Effects of Wildfire and Forest Management on Greenhouse Gas Emissions and Carbon Stock Change (SB 901 Report)

Appendix A

Contents

Executive Summary

This report is to fulfill Senate Bill (SB) 901 – Wildfires (Dodd, statutes of 2018, chaptered 626), which directs the California Air Resources Board (CARB) to prepare "a report that assesses greenhouse gas emissions associated with wildfire and forest management activities". It presents state-wide retrospective estimates of: (1) greenhouse gas (GHG) emissions associated with wildfires for the period 2000-2024; and (2) changes in biomass carbon stocks associated with other vegetation management activities (e.g., prescribed fire, timber harvest, thinning, and other activities that reduce fire risk) for the period of 2002–2022.

Wildfire continues to play an important role in renewing and maintaining the abundance and diversity of vegetation populating California's landscapes. At the same time, one of the key climate policy goals of the State is to reduce the occurrence of severe wildfires through the implementation of strategic vegetation management practices aimed at reducing fuel loads and improving ecosystem health. This report considers the effects that all wildfire and all vegetation management practices have on GHG emissions and ecosystem carbon.

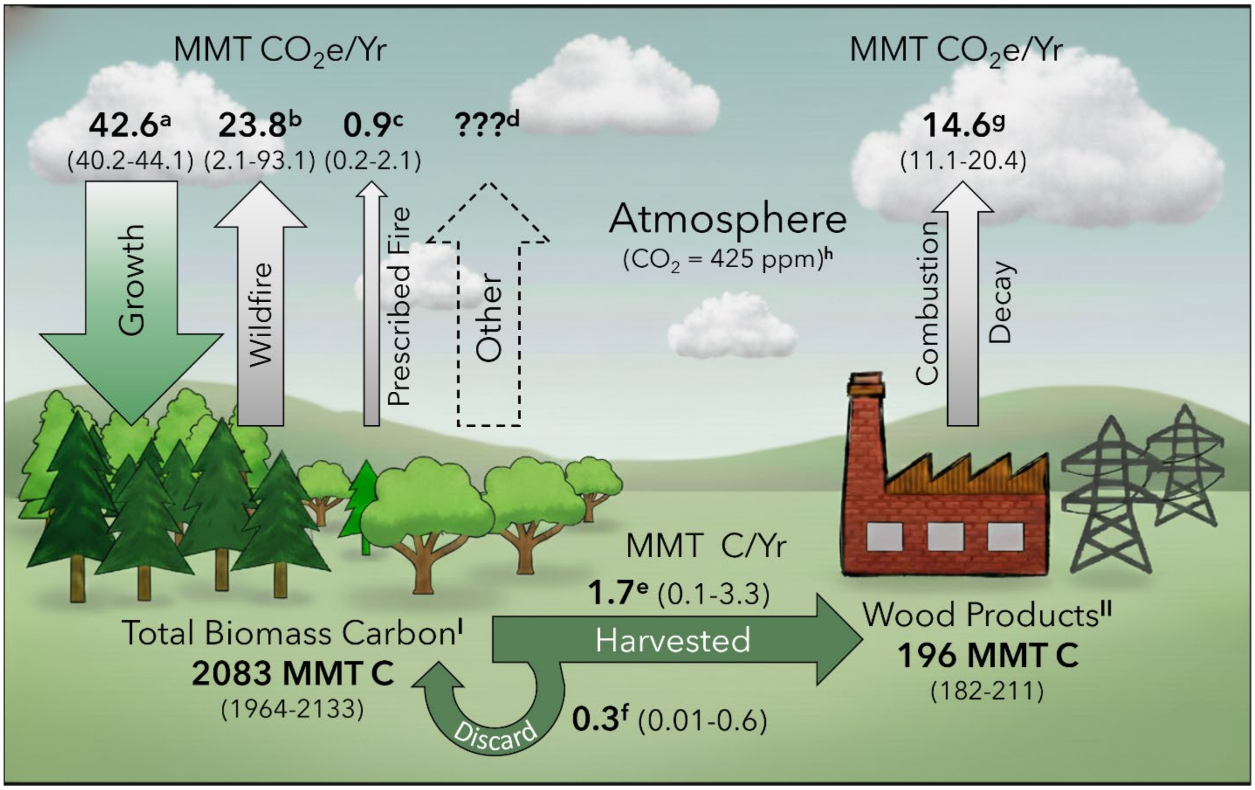
Main Findings

California's forests, shrublands, and grasslands contain large quantities of carbon in the forms of living and dead plant biomass as well as in soil organic matter. The annual amounts of carbon transferred between the atmosphere and various biomass carbon pools represent only a small portion of the total carbon stored in biomass (<1%, Appendix Figure E 1).

Despite the proliferation of wildfire over the 21st century, average annual GHG emissions from wildfires are just over half of the average annual carbon dioxide taken up by plants in support of net primary production (23.8 vs. 42.5 MMT CO_2e/Year). In most years, emissions from wildfire were an order of magnitude lower than rates of uptake due to net primary production. However, emissions due to wildfires greatly exceeded net uptake by trees, shrubs, plants, and grasses in years when wildfires were particularly abundant (>50 MMT CO_2e/Year in 2008, 2020, and 2021).

Average annual GHG emissions from prescribed fire reported here were more than an order of magnitude lower than emissions from wildfire. In contrast, emissions of GHGs from the combustion and decay of harvested wood products manufactured within the state occurred at levels that were, on average, roughly 60% of GHG emissions due to wildfires (14.6 MMT CO_2e/Year).

The extent to which disturbances like wildfires or vegetation management alter biomass carbon across California's is highly dependent on the extent to which those disturbances instigate a change in landcover from higher biomass density forests to lower biomass density shrublands and grasslands. For example, most of the total biomass carbon transformed by wildfires and clearcutting occurred where there was a subsequent change in landcover (75% and 68% by mass, respectively) even though only a minority of the land affected by these disturbances actually experienced a change in landcover (34% and 30% by area, respectively).

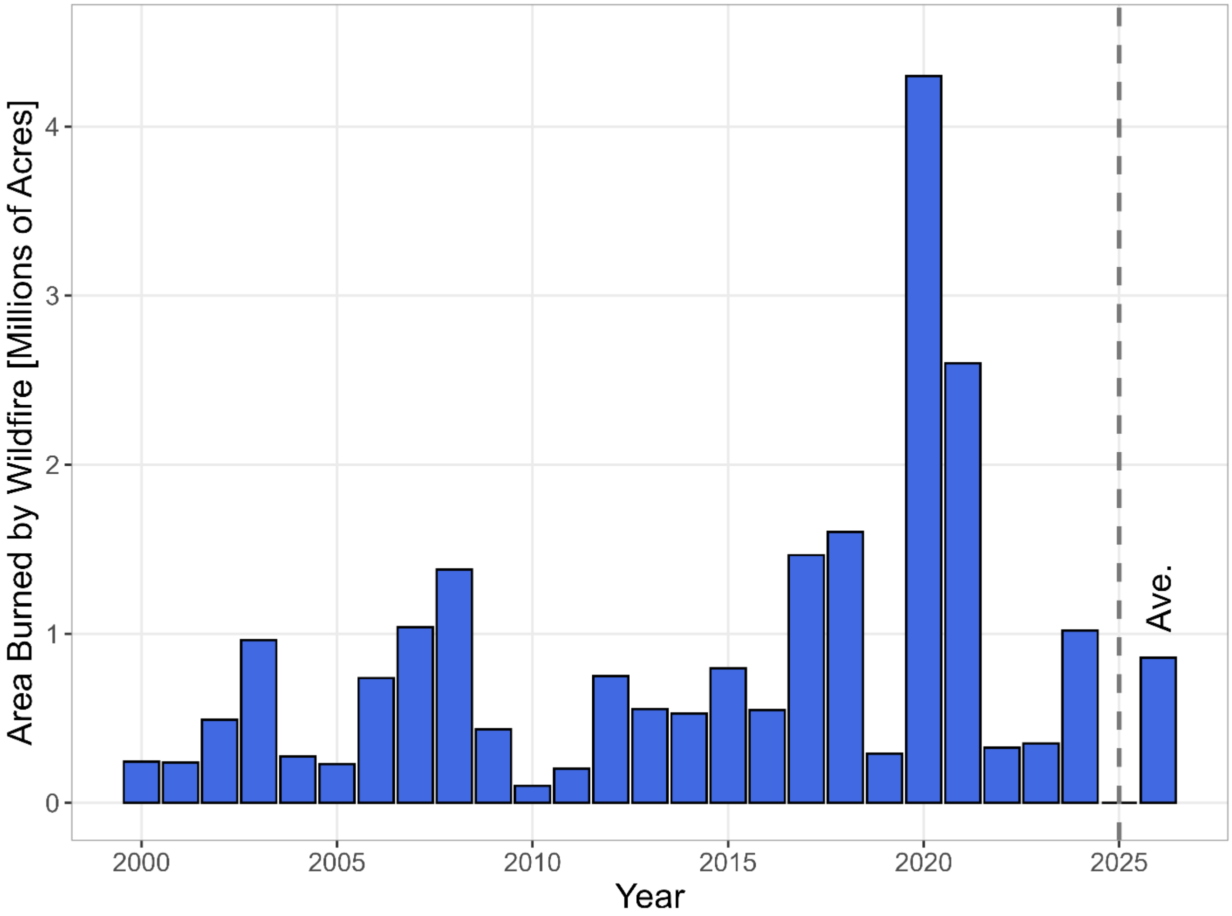


Appendix Figure E 1 - Flows of carbon and CO_2 between the atmosphere and California's forests, shrublands, and grasslands. The upper portion of this diagram represents the reservoir of carbon in the atmosphere. The lower portion of this diagram represents the amount of biomass carbon stored in **I**) all forests, shrublands, and grasslands (2083 MMT of carbon, bottom left), and **II**) all harvested wood products manufactured within California (196 MMT of carbon, bottom right). The bold numbers represent the average annual values over the period of 2002-2022 while the numbers in parentheses represent the range of all values over the same period (minimum to maximum).

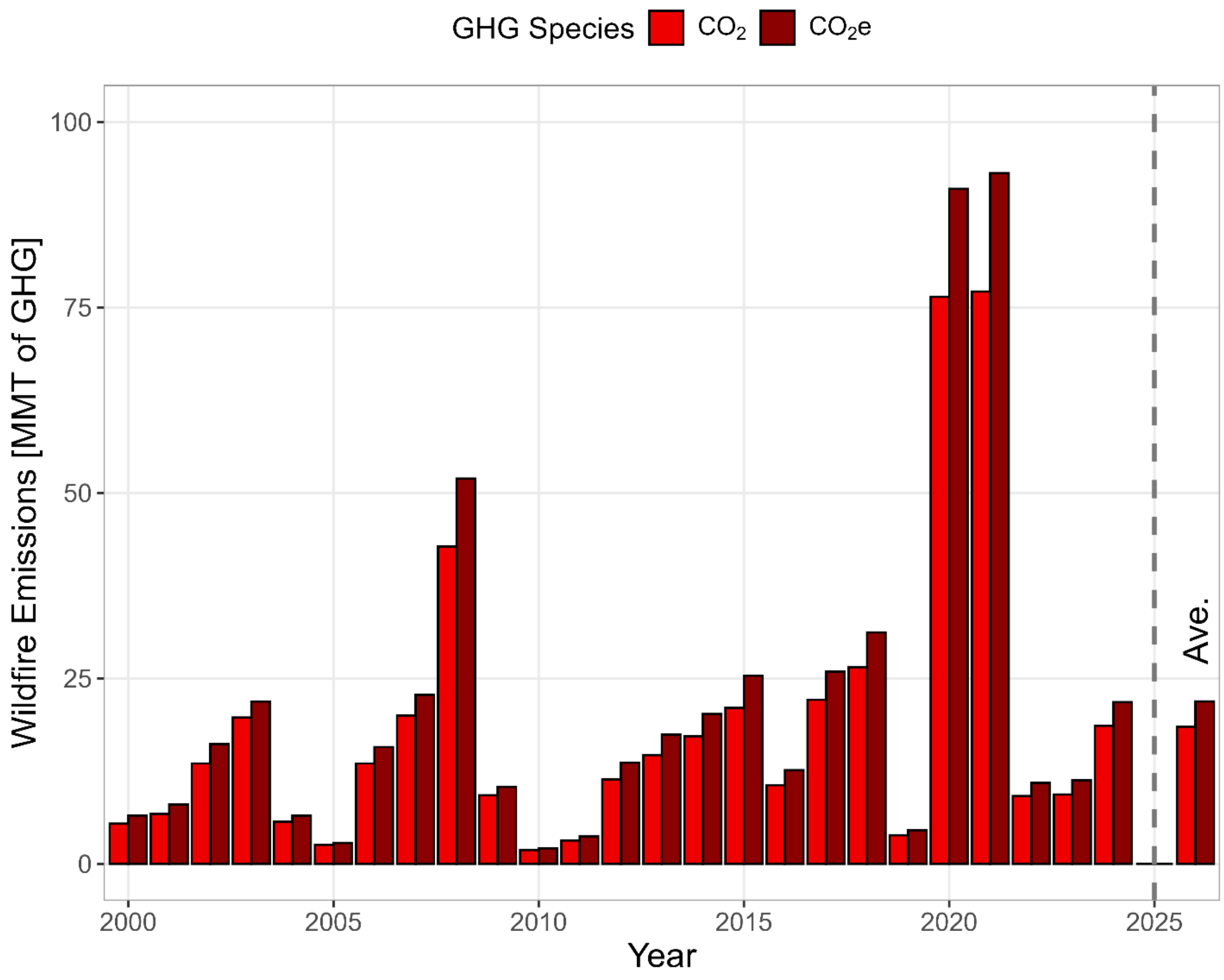
Exchanges of carbon and CO_2 between different reservoirs are shown by arrows and represent average annual fluxes in MMT CO_2/Yr and MMT CO_2e/Yr, respectively, according to the following transfer pathways: (**a**) 'Growth' includes all of the carbon taken up through photosynthesis and converted to live and dead woody or herbaceous biomass in forest and other natural lands (i.e., net primary production). (**b**) 'Wildfire' represents the combined emissions of all GHG species produced during a wildfire (carbon dioxide, methane, and nitrous oxide). (**c**) 'Prescribed Fire' represents the total GHG emissions from all prescribed fires based on amount of biomass carbon transformed and a ratio of CO_2e to CO_2 similar to that of wildfire emissions. Estimates shown here were estimated from losses in biomass carbon calculated for this report using data from the 2025 Natural and Working Lands Carbon Inventory. Ongoing work by CARB staff suggests that the amount of biomass carbon transformed by prescribed fire may be higher than reported here due to the underreporting of prescribed burns in the LANDFIRE annual disturbance layers. (**d**) 'Other' represents the presently unknown exchange (release) of greenhouse gases into the atmosphere due to processes not considered in the present analysis such as the in-situ decay of dead biomass or the hydrological export and subsequent remineralization of biogenic carbon. (**e**) 'Harvested' represents the amount of biomass carbon mobilized for the manufacture of wood products. (**f**) ‘Discard’ represents the amount of degraded biomass carbon left on site as a part of vegetation management. (**g**) ‘Combustion + Decay' represent the combined GHG emissions resulting from the combustion of harvested wood products for the purposes of energy capture as well as from the decay of wood products in landfills, dumps, and other solid waste disposal sites. (**h**) Average level of atmospheric carbon dioxide in 2024 (National Oceanic and Atmospheric Administration, 2025).

Wildfire Emissions

The total area of forests, shrublands, and grasslands affected by wildfires between 2000 and 2024 ranged from 101,000 acres to 4.30 million acres and averaged 859,000 acres (Appendix Figure E 2). Statewide annual emissions of carbon dioxide due to wildfires ranged from 1.9 to 77.1 million metric tons of carbon dioxide (MMT CO_2/year) and averaged 18.5 MMT CO_2/year between 2000 and 2024 (Appendix Figure E 3). Statewide annual emissions of greenhouse gases due to wildfires ranged from 2.1 to 93.1 MMT CO_2e/year and averaged 21.9 MMT CO_2e/year between 2000 and 2024.



Appendix Figure E 2 - Annual statewide area affected by wildfire. Areas affected by wildfires included all landscapes that contained fuel according to the LANDFIRE Fuel Characteristics Classification System (FCCS). The value plotted to the right of the gray dashed line represents the average of all calendar years between 2000 and 2024 and is equal to 859,000 acres.



Appendix Figure E 3 - Annual statewide emissions of carbon dioxide (CO_2) and total greenhouse gases (CO_2e) due to wildfires. Values for CO_2e were calculated using greenhouse warming potential factors (GWPs) oriented to a 100-year time horizon of 28 and 273 for methane and nitrous oxide, respectively. Areas affected by wildfires included all landscapes that contained fuel according to the LANDFIRE Fuel Characteristics Classification System (FCCS). The values plotted to the right of the gray dashed line represent the average of all calendar years between 2000 and 2024 and are equal to 18.5 MMT of carbon dioxide emissions per year and 21.9 MMT CO_2e/year.

Effect of Vegetation Management on Biomass Carbon

Inter-annual changes in biomass carbon transformed by all vegetation management practices (i.e., within the same calendar year) ranged from 0.43 million metric tons of carbon per year (MMT C/Year) to 4.25 MMT C/Year between 2002 and 2022 and averaged 2.22 MMT C/Year over this period (Appendix Figure 4). Note that these units are in terms of elemental carbon and not CO_2e. On average, thinning had the biggest impact on biomass carbon transformed (0.78 MMT C/Year), followed by clear cutting (0.51 MMT C/Year), and then harvesting (0.41 MMT C/Year). The combined category of biological, chemical, and herbicide treatments was the vegetation management practice with the least effect on biomass carbon (0.01 MMT C/Year) over the 21-year period examined. The effect of vegetation management on biomass carbon was heavily slanted towards forests relative to shrublands and grasslands over the past two decades. The total amount of biomass carbon transformed by all vegetation management practices between 2002 and 2022 averaged 2.2 MMT C/Year for forests and only 0.047 and 0.035 MMT C/Year for shrublands and grasslands, respectively. These values are equivalent to a proportional distribution of transformed biomass carbon of 96.4%, 2.0%, and 1.5% between forests, shrublands, and grasslands; respectively.

