Natural and Working Lands Carbon Inventory: Forest and Shrubland

Proposed 2025 Inventory Update Methods
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Background

The Earth's carbon cycle involves the exchange of carbon between the atmosphere, biosphere (plants, animals, and other life forms), hydrosphere (water bodies), pedosphere (soils), and lithosphere (Earth's crust and mantles, including rocks and fossil fuels). Carbon moves between land types (e.g., forests and grasslands) and carbon pools (e.g., wood, roots, and soils) due to natural processes (growth, decay, and succession) and disturbances (e.g., wildfire) or anthropogenic forces such as land use change. The Natural and Working Lands (NWL) Inventory tracks how much carbon exists in California's ecosystems, where that carbon is located, and estimates how much carbon is moving in and out of the various land types and carbon pools. It provides stored carbon "snapshots" and gives insight into the location and magnitude of NWL carbon stocks at discrete moments in time. NWLs play an important role in the State's climate strategy by contributing to carbon sequestration and GHG reduction, and the NWL Inventory is a key tool for tracking the impacts of these strategies. The NWL Inventory was developed based on the Guidelines for National

Greenhouse Gas Inventories of the United Nations Intergovernmental Panel on Climate Change ("the IPCC Inventory Guidelines"), which includes quantification of direct emissions from human activities, as well as ecosystem carbon stock change on land.

Under the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) forests and shrublands are categorized together, with shrublands considered a subgroup of forested lands. Forests and Shrublands are defined as land exhibiting greater than or equal to 10% canopy cover comprised of live trees and/or shrubs or chaparral. For tree-dominated lands this may include oak woodlands, riparian forests, and conifer forests. For shrub-dominated lands this may include woody plants such as manzanita, coastal scrub, huckleberry oak, as well as desert shrubs. Highways and roads that run through forests and shrublands are counted as developed lands.

Forests and shrublands cover more than half of California's land surface. Within California forests make up 27% of the area (28.7M acres), while shrublands currently comprise 31% of the state (32.9M acres), the largest extent of any vegetation category. Most of the forest areas concentrated along the North Coast and in the Sierra Nevada, while the shrublands areas are concentrated in the southern portion of the Coast Range and desert areas. Collectively, forests and shrublands contain more carbon than any of the other land types in California (CARB 2018a) and are frequently subject to disturbances and management.

The State of California is committed to achieving a just and equitable transition to carbon neutrality by 2045. *California's Nature Based Solution Climate Targets* call for restoring nature and landscape health to deliver on our climate change goals and other critical priorities, including improving public health and safety, securing our food and water supplies, and achieving greater equity across California. To quantify the contribution of natural and working lands towards carbon neutrality, CARB must assess the effect that climate, wildfire, droughts, pathogens, management, and anything else that impacts plants and soils have on these systems. The NWL Carbon Inventory will act as a basis from which CARB can assess the impact that the AB 1757 Nature-Based Solution Climate Targets are having on the State's efforts to achieve carbon neutrality.

Many of the methods for quantifying carbon for the NWL Carbon Inventory differ between forests and shrublands. In these instances, each land type will be treated separately in this document.

State of the Science

Forests: A forest inventory is a detailed assessment of the carbon stocks within the area of forests. Inventories used to account for a jurisdiction's contribution to global climate mitigation are conducted according to the methodologies standards established by the Intergovernmental Panel on Climate Change (IPCC). IPCC approaches are classified into three tiers depending on the amount of data available and the methodology used. The most basic tier, Tier 1, uses default stock change factors and generalized forest and climate data, while Tiers 2 and 3 integrate country-specific data and higher-resolution models or monitoring systems for greater accuracy. Tier 3 inventory approaches vary, as the approaches often incorporate combinations of empirical or process-based modeling, remote sensing, plot-scale forestry measurements, meteorological data, land use and land cover change data, and management practices, providing a detailed assessment of forest carbon stocks within jurisdictional boundaries.

For the United States, the standard approach for generating the forest carbon inventory is via a Forest Inventory and Analysis (FIA)-based stock difference approach (United States Environmnetal Protection Agency 2024). FIA is a program that is designed to sample and assess forest data across a set of permanent, geographically unbiased field plots. Each field plot is sampled at 10-year intervals in most locations, providing consistent, repeatable samples. Recently, FIA has updated their approach for predicting tree volume, biomass, and carbon attributes. The National Scale Volume and Biomass (NSVB) Estimators system will provide a more consistent accounting of forest structural components across the U.S. (Westfall et al. 2024). For the U.S. Carbon Inventory, FIA data is combined with the National Resources Inventory (NRI) and the National Land Cover Dataset (NLCD) to estimate stocks for five carbon pools, aboveground biomass, belowground biomass, litter, dead wood, and soil organic matter. Changes in carbon stocks though time are computed by differencing carbon estimates at different points in times.

