CALIFORNIA
AIR RESOURCES BOARD

Public Comment Draft

Greenhouse Gas Emissions of Contemporary Wildfire, Prescribed Fire, and Forest Management Activities

Prepared by the California Air Resources Board

December 2020

Executive Summary

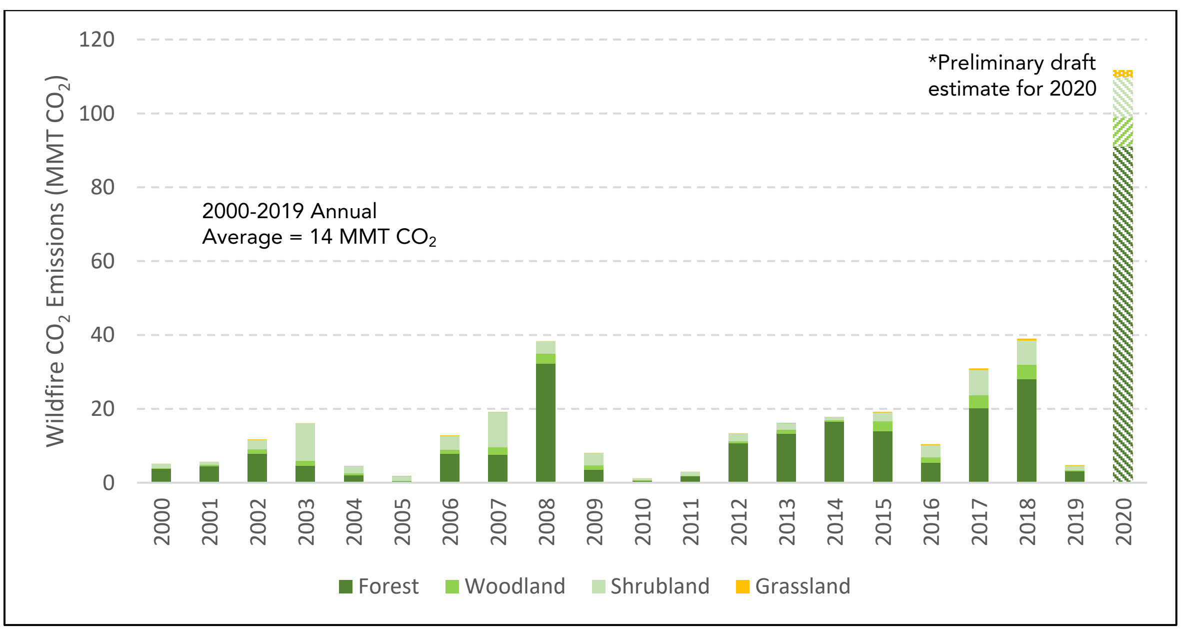
This report presents state-wide retrospective estimates of: (1) greenhouse gas (GHG) emissions associated with contemporary wildfires and prescribed burning activities for the period 2000–2019; and (2) changes in ecosystem carbon stocks associated with other non-fire forest management activities (e.g., timber harvest, forest thinning, and other activities that reduce fire risk) for the period 2002–2019.

An assessment of the GHG emissions and carbon impacts of wildfire and forest management activities supports a better understanding of the effects of current forest management practices and helps prioritize efforts to leverage natural and working lands for addressing climate change. This report is a result of 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." CARB staff developed this report in consultation with staff at the California Department of Forestry and Fire Protection (CAL FIRE) and other state agencies.

Wildfire Emissions

Wildfire activity varies as landscapes cycle through periods of vegetation fuel abundance and scarcity in response to climate, management, and ignitions. Using a vegetation combustion model and geospatial fire perimeters, annual wildfire GHG emissions in California were calculated for the years 2000–2019 (Figure E-1)

Figure E-1. Annual wildfire CO_2 emissions (million metric tons, MMT) by general vegetation category.

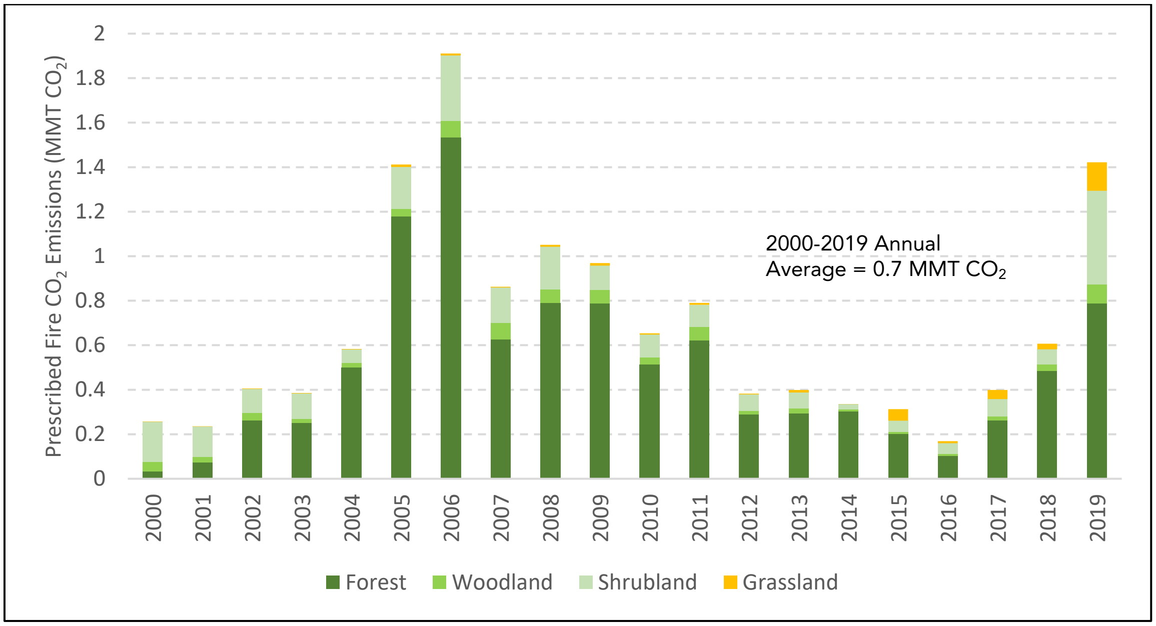


**Preliminary draft estimate of 2020 wildfire emissions will be updated and revised when CAL FIRE's final fire perimeters become available in mid-2021.*

Prescribed Fire Emissions

Prescribed fire is used by land managers to elicit beneficial ecosystem responses and to reduce risks from potential wildfires. In general, prescribed fire emissions occur in forests and woodlands. Figure E-2 shows the prescribed fire emissions from 2000–2019. The annual acreage and emissions associated with prescribed fire are two orders of magnitude lower than wildfires.

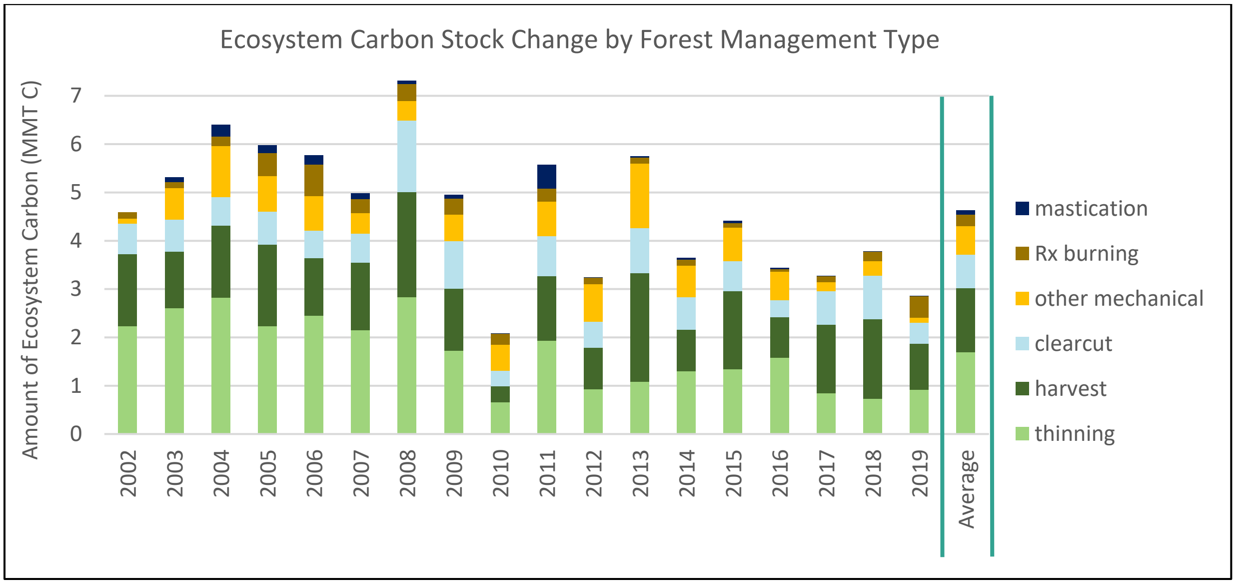
Figure E-2. Prescribed fire emissions (million metric tons CO_2, MMT CO_2) by general vegetation categories.