Regional and Statewide Effects of Disturbance

The effects of wildfire and vegetation management on biomass carbon across California were tallied both statewide as well as divided spatially into individual regions defined by California's Fifth Climate Change Assessment. Wildfires were responsible for transforming the largest amount of biomass carbon statewide (14.1 MMT C/Year) and at a rate that was more than six times higher than the total amount of biomass carbon transformed by all vegetation management practices on average (2.2 MMT C/Year). The regions experiencing the largest effects of both wildfire and vegetation management on biomass carbon were those with the greatest amount of forested lands including (in decreasing order of degree affected) the North Coast, Sierra Nevada, Sacramento Valley, and Central Coast regions.

Influence of Landcover Changes on Changes in Biomass Carbon

The results of this report indicate that the changes in landcover type brought on by a given disturbance have a profound effect on how much biomass carbon is ultimately transformed by that disturbance. These results further suggest that even if climate-smart practices such as prescribed fire, mechanical fuel reduction, and sustainable harvesting cause some carbon to be transformed and removed from the landscape in the short-term, they will nonetheless have a net beneficial effect on the preservation of biomass carbon in the long-term if they can minimize the kind of substantial landcover conversions that would have occurred in the presence of more extreme disturbance events such as severe wildfires or extensive clearcutting.

1. Introduction

Fire serves several key ecological functions in California's diverse ecosystems, including facilitating germination of seeds for certain tree species, replenishing soil nutrients, maintaining diverse ecosystems, and reducing the accumulation of wildfire fuels. Since time immemorial to present day, the Indigenous People of California have been stewards of this land proactively managing its landscapes and have used fire to shape and maintain its diverse ecosystems. Since the late 19th Century, however, the management of California's forests and rangelands have come to be dominated by various forms of public and private control and, with that fire exclusion and new vegetation management objectives.

Throughout California, fire and vegetation management activities intersect with public safety, natural resources management, the built environment, air quality, and climate change. Trends brought about by climate change and legacies of California's historical development, together with society's efforts to address them, accentuate the importance of forests and rangelands in California. An assessment of greenhouse gas (GHG) emissions and carbon impacts of wildfire and vegetation management activities helps California better understand the effects of current vegetation management practices and leverage natural and working lands to ameliorate the effects of ongoing climate change.

1.1 Background: SB 901

Section 4 of Senate Bill (SB) 901 -Wildfires (Dodd, statutes of 2018, chaptered 626) adds Section 38535 to the California Health & Safety Code (H&SC). This this report fulfills the directive in subsection (c) of H&SC Section 38535, which reads:

> "38535. The state board, in consultation with the California Department of Forestry and Fire Protection, shall develop all of the following:… (c) On or before December 31, 2020, and every five years thereafter, a report that assesses greenhouse gas emissions associated with wildfire and forest management activities."

1.2 Scope of this Analysis

This report presents statewide, retrospective estimates of: (1) GHG emissions associated with contemporary wildfires for the period 2001–2024; and (2) changes in forest and rangeland biomass carbon stocks associated with wildfires and modern vegetation management practices (e.g., prescribed fire, timber harvest, forest thinning, and other activities that reduce fire risk) for the period 2002–2022. This report will show that much of the effects that both wildfire and proactive forest management practices have on stored biomass carbon (and the implied, long-term losses or gains of greenhouse gases) depend less on the nature of the natural or management disturbance, and more on the resulting transition in landcover type that does or does not occur in response to a given disturbance; particularly those transitions resulting in the conversion of forested landscapes to shrublands or grasslands. Therefore, the present report addresses the effects of disturbances occurring not just in forests, but also in shrublands and grasslands as well.

CARB recognizes that some vegetation management activities can indirectly enhance rates of carbon sequestration or the resiliency of carbon stores through their long-term effects on the structure and composition of predominant vegetation. This is an area of active and on-going scientific development. However, inventorying and analyzing these benefits at the statewide level would require the use of complex ecological models that are not yet easily and immediately available. Therefore, the present report focuses solely on the direct and immediate impact that wildfire and vegetation management are having on GHG emissions and stored biomass carbon but not on long-term rates of carbon sequestration and ecosystem recovery.

2. Overview of Data and Methodology

2.1 Wildfire Emissions Estimates

General Approach

To estimate emissions due to wildfires, CARB staff use a vegetation fuel combustion model to estimate GHG emissions associated with wildfires. The fire emission estimates rely on model inputs developed from geospatial wildfire fire activity (wildfire “footprints”) compiled by the California Department of Forestry and Fire Protection (CAL FIRE) as well as by the National Aeronautics and Space Agency (NASA). CARB’s 2025 Natural & Working Lands Ecosystem Carbon Inventory (NWL Carbon Inventory) is used to quantify the biomass carbon transformed by wildfire and vegetation management. To identify vegetation management activity disturbance and vegetation management data from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) consortium, and comprehensive vegetation management data taken from the Wildfire and Landscape Resilience Interagency Tracking System maintained by the Wildfire and Forest Resilience Task Force (TFITS) were used.

Overview of Methodology Refinements for the Present Analysis

The prior editions of the wildfire emission inventory before the 2025 edition used the following method. CARB estimated total bulk emissions and consumption for each wildfire included in the annually released wildfire perimeter dataset from the California Department of Forestry and Fire Protection (CAL FIRE) which is the authoritative source for final wildfire perimeters in California. For each wildfire, Fuel Characteristic Classification System (FCCS) fuel bed maps were developed under a CARB contract (University of California, Berkeley 2019), and now sourced from the

LANDFIRE program, were clipped to the perimeter of each wildfire. The monthly average 1000-hr fuel moisture was assigned to each wildfire based on data provided by gridMET (Abatzoglou, 2013) identified for the ignition month and the given wildfire perimeter centroid. These fuelbed and fuel moisture data were then used as inputs to the First Order Fire Effects Model (FOFEM) (Lutes, 2020), which produces estimates of flaming emissions, smoldering emissions, and consumption. In this report, this earlier approach was used to estimate wildfire emissions from 2001-2014.

To generate a more accurate inventory of daily emissions and consumption for wildfires, and to incorporate the latest science in emissions estimation, CARB staff updated the methodology pipeline for the 2025 edition of the wildfire emission inventory. The new pipeline integrates satellite-derived fire perimeters, spatiotemporally aligned fuelbed and fuel moisture data, and improved modeling of smoldering emissions. Compared to the previous inventory edition, the new approach enhances temporal precision and better reflects fire activity. The 2025 edition inventory added 2024 emissions to the time series and also remodeled 2015-2023 wildfire emissions. Thus, this newer, modified approach was used to estimate wildfire emissions from wildfires occurring between 2015-2024.

In the new methodology, CARB substitutes the final fire perimeters taken from CAL FIRE with daily fire perimeters derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) Active Fire Product (AFP, see next section) (Schroeder, 2014). For each day’s perimeter, FCCS fuelbeds are similarly clipped. For fuel moisture inputs, instead of extracting a single point estimate of 1000-hour fuel moisture from the polygon centroid, day-specific rasters are clipped to the spatial domain of an entire day’s perimeter. The fuelbed and fuel moisture rasters are stacked, spatially and temporally associating fuelbeds with correct fuel moistures, improving the precision of wildfire emissions estimates. In the following sections, steps to generate daily fire perimeters and pre- and post-processing steps in the FOFEM workflow are described in greater detail.

Daily perimeters derived from VIIRS active fire product

Most wildfires in California last one day or less, so for these fires, the CARB Wildfire Emissions Inventory (this inventory is separate from the NWL Carbon Inventory in that it focuses only on wildfire emissions as opposed to statewide ecosystem carbon stocks and stock change) defaults to using perimeters from the CAL FIRE dataset. For the remaining wildfires, CARB attempts to estimate daily perimeters derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) Active Fire Product (AFP) (Schroeder, 2014). This product detects actively burning pixels during each 12-hour satellite overpass (around 1 a.m. and 1 p.m. local time) with a 375-meter spatial resolution. As of 2022, VIIRS sensors are aboard three satellites: NOAA-20, NOAA-21, and the Suomi National Polar-orbiting Partnership (SNPP). For the purposes of this methodology, AFP data from SNPP only are used, as it is the only product in the Standard Processing collection (i.e., science quality, 'Archive collection') that spans the entire time period of this inventory and has undergone additional quality assurance and quality control compared to the Near Real-Time collection. SNPP AFP from the Standard Processing collection (VNP14IMGTML) are downloaded from the online Fire Information for Resource Management System site.

To interpolate daily perimeters from VIIRS, CARB used modified methods by (Chen Y. H., 2022). For each 12-hour time interval AFP, which are formatted as spatial points, and clustered using a ball-tree algorithm (Omohundro, 1989) and a nearest neighbor search (Pedregosa, 2011) for points within the same vicinity. Perimeters of these clusters were drawn using an alpha shape hull algorithm (Eidenshink, 2007), creating vectorized boundaries of discrete fire objects. As the algorithm processes each time step, fire objects may continue to be created, grow, merge with others, or stop when no new AFP are located nearby. These fire objects form the basis of the sub-daily fire progression perimeters, called Fire Events Data Suite (FEDS) (Chen Y. H., 2022). The Wildfire Tracking Lab within NASA's Goddard Space Flight Center and scientists at University of California, Irvine continue to optimize FEDS in order to track fires globally (see Github for the latest developments). To develop a daily wildfire inventory, the 12-hour FEDS perimeters were aggregated into 24-hour sets, such that the perimeters from 1 PM on day t are joined with those from 1 AM on day $t+1$.

While FEDS is capable of detecting the presence of fires with very high accuracy, it can overestimate actual fire perimeters as a result of VIIRS detecting high heat signatures in large smoke plumes that are much larger than the true burn perimeter (Zhang, 2017). Furthermore, even though the 375-meter spatial resolution of VIIRS is relatively fine compared to other fire-detecting satellites (such as MODIS at 1 km or GOES at 4 km), it can still be too coarse to discern the boundaries of co-occurring, nearby fires such as small lightning fires. Thus, FEDS can erroneously merge independent fires together.

To address these issues, CARB then modified the FEDS algorithm by pre-filtering AFP to the final fire footprints of known wildfires. This was done using wildfire perimeters from the CAL FIRE dataset which were buffered by 187.5-meter—equivalent to the radius of the spatial resolution of VIIRS. The FEDS algorithm was then looped through each wildfire, solving the two previously mentioned issues: 1) removing false positive AFP data to reduce the extent of overestimated fire perimeters, and 2) preventing the merging of coinciding, close fires since each fire is independently processed. Another outcome of using this approach was that it removed any non-wildfires that would have been detected by FEDS, which is beneficial for the purpose of building an emissions inventory of wildfires.

FOFEM emissions and consumption

CARB estimates emissions and consumption from each wildfire by providing two user-based inputs to FOFEM: 1000-hr fuel moisture data and FCCS fuelbeds. Combustion efficiency and therefore emissions are highly influenced by fuel moisture (Garg, 2021), which can vary greatly with temperature, precipitation, and relative humidity. Daily 4-km resolution rasters of 1000-hour fuel moisture were obtained from gridMET (Abatzoglou, 2013) and reprojected to 30-meter resolution to align with FCCS data. FCCS fuelbeds describe the inherent physical properties of fuel that influence fire behavior and effects, capturing the structure and quantity of fuel across multiple strata (Ottmar, 1993).

Currently, LANDFIRE hosts publicly available versions of FCCS for the United States for 2001, 2014, 2016, 2020, and 2023. Each vintage corresponds to disturbances occurring through the end of the indicated year. For example, the 2023 version incorporates disturbances through December 31, 2023 (La Puma, 2023). The most recent version available *prior to the fire* (e.g., a fire in 2020 uses version 2016) gets used since newer versions would reflect post-fire conditions rather than pre-fire fuels. CARB acknowledges that fuelbed accuracy diminishes as time since the last update increases, and that significant step-changes in fuelbeds may occur between LANDFIRE vintages.

FOFEM also allows users to specify canopy mortality. Currently, CARB assumes 39% canopy mortality for all wildfires, which stems from a study of the Monitoring Trends in Burn Severity (MTBS) project. (Eidenshink, 2007) demonstrated that of the 347 fires (7.8 million acres) surveyed in MTBS, 39% of the area burned at moderate and high severity. Future enhancements to CARB’s methodology could incorporate satellite-derived fire severity to more accurately estimate canopy mortality.

While emissions for most wildfires were estimated using final fire perimeters from CAL FIRE, daily perimeters from FEDS were used instead when VIIRS detected fire activity lasting more than 24 hours. In such cases, the process as described below was repeated for each day, and emissions were quantified only for the new growth occurring on that day. Raster-based inputs were stacked, clipped to each fire perimeter, and then converted to a tabular format with the total acreage of each fuelbed–fuel moisture combination quantified. Input data is processed through FOFEM version 6.7 in "batch mode" (Lutes 2020) using Emissions Factors (EFs) suggested by (Urbanski, 2014) and where the default output included consumption of various fuel strata and emissions of CO and CO_2 disaggregated into emissions occurring during the short-term flaming and smoldering (‘flaming’) phase and the residual smoldering (‘smoldering’) phase that followed the short-term flaming and smoldering phase. Nitrous oxide (N_2O) emissions were estimated using equations derived from the relationship between N_2O and CO_2 emissions based on molecular weight relationships according to (Lobert, 1991).

Post-processing of emissions

FOFEM produces estimates of total bulk emissions, which inherently assumes that all emissions from a single day's perimeter are completely released within a 24-hour period. For fires using FEDS perimeters, smoldering emissions are empirically allocated over time for each day using the VIIRS-derived Fire Radiative Power (FRP) which relates fire intensity to fuel consumption (Schroeder, 2014). Within each daily perimeter x, VIIRS-derived AFPs may be detected over multiple days. The partial emissions E_{xt} from perimeter x on day t were calculated by multiplying the total smoldering emissions E_x by a daily scalar weight w_{xt}:

$$w0_{xt} = \sum FRP_{xt} \tag{1}$$

$$w_{xt} = \frac{w0_{xt}}{\sum_t^T w0_{xt}} \tag{2}$$

$$E_{xt} = E_x \cdot w_{xt} \tag{3}$$

where $w0_{xt}$ is the sum of all FRP on day t within wildfire perimeter x (Eq. 1), w_{xt} is the normalized weight for day t across all T days (Eq. 2). Thus, the summed partial emissions from all perimeters for day t yields the adjusted smoldering emissions for that day.

To ensure that acres burned, emissions, and consumption generated from FEDS perimeters are of similar magnitude to those estimated from CAL FIRE perimeters, each of these quantities were then scaled according to the ratios of the burn area as reported by the CAL FIRE perimeter data to the burn area as reported by FEDS (Eq. 4).

$$y_{rep} = \varphi \cdot \mathrm{y}_{FEDS} \tag{4}$$

where y_{rep} is the attribute value reported here, y_{FEDS} is the same quantity calculated from the FEDS data, and φ is the ratio of the burn area defined by the CAL FIRE perimeter to the area of the perimeter reported by FEDS for the same fire.

2.2 Drivers of Change in Biomass Carbon

The analysis presented here focuses on the biomass carbon transformed primarily by vegetation management practices and to some extent wildfires. It does not include other types of emissions associated with vegetation management such as emissions associated with machinery and transport. Nor does it address the indirect effects that vegetation management have on key ecosystem attributes such as its physical structure and biological composition. This is different than calculating emissions associated with wildfires and management because large amounts of carbon in ecosystems are transformed from live to dead or removed from the ecosystem and used for harvested wood products. This carbon does not immediately enter the atmosphere in the form of emissions. By presenting both the immediate direct emissions associated with wildfires, as well as the biomass transformed by fires, management, and harvested wood products, CARB presents a more wholistic picture of the dynamics of carbon associated with these agents of change.

Data Sources

Many entities perform vegetation management activities throughout California including tribes, federal, state, and local government agencies, local collaboratives, non-governmental organizations, and various private institutions. These entities have varying levels of reporting, tracking, and data verification for recording forest management activities. To be applicable within the methodology used to estimate the biomass carbon affected by vegetation management, activity data must have included geospatial perimeters, the year when the activity occurred, and a description of the type of activity being implemented. The datasets that satisfied this criteria and were available to CARB staff included the 2025 Natural and Working Lands (NWL) Carbon Inventory (California Air Resources Board, 2025), LANDFIRE annual disturbance layers (La Puma, 2023), and the Wildfire and Landscape Resilience Interagency Treatment Tracking System (Wildfire and Forest Resilience Task Force, 2024). Additional information was also compiled from multiple sources on the domestic production of harvested wood products and their associated end-of-lifecycle emissions to more fully assess the emissions of GHGs that occurred as a result of vegetation management beyond what was emitted from the combustion and decay of degraded material left on site.

The CARB Natural and Working Lands Carbon Inventory

The CARB NWL Carbon Inventory is an inventory of ecosystem carbon stocks throughout California’s natural and working lands (NWL). The forest and shrubland portions of the NWL Carbon Inventory are created by using carbon densities based on LANDFIRE map products of vegetation type, canopy cover, and canopy height, along with US Forest Service Forest Inventory and Analysis (FIA) data, spatiotemporal disturbance records, and regional growth models to calculate spatially explicit estimates of biomass carbon on an annual basis. All data on biomass carbon presented here are based on the 2025 NWL Carbon Inventory. Please refer to Appendix B of the NWL Carbon Inventory for additional details on the methods used to create those data.

