Assessing existing data, models, and opportunities for California's blue carbon ecosystems in the context of California Air Resources Board's 2027 Climate Change Scoping Plan

About this Report

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CALIFORNIA OCEAN PROTECTION COUNCIL

Executive Summary

The California Air Resources Board (CARB) is responsible for co-developing and modeling Natural and Working Lands (NWL) future projected scenarios to set State carbon targets - scenarios that include environmental changes, management changes, restoration, and conservation. Not all of California's blue carbon ecosystems (tidal marshes, seagrass meadows, and kelp) were previously included, in part due to lack of historical data. However, recent advancements in data quantity and quality over past years, particularly in tidal marshes, mean that an assessment should be performed to determine if this new information is sufficient to include these ecosystems into the CARB's target setting and NWL carbon stock inventory methodology.

Here, we outline definitions and frameworks used in California's carbon inventories and carbon target modeling, along with the criteria and data required for including novel ecosystems in the future, with a focus on blue carbon ecosystems. For inclusion, the applied models need to meet several criteria to fit State needs (e.g., scalability, transparency, complexity). We identify existing data, and models that can act as a foundation for inclusion of blue carbon ecosystems as an additional 'land-type', acknowledging the many references and existing resources that have previously summarized many of these aspects (Table 3). The provided context and background aim to bridge the gap between site-specific data collection, existing models, and the requirements for models to be applied for statewide carbon targets and inventories. This report is intended to act as guide when considering model or inventory development as well as investment prioritization for blue carbon ecosystems.

Through this summary process, we identify several key findings:

- Models exist that can act as a foundation from which further developments can be made to meet criteria identified in this report. The PEPRMT-DAMM and CWEM/MEM models (Section 3.1), along with future models that integrate these two models are the most likely candidates for further development.
- Scaling these models for statewide application will require investment in reliable, high-quality mapping and appropriate validation of the model(s) across representative sites. These data do not yet exist in a manner that can be used to fit the Scoping Plan needs.
- No single database exists to track restoration projects, success, costs, and monitoring. Additional investment to address key data gaps for tidal wetlands include synthesis of the locations, costs, success rates, and monitoring data of ongoing restoration projects to track outcomes and inform future prioritization.
- Models to include seagrass meadows, estuaries with dynamic ocean inlets, heavily degraded wetlands, and other blue carbon ecosystems in the NWL Inventory and

scoping plan could ultimately be developed based on the paradigm used for coastal wetlands. However, this will require further investment to meet modeling needs and fill empirical data gaps to enable statewide application (see section 5).

Management of blue carbon ecosystems, particularly with respect to use and movement of sediment, can drastically alter associated carbon fluxes. An improved understanding of these processes, supported by robust models, could further elucidate the carbon benefits gained in the coastal zone relative to other ecosystem types and management approaches.

1. Introduction

The California Air Resources Board (CARB) is responsible for the State's carbon inventory and developing the state's path towards carbon neutrality. Part of this process includes modeling management and climate scenarios to develop Natural and Working Lands (NWL) carbon targets. This is done through the Scoping Plan process and will be updated every five years (CARB Scoping Plan, 2022). CARB also maintains California's NWL carbon inventory (CARB inventory, 2018). NWL currently includes seven land types - forests, shrublands/chaparral, grasslands, croplands, developed lands, wetlands, and sparsely vegetated lands. Interventions including conservation, restoration, and management actions on the State's NWL are used to set California's carbon target and neutrality goals, a process CARB aims to track and model.

Blue carbon ecosystems (tidal marshes, seagrass meadows, and kelp) support fisheries and biodiversity, improve water quality, stabilize sediments, and provide recreational and cultural value, among many other ecosystem functions. While ecosystem restoration and conservation build climate resilience through recovery of these essential functions, different interventions in different land types across the State will each come with uniquely associated carbon dynamics. While CARB seeks to ultimately include all land types (including blue carbon) into modeling efforts, each ecosystem type is considered differently, as carbon dynamics vary from system to system. Assessing where climate beneficial opportunities are and quantifying them can be challenging, requiring support from extensive bodies of scientific evidence. The effect of interventions and environmental change on long-term, statewide carbon stocks must also be reliably modellable, making evident the need for robust, data-driven models.

Although California's coastal blue carbon was not included in the 2022 Scoping Plan Update, the Delta wetlands were included. This is because of all the wetlands in California, the Delta has been extensively studied, has tailored models to that system, and has relatively high levels of monitoring and mapping resources (CARB, 2022; Deverel and Leighton, 2010). However, it should be noted that even though the Delta was included in the Scoping Plan, the NWL Carbon inventory still lacks the needed sensitivity to track impact of management and climate change in the Delta.

There are wetlands beyond the Delta throughout the state, including significant coverage of tidal marshes and seagrass meadows, that are not currently dominated by agricultural land use or drastic sediment loss. As described in Vaughn et al. 2022, "*Adding statewide saline wetlands and eelgrass to the Delta wetlands included in the May 2022 Scoping Plan draft would increase the extent of existing wetlands evaluated in Scoping Plan NWL scenarios by 57,000 acres, or nearly 70%*." The Delta example serves to highlight how one wetland type was included into CARB's modeling efforts, while also recognizing that there are key differences between coastal wetlands and the subsidence-dominated Delta wetlands over which this model was applied.

In this report, we focus on tidal marshes, seagrass meadows to a lesser extent, and exclude seaweed ecosystems, given the increasing relative data paucity and scientific uncertainty associated with each (see sections 5.1 and 5.2). Areal coverage of these habitats state-wide is currently estimated at >1200 km^2 for tidal salt marshes, >60 km^2 for eelgrass, and ~72 km^2 for canopy forming kelp, but with high uncertainty associated with eelgrass and kelp (Ocean Science Trust, 2021). Like the Delta, but contrary to many other ecosystem types where carbon is stored in the living biomass, tidal marshes and seagrass meadows store carbon predominantly in underlying sediment, where inundation, low oxygen concentrations, and high sedimentation rates lead to high sequestration and permanence, removing labile carbon for millennia (Duarte et al. 2013).