At the state level, alternative approaches have been or are being developed for quantifying forest carbon inventories. Some of these alternative approaches are centered around FIA data (e.g. Volster et al. 2024, NYS 2024). Others expand on the FIA approach by incorporating remote sensing. The 2018 NWL Carbon Inventory for California combined Landsat data processed through LANDFIRE with FIA data to estimate forest carbon stocks (CARB 2018b). More recent approaches combine Landsat remote sensing data, airborne Light Detection and Ranging (LiDAR), and FIA plot data using machine learning (Tamiminia et al. 2024). In other cases, inventory approaches incorporate the modeling of vegetation dynamics combined with remotely sensed LiDAR to estimate carbon stocks (Maryland 2020, Hurtt et al. 2024). The variety of approaches used to estimate state-level inventories reflect differences in inputs available for different states, as well as differences in priorities for how to quantify carbon stocks and change.

Due to the need for quantifying aboveground carbon for purposes beyond carbon inventories (e.g. research and offset programs), many commercial and non-commercial carbon products have been produced over the past decade that may also be leveraged for carbon inventories. These products range from global scale to national and regional scales, with some products developed primarily for forests whereas other products encompass all land cover types. The products generally differ in the data, methods, and sensors employed to derive carbon stock estimates. For example, one approach uses gradient nearest neighbor (GNN) models and imputation to associates every pixel on a landscape to the most similar inventory plot(s) (Ohmann et al. 2011). Another approach combines FIA data and Landsat remote sensing using a modified random forest and imputation to generate carbon stocks across the U.S. (Riley et al. 2022). A third approach integrates FIA data with the Forest Vegetation Simulator (FVS), and a change detection product (FastEmap) to generate a modeling framework that can simulate spatiotemporal biomass change (Huang et al. 2018).

LiDAR can be an effective tool for quantifying biomass, but most LiDAR maps are only produced at the local or regional scale, and not at regular time intervals, making LiDAR-derived estimates limiting for state-wide carbon inventories. An exception is the LiDAR sensor located on the International Space Station (i.e. GEDI project), which provides LiDAR coverage across most of the U.S. However, although aboveground live carbon maps are being directly generated using GEDI, the temporal coverage is currently limited to a single time-point (Duncanson et al. 2022). More sophisticated approaches are being developed that integrate combinations of LiDAR, ecological modeling, in situ inventory plots, and microwave and optical remote sensing imagery (Planet 2024, Xu et al. 2021).

Current challenges for the state of forest carbon inventory science include the ability to estimate total carbon including above and below, live and dead, and soils in a consistent way. Combining carbon stocks with other important forest metrics consistently, such as fuels for fire emissions modeling, remains an ongoing area of research. Finally, quantifying post disturbance carbon stocks from fire and harvest is an area of research that is developing.

Shrublands: The Intergovernmental Panel on Climate change (IPCC) Guidelines for National Greenhouse Gas Inventories categorize shrublands as a subgroup of forested lands (Intergovernmental Panel on Climate Change, 2019). This categorization is echoed by inventory efforts such as the US EPA's National GHG Inventory (United States Environmnetal Protection Agency, 2024). Within the National GHG Inventory, shrubland carbon is calculated as a component of above-ground biomass carbon pools (live understory) and as deadwood with a set ratio for associated below-ground biomass (Woodall, 2010; Westfall, 2024). These calculations rely on US Forest Service's Forest Inventory Analysis (FIA) plot data. While FIA products are among the most robust and valuable datasets for carbon accounting in forested systems, the utilized methodology is less suitable for shrub-dominated systems compared to tree-dominated systems (Chojnacky, 2008).

Due to these data limitations, existing efforts to quantify shrubland carbon stocks often seek to expand plot-level datasets of above-ground and soil organic carbon stocks. This is the case for California's current research in these systems, with most contributors to quantification methods either consolidating or contributing allometric equations or plot-scale measurements (Bohlman, 2018; Schrader-Patton, 2021; Lutz, 2017). Some efforts have taken place to quantify carbon densities for just shrublands and chaparral communities by synthesizing available plot level data, such as a recent collaboration lead by the USFS (Schrader-Patton, 2021). The generation of a robust, empirical dataset compatible with common remote sensing carbon accounting methods is a priority identified by multiple academic and governmental organizations, including CARB. Despite limitations in calibration and validations data, there is a large body of evidence on the effects of disturbance on shrubland carbon (Pratt, 2014; Storey, 2021; Guiterman, 2022; Safford, 2014). Quantification methods must assess the effects of disturbances, such as frequent short-return wildfires, on carbon stocks to accurately reflect reality.

Key knowledge gaps in these systems include connecting species scale allometric equations with remote-sensing imagery and empirical quantification of below ground carbon stocks. Allometric equations relate measurable features of plants to carbon densities, and underly the methods of many inventories, including CARB's quantification of shrubland carbon density. These equations are often species-specific rather than spatially explicit (e.g., plot-level). While a density can be assumed based on remotely sensed relationships, explicit detection of actual shrub density within remotely sensed pixel can be challenging due to canopy overlap. For deeply-rooted shrub species, few studies have explicitly quantified belowground carbon down to appropriate rooting depths. This limits our ability to generate robust allometric equations for belowground carbon that are sensitive to management and disturbance.

