# Natural and Working Lands Carbon Inventory: Wetlands

## 2025 Proposed Inventory Update Methods
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# Background

Wetlands in California cover approximately 2% of the state, or two million acres. These lands comprise a diverse set of ecosystems that experience recurring inundation seasonally or perennially. According to the Intergovernmental Panel on Climate Change (IPCC), major wetland categories include tidal marshes, rewetted organic soils, and inland wetland mineral soils (Intergovernmental Panel on Climate Change, 2019). Within California's academic research and state regulatory groups, these wetland categories are more commonly referred to as coastal wetlands, restored Delta soils, and inland wetlands (including mountain meadows and vernal pools) respectively.

In the 2018 NWL Carbon Inventory, CARB found wetland soils comprise approximately 30 million metric tons of carbon throughout the state. This relatively small proportion of carbon in wetlands when compared to other land types is largely attributable to the fact that 90% of California's historic wetlands have been converted to other land types within the past two centuries.  Wetlands within California, particularly along the coast and in the Delta have some of the most concentrated soil organic carbon pools per area when compared to other ecosystems.

## State of the Science

Under the IPCC carbon inventory framework, wetlands are distinct from other land types. Unlike other land types, which only report carbon stock changes and, at specific tiers, $CO_2$ emissions, wetlands quantify emissions of $CO_2$ and $CH_4$ across all methodology tiers. Inventory efforts, such as the US EPA's National GHG Inventory, use a combination of Tier 1 (globally-derived emissions factors) and Tier 2 (country-specific factors) to quantify emissions (United States Environmnetal Protection Agency, 2024). The National GHG Inventory employed Tier 2 syntheses of above-ground and soil carbon stocks for coastal wetlands but relied on Tier 1 methods for CH4 emissions and other wetland types due to limited data. In California, tailored biogeochemical models and available data could enable Tier 3 quantification of coastal and Delta wetlands, as noted by the Ocean Protection Council (OPC) in their Blue Carbon Report (Ocean Protection Council, 2024). However, other wetland categories, such as vernal pools and mountain meadow systems, still lack tailored models and sufficient data for Tier 3 approaches.

Wetland carbon inventories require a significant amount of data to model wetland systems at a tier 3 level. Biogeochemical models must be tailored to the primary drivers of change, quantify carbon stocks and GHG fluxes, and be scalable using available, statewide, spatial datasets. The OPC's Blue Carbon Report highlights that coastal wetlands currently have models that capture the primary drivers of change and produce the required outputs. However, scaling these models poses several challenges including difficulties in mapping wetland composition using remote sensing and mapping abiotic factors such as salinity, inorganic sedimentation, elevation, and disturbance.

## Primary Drivers of Change

Wetlands have experienced drastic changes in their extent and functioning since 1850, with vectors of change, other than restoration, generally reducing the extent of wetlands compared to their historic distributions. The priority drivers assessed in this methodological proposal include land use conversion, which has resulted in California losing upwards of 90% of its historic wetland extent due to practices like agricultural drainage, urban development, infrastructure, pollution, and invasive species (Wetland Monitoring Workgroup, 2016). Another key driver is subsidence, which refers to the vertical sinking of wetland elevation in response to changing conditions. Since 1850, drainage and cultivation in the Delta have resulted in subsidence ranging from 3 to over 30 feet (Deverel S. J., 2010), highlighting the need for accurate representation of subsidence rates for both carbon accounting and predicting the effects of sea level rise.

Sea level rise is a significant driver of change, with statewide projections indicating an average rise of 0.8 feet by 2050, and between 1.6 feet and 3.1 feet by 2100 (Ocean Protection Council, 2024). This change would affect a large portion of the state's coastal and Delta wetlands, altering inundation dynamics. While some natural adaptation can be achieved through accretion, where wetlands can increase in elevation over time as organic carbon and sediments are assimilated into soils, it's uncertain if these processes can keep pace with sea level rise. Additionally, upland migration of wetland communities could potentially mitigate the effects of sea level rise, but the suitability of upland space for migration is not clearly defined, depending on factors like upland land type, natural and artificial tidal barriers, and colonization ability of wetland communities (Osland, 2022).