LANDFIRE Disturbance Data

LANDFIRE disturbance layers (DISTYEAR) are national datasets that combine remote sensing and reported disturbance data from multiple sources. LANDFIRE is a vegetation and disturbance mapping collaborative between the United States Forest Service and Department of Interior in partnership with The Nature Conservancy. The disturbances map product is developed from remotely sensed fire perimeters and management information reported by local, state and federal agencies. At the time of this analysis, LANDFIRE disturbance layers existed for the calendar years 2001–2022. In addition to providing georeferenced raster data on the occurrence of disturbances due to wildfires, LANDFIRE classifies seven types of forest management activities: 1) clearcutting, 2) harvesting, 3) thinning, 4) mastication, 5) other mechanical, 6) prescribed fire, and 7) biological-chemical treatments which are described as follows:

- **Clearcutting** is the cutting of essentially all trees in a location, fully exposing the forest floor for the development of a new age class of trees.

- **Harvesting** is a general term for the cutting, felling, and gathering of forest timber. LANDFIRE assigns the term in cases where there is insufficient information to classify the event as clearcut or thinning.
- **Thinning** is a tree removal practice that reduces tree density and competition between trees in a stand. Thinning serves to concentrate growth and vigor in fewer, high-quality trees.
- **Mastication** is a process in which vegetation is mechanically "mowed" or "chipped" into small pieces and left on-site, reconfiguring a portion of forest biomass from a vertical to horizontal arrangement.
- **Other Mechanical** is a generic term for a variety of forest and rangeland mechanical activities involving mechanical fuels reduction and site preparation methods other than the four listed above including piling of fuels, chaining, lop and scatter, thinning of fuels, etc.
- **Prescribed Fire** for the present study is predominantly represented by two vegetation management practices: broadcast burning and pile burning. It does not include either planned treatments burned by wildfire for resource benefit nor wildfires managed for 'use' (resource benefit).
- **Biological-Chemical** represents the combined set of practices involving biological treatments, chemical treatments, and the application of herbicides for the purposes of reducing or eliminating standing vegetation where 'biological treatments' most often imply the use of prescribed herbivory.

Wildfire and Landscape Resilience Interagency Treatment Tracking System

Established by the California Natural Resources Agency and the Wildfire and Forest Resilience Task Force (WFRTF), the Wildfire & Landscape Resilience Interagency Treatment Tracking System, or more succinctly the 'Task Force Interagency Tracking System' (TFITS), provides a single repository for storing geospatial data on completed vegetation management projects across California from over a dozen different federal and State agencies. The primary purpose of TFITS is to track the collective progress that the State and its partners are making towards reducing the occurrence of catastrophic wildfires and promoting healthy landscapes. The TFITS have primarily focused on the tracking of recent vegetation management and reporting into this system is voluntary. All data presented here was taken from version 2.0 of the TFITS released on 12 December 2025.

Harvested Wood Products

Data on the domestic production of harvested wood products and their end-of-lifecycle emissions were taken from the 2025 NWL Carbon Inventory and are based on source data provided by United States Forest Service (USFS) Timber Product Output (TPO) reports, California Department of Trade and Fee Administration (CDTFA) Timber Yield Tax reports, the California Department of Resources Recycling and Recovery (CalRecycle) SWIS database, and Western Wood Products Association (WWPA) Western Lumber Statistics reports.

Methodology

All biomass carbon data used in the present report were taken from georeferenced raster maps created as part of the 2025 NWL Carbon Inventory. Briefly, maps of biomass carbon in forests and shrublands were created using a modified version of the LANDFIRE-C model (P. Gonzalez, 2015). LANDFIRE-C uses a combination of remotely sensed emergent vegetation attribute and disturbance data provided by the LANDFIRE program to estimate biomass carbon using allometric relationships derived from plot-level observations of vegetative structure and dead material. For forests, these allometric relationships are based on georeferenced forest plots maintained by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service (Battles, 2013). For shrublands, these relationships were based on canopy cover, height, and root to shoot ratios synthesized from federal programs (Reeves & Frid, 2016). Maps of biomass carbon in grasslands were created using a Tier 3 approach based on annual herbaceous biomass estimates from the Rangeland Analysis Platform (RAP). For the present purposes and that of the 2025 NWL Carbon Inventory, the term 'biomass carbon' used throughout this report refers specifically to the cumulative amount of organic carbon stored in aboveground live tissue, belowground live tissue, and all dead vegetation above ground. It does not include soil organic carbon. For forests, the aboveground live component consisted only of tree boles. For forests and shrublands, the belowground live component did not include fine roots. The method for estimating biomass carbon in grasslands did not discriminate between the amount of carbon stored in different live vegetative components except for the disaggregation of dead wood remaining on the grasslands following a wildfire and subsequent landcover transition of forest to grassland.

Quantifying Changes in Biomass Carbon

Maps of interannual changes in biomass carbon were created by computing the difference between annual maps of biomass carbon in forests, shrublands, and grasslands in adjacent years over a period of 2001-2022. These inter-annual biomass carbon difference maps were then subset according to the spatial distribution of natural and management disturbance data indicated in the corresponding LANDFIRE annual disturbance layers for each calendar year in question. Pixels within these disturbance-masked, inter-annual biomass carbon difference maps were then identified and sorted according to the following five categorical attributes: 1) the calendar year of the relevant annual disturbance layer (which corresponded to the interannual change in biomass carbon), 2) the predominant landcover in the initial year of interest (forests, shrublands, or grasslands), 3) the predominant landcover in the subsequent year of interest (forests, shrublands, or grasslands), 4) the natural or management disturbance applied over the given calendar year of interest (Wildfire, Prescribed Fire, Clearcut, Harvest, Thinning, Mastication, Other Mechanical, or

Biological-Chemical), and 5) the specific region of California as identified by California's Firth Climate Change Assessment to which the pixels belonged.

Individual values of interannual changes in biomass carbon for each pixel identified in the biomass carbon change maps were then summed across all pixels belonging to the same set of all five categorical variables (or features) to obtain a single, scalar value of spatially integrated change in biomass carbon for all possible categorical sets herein referred to as '*the total amount of biomass carbon transformed*'. The value of this quantity is reported in millions of metric tons of carbon (MMT C). The number of pixels belonging to each possible categorical set were also counted to create a similar scalar distribution of total annual area belonging to all possible categorical sets defined above and are reported in thousands of acres (kAc). Data on the distribution of biomass carbon in the year prior to the disturbance was used to record the initial amount of biomass carbon present prior to each disturbance across each categorical set. Finally, the total amount of biomass transformed in each categorical set was divided by the area affected in each categorical set to calculate the spatially averaged *change in biomass carbon density* (per area) in MT of carbon per acre (MT C/Acre) for each categorical set. This process of distilling the geospatial data into categorically classified scalar data resulted in the creation of four different continuous variables each distributed over five categorical dimensions: the total amount of biomass carbon transformed, the area affected, the initial amount of biomass carbon present prior to disturbance, and the spatially averaged change in biomass carbon density.

Comparing Results with the Task Force Interagency Tracking System

To promote a fair comparison between vegetation management activities recorded in the Task Force Interagency Tracking System (TFITS) with the mutually exclusive spatial distribution of vegetation management effects recorded in the LANDFIRE disturbance layers, the footprint areas (rather than total areas) of all completed vegetation management activities reported in TFITS were summed over every individual calendar year where the broad vegetation type was identified as either forests, shrubland/chapparal, or grassland/herbaceous. Direct calculations of the total footprint of relevant vegetation management practices implemented in California's forests, shrublands, and grasslands for the calendar years 2021 and 2022 were and are provided by the Task Force dashboard based on an approximate method for calculating the geospatial intersection and union of all relevant activities occurring within a given calendar year. At the same time, the vegetation management data provided by the Task Force revealed that in recent years (2021-2024) the total spatial footprint of all vegetation management activities conducted in forests, shrublands, and grasslands throughout California in a given calendar year was approximately 78% of the total scalar area of all reported activities recorded for that calendar year owing to the occasional spatial intersection of vegetation management over the same treatment area. Therefore, the total footprint of vegetation management activities conducted during all calendar years prior to 2021 were calculated by first summing the reported areas of all vegetation management activities recorded in the TFITS in a given calendar year and then multiplying that quantity by 0.78 to create an estimate of the mutually exclusive areas of forest, shrubland, and grassland affected by vegetation management for each calendar year as recorded in TFITS prior to 2021.

The Task Force Interagency Tracking System does not report the biomass carbon transformed by the vegetation management activities it records. However, it is possible to make at least rough estimates of the biomass carbon transformed by activities recorded in TFITS data by first calculating the distribution of activity footprint areas recorded in the TFITS disaggregated by year, vegetation management type, and predominant landcover type and then averaging over all calendar years available to create a bivariate distribution of average area affected per calendar year as a function of vegetation management type and landcover type alone (see Appendix Figure 7). This was done by first mapping the more granular TFITS Activity Descriptions to the more generic LANDFIRE vegetation management types on a non-degenerate, many to one basis in order to generate estimates of areas affected by vegetation management as recorded in TFITS but expressed according to the LANDFIRE disturbance classification and landcover classification schemes. Next, an equivalent bivariate distribution of the effect that different vegetation management practices had on biomass carbon density (per area) additionally disaggregated by landcover type was calculated from the Inventory and LANDFIRE data by dividing the distribution of the average total biomass carbon transformed per calendar year disaggregated by vegetation management type and landcover type (see Appendix Figure 6) by a similar distribution of average area affected per calendar year disaggregated by vegetation management type and landcover type (see Appendix Figure 5). The product of this bivariate distribution and the bivariate distribution of area affected calculated from the TFITS data was then taken to create a similar bivariate distribution of average total biomass carbon transformed per calendar year disaggregated by vegetation management type and landcover type as estimated from vegetation management data recorded in TFITS rather than in the LANDFIRE disturbance layers. Finally, the resulting estimate of the bivariate distribution of average biomass carbon transformed per calendar year disaggregated by management type and landcover type as recorded TFITS was then summed over all three landcover types (forests, shrublands, and grasslands) to create a singular distribution of the average amount of biomass carbon transformed per calendar year for each class of vegetation management practices as defined in the LANDFIRE disturbance layers.

Statistically Discriminating Factors Affecting Changes in Biomass Carbon Density

A predictive, non-parametric statistical model was developed to more fairly and robustly intercompare the relative influence that disturbance type, initial biomass density, and landcover transition (for example: Forest to Grassland or Shrubland to Shrubland) had on the calculated changes in biomass carbon density described above. The model consists of an ensemble learning method that utilizes gradient boosting on sequential predictions made by multiple regression trees (XGBoost). It was applied over a finite model parameter domain that includes learning rate, sampling rate, and maximum tree depth. The goal was to find the optimal set of model parameters that minimized the Mean Square Error (MSE) as calculated by 10-fold cross-validation and use the predictions made from this optimal model. All observed values of change in biomass carbon density were weighted by inverse propensity score as determined from their bivariate categorical frequency against disturbance type and landcover transition to ensure that there was a relatively uniform representation of information from across the entire feature domain prior to model fitting.

The reference model disturbance type category was biological-chemical treatments and the reference landcover transition category Grassland to Grassland. To avoid unwanted collinearity between initial biomass carbon density and the initial landcover types on which biomass carbon density is highly dependent, initial biomass carbon densities were separately normalized by the mean and standard deviation of the individual landcover type to which they belonged (forest, shrubland, or grassland) thus creating a non-dimensional covariate with an approximately unit normal distribution for all landcover types.

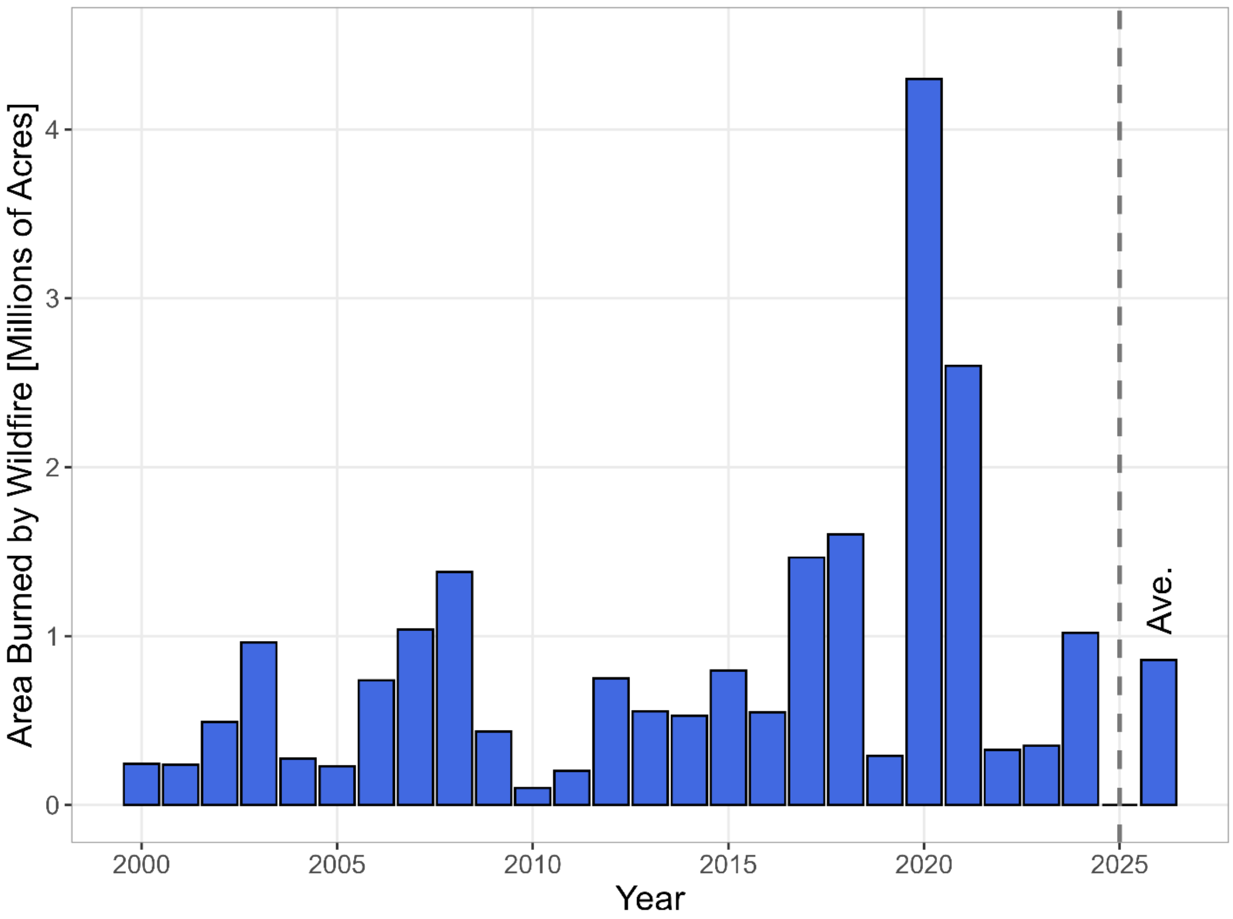
Once an optimal statistical model had been identified, each feature of interest (disturbance type, normalized initial biomass carbon density, and landcover transition) was permuted 10 times to calculate an average importance score that reflected the average increase in model MSE resulting from the randomly permuted feature relative to the performance of the full model (i.e., the model including all features with no permutation). Additional importance testing was conducted by simultaneously permuting all one-hot encoded covariates corresponding to each of the three feature groups while preserving the uniqueness of each multiclass categorical variable. Time (year) was not explicitly considered in the model in order to provide adequate replication and coverage across the combined multivariate distribution of the three features of interest.