Given the importance of the ecosystems and current gaps in existing models, this document seeks to:

1. review coastal carbon dynamics in the context of carbon inventories and models.
2. summarize and identify criteria and data necessary for inclusion of tidal marshes and seagrass meadows in future Scoping Plan updates; identify possible models that can act as a foundation to develop implementable, process-based models for tidal marshes.
3. identify research and data gaps that need investment so that coastal wetlands can be included in California's climate mitigation strategies.

As CARB's efforts expand to include more nuanced ecosystem types, higher data quality, and improved model performance, incorporation of blue carbon ecosystems can advance carbon neutrality goals using low risk, nature-based solutions that improve, restore, and conserve NWLs.

2. Coastal carbon dynamics in the context of carbon inventories and models

2.1 Carbon cycling

In tidal wetlands and seagrass meadows, carbon is stored primarily in sediment, with lower relative carbon stocks in the living biomass. As a result, the processes for inventorying and tracking carbon can vary. In tidal wetlands and seagrass meadows, the low carbon degradation in inundated sediments facilitates sequestration of carbon sourced either from the overlying vegetation itself (i.e., seagrass or marsh vegetation) or other sources (e.g., particulate organic matter, plankton, imported terrestrial biomass). Tidal wetlands and seagrass meadows can also dampen hydrodynamic energy, further facilitating the settlement of suspended particles from terrestrial or tidal flows, trapping and preserving organic material that may have otherwise remained suspended and ultimately remineralized (Al-Attabi et al. 2023; Temmink et al. 2022).

Differences in where and how carbon is sequestered and preserved between terrestrial and coastal ecosystems can make it challenging to understand where the carbon in coastal zones came from, especially addressing double counting[1] due to lateral flows. While a large proportion of sedimentary carbon can be sourced from within each ecosystem (autochthonous), some carbon can be imported (allochthonous) (Krause et al., 2022; Oreska et al., 2018). Sources and quantity of carbon sequestered depend on many factors such as hydrography, geomorphology, the surrounding ecosystems, and underlying sedimentary processes within the watershed (de los Santos et al, 2022; Schulte Ostermann et al. 2021). Currently, CARB's models of NWLs are applied over unique ecosystem types. While understanding lateral flows of organic carbon across seascapes is important, it is not a requisite to modeling individual ecosystem types - understanding the fate of carbon exported outside of the ecosystem in question would fall outside the scope of its associated model, so long as the model accounts for this loss. However, iterative improvements to understand and model coastal sediment dynamics and lateral flows can still further inform the coasts' role in California carbon cycling and opportunities for carbon reduction, beyond the scope of blue carbon ecosystems alone. Of note, lateral flows have been poorly incorporated into large-scale blue carbon assessments across the globe to date, largely due to lack of data and the challenges associated with collecting these data. However, new data and research indicate that this lack of inclusion could be greatly underestimating climate mitigation potentials, meriting exploration.

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1. Double-counting refers to carbon that is considered 'removed' in more than one ecosystem (e.g., carbon counted as sequestered in salt marsh biomass that is counted again after lateral import to seagrass meadow sediments).

Of additional note, other greenhouse gas (GHGs – methane and nitrous oxide) fluxes can counter carbon sequestration occurring in these ecosystems, particularly in low salinity environments (<18 parts per thousand or ppt) or in areas with excess nutrient inputs (Poffenbarger et al. 2011; Martinez-Espinosa et al. 2021). As salinity increases, it is likely to reduce methane fluxes, which is of particular interest when considering saltwater intrusion associated with sea level rise (Luo et al., 2019). In the absence of process-based models informed by *in situ* emissions data (e.g., the PEPRMT-DAMM model; Oikawa et al. 2017), emissions factors can be applied, as outlined by the United Nations Intergovernmental Panel on Climate Change (IPCC) and from Vaughn et al. 2022 as alternatives, although this approach is less rigorous and less sensitive to future changes to ecosystems and environmental drivers.

Despite these complexities, a body of science exists both globally and within the state to lay the preliminary groundwork for estimating how much carbon is sequestered and stored within tidal wetland ecosystems (OST, 2021), and where it came from. Using these data, we can glean a broad brush understanding of our current carbon inventory stored in California's tidal wetlands and look towards development of a model to be applied statewide.

2.2 Conceptual frameworks for carbon inventory and future projection modeling

The State of California supports efforts to estimate the state of ecosystem carbon stored in its land base (the NWL Inventory) as well as developing a road map for how to reach climate goals (future projection modeling in the Scoping Plan) in order to develop, track and meet its ambitious climate goals. Here, we aim to provide clarity on how existing data and models are used to support these approaches. In addition, within the context of tracking and modeling carbon within California's tidal wetlands and seagrass meadows, estimates can be conceptualized both at a steady state, where no external changes occur within the ecosystem in question or a non-steady state 'projection' of expected future changes in carbon. This first can be helpful when conceptualizing California's carbon inventory, and the latter for projections for future carbon stocks. We step through these approaches here to illustrate the differing needs, challenges and merits associated with each.

2.2.1 Carbon inventory

The NWL inventory is an important tool for informing how California's land base contributes to the State's climate goals and tracking statewide progress toward the State's long-term objectives for NWL. Previous work indicates that models, data, and emission factors can be used to produce snap shots of carbon stocks within California blue carbon ecosystems (see Vaugh et al. 2022; OST, 2021; Wedding et al. 2021). However, the NWL inventory "provides estimates of carbon stocks *and stock changes*" attributed to disturbances or management changes, and includes GHG fluxes from wetlands (CARB, 2022), which can be a more challenging estimate to make. One broad approach to estimate changes in carbon stocks over time is through the use of emissions factors, as laid out within the IPCC. Specifically, emissions factors are "*used to link the emission of a greenhouse gas for a particular source to the amount of activity causing the emission*" (IPCC, 2019). While feasible, emissions-factor approaches remain relatively insensitive to future changes to landscape stressors and drivers of change, making them less robust than process-based models. In the case of California tidal wetlands and seagrass meadows, emissions factors developed from California-specific data can improve the use of these factors and can be iteratively improved as new data are collected (see Table 2 from Vaughn et al, 2022)