Primary Drivers of Change

Forests: The primary controls on forest land carbon dynamics are tightly coupled to climatic drivers, disturbances, and both temporary and permanent landuse conversions. Disturbances like fire, harvest, and climate action can all affect carbon stocks of forests. In California, more than a century of fire exclusion has resulted in a substantial increase in forest carbon stocks, creating forests that are more vulnerable to wildfire and drought (Kennedy, 2021). Climate change is causing rising temperatures, increasing the frequency and duration of drought, and producing other changes in the spatial and temporal patterns of precipitation. These trends are expected to change forest growth patterns, exacerbate the spread of disease and pests, increase the mortality rate of trees, and generally increase fire activity into the future (Allen, 2010).

Vegetation conversions to and from forests are driven by climate change and catastrophic wildfire and are changing the nature of forests in California's landscape. Following severe fire, forests are vulnerable to type conversion to grasslands or shrublands, particularly if the climate is not conducive for sapling regrowth (Davis, 2019). Climate in and of itself is also a major driver of change in California's forests. Between 2012 and 2016 more than 129 million trees died from drought (Restaino, 2019). This is expected to increase as climate becomes hotter and drier (Bernal, 2022). Another dominant conversion away from forests is driven by the pressure to develop tracts of forest lands into new housing, thus changing forests into developed lands. On the other hand, woody encroachment of forests into meadows and grass lands due to fire suppression can lead to the expansion of forests, converting other landuse types into forests (Lubetkin, 2017).

Shrublands: Shrublands are systems of change, regularly expanding into areas previously occupied by other ecosystems or contracting as a result of type conversion and management. Like many of California's landscapes, shrublands change in extent due to a variety of factors, including wildfire, changing climate conditions, management, and site history. In California, some of the primary changes observed in shrublands include type conversion, management, restoration, and climate impacts.

Post-wildfire, especially high-severity wildfire in forests, shrublands can grow over previously forested systems (Guiterman, 2022). This expansion can delay forest reestablishment or result in more permanent type conversion, depending on conditions such as drought, climate, and restoration efforts (Davis, 2023). Additionally, while shrublands are adapted to wildfire, many communities are not adapted to frequent, short-return-interval wildfires. The departure from historically infrequent, high-severity wildfire across large portions of the state's shrubland communities has resulted in degradation and type conversion to other systems, such as annual grasslands (Safford, 2014).

Management of shrublands within the wildland-urban interface (WUI) often involves strategies such as clearing, mastication, and thinning to reduce hazards to humans and to reduce the risk of ignitions around infrastructure. This results in changes to carbon stocks in the WUI and can have disparate effects which can be complex and difficult to predict. Restoration occurs in all of the state's shrubland communities to varying extents. Some communities, such as coastal sage scrub in California's coastal zone, are protected from development through regulation. Required mitigation in these situations can systematically increase the cover of shrublands, given a successful restoration project, but will still affect average age (time since wildfire) and other characteristics of habitats.

California includes a range of shrubland communities, existing across a huge gradient of climactic conditions. Changing climate and increased aridity can affect these communities by decreasing carbon uptake, disrupting recovery from disturbance, decreasing resilience to insects and diseases, and increasing mortality rates (Pratt, 2014; Storey, 2021). Climate effects and those other primary drivers of change highlight the dynamic and evolving nature of shrubland ecosystems in California.

Nature Based Solutions Targets

Forests: California’s Nature-based Solutions Climate Targets (AB1757) aim to increase the health and resilience of forests, which in turn supports state priorities of protecting water, safeguarding public health, advancing equity, expanding economic opportunity and prosperity, increasing food and water security, and protecting biodiversity (California’s Nature-Based Solutions Climate Targets). The NBS targets for forested lands are divided into three types of targets, wildfire risk reduction targets, NBS acreage targets, and NBS percentage targets. The target amounts reported below all refer to the year 2045 target.

The NBS wildfire risk reduction targets are centered around increasing beneficial fire to over 1.5 million acres/year and increasing fuel reduction activities to 1 million acres/year, at a statewide level. Beneficial fire includes activities such as prescribed broadcast burning, cultural burning, planned managed fire, and planned treatment burned in wildfire. Fuel reduction activities include thinning, invasive species removal, prescribed herbivory (grazing), mechanical treatments (first entry and retreatments), and uneven-aged timber harvest. While these targets are at a statewide level and include lands other than forests (e.g. shrublands, grasslands), the substantial proportion of the wildfire risk reduction activities are likely to occur in forested lands.