3. Results and Quantification

3.1 Wildfire Emissions

Area Impacted by Wildfire

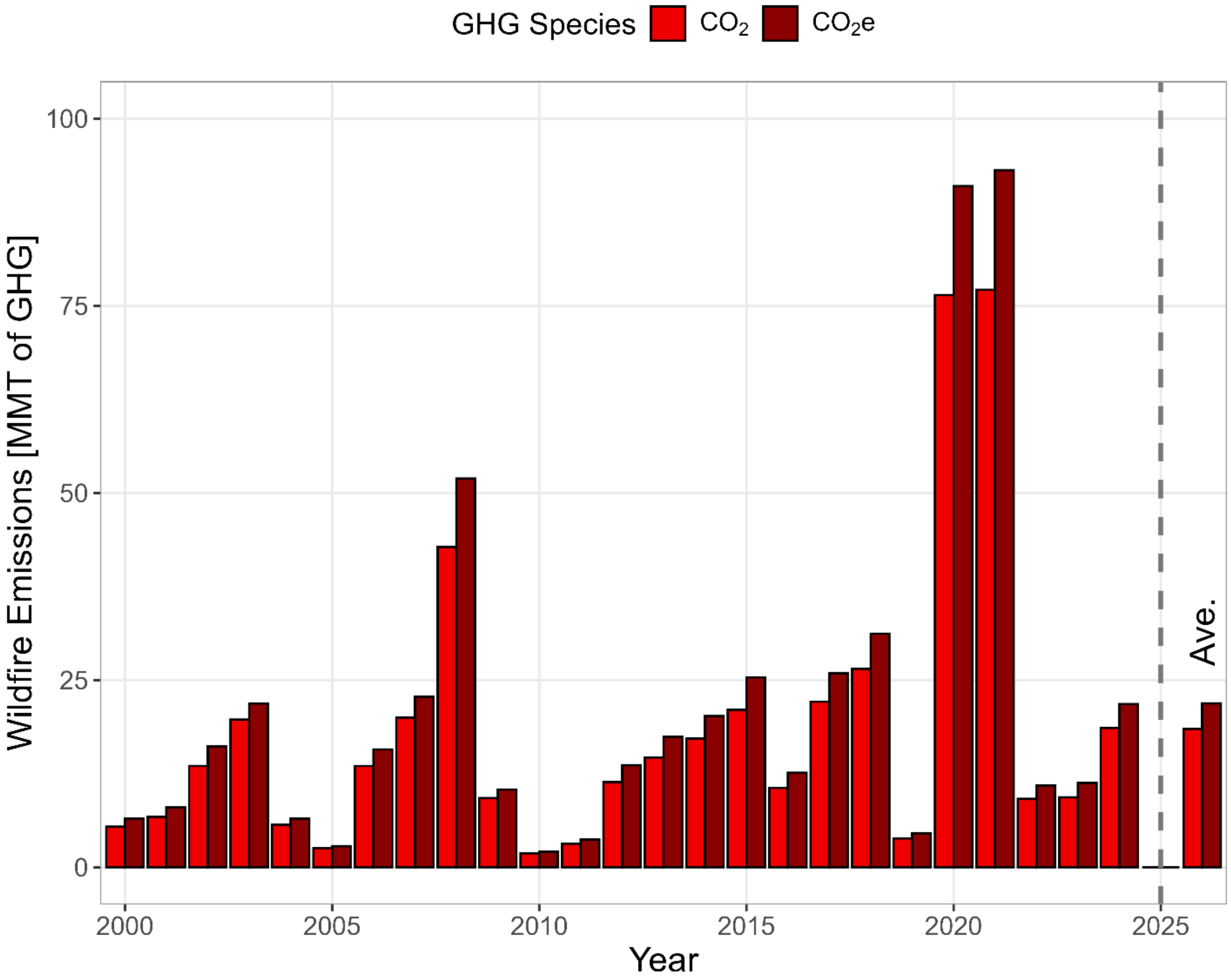
The total area of forests, shrublands, and grasslands affected by wildfires between 2000 and 2024 ranged from 101,000 acres to 4.30 million acres and averaged 859,000 acres (Appendix Figure 1).



Appendix Figure 1 - Annual statewide area affected by wildfire. Areas affected by wildfires included all landscapes that contained fuel according to the LANDFIRE Fuel Characteristics Classification System (FCCS). The value plotted to the right of the gray dashed line represents the average of all calendar years between 2000 and 2024 and is equal to 859,000 acres.

Annual Emissions

Statewide annual emissions of carbon dioxide due to wildfires ranged from 1.9 to 77.1 MMT CO_2 and averaged 18.5 MMT CO_2 between 2000 and 2024 (Appendix Figure 2). Statewide annual emissions of greenhouse gases due to wildfires ranged from 2.1 to 93.1 MMT CO_2e and averaged 21.9 MMT CO_2e between 2000 and 2024 (Appendix Figure 2).



Appendix Figure 2 - Annual statewide emissions of carbon dioxide (CO_2) and total greenhouse gases (CO_2e) due to wildfires. Values for CO_2e were calculated using greenhouse warming potential factors (GWPs) oriented to a 100-year time horizon of 28 and 273 for methane and nitrous oxide, respectively. Areas affected by wildfires included all landscapes that contained fuel according to the LANDFIRE Fuel Characteristics Classification System (FCCS). The values plotted to the right of the gray dashed line represent the average of all calendar years between 2000 and 2024 and are equal to 18.5 MMT of carbon dioxide emissions per year and 21.9 MMT CO_2e/year.

Gases emitted from wildfires consisted primarily of carbon dioxide; however, carbon monoxide emissions were 12% of carbon dioxide emissions by mass on average (Appendix Table 1Appendix Table 1). Methane and nitrous oxide emissions were much smaller than carbon dioxide emissions by mass, but generally large enough to elevate the emission of all greenhouse gases to levels that were roughly 20% higher than emissions from carbon dioxide alone. Furthermore, the total emissions of both carbon dioxide and total greenhouse gases appear to be close to evenly divided between emissions occurring during the flaming phase versus those occurring during the post-flame smoldering phase.

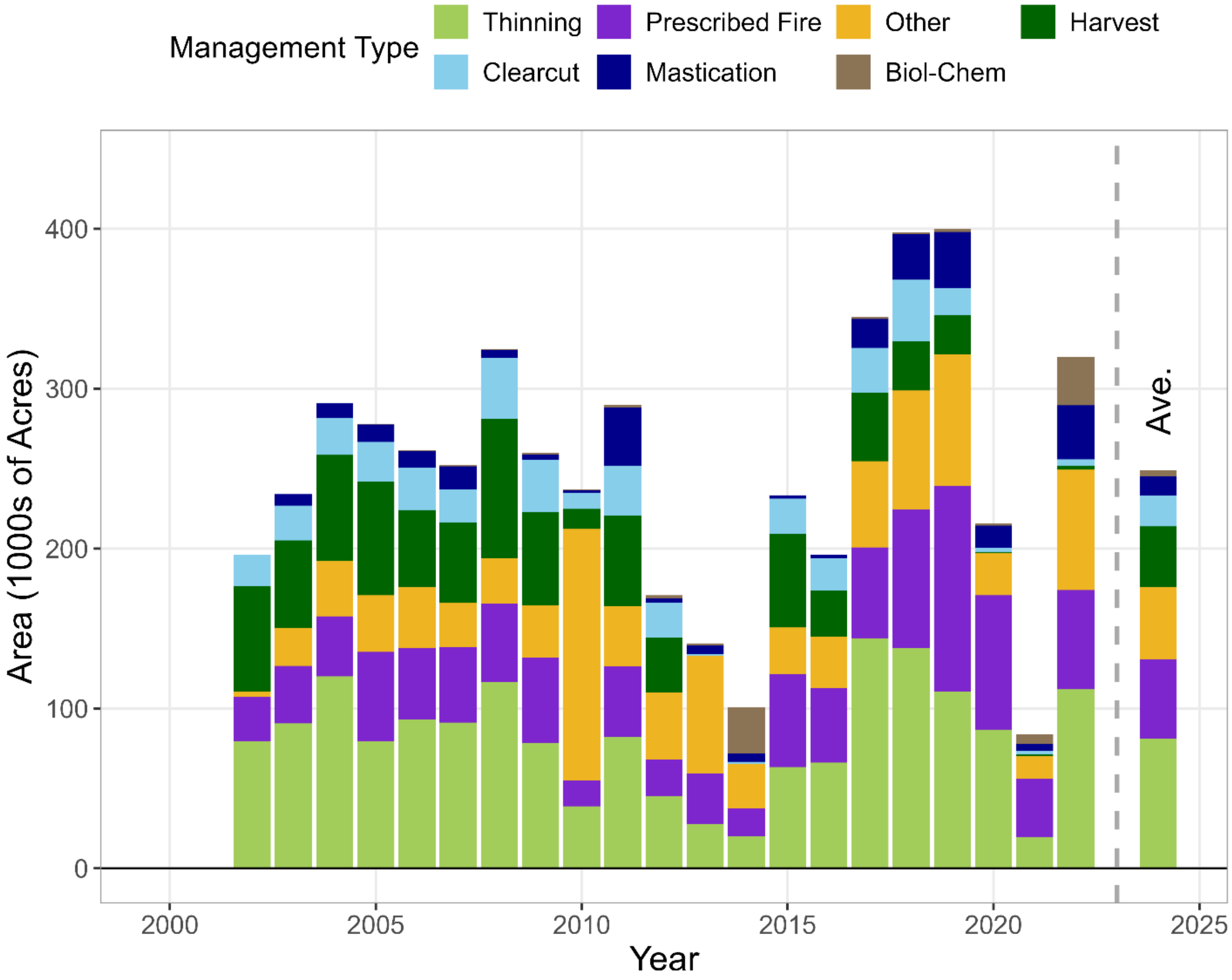
Appendix Table 1 - Average amounts carbon dioxide, carbon monoxide, methane, nitrous oxide, and total greenhouse gases ('CO_2e') emitted in metric tons per acre due under either active flaming and post-fire smoldering conditions ('Combustion Phase') for wildfires recorded between 2015 and 2024 (when data on all quantities was available). Also shown are values for the total fuel consumed ('ΔFuel') and total gases emitted as reported in the bottom row ('Total'). Values for CO_2e shown were calculated using greenhouse warming potential factors (GWPs) oriented to a 100-year time horizon of 28 and 273 for methane and nitrous oxide, respectively. The amount of fuel consumed per acre was not disaggregated by combustion type as indicated by '*na*'.

Combustion Phase	ΔFuel (MT/Acre)	CO_2 (MT/Acre)	CO (MT/Acre)	CH_4 (MT/Acre)	N_2O (MT/Acre)	CO_2e (MT/Acre)
Flaming	*na*	12.1	0.9	0.046	0.0017	13.9
Smoldering	*na*	10.6	1.9	0.079	0.0015	13.2
Total	15.1	22.7	2.7	0.125	0.0032	27.1

3.2 Amount of Biomass Carbon Transformed by Vegetation Management

Area Affected by Year

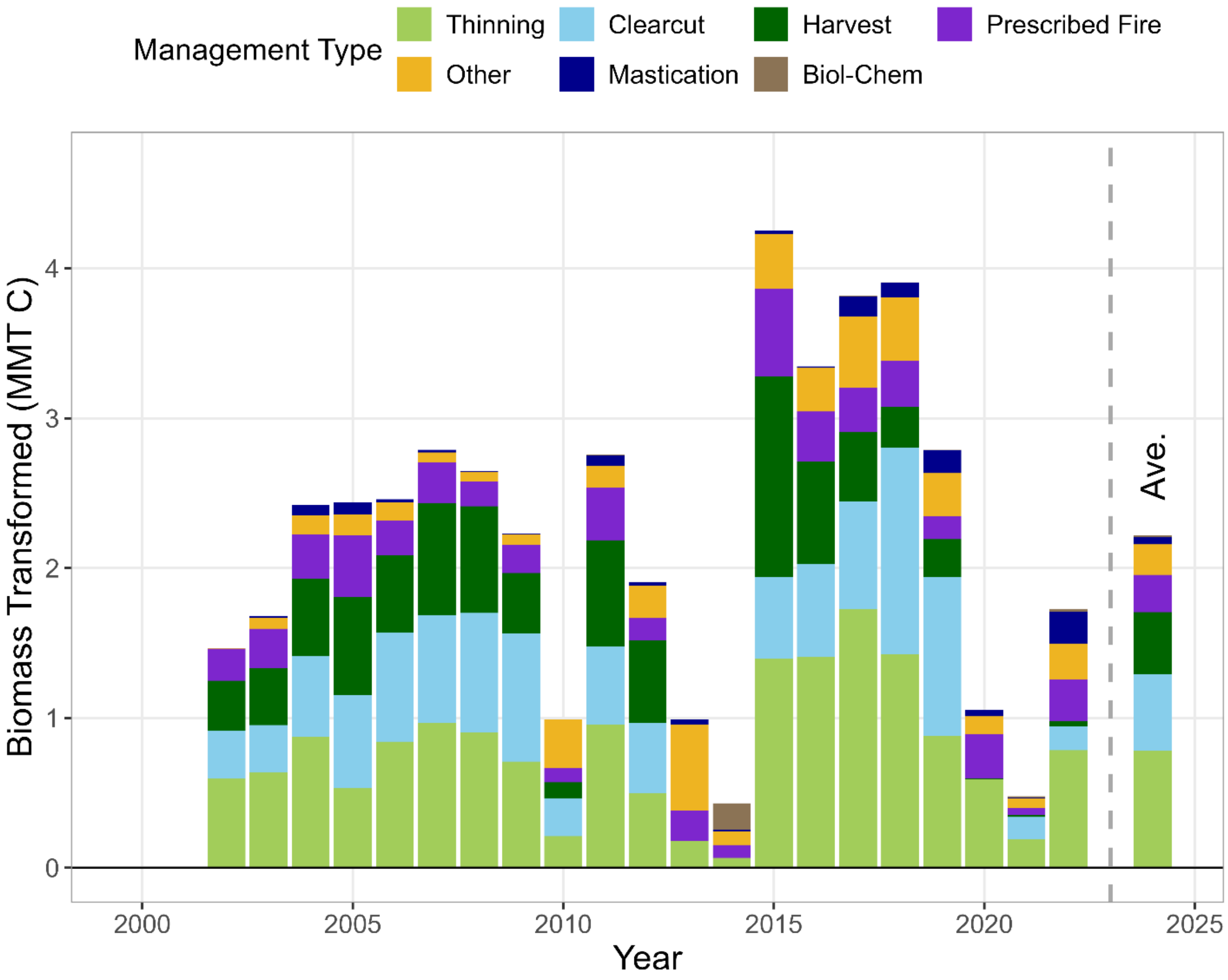
Annual areas affected by all vegetation management practices ranged from 83,800 acres to just over 400,000 acres per year and averaged 249,000 acres per year over the 2002-2022 period (Appendix Figure 3). On average, thinning was the most applied vegetation management practice (81,100 acres per year), followed by prescribed fire (49,700 acres), other mechanical treatments (45,100 acres per year), and then harvesting (38,000 acres per year) while the combined category of biological, chemical, and herbicide treatments ('Biol-Chem') was the least applied vegetation management practice (3,900 acres per year).



Appendix Figure 3 – Annual area of all forests, shrublands, and grasslands affected by different vegetation management practices each calendar year from 2002 through 2022 in thousands of acres as identified by LANDFIRE disturbance data. The color of each segment relates to the corresponding management practice shown in the legend where 'Biol-Chem' represents the application of biological treatments (mainly prescribed herbivory), chemical treatments or herbicides; and 'Other' represents other mechanical vegetation management practices not already described. The height of each segment represents the cumulative projected area of landscape affected by the corresponding management practice in a given calendar year, and the total height of all segments represents the total area of projected landscape affected by all management practices in a given calendar year. The stacked segments plotted to the right of the gray dashed line represent the average of all segments for all calendar years between 2002 and 2022 and its total height is equivalent to 249,000 acres.

Amount of Biomass Carbon Transformed by Year

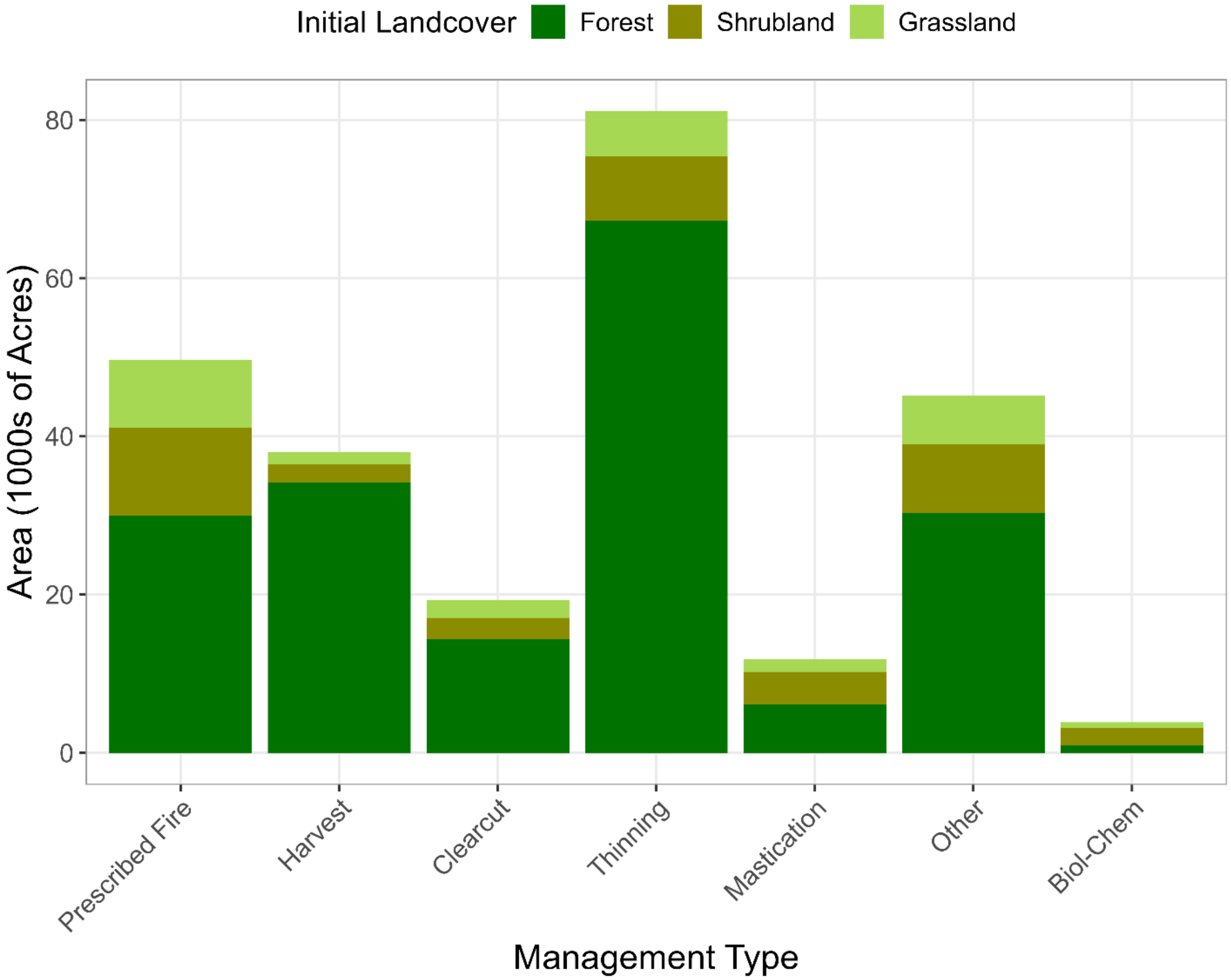
The amount of biomass carbon transformed by all vegetation management practices within the same calendar year ranged from 0.43 MMT carbon to 4.25 MMT carbon in a given calendar year and averaged 2.22 MMT C/Year over the 2002-2022 period (Appendix Figure 4). On average, thinning had the biggest impact on biomass carbon transformed (0.78 MMT C/Year), followed by clearcutting (0.51 MMT C/Year), and then harvesting (0.41 MMT C/Year). The combined category of biological, chemical, and herbicide treatments ('Biol-Chem') was the vegetation management practice with the least effect on biomass carbon (0.01 MMT C/Year) over the 21-year period examined.