A static approach to estimate carbon stocks entails evaluating carbon stored within tidal wetlands and seagrass meadows at a single point in time (i.e., a 'snapshot'). These inventory estimates can be made using existing data, to varying degrees of certainty based on data quality and availability. Statewide estimates of tidal wetlands and seagrass meadow extent paired with sufficient associated carbon data can be scaled to produce estimates of the existing, statewide carbon standing stocks in these ecosystems. For example, OST (2022) outlines existing key empirical data on carbon fluxes and ecosystem acreages, estimating that seagrass meadows within California sequester carbon in sediment at rates ranging from 1.58 - 14.2 g C m^{-2} yr^{-1} and California salt marshes at rates of 7.08 - 40.33 TCO_2 ha^{-1} yr^{-1} (i.e., estimates of stock changes over long-term timescales). These rates are scaled up using statewide acreage estimates (Table from OST, 2021). Similarly, Vaughn et al. (2022) estimate State coverage of roughly 43,000 acres of tidal marsh and tidal scrub/shrub wetlands and 13,000 acres of eelgrass, reporting California-specific emissions factors where possible that can be used to inform these steady state approaches. Lastly, Wedding et al. (2021) present stock estimates based off of the InVest blue carbon model in three key estuaries across the state; for example, estimating one restored tidal marsh in Humboldt Bay to sequester 211,000 to 885,000 T CO_2 from 2016 to 2100 (Natural Capital Project, 2022). The InVest model has been used to make broad spatial scale (national), first order estimates of carbon stocks in multiple locales (e.g., Monter-Hidalgo et al. 2023; Gonzalez-Garcia et al. 2022) and could be similarly applied within California - recognizing though that this approach is not sufficient to meet the needs for advanced modeling we describe below. An example of this 'snapshot' approach is demonstrated in Fig. 1 reprinted from CARB (2018) and underpins California's carbon inventory approach. While a valuable piece of information, these types of assessments will not address carbon accumulation or changes to stocks over time - a key NWL modeling need.

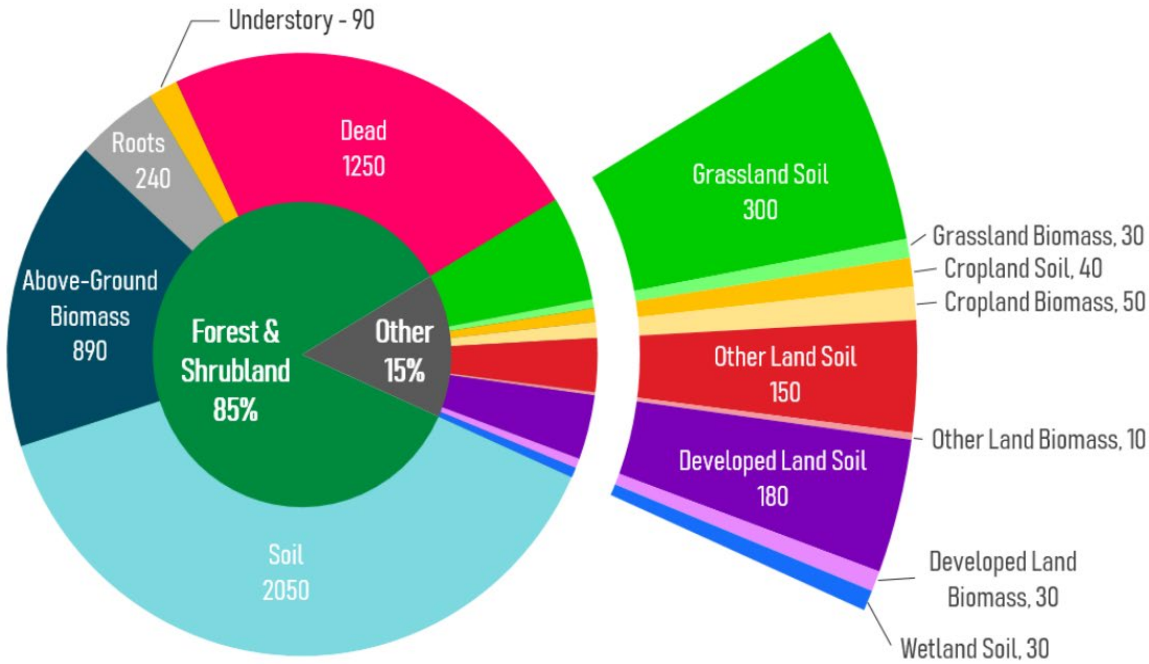

Figure 1 (reprinted from CARB, 2018): "2014 distribution of biomass and soil carbon stocks on the California landscape in MMT carbon (rounded to the nearest 10 MMT). There is approximately 5,340 MMT of carbon in the carbon pools for the year 2014"

Evaluating net carbon accumulation within ecosystems over time becomes more challenging, even assuming a steady state, i.e., no changes in factors such as environmental stress or Land Use Change (LUC). This requires additional data on key parameters including carbon fluxes, sediment carbon accumulation, ecosystem extent and other essential input parameters specific to an applied model. Within blue carbon ecosystems, sediment carbon accumulation rates are commonly estimated using long-term dating techniques, such as ^{210}Pb and ^{137}Cs (e.g., Arias-Ortiz, 2018). Carbon sequestration rates from long-term sedimentation rates have been evaluated in many locations across California tidal wetlands, with more data available in tidal marshes than seagrass meadows (Coastal Carbon Atlas), and data collection ongoing (See Table 2 in OST, 2021). These sedimentation rates, when paired with the carbon stock data and spatial extent, inform how much carbon is stored and accumulating annually in California wetland sediments (living wetland biomass also sequesters organic carbon but is minimal compared to the carbon sequestered in sediment). *In situ* estimates of GHG fluxes could further improve estimates, by accounting for any emissions that counteract the overall carbon benefit from accumulated organic carbon.