The NBS acreage targets for forest lands include 52,900 acres/year of afforestation, primarily to re-establish oak woodlands within historical range (Table 1). Conservation of old growth forests that contain the oldest trees, as well as conifer, riparian, and oak woodland forests, have a NBS target of 55,100 acres/year. NBS targets for Restoration include post high severity fire reforestation and restoration as well as restoring the health of degraded oak woodlands. These targets are set at 322,100 acres/year. Working Forest Conservation targets of 165,200 acres/year are focused on improving the functioning of managed forests, including extending harvest rotation lengths, shifting the intensity of harvests, and restoring and/or conserving wildlife habitat.

The NBS percentage targets for forest lands include 1) a 90% decrease in the rate of illegal forest conversion and degradation, and 2) an increase in beneficial fire and fuel reduction activities, such that low to moderate severity fire collectively makes up 90% of all wildfires (Table 1).

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

AB 1757 Nature-Based Solution (NBS)	2030 Target	2038 Target	2045 Target
Beneficial Fire	800K acres/yr	1.2M acres/yr	1.5M acres/yr
Other Fuel Reduction Activities	700K acres/yr	800K acres/yr	1M acres/yr
Afforestation (adding trees)	52.9K acres/yr	52.9K acres/yr	52.9K acres/yr
Conservation	55.1K acres/yr	55.1K acres/yr	55.1K acres/yr
Restoration	322.1K acres/yr	462.1K acres/yr	322.1K acres/yr
Working Forest Conservation	165.2K acres/yr	165.2K acres/yr	165.2K acres/yr
Decrease the rate of illegal conversion and forest degradation by	20%	50%	90%
Through beneficial fire and other fuel reduction activities, shift the proportion of statewide high severity wildfire to low or moderate severity wildfire such that the total percentage of low to moderate severity wildfire is	75%	83%	90%

Shrublands: 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 shrublands and chaparral communities, these targets call for 140,000 - 150,000 acres of climate action every year between now and 2045, focused primarily on conservation and restoration (Table 2). Concurrent with statewide targets, shrublands and chaparral currently experience changes due to management. Management can include post fire restoration, defensible space, expansion of developed lands, and vegetation management within the wildlands urban interface. Management events can connect shrublands and forest ecosystems, especially during post-high-severity-wildfire afforestation efforts to hasten recovery of forests or prevent forest conversion to shrublands. In developing an updated methodology for the NWL Carbon Inventory, our methods must be able to track the implementation and carbon consequences of these targets and management activities.

Table 2: Nature-Based Solution Targets for shrublands as defined in *California's Nature-Based Solutions Climate Targets*.

AB 1757 Nature-Based Solution (NBS)	2030 Target	2038 Target	2045 Target
Conservation	104.6K acres/yr	104.6K acres/yr	104.6K acres/yr
Restoration	37K acres/yr	40K acres/yr	45K acres/yr

2018 NWL Carbon Inventory Methods

Methods Description

The 2018 NWL Carbon Inventory tracked how much carbon exists in California's forest and shrubland ecosystems, where that carbon was located at discrete moments in time, and produced estimates of how much carbon was moving in and out of the various land types and carbon pools (CARB 2018a). The forest inventory was separated into biomass carbon and soil carbon. CARB developed the NWL Inventory using design principles established by the *Intergovernmental Panel on Climate Change (IPCC)*. CARB's NWL inventory methodologies used a combination of remote sensing data and ground-based measurement data, as well as other default assumptions where California-specific data are not available (CARB 2018b).

Forest Biomass Carbon: In 2015, CARB commissioned a data-driven methodology, called LANDFIRE-C, for assessing carbon stocks and changes for all land categories in California with the exception of agricultural and urban areas (Battles et al., 2013, CARB 2018b). This method uses California specific land-based data sets and satellite remote sensing data. The covered ecosystems include forests, woodlands, shrublands, grasslands, wetlands and sparsely vegetated lands, which include desert and beach areas. The method includes carbon contained in aboveground and belowground pools for both live and dead vegetation but excludes soil carbon. Data sources for the method include ground-based data from the Forest Inventory and Analysis (FIA) program of the USDA-Forest Service, remote sensing products from NASA's MODIS sensor, geospatial vegetation attributes and disturbance activity (fire, harvest etc.) data from the federal Landscape Fire and Resource Management Planning Tools Project (Landfire.gov), and ancillary data on shrublands and grasslands. LANDFIRE-C calculates carbon stocks based on three LANDFIRE products; vegetation type (EVT), canopy cover (EVC), and height (EVH); and established look-up tables. The look-up tables were created using the relationship between the LANDFIRE products and FIA data. The method enables analysts to retrospectively assess ecosystem carbon stocks and to attribute stock-changes to fire and other processes. LANDFIRE-C is generally considered a Tier 3 level inventory.

Shrubland Biomass Carbon: Similar to forests, previous iterations of the NWL Carbon Inventory for shrublands used LANDFIRE-C. LANDFIRE-C has undergone iterative revisions to improve model functioning and to incorporate additional allometric data for shrubland ecosystems (Gonzalez, 2015; Saah, 2016). Allometric equations for shrublands included all available studies with the required minimum information for this method of plot location, date of sampling, and canopy height.

