overwhelmed (Osland et al., 2022; Owers et al., 2022; Rogers et al., 2022; Wang et al., 2023).

Perhaps of more immediate concern regarding restored site permanence are short-term disturbances, such as stochastic storm impacts and anthropogenic pressures on restored coastal wetlands (Hanley et al., 2020; Newton et al., 2020). Minimizing the risk of such short-term perturbation will support permanence. If short-term perturbation risks can be minimized, sites with high sediment supply, large tide ranges, high rates of foundation species primary productivity, shallow elevation gradients, and harmonious upslope land use may both accumulate carbon rapidly and be resilient to future sea-level rise, retaining carbon in the long term (Cahoon et al., 2021; Osland et al., 2022; Saintilan et al., 2022). Overall, restoration may be most successful at achieving permanence when targeting areas where intertidal surfaces can readily adjust vertically and/or laterally through a combination of allochthonous and autochthonous processes, ensuring resilience through 2050. Projects that do submerge from relative sea-level rise after management-relevant timescales can still have important mitigation contributions over the next several decades.

## Local factors

Whether or not the fundamental requirements of additionality, feasibility and permanence are met by a restoration action is largely set by global and regional-scale factors. However, local-scale factors including restoration design and the identity/abundance of biota can enhance or detract from site-specific restoration effectiveness as NCS. Restoration design decisions can determine channel density and flow path, wetland elevation and inundation, and vegetation cover and community identity through planting or natural colonization approaches (Lester et al., 2020; Vanderklift et al., 2020; Valach et al., 2021), all of which can influence the net cooling benefit of restoration compared to initial conditions. Research exploring the impact that coastal wetland restoration design decisions have on restored site effectiveness as NCS could expand on what little is currently known about which designs maximize carbon sequestration. These studies may be especially informative if they focus explicitly on how design options influence additionality, feasibility and permanence.

Local interactions of environmental conditions with biota, including macrophytes, macrofauna and microbes, can influence restoration effectiveness as NCS as well. Vegetation influence on local-scale carbon dynamics is becoming better characterized (Jones et al., 2018; Mueller et al., 2020; Kennedy et al., 2022; Kong et al., 2022; Jeffrey et al., 2023), although current work is often less clear on the precise mechanisms of plant-mediation of carbon processes (but see Vroom et al., 2022). Foundation plant species often establish quickly after restoration, jump-starting wetland carbon uptake, but this is not universally true where foundation species are large and/or slow growing (Marbà et al., 1996; Ballanti et al., 2017). Less well known are macrofaunal influences on restoration effectiveness as NCS. A growing body of literature has emphasized the importance of crab bioturbation on carbon loss in tidal marshes and mangroves, for example, via changes in sediment permeability/exchange and microbial communities, among other mechanisms (Gutiérrez et al., 2006; Guimond et al., 2020; Xiao et al., 2021; Qin et al., 2024; Smith, 2024). Microbial processes, dependent upon the abundance and identity of microbial communities, vary at small spatial scales and are strongly influenced by tidal inundation and associated abiotic factors (e.g., water content, salinity, oxygen and nutrient availability; Cheung et al., 2018; Rinke et al., 2022). Following wetland restoration, changes can occur in fungal communities as well, as the ecosystem matures into a marine setting (Walker and Campbell, 2010; Dini-Andreote et al., 2016). Microbial communities may have a strong impact on restoration effectiveness as NCS by exerting a key influence on carbon cycling processes important for cooling benefits (e.g., methanogenesis and methane oxidation; Oremland and Polcin, 1982; Segarra et al., 2013; Capooci et al., 2024). Additional studies that explore how organism presence and abundance impact a site's capacity to meet the fundamental NCS requirements within the range set by climate and geomorphology would be helpful.

## Future perspectives

Coastal wetland restoration will be most effective as NCS where additionality, feasibility and permanence are maximized. Verifying these requirements are met in an ecological context (Table 1) is more straightforward than the complex task of quantifying the magnitude of project-specific cooling benefits for carbon finance or accounting purposes. Issues with quantifying magnitudes of climate benefit are not addressed here, as we focus below on the issues impeding initial deliberation of whether restoration has a net climate benefit, the crucial point for restoration implementation.