2.2.2 Future projection modeling

To incorporate tidal wetlands into the Scoping Plan as ecosystems that can be leveraged to meet climate goals, 'scenarios' associated with these ecosystems must be evaluated to determine how they aid in reaching these goals (e.g., '*what climate benefits do we gain if we restore 1,000 acres of tidal marsh in a given location?*'). Steady-state carbon gains and losses, as described above, do not inform how such scenarios aid in reaching climate goals. This requires knowledge of non-steady state processes such as land use change, management change, environmental changes and the subsequent effects on carbon fluxes associated with each. For these projections, more complex models become essential.

For example, the model currently applied to Delta wetlands simulates expected subsidence on agricultural lands in the Delta, primarily due to microbial oxidation of organic carbon, along with other factors such as erosion, burning, and effects from increasing temperatures (Deverel and Leighton, 2010). While useful, the processes and drivers of change in tidal wetlands will differ, given they are not agricultural soils undergoing intense subsidence in a watershed of highly mixed salinities. Models that include similar likely drivers of change within tidal wetlands should be applied. For instance, sea level rise is highly likely to drive alterations in coastal carbon uptake (Raw et al. 2020), given the intrusion of salt water into higher elevation lands and the strong correlation between salinity and methane emissions (e.g., Luo et al. 2014). Inclusion of other environmental drivers and anticipated management changes (e.g., restoration), particularly those that might alter geomorphology or sediment supply, can enable modeling of a portfolio of scenarios to reach carbon targets with the support of tidal wetlands. For instance, questions such as how delivered carbon benefits vary across management approaches (e.g., where tidal flow is restored vs. re-use of dredge sediment vs. transplant-based projects) (Moritsch et al., 2021) could be addressed by developing projections to reach future carbon targets and relying on process-based models for effective inclusion.

3. Summary of existing models and model criteria for inclusion into Scoping Plan

3.1 Existing tidal wetland models

While new models could be developed to include tidal wetlands and their management into the future Scoping Plans, existing models can be used as a starting point for further development. Using existing models also comes with the benefit of possible previous validation and testing, which increases the certainty of its accuracy and enables faster uptake into state planning (see Table 1, 2). Here, we summarize some key models that could be broadened for use to incorporate tidal wetlands into carbon targets. Seagrass ecosystems, estuaries with interannually dynamic ocean inlets, and heavily degraded wetlands could ultimately be additionally modeled, but have larger data gaps and associated uncertainty, with a smaller foundation to work from (see section 5.1 below).

The Peatland Ecosystem Photosynthesis Respiration and Methane Transport - Dual Arrhenius Michaelis-Menten (PEPRMT-DAMM) model developed by Oikawa et al. (2017) can act as a foundation for modeling CO_2 fluxes and climate benefits associated with the restoration of tidal and impounded wetlands, with a particular focus on understanding the role of methane emissions. Importantly, this process-based model includes environmental parameters sensitive to future climate stressors (e.g., water table height and air temperature). This model has also been validated against *in situ* data, accurately predicting annual budgets within 11 and 31% for CO_2 and methane exchange, respectively. The PEPRMT-DAMM model has been applied to restored wetlands within the Delta but could ultimately be expanded or built off to include other processes within other regions with appropriate testing and validation. See the PEPRMT-DAMM open-source model data and code.

Other models, such as the CWEM/MEM (Coastal Wetlands Equilibrium Mode/Marsh Equilibrium) and WARMER models (see Morris et al. 2022/Schile et al. 2014 and Buffington et al. 2021, respectively) could also act as starting points for application across California tidal wetlands, both estimating carbon reductions via sediment accretion and elevation change in tidal wetlands, incorporating sea level rise along with key sediment parameters. Specifically, the CWEM/MEM models (CWEM is an adaptation of the MEM model) have been applied to coastal wetlands in the Delta, across ranges of salinities and have effectively incorporated '*feedbacks of vegetation with inundation, elevation, and sediment supply into a hybrid modeling approach*' to model changes in sediment accretion (Morris et al. 2022; Schile et al. 2014). See MEM/CWEM open source data, code, and tools for the MEM/CWEM models.. The WARMER-2 model is nearly identical to the MEM-type models and is similarly complex, incorporating elevation, sediment availability, sea level rise, salinity, and responsiveness to changes in vegetation composition and production (Buffington et al. 2021) (See documentation of the WARMER-2 model and input data). However, the WARMER models are not currently open source, and thus are discussed in less detail herein (Table S1). Of note, when compared to the CWEM/MEM and WARMER models, one of the PEPRMT-DAMM model's strengths lies in its ability to accurately predict methane fluxes – a feature the CWEM/MEM and WARMER models do not currently have that will become important to include in mixed salinity systems.

The SUBCALC/SEDCALC models (Deverel and Leighton, 2010; Deverel et al. 2014), are useful to consider within the context of the Delta. These models estimate changes in soil organic carbon, and can incorporate sea level rise into model inputs, along with other factors such as temperature, fire, and erosion. While they have been applied and validated and could be expanded upon, they were designed specifically for impounded and subsiding Delta wetlands, largely for agricultural use, where significant data (e.g., Eddy Covariance data) were available to parameterize the model, focusing on emissions from these systems. Thus, we look towards other existing models designed explicitly for coastal systems, whose processes vary significantly than those captured within the Delta. Existing tools, such as the Landscape Scenario Planning Tool (SFEI, 2022), or the LUCAS model could be used and developed to scale application of such models across the State – another key component of target setting once models are developed and tested. Lastly, the InVest Blue Carbon model can also act as a useful model for first order estimates (as mentioned above), but it is not a process-based model, is less complex in its parameterization, and less sensitive to key environmental changes, making it a less likely candidate for broader application within the context of CARBs NWL and carbon neutrality goals (Wedding et al. 2021; Natural Capital Project, 2022).