Soil Carbon: Forest and shrubland soil carbon stock change was calculated using the 2006 IPCC Tier 2 methodology. All stocks were reported to a 30 cm depth as designated by IPCC (IPCC, 2006). 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 v1.0 (Hengl et al., 2017), a third-party dataset produced using the WoSIS dataset (Batjes et al., 2017). Stock change factors (Table 17 of NWL Inventory Technical Support Document) were determined as the ratio of average soil organic carbon between each IPCC land-type category following standard IPCC equations (Eqn 20, 21, and 22 of 2018 NWL Inventory Technical Support Document). For example, the stock change factor for shrublands converted to sparsely vegetated lands was 0.20, indicating that California's shrublands, on average, have 5 times more carbon than sparsely vegetated ecosystems.

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. In the above example, a pixel converted from the shrubland category to a sparsely vegetated category in 2010 would not fully transition until 2030. Each year, SOC would decrease by 4%. The result was annualized and total estimates for carbon stock change over the inventory period (2001-2010).

Benefits and Limitations

Forest Biomass Carbon: The geospatially explicit carbon estimates in the 2018 NWL Carbon Inventory using LANDFIRE-C provide information about what vegetation type is present on forest lands, how carbon density varies in different areas, how much live and dead biomass carbon are present on the landscape, and what changes are occurring on land. It provides a consistent approach to quantification of carbon stocks and track any changes that occur in carbon stocks. Finally, this process can be completed by CARB staff utilizing open-source data which makes this a replicable, scalable method to other states across the nation.

Some of the limitations of LANDFIRE-C include the underlying LANDFIRE product being inconsistent through time. For example, LANDFIRE regularly updates its classification system by splitting vegetations types, requiring constant refreshes of the model that converts LANDFIRE inputs to carbon stocks. CARB compensates for these changes through a manual effort of cross walking different versions of LANDFIRE so that they are comparable between years. A further limitation is that remote sensing does not currently reliably detect dead wood such as logs and snags on the landscape. This is a limitation of the science, limiting detection of dead wood after fire. A final limitation is the manual nature of the process itself. Previous versions of LANDFIRE-C have relied upon proprietary software that is not easily updated.

Shrubland Biomass Carbon: LANDFIRE-C provides an empirically based structure for assigning carbon density based on geolocated FIA plot data and LANDFIRE products. This method can be applied at large scales and provides spatially explicit information. However, the accuracy of any empirical model relies on the input calibration data. As FIA data is primarily collected in tree-dominated systems, this can create disparate levels of uncertainty for shrublands when compared to tree-dominated systems.

This limitation prompted the inclusion of external allometric equations for shrublands within LANDFIRE-C (Gonzalez, 2015). 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*:* The prior use of Tier 2 methodology for mineral soils allowed for the development of temporally consistent and spatially explicit carbon inventory estimates. This is a significant benefit. Additionally, using a Tier 2 approach enabled potentially greater accuracy than a Tier 1 approach, which would have relied on a global reference carbon stock value as input rather than more localized initial stock estimates from SoilGrids. 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 did not account for management or disturbance effects.

2025 NWL Carbon Inventory Update Proposed Methods

Methods Description

Forest Biomass Carbon: The proposed inventory method update for forest biomass carbon expands upon the LANDFIRE-C approach with new updates to the LANDFIRE-C framework. A new ensemble approach will then be incorporated that will integrate multiple carbon datasets to inform the forest carbon inventory.

The proposed updates to the LANDFIRE-C framework include regular updates to the model that converts LANDFIRE inputs to carbon-stocks via lookup tables. Further enhancements include the mapping and tracking of post-fire dead wood (new dead) via the incorporation of a new dead wood module into LANDFIRE-C. Previously all carbon stocks were lost when forest areas were converted to non-forest land use types after a wildfire. The updated LANDFIRE-C new-dead module retains 80% of the pre-fire forest aboveground live biomass in the form of post-fire new standing dead. The other 20% of killed tree aboveground live biomass is assumed to be consumed by the fire or is otherwise lost to the ecosystem. This estimate is based on more than 5,000 simulations using the First Order Fire Effects Model (FOFEM) for 100's of wildfires using a range of overstory mortality data. Finally, annual estimates of carbon stocks will be produced, allowing us to track dead wood and other carbon pools that remain on the landscape by taking into account decay rates and subsequent disturbances on dead wood. This effort will also help contribute to CARB's efforts to address changes in greenhouse gas emissions associated with contemporary wildfire for Senate Bill (SB) 901 – Wildfires (Dodd, statutes of 2018, chaptered 626).