Salinity is a primary control of $CH_4$ emissions, particularly in freshwater/brackish systems when coupled with sea level rise, which can lead to saltwater intrusion and changes in salinity levels. $CH_4$ production sharply declines with increasing salinity, approaching zero at salinities greater than 18 ppt. In areas with shallow unconfined groundwater, the water table will generally rise with sea level, affecting freshwater systems via saltwater intrusion (Ocean Protection Council, 2024). This highlights the importance of considering salinity and its interactions with sea level rise when assessing $CH_4$ emissions from wetlands.

Restoration is a necessary and ongoing process being implemented by various entities in California, involving activities like weeding, planting, grading modifications, and rewetting. Tracking the implementation and effects of restoration is critical for carbon inventories but challenging to map statewide. To quantify the carbon stocks and GHG emissions of wetlands, it is essential to accurately assess and model the effects of these multiple drivers simultaneously, considering both beneficial and negative impacts on ecosystem resilience and carbon storage.

## Nature Based Solutions Targets

In April 2024, the Governor's Office released a set of ambitious nature-based solution targets to strategically harness the power of California's lands to fight the climate crisis. Nature-based solutions are land management practices that increase the health and resilience of natural systems, which supports their ability to serve as a durable carbon sink. In California's wetlands, these initiatives call for 12,000 acres of wetland and seagrass climate action annually through 2045, including conservation, restoration, and sea-level rise protection (Table 1). It is a goal of the NWL Carbon Inventory to be sensitive to these interventions going forward.

Table 1: Nature-Based Solution Targets for wetlands as defined in *California's Nature-Based Solutions Climate Targets*.

| AB 1757 Nature-Based Solution (NBS) | 2030 Target | 2038 Target | 2045 Target |
|---|---|---|---|
| Conservation | 1.3k acres/yr | 1.3k acres/yr | 1.3k acres/yr |
| Restoration | 9.2k acres/yr | 9.2k acres/yr | 9.2k acres/yr |
| Sea Level Rise Protection of Ecosystems | 1.7k acres/yr | 1.7k acres/yr | 1.7k acres/yr |

## 2018 NWL Carbon Inventory Methods

### Methods Description

GHG Emissions: The previous wetlands methodology employed an IPCC Tier 1 approach to quantify $CO_2$ and $CH_4$ emissions from three key wetland types: inland wetland mineral soils, rewetted organic soils, and tidal marshes. Direct quantification of emission, rather than stock change factors, follows from IPCC guidance and is unique to wetlands (Intergovernmental Panel on Climate Change, 2014). Emissions of $CO_2$ are converted into soil organic carbon stock changes. Emissions calculations incorporated land cover data from the California Aquatic Resources Inventory (CARI) (San Francisco Estuary Institute, 2024) and IPCC emission factors to determine statewide emissions. The effects of restoration on wetlands were accounted for by mapping rewetted organic soils using EcoAtlas's Habitat Project Tracker (San Francisco Estuary Institute, 2024).

Soil Carbon: The 2018 NWL Carbon inventory used an IPCC Tier 2 approach to estimate soil organic carbon (SOC). This approach combines a reference soil carbon raster with stock change factors to describe changes over the inventory time period. The initial soil carbon raster was based on SoilGrids v1.0 (Hengl, 2017), a third-party SOC map produced using the WoSIS dataset (Batjes, 2017). However, due to limitations in available, annualized mapping data, wetlands were assumed to remain unchanged in extent over the inventory time period.

### Benefits and Limitations

Previous methodologies followed the IPCC reporting framework and focused on the potential benefits of restoring wetlands. These methods were straightforward, and inherently compatible with the IPCC reporting framework. However, these methods had limited ability to quantify the effects of primary drivers on wetland extent and carbon cycling. Emission factor-based estimates are globally sourced and not tuned for California's systems. Combined with limitations in mapping extent of wetlands over time, this made the inventory values less sensitive to management and disturbance events.