3.2 Model implementation and feasibility criteria

In addition to scientific challenges in development of an adoptable model for inclusion of tidal wetlands, there are several quality and practical criteria required for the State to produce estimates continuously and reliably for any ecosystem under consideration. To include ecosystems in inventories or in modeled management scenarios, they must have sufficient spatial and temporal coverage, be sensitive to environmental (e.g., sea level rise for coastal wetlands) and management or land-use changes, be of sufficient quality, and meet CARB's reporting requirements. In addition, given finite state-level resources, constraints exist that aim to maximize the efficiency of use of any developed models. These emphasize that produced models must balance the need for rigor and precision, with simplicity such that they can be adopted quickly and efficiently into future Scoping Plans and inventory reports. We identify such criteria in more detail in column one of Tables 1 and 2 for consideration in model development and selection. PEPRMT-DAMM model (Table 1) and CWEM/MEM model (Table 2) are each evaluated against the identified criteria.

Table 1 (PEPRMT model): Column one summarizes criteria for models that fit within California's existing frameworks for estimating carbon reduction potential. Columns two and three summarize if and how the model meets these criteria, with recommendations for improvement when relevant. For model schematics, refer to Figure 2, Morris et al 2022.

Model Requirements	Meet requirements?	Recommendations
Models for target development should be scalable spatially, generating ecosystem-specific statewide carbon estimates, and be temporally explicit.	**Yes (In Part)**: Model was developed and validated against sites in the Delta but is currently being expanded and validated in regions outside California. Model outputs are temporally explicit, at 30-minute time intervals (except for methane, which is output daily). The model is not currently scalable spatially statewide – it was validated using EC tower data and applied for Delta sites.	With the correct remote sensing and climate data, the model can be run at large spatial scales. The grid cells do not interact, which could improve the model. However, the simplicity enables model runs without strong computing power.
Models for target development should be dynamic and include key ecosystem processes, sensitive to how management and novel conditions (such as environmental and climate change stress) impact carbon dynamics.	**Yes:** Model accounts for respiration and methane production changes due to water table height, availability of Carbon substrate following restoration. The model is also sensitive to wetland age (under 5 years), air temperature, and salinity among other factors.	This model is less sensitive to long-term and short-term changes in the sediment carbon pool (e.g., storms, floods), and could be improved to capture this, or paired with similar models to enable this.

Key modeled carbon dynamics must include carbon stocks, and if possible, emissions and other relevant carbon fluxes.	**Yes (In Part):** Modeled carbon dynamics include net ecosystem exchange (NEE) of CO_2 and methane, incorporating the soil organic carbon pool, among other key carbon pools (Fig 2, Morris et al, 2022).	The model meets criteria for emissions but is less dynamic in its inclusion of changes to organic carbon in sediment through time. Coupling it with other models (e.g., CWEM/MEM) could enable organic carbon tracking over time.
Data should have a proven basis in reality, and ideally be validated with error, accuracy, or uncertainty statistics.	**Yes:** Data and model have been validated based on the relationship between the modeled and observed fluxes, measured within multiple sites within the Delta. This model explained "70% of the variation in NEE and 50% of the variation in CH4 exchange during model validation, predicting annual budgets of CO2 and CH4 within 11% and 31% of observed budgets, respectively." (Oikawa et al. 2017). Additional accuracy and uncertainty statistics are also provided in text.	Models meets these criteria, but it should be acknowledged that predictions in a future of sea level rise and other environmental changes cannot be validated using hindcast techniques, given the uncertainty in an era of changes not previously experienced).

Model outputs should aim to be regularly updated, ideally in an automated fashion, to detect change.	**No:** No efforts have yet been made to regularly update model outputs	Further investment and development could support for a platform to share updated code and run model iterations.
Models and reporting should be transparent and reproducible, with publicly available and open-source data and code where possible	**Yes:** Documentation exists within Oikawa et al. 2017, with code reported on GitHub.	An updated model (PEPRMT-Tidal) manuscript is currently in review but has not been published yet. However, new and final model code is available: https://github.com/pattyoikawa/PEPRMT-Tidal
If competing models exist, the model preference should be given to those that are more mature, have larger bodies of literature, are more transparent, address priority questions, and have an existing user base.	Not Applicable	The model has been applied to Sacramento rice (Fertitta-Roberts et al. 2019) and is being expanded to rice in Arkansas (Runkle et al. 2022). It has been applied within the Delta (Hydrofocus), Louisiana (Sarah Mack, Patty Oikawa Pers. Comms), and in Germany by scientists with Max Planck. It is also being expanded to account for lateral carbon fluxes in tidal wetlands (NASA Award; Kroeger CMS 2022).

Data should be curated, off the shelf, limiting the need for processing by State staff	**Yes**: CH_4 and CO_2 NEE were measured *in situ* for validation, along with other meteorological data inputs. However, the PEPRMT model was applied to sites without model training data, using only remote sensing and local data on weather, water quality, etc. Model inputs were designed to be simple (e.g., greenness index from Landsat, air temperature, light, water table height, SOC). Uncertainty statistics are generated from these validation sites. This approach could be similarly taken elsewhere, limiting the need for additional data.	Improved and ongoing data collection can reduce uncertainty and reduce the need for additional data in the future, however, validation could still be possible without it (see description left). In the updated PEPRMT model (PEPRMT-Tidal), salinity and nitrate estimates will also be needed but could be constants or measured daily (e.g.).

Table 2 (MEM/CWEM model): Column one summarizes criteria for models that fit within California's existing frameworks for estimating carbon reduction potential. Columns two and three summarize if and how the model meets these criteria, with recommendations for improvement when relevant. For model schematics, see Fig. 2 in Morris et al, 2022.