Practical considerations are an important part of implementing a model such as LANDFIRE-C, as there is a need for methods to be transparent, repeatable, and minimize processing time. To achieve these goals, the number of upgrades will be made to LANDFIRE-C. First, the code underlying LANDFIRE-C is being rewritten in an open-source computing language and will rely only on open-source geospatial data formats. Second, the framework is being migrated to a High-Performance Computing Cluster to improve computational time. These proposed upgrades to the LANDFIRE-C framework for the 2025 Update to the Carbon Inventory will ensure that CARB's inventory methods can be updated as needed in support of California's 2045 Carbon Neutrality Goals and tracking of progress while the State implements its Nature-Based Solution Climate Targets.

Since the previous inventory, multiple research groups have developed aboveground live carbon datasets for California, providing unique approaches for estimating carbon across the state. The methodologies underlying these approaches provide different strengths and weaknesses. CARB will leverage the expertise and knowledge underlying these products to inform California's understanding of carbon stocks via an ensemble.

The ensemble approach allows multiple product datasets to be collated into a carbon estimate (Figure 1). CARB will be establishing criteria (e.g. format, metadata) that product datasets must satisfy to be considered for ensemble membership. All product datasets that meet these criteria will be evaluated for inclusion, including products operating at global, national, state, regional, and local scales.

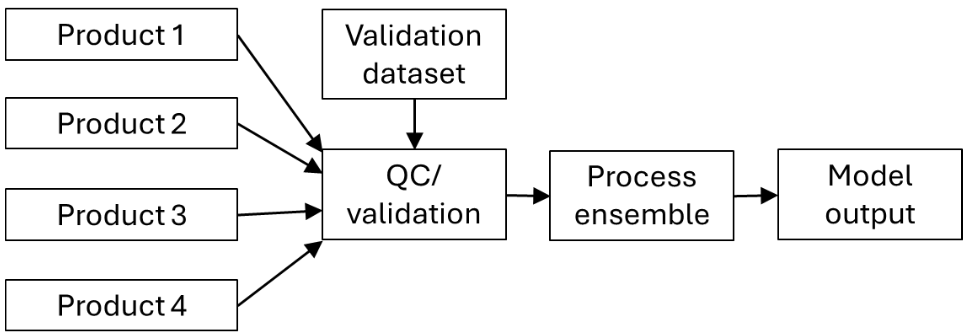

Figure 1: The workflow underlying the proposed forest ensemble methodology. Multiple carbon products will be collated, assessed for quality of data, and validated to an independent validation dataset. These products will then be processed in the ensemble and model output will be generated.

The ensemble approach will bring together multiple spatially explicit carbon product datasets, developed both in-house at CARB and from external projects. Each product dataset will be required to estimate total aboveground live carbon, as this variable will allow comparability among all datasets. In addition to total aboveground live carbon, multiple secondary variables of interest to CARB, such as total aboveground dead carbon, will also be incorporated into the ensemble if datasets of these variables are available (Table 3). These secondary variables provide a better picture of how carbon throughout forested regions is distributed among the primary forest canopy, understory, dead wood, and litter. These secondary variables may also contribute to non-inventory metrics to estimate forest structure and function.

Table 3: The secondary variables being collected for the forest ensemble, if available.

Forest ensemble variables
Total aboveground live biomass or carbon (required)
Total aboveground dead biomass or carbon
Total aboveground biomass or carbon, live and dead
Total belowground biomass or carbon
Total biomass or carbon, aboveground and belowground, live and dead
Soil carbon
Overstory live biomass or carbon
Understory live biomass or carbon
Standing dead biomass or carbon
Down dead biomass or carbon
Litter biomass or carbon

CARB will assess the extent to which a carbon dataset will contribute to the ensemble using an independent validation dataset of total aboveground live carbon. CARB is working to collect this validation dataset as representative of California's diverse ecosystems as possible. Based on the validation, contribution of the product datasets will be weighted within the final ensemble carbon estimate, such that the best products will contribute the most. For regions of the state where validation is inadequate to assess the quality of a carbon dataset, an alternative approach will be used that identifies high-confidence pixels. High-confidence pixels refer to pixels within a spatial dataset (such as a raster) that exhibit a high level of reliability and accuracy in their values based on specific criteria. These high-confidence pixels will be used to evaluate and weight each potential ensemble member.

Outputs from the ensemble will help exemplify the current state of the science on estimating aboveground live carbon stocks throughout California's diverse forest systems.

<u>Shrubland Biomass Carbon</u>: The updated methods for biomass carbon in shrublands 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 shrubland ecosystems, 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.

<u>Forest Soil Carbon</u>: For forests, a unified framework is proposed for space-time mapping of soil carbon, which is described in detail in the Soil Methods Document. The RothC model will be used to generate point-based estimates of soil carbon over time that will be integrated into this framework. RothC accounts for decomposition processes and organic matter turnover under varying conditions by partitioning soil organic matter into distinct pools, each with different turnover rates. The primary driver of RothC is organic carbon inputs (e.g. litter, coarse woody debris). To capture these dynamic inputs in forested systems, the MODIS Net Primary Productivity (NPP) product will be used as an input to the model. MODIS NPP is expected to implicitly capture forest changes due to disturbances such as wildfire, allowing the simulation of changes in SOC through time at the plot-scale.