# 2025 NWL Carbon Inventory Update Proposed Methods

## Methods Description

GHG Emissions: The proposed methodology will quantify $CO_2$ and $CH_4$ emissions for coastal and Delta wetlands using a Tier 3 biogeochemical model. The Peatland Ecosystem Photosynthesis, Respiration, and CH4 Transport Model (PEPRMT) is a flux model developed using eddy covariance measurement sites in San Francisco Bay and the Delta. Recently, this model has been recalibrated using eddy covariance sites across the Western coast (Oikawa, 2024). This methodology will expand model parameterization to include additional measurement sites throughout California and scale these measurements statewide using a coupled process-based and machine-learning method.

Quantification of emissions for inland wetland mineral soils will still rely on Tier 1 methods. CARB staff were unable to locate sufficient mapping, modeling, and data resources to support a tailored biogeochemical approach for vernal pools and mountain meadows. However, the extent of inland wetland mineral soils, including land-use change conversion, will be tracked where possible. While the transition of inland wetlands to developed lands can be tracked with current data products, mapping products tracking conversion to other land types (such as forests, grasslands, and shrublands) and mapping of mountain meadows over time are currently limited.

Soil Carbon: Soil organic carbon (SOC) will be quantified for coastal and Delta wetlands using a Tier 3 approach. The Cohort Wetland Equilibrium Model (CWEM) is a method of quantifying current and predicted SOC and has been used extensively throughout California (Vahsen, 2024). CWEM is based on the Marsh Equilibrium Model (MEM), which has been implemented in various forms to understand accretion and subsidence rates across California (Deverel S. J., 2016; Vahsen, 2024). A version of CWEM is already coupled with PEPRMT (Oikawa, 2024). This methodology will use the merged model to couple statewide carbon stocks with GHG flux consistently for coastal and Delta wetlands.

CARB staff were unable to locate sufficient modeling and data resources to implement process-based modeling of soil organic carbon stocks for inland wetland mineral soils. Available soil cores and time series data for vernal pools and mountain meadow systems will be synthesized and scaled statewide through the unified soil mapping.

The proposed unified soil mapping framework implements space-time mapping of soil carbon across all land types, which is described in detail in the Soil Methods Document. Many of the inputs used for process-based modeling in wetlands are currently only available at the point scale (where existing studies have expressly measured input data). Input data for the unified soils framework will include the results of CWEM and PEPRMT modeling at representative sites and synthesized literature values of inland wetland mineral soil carbon stocks and time-series. Ecosystem specific covariates will include remotely sensed tidal inundation, salinity, wetland class, and other inputs. Covariate inputs will closely correlate with the inputs required by process-based models, but will use datasets available at statewide extents.

## Benefits and Limitations

GHG Emissions: The proposed methodology offers several benefits for quantifying $CO_2$ and $CH_4$ emissions. In coastal and Delta systems, PEPRMT leverages the significant eddy covariance datasets generated for wetlands in California. Notably, when comparing publicly available eddy covariance datasets across California in the Ameriflux network (Ameriflux, 2024), there are more measurement sites in wetlands than in forests, grasslands, and shrublands combined. This updated method enables the use of these data in calibrating and validating GHG emissions estimates. However, the large quantity of eddy covariance sites is heavily concentrated in San Francisco and Delta wetlands, with no current eddy covariance towers available for wetlands south of Monterey, CA or in systems with comparable anthropogenic impacts. This limitation will result in less certain predictions in these understudied regions.

Soil Carbon: Please see the Soil Methods Document for benefits and limitations of the unified soil inventory framework.

## Input and Validation Datasets

For required input data, it is essential to distinguish between data needed for process-based modeling at calibration sites and data required for upscaling through the unified soils framework. Process-based models often require site-specific, field-collected measurements for proper parameterization, whereas upscaling datasets are often remotely sensed and/or spatial data that correlate with process-based model parameters but are available statewide (Table 2).

GHG Emissions: Input data required for parameterizing the PEPRMT model will include climate and eddy covariance flux data. Fluxes of $CO_2$ and $CH_4$ will be sourced from the Ameriflux network (Ameriflux, 2024), including towers in the Delta and coastal towers of California and Oregon. Upscaling will rely on statewide climate data from Cal-Adapt (Thomas, 2018), remotely sensed inundation status, spectral indices, and community composition (Table 2).