Non-Fire Forest Management Activities

Non-fire forest management activities included in this analysis are classified into 5 categories: thinning, clearcutting, mastication, harvesting, and other mechanical. Using a CARB-developed carbon stock change model, staff estimated the amount of total forest and other natural land biomass carbon (live and dead) transformed by these forest management activities. These estimates do not include soil carbon. Forest management activity varied from year to year in 2002–2019, with a peak in 2008 followed by a slight downward trend (Figure E-3).

Figure E-3. Annual ecosystem carbon stock transformed by forest management category.



The 2002–2019 average annual amount of total biomass carbon (live and dead) transformed by forest management (including prescribed fire) is 4.6 MMT of carbon. Transformed carbon refers to the transformation of carbon from one pool to another. For example, ecosystem biomass carbon in live trees can be transformed into dead biomass carbon through harvest or other non-fire forest management activities. Fire transforms carbon from live and dead biomass carbon into emissions. To put this into context, CARB's 2018 NWL Inventory estimated that California's natural and working lands currently store 5,340 MMT of carbon in plant biomass and soils across the State; the 4.6 MMT of carbon represents 0.09 percent of this total. Further, 4.6 MMT of carbon is equivalent of 16.8 MMT of CO_2 that was previously sequestered in biomass. However, because some of this carbon reaches long-term carbon stores and is not released back into the atmosphere, it does not mean that 16.8 MMT of CO_2e have been released into the atmosphere.

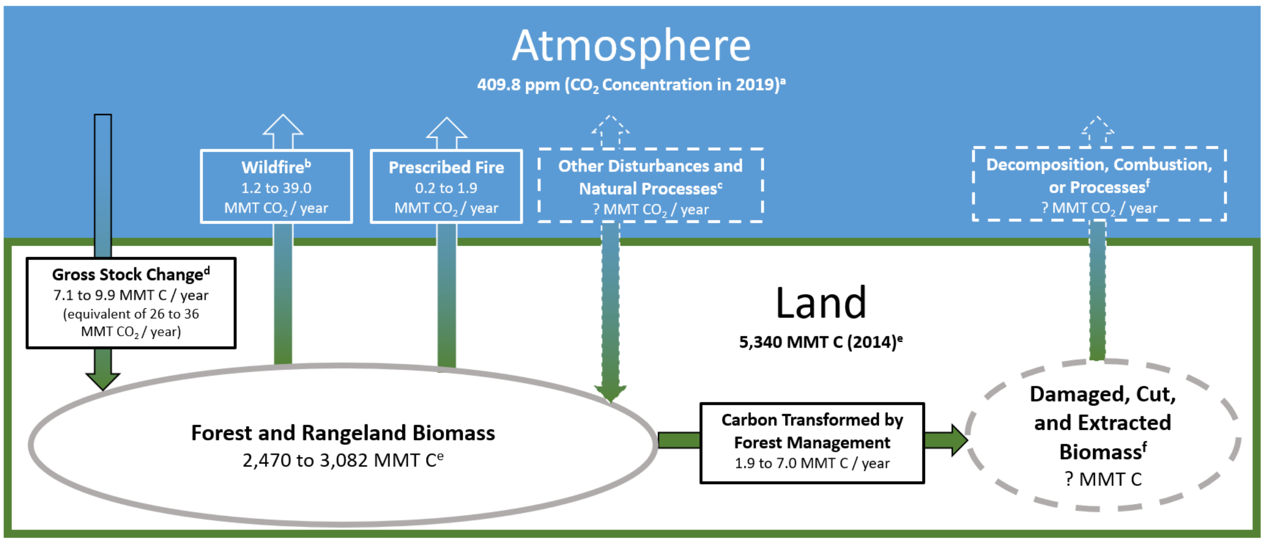
Ecosystem Carbon Flow

The estimate of ecosystem carbon transformed from forest management includes all wood that may be cut or damaged during this process. This cut forest biomass represents a transfer of previously sequestered CO_2 stored as carbon in live plants to other forms including dead plants, biofuels, and harvested wood products. Some carbon eventually returns to the atmosphere through various processes and at the end of wood product use-life. The carbon contained in harvested wood products is part of a complex system with many carbon flow pathways that can be challenging to track. CAL FIRE is developing a system to quantify the amounts of harvested carbon in various wood product pathways (within and beyond the state boundary). CARB plans to incorporate CAL FIRE's harvested wood product data in future editions of this report.

Summary

The amount of carbon transferred from the atmosphere to biomass and the transfer of carbon out of forests represent a small portion of the land carbon reservoir. Figure E-4 summarizes CARB staff's estimates of GHG emissions from wildfire, prescribed fire, and forest management activities.

Figure E-4: Flows of carbon and CO_2 between the atmosphere and California's forests and other natural lands



[a] *Source of atmospheric CO_2 concentration: National Oceanic and Atmospheric Administration [1]*

[b] *1.2 to 39.0 million metric tons of CO_2 per year represent the range of values in 2000-2019, which has an annual average of 14 MMT million metric tons of CO_2 per year. Final fire perimeters and updated fire emission estimate for 2020 will be available in mid-2021.*

[c] *"Other disturbances and natural processes" include emissions associated with land use and land cover change, erosion, decomposition, plant respiration and any other non-fire disturbance or emission source. This also includes carbon sequestered into non-woody biomass such as foliage, fine roots, or any other vegetative component that are not included in CARB's net carbon stock change estimate. A portion of carbon sequestration may be attributable to the result of forest management activity or natural processes. These flows have not yet been quantified due to limitation in existing data availability.*

[d] *"Gross stock exchange" 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. The values represent CARB's and CAL FIRE's estimates [2, 3]. Improvements in forest productivity as a result of forest management activities are inherent in the gross stock change estimates but difficult to separate from other effects on productivity such as changes in precipitation and temperature.*

[e] *The range of values represent carbon stock estimates from CARB's NWL Inventory [2] and CAL FIRE's Forest Carbon Inventory [3].*

[f] *"Damaged, cut, and extracted biomass" include biomass that is transferred into slash piles, biofuels or into other harvested wood products. These flows have not yet been quantified due to limitation in data availability. Section 3.4 and Figure 7 have additional information about life cycle of harvest wood products and their various fates, including long-term carbon stores and potential emission pathways.*

Future Work

Standard record-keeping and reporting systems capture portions of the varied management activities occurring in California's forests. On-going refinements to existing data systems, development of new reporting and tracking, and advances in remote sensing will begin to fill data gaps.

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1. Introduction

Earth's carbon cycle transfers carbon between land, oceans, and the atmosphere, and in turn, facilitates the life cycle of all life forms globally. Fire is a part of Earth's terrestrial carbon cycle that is balanced by vegetation recovery and growth. By contrast, fossil fuels consist of ancient carbon that has been stored underground for millions of years. Fossil fuel combustion contributes to climate change by releasing fossil carbon that the Earth's atmosphere has not seen for millions of years.

For millennia, fire has served 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 fuels that otherwise sustain high-severity wildfires. From time immemorial to the present, Indigenous People have been stewards of the land and have used fire to shape and maintain California's diverse ecosystems. Since the late 19th Century, California's forests have come under various forms of public and private control with corresponding management activities.

In addition to the natural world, fire and forest 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, amplify the standing of forests in California. An assessment of greenhouse gas (GHG) emissions and carbon impacts of wildfire and forest management activities helps California better understand the effects of current forest management practices and prioritize efforts to leverage natural and working lands for addressing climate change.

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). H&SC Section 38535 contains three subsections. Subsection (a) addresses aspects of the quantification methodology utilized in the California Climate Investment program. Subsection (b) pertains to GHG emissions of historical natural fire regime. A companion report in response to subsection (b) will be made available in early 2021. This report fulfills the directive in subsection (c), 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.*"

CARB staff developed this report in consultation with staff at the California Department of Forestry and Fire Protection (CAL FIRE) and other state agencies.

Scope of This Analysis

This report presents state-wide, retrospective estimates of: (1) GHG emissions associated with contemporary wildfires and prescribed burning activities for the period 2000–2019; and (2) changes in forest carbon stocks associated with other non-fire forest management activities (e.g., timber harvest, forest thinning, and other activities that reduce fire risk) for the period 2002–2019.