<u>Shrubland Soil Carbon</u>: For shrublands, a unified framework is proposed for space-time mapping of soil carbon, which is described in detail in the Soil Methods Document. Specifically, key environmental and anthropogenic predictors include frequent wildfire, type conversion, canopy cover change, and biocrust disturbance. Additional soil core measurements from literature will be incorporated. This data collection will focus on shrubland ecosystems with limited representation in existing data syntheses. This may also incorporate time series data of soil carbon during management or disturbance. 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.

Benefits and Limitations

Forest Biomass Carbon: The new LANDFIRE-C framework has several benefits. The model will now account for carryover of dead wood from one year to the next, accounting for decay rates and subsequent disturbances. This change will provide better carbon estimates through time. The new framework will also improve usability since it will be coded using open-source computing language and open-source geospatial platforms.

The new LANDFIRE-C update will not address all LANDFIRE-C limitations. LANDFIRE-C is still likely to overestimate the immediate impact of wildfires on carbon stocks, since the remote sensing underlying LANDFIRE products cannot adequately detect post-fire dead wood. CARB acknowledges this challenge and is currently working on enhancing this aspect of our mapping efforts within LANDFIRE-C. Another challenge arises from our limited ability to update the underlying validation and calibration data that links vegetation cover classes to actual biomass estimates due to FIA access limitations. We will also continue to contend with changing vegetation classification schemes in the underlying LANDFIRE datasets. As such, all these challenges will require regular updates to the LANDFIRE-C framework.

The ensemble approach has the major advantage in that it will bring together the state of the science for estimating aboveground live forest biomass carbon, in that it provides statewide carbon estimates based on all available science, methods, and data. For each pixel throughout the state, a mean and variability metric can be generated, providing an estimate of which regions of California have better spatial and temporal agreement between all these products. Further, the ensemble approach benefits from greater diversity of methods and datasets underlying each product dataset, as it will help improve our understanding and better quantify the accuracy of the state of science. As new carbon product datasets are generated in the future, these datasets can be incorporated into the current workflow, refining carbon estimates even more. The ensemble, however, will not be a replacement for LANDFIRE-C because total carbon, not just aboveground live carbon, must be estimated for the Inventory. Too few product datasets are likely to provide total carbon to generate an ensemble for this metric. Further, an inventory must be a replicable transparent process, and individual datasets may or may not continue into the future, and not every dataset has transparent and open data to meet CARB's inventory requirements.

The challenges associated with the ensemble approach are largely related to the statistical robustness of the carbon estimates due to the limited number of carbon product databases available for the ensemble. Examples of potential issues include biased datasets and an inconsistent number of ensemble datasets available for inference during individual years. There may be further issues related to the temporal continuity of product datasets if methodologies changed over time. When possible, CARB will work with the research groups that are generating carbon datasets to identify potential issues and refine the methodologies as needed.

Shrubland Biomass Carbon: The proposed quantification of biomass carbon values has multiple benefits. Primarily, direct connection of allometric equations with remote sensing imagery establishes realistic carbon estimates without ingesting reported management and disturbance data. The effects of primary drivers are implicitly included in this analysis, as measured changes in canopy structure, coverage, and density are assessed directly. However, this benefit does not provide insight into the cause of these changes. In assessing the implementation of management and its associated effects, the availability of reported management data may be limited. The proposed method is sensitive to real changes to shrubland carbon density, but cannot yet attribute those changes to specific management practices. This would require a complete dataset of relevant management activity data across the inventory time period.

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

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

Input and Validation Datasets

Forest Biomass Carbon: Existing geospatially explicit estimates of aboveground live carbon stocks that may serve as inputs to the new ensemble method (Table 4). This is a preliminary table and will likely expand as CARB gathers more datasets.

Table 4: Forest carbon datasets that will be considered for ensemble inclusion.

Maps	Temporal coverage	Spatial coverage	Spatial resolution
LEMMA	1990 to 2021	CA	30m
EMAPR	1990 to 2017	CONUS	30m
GEDI - L4A	single time point, comprised of data 2019-2023	CA	25m
GEDI - L4B	single time point, comprised of data 2019-2023	CA	1km
CECS	1985-2023	CA - GAP Forest	30m
TREEMAP	2008, 2014, and 2016, 2020(soon)	National	30m
LANDFIRE-C	2016, 2020, 2022	CA	30m

For the ensemble validation dataset, CARB is currently reaching out to researchers, agencies and other entities to request field plot level measurements of trees, shrubs, and soil of forest and shrublands within California's borders. Field plot data should be sufficient for estimating at least the above ground biomass carbon of the plot. The data will be used to assess the ensemble of aboveground carbon stocks maps of California forest and shrublands and incorporated into the integrated SOC approach.

