California Natural and Working Lands Carbon and Greenhouse Gas Model (CALAND)

Technical Documentation
June 2019

Alan Di Vittorio
Maegen B. Simmonds
Lawrence Berkeley National Laboratory

Please cite as:
Di Vittorio, A., and M. Simmonds (2019) California Natural and Working Lands Carbon and Greenhouse Gas Model (CALAND), Version 3, Technical Documentation.

California Natural and Working Lands Carbon and Greenhouse Gas Model (CALAND)

Contents

1. Summary

The California Natural and Working Lands Carbon and Greenhouse Gas Model (CALAND) is a system of algorithms (.r files) and input data[1] developed to quantify the impacts of various suites of California State-supported land use and land management strategies on land-atmosphere carbon dioxide (CO_2) exchange and emissions of methane (CH_4) and black carbon (BC, optional) relative to a baseline scenario for the Draft California 2030 Natural and Working Lands Climate Change Implementation Plan (2019). The .r files include the computer simulation model (CALAND.r), a data pre-processing algorithm (write_caland_inputs.r) for generating model input files, and three post-processing algorithms (plot_caland.r, plot_scen_types.r, plot_uncertainty.r) for diagnosing, visualizing, and summarizing model outputs. The CALAND model has a hybrid modeling structure, combining California-specific empirical data with externally mechanistically modeled data. Sources of CH_4 emissions are from wetland soils and biomass burning (wildfire, controlled burning, bioenergy), which also emits BC. The global warming potential (GWP) of net emissions of these three greenhouse gases (GHG)[2] is computed on an annual time-step; starting with historical carbon stock and flux data and two options for historical land use and land cover change,[3] CALAND simulates annual carbon stocks and fluxes, including material flow to wood products and bioenergy, for given land use and land management scenarios from 2010 through 2100. The potential effects of climate change on carbon dynamics and wildfire are optional, with three choices: historical (no climate change effects), Representative Concentration Pathway (RCP) 4.5, or RCP 8.5.

The primary function of CALAND is to quantify the difference between expected net GHG emissions from a historically grounded, baseline land use and land management scenario and net GHG emissions from alternative land use and management activities pursued on a range of spatiotemporal scales. This is accomplished by using CALAND.r to simulate the individual scenarios and plor_caland.r to quantify the differences between them. This comparison will quantify the change in net GHG emissions that is expected to arise from applied land conservation and management activities, relative to the reference baseline.

---

[1] Model development history and version releases available for download at https://github.com/aldivi/caland.

[2] Version 1 (November 2016) did not include these greenhouse gas outputs. Version 2 (October 2017) did not have the option to output only CO_2 and CH_4 emissions.

[3] The default option is land –use-change driven data from the CA Fourth Climate Assessment, and the alternative is remote sensing based change data from 2001-2010. Previous versions used only the remote-sensing based data.

[4] Currently, the absolute outputs for any individual scenario are not robust due to extremely high uncertainty of input carbon density and flux data and historical baseline land use/cover change, combined with unknown distribution and carbon dynamics of savanna/woodland with woody versus grass understory. The default land use/cover baseline uses a land use change driven approach, but does not address non-anthropogenic land cover change or data limitations for particular land types. Uncertainties in initial carbon density and net ecosystem carbon exchange are better quantified, but also dramatically affect absolute projections.

Currently, CALAND should only be used to examine differences between GHG emissions arising from the baseline and alternative scenarios, as opposed to absolute GHG emissions of an individual scenario, due to high uncertainty in the input data.[4] CALAND operates statewide on 940 land categories (i.e., region-land-type-ownership combinations) plus ocean seagrass (Table 1, Figure 1).[5] Usage of CALAND is described in detail in the readme file that is provided when downloading CALAND. A general overview is provided here.

The CALAND user first uses functions contained in CALAND.r to simulate individual scenarios and generate one main output file (.xls) of carbon and GHG emissions for each scenario. This output file is an Excel workbook (.xls) containing 214 tables as individual sheets. The functions in plot_caland.r are then used to compute differences between individual scenario outputs, and create a suite of graphics (.pdf) and corresponding data tables (.csv). This is essential for estimating the carbon and GHG impacts of land use and land management scenarios relative to an appropriate baseline scenario. There are two additional plotting functions contained in plot_scen_types.r and plot_uncertainty.r that can be used to create more detailed plots using the outputs from plot_caland.r (Section 3). All functions can be implemented in R (www.r-project.org) or in command line.