Some forest management activities result in ecological outcomes that can enhance the rate of carbon sequestration or the resiliency of carbon stores. To inventory these benefits at a state-wide level would require a complex model and additional research to analyze the retrospectively observed carbon gains and attribute them to either prior forest management activities or natural processes. This is an area of on-going scientific development. An assessment of changes to carbon sequestration rates attributable to forest management is not a part of the analysis performed for this report. Although this report focuses on GHG emissions, estimates of state-wide carbon sequestration (not attributed to activities, disturbance, or natural processes) are presented in Section 5 to provide context to the emissions estimation.

CARB staff utilizes a vegetation fuel combustion model to estimate GHG emissions associated with wildfires and prescribed fires. The fire emission estimates rely on model inputs developed from geospatial wildfire and prescribed fire activity (wildfire "footprints" and prescribed fire project boundaries) compiled in a multi-agency database by CAL FIRE, as well as other datasets. CARB staff developed a carbon stock change model to estimate the amount of forest carbon transformed by non-fire forest management activities. Data used for this analysis include CARB's Natural & Working Lands Ecosystem Carbon Inventory (the NWL Inventory), data from the Landscape Fire and Resource Management Planning Tools (LANDFIRE) consortium, CAL FIRE's California Forest Practice database, U.S. Forest Service's Forest Activity Tracking System (FACTS), and other datasets.

For future editions of the SB 901 report, CARB staff plans to work with other agencies to more comprehensively capture prescribed fire activities and additional forest management activities. Section 4.1 further discuss the need for future data development.

2. Overview of Data and Methodology

2.1. Wildfire and Prescribed Fire Emissions Estimates

GHG emissions associated with the combustion of live and dead vegetation fuel by wildfires and prescribed fires are a function of the amount of fuel consumed and the efficiency of the combustion. Fuel consumption in the flaming and smoldering phase is influenced by fuel moisture content. Combustion efficiency refers to the conversion of fuel to carbon dioxide [CO_2] versus to products of incomplete combustion, such as carbon monoxide [CO], nitrous oxide [N_2O], methane [CH_4], other hydrocarbon gases, and particles. Greenhouse gases emitted by fires include CO_2, CH_4 and N_2O.

2.1.1. Fire Emission Model

CARB staff developed estimates of GHG emissions from wildfires and prescribed fires that occurred throughout the State in 2000–2019. Estimates were generated using the First Order Fire Effects Model (FOFEM), a computer application developed by the U.S. Forest Service to estimate vegetation fuel consumption, heat output, soil heating, tree mortality, and emissions of particles and gases by wildfires and prescribed fires [4]. Users prescribe model inputs according to vegetation types and their associated fuel loadings, fuel configuration (natural versus altered, in piles or post-harvest timber slash residues), and pre-fire fuel conditions (fuel loading and moisture content). The analysis in this report uses the latest version of FOFEM, Version 6.7, which was released in March of 2020.

Fire emission modeling requires an array of input data about fire locations, extent, timing, fuels and fuel conditions. Inputs to FOFEM include:

- Fuel loading (tons/acre) information derived by staff from geographic information systems (GIS)-based wildfire "footprints" (perimeters) and prescribed fire project boundaries published by CAL FIRE [5];
- GIS-based vegetation fuel maps produced by the LANDFIRE Fuel Characterization Classification System (FCCS) [6, 7] as augmented for CARB by the University of California – Berkeley (UC Berkeley) [8]; and
- GIS-based fuel moisture maps from the Wildland Fire Assessment System (WFAS) [9] and the University of Idaho climatology lab [10, 11].

2.1.2. Data Sources

Fire Perimeters

Each spring the CAL FIRE Fire and Resource Assessment (FRAP) program publicly releases a GIS database of final area-extent perimeters of wildfires and prescribed fire project boundaries that occurred throughout the State, up to and including the prior year [5]. Data are compiled from reporting by federal, state, and local land and fire management agencies. Prescribed fire projects reported to the database are predominantly activities performed by public land management agencies and other entities (e.g., universities, non-governmental organizations, industrial timberland owners) that are managing vegetation in natural or semi-natural areas. Prescribed fire types include broadcast and pile burning.

Vegetation Fuel Data

The Fuel Characterization Classification System (FCCS) is a system for quantitatively characterizing components of combustible live and dead vegetation across different ecosystems for use in fire behavior and fire emission models [7]. Metrics include fuel loading (tons/acre) associated with live shrubs, grasses and herbaceous vegetation, live tree canopies, forest understory vegetation, fine-grained dead fuels such as litter and duff, and stem diameter classes of dead vegetation. A look-up table of FCCS vegetation types and associated reference fuel loadings is embedded in FOFEM. FCCS vegetation maps are available in GIS form (rasters) as the FCCS Fuel Beds product for vintages 2001 and 2008, distributed by the LANDFIRE consortium [6]. For years not represented by LANDFIRE (2002–2007 and 2009–2018), UC Berkeley researchers developed FCCS vegetation maps for CARB [8]. FCCS vegetation maps depict the state of fuels present on December 31 of each year, representing lingering effects of prior disturbance and ecological succession. The maps serve as initial conditions for vegetation fuels in the following year for purposes of emission estimation.

Fuel Moisture

The moisture content of live and dead vegetation influences the proportions of fuel consumed in the flaming and smoldering phases, and in turn, the chemical composition of emissions. For both wildfires and prescribed fires, fuel moisture values were drawn from geospatially and temporally explicit mapped values contained in WFAS and gridMET products. WFAS is a public website hosted by the US Forest Service that collects and displays spatial fuels and fire behavior information. GridMET is a dataset of daily high-spatial resolution surface meteorological data.

Impact on Tree Canopy (Burn Severity)

Wildfires that propagate vertically from the ground surface to tree canopies (crown fire) can grow to large areas and persist for long duration. Crown fires can kill forest trees, creating new areas of dead vegetation that can serve as fuel for future fires. Because tree mortality has important implications for post-fire recovery, the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) program [12, 13] maps the proportion of the tree population within a wildfire footprint that were killed. A common burn severity metric is the percent loss of tree canopy within the area burned. CARB staff used mapped burn severity values to assign crown fuel consumption parameters in FOFEM and used a nominal crown consumption value for prescribed fires (Restaino, personal communication).

2.2. Non-Fire Forest Management Activities

This analysis focuses on the ecosystem carbon transformed by cutting of forests. This analysis covers forest management activities classified into 5 categories: thinning, clearcutting, mastication, harvesting, and other mechanical. This analysis does not include other types of emissions associated with forest management such as emissions associated with machinery and transport, emissions from the life cycle of the wood after it is cut (e.g., harvested wood products), and the emissions impacts of ecosystem process changes associated with forest management (i.e., growth, fire, etc.). Greenhouse gas emissions of machinery and transport are predominately fossil fuel emissions, and are outside the scope of a forest carbon assessment. The carbon contained in harvested wood products is part of a complex system with many carbon flow pathways that can be challenging to track. CAL FIRE has developed a system to quantify the amounts of harvested carbon in various wood product pathways that will be included in future versions of this report (within and beyond the state boundary). There is currently insufficient information to quantify the impact that forest management has on ecosystem processes under current climate conditions and extreme fire behavior.

2.2.1. Data Sources Used in This Analysis

Many entities across the State of California perform forest management activities. These include Tribes; federal, state, and local government agencies; local collaboratives; non-governmental organizations; private institutions; and companies throughout California. 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 ecosystem carbon impacted by forest management, activity data must have geospatial perimeters, the year when the activity occurred, and a description of the type of activity. The datasets that contain the kind of information that could be utilized for this analysis and were available to CARB staff were: CARB NWL Inventory [2], LANDFIRE disturbance layers [6], U.S. Forest Activity Tracking System (FACTS) [14], and California Forest Practice GIS [15].

The CARB NWL Inventory is a geospatially explicit estimate of ecosystem carbon stocks in California's natural and working lands. This inventory is derived by utilizing linear regression models based on LANDFIRE map products of vegetation type, canopy cover, and canopy height, along with US Forest Service Forest Inventory and Analysis (FIA) data, to calculate geospatially explicit carbon estimates for years that LANDFIRE products are available. CARB staff derives yearly estimates of carbon stock and stock change in forests and other natural lands through additional modeling.

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 years 2001–2016. LANDFIRE classifies 5 types of forest management activities: harvest, clearcuts, thinning, mastication, and other mechanical. These activity categories 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.
- **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.

- **Harvest** 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.
- **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 related to fuels reduction and site preparation including piling of fuels, chaining, lop and scatter, thinning of fuels, Dixie harrow, etc.