Model Requirements	Meet requirements?	Recommendations
Models for target development should be scalable spatially, generating ecosystem-specific statewide carbon estimates, and be temporally explicit.	**Yes:** The model simulates the vertical evolution of a soil profile in response to sea-level rise for a certain initial elevation, sea-level rise scenario, and set of plant and sediment inputs. It simulates a point (see Figure 1) but can simulate surfaces by simulating a transect of points (Vahsen et al., In Revision) and interpolating between them, and/or adding separate model runs for different marsh zones, for examples different plant communities, high and low within the tidal range, or near or far to a stream edge to simulate levee building. This model has been applied for bays and estuaries within the Delta and regions in other states.	This model can be improved through advancements in parameterization and model structure/development. *Parameterization*: The direct parameterization with sediment, plant and elevation data is advantageous. However, data availability, uncertainty, and spatial variability are challenges. Data from the Coastal Carbon Network (CCN) is well suited to identify and build data streams. Dedicated funding would accelerate implementation of needed synthetic datasets. Future work could determine which and to what extent environmental variables determine spatial variation in model parameters. Initial elevation data are also needed and can be gained from LiDAR. However, vegetation interferes with LiDAR scans resulting in digital elevation models (DEMs) that are artificially too high. This error can be corrected for, but the best strategies for creating corrected DEMs require site specific high-precision elevation surveys. There

		may be better ways to calculate site and pixel level elevation corrections, but more research is needed, as well as synthesis of available marsh elevation survey points. *Model Development:* More work is needed to add dimensionality to the model, for instance allowing 'cells' to affect adjacent cells. Currently, it cannot explicitly model the edge and interior dynamics, which could be feasible with further development. However, more complexity may also detract from the strengths of this model, simplicity and quick run time.
Models for target development should be dynamic and include key ecosystem processes, sensitive to how management and novel conditions (such as environmental and climate change stress) impact carbon dynamics.	**Yes:** Model evaluates changes in vertical sediment accretion and resulting changes to the carbon inventory but does not include evaluation of CH_4 or CO_2 NEE. The model is also sensitive to sea level rise, changes in sediment availability, and ecosystem migration. The model accounts for numerous physical (e.g., elevation, flood frequency, storms, sea level) and biological (e.g., vegetation growth, biomass, and below-ground processes) inputs (see Morris et al. 2022)	Terms to additionally include methane fluxes could be added, although these may be negligible in coastal systems with salinities above ~18 ppt

Key modeled carbon dynamics must include carbon stocks, and if possible, emissions and other relevant carbon fluxes.	**Yes:** Dynamically accounts for changes in sediment carbon accumulation but does not yet include methane or other atmospheric exchange fluxes	Model meets carbon stock criteria but could be adapted or merged with other models (e.g., PEPRMT) to account for methane emissions (although these may be small in saline, coastal systems)
Data should have a proven basis in reality, and ideally be validated with error, accuracy, or uncertainty statistics.	**Yes:** This model was validated through hindcasting (100 years). Predicted vs. actual accretion rates were 2.86 and 2.98 mm/yr, respectively, within the Delta (Morris et al. 2022). Accuracy and uncertainty details are also provided in text (see Morris et al. 2022 and Moritsch et al. 2022).	Holmquist et al. (In Prep) are attempting a combination of direct parameterization and inverse modeling approaches using Bayesian statistics to account for uncertainty in all aspects of a hindcast and forecast.
Model outputs should aim to be regularly updated, ideally in an automated fashion, to detect change.	**No:** No efforts have yet been made to regularly update model outputs	Further investment and development of these models should include support for a platform to share regular updates to forecasts as well as independent validation of previous forecasts (Dietze et al., 2017).

Models and reporting should be transparent and reproducible, with publicly available and open-source data and code where possible	**Yes:** Documentation exists within Moritsch et al. 2022; Morris et al. 2022, including model input data and sources. An R package titled RCMEM, is the same model under different branding. It is public and well documented. https://github.com/tilbud/rCMEM	The code package is currently stable, reliable, and under peer review. It is under active development by a community of collaborators working as volunteers or for their own funded projects. Further investment could keep code active and responsive to user needs. Basic computational skill is needed to run the model, but those with background in open-source scripting languages, wetland ecology, and physics can be trained to run the model and evaluate outputs.
If competing models exist, the model preference should be given to those that are more mature, have larger bodies of literature, are more transparent, address priority questions, and have an existing user base.	Not applicable	The existing user base is academic scientists, and to a lesser extent land use managers. This family of models was initially developed in the U.S. southeast, but has been run in the San Francisco Bay, Delta, Massachusetts, the Gulf of Mexico, and in a Florida marsh/mangrove transition zone. Vahsen et al. (in revision) runs localized simulations in various watersheds around the U.S. (Pacific Norwest, SF Bay, Texas, Gulf of Mexico, U.S. southeast, and Chesapeake Bay) to show the effects of geographic drivers on forecasts. More investment in the data streams needed to run these models would help them to be integrated into state and local-level decision making.

Data should be curated, off the shelf, limiting the need for processing by State staff	**No:** some 'off the shelf' data do exist, requiring limited processing. However, ongoing monitoring programs for plant communities and traits are still needed. Plant communities can undergo rapid evolution which can affect belowground plant traits, which can shift the carbon and accretion properties of the system (Vahsen et al., 2023). Sea-level rise and invasive species can create novel communities at the migrating edge of a wetland (Gedan et al., 2019).	Investment and increased data collection could reduce data inputs needs. For example, plant species and elevation could be mapped with remotes sensing, plant traits constrained enough to enable reliance on databases rather than new data collections, and sediment availability could become more predictable from GIS products.

When models described above are evaluated against the criteria outlined in Tables 1 and 2, it is observed that that these models meet needs to varying degrees. For example, existing models have undergone some degree of validation, typically have open-source data and code, are of sufficient quality and rigor, where applied. Of relevance, however, is the spatial scales over which existing models are currently applied – over single marsh or estuarine areas. To meet the spatial/temporal criteria outlined in the criteria, these models will need to scale to larger, statewide applications. As discussed above, numerous mapping datasets and tools are available and can help facilitate this scaling process as models are developed and improved (SFEI, 2022; Vaughn et al. 2022). However, improved, consistent ecosystem mapping with details on type (plant communities) and accurate elevation data are needed for statewide modeling to be possible. When possible, application of a statewide model to new locales over the state will be accompanied by support for *in-situ* data collection to validate and understand model efficacy across a suite of representative sites (ensure the models meet criteria for quality and sensitivity to environmental and management changes). At present, models have been largely developed using the greater San Francisco Bay area as test cases for calibration. To move beyond this geography, ground-truthing and calibration of these models will be required. One feasible approach, for example, would be to use the CWEM model and PEPRMT-DAMM models as components to a broader spatial model for statewide application. In this way, we have much of the foundational science and reliable models ready for deployment now, requiring some improved mapping data and data synthesis to enable the broader scaling of these models. Current work is underway by Oikawa and colleagues to link MEM with PEPRMT for CO_2 and methane budgets in tidal wetlands (called PEPRMT-Tidal) and may be a promising step forward in these modeling needs.