The CALAND.r file has two input data files (.xls) per scenario. The two input files contain the carbon data and scenario prescriptions, respectively. Each input file is comprised of individual worksheets, defining the initial land category areas; initial carbon densities; annual area changes; ecosystem carbon fluxes; management parameters; parameters for land conversion to cultivated or developed lands; wildfire parameters; wildfire areas; mortality fractions; climate change scalars; and management scenarios. The carbon input data are constant across compared scenarios and comprise an integration of many data sources, which are described here and detailed in the appendices to this report. Each scenario is defined in an individual scenario input file, which prescribes the initial landscape state and annual areas of land cover change, management, and wildfire, along with climate scaling factors and annual mortality rates for vegetation.

Due to the complexity of the two input files for CALAND.r, the write_caland_inputs.r file is used to process a suite of individual raw data files to generate the two input files. Most of these raw data are provided with the installation of CALAND, but the user must create a raw scenario file that defines one or more management scenarios. The areas in the raw scenario file can be in acres or hectares, but it must be specified when using write_caland_inputs.r as areas will be converted to hectares for input the model if the scenario is specified in acres.

[5]Version 1 had 45 land categories with 15 land types and three ownership classes.

Table 1: Land Category Delineations

The 940 land categories are defined by the intersection of nine ownership classes, nine spatial regions, and 15 land types. Seagrass is offshore and is assigned to the coastal region and other federally owned lands. (See Appendix B for definitions).

Spatial Regions	Ownership Classes	Land Cover Types	
Central Coast	U.S. Bureau of Land Management	Barren	Savanna
Central Valley	National Park Service	Cultivated Land	Seagrass
Sacramento-San Joaquin Delta	U.S. Department of Defense	Desert	Shrubland
Deserts	USDA Forest Service (non-wilderness)	Forest	Sparse
Eastside	Other Federal Government[6]	Fresh Marsh	Coastal Marsh
Klamath	State Government	Grassland	Urban Area[7]
North Coast	Local Government	Ice	Water
Sierra Cascades	Private	Meadow	Woodland
South Coast	Conservation Easement Protected		

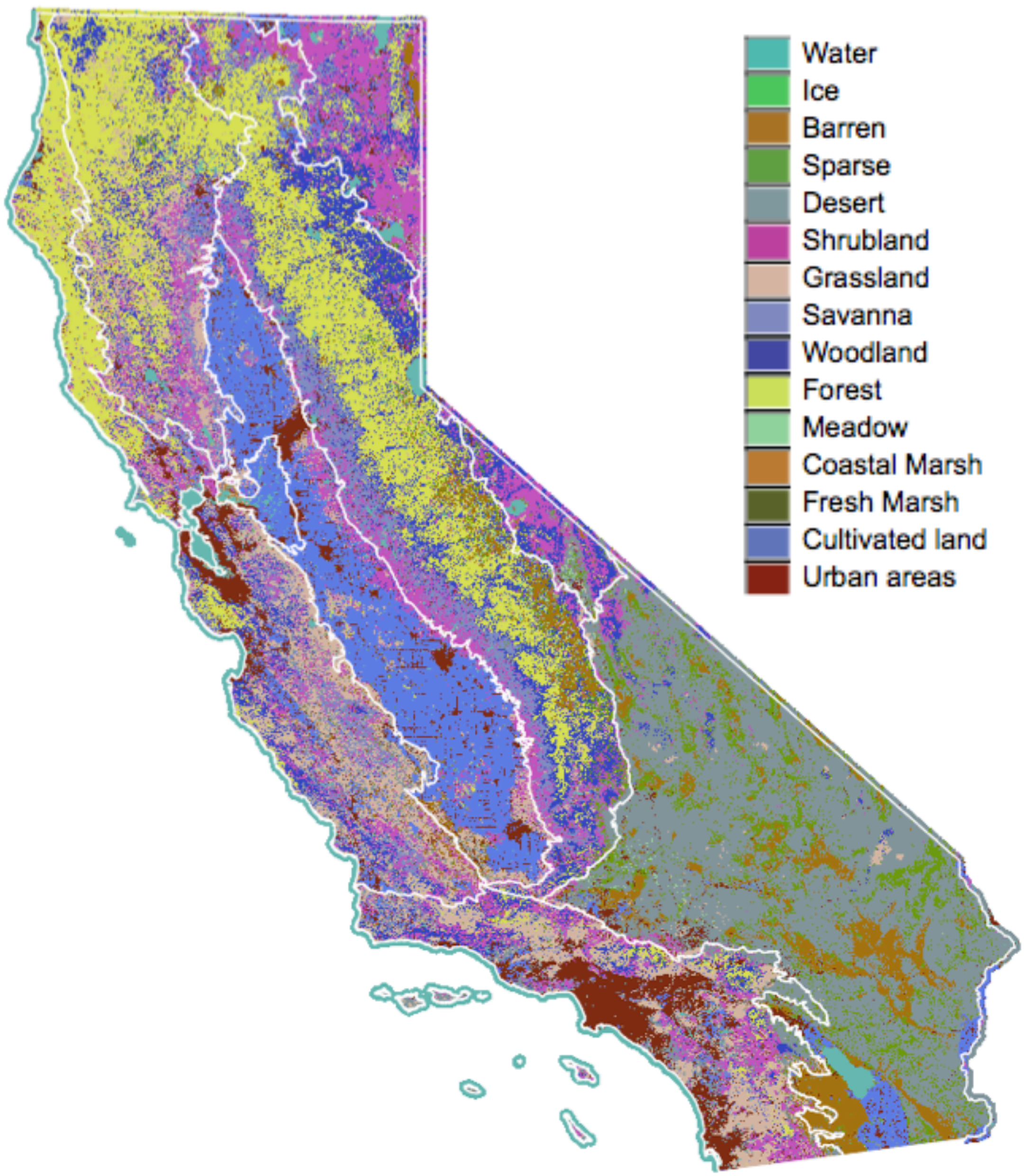
[6]U.S.Bureau of Indian Affairs, U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, USDA Forest Service Wilderness Area, and other Federal lands