The U.S. Forest Service FACTS database collects forest management information from National Environmental Protection Act (NEPA) decision letters. FACTS tracks any project that has received a NEPA decision letter. The database includes information on timber operations and fuels reduction treatments, as well as other activities. FACTS data include information on the location (project boundary), timing, and activity type. CARB staff categorized activities reported in FACTS to the LANDFIRE forest management categories. Project boundaries do not necessarily represent the actual perimeters of the activity that occurred, and contribute to uncertainty in the forest management carbon estimates.

The California Forest Practice Rules GIS (FPG) database provides geospatial data on Timber Harvest Plans (THP), Non-Industrial Timber Management Plans (NTMP), Notice of Timber Operations (NTO), emergency notices, exemption notices, roads associated with timber harvesting and hydrology associated with timber harvesting. FPG includes geospatial information on reported forest management activities and when they were completed for all non-fire forest management activity that is legally required to report to CAL FIRE. THPs have the kind of spatial, temporal, and thematic specificity that can be used to estimate carbon impact from the activity. Like FACTS, this dataset includes reported information about planned activities and may not necessarily represent the exact boundary and intensity of the activity that occurred.

2.2.2. Methodology

CARB staff derived estimates of annual ecosystem carbon transformed by forest management activities using data on carbon stock and forest management activities within a statistical model (Figure 1).

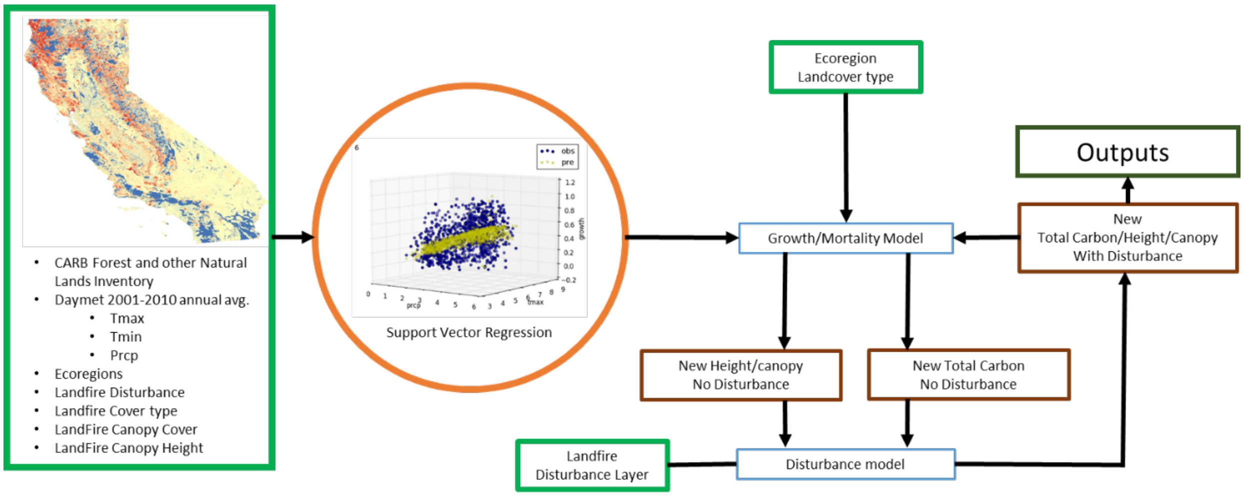
The input data for this model are:

- Total carbon stock change between the beginning and end of the simulation, as determined by the NWL Inventory
- Daymet annual maximum temperature, minimum temperature, and precipitation data [16]
- Ecoregions from the U.S. Geological Survey [17]

- LANDFIRE periodic existing vegetation type (evt), canopy cover (evc), canopy height (evh)
- Annual LANDFIRE disturbance layer

Calculations within the model for this analysis are performed on a 1-km spatial resolution and on an annual time-step. The 1-km resolution is used to match the Daymet climate data. Other datasets used in the model are upscaled to 1-km resolution.

Figure 1. Diagram depicting statistical model used to estimate carbon transformed by forest management from 2002 to 2016.



Input datasets are delineated in green boxes. The machine learning algorithm used to derive growth models is in the orange circle. Derived datasets, both internal-interim and outputs, are in brown boxes. Blue boxes represent computations performed.

Growth rates for each ecoregion cover type combination in California are derived using the NWL Inventory; LANDFIRE existing vegetation types, heights, and canopy cover; and climate data within a machine learning algorithm. The algorithm derives independent linear regression models of growth for every ecoregion and LANDFIRE existing vegetation type combination in California. This model calculates the growth in carbon, height, and canopy for each year.

After annual growth, if LANDFIRE identifies a disturbance, either fire or forest management, a constrained stochastically derived percentage of existing ecosystem carbon is removed from the carbon stocks, and the canopy height and cover are similarly reduced. The model is executed in a Monte Carlo simulation, where the annualized inventory is simulated multiple times and the mean value of ecosystem carbon transformed is conveyed in this report.

This model is used to estimate carbon transformed by forest management from 2002 to 2016, the time period for which LANFIRE disturbance and the NWL Inventory estimates are available. The model requires a carbon inventory estimate at the beginning and end of the simulation period, and annual disturbance perimeters for each year in the simulation. The NWL Inventory is calculated every few years (2001, 2010, 2012, 2014, 2016). In the years 2010, 2014, and 2015, known errors in LANDFIRE disturbance data were corrected using California Forest Practice GIS and FACTS data.

For the years 2017, 2018, and 2019, California Forest Practice GIS and FACTS data were used exclusively to estimate where, when, and what type of activity (other than prescribed fire) occurred. The silvicultural practices described in these datasets were categorized into one of the five LANDFIRE forest management categories. The area for each forest management category was summed for each year. CARB staff derived an average estimate of carbon transformed per acre for each forest management activity from the modeled estimates for 2002–2016. This average estimate of carbon transformed per acre for each forest management activity was then multiplied by the area associated with that activity to derive a non-spatial annual estimate. For every year, all carbon transformed for each management type was summed.

3. Results of Quantification

3.1. Wildfire Emissions

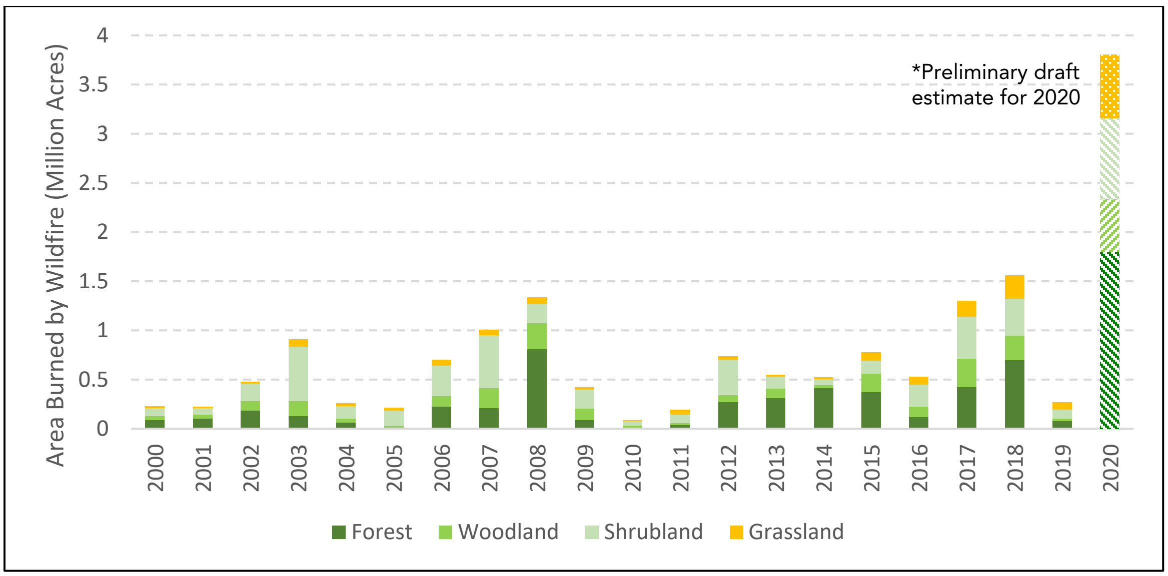
Wildfire in California is characterized by inter-annual variability in area burned (Figure 2). The frequency and area extent of wildfire is the product of multiple factors, such as fuel abundance and availability, climate episodes such as drought, the strength of seasonal events such as Diablo and Santa Ana winds, topography, ignition sources, and fire behavior. Wildfire GIS data indicate that years 2003, 2006–2008, 2017 and 2018 had elevated fire activity levels resulting from large-area, long duration wildfires [18]. CARB staff cross-walked general vegetation categories (forest, woodland, shrubland, and grassland) to the over 100 different FCCS vegetation types presented in California. Geospatial analysis of FCCS vegetation types associated with wildfire footprints reveals inter-annual variation in the relative contribution of general vegetation types to annual burned area. In eight of the years, forests and woodlands comprise the majority of burned area (2000-2002, 2008, 2013–2015, 2018). In 2003, 2006, and 2007, large wildfires occurred in areas of southern California were dominated by shrublands. In 2017 large wildfires occurred in both northern and southern California. Shrublands contributed to 2017's burn acreage, which featured the 281,791 acre Thomas Fire in Santa Barbara and Ventura counties. The contribution of grasslands to statewide burned area over the period has been modest.