Soil Carbon: Inputs for CWEM include tidal regime parameters, vegetation composition, sediment inputs, and ecological parameters (such as root:shoot ratios and turnover rates). This information will be sourced from available studies implementing CWEM modeling and meta-analyses that have already collected this information (Byrd, 2018). Parameterization and calibration data will be sourced from the Coastal Carbon Atlas tool (Holmquist, 2024). Alongside the factors included in the unified soil framework, wetland-specific inputs will include remotely sensed tidal inundation rates (annual scale), spectral vegetation indices, and community composition (Table 2).

Table 2: Required model inputs and proposed data sources to be used for parameterization and scaling of process-based models to the statewide extent of wetlands. Where possible, literature-derived, empirical data will be used for parameterization of process-based models at calibration.

| **Input** | **Proposed Data Source** |
|---|---|
| Tidal Inundation | Remotely Sensed Tidal Inundation (Narron, 2022) |
| Suspended Sediment | Water quality monitoring stations (Rasmussen, 2009) |
| Climate Data | Cal-Adapt (Thomas, 2018) |
| Land Type Conversion | LANDFIRE Existing Vegetation Type (LANDFIRE, 2024) |
| Restoration and Rewetting | EcoAtlas Habitat Tracker (San Francisco Estuary Institute, 2024) |
| Wetland Extent | NOAA Coastal Change Analysis Program (National Oceanic and Atmospheric Administration) |
| Dominant Vegetation Cover | California Aquatic Resources Inventory (San Francisco Estuary Institute, 2024) |
| Biomass Control Parameters | Synthesized parameters (Byrd, 2018) |
| Salinity | NOAA Buoy Network (NOAA National Centers for Environmental Information)<br><br>California Aquatic Resources Inventory (San Francisco Estuary Institute, 2024) |

## Alternative Method for 2025 Update

<u>GHG Emissions</u>: Should the proposed Tier 3 methodology prove infeasible or result in untenable uncertainty, the synthesized input data can still accommodate Tier 2 quantification. Eddy covariance tower data can be used to estimate the average emissions from at least twelve measurement sites across California. Input GHG flux data would provide California-specific emissions factors and constitute an improvement over the globally derived emissions factors used in previous inventory efforts.

<u>Soil Carbon</u>: The alternative method for soil carbon will be the same as the prior inventory methods.

## Criteria Assessment

All decisions regarding proposed updates to the NWL Carbon Inventory were made in relation to standardized criteria set forth by CARB (Table 3). These criteria help to ensure that the methods and data CARB uses are appropriate to meet the goals of the NWL Carbon Inventory, are as rigorous and comprehensive as possible, and are reproducible for others.

Table 3: Criteria used to assess methodological updates for the 2025 NWL Carbon Inventory.