[7]Referred to as Developed_all in CALAND data files and R scripts.

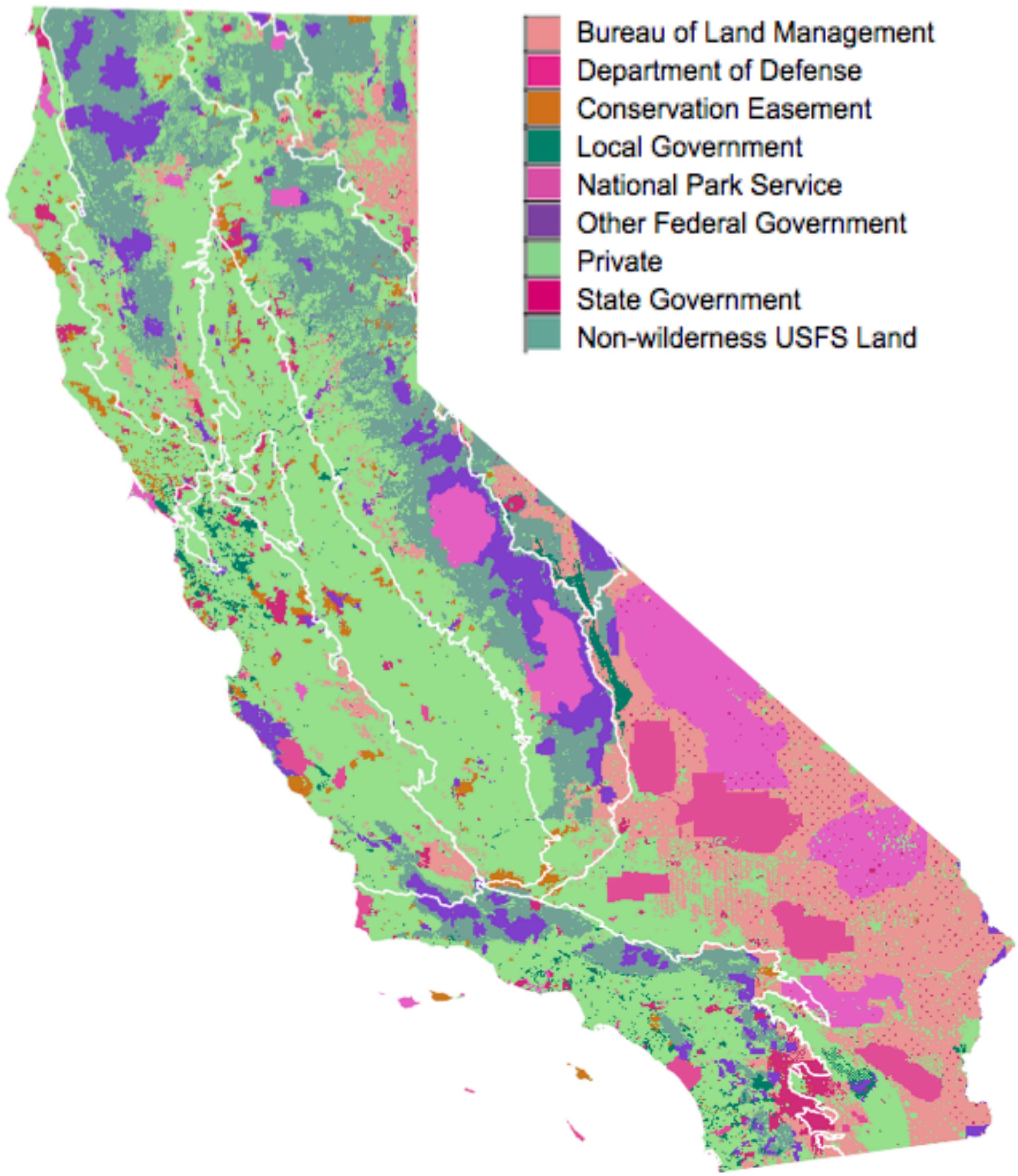
Figure 1: CALAND Land Categories

Corresponds to Table 1. The land categories are defined by the intersection of nine spatial regions (delineated by white lines), a) 15 land types, and b) nine ownership classes. Seagrass is considered separately. The geographical boundaries of the land categories are defined only in the initial year of the simulation, and the region and ownership boundaries do not change over time. The changes in total area of each land category are modeled over time as changes in land cover type area within each region-ownership.

a) 15 land cover types



a) Nine ownership classes



2. Model structure

CALAND is a system of algorithms (.r files) and data designed to project changes in the accumulation and fate of above- and below-ground carbon in up to seven carbon pools (Table 2), including carbon flow to wood products and bioenergy and emissions of CO_2, CH_4, and BC in each land category, due to a variety of management activities and options for climate, wildfire, land use and land cover change. The CALAND model (CALAND.r) has a hybrid modeling structure, combining California-specific empirical data with externally modeled data. By default, CALAND outputs only CO_2 and CH_4 emissions, while still tracking the amount of BC that could be emitted (this small BC fraction is emitted as CO_2 for GHG calculations in order to conserve carbon in the modeling system). Optionally, BC can be emitted separately with a GWP of 900 (however, this is not recommended because BC does not behave like primary GHGs). The California-specific data are from academic literature, state institutions, and state partner organizations. CALAND implements basic density (stock) and flow processes in line with IPCC Tier 3 protocols by integrating California-specific, observed historical carbon flows (fluxes) and initial carbon densities with wildfire, climate effects, and land cover change derived from external models.