In tandem with acreage, estimated wildfire CO_2 emissions also exhibit large inter-annual variability (Figure 3), averaging approximately 14 MMT in the 2000–2019 time period. Annual emissions range from 1 MMT of CO_2 in 2010 to 39 MMT of CO_2 in 2018. For almost all years, forests and woodlands represent the largest contributors to annual wildfire CO_2 emissions. The years 2003 and 2007 exhibit contributions from shrublands associated with large wildfires that occurred in southern California. The variation in the contributions of vegetation types to annual wildfire CO_2 emissions is a function of not only acreage, but also fuel load (tons/acre). Forests and woodlands exhibit higher fuel loads than lands dominated by shrubs or grasses. In years 2002 and

2017, forests and shrublands comprised roughly equal areas of burned acreage (Figure 2), but forests contributed double the amount of CO_2 emissions than did shrublands (Figure 3). In 2003, wildfires burned four times more shrubland area than forest area, such that fires in shrublands contributed twice as much CO_2 emissions as did fires in forests. In 2008, the amount of forest area affected by wildfire was four times greater than affected shrubland area (Figure 2), with forest fire CO_2 emissions approximately ten times greater than emissions associated with fires in shrublands.

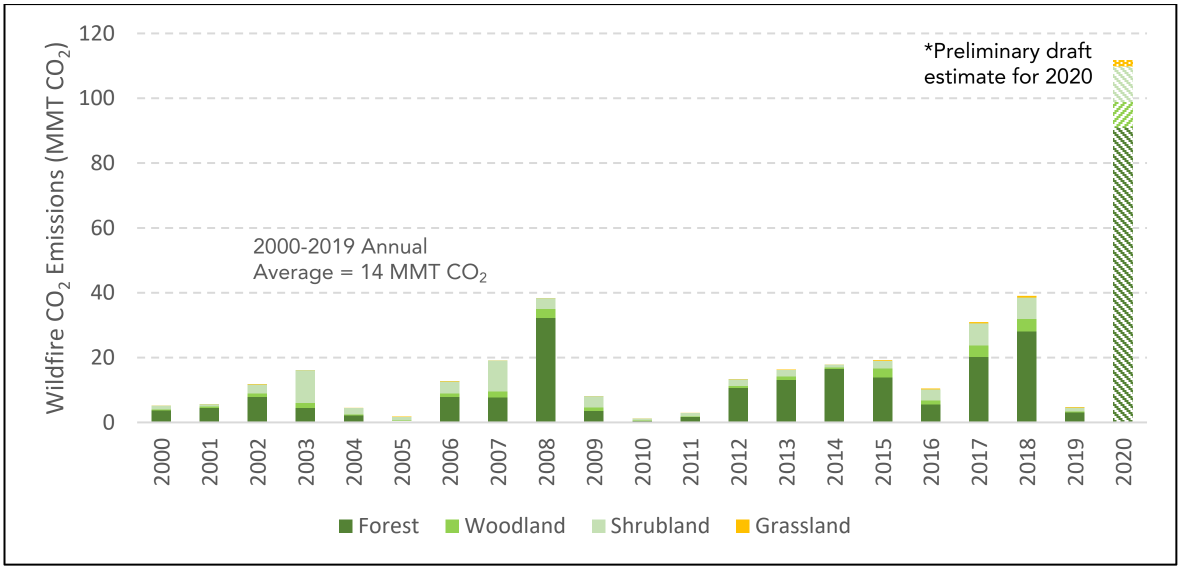
At the time of this analysis, the 2020 fire season had not yet concluded. CAL FIRE estimates that 4.2 million acres have been burned to date in 2020. Using the preliminary wildfire perimeter data available from the National Interagency Fire Center [19], CARB staff's preliminary draft estimate of 2020 wildfire emissions is 112 million metric tons of CO_2. CARB staff will analyze and update 2020 wildfire emission estimates when final 2020 fire perimeters become available in mid-2021.

Figure 2. Annual wildfire acreage by general vegetation categories



**Preliminary draft estimate of 2020 wildfire emissions will be updated and revised when CAL FIRE's final fire perimeters become available in mid-2021.*

Figure 3. Annual wildfire CO_2 emissions (million metric tons, MMT) by general vegetation category



**Preliminary draft estimate of 2020 wildfire emissions will be updated and revised when CAL FIRE's final fire perimeters become available in mid-2021.*

Previous wildfire emission estimates published by CARB were based on an earlier version of FOFEM [20]. In the latest version of FOFEM, fuel loadings for duff and dead woody fuels for common California forest types are lower than in previous versions. The FOFEM development team revised the fuel loadings based on data updates from the US Forest Service FIA program and on other wildland fuel inventory efforts. On average, the newer CARB emission estimates are approximately 16 percent lower than previous CARB estimates.

3.2. Prescribed Fire Emissions

Figure 4 displays the year-to-year variation in area treated by prescribed fire. Treated area is a product of institutional capacities and goals, prescriptions developed by land managers, and opportunities. Area treated by prescribed fire over the period is approximately two orders of magnitude smaller than area affected by wildfires. Prescribed fire activity in 2000–2004 was at or below 20,000 acres/year. Activity increase in 2005 and 2006 to approximately 60,000 acres/year and began to decline thereafter, with increases beginning in 2017 (Figure 4). In most years, prescribed fire is principally performed in forests and woodlands, followed by grasslands. In recent years, the extent of prescribed fire activity in shrublands is on par with activity in grasslands.

Estimates of prescribed fire GHG emissions are presented in Figure 5. For 2002–2018, CO_2 emissions associated with prescribed fire occurred primarily in forests and woodlands. In 2019, emissions associated with treatments in shrublands approaches that of forests and woodlands. Prescribed fire emissions in the 2000–2019 period range from 0.16 MMT CO_2 in 2016 to 1.9 MMT CO_2 in 2006, with a statewide annual average of 0.68 MMT CO_2. Annual prescribed fire CO_2 emissions have been less than 1 MMT/year except in 2005, 2006, 2008, and 2019.