Tidal wetlands across the State occupy vastly different environmental and management regimes, and while more recent data expand model application and calibration, Southern California is less represented and require additional resources without which modeling and monitoring are not possible. Lastly, while some documentation of code and data is available for these models (section 3.1), confidence that this documentation is up to date and readily deployable will aid in more efficient uptake and application of models. Future development of such models should emphasize the importance of high transparency to meet quality and reporting requirements.

4. Existing research and data gaps

In order to develop and deploy statewide models accurately incorporating tidal wetlands and seagrass meadows into carbon targets, several datasets must exist to demonstrate robustness and accuracy of such models. We summarize many of these data or key data references, to highlight resources that can be used within the context of model development for tidal wetlands.

One key data type needed for statewide inclusion of tidal wetlands and seagrass meadows is high-quality spatial data of ecosystem coverage. Specifically, understanding how ecosystems contribute statewide to and could be managed to help reach carbon neutrality goals requires spatially explicit estimates of ecosystem coverage changes over time (including what these ecosystems are being converted to). Numerous resources and databases currently exist and are being improved upon (Table 3) and are discussed in Vaughn et al. 2022. As mentioned above, improved understanding of how land use and management practice changes will alter coverage must also be paired with associated data on carbon biogeochemistry (Moritsch et al., 2021).

Table 3*: A summary of key, existing California-specific references that identify key data and information that can serve to underpin development and improvement of California carbon inventories and models from blue carbon ecosystems as a Natural Working Lands.*

Resource	Description	Links
Vaughn et al. (2022)	Report providing a roadmap, data references and resources to inform blue carbon inclusion in State climate planning and future modeling efforts. In particular, the report includes state-specific emissions factors for blue carbon ecosystems, identification and discussion of existing mapping resources, and consideration of scenarios and State ecosystems goals for consideration in CARB's modeling scenarios.	Leveraging Wetlands for a Better Climate Future
Pacific Northwest (PNW) Blue Carbon Working Group	An ongoing effort to compile a database of all available West coast data from Blue carbon ecosystems (emergent marshes, seagrass meadows, tideflats, tidal swamps and mangroves) from Mexico to Alaska. This includes carbon stocks and sequestration data in addition to many additional key data being used to evaluate drivers and correlates of variability such as ecoregion, climate regimes, upland sediment supply, tidal elevation, salinity and sediment grain size.	PNW Blue Carbon Working Group; PNW Science Collaborative

Coastal Carbon Atlas	A spatially explicit data repository for available coastal carbon stock and sequestration data, including hundreds of cores taken within California. When available, additional data can also be accessed, such as salinity and tidal elevation.	Coastal Carbon Research and Coordination Network; Coastal Carbon Atlas
Ocean Science Trust (OST, 2021)	A guidance document highlighting existing summary data on California blue carbon ecosystems (seagrass meadows, tidal salt marshes, and kelp forests). In addition to data on carbon stocks and sequestration rates, data on ecosystem coverage and status, emissions data, and lateral fluxes of carbon and associated references are also included, highlighting global values where California-specific data are not available. This document also makes broad brush estimates of potential annual emissions reductions statewide from blue carbon ecosystems.	The State of the Science: Carbon Accounting Methods and Sequestration Benefits of California's Wetlands
1757 Expert Advisory Committee, 2023	This guidance document, compiled by the California AB 1757 Natural and Working Lands Expert Advisory Committee, informs, review, and recommends strategies and approaches to implement State climate action in Natural and Working Lands. The document specifically details goals and priorities in wetlands and blue carbon habitats (pp. 43).	1757 Expert Advisory Committee (EAC) Recommendations for Implementation Targets for Natural and Working Lands (NWL) Sector Climate Actions

Knowledge of changes to environmental factors (e.g., sea level rise, temperature, sediment characteristics, biomass) that may drive changes in carbon biogeochemistry is also required. Research on drivers of variability in blue carbon stocks is ongoing, and shows high levels of site-specific variation, which can make broader application of models challenging. However, it is evident that sediment grain size, elevation, and vegetation properties can all be predictors of carbon stocks and accumulation in tidal marshes, highlighting the utility of studies further validating these drivers in California's blue carbon ecosystems and including them in robust models (Kelleway et al. 2016; Oikawa et al. 2016; Janousek et al. *in prep*). Drivers of change within blue carbon ecosystems can also be highly variable, such as sea level rise and sediment supply changes over long scales, and stressors such as dredging or development over short time scales (Van Dyke and Wasson, 2005; Kauffman et al. 2019; Moristch et al. 2021). Table in OST, 2021 summarizes data and can be used for reference and makes evident that more data exist for tidal marshes than seagrass meadows (and more data for seagrass meadows than macroalgae), with the likelihood for effective model development following this ranking as well. Specifically, there are very few carbon accumulation rates, methane fluxes, and regularly updated maps published or available from California seagrass meadows, representing a significant, but not insurmountable, challenge for these ecosystems.

Regarding specific needs for the PEPRMT and CWEM/MEM models, additional effort and investment must be made to derive new datasets from existing ones that can drive these models for both inventory and future projection modeling purposes. For example, salinity and initial elevation data are required model inputs, and can be determined with existing, available datasets. However, the latter could be improved by elevation corrections that would improve model accuracy. This does not prohibit model application now, but like many other aspects of the model (e.g., plant trait data), could become more precise with ongoing investment and validation data collection. Evaluating nutrient data availability and syntheses is also required for model ingestion and not readily available as model inputs if it is to be applied statewide. Specially, nitrogen data inform modeled nitrous oxide emissions, which could significantly affect model outcomes. There is no singular dataset for this currently, however, they may be extractable from statewide water quality datasets, requiring development and investigation. Additionally, no singular database exists to track restoration projects, success, costs, and monitoring. The EcoAtlas database comes closest, but projects aren't required to contribute data, leaving many gaps and unincluded projects. Similarly, there is no standardized approach to project monitoring, which can make some data of limited use to cross-check projects with model predictions. Future guidance on project tracking and on implementing before-after-control-impact monitoring to inform models could help broaden rigorous model application and evaluation of state carbon reduction progress. Lastly, of note, the CWEM/MEM and PEPRMT models are currently being merged into a single, operational model to marry the sediment processes and GHG flux processes that each captures currently in isolation.