### *Coastal wetlands as cross-ecosystem linkages*

One issue in understanding when and where coastal restoration actions are effective NCS is uncertainty in additionality for ecosystems that are interfaces and integrators of terrestrial and aquatic habitats. It is sometimes unclear if a restoration project meets the fundamental requirement of having a net cooling benefit when those cooling benefits can occur in habitats outside of project footprints. For example, connectivity between restored sites and surrounding landscapes can be an important driver of the carbon cycling benefits of restoration (Woo et al., 2022; Mazarrasa et al., 2023). Allochthonous material, in particular, can be buried at substantial rates upon initial restoration in salt marshes (Wollenberg et al., 2018; Mossman et al., 2022). The reduced water movement through seagrass meadow canopies (Peralta et al., 2008) not only facilitates high retention of autochthonous production, but also results in increased deposition of allochthonous carbon (Fonseca and Fisher, 1986; Hendriks et al., 2008), estimated to contribute to ~50% of the sediment organic C pool in these meadows on average (Kennedy et al., 2010). Tidal forests can also trap substantial amounts of allochthonous material (e.g., Noe et al., 2016). However, there remains uncertainty on whether allochthonous carbon removed from the atmosphere upstream or upslope and then buried in a coastal wetland should be considered part of the cooling benefit from the restoration action. Similarly, there remains uncertainty on if autochthonous carbon that is removed from the atmosphere in a coastal wetland restoration area and then exported laterally to the near-shore environment with potential long-term storage (especially as dissolved inorganic carbon or total alkalinity; Santos et al., 2019, 2021; Yau et al., 2022; Reithmaier et al., 2023) should be considered part of the cooling benefit. Ignoring these lateral connections can affect the estimated cooling benefit of a restoration action, potentially influencing if projects meet the fundamental requirement of additionality (Bogard et al., 2020; Schutte et al., 2020; Correa et al., 2022).

To address this issue, one approach is to take a landscape/systems view for determining if a specific management action will lead to a net cooling benefit (Figure 2), regardless of the spatial footprint that benefit occurs in (similar to the efforts underway for landscape-scale carbon accounting; Glass et al., 2024). In other words, tracking the response of a landscape (e.g., a watershed) to management actions, not the response of one habitat type to management actions. Lateral export of carbon that is buried (or emitted) outside of the restoration site should contribute to understanding a wetland's cooling benefit compared to initial conditions, as long as the export would not have occurred without restoration action. In the case of greenhouse gas emissions, particular care must be taken to ensure appropriate baseline comparisons that consider surrounding land uses as potential sources contributing to wetland fluxes (e.g., $N_2O$ from prairie pothole wetlands; Tangen and Bansal, 2022), to avoid penalizing wetlands as the spot where allochthonous carbon enters the atmosphere even when the land management decisions driving carbon and nutrient export and mineralization are made upslope or upstream. For allochthonous carbon burial, if the accommodation space created by restoration allows the preservation of carbon that would have otherwise been mineralized, that leads to a cooling benefit even if the carbon was removed from the atmosphere offsite (Wollenberg et al., 2018). We acknowledge that taking a landscape approach to the cooling benefit of coastal wetland restoration may be difficult in practice,