Figure 4. Area treated by prescribed fire, by general vegetation categories

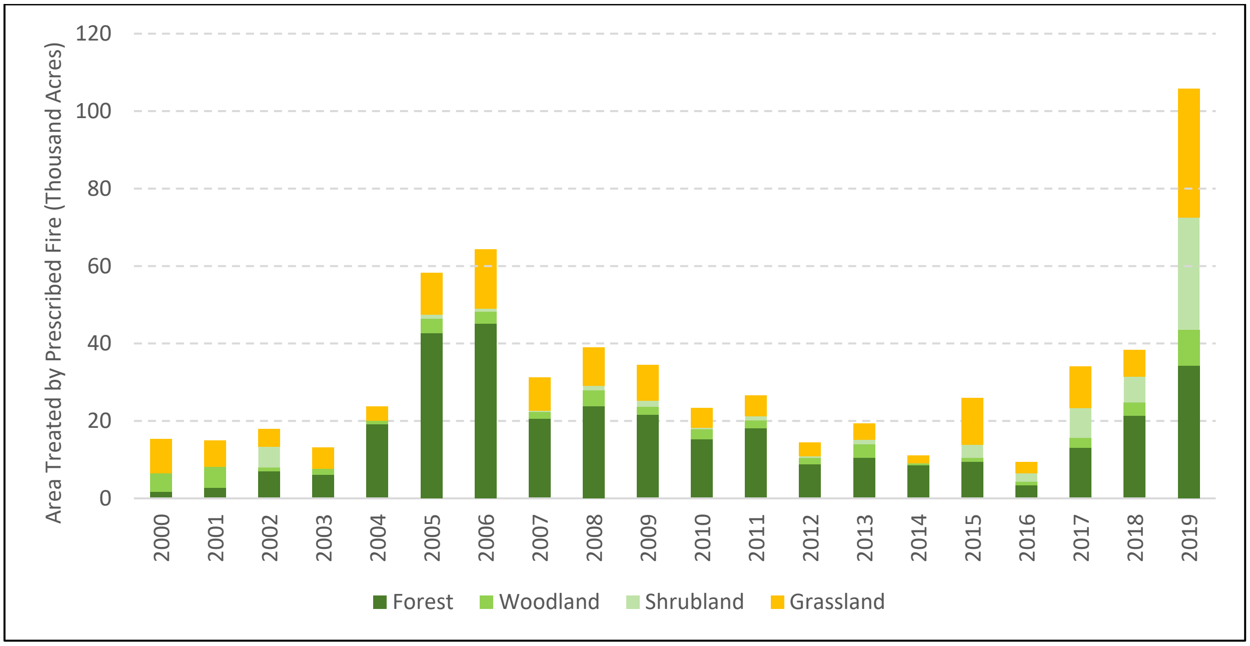
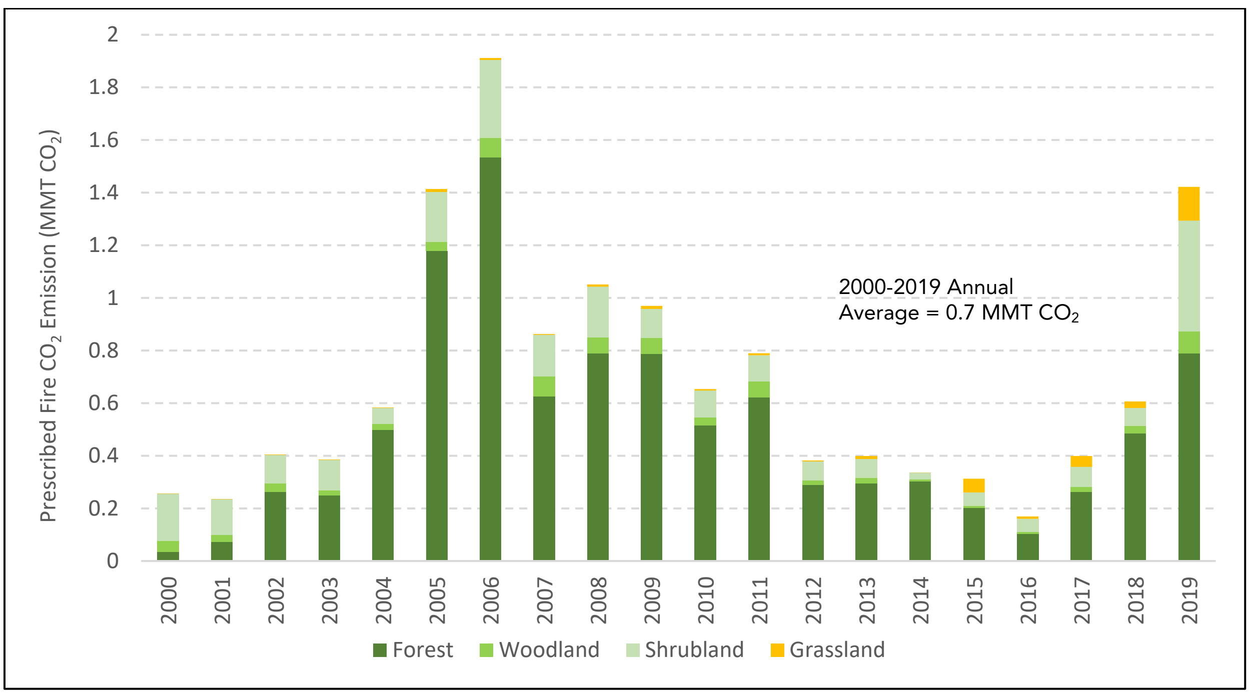


Figure 5. Prescribed fire emissions (million metric tons CO_2, MMT CO_2) by general vegetation categories

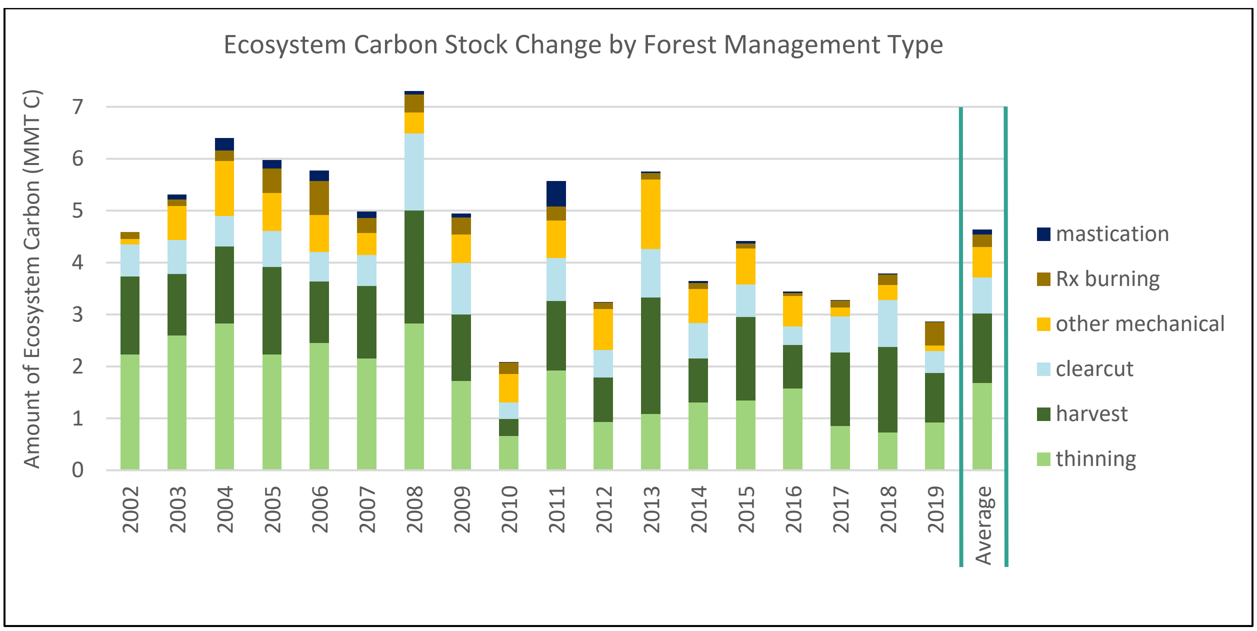


3.3. Non-Fire Forest Management Activities – Carbon Stock Change

An assessment of the annual ecosystem carbon transformed by non-fire forest management activities shows variation from year to year with a slight downward trend (Figure 6). On average, thinning transformed the most carbon of all forest management activities in California, followed by harvest, clearcutting, other mechanical, prescribed burning, and mastication (see Section 2.2.1 of this report for definitions of these categories). Temporally, management activities transformed more carbon towards the beginning of the 2000s, with a peak in 2008. Management decreased after 2008 with a minimum of carbon transformed in the year 2010, followed by an increase in 2011. From 2012 to 2019, the average carbon impact was lower than from 2002-2009.

Prescribed fire is also a forest management activity. To provide a more complete picture of the carbon impact of fire and non-fire forest management activities, the GHG emissions of prescribed fire (described in Section 3.2) are converted into carbon quantity for comparison with non-fire forest management activities. An assumed carbon fraction of vegetation fuel of 0.47 is used in the conversion. The carbon impact of prescribed fire has been included in Figure 6 along with other forest management activities.

Figure 6. Annual ecosystem carbon stock transformed by forest management category



The 2002–2019 average annual amount of carbon transformed by forest management (including prescribed fire) is 4.6 MMT of carbon. This carbon quantity represents the amount of CO_2 that was previously sequestered as biomass carbon. This carbon is not immediately emitted to the atmosphere but may have many possible fates. Through various pathways, a portion of this carbon may eventually return to the atmosphere by combustion, decomposition, or other processes; while a portion may eventually reach long-term carbon stores (places where carbon does not decompose and will persist in the landscape for hundreds to thousands of year). Although this carbon quantity should not be treated as GHG emissions, discussing carbon stock impact in term of GHG may still be helpful for putting numbers into context. For example, 4.6 MMT of carbon is equivalent of 16.8 MMT of CO_2 that was previously sequestered in biomass, though it should not be construed that 16.8 MMT of CO_2 have been released into the atmosphere.