Appendix Figure 4 - Annual amount of biomass carbon transformed in all forests, shrublands, and grasslands as a result of different vegetation management practices each calendar year from 2002 through 2022 in MMT of carbon. The color of a segment corresponds to the vegetation management practice shown in the legend where 'Biol-Chem' represents the application of biological treatments (mainly prescribed herbivory), chemical treatments or herbicides; and 'Other' represents other mechanical vegetation management treatments that do not fall into the other listed classifications. The length of each segment represents the amount of biomass carbon transformed by a specific vegetation management practice and the total height of all segments represents the cumulative amount of biomass carbon transformed by any and all management practices shown in the legend. The stacked segments plotted to the right of the gray dashed line represent the average amount of biomass carbon transformed for every vegetation management practice for all calendar years between 2002 and 2022 and its total height is equivalent to 2.22 MMT C/Year.

Area Affected by Landcover

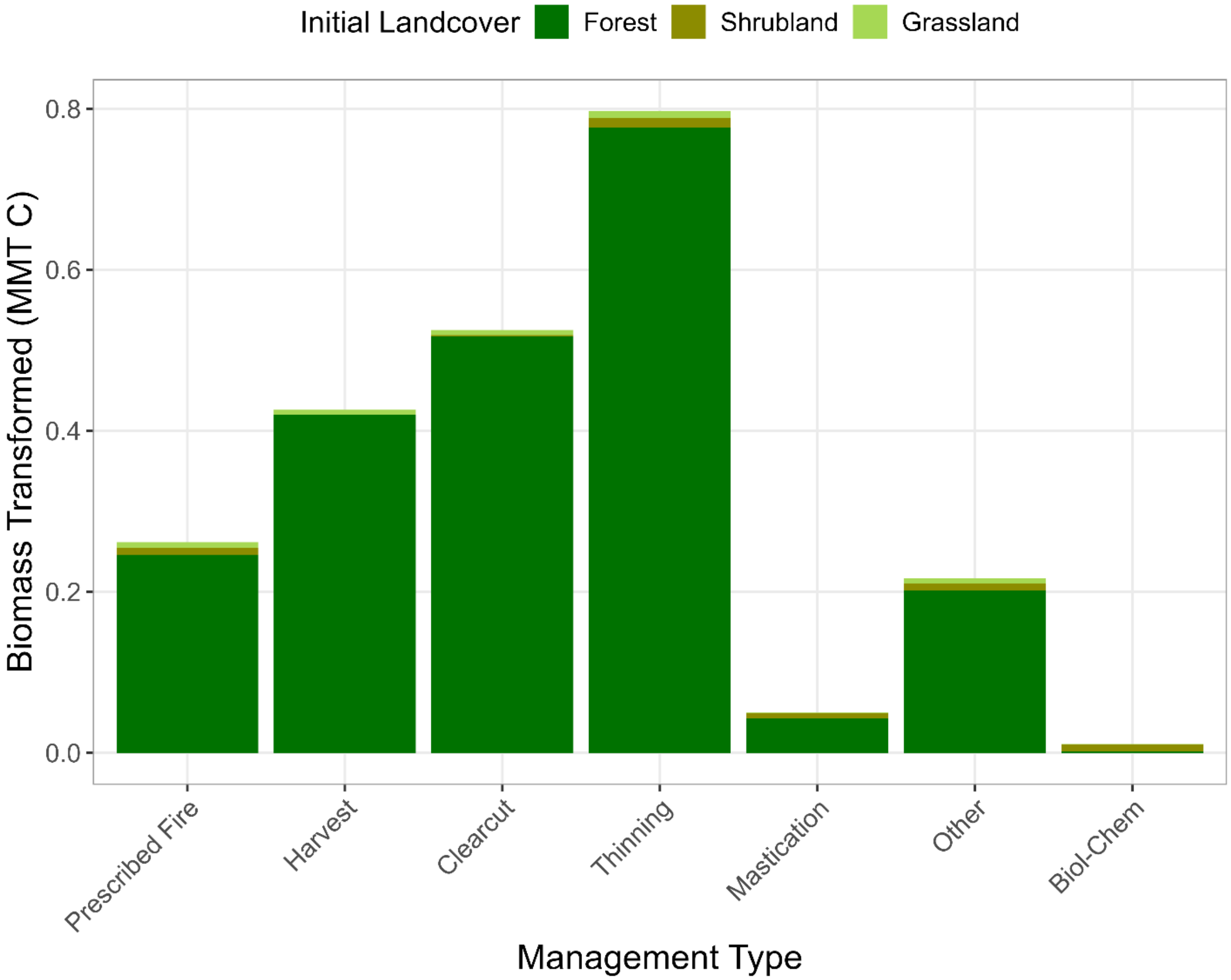
Vegetation management efforts have been predominantly directed towards forests for the past 20 or more years (Appendix Figure 5). The total amount of landscapes subject to vegetation management between 2002 and 2022 averaged 183,000 acres, 39,200 acres, and 26,700 acres per calendar year for forests, shrublands, and grasslands; respectively. These values are equivalent to a proportional distribution of area affected (or effort applied) of 73.5%, 15.8%, and 10.7% between forests, shrublands, and grasslands; respectively. Clear cutting, harvesting, and thinning can occur in shrublands and grasslands because the definition of these land types allows for the existence of some trees with these ecosystems.



Appendix Figure 5 – Average annual area of all forests, shrublands, and grasslands affected by different vegetation management practices from 2002 through 2022 in thousands of acres. The color of each segment relates to a different landcover (forests, shrublands, and grasslands). The height of each segment represents the total area of landcover affected by the vegetation management practice shown while the total height of all segments represents the total area of all forests, shrublands, and grasslands affected by the vegetation management practice.

Amount of Biomass Carbon Transformed by Landcover

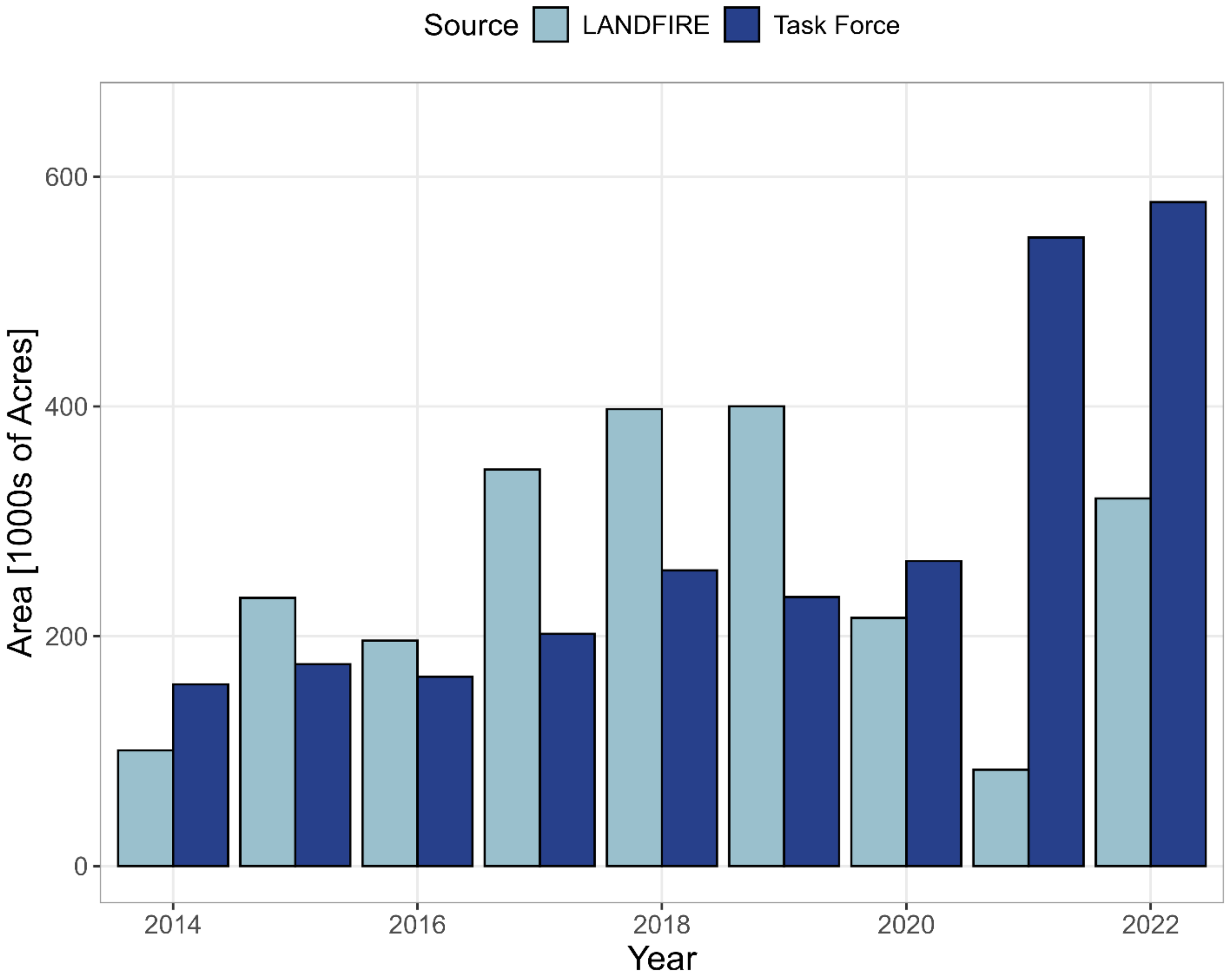
The effect of vegetation management on the total amount of biomass carbon transformed was higher in forests relative to shrublands and grasslands over the 21-year period examined than it was in terms of area affected (Appendix Figure 6). The total amount of biomass carbon transformed by all vegetation management practices between 2002 and 2022 averaged 2.2 MMT C/Year for forests and only 0.047 and 0.035 MMT C/Year for shrublands and grasslands, respectively. These values are equivalent to a proportional distribution of transformed biomass carbon of 96.4%, 2.0%, and 1.5% between forests, shrublands, and grasslands; respectively.



Appendix Figure 6 – Total amount of biomass carbon transformed in all forests, shrublands, and grasslands in response to different vegetation management practices annually averaged from 2002 through 2022 in MMT of carbon. The color of each segment relates to a different landcover (forests, shrublands, and grasslands). The height of each segment represents the total amount of biomass carbon within a given landcover transformed by the vegetation management practice shown while the total height of all segments represents the total amount of biomass carbon transformed in all forests, shrublands, and grasslands by the vegetation management practice.

Differences in Areas Affected by Vegetation Management as Recorded by the Task Force Interagency Treatment Tracker

Historically, the US Forest Service has created LANDFIRE disturbance layers by compiling natural and management disturbance data from a number of different sources (La Puma, 2023). However, in recent years, the California Natural Resources Agency and Governor’s Wildfire and Forest Resilience Task Force has made substantial efforts to track the implementation of all vegetation management practices that would alter, or more likely reduce, the risk of severe wildfire. While efforts to track and compile statewide vegetation management efforts preceded the creation of the Task Force in 2021, voluntary comprehensive and coordinated statewide reporting across federal, State, and privately supported vegetation management operations began in 2020. A comparison of vegetation management activities recorded in LANDFIRE versus those recorded by TFITS for the years 2020, 2021, and 2022 indicates that the LANDFIRE annual disturbance layers are underestimating the total amount of management activities occurring within California by more than half over this period (207,000 acres per year on average reported in LANDFIRE versus 463,000 acres per year on average reported in TFITS (Appendix Figure 7).

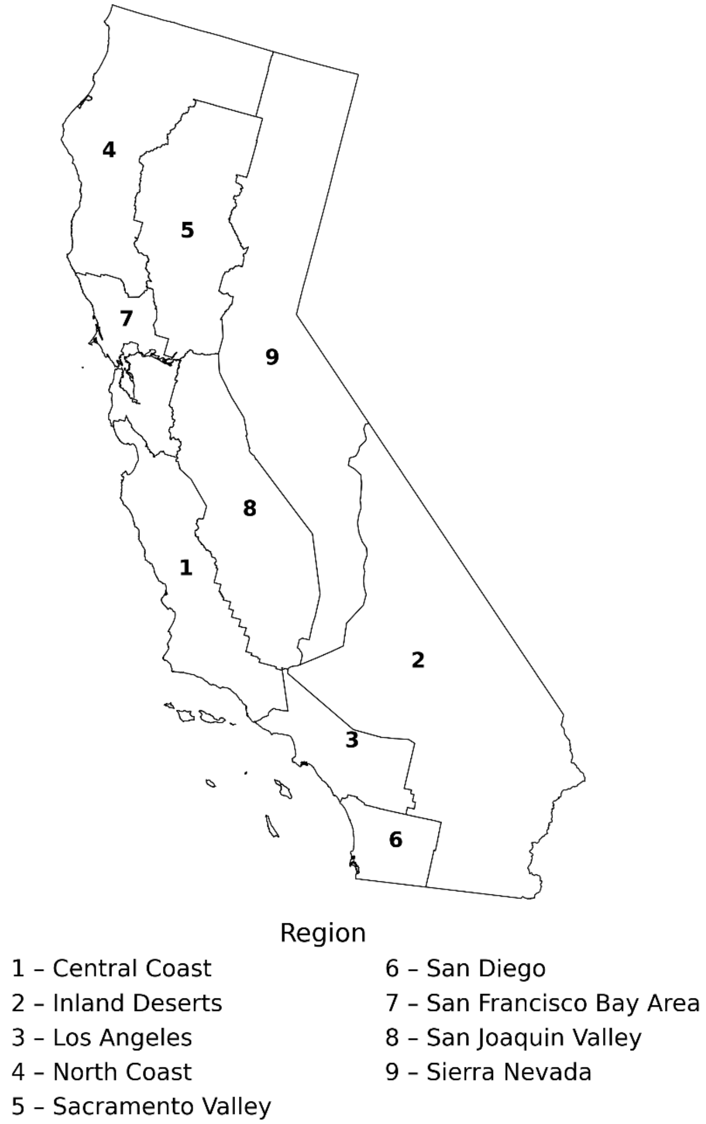


Appendix Figure 7 – Total area of all forests, shrublands, and grasslands affected by vegetation management practices per calendar year from 2014 through 2022 in thousands of acres according to the annual disturbance layers provided by both LANDFIRE ('LANDFIRE', light blue) and the Task Force Interagency Tracking System (TFITS or 'Task Force', dark blue). Note that the average cumulative area affected by vegetation management practices not involving fire per calendar year from 2020 to 2022 was 207,000 acres as recorded by LANDFIRE and 463,000 acres as recorded by TFITS.

TFITS does not track the amount of carbon transformed by vegetation management, only the area affected by management and the type of landcover affected. Nonetheless, it is still possible to roughly estimate the amount of biomass carbon that would have been transformed by the levels of vegetation management reported in the TFITS from the changes in biomass carbon density being reported here (see §2.2 Methodology). Estimates of the amount of biomass carbon transformed by different vegetation management practices as recorded in TFITS between 2020 and 2022 indicate that the average annual amount of biomass carbon transformed by all vegetation management practices as reported in TFITS were nearly three times higher than the same average calculated from the LANDFIRE data over this three-year period (3.1 vs. 1.1 MMT C/Year). These same calculations indicate that the average annual amount of biomass carbon transformed by prescribed fire in particular was also two and a half times higher than reported here over the same three-year period (0.50 MMT C/Year vs. 0.21 MMT C/Year). Data from the TFITS further indicate that the amount of biomass carbon transformed by harvesting was more than 16 times higher than reported here over the same three-year period (0.33 vs. 0.02 MMT C/Year). These comparisons indicate that much of the relevant vegetation management occurring within California is not being reported in centralized federal databases and further emphasize the need for comprehensive tracking of land management efforts across all relevant regions, sectors, institutions, and initiatives.

3.3 Effects of Wildfire and Vegetation Management on Biomass Carbon by Region and Epoch

The following summary focuses on the areas affected and amounts of biomass carbon transformed by different disturbance types in regions defined by California's Fifth Climate Change Assessment (Appendix Figure 8) as well as across the entire state. It further divides the entire study period into two epochs with the first epoch including all calendar years between 2002 and 2013 (a 13-year period) and the second epoch including all calendar years between 2014 and 2022 (a 9-year period). 2014 is the base year for California's natural and working lands carbon target: to lose no more than 4% of 2014 carbon stocks by 2045. For this reason, the time periods are split into these epochs.



Appendix Figure 8 – Map of the sub-regions defined for California’s Fifth Climate Change Assessment.

