Natural and Working Lands Carbon Inventory: Sparsely Vegetated Lands

Proposed 2025 Inventory Update Methods
January 2025

Photo Credit: James O'Neil

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Background

Within California, approximately 10% of the state's lands consist of sparsely vegetated ecosystems, including a wide variety of communities such as desert, beach, and dune areas with less than 10% vegetation cover. These ecosystems also include bare rock landscapes or areas covered in ice or snow. Proportionately, these systems have fewer organic carbon stocks than other ecosystems but constitute large carbon pools across their extensive area. According to the 2018 NWL Carbon Inventory, sparsely vegetated lands had an estimated 10 MMT of carbon in vegetative biomass and 150 MMT of carbon in soils (SOC).

State of the Science

Under the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, carbon stock changes and GHG emissions from sparsely vegetated lands are assumed to be zero using default values because these areas are considered devoid of biomass, litter, and soil carbon pools (Intergovernmental Panel on Climate Change, 2019). This approach is followed within the US EPA National GHG Inventory, with the additional qualifier that, "research is ongoing to track carbon pools in this land use. Until such time that reliable and comprehensive estimates of carbon for other land remaining other land can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on other land remaining other land at this time." (United States Environmnetal Protection Agency, 2024).

Within California's NWL Carbon Inventory, carbon stocks are not zero and are explicitly quantified. While data limitations in sparsely vegetated lands exist at global and national scales, there is relatively more information available on California's ecosystems. For example, a recent meta-analysis on global dryland carbon cycling dynamics relied on data from California and Mexico when sourcing all available datasets in North America (Xu, 2022). Even with the relative availability of data in California, challenges persist in quantifying carbon in sparsely vegetated lands. An assessment of the available soil core data in the World Soil Information Service (WoSIS) database found that only 35 of California's approximate 3,000 listed soil cores are located in sparsely vegetated lands (Batjes, 2017).

In addition to biomass and soil carbon pools, research exists on soil inorganic carbon (SIC) as a potential portion of the carbon cycling budget in sparsely vegetated lands. While these pools have traditionally been viewed as static on decadal to century time scales, recent evidence has shown that disturbances affecting hydrology and soil structure can cause emissions from SIC degradation on more rapid time scales (Ebouel, 2024). When compared with the models, data, and research available for soil organic carbon pools, SIC has limited resources available to quantify carbon stocks and the possible effects of management or disturbance. IPCC does not provide default values for the quantification of soil inorganic carbon and IPCC guidance is to not include SIC in inventories (Intergovernmental Panel on Climate Change, 2019).

Primary Drivers of Change

Sparsely vegetated systems are characterized by natural processes that occur over long timescales, with a typical lag between disturbance and re-establishment taking decades to centuries. As a result, many temporally relevant drivers of change relate to disturbance or land use conversion. Restoration is an important and necessary action in these systems, but traditional metrics and tools to assess the success of restoration are difficult to implement due to long establishment periods. Management conducted today will affect ecosystem carbon sequestration and durability, but it may take many years for these effects to be observed.

Two major physical drivers to consider are biocrust damage and land use change. Biocrusts are biologically active layers of soil that affect carbon and other ecosystem functions. Biocrusts form over decadal or century timescales but can be easily disrupted by human activity, resulting in rapid consequences for nutrient cycling and carbon stocks (Xu, 2022). Similarly, anthropogenic use of sparsely vegetated ecosystems - such as recreational usage, development, agriculture, and mining - can interact with other driving factors to create long standing changes in the landscape's vegetation, carbon storage potential, diversity, and hydrologic processes.

Climate is another key driver of change in these systems. As arid systems, existing vegetation and ecosystem processes are adapted to stressful conditions. However, increases in extreme heat and changes in precipitation can push the stress tolerance of vegetation, potentially reducing carbon stocks in both above-ground and soil carbon pools (Munoz-Rojas, 2013).

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 sparsely vegetated lands, these targets call for 75,000 - 95,000 acres of increasing climate action every year between now and 2045, including conservation and restoration (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 sparsely vegetated lands as defined in *California's Nature-Based Solutions Climate Targets.*

AB 1757 Nature-Based Solution (NBS)	2030 Target	2038 Target	2045 Target
Conservation	20k acres/yr	30k acres/yr	40k acres/yr
Restoration	55.1k acres/yr	55.1k acres/yr	55.1k acres/yr

2018 NWL Carbon Inventory Methods

Methods Description

Biomass Carbon: The 2018 NWL Carbon Inventory utilized LANDFIRE-C, an IPCC Tier 3 model based on Forest Inventory Analysis (FIA) data and literature derived values, to quantify carbon stocks in forests and other natural lands (Battles, 2013; USFS, 2012). LANDFIRE-C has undergone iterative revisions to improve model functioning and to incorporate additional allometric data for sparsely vegetated ecosystems (Gonzalez, 2015; Saah, 2016). As the FIA program does not sample within sparsely vegetated ecosystems, literature derived values of biomass were used for sparsely vegetated lands and some shrubland communities. Allometric equations for sparsely vegetated lands included all available studies with LANDFIRE-compatible metadata, including at least plot location, date of sampling, canopy height, and canopy cover/density.