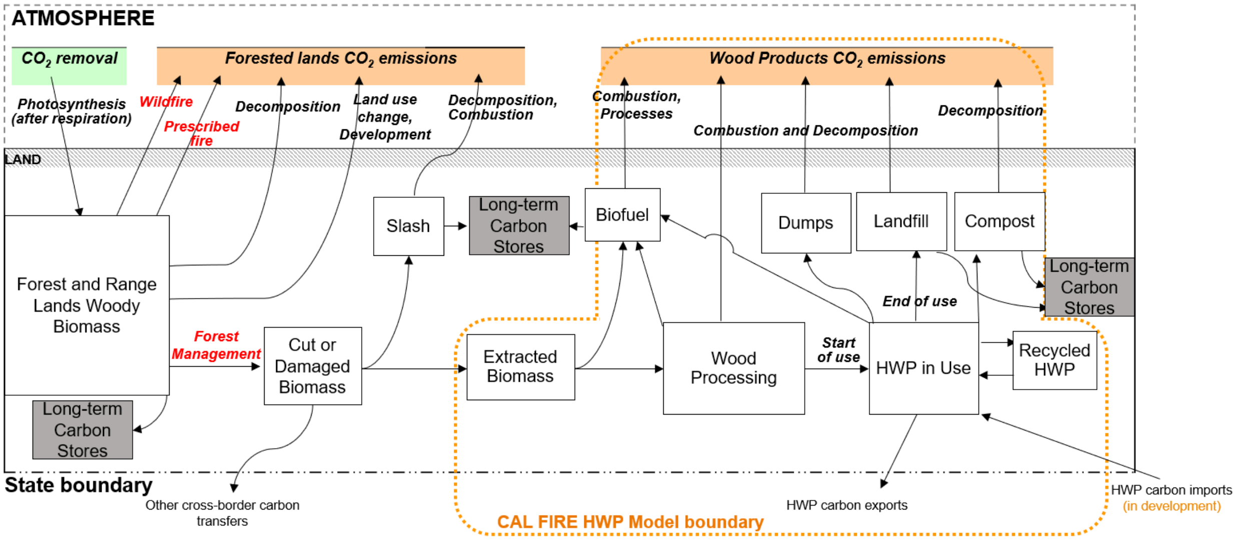
CARB's 2018 NWL Inventory estimated that California's natural and working lands currently store 5,340 MMT of carbon in plant biomass and soils across the State. The estimate of 4.6 MMT of carbon is 0.09 percent of the total ecosystem carbon stored in California's land base. Section 3.4 provides additional context for comparing carbon stock with GHG and describes the various potential fates of the transformed carbon.

3.4. Ecosystem Carbon Flow

The amount of transformed carbon quantified in this report comes from CO_2 that was previously sequestered in biomass. The carbon that is transformed by cutting of trees is not immediately emitted to the atmosphere. Once cut, this carbon in ecosystem biomass may have many possible fates. Figure 7 is a conceptual flow diagram that shows what may happen to the carbon once a forest is cut. There are many pathways through natural processes (e.g., decomposition and wildfire) or through wood products for the carbon to eventually return to the atmosphere as emissions or reach long-term carbon stores.

To see a full picture of ecosystem carbon flows, the amount of carbon moving from forest and natural lands to either the atmosphere or Harvested Wood Product (HWP) should be viewed along with carbon sequestration processes. Carbon from the atmosphere (in the form of CO_2) enters the biosphere, or land vegetative biomass, through photosynthesis. Photosynthesis is influenced by many factors including forest type, climate, topography, soil, and prior forest management. Some forest management activities result in ecological outcome that can enhance the rate of carbon sequestration or the resiliency of carbon stores. Attributing carbon gains to forest management activities at a state-wide level is an area of on-going scientific development, and it is not a part of the analysis performed for this report.

Figure 7. Flow diagram of carbon



This diagram depicts carbon flows from the atmosphere into the ecosystem and to the carbon's ending point whether through natural processes, like decomposition, or through wood products. Arrows show the flow of carbon. The top of the diagram represents the atmosphere. The land boundary is demarcated with a thick hatched line. Wildfire, prescribed fire, and forest management are shown in red to illustrate what is quantified in this report. Long-term carbon stores are shown in brown, which represent carbon that does not decompose and will persist in the landscape for hundreds to thousands of years. The California state boundary is indicated by a dashed line which limits the bounds of this diagram. The "CAL FIRE Harvested Wood Product (HWP) Model boundary" box shows the scope of CAL FIRE's harvested wood products model, which quantifies stores and flows of carbon entering the wood products system.

Life Cycle of Plants

Carbon enters biomass in forest and other natural lands through photosynthesis. After the plants use some of this carbon for respiration, and to make leaves, fine roots, and various exudates (carbon released through sap or roots to feed symbiotic micro-organisms and other processes), the remaining carbon is transformed into woody biomass. The amount of carbon sequestration that occurs through photosynthesis is influenced by site conditions, climate, and prior forest 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 or up to thousands of years for certain tree species. 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 or wetland, and eventually become a long-term carbon store that is not released into the atmosphere for possibly thousands of years.

Estimation of carbon flows resulting from photosynthesis and other life cycle of plants has high uncertainty and is expected to vary from year to year depending on temperature, precipitation, and sunlight availability of the year. Using remotely sensed data and a six percent decadal growth rate [21], CARB estimated an annual average of 9.9 MMT C / year of gross stock change (excluding impacts from disturbance). Based on ground measurement data from sampling forest plots and statistical extrapolation [3], CAL FIRE's Forestry Carbon Inventory estimates an annual average of 7.1 MMT C / year. These two estimates represent a range of estimates based on current scientific understanding and existing data.

Cut or Damaged Biomass After Disturbance

Some carbon in forest and other natural land biomass is affected by fire, development, forest management, or other forms of disturbance. In the case of fire (either a wildfire or a prescribed fire), some CO_2 is immediately released to the atmosphere through combustion. Some of the affected biomass is damaged and will decompose or be removed through salvage logging. Residual un-combusted carbon (such as cinders and ash) will remain in the landscape and become a long-term store.

Cut or damaged biomass may remain on the landscape in the form of slash. Portions will decompose or be burned and released into the atmosphere. Some carbon contained in slash will not fully decompose and instead will become a long-term carbon store in the soil. A portion of the cut or damaged carbon will be exported out of state and outside the boundaries of this flow chart, through timber or biomass exports. The remainder of this carbon will be extracted but stay within the State for processing.

Extracted Biomass for Energy and Fuel Applications

Some of the extracted biomass may be used as biofuel. The fuel may be consumed in an industrial biomass burning facility or as household firewood. The combustion of this fuel will release GHG into the atmosphere. Moreover, biomass can be transformed into other forms of gaseous or liquid fuels. 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.

Wood Processing

Extracted biomass not directly destined for fuel use will enter wood processing pathways. CAL FIRE uses a wood products model to quantify the stocks and flows of carbon in wood products in California. CARB plans to utilize CAL FIRE's Harvested Wood Product (HWP) model in the future for tracking wood products carbon and fluxes. Carbon in the wood product pathways may enter via lumber mills or other facilities that produce wood products. The portion that becomes wood product enters the pool of wood products in-use, and this includes the recycling of waste for secondary products, such as wood chips or mulch. A large portion of the wood waste from wood processing is utilized as fuel, while the remainder is discarded where it will decompose or be combusted.

Wood Products

Some wood products exit the State as exports and leave the boundary of this flow chart. Imported wood products also enter the system from outside the State. (CAL

FIRE is in the process of developing estimates of wood product carbon entering the State.) A portion of wood products in-use will be recycled and reenter the system in new forms. At the end of use-life, wood product carbon will enter the waste management system to be landfilled, composted, or burned for energy. Through anaerobic decomposition, approximately half of the carbon contained in landfilled wood products will become landfill gases, which may then be collected and combusted (and released to the atmosphere) or escape as fugitive emissions. The remainder of landfilled wood carbon will persist in solid form indefinitely. Aerobic decomposition will release a portion of composted wood carbon to the atmosphere, with the remainder entering long-term soil carbon stores. Historically, wood was also discarded to dumps where it was subject to aerobic decomposition.

4. Future Development and Research Needs

4.1. Addressing Data Gaps and Expanding Data Collection

Quantifying emissions from fires and forest management is an evolving area of science. More refined data may enhance emission estimates. Data from existing reporting on forest management activities represent only a portion of the action that is occurring throughout the State. There may be some forest management activities that are currently not reported or otherwise captured by existing datasets, and these may include activity that is too small to report, activity occurring within an emergency or exempted area, or illegal activity.

Forest management activities are currently being performed by many public, private, and non-profit entities throughout California. Existing data collection and reporting programs of a data collection agency were generally designed to support the specific mission of the agency, which may or may not include carbon estimation as a goal. These datasets provide varying levels of quantitative details, reliability, and data coverage, and they may be collected in different ways from self-reporting to independently measured remotely sensed information with satellites. Some data are publicly available, while other data are considered confidential business information that require formal interagency agreement and/or data Non-Disclosure Agreements to access. Some datasets include spatial and temporal information while others do not. The level of information about the type of activity that occurred also varies. For example, the FACTS geodatabase provides information on specific silvicultural practices that had occurred, while other databases (such as FIA data) may not include information about the specific type of silvicultural practice. Information collected in the permitting process of Emergencies and Exemption Notices currently does not include the detailed data needed for estimating the amount of carbon transformed by these activities. To spatially and temporally estimate the amount of carbon transformed by forest management activity throughout the State and through time, information on the location, timing, and type of forest management activity that occurred would be needed. Ideally, measurements would be taken in the field to estimate the carbon transformed through management activities.