4.1 Research and data gaps in other coastal ecosystems

4.1.1 Seagrass meadows

While the work presented here focuses primarily on tidal marshes, seagrass meadows also contribute to carbon stocks across the state. However, existing data on seagrass meadows is even more sparse than that of tidal marshes. For example, the limited data on eelgrass sediment carbon accumulation rates (Ward et al., 2021; Capece et al. 2020) make it challenging to produce State-specific emission factors, instead relying on global seagrass emissions factors defined within the IPCC. While it is possible with existing data to estimate broad-scale, carbon inventory contributions from California eelgrass meadows, it is harder to design models that can estimate carbon change due to future management and climate change. In addition to the patchwork of existing spatial data, seagrass populations and meadow extent can be highly variable, even on an interannual basis (e.g., Walter et al., 2020). Similar to tidal marshes, the vast proportion of the carbon stored by seagrass is not in the living seagrass biomass, but rather, the underlying sediment. In some cases, other soft bottom, estuarine sediments can store equally as much carbon as neighboring seagrass sediments – representing additional complexities (Ward et al., 2021). To truly capture the potential of estuarine ecosystems to contribute to carbon dynamic change (regardless of the presence of seagrass), we might ultimately consider cohesive models that capture the import, export, and permanence of organic matter within intertidal and subtidal soft-bottom sediments more broadly. Moreover, models will ideally be able to incorporate how management actions, both within these systems (e.g., dredging) and 'upstream' (e.g., agricultural water use), affect these sediment processes and resulting carbon accumulation.

4.1.2 Other coastal ecosystems

Carbon inventory and future projection modeling considerations for coastal ecosystems such as kelp, other soft-bottomed estuarine sediments occupying intertidal and subtidal mudflats, estuaries with interannually dynamic ocean inlets, and systems heavily degraded by human activity are beyond the scope of this report. There is nascent scientific evidence revealing uncertainty about the permanence of carbon sequestered in macroalgal ecosystems. There are also limited datasets on the sequestration rates and sediment stability and dynamics within these ecosystems and on their statewide spatial extent, making it difficult to grasp even a first order estimate of their contributions to carbon stocks statewide and highlighting the need for additional research.

5. Conclusions

Existing resources on blue carbon ecosystem models and inventory are summarized herein, highlighting that data gaps exist, and that work still must be done to develop models for statewide future projection modeling and inventory purposes. Additional scientific work should seek to:

- Fill existing data gaps (e.g., biogeochemical data, mapping improvements)
- Improve estimates of carbon benefits conferred through varying strategies for action (conservation, tidal restoration, etc.)
- Estimate cost of inaction by quantifying the carbon dynamics in areas where no investments are made.

Through this process, the State can identify interventions (and their spatial opportunities) that balance carbon benefits, biodiversity, environmental justice, and reducing risk. Data, models, and tools exist that may act as a starting point for near-term development of a statewide model to include tidal marshes into carbon reduction targets. Specifically, strong candidate models exist now including the PEPRMT-DAMM and CWEM models. These models are sensitive to key environmental parameters likely to affect carbon stocks and accumulation rates, including elevation, sea level rise, salinity, and vegetation parameters. Models also currently meet many of the criteria for inclusion outlined here (Table 1, 2), but not all, requiring additional support to be robustly applied for Statewide application. By addressing these recommendations, the State can better identify the climate resilience opportunities offered by its long-valued coastal ecosystems.

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7. Supplemental information

Table S1 (WARMER model): Column one summarizes criteria for models that fit within California's existing frameworks for estimating carbon reduction potential. Column two summarizes if and how the model meets these criteria. Limited documentation and details were available for the WARMER model, and it is not currently open-source, and thus recommendations were not made for this model, with priority given to the MEM/CWEM models.

Model Requirements	Meet requirements?
Models for target development should be scalable spatially, generating ecosystem-specific statewide carbon estimates, and be temporally explicit.	No: The model is currently applied and validated within sites in the San Francisco Bay Estuary but is constructed to be "transferable across coastlines" (Buffington et al. 2021).
Models for target development should be dynamic and include key ecosystem processes, sensitive to how management and novel conditions (such as environmental and climate change stress) impact carbon dynamics.	**Yes:** The model evaluates changes in sediment carbon, considering plant community transitions, salinity and its effects on productivity, and changes in sediment availability (Buffington et al. 2021). This model is also sensitive to sea level rise but does not include evaluation of CH_4 or CO_2 NEE.
Key modeled carbon dynamics must include carbon stocks, and if possible, emissions and other relevant carbon fluxes.	**Yes (IP):** This model accounts for changes in wetland elevation and carbon sequestration but does not yet include methane or other atmospheric exchange fluxes.
Data should have a proven basis in reality, and ideally be validated with error, accuracy, or uncertainty statistics.	**Yes:** Model validation shows comparable rates of sediment accumulation between model outputs and (See Table 2 in Buffington et al. 2021). Uncertainty is discussed at length in Buffington et al. 2021.

Model outputs should aim to be regularly updated, ideally in an automated fashion, to detect change.	**No:** No efforts have yet been made to regularly update model outputs
Models and reporting should be transparent and reproducible, with publicly available and open-source data and code where possible	**No:** Documentation exists within Buffington et al. 2021 and Thorne et al. 2018. Also see the USGS page for model documentation and data. Open source model code is not currently available to enable public use.
If competing models exist, the model preference should be given to those that are more mature, have larger bodies of literature, are more transparent, address priority questions, and have an existing user base.	Not applicable
Data should be curated, off the shelf, limiting the need for processing by State staff	No: Limited in situ data is necessary for collection to run these models, depending on the desire for regional accuracy, but model iterations could be improved through additional data collection for validation.