Area Affected by Region and Epoch

Wildfires by far affected the largest area of land of all disturbance types during both the first epoch (Appendix Table 2) and the second epoch (Appendix Table 3). This result was universally true both statewide and for every region identified. Furthermore, the amount of area affected by wildfire more than doubled statewide between the first and second epochs, rising from 627,000 acres to 1.31 million acres per year on average (Appendix Table 2, Appendix Table 3). Even beyond this statewide increase, particularly substantial increases in average annual area affected by wildfire in specific regions occurred including the Bay Area (+715%), North Coast (+278%), Sierra Nevada (+63%), and Sacramento Valley (+288%). The increase in areas affected by wildfire observed in these regions were partially moderated by more modest decreases in the Inland Desert (-31%) and Los Angeles (-31%) regions as well as by a more substantial decrease in the San Diego region (-89%).

In contrast, average annual areas affected by vegetation management increased by just 4% statewide between the first and second epochs with most of the effort being directed toward the implementation of thinning, prescribed fire, and other mechanical fuel reduction methods in that order (Appendix Table 2, Appendix Table 3). Statewide harvesting decreased by nearly 60% between the first epoch (where it was the second-most implemented vegetation management practice by area) and the second epoch indicating an overall slowdown in reported timber harvesting between the two periods. In both epochs, most of the reported harvesting occurred in the North Coast and Sierra Nevada regions with a lesser but still substantial amount occurring in the Sacramento Valley region. Regardless, vegetation management efforts increased overall by ~50% or more in the Central Coast, Inland Desert, Los Angeles, San Diego, San Joaquin Valley. These increases were more than moderated by the ~20% decrease in implemented vegetation management observed in North Coast region because so much more vegetation management is implemented in that region relative to all other regions except for the Sierra Nevada. The Sierra Nevada received the most vegetation management by area in both epochs: 110,200 and 117,900 acres per year on average during the first and second epochs, respectively.

Amount of Biomass Carbon Transformed

Not surprisingly, the average amount of biomass carbon transformed per year statewide was dominated by the impact of wildfires in both the first and second epochs (8.09 and 122.1 MMT C, respectively). Most of the biomass carbon transformed by wildfire was located in the Sierra Nevada, North Coast, and Sacramento Valley regions. The amount of biomass carbon transformed in the Sacramento Valley is somewhat surprising given that this region is better known for its farms, rangelands, and wetlands. However, regions prescribed by California's Fifth Climate Change Assessment were defined using boundaries inherited from the jurisdictional borders of the counties they contain. For the Sacramento Valley region, this includes Shasta, Tehama, Glenn, Butte, and Yuba counties, each of which contain substantial tracts of forested lands. This would explain why biomass carbon in the Sacramento Valley region has been affected by both wildfire and vegetation management more than all other regions except for the Sierra Nevada and North Coast.

The total amount of biomass carbon transformed by all vegetation management practices statewide increased by just under 20% between the first and second epochs but were still less than 25% of the impact of wildfires in the first epoch and less than 11% of the impact of wildfires in the second epoch. Following the decline in area affected, the amount of biomass carbon transformed by harvesting also decreased by nearly 30% statewide between the first epoch (when it had the third-largest effect on biomass carbon) and the second epoch indicating an overall slowdown in reported timber harvesting volume between the two periods that was not quite as large as the decrease in area affected (27% by carbon vs. 58% by area, Appendix Table 4, Appendix Table 5). In both epochs, most of the biomass carbon transformed by reported harvesting occurred in the North Coast, Sierra Nevada, and Sacramento Valley regions. The amount biomass carbon harvested from the Sierra Nevada region declined by 52% between the first and second epochs while the amount biomass carbon harvested from the Sacramento Valley region declined by 32% between the first and second epoch. In contrast, the average amount of biomass carbon transformed by harvesting in the North Coast remained very similar between the two epochs (174 vs. 181 kMT C).

Changes in Biomass Carbon Density

Not surprisingly, clearcutting and wildfires had the largest effects on biomass carbon of all disturbance types (in that order) and in both epochs as reflected by average changes in biomass density per acre statewide (Appendix Table 6 and Appendix Table 7). The magnitudes of these two disturbance effects on biomass carbon were then followed by those due to harvesting, then thinning, and then all other disturbance types (i.e., the vegetation management practices of prescribed fire, mastication, other mechanical fuel reduction, and biological-chemical treatments). The average effect of disturbance on biomass carbon density increased for all disturbances other than prescribed fire between the first and second epochs. Thus, not only did wildfire affect a much greater area in the second epoch than in the first (Appendix Table 3 vs. Appendix Table 2), the average effect that wildfires had on biomass carbon density was 30% higher in the second epoch than in the first epoch. This increase may be reflective of the fact that forests, being much higher in biomass density than all other types of landcover, represented nearly 60% of the total land area affected by wildfire in the second epoch versus just 40% of the total land area affected in the first epoch. Similarly, biomass carbon densities subject to clearcutting, harvesting, and thinning statewide were 51%, 74%, and 33% higher in the second epoch than in the first epoch.

Regional trends in the effects that different disturbance types had on biomass carbon densities largely mirrored statewide trends. However, changes in biomass carbon density caused by wildfire was noticeably highest in the three regions containing the largest amount of forest during both epochs: the North Coast, Sierra Nevada, and Sacramento Valley (e.g.; 23.4, 17.9, and 16.4 MT C /Acre, respectively, in the second epoch; Appendix Table 7). Clearcutting and harvesting were only implemented over substantial areas in these same three regions in both epochs; however, there was some limited harvesting performed in the Bay Area in both epochs (<700 acres per year on average, Appendix Table 2 and Appendix Table 3). In contrast, substantial quantities of thinning (>100 acres per year on average) were implemented in all regions except for the Inland Desert. It is not yet clear why the effects of thinning appeared to be larger in the Bay Area and Central Coast than in the North Coast, Sierra Nevada, and Sacramento Valley during the second epoch (Appendix Table 7).

The total areas affected by thinning were much smaller on average in the Bay Area and Central Coast (1,400-1,700 acres per year) than in the North Coast, Sierra Nevada, and Sacramento Valley (13,000-41,400 acres per year) during the second epoch; thus, they may not be particularly representative of the effects that thinning has on biomass carbon density more broadly.

Appendix Table 2 - Average area affected by different disturbances on all forests, shrublands, and grasslands in thousands of acres (kAc) from 2002 through 2013 for the entire state ('State') and for each of the regions defined in California's Fifth Climate Change Assessment where 'Sacram. Valley' represents the Sacramento Valley. No value indicates no record of disturbance in that region.

Disturbance (2002-2013)	Statewide (kAc)	Bay Area (kAc)	Central Coast (kAc)	Inland Desert (kAc)	Los Angeles (kAc)	North Coast (kAc)	San Diego (kAc)	San Joaquin Valley (kAc)	Sierra Nevada (kAc)	Sacram. Valley (kAc)
Wildfire	**627.0**	10.5	99.2	36.6	75.3	97.0	80.3	26.9	145.5	55.6
Rx Fire	**38.9**	0.9	2.8	0.1	1.3	6.5	1.2	0.4	21.1	4.5
Harvest	**50.6**	0.7	0.0		0.0	19.8			19.5	10.6
Clearcut	**22.6**	0.1				12.6			5.4	4.6
Thinning	**78.6**	1.0	0.8	0.2	1.1	23.1	0.1	0.4	42.3	9.6
Mastication	**8.8**	0.0	3.0	0.1	1.1	0.6	0.4	0.1	3.1	0.5
Other	**44.5**	0.0	0.7	0.4	3.9	17.9	0.6	0.2	18.3	2.6
Biol-Chem	**0.8**	0.0	0.0	0.0	0.0	0.0	0.0		0.6	0.1

Appendix Table 3 - Average area affected by different disturbances on all forests, shrublands, and grasslands in thousands of acres (kAc) from 2014 through 2022 for the entire state ('State') and for each of the regions defined in California's Fifth Climate Change Assessment where 'Sacram. Valley' represents the Sacramento Valley. No value indicates no record of disturbance in that region.

Disturbance (2014-2022)	Statewide (kAc)	Bay Area (kAc)	Central Coast (kAc)	Inland Desert (kAc)	Los Angeles (kAc)	North Coast (kAc)	San Diego (kAc)	San Joaquin Valley (kAc)	Sierra Nevada (kAc)	Sacram. Valley (kAc)
Wildfire	**1313.3**	85.9	100.7	25.2	51.8	366.4	9.1	43.8	414.7	215.8
Rx Fire	**64.1**	0.7	5.6	0.1	7.0	15.5	0.8	0.4	24.8	9.3
Harvest	**21.2**	0.1			0.0	7.0	0.0		8.9	5.1
Clearcut	**15.0**	0.1				6.4			4.7	3.9
Thinning	**84.5**	1.7	1.4	0.1	1.3	25.1	0.3	0.2	41.4	13.0
Mastication	**15.9**	0.6	1.1	0.5	3.1	1.2	2.4	0.8	4.2	2.1
Other	**46.1**	0.4	2.1	0.7	1.4	7.7	1.0	0.4	28.6	3.8
Biol-Chem	**8.0**		0.4	0.2	0.1	0.1	0.0		5.3	1.8

Appendix Table 4 - Average amount of biomass carbon transformed in a given calendar year by wildfire and various vegetation management practices in all forests, shrublands, and grasslands reported in thousands of metric tons of carbon (kMT C) from 2002 through 2013 for the entire state ('Statewide') and for each of the regions defined in the Fifth Climate Change Assessment. Note that the units shown here are in thousands of metric tons of carbon (kMT C) rather than in MMT C as reported elsewhere in this report to better reveal variation in the quantities across different sub-regions of California. No value indicates no record of disturbance in that region.

Disturbance (2002-2013)	Statewide (kMT C)	Bay Area (kMT C)	Central Coast (kMT C)	Inland Desert (kMT C)	Los Angeles (kMT C)	North Coast (kMT C)	San Diego (kMT C)	San Joaquin Valley (kMT C)	Sierra Nevada (kMT C)	Sacram. Valley (kMT C)
Wildfire	**8,086.9**	79.4	1,210.6	147.0	625.8	2,324.9	508.3	67.7	2,183.2	939.9
Rx Fire	**236.5**	2.5	14.8	0.0	3.3	52.1	6.8	2.4	126.0	28.4
Harvest	**469.1**	4.0	0.0		0.1	180.7			186.3	98.0
Clearcut	**511.6**	1.2				309.4			90.6	110.4
Thinning	**658.3**	1.7	4.4	0.4	1.6	188.2	0.2	1.3	361.4	99.1
Mastication	**28.1**	0.1	3.9	0.4	2.2	2.4	1.7	0.0	16.6	0.8
Other	**160.7**	0.0	1.7	1.1	7.4	66.4	1.5	0.2	69.6	12.7
Biol-Chem	**0.4**	0.0	0.1	0.1	0.0	0.0	0.1		0.5	0.1

Appendix Table 5 - Average amount of biomass carbon transformed in a given calendar year by wildfire and various vegetation management practices in all forests, shrublands, and grasslands reported in thousands of metric tons of carbon (kMT C) from 2014 through 2022 for the entire state ('State') and for each of the regions defined in the Fifth Climate Change Assessment. See Table 4 for additional details. No value indicates no record of disturbance in that region.

Disturbance (2014-2022)	Statewide (kMT C)	Bay Area (kMT C)	Central Coast (kMT C)	Inland Desert (kMT C)	Los Angeles (kMT C)	North Coast (kMT C)	San Diego (kMT C)	San Joaquin Valley (kMT C)	Sierra Nevada (kMT C)	Sacram. Valley (kMT C)
Wildfire	**22,091.3**	862.4	1,122.8	51.9	383.0	8,583.4	27.3	98.0	7,426.2	3,536.2
Rx Fire	**264.2**	0.9	6.9	0.2	3.0	92.0	1.9	1.5	137.8	20.0
Harvest	**341.7**	3.2			0.1	173.7	0.2		98.3	66.3
Clearcut	**513.5**	3.5				273.4			120.1	116.5
Thinning	**940.7**	31.3	21.9	0.3	5.4	349.6	1.9	0.8	400.3	129.3
Mastication	**76.4**	6.2	7.8	1.1	7.0	11.2	3.3	0.4	23.7	15.8
Other	**261.9**	4.3	17.5	0.8	2.6	55.3	6.1	1.4	150.2	23.8
Biol-Chem	**24.6**		0.5	0.0	0.1	0.4	0.0		22.1	1.4

Appendix Table 6 - Average changes in biomass carbon density in a given calendar year as a result of wildfire and various vegetation management practices in all forests, shrublands, and grasslands reported in of metric tons of carbon per acre (MTC/Ac) from 2002 through 2013 for the entire state ('Statewide') and for each of the regions defined in the Fifth Climate Change Assessment. No value indicates no record of disturbance in that region or where the average area affected by the disturbance was less than 100 acres per calendar year.

Disturbance (2002-2013)	Statewide (MTC/Ac)	Bay Area (MTC/Ac)	Central Coast (MTC/Ac)	Inland Desert (MTC/Ac)	Los Angeles (MTC/Ac)	North Coast (MTC/Ac)	San Diego (MTC/Ac)	San Joaquin Valley (MTC/Ac)	Sierra Nevada (MTC/Ac)	Sacram. Valley (MTC/Ac)
Wildfire	**12.9**	7.5	12.2	4.0	8.3	24.0	6.3	2.5	15.0	16.9
Rx Fire	**6.1**	2.7	5.4	0.2	2.5	8.0	5.6	6.8	6.0	6.3
Harvest	**9.3**	6.1				9.1			9.6	9.2
Clearcut	**22.6**					24.6			16.8	24.2
Thinning	**8.4**	1.7	5.7	1.8	1.5	8.1		3.0	8.5	10.3
Mastication	**3.2**		1.3		2.0	3.9	4.6	0.2	5.4	1.5
Other	**3.6**		2.5	2.6	1.9	3.7	2.5	1.0	3.8	5.0
Biol-Chem	**0.5**								0.8	0.8

Appendix Table 7 - Average changes in biomass carbon density in a given calendar year as a result of wildfire and various vegetation management practices in all forests, shrublands, and grasslands reported in of metric tons of carbon per acre (MTC/Ac) from 2014 through 2022 for the entire state ('Statewide') and for each of the regions defined in the Fifth Climate Change Assessment. No value indicates no record of disturbance in that region or where the average area affected by the disturbance was less than 100 acres per calendar year.

Disturbance (2014-2022)	Statewide (MTC/Ac)	Bay Area (MTC/Ac)	Central Coast (MTC/Ac)	Inland Desert (MTC/Ac)	Los Angeles (MTC/Ac)	North Coast (MTC/Ac)	San Diego (MTC/Ac)	San Joaquin Valley (MTC/Ac)	Sierra Nevada (MTC/Ac)	Sacram. Valley (MTC/Ac)
Wildfire	**16.8**	10.0	11.1	2.1	7.4	23.4	3.0	2.2	17.9	16.4
Rx Fire	**4.1**	1.3	1.2		0.4	5.9	2.3	3.4	5.6	2.2
Harvest	**16.1**	26.8				24.9			11.0	13.0
Clearcut	**34.2**					42.6			25.6	30.2
Thinning	**11.1**	18.4	15.5		4.0	13.9	6.9	4.6	9.7	10.0
Mastication	**4.8**	10.6	7.3	2.0	2.3	9.1	1.4	0.5	5.7	7.6
Other	**5.7**	11.5	8.3	1.0	1.8	7.1	6.3	3.7	5.3	6.3
Biol-Chem	**3.1**		1.2	0.2	0.8				4.2	0.8

3.4 Effects of Disturbance Type on Biomass Carbon in the Presence and Absence of Landcover Change

Area Affected

The amount of biomass carbon transformed by a given disturbance depends not only on the type of disturbance involved, but also on the landcover transition that occurs as a result of that disturbance. Here the term ‘landcover transition’ represents the possibility of both a change in landcover (e.g., forest changing to grassland) or no change in landcover (e.g., shrubland remaining shrubland). Looking across the entire state and over the 21-year period examined, most of the forests, shrublands, and grasslands exposed to wildfire and vegetation management did not change landcover type immediately following a disturbance with 65.7%-98.1% of the landscape remaining the same landcover type both before and after the disturbance (Appendix Table 8). While wildfires and clearcutting appeared to cause substantial rates of landcover transitions (34.3% and 29.9%, respectively; Appendix Table 8), other management practices such as harvesting, thinning, and biological-chemical treatments appeared to cause very low rates of landcover transitions (<10%, Appendix Table 8).

Appendix Table 8 – Average annual area affected by wildfire and different vegetation management disturbance types across all forests, shrublands, and grasslands from 2002 through 2022 disaggregated by 1) all possible landcover transitions (‘All Landcover’), 2) cases where the landcover did not change with the disturbance (‘Same Landcover’), and 3) cases where the landcover did change with the disturbance (‘Different Landcover’) expressed in A) dimensional units of thousands of acres (kAc), and B) as a percentage of the total change for the attribute in question as reported in the corresponding ‘All Landcover’ column for that attribute.

Disturbance	All Landcover (kAc)	Same Landcover (kAc)	Different Landcover (kAc)	Same Landcover (%All)	Different Landcover (%All)
Wildfire	921.2	605.5	315.7	65.7	34.3
Rx Fire	49.7	43.3	6.4	87.1	12.9
Harvest	38.0	34.5	3.4	90.9	9.1
Clearcut	19.4	13.6	5.8	70.1	29.9
Thinning	81.1	74.5	6.6	91.9	8.1
Mastication	11.8	10.0	1.9	84.3	15.7
Other	45.2	40.5	4.7	89.7	10.3
Biol-Chem	3.9	3.8	0.1	98.1	1.9

Amount of Biomass Carbon Transformed

Examination of a similar division between the amount of biomass carbon transformed by wildfire and vegetation management in forests, shrublands, and grasslands reveals a different story than the amount of area affected by these disturbances. In contrast to area affected, the majority of biomass carbon transformed by wildfires and clearcutting (two of the most severe disturbances that landscapes can experience) occurred in landscapes where there was a corresponding change occurred in landcover type following these disturbances (74.6% and 67.8%, respectively; Appendix Table 9). Furthermore, proportions of biomass carbon transformed in response to a given disturbance in landscapes where the landcover changed were approximately 2-4 times higher than proportions of area affected by a disturbance in landscapes where the landcover changed (Appendix Table 8, Appendix Table 9). For example, the proportion of all biomass carbon transformed by harvesting in landscapes where the landcover changed was 3.3 times higher than the proportion of total area affected by harvesting where the landcover changed (29.8% by mass vs. 9.1% by area).