In addition, multiple agencies may be conducting, monitoring, or overseeing similar types of forest management activities on different land types depending on each agency's respective jurisdiction and purview. As the result, information specifically useful for estimating carbon impacts is not centralized. However, it is possible to develop new data standards for long-existing forest management activities. For example, the Wildfire Safety Division (WSD) is currently working with various stakeholders and utilities to develop new standards that will be required of utilities in support of their wildfire mitigation efforts [22]. Also, local air quality management agencies, CARB, and CAL FIRE are working towards enhanced coordination on reporting of prescribed fire activities into the Prescribed Fire Information Reporting System (PFIRS) and to CAL FIRE databases. Efforts like these present opportunity to expand data collection and increase utilization of data collected by agencies.

Expanding utilization of data collected by various agencies will require extensive inter-agency coordination and collaborative effort. CARB staff plans to work with state, federal, and local agencies to explore how to leverage data sets across agencies to develop a more comprehensive picture of vegetation carbon management in the State.

4.2. Using Remote Sensing Data to Complement Data Reporting

Not all forest management activity can be completely captured by reported data. Forest management activity data needed to calculate carbon stock changes and emissions are not currently collected for all types of management activities. For example, activities done under declared large emergencies or exemptions, small scale forest management, or illegal activities do not have associated recorded data needed to estimate carbon stock changes and emissions. In these cases, CARB has limited ability to ascertain how large or small an impact such activity may have on forest carbon. Remote sensing technology may assist in determining where activities are occurring that are not fully reported. For example, CARB staff anticipates that advances in mapping vegetation fuels using remote sensing technology – largely intended for use in fire behavior and emissions modeling – will also reveal the extent of unreported forest management activity and yield clues to quantifying the associated impacts to forest carbon. Moreover, coupling vegetation fuels mapping with carbon quantification will allow fire emission modeling to better take into account the effects of prior forest and vegetation fuels management.

4.3. Research Needs

4.3.1. Characterization of the Effects of Forest Management on Carbon in Diverse Landscapes

Research associated with how specific types of forest management affect various carbon compartments, including soil, is needed to refine estimates of how management transform carbon stocks. The effects that forest management has on ecosystem carbon varies by forest type, topography, and intensity of the activity.

Researchers have studied such variation for a limited number of California forest types and soils. More research is needed to evaluate the efficacy of forest management and to characterize effects across the diverse array of forests in the State. Additionally, the effects of forest management on below ground carbon, including soils, needs further empirical experimental research in the long term.

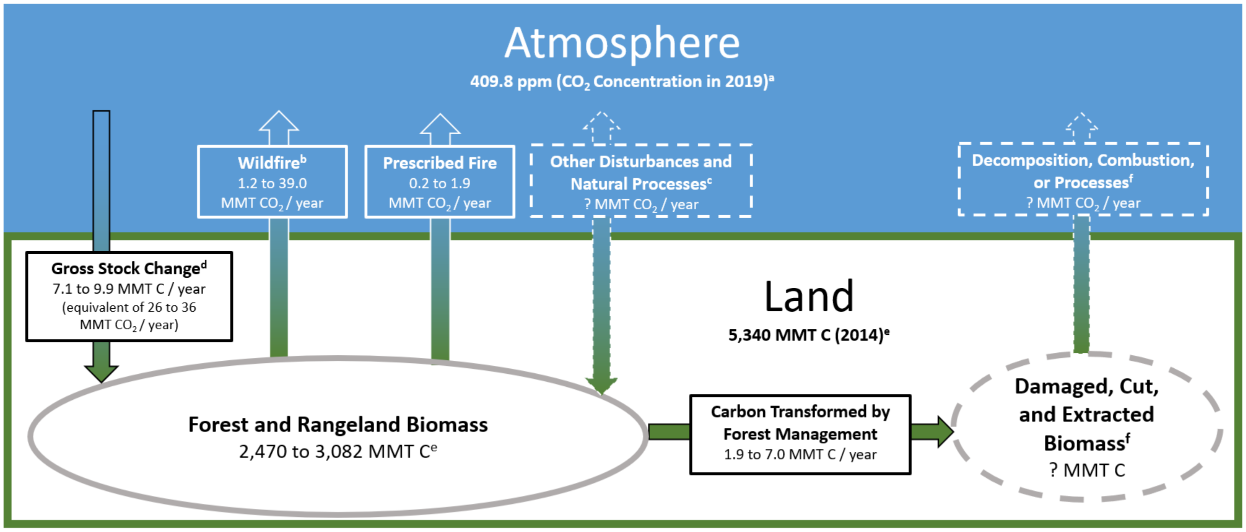
4.3.2. Modeling Refinements

Methods for estimating GHG emissions and carbon stock change are active areas of research and development. Measuring emissions from fires or forest management activities is principally a scientific research activity, employing special purpose instruments deployed at the surface or mounted on airborne platforms at a site. Therefore, model-based approaches are used for statewide estimation of forest management activities and fire emissions. As science advances and understanding of carbon dynamics deepens, models can incorporate new information. Modeling refinements that would assist CARB in refining emission estimates include: utilizing updated fuel models and fuel maps, fire emission models, annual remotely sensed and directly measured estimates of forest structure change, and identification of forest management activities that are not reported.

5. Summary

California's forests and other natural lands contain large quantities of carbon in the forms of plant biomass, dead organic matter, and soil organic matter. The current carbon stores represent slow accumulation over long periods of time. The annual amounts of carbon transferred from the atmosphere to biomass and the transfers of carbon out of the land base represent a small portion of the land carbon reservoir. Figure 8 summarizes CARB staff's estimates of carbon stock and GHG emissions from wildfire, prescribed fire, and forest management activities. These estimation results are shown along with carbon sequestration and other processes to provide broader context to the estimated emissions.

Figure 8: Flows of carbon and CO_2 between the atmosphere and California's forests and other natural lands



The upper portion of this diagram represents the reservoir of carbon in the atmosphere. The lower portion of this diagram represents reservoir of carbon within California's land base and extracted biomass. The exchanges of carbon and CO2 between the land and atmosphere are shown by arrows, and the boxes attached to each arrow indicate the type and quantity of the exchange. Arrows and boxes that have dashed outlines represent reservoirs and transfers of carbon or CO2 that have not yet been quantified due to limitation in existing data availability.

[a] Source of atmospheric CO_2 concentration: National Oceanic and Atmospheric Administration [1]

[b] 1.2 to 39.0 million metric tons of CO_2 per year represent the range of values in 2000-2019, which has an annual average of 14 MMT million metric tons of CO_2 per year. Final fire perimeters and updated fire emission estimate for 2020 will be available in mid-2021.

[c] "Other disturbances and natural processes" include emissions associated with land use and land cover change, erosion, decomposition, plant respiration, and any other non-fire disturbance or emission source. This also includes carbon sequestered into non-woody biomass such as foliage, fine roots, or any other vegetative component that are not included in CARB's net carbon stock change estimate. A portion of carbon sequestration may be attributable to the result of forest management activity or natural process. These flows have not yet been quantified due to limitation in existing data availability.

[d] "Gross stock exchange" 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. The values represent CARB's and CAL FIRE's estimates [2, 3]. Improvements in forest productivity as a result of forest management activities are inherent in the gross stock change estimates but difficult to separate from other effects on productivity such as changes in precipitation and temperature. See Section 3.4, Life Cycle of Plants subsection, for more information.

[e] The range of values represent carbon stock estimates from CARB's NWL Inventory [2] and CAL FIRE's Forest Carbon Inventory [3].

[f] "Damaged, cut, and extracted biomass" include biomass that is transferred into slash piles, biofuels or into other harvested wood products. These flows have not yet been quantified due to limitation in data availability. See Section 3.4 and Figure 7 for additional information about life cycle of harvest wood products and their various fates, including long-term carbon stores and potential emission pathways.

Acknowledgment

CARB staff worked in consultation with many state agencies that have either oversight of forest management activities or actively conduct forest management on the ground. The technical methodology developed by CARB staff for producing these GHG and carbon estimates incorporates work and products from partner agencies and academic researchers. CARB staff's understanding of wildfire and forest management has been enhanced by these contributors and other stakeholders who have shared their time and expertise.

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