Soil Carbon: The previous inventory relied on an IPCC Tier 2 approach to estimate soil organic carbon. This approach used a combination of a reference soil carbon raster and stock change factors to describe changes across the inventory time period. The initial soil carbon raster was based on SoilGrids (Hengl, 2017), a third-party dataset produced using the WoSIS dataset (Batjes, 2017). Stock change factors were determined as the ratio of average soil organic carbon between each IPCC land-type category. Following IPCC guidance, stock change factors were not applied instantaneously during land-use conversion. Instead, the effects were applied equally across a twenty-year interval, resulting in a gradual, linear change in SOC following conversion.

Benefits and Limitations

Biomass Carbon: LANDFIRE-C provides an empirically based structure for assigning carbon density based on geolocated FIA plot data. As with all empirical models, model performance is directly connected the underlying calibration dataset. Within this methodology, there was less information available for sparsely vegetated biomass classes when compared to tree-dominated biomass sampling due to FIA sampling locations. This can create disparate levels of uncertainty in the predictions of the LANDFIRE-C tool for sparsely vegetated systems when compared to forest systems.

This limitation prompted the inclusion of external allometric equations for sparsely vegetated lands within LANDFIRE-C. Despite limited allometric equation availability in the previous method, the benefit of this system is CARB can continue to incorporate literature values as they become available, improving accuracy in step with existing research and data availability. However, literature values are most commonly reported as allometric equations for individual plants, rather than remote-sensing compatible plot-level data. A disadvantage of this system is the requirement that allometric equations are scaled from species-specific equations to compatible scales for accurate quantification.

Soil Carbon: Previous methods provided multiple benefits. The first is Tier 2 methodology explicitly quantified soil organic carbon, rather than assuming it to be zero under a Tier 1 approach. The 2018 NWL Carbon Inventory demonstrates there is a significant pool of soil carbon in these systems that would have been unaccounted for using default values. Additionally, the products used in the previous methods allowed CARB to leverage the available data from other land types and other arid ecosystems during quantification, mitigating data scarcity. However, Tier 2 methods are inherently broadscale and generalized, and thus do not allow for contextualized estimates of change over time. Furthermore, the methods employed previously only captured land use change and were less sensitive to management and disturbance.

2025 NWL Carbon Inventory Update Proposed Methods

Methods Description

Biomass Carbon: The updated methods for biomass carbon in sparsely vegetated lands will rely on two primary updates to the LANDFIRE-C tool. These updates will incorporate the literature biomass carbon values published since 2015, and conduct an analysis of high-resolution aerial imagery to better connect allometric equations with plot-level carbon density estimates. Synthesized literature values will include any published plot-level carbon densities or allometric equations with LANDFIRE-C-compatible metadata (including at least plot location, date of sampling, canopy height, and canopy cover/density). This will quantify total biomass carbon, which includes above ground vegetation, below-ground roots, dead, and litter carbon pools. In the absence of explicit below-ground carbon data, literature-derived root:shoot ratios will be used. As allometric equations are usually published for individual plants, rather than plot-scale areas (30mx30m), this method must determine the density of individuals to connect literature values with remote sensing products.

Connection between allometric equations and remote sensing data will rely on an analysis of National Agricultural Imagery Program (NAIP) data. NAIP data is high resolution aerial imagery collected every two years in California. Within sparsely vegetated systems, this data will be used to quantify the number of individual shrubs within a pixel and apply allometric equations through spectral index thresholding and segmentation.

Soil Carbon: We propose a unified framework for space-time mapping of soil carbon across all land types, which is described in detail in the Soil Methods Document. Specifically for sparsely vegetated lands, key environmental and anthropogenic predictors include biocrust disturbance, land use change, and restoration. Additional soil core measurements from the literature will be incorporated. There is a known limitation in the availability of soil core data for sparsely vegetated systems. If available, inputs may also incorporate time series data of soil carbon during management or disturbance events. This time series data can be from either process-based model outputs or direct sampling. Process-based modeling outputs must quantify uncertainty using withheld verification data.