| Category | Criteria Assessment |
|---|---|
| Spatial scale<br>• Have accuracy optimized to statewide scales while also providing sufficient accuracy at the county scale<br>• Ensure wall-to-wall coverage with no double counting | This method will be done at the statewide scale and is appropriate for county scale aggregation and will include all wetlands in California. |
| Temporal scale<br>• Go back as far in time as possible, at least to 2001<br>• Be as up to date as possible | The proposed method will quantify wetland carbon stocks and GHG emissions for the entire inventory time period (2001-2023). |
| Spatial resolution<br>• Be as spatially explicit as possible, at least to the resolution of ecosystem boundaries<br>• Permit analysis at different stratifications, such as by ownership, management action type, land type, or ecoregion | This method will quantify wetlands at 30m spatial resolution. This is inherent to the input remote sensing datasets. |
| Temporal resolution<br>• Produce annualized values that can be reported every 3-5 years | The proposed method is dependent on data from the NOAA Coastal Change Analysis Program for mapping the extent of wetlands over time. This data is produced on a five year cycle, thus this method is a maximum temporal resolution of five years.<br><br>It may be possible to annualize this analysis by assuming rates of change or integrating other, higher temporal resolution data, but this is not guaranteed. |
| Thematic resolution<br>• Include as many carbon pools and fluxes as possible<br>• Capture at minimum aboveground biomass carbon<br>• Be generally consistent with IPCC GHG inventory guidelines | This method will quantify GHG emissions of carbon dioxide and methane along with soil carbon and biomass carbon stocks for coastal and Deltaic wetlands. This is in accordance with IPCC guidelines. Aboveground carbon of inland wetland mineral soils will not be quantified, however the major pool (soil carbon) and GHG emissions will be included. |
| Sensitivity<br>• Be sufficiently sensitive to quantify changes as a result of management and other major drivers of change, including climate change<br>• Prioritize assessing directionality and general magnitude of change through time | This method will enhance the sensitivity of coastal and Delta wetlands, better capturing the magnitude and direction of change resulting from management and primary drivers of change.<br><br>Tier 1 methods for inland wetland mineral soils will not be sensitive to climate effects and many drivers of change, but will be sensitive to land-use change where sufficient mapping resources exist. |
| Practical criteria<br>• Generate transparent, repeatable methods that use free or low-cost tools<br>• Prioritize base data that has reasonable expectation of sustainment and openness for use by state staff<br>• Use models that are publicly available and open source<br>• Use base data that require as little pre-processing for state staff as possible<br>• Use base data that have a proven basis in reality and, where applicable, are validated with error or accuracy | This method will exclusively use open-source biogeochemical models for transparency and replicability. In most cases, this method will use open-source, free datasets that have reasonable expectation of sustainment and openness for use by state staff and others. However, some calibration/validation datasets may have privacy considerations that will be honored to the extent permitted by the law |

CARB staff, in collaboration with the California Ocean Protection Council (OPC) and Windward Sciences, assess the available biogeochemical models to include coastal and Delta wetlands using an IPCC tier 3 approach. The full list of assessed models may be found in the OPC Blue Carbon Ecosystem Data and Modeling Assessment Report (Ocean Protection Council, 2024). From this report, two models were found to quantify GHG emissions and carbon stocks and meet the criteria for inclusion (Table 4).

Table 4: Assessed biogeochemical models for wetland ecosystems. Assessed models include the Peatland Ecosystem Photosynthesis, Respiration, and CH4 Transport Model (PEPRMT) (Oikawa, 2024) and the Cohort Wetland Equilibrium Model (CWEM) (Vahsen, 2024). Scaling will be implemented through the unified soils framework, as denoted by the asterisk in the associated criteria.

| **Model Name** | **PEPRMT** | **CWEM** |
|---|---|---|
| Must fit context of specific landscape type | Yes | Yes |
| Is the model scalable? | No* | No* |
| Can this model do future projections needed for scoping plan? | No, currently has not been calibrated for projection modeling | Yes |
| Does the model include the major drivers of change in this system and key ecosystem processes? | Yes | Yes |
| Is this model sensitive to climate change | Yes | Yes |
| Can this model estimate the impacts of management/NBS actions? | Yes, with minor modification | Yes |
| Does the model output carbon stocks and/or GHGs? | Yes, GHG | Yes, Carbon Stocks |
| Is the model validated and have a basis in reality? | Yes | Yes |
| Can this model be run on a regular basis to develop updates and incorporate improvements? | Yes | Yes |
| Is this an open-source model that we can modify and share without restriction? | Yes | Yes |
| Is this a mature model with a scientific track record? | New, but validated | Yes |
| Are people currently using this model and is there a current user base? | Yes | Yes |
| Will this model require a lot of work to make usable for CARB's purposes, or is it ready off the shelf? | Ready off the shelf, requires calibration | Ready off the shelf, requires calibration |
| Do we have sufficient off the shelf data to parameterize, calibrate, validate (w/ uncertainty statistics) and run this model through time, or will this require new or highly processed data by CARB staff? | Pre-processing required | Pre-processing required |
| Can CARB staff run this model within our current timeframe for deliverables | Likely | Yes |

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