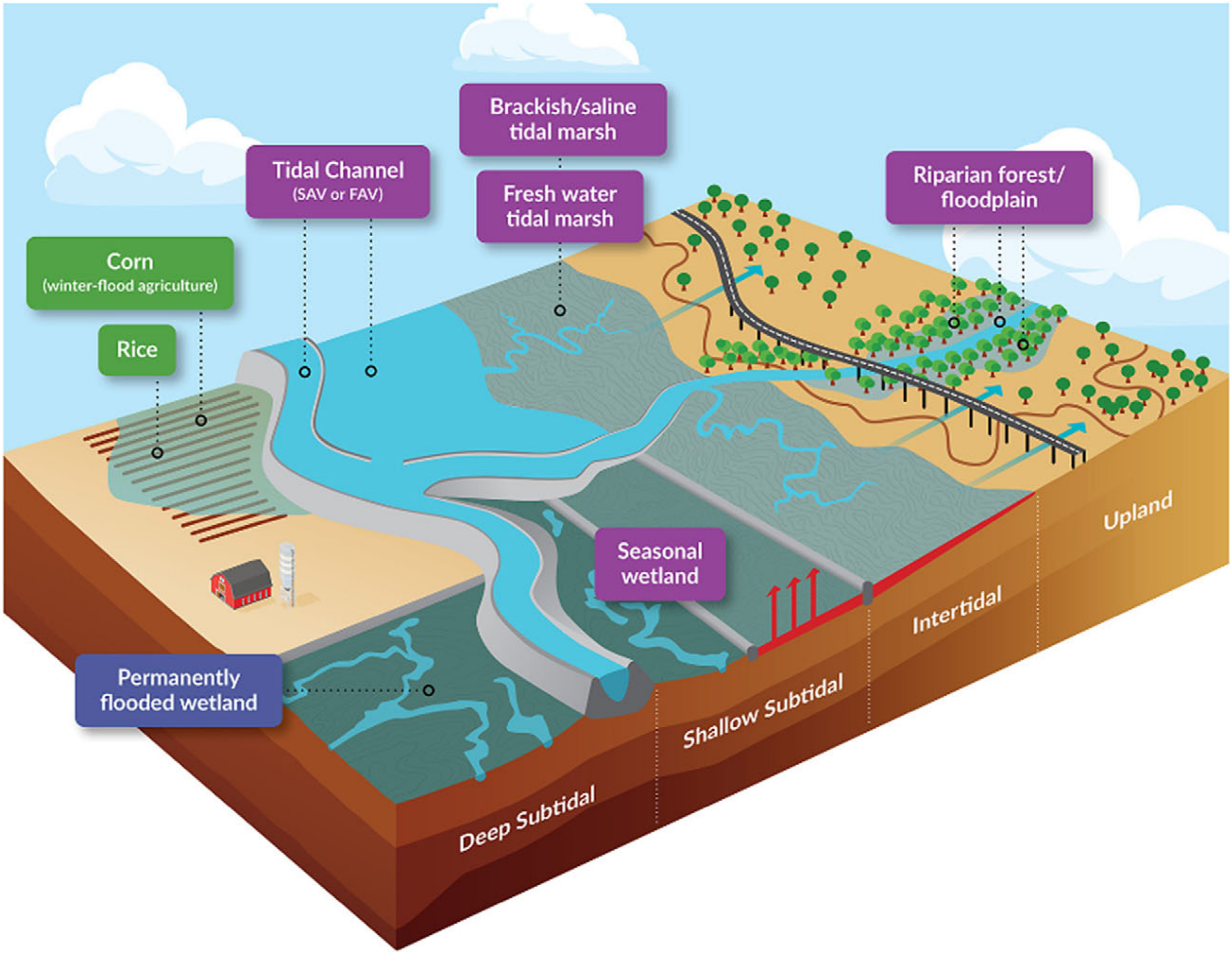


**Figure 2.** Land-use types of interest to carbon sequestration and/or GHG mitigation across the relative tidal elevation range in Suisun Bay and Delta lands. Corn indicates conventional row crops. Tidal channel refers to open-water aquatic habitats, whether deep or shallow (such as flooded islands) and which may be populated by submerged or floating aquatic vegetation (SAV and FAV). Permanently flooded wetland refers to wetlands impounded to reverse subsidence. Seasonal wetland refers to wetlands managed via freshwater flooding to benefit wildlife. *Credit: Illustrated by Vincent Pascual, California Office of State Publishing, adapted from SFEI.*

as mass balance approaches are most tractable at site-level scales. However, this approach may allow a more holistic understanding of additionality and cooling benefit from restoration actions in coastal wetlands, incorporating the true connectivity of these habitats as cross-ecosystem linkages.

## *Coastal wetland migration*

Another issue in understanding when and where coastal restoration actions are effective NCS is uncertainty in permanence for ecosystems that are dynamic on the landscape. As they cope with accelerating sea-level rise, coastal wetlands have the potential to migrate both upslope and upstream over management-relevant timeframes (Krauss et al., 2018; Gedan and Fernández-Pascual, 2019; Osland et al., 2022; Wang et al., 2023). Restored wetlands may therefore move out of the original project footprint over time, making it difficult to estimate the longevity of cooling benefits from management actions. Restored coastal wetlands may submerge under relative sea-level rise rates above ~5–7 mm/year (Saintilan et al., 2022; Morris et al., 2023), converting to unvegetated flats (Haywood et al., 2020; Schoolmaster et al., 2022). The fate of wetland carbon cycling with such state change and concurrent potential erosion is not clear (Creamer et al., 2024), but cooling benefit losses may be at least partially offset by cooling benefit gains as upslope or upstream habitats are converted to new wetlands (Osland et al., 2022; Wang et al., 2023). In certain regions with large areas of accommodation space, in fact, relative sea-level rise may increase the total habitat of coastal wetlands (Schieder et al., 2018), although newly colonized habitat from upslope migration may initially have lower soil carbon accumulation rates than mature habitat (Sandi et al., 2021). The resilience of a restored wetland to submergence over management-relevant decadal scales, including the availability of accommodation space to migrate upslope or upstream, therefore becomes of prime importance.