Soil inorganic carbon (SIC) will not be quantified within this iteration of the NWL Carbon Inventory. In response to new research on emissions from SIC pools in disturbed, sparsely vegetated lands, CARB conducted a review of available models for quantification of SIC.

While models such as the Soil-Landscape Inorganic Carbon model (SLIC) have been calibrated for the Mojave Desert (Hirmas, 2010), these models do not fulfill the needs of the NWL Carbon Inventory in their current state. For more information on the criteria used to assess models, please refer to the criteria assessment section below (Table 4).

Benefits and Limitations

Biomass Carbon: The proposed methods for biomass carbon quantification have multiple benefits. Primarily, direct remote sensing of shrub density and canopy structure will leverage existing and new literature-derived allometric equations to produce more accurate, temporally-specific estimates of biomass carbon. The effects of primary drivers are implicitly included in this analysis, as measured changes in canopy structure and the distribution of individual organisms can be tracked during each two-year NAIP cycle. However, this benefit does not provide insight into the cause of these changes. In assessing the implementation of management and its associated effects, we may be limited by the availability of reported management data, as the proposed method cannot attribute cause of changes beyond what is provided by external datasets. As external datasets of implemented restoration and management events are built, the proposed methods will provide a foundation to both attribute changes and quantify carbon consequences.

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

Input and Validation Datasets

Biomass Carbon: The required input data for quantifying vegetative biomass carbon will include a variety of remote sensing and literature values. Literature values will include published allometric equations, plot-level carbon densities, and root:shoot ratios. Remote sensing products will include NAIP imagery, LANDFIRE vegetation type and height classes, and LANDFIRE disturbance maps (Table 2).

Soil Carbon: Input data required for the digital soil mapping portion of the unified soils framework is described in Soil Methods Document. Alongside universal soil forming factors implemented for all land types, ecosystem-specific predictors of soil organic carbon in sparsely vegetated lands will include biocrust disturbance and LANDFIRE disturbance maps (Table 2).

Table 2: Required model inputs and proposed data sources for quantification of carbon stocks in sparsely vegetated ecosystems.

Input	Proposed Data Source
Ecosystem Type	LANDFIRE Existing Vegetation Type (EVT) (LANDFIRE, 2024)
Canopy Height	LANDFIRE Existing Vegetation Height (EVH) (LANDFIRE, 2024)
Canopy Cover/Density	LANDFIRE Existing Vegetation Cover (EVC) (LANDFIRE, 2024) NAIP Imagery (USDA, 2025)
Biocrust Disturbance	Human Modification Index (Theobald, 2020)
Land Use Conversion	LANDFIRE Existing Vegetation Type (EVT) (LANDFIRE, 2024)
Disturbance Events	LANDFIRE Disturbance (LANDFIRE, 2024)
Allometric Equations	Literature-Derived

Alternative Method for 2025 Update

Biomass Carbon: While updates to LANDFIRE-C have an established protocol (Gonzalez, 2015) and can succeed with varying levels of improvement, the NAIP analysis is a new methodology within the 2025 NWL Carbon Inventory update. The NAIP analysis will include a verification of detected vegetation to ensure it captures information appropriate for direct scaling of allometric equations. Should the analysis prove infeasible or result in untenable uncertainty, CARB may limit the ingested literature values to only plot-level data and/or develop regression equations of aboveground biomass density as a function of only LANDFIRE height and fractional cover as in the previous methodology (Gonzalez, 2015).