Shrubland 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 5). Verification of canopy cover will involve comparing manually labeled canopy cover with NDVI-thresholding predictions. To estimate uncertainty, analysis will be performed to understand the potential range of uncertainty within model predictions.

Table 5: Required model inputs and proposed data sources for quantification of carbon stocks in shrubland ecosystems.

Input	Proposed Data Source
Ecosystem Type	LANDFIRE Existing Vegetation Type (EVT)
Canopy Height	LANDFIRE Existing Vegetation Height (EVH)
Canopy Cover/Density	LANDFIRE Existing Vegetation Cover (EVC) NAIP Imagery
Frequent Wildfire	LANDFIRE Disturbance
Land Use Conversion	LANDFIRE Existing Vegetation Type (EVT)
Disturbance Events	LANDFIRE Disturbance

Alternative Method for 2025 Update

Forest Biomass Carbon: The carbon ensemble is expected to bolster our work using LANDFIRE-C. However, the exact extent to which the ensemble contributes to the 2025 inventory will be determined as this work develops, because this exercise's success is highly dependent on the data that CARB can acquire, the robustness and representativeness of the ensemble members, as well as the practical aspects of working with many different groups to collect and harmonize complex datasets at different scales and with different temporal and spatial resolutions. The alternative method for the forest carbon inventory without the use of an ensemble will utilize the updated version of LANDFIRE-C.

Shrubland 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. The previous Tier 2 approach, incorporating primary drivers of change as stock change factors based on literature values and a third-party carbon reference map (as described in the previous methodology section) would still benefit from the additional data gathered as part of this update.

Criteria Assessment

All decisions regarding proposed updates to the NWL Carbon Inventory were made in relation to standardized criteria set forth by CARB (Table 6). 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 6 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	These methods will be done at the statewide scale and is appropriate for county scale aggregation and will include all forests and shrublands in California.
Temporal scale • Go back as far in time as possible, at least to 2001 • Be as up to date as possible	These methods will go back to at least 2001 and will provide estimates through as close to present as possible, likely 2023 or one of the surrounding years.
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	These methods will provide a spatial resolution well beyond the resolution of ecosystem boundaries, between 30m-250m resolution, depending on the carbon pool. It will allow for various categorical analyses.
Temporal resolution • Produce annualized values that can be reported very 3-5 years	These methods will produce annual values that can be updated and reported every 3-5 years.
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	These methods capture the primary pools of carbon in forests and grasslands, including aboveground biomass carbon. They are consistent with IPCC GHG 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	These methods are able to quantify changes in carbon through time that result from management or other major drivers of change.
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	In most cases, these methods use 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. Base data requires minimal pre-processing and is vetted by data developers.

For forest soils, a process-based model is being proposed as part of the unified soil framework. Because of this, additional criteria were considered by CARB staff for model selection specifically. These criteria encompass the broader inventory requirements that are tailored to consider model specifications and support model selection (Table 7).

For forest soils, many of the prevailing process-based models are coupled to biogeochemical models (e.g. RHESSys). The complexity associated with running these models wall-to-wall for the state of California within our current timeframe for deliverables was prohibitive. RothC, which is being used to model soil organic carbon for multiple land types, should be suitable for forests as well given the modifications to input variables (i.e. NPP).

For shrubland soils, there are known limitations of RothC. 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 shrublands ecosystems. Given these limitations, quantification of shrubland soil organic carbon will likely not involve using RothC to generate training data. If - while developing this NWL Carbon Inventory - CARB staff find these deficiencies in RothC can be overcome, RothC may be implemented at select shrubland sites. This implementation would be limited to sites where explicit verification data exists to quantify the uncertainty of this method.

Table 7: Process-based model candidates for quantifying soil organic carbon (SOC) in grassland mineral soils, evaluated according to California Air Resources Board (CARB) model criteria.

Model Name	**RothC**
Must fit context of specific landscape type	**Yes**
Is the model scalable?	**Yes**
Can this model do future projections needed for scoping plan?	**Yes**
Does the model include the major drivers of change in this system and key ecosystem processes?	**Yes, minus coupled nutrient dynamics**
Is this model sensitive to climate change	**Directly via a temperature sensitive decay parameter, indirectly through soil carbon inputs.**
Can this model estimate the impacts of management/NBS actions?	**Yes, simplified**
Does the model output carbon stocks and/or GHGs?	**Yes**
Is the model validated and have a basis in reality?	**Yes**
Can this model be run on a regular basis to develop updates and incorporate improvements?	**Yes**

Is this an open-source model that we can modify and share without restriction?	**Yes**
Is this a mature model with a scientific track record?	**Yes**
Are people currently using this model and is there a current user base?	**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**
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?	**Yes, simplified parameterization requirements**
Can CARB staff run this model within our current timeframe for deliverables	**Yes**

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