To address this issue, a landscape/systems approach again may be helpful (Figure 2), but for permanence: not tying permanence of restoration cooling benefit to a specific spatial footprint, unless human constraints on wetland migration preclude movement of carbon benefits across the landscape. This approach incorporates the natural dynamism of coastal wetlands and the reality of complex landscapes. Dealing with disturbance and dynamism is not new for habitats used as NCS: forests also experience disturbances like wildfire that can release stored carbon (Hurteau et al., 2008). Unlike forests experiencing fire, it is possible that stored carbon from submerging wetlands can continue to be stored with lateral export to shallow ocean shelves (Santos et al., 2021). Existing remote sensing tools and analyses can help to identify priority areas where restoration could be resilient and extend the lifetime of restored wetlands undergoing relative sea-level rise impacts (e.g., Rogers et al., 2023b; Ganju et al., 2024). Taking a landscape approach to permanence provides an opportunity to move beyond single–habitat focused restoration, thus aggregating restoration action influence across the landscape (Thorslund et al., 2017). Framing permanence in a management-relevant context (i.e., the next few decades) addresses the concern that some wetlands will submerge in the future (especially by the end of the century; Saintilan et al., 2022); having enhanced uptake in the next few decades can buy time for more robust climate solutions even if additionality somewhat decreases with migration. Ultimately, a landscape approach prevents focusing on the storage of a particular molecule in a particular place, shifting perspective to the overall cooling benefit of a management action.

### *Methane and management-relevant timeframes*

Uncertainty in how to incorporate methane emissions is another issue preventing understanding of when and where coastal restoration actions are effective NCS. Methane is a potent but short-lived greenhouse gas (Neubauer and Megonigal, 2015), and becomes a crucial component of the cooling benefit of restoration actions given decadal management-relevant timescales. Regardless of methane emissions, wetlands commonly exhibit climate cooling impacts on geologic timescales (Frolking et al., 2006; Neubauer and Megonigal, 2015); on management-relevant timescales, however, methane emissions can significantly influence the efficacy of restoration activities as NCS (Schutte et al., 2020; Arias-Ortiz et al., 2021b). Microbial communities responding to environmental conditions control the balance between methane production (methanogenesis) and consumption (methanotrophy/oxidation) in soils, as they break down organic matter for energy (Oremland and Polcin, 1982; Segarra et al., 2013; Capooci et al., 2024; Hartman et al., 2024). There is broad agreement that salinity (often used as a proxy for sulfate concentrations) decreases methane emissions in coastal wetlands, even if mechanisms remain uncertain (Bartlett et al., 1987; Poffenbarger et al., 2011; Bridgham et al., 2013; Chuang et al., 2016; Rosentreter et al., 2021; Sanders-DeMott et al., 2022). Dominant plant communities can also control methane emissions, through plant-mediated gas fluxes. These fluxes can make up the dominant pathway of methane emissions to the atmosphere in coastal wetlands, as methane vents through herbaceous or woody tissues (Jeffrey et al., 2019; Mueller et al., 2020; Villa et al., 2020; Comer-Warner et al., 2022). Finally, it is becoming clear that lateral export of dissolved methane is a potentially important, but under-recognized, methane flux pathway (Santos et al., 2019; Schutte et al., 2020; Chen et al., 2022; Wang et al., 2022b). Especially in low-salinity conditions and/or with high productivity of wetland-adapted plants, methane can complicate understanding if restoration actions meet the basic requirement of NCS of having a net cooling benefit.