The input data consist of initial carbon densities; net annual carbon fluxes (sequestration is positive and emissions are negative); the proportion of CO_2, CH_4, and BC in carbon emissions from burned biomass; and the effects of management, climate, land conversion, and fire on carbon stocks and fates. These data are provided in various formats and are representative of specific locations, ranging from experimental field sites to general land types (e.g., Forest). In general the average of each type of data were calculated and disaggregated to each of the 940 land categories—the intersection of 15 land types, nine ownership classes, and nine regions (Table 1, Fig. 1)—and one Seagrass category, along with uncertainty ranges for the carbon data.

The impacts of management on landscape carbon are estimated by computing the differences between a simulated management scenario and a simulated baseline scenario using CALAND.r and plot_caland.r. Baseline scenarios are often extrapolations of recent trends but can also represent the absence of mangement[8] to estimate the total effects of a management scenario. The baseline and management scenarios can also include future projections of climate change effects on wildfire and ecosystem carbon fluxes.

The California Natural Resources Agency provided two management scenarios and one limited-management baseline scenario that are in accordance with the Draft California 2030 Natural and Working Lands Climate Change Implementation Plan (CA, 2019) (Section 2.2). Each scenario was simulated independently using CALAND.r under a projected future climate (RCP 8.5), starting from an initial condition in 2010, with computations made on an annual time-step based on the given scenario through 2100.

[8] i.e., includes only wildfire, mortality, ecosystem carbon fluxes, historical land use and cover. change, and optional climate change effects.

Table 2: Carbon Pools Represented in CALAND

Boxes marked by "X" indicate carbon pools included in CALAND. Seagrass starts with non-zero area and zero carbon, and Fresh Marsh starts with zero area and zero carbon.

Carbon Pool: / Land Type:	