Soil Carbon: 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 • Have accuracy optimized to statewide scales while also providing sufficient accuracy at the county scale • Ensure wall-to-wall coverage with no double counting	The proposed methodology will span all sparsely vegetated lands within California, with sufficient accuracy to quantify trends in carbon stocks at county-level or larger scales.
Temporal scale • Go back as far in time as possible, at least to 2001 • Be as up to date as possible	All utilized LANDFIRE products are available for 2001 – 2023. New data is released with a one – two year latency. While NAIP data began collection began in 2002, multispectral imagery in California is only available from 2010 to present. This may limit the allometric equations we can integrate to only samples collected after 2010, however it will not limit the timeframe of the overall method (2001 – 2023).
Spatial resolution • Be as spatially explicit as possible, at least to the resolution of ecosystem boundaries • Permit analysis at different stratifications, such as by ownership, management action type, land type, or ecoregion	The proposed methods will produce results at 30m resolution, which is sufficient for most dynamics in this ecosystem. Outputs will be gridded, allowing further stratification.
Temporal resolution • Produce annualized values that can be reported very 3-5 years	As proposed, this method is dependent on LANDFIRE data products. While modern LANDFIRE products are produced every one-two years, there is a nine year gap between the 2001 release and subsequent 2010 release. It may be possible to annualize this analysis using the annual LANDFIRE disturbance product, however this is not guaranteed given the limitations of both LANDFIRE and NAIP data prior to 2010.
Thematic resolution • Include as many carbon pools and fluxes as possible • Capture at minimum aboveground biomass carbon • Be generally consistent with IPCC GHG inventory guidelines	The proposed methodology captures total biomass carbon (above ground live, dead, belowground, and litter) and soil organic carbon. These methods are compatible with IPCC tier 3 inventory guidance.
Sensitivity • Be sufficiently sensitive to quantify changes as a result of management and other major drivers of change, including climate change • Prioritize assessing directionality and general magnitude of change through time	The proposed methods increase the sensitivity of biomass carbon pools to management significantly and are expected to capture the directional effects of primary drivers on biomass carbon. In the absence of a suitable process-based model of soil organic carbon (SOC) and given the limitation of existing time series data, SOC pools in this ecosystem may be less sensitive to primary drivers. The proposed methods are expected to capture changes due to land-use change and disturbance but may be less sensitive to climate and management events. The limitation of available data also limits our ability to robustly verify time series estimates and management effects, increasing uncertainty.
Practical criteria • Generate transparent, repeatable methods that use free or low-cost tools • Prioritize base data that has reasonable expectation of sustainment and openness for use by state staff • Use models that are publicly available and open source • Use base data that require as little pre-processing for state staff as possible • Use base data that have a proven basis in reality and, where applicable, are validated with error or accuracy	The proposed method relies on LANDFIRE-C, an established empirical model of biomass carbon. Supporting data (LANDFIRE) is publicly available. Every effort will be taken to use publicly available NAIP imagery, however higher resolution, proprietary data may be used if required to support the analysis. In most cases, the unified soils framework method uses open-source, free datasets and tools 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.

In assessing the available biogeochemical models to create training data for sparsely vegetated lands in the unified soils framework, CARB staff identified two models. Neither of these models currently fulfill the criteria for inclusion in the NWL Carbon Inventory for sparsely vegetated lands (Table 4). RothC quantifies soil organic carbon by modeling the turnover of organic carbon in non-waterlogged soils (Coleman, 1996). While this model has been used extensively and across many different ecosystem types, RothC has been shown to underperform in arid and semi-arid ecosystems (Lobe, 2005). There are modifications to RothC to improve dryland performance (Farina, 2013). However, CARB staff could not locate a version verified for California's sparsely vegetated ecosystems, nor could staff locate sufficient calibration/validation data to create a modified model version in-house.

The Soil Landscape Inorganic Carbon model (SLIC) was assed as a potential model to quantify soil inorganic carbon (Hirmas, 2010). SLIC has been used in portions of California's Mojave Desert to quantify soil inorganic carbon, however CARB staff did not find broad-scale usage in California or elsewhere. SLIC model source code is not publicly available, and the model currently does not capture the primary drivers of change assessed by the NWL Carbon Inventory (Table 4).

Table 4: Assessed biogeochemical models for sparsely vegetated ecosystems. Assessed models include RothC (Coleman, 1996) and the Soil Landscape Inorganic Carbon model (SLIC) (Hirmas, 2010).

Model Name	**RothC**	**SLIC**
Must fit context of specific landscape type (Sparsely Vegetated Lands)	No, but some efforts have been made in arid lands.	Yes
Is the model scalable?	Yes	Yes, spatially
Can this model do future projections needed for scoping plan?	Yes	No
Does the model include the major drivers of change in this system and key ecosystem processes?	No, does not represent major drivers of this ecosystem.	No, currently models the effects of increased atmospheric CO2 concentration
Is this model sensitive to climate change?	Yes	Yes
Can this model estimate the impacts of management/NBS actions?	Yes, simplified	No
Does the model output carbon stocks and/or GHGs?	Yes, Soil Organic Carbon Stocks	Yes, Soil Inorganic 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	Uncertain, model code is not publicly available
Is this an open-source model that we can modify and share without restriction?	Yes	No
Is this a mature model with a scientific track record?	Yes	No, limited usage found within the literature
Are people currently using this model and is there a current user base?	Yes, but mostly outside of arid lands	No
Will this model require a lot of work to make usable for CARB's purposes, or is it ready off the shelf?	Would require major modification for arid lands	Would require major or complete overhaul to integrate primary drivers
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?	No, off the shelf data not available for the required modifications	No, insufficient data on SIC and response to drivers.
Can CARB staff run this model within our current timeframe for deliverables	Unlikely	No, additional research required

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