Incorporating methane emissions is crucial, but may be most helpful within the context of coastal restoration as NCS when focused on the cooling benefit of specific management actions. Methane emissions are not inherently bad, and productive low-salinity restored sites with high methane emissions may still provide large cooling benefits compared to pre-restoration conditions (Hemes et al., 2019; Günther et al., 2020; Arias-Ortiz et al., 2021b; Nyberg et al., 2022; Adame et al., 2024). Methane emissions are sometimes measured in restored coastal wetlands, but often pre-restoration baseline data or data from analog/alternative land use sites are lacking, preventing an understanding of the net change in methane emissions and overall cooling benefit attributable to restoration actions. Therefore, effective methane monitoring includes data collection at alternative land use sites and begins pre-restoration where possible. Additionally, coordinated synthesis activities can help in gathering, making available, and interpreting the rapidly accumulating greenhouse gas flux datasets from blue carbon ecosystems, especially for marshes and mangroves (Knox et al., 2019; Rosentreter et al., 2023; Arias-Ortiz et al., 2024). Seagrasses pose a particular challenge here, as they exchange dissolved inorganic carbon with the water column rather than carbon dioxide directly with the atmosphere. Coordinated synthesis of benthic, air–water, and lateral fluxes in seagrass ecosystems, including methane, can provide needed insight into their restoration benefit as NCS, as with lateral fluxes in blue carbon ecosystems more generally (Santos et al., 2021). Incorporating methane emissions over management-relevant timeframes (e.g., by using sustained-flux global warming potential for a 20-year time horizon; Neubauer, 2021) without forgetting that methane emissions do not inherently preclude effectiveness as NCS can help to move the field toward inclusion of all tidal wetlands that may provide climate mitigation benefits (Adame et al., 2024).

### *Minimum data requirements*

Information supporting the likelihood that a project will, at a minimum, lead to a cooling benefit is a prerequisite for taking restoration action as NCS, but it is unclear if the magnitude of cooling benefits also needs to be quantified before action takes place. Modeling is often used as a tool for guiding restoration decision-making, but some projects do not require modeling approaches to understand the binary outcome of whether or not an action will have a cooling benefit (e.g., Twomey et al., 2024). Coastal wetland restoration projects are already happening around the world without a modeled estimate of cooling benefit; this lack of carbon accounting does not influence whether or not a real climate benefit is occurring. In landscapes with multiple competing values, or where a high level of precision is needed, complex models are certainly required to understand if an action has a net benefit. In the cases where more complex modeling is required, several biogeochemical models designed for tidal wetlands enable the prediction of organic carbon accumulation, sediment accretion, and other carbon-related processes with changes in relative sea levels (Buffington et al., 2021; Morris et al., 2023; Vahsen et al., 2024). This particular scenario may be uncommon when considering all the locations where blue carbon restoration is likely to be successful globally. Where complex models are not required, there remains disagreement on the data necessary to understand project effectiveness as NCS. When plot-level data exist, an additional uncertainty is how best to use spatially explicit information to scale up to footprints relevant for projecting landscape-level response to restoration action (Duarte de Paula Costa et al., 2022; Matthes et al., 2014; Shahan et al., 2022). Regardless of the complexity of data required, long-term post-implementation monitoring allows evaluating actual restoration project responses and ensures projects are meeting expectations and targets over time (Wortley et al., 2013; Cadier et al., 2020; Lovelock et al., 2022c). A robust understanding of carbon cycling responses to restoration action is crucial for quantifying the total magnitude of cooling benefit, but where cooling benefit is not predicted to be large, it may be critical for understanding if a cooling benefit exists at all.