These results indicate that the changes in landcover type brought on by a given disturbance have a profound effect on how much biomass carbon is ultimately transformed by that disturbance. They further suggest that even if climate-smart practices such as prescribed fire, mechanical fuel reduction, and sustainable harvesting cause some carbon to be transformed and removed from the landscape in the short-term, they will nonetheless have a net beneficial effect on the preservation of biomass carbon in the long-term if they can minimize the kind of substantial landcover conversions that would have occurred in the presence of more extreme disturbance events such as severe wildfires or extensive clearcutting.

Appendix Table 9 - Average annual amount of biomass carbon transformed in association with wildfire and various vegetation management practices across all forests, shrublands, and grasslands from 2002 through 2022 disaggregated by 1) all possible landcover transitions ('All Landcover'), 2) cases where the landcover did not change with the disturbance ('Same Landcover'), and 3) cases where the landcover did change with the disturbance ('Different Landcover') expressed in A) dimensional units as MMT carbon (MMT C), and B) as a percentage of the total change for the attribute in question as reported in the corresponding 'All Landcover' column for that attribute.

Disturbance	All Landcover (MMT C)	Same Landcover (MMT C)	Different Landcover (MMT C)	Same Landcover (%All)	Different Landcover (%All)
Wildfire	14.09	3.57	10.52	25.4	74.6
Rx Fire	0.25	0.12	0.13	48.7	51.3
Harvest	0.41	0.29	0.12	70.2	29.8
Clearcut	0.51	0.16	0.35	32.2	67.8
Thinning	0.78	0.52	0.26	66.5	33.5
Mastication	0.05	0.03	0.02	52.3	47.7
Other	0.20	0.12	0.09	57.2	42.8
Biol-Chem	0.01	0.01	0.00	94.9	5.1

3.5 Discriminating the Effects of Disturbance Type, Initial Biomass Carbon, and Landcover Change on Changes in Biomass Carbon

Direct comparison of areas affected by different disturbances and the corresponding amounts of biomass carbon transformed in the presence and absence of landcover change indicate that changing landcover plays an important role in determining how much biomass carbon is ultimately transformed by a given disturbance type over space and time (Appendix Table 8, Appendix Table 9). Unfortunately, directly examining the combined effects and outcomes of disturbances doesn't allow us to clearly separate how much each individual factor contributed to the total amount of biomass carbon that was transformed. This is because the factors that influence how biomass carbon responds to a disturbance might not be evenly spread across all disturbances or other influencing variables, due to the uneven conditions under which those disturbances happened. The total amount of biomass carbon transformed by a given disturbance is a product of 1) the total area affected by the disturbance, 2) the initial amount of biomass carbon within the affected region vulnerable to being disturbed, and 3) the 'severity' of the disturbance effect (i.e., the amount of biomass carbon per acre that is transformed by the disturbance). The strength of a given disturbance's impact can also depend on the type of disturbance and regional implementation differences.

Over the past 20 years, wildfires have exerted the largest impacts on natural lands across California in terms of area affected (Appendix Figure 1, Appendix Table 8). The total areas affected by all vegetation management practices were far smaller than areas affected by wildfires, but still varied with both time and management practice (Appendix Figure 3, Appendix Figure 5). Given that average annual area affected ranged by more than a factor of 200 across all disturbance types and by a factor of 20 across all vegetation management practices (Appendix Table 8), it was therefore necessary to focus the subsequent analysis on changes in the density of biomass carbon per acre to help prevent it from being swamped by variation in area affected alone.

In light of the above considerations, a predictive statistical model was developed to fairly and robustly intercompare the relative influence that disturbance type, landcover transition, and initial biomass density had on observed changes in biomass carbon density (see §2.2. Methodology). Once optimized and calibrated, the model could be used to simultaneously assess and discriminate the relative importance of these factors on observed changes in biomass carbon density. This was done by estimating an importance score for each 'feature' in the model (e.g., a specific disturbance type or landcover transition) whose value reflected how much the overall performance of the model suffered when the data for that feature was randomly scrambled.

Importance testing on the optimized and calibrated statistical model developed showed that the most important features for predicting change in biomass carbon density were transitions from forests to grasslands and then from forests to shrublands followed by the initial biomass carbon density categorically normalized by the initial landcover type (Carbon Density*, Appendix Table 10). In contrast, wildfire and all vegetation management practices were found within the middle to the bottom of the importance score rankings. There was also a significant disparity between the score for the most important landcover transition feature (Transition: Forest to Grassland, Score = 1434.5, Rank = 1) and for the most important disturbance type feature (Disturbance: Wildfire, Score = 11.7, Rank = 8). Furthermore, the average importance score rank for all landcover transitions was significantly lower than the average rank for all disturbance types (Mann-Whitney non-parametric U-test, $p = 0.029$), thus indicating that landcover transitions in general were more powerful features for predicting changes in biomass carbon density than were disturbance types.

Appendix Table 10 – Importance scores for individual features predicting changes in biomass carbon density over individual features representing components of the broad feature groups disturbance type, initial biomass carbon density, and landcover transition using a boosted gradient forest model optimized by cross-validation ($R^2_{CV} = 0.954$, $n = 925$). See §2.2. Methodology for details.

Feature Group	Feature	Importance Score	Rank
Transition	Forest to Grassland	1434.5	1
Transition	Forest to Shrubland	861.6	2
Initial Carbon	Carbon Density*	219.1	3
Transition	Grassland to Forest	183.7	4
Transition	Shrubland to Forest	55.2	5
Transition	Shrubland to Grassland	18.7	6
Transition	Forest to Forest	11.9	7
Disturbance	Wildfire	11.7	8
Disturbance	Rx Fire	4.1	9
Disturbance	Clearcut	2.5	10
Transition	Grassland to Shrubland	1.3	11
Disturbance	Other Mechanical	1.2	12
Disturbance	Thinning	1.1	13
Disturbance	Mastication	0.3	14
Transition	Shrubland to Shrubland	0.3	15
Disturbance	Harvest	0.3	16

To more holistically assess the relative predictive power of disturbance type, landcover transition, and initial biomass carbon density as a feature group, the same importance testing was simultaneously performed on all features within a given feature group (see Appendix Table 10). This more systemic approach to evaluating whole categorical variables showed that landcover transition is by far the most important feature group on which predicted changes in biomass carbon density depended, followed by the normalized initial biomass carbon density (Appendix Table 11). In contrast, properly identifying the disturbance type 'driving' the resulting distribution in landcover transitions only marginally increased the proportion of variance explained by just 1% on average (R^2 = 0.981 vs. 0.968). Thus, it appeared that a statistical model which included only the amount of landcover change and the initial biomass carbon density could explain nearly the same amount of variance as a model which included those same factors as well as the identity of the disturbance type. In other words, identifying the nature of disturbance type involved was largely unnecessary to accurately predict changes in biomass carbon density. This can also be a product of the way in which the NWL Carbon Inventory was developed. More field research and extensive reported management data are required to better understand the effect of management on carbon. Nonetheless, the results of the importance testing performed on both individual features and entire feature groups via discriminatory statistical modeling show that how much landcover changes or does not change in response to a given disturbance plays a significant role in determining how much biomass carbon is ultimately transformed by a disturbance.

Appendix Table 11 – Importance scores for each of the three general feature groups predicting change in biomass carbon density (per area) using the same statistical model whose individual feature importance scores were reported in Appendix Table 10 but by simultaneously permuting all individual features belonging to the same feature group.

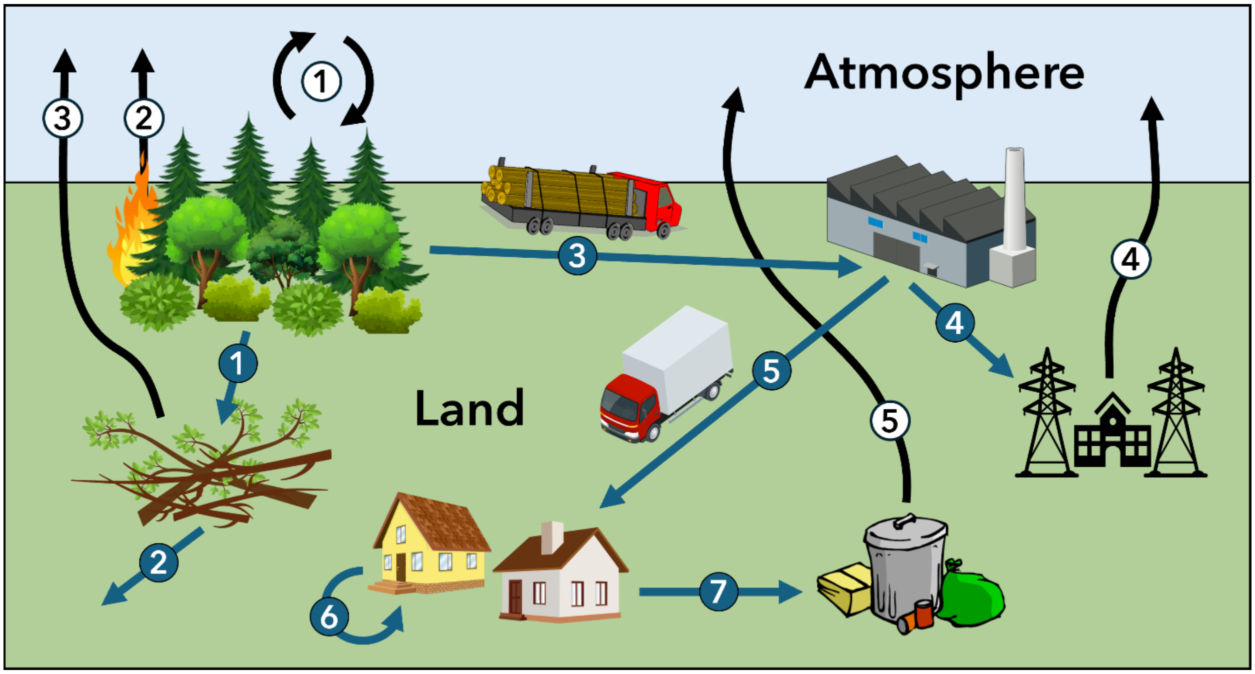
Feature Group	Importance Score
Landcover Transition	2405.7
Initial Carbon Density	217.2
Disturbance	17.9

3.6 Ecosystem Carbon Flow

Life Cycle of Plants

All terrestrial plants take up carbon dioxide from the atmosphere and convert it into organic carbon via photosynthesis. Some of this carbon is then used to support respiration by the plants themselves (Appendix Figure 9). The remaining fixed carbon not consumed by respiration is then used to make leaves, fine roots, and various exudates (carbon released through sap or roots to feed symbiotic microorganisms and other processes) as well as the woody biomass that ends up constituting the bulk of plant biomass in forests and shrublands. The amount of carbon sequestration that occurs through the production of fixed carbon by photosynthesis in excess of plant respiration (commonly referred to as 'net' primary production) is influenced by site conditions, climate, and prior applications (if any) of vegetation management. If not cut or burned, some of this carbon will eventually fall to the forest floor through mortality as part of the plant's natural life cycle, which could range from a few years to sometimes hundreds to thousands of years. After dead biomass falls to the forest floor, some of that carbon is decomposed and gradually released into the atmosphere over decades. Some of the carbon in dead wood, however, will not decompose and will instead be mixed into the soil or transported to the bottom of a lake, reservoir, wetland, embayment or other impoundment at which point it will not be released back into the atmosphere for hundreds of years. Some of the exported carbon may even make its way into the sediments lining the continental shelves where it could remain trapped for thousands of years.

Using regionally dependent growth factors taken from the 2025 NWL Carbon Inventory, CARB estimated an annual average of growth rate (net primary production) of 11.6 MMT C/Year across all forests, shrublands and grasslands in California. This translates into 42.5 MMT of carbon dioxide being taken up from the atmosphere on average per year.



Appendix Figure 9 – Diagram showing the major pathways of biomass carbon transfer between key carbon reservoirs (dark blue arrows and dark blue circles with white text) and the exchange of greenhouse gases between those reservoirs and the atmosphere (black arrows and white circles with black text).

The major pathways carbon transfer shown include: **1**) the formation of dead litter and slash as a result of natural disturbance and vegetation management practices (respectively), **2**) the loss of dead litter and slash via degradation and conversion into the soil organic carbon pool OR export from the site via hydrological transport pathways, **3**) the mobilization of harvested wood, **4**) the conversion of harvested wood into fuel for power and/or heat generation, **5**) the conversion of harvested wood into 'products in use' (or PIU), **6**) the recycling of PIU at the end of their lifespan, and **7**) the transfer of PIU to landfills and dumps at end of their life span.

The major pathways for GHG exchange between biomass carbon reservoirs and the atmosphere shown include: **1**) the uptake of carbon dioxide via photosynthesis by plants minus emissions from respiration, **2**) emissions from wildfires and prescribed fires which burn both living and dead biomass, **3**) emissions from the decay of dead litter and slash, **4**) emissions from the combustion of biogenic fuels created from wood products, and **5**) the emissions from the decay of PIU deposited in landfills and dumps.

Cut or Damaged Biomass Left on Site

Biomass in forests, shrublands, and grasslands is episodically subject to natural disturbances such as wildfires, insects, and disease. It is also subject to the planned management of vegetation which includes a number of different mechanical fuel reduction techniques, proactive revegetation, and the use of prescribed fire. In the case of the landscape being subject to wildfire and prescribed fire, some biomass carbon is immediately released as CO_2 into the atmosphere through combustion along with a modest amount of particulate carbon in the form of smoke and other trace gases (Appendix Figure 9). In the case of vegetation management practices, some of the affected biomass eventually becomes damaged and remains on the landscape in the form of slash. Portions of this slash will decompose or be burned and released into the atmosphere during subsequent wildfires. Some of the carbon contained in slash will not fully decompose and instead will become a long-term carbon store in the soil. Cut or damaged biomass with commercial value will be first mobilized and transported to processing centers before being sent on to facilities capable of converting the harvested wood into a form that is more directly consumable by the broader economy (e.g., lumber, mulch, chips, compost, paper, etc.). Some of these harvested wood products are then either sold within the state or exported for sale outside of California.

Use of Harvested Biomass

Some of the harvested biomass may be used as fuel in an industrial biomass burning facility to generate electric power or as household firewood to generate heat. Either way, the combustion of this fuel will release GHGs into the atmosphere much in same way the wildfires convert biomass carbon into GHGs on site. Moreover, some harvested biomass can be transformed into other forms of gaseous or liquid fuels intended for combustion. Such pathways will release additional carbon to the atmosphere through fuel combustion in vehicles or equipment, through other processes in the fuel life cycle, or become long-term carbon stores.

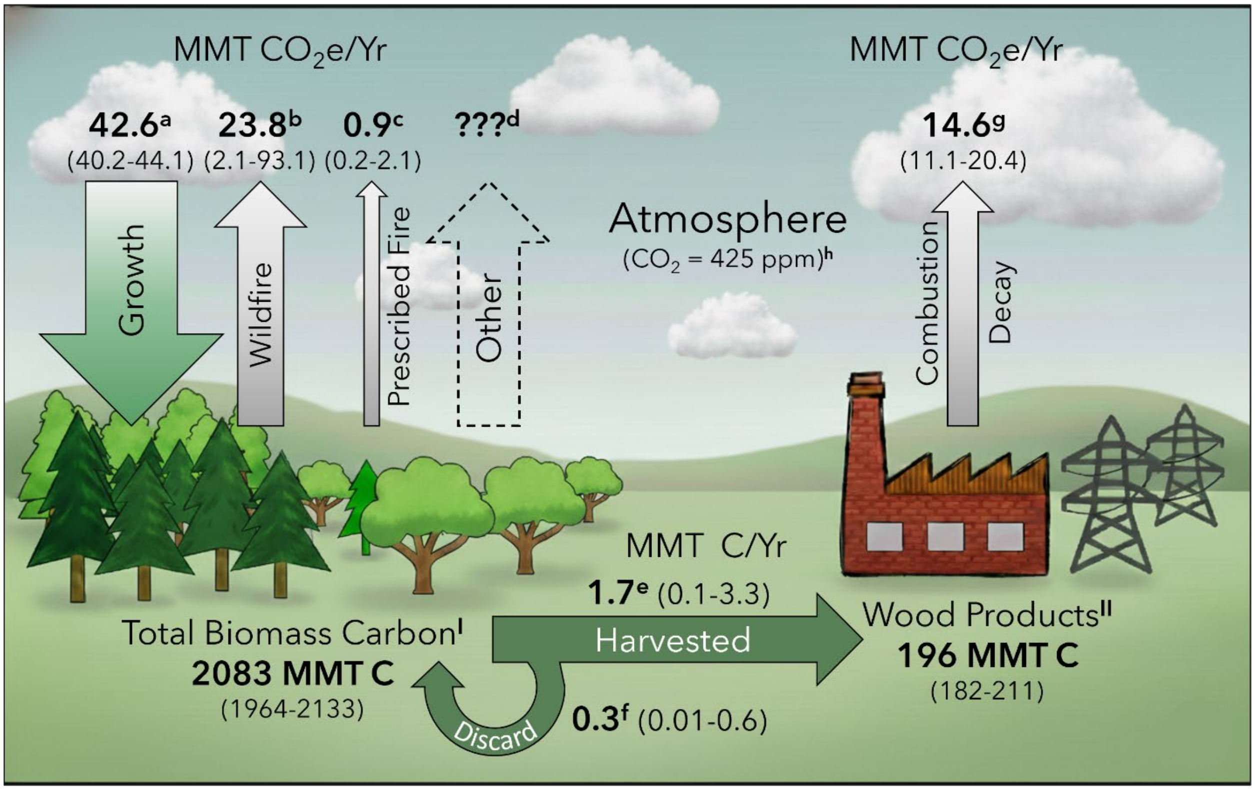
Other harvested biomass not directly destined for use as a fuel will instead enter pathways leading to the manufacture of other products. Carbon in the wood product pathways may enter via lumber mills or other facilities that produce wood products. The portion that becomes a wood product enters the pool of ‘products in use’ (or PIU). This pool includes recycled waste generated from the creation of primary products such as lumber to produce secondary products such as wood chips, mulch, or compost. A portion of wood products whose initial PIU lifecycle has ended will then be recycled and re-enter the system as new products. Ultimately, carbon in harvested wood products will enter the waste management system to be deposited in landfills, composted, or even burned for energy as a secondary fuel after its viability as a ‘product in use’ has expired. Through anaerobic decomposition, approximately half of the carbon contained in biomass products deposited in landfills will contribute to landfill gas emissions. These gases may or may not then be collected and combusted (and released to the atmosphere as CO_2) or escape as fugitive emissions with high global warming potentials. The remainder of carbon contained in wood products deposited in landfills will persist in solid form almost indefinitely. Aerobic decomposition will release a portion of composted biomass carbon into the atmosphere, with the remainder entering long-term soil carbon stores. Historically, biomass was also discarded in dumps where it was subject to aerobic decomposition.