It may be useful to explicitly differentiate the minimum data requirements for coastal restoration as effective NCS (i.e., answering ‘does this management action accrue a climate benefit?’) from the data requirements for quantifying the magnitude of cooling benefits for carbon accounting purposes (i.e., answering ‘how much climate benefit does this management action accrue?’). There is a need for widely distributed, standardized minimum data that can be applied to address the former question (Table 1). Much of the minimum data needed is spatial in nature, as spatially explicit data are most useful to land managers and restoration practitioners for on-the-ground prioritization (Lovelock et al., 2022b; Rogers et al., 2023b). These spatial data include up-to-date maps of regional land use/land cover (Sleeter et al., 2018, 2022), land ownership (Lovelock and Brown, 2019), and topography (including human alterations that impede wetland migration; Osland et al., 2022; Rogers et al., 2023b). Vegetation types in particular are often mappable, and may be crucial to up-scale data on climate benefits using remote sensing observations (e.g., Kong et al., 2022). Other minimum data requirements are not explicitly spatial (but may still vary regionally), including carbon balance or emissions/removal factor estimates for land use/land cover classes (from direct measurements or model outputs; Hagger et al., 2022; Windham-Myers et al., 2023), estimates of restoration cost per area restored given the prevailing restoration culture and financial incentive (Taillardat et al., 2020; Hagger et al., 2022), and resilience to relative sea-level rise (Holmquist et al., 2021; Ganju et al., 2024). Further, communicating and collaborating with local communities to ensure stakeholder involvement and equitable distribution of restoration co-benefits is key in any project (Surgeon Rogers et al., 2019; Dencer-Brown et al., 2022; Lovelock et al., 2022c). Beyond these suggested standard data types, additional project-specific considerations that impact additionality, feasibility and permanence will arise. If minimum data requirements are unavailable in a region, that helps prioritize new data collection efforts. One way to fill gaps for areas without the minimum required data is to leverage areas with more intensive data. Using regional-scale data stratified by local-scale gradients like elevation, for example, can provide a path forward for estimating the value of restoration from a carbon perspective (Wang et al., 2022a; Lovelock et al., 2022b; Windham-Myers et al., 2023; Yando et al., 2023). Understanding the magnitude of cooling benefits for accounting purposes is a crucial, but distinct, second step in the process of addressing effectiveness of coastal wetland restoration as NCS. We posit that confounding these distinct questions can impede implementation of restoration projects that are likely to have a climate benefit.

## Conclusion

Here, we synthesize the fundamental requirements of additionality, feasibility and permanence to address the question, ‘when and where is coastal wetland restoration effective as a natural climate solution?’ Maximizing the values underpinning these three key factors can increase the effectiveness of restoration projects, for example, by targeting regions with large areas of degraded habitat that will net a substantial climate cooling benefit when restored (additionality); where socio-economic and governance factors are in place to support action (feasibility); and where there is high resilience to future relative sea-level rise (permanence). Recent work is leading the way for effective site-level prioritization (Rogers et al., 2019b; Moritsch et al., 2021; Duarte de Paula Costa et al., 2022; Rogers et al., 2023b). To move toward successful implementation at scale, we highlight paths forward on several issues impeding confidence in coastal wetland restoration as NCS. First, tracking the cooling benefit of specific management actions across the interconnected coastal landscape, not project-specific spatial footprints. Second, the importance of incorporating methane into restoration considerations, as effective NCS will function over management-relevant decadal timescales. Finally, the minimum data required to understand if an action has a climate benefit is likely more tractable than the data required to understand the separate issue of quantifying the magnitude of climate benefit. Ultimately, for maximal NCS effectiveness, energy and resources will be focused on prioritizing sites with high additionality, where restoration actions are feasible and where permanence is likely. We stress that within this framework, coastal wetland restoration provides immense benefits beyond mitigating climate change (Vegh et al., 2019; Pindilli, 2022; Hambäck et al., 2023). There are strong calls for ecosystem restoration over the next decade (United Nations Environment Programme (UNEP), 2021). Reducing uncertainty can help to ensure that coastal restoration actions deliver climate cooling benefits within the decadal timeframes necessary to function as one climate mitigation strategy among many.

**Open peer review.** To view the open peer review materials for this article, please visit http://doi.org/10.1017/cft.2024.14.

**Data availability statement.** No data were used in the preparation of this manuscript.

**Acknowledgments.** Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank the editor and anonymous reviewers for their comments that improved the manuscript.

**Author contribution.** S.F.J. led the conceptualization of the manuscript with substantial input from co-authors. S.F.J. led the writing of the original drafts with contribution from co-authors. All authors contributed to revision and review.

**Financial support.** A.A.-O. acknowledges support from MCIN/AEI RYC2021-034455-I. D.B. acknowledges support by the Delta Science Stewardship Council and the US Department of Energy Ameriflux project. C.L.S. and K.T. acknowledge support by the U.S. Geological Survey Ecosystem Mission Area. E.J.W. acknowledges support from the NASA Terrestrial Ecology Program and Carbon Monitoring System that support the BlueFlux field campaign and related efforts.

**Competing interest.** The authors declare none.

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