The 2025 NWL Carbon Inventory estimated that each year, on average, 2.9 MMT of carbon in harvested wood products made from wood grown within California were either combusted to generate heat and/or power or left in dumps, landfills and other solid waste disposal sites (SWDS) to decay via aerobic and anaerobic pathways between 2002 and 2022. The Inventory further estimated that the combined GHG emissions from all of these degradation pathways averaged 14.6 MMT CO_2e per year over the same period.

4. Summary

California's forests, shrublands, and grasslands contain large quantities of carbon in the forms of living and dead plant biomass as well as soil organic matter. The annual amounts of carbon transferred between the atmosphere and various biomass carbon pools represent a small portion of the biomass carbon reservoir (<1%, Appendix Figure 10). Despite the proliferation of wildfire over the 21st century, average annual GHG emissions from wildfires are just over half of the average annual carbon dioxide taken up by plants in support of net primary production (23.8 vs. 42.5 MMT CO_2e/Year). In most years, wildfire emissions were an order of magnitude lower than rates of uptake due to net primary production; however, emissions due to wildfires greatly exceeded net uptake by trees, shrubs, plants, and grasses in years when wildfires were particularly abundant (>50 MMT CO_2e/Year in 2008, 2020, and 2021; Appendix Figure 2). Average annual GHG emissions from prescribed fire reported here are more than an order of magnitude lower than from wildfire; however, the actual rate at which prescribed fire is being implemented throughout California (acres per year) is likely much higher than reported here. Emissions from the combustion and decay of harvested wood products manufactured from wood grown within the state also constitute significant pathways by which biomass carbon is transferred back into the atmosphere. The combined emissions of GHGs through these two pathways occur at levels that are, on average, roughly 60% of annual average GHG emissions due to wildfires (14.6 vs. 23.8 MMT CO_2e/Year). This is likely due to the fact that harvested wood products manufactured in-state continue to accumulate within California despite an ever-greater reliance of total state consumption on imported wood products.

It is worth noting that there are a number of pathways by which carbon in plant biomass can be returned to the atmosphere that have not been quantified here. This is largely due to the technical difficulty involved in accurately making such estimates. Such pathways include the speciation of emissions (i.e., CO_2 vs. CH_4) from in-situ decay of dead biomass generated as a product of a natural disturbance or vegetation management practice, the hydrological export and subsequent remineralization of biogenic carbon in freshwater impoundments and in the coastal margins, and the conversion of biomass carbon into soil organic carbon which is then eroded, respired or transferred into long-term carbon stores. It is expected that emissions of GHGs via these decomposition pathways are at least nominally positive. Thus, the combined emissions resulting from these pathways as well as from prescribed fire and from the degradation of harvested wood products are at least comparable in scale with total GHG emissions from wildfire combustion. Furthermore, GHG emissions from wildfire combustion are not the only means by which wildfires generate GHG emissions. For instance, the average annual emission of carbon from wildfires was just under half of the average annual amount of biomass carbon transformed by those wildfires over the period examined (6.5 vs. 14.1 MMT C/Year between 2002 and 2022). This indicates that the decay of live biomass killed by wildfires is an important contributor to total wildfire GHG emissions in addition to the emissions resulting from combustion alone. Regardless, the extent to which California's lands contribute to the state's overall GHG budget and therefore influence the State reaching its key climate policy target of carbon neutrality by 2045, cannot be assessed from any single carbon or GHG transfer pathway. That is to say, wildfire emissions do not, by themselves, represent how much natural and working lands are contributing to or detracting from the State reaching carbon neutrality. Likewise, the amount of carbon sequestered in trees and other vegetation does not singularly represent the total contribution that natural and working lands are making towards the State reaching carbon neutrality. Tracking the net change in carbon stocks, and subsequently the equivalent annual sequestration and emissions in terms of CO_2e, from California's lands and harvested biomass will require closely monitoring a wide range of natural disturbances and land management practices as well as assessing their collective effects in transforming biomass carbon.



Appendix Figure 10 - Flows of carbon and CO_2 between the atmosphere and California's forests, shrublands, and grasslands. The upper portion of this diagram represents the reservoir of carbon in the atmosphere. The lower portion of this diagram represents the amount of biomass carbon stored in **I**) all forests, shrublands, and grasslands (2083 MMT of carbon, bottom left), and **II**) all harvested wood products manufactured within California (196 MMT of carbon, bottom right). The bold numbers represent the average annual values over the period of 2002-2022 while the numbers in parentheses represent the range of all values over the same period (minimum to maximum).

Exchanges of carbon and CO_2 between different reservoirs are shown by arrows and represent average annual fluxes in MMT CO_2/Yr and MMT CO_2e/Yr, respectively, according to the following transfer pathways: (**a**) 'Growth' includes all of the carbon taken up through photosynthesis and converted to live and dead woody or herbaceous biomass in forest and other natural lands (i.e., net primary production). (**b**) 'Wildfire' represents the combined emissions of all GHG species produced during a wildfire (carbon dioxide, methane, and nitrous oxide). (**c**) 'Prescribed Fire' represents the total GHG emissions from all prescribed fires based on amount of biomass carbon transformed and a ratio of CO_2e to CO_2 similar to that of wildfire emissions. Estimates shown here were estimated from losses in biomass carbon calculated for this report using data from the 2025 Natural and Working Lands Carbon Inventory. Ongoing work by CARB staff suggests that the amount of biomass carbon transformed by prescribed fire may be higher than reported here due to the underreporting of prescribed burns in the LANDFIRE annual disturbance layers. (**d**) 'Other' represents the presently unknown exchange (release) of greenhouse gases into the atmosphere due to processes not considered in the present analysis such as the in-situ decay of dead biomass or the hydrological export and subsequent remineralization of biogenic carbon. (**e**) 'Harvested' represents the amount of biomass carbon mobilized for the manufacture of wood products. (**f**) 'Discard' represents the amount of degraded biomass carbon left on site as a part of vegetation management. (**g**) 'Combustion + Decay' represent the combined GHG emissions resulting from the combustion of harvested wood products for the purposes of energy capture as well as from the decay of products in landfills, dumps, and other solid waste disposal sites. (**h**) Average level of atmospheric carbon dioxide in 2024 (National Oceanic and Atmospheric Administration, 2025).

5. Future Development and Research Needs

5.1. Addressing Data Gaps and Expanding Data Collection

Wildfire Emissions

The wildfire emission inventory currently relies on the wildfire perimeters in CAL FIRE's wildfire database, which has different reporting thresholds based on land type. Smaller wildfires would not be captured in the CAL FIRE database, and by extension, would not be included in CARB's wildfire emission inventory. Moreover, the national fire emission inventory compiled by the U.S. Environmental Protection Agency contains some large unidentified fires in California that are not found in the CAL FIRE wildfire database. CARB would like to work with CAL FIRE to identify additional data for wildfires that the CAL FIRE database typically does not capture. This would help increase the comprehensiveness of the CARB wildfire emission inventory.

Currently, CARB assumes 39% canopy mortality for all wildfires, which stems from a study of the Monitoring Trends in Burn Severity (MTBS) project, where Eidenshink *et al.* (2007) demonstrated that of the 347 fires (7.8 million acres) surveyed in MTBS, 39% of the area burned at moderate and high severity. However, the uniform statewide assumption does not capture the spatial heterogeneity of fire effects observed across California. Assumptions for California may benefit from improved satellite-derived fire severity metrics (Dixon, Zhu, Brown, & Jin, 2023), development of vegetation-specific canopy mortality factors, and improved integration of management/treatment history to improve mortality estimates.

Fuels Data Update

California's ecosystems are experiencing rapid increases in both natural disturbances—such as wildfire, drought, and pest outbreaks—as well as human-driven management treatments like prescribed burning, thinning, and mechanical removal. These accelerating changes underscore the need for more robust, spatially and temporally resolved fuels data that capture the evolving condition of vegetation and surface fuels. Improved fuels datasets are essential for accurately modeling emissions and understanding the effects of adaptive management in an increasingly dynamic and disturbance-driven landscape. Among the known drivers of uncertainty, vegetation fuel data contribute the highest uncertainty in emission estimation and have been identified as the most influential input to FOFEM-generated emissions (Tasnia et al. 2025). Further refinements to FCCS fuelbeds data may help reduce this uncertainty.

Some of the potential improvements that could enhance the precision of modeled fuel loading and emissions estimates across California's landscape may include the following: CARB would like to explore approaches to improve the spatial and temporal resolution of fuels data, including the use of remote sensing and machine learning. However, CARB has identified a need for working with CAL FIRE to potentially obtain additional resources—including expanded field data collection and new measurement techniques—to improve the accuracy of FCCS fuelbed characterization. For example, CARB would need sustained funding and staffing to produce annually updated fuelbed spatial data that reflect post-disturbance conditions (e.g., after wildfire, prescribed fire, or thinning). This would enable emission modeling to incorporate more contemporaneous fuel conditions. CARB is also considering methods to assess canopy fuels as three-dimensional objects and to track vegetation mortality from drought and other disturbances.

Vegetation Management Practices

Assessing the full extent of statewide vegetation management activities occurring throughout California requires aggregating and compiling data from a number of different sources in order to ensure complete coverage of all activities implemented. Recent efforts by the Wildfire and Forest Resilience Task Force have resulted in the most comprehensive tracking of vegetation management efforts throughout California thus far and the fruits these efforts are exemplified in the TFITS database. Data compiled from this effort has shown that more than twice the amount of vegetation management has been occurring within California in recent years than is recorded in the LANDFIRE annual disturbance layers (463,000 vs. 207,000 for 2020-2022; Appendix Figure 7) and this more elevated level of activity implies that nearly three times as much biomass carbon is being transformed by vegetation management than documented in the 2025 NWL Carbon Inventory over this period. Intercomparing the TFITS and LANDFIRE annual disturbance layers further shows that LANDFIRE has been particularly deficient in reporting levels of timber harvesting in recent years.

Resolving disparities between the amount of vegetation management being reported and the actual amount of management occurring is critical for the State to accurately track how much vegetation management efforts are transforming biomass carbon across California. This general issue is particularly salient for prescribed fire given that prescribed fire has been identified as the most important vegetation management practice for reducing future statewide wildfire risk as well as being the largest overall land management practice aimed at improving future climate resilience in California by area. Current policy recommendations call for 800,000 acres of prescribed fire per year by 2030 rising to 1.5 million acres per year by 2045 (State of California, 2024). The current challenges faced in reconciling the total amount of prescribed fire occurring throughout California are emblematic of a more fundamental issue that is nonetheless true for all vegetation management practices. It is simply not possible for the State of California to track the amount of vegetation management occurring statewide, along with the benefits these activities are achieving, without also providing guidance on the standards with which to comprehensively collect and compile this information across all regions, sectors, institutions, and initiatives. Further, most all information the State possesses on vegetation management in the TFITS is collected through voluntary means. This has resulted in data that remains either incomplete or uncollected, thus leaving gaps in our current understanding of the full effect that vegetation management Is having on all of California's landscapes.

5.2. Using Remote Sensing Data to Complement Data Reporting

To accurately estimate carbon changes over time and space, detailed information on the location, timing, and type of forest management activities is essential. Ideally, this would include reported information on management activities and/or field-based measurements to quantify carbon changes directly as a complement to making large-scale model predictions. Currently, CARB is working with various partners towards developing new and highly granular methods for monitoring California’s ecosystems with customized data products derived from remote sensing data sets. Ideally, this next generation of products will be able to provide data on changes in the composition and amount of biomass carbon stored in natural and working landscapes that will complement the highly necessary reported data from land managers. This would allow future investigators to assess the impact of natural and management disturbances on biomass carbon and carbon density more holistically and with a higher level of confidence. Nonetheless, while the remote sensing products used to inform natural- and management-driven changes in the landscape continue to improve over time, remote sensing can never replace the need for reported management information. Thus, full comprehension of the effects that land management activities are having throughout California will still require improvements in the standardized, ground-level reporting of their implementation, even if the remote sensing data products supporting these assessments continue to improve over time.

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References

Abatzoglou, J. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology, 33*, 121-131.

Battles, J. J. (2013). *California Forest and Rangeland Greenhouse Gas Inventory Development. Final Report, CARB Contract 10-778.* Sacramento, California: California Air Resources Board.

California Air Resources Board. (2023). *Section 9.3, Wildfires.*

California Air Resources Board. (2025). *The 2025 Natural and Working Lands Carbon Inventory.* California Air Resources Board.

Chen, L.-W. M. (2007). Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Environ. Sci. Technol., 41*, 4317–4325.

Chen, Y. H. (2022). California wildfire spread derived using VIIRS satellite observations and an object-based tracking system. *Sci Data, 9*, 249.

Dixon, D., Zhu, Y., Brown, C., & Jin, Y. (2023). Satellite detection of canopy-scale tree mortality and survival from California wildfires with spatio-temporal deep learning. *Remote Sensing of Environment, 298*, 113842. doi:https://doi.org/10.1016/j.rse.2023.113842

Eidenshink, J. S.-L. (2007). A Project for Monitoring Trends in Burn Severity. *Fire Ecol., 3*, 3-21.

Garg, P. R. (2021). Effect of moisture content and fuel type on emissions from vegetation using a steady state combustion apparatus. *Int. J. Wildland Fire, 30*. doi:10.1071/WF20118

La Puma, I. e. (2023). *LANDFIRE technical documentation: U.S. Geological Survey Open-File Report 2023–104.* U.S. Geological Survey, U.S. Dept. of Interior. doi:https://doi.org/ 10.3133/ ofr20231045

Lobert, J. S.-M. (1991). Experimental evaluation of biomass burning emissions: nitrogen and carbon containing compounds. In J. Levine (Ed.), *Experimental evaluation of biomass burning emissions: nitrogen and carbon containing compounds* (pp. 1075–1077).

Lutes, D. (2020). *FOFEM 6.7 First Order Fire Effects Model User Guide.* Fire and Aviation Management Rocky Mountain Research Station Fire Modeling Insititute.

National Oceanic and Atmospheric Administration. (2025, May 21). *Climate change: atmospheric carbon dioxide*. Retrieved from Climate.gov:

https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Omohundro, S. M. (1989). *Five Balltree Construction Algorithms.* International Computer Science Institute. International Computer Science Institute.

Ottmar, R. B. (1993). *CONSUME: users guide.* Forest Service, Pacific Northwest Research Station.

P. Gonzalez, J. J. (2015). Aboveground live carbon stock changes of California wildland ecosystems, 2001–2010. *Forest Ecology and Management, 348*, 68-77.

Pedregosa, F. V. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research, 12*, 2825–2830.

Reeves, M., & Frid, L. (2016). The Rangeland Vegetation Simulator: A user-driven system for quantifying production, succession, disturbance and fuels in non-forest environments. *Proceedings of the 10th International Rangelands Congress: The Future Management of Grazing and Wild Lands in a High-Tech World* (pp. 1062-1063). Saskatoon, Saskatchewan: The International Rangeland Congress.

Schroeder, W. O. (2014). The New VIIRS 375 m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment, 143*, 85-96.

State of California. (2024). *California's Nature-Based Solutions Climate Targets.*

U.S. Dept. of Agriculture Forest Service. (n.d.). LANDFIRE. Retrieved from https://landfire.gov/

Urbanski, S. (2014). Wildland fire emissions, carbon, and climate: Emission factors. *Forest Ecology and Management, 317*, 51-60.

Wildfire and Forest Resilience Task Force. (2024). Wildfire and Landscape Resilience Interagency Treatment Tracking System. Retrieved from https://interagencytrackingsystem.org/

Wildfire and Forest Reslience Task Force. (2021). *California's Wildfire and Forest Resilience Action Plan.* Sacramento: State of California.

Zhang, T. W. (2017). Approaches for synergistically exploiting VIIRS I- and M-Band data in regional active fire detection and FRP assessment: A demonstration with respect to agricultural residue burning in Eastern China. *Remote Sensing of Environment, 198*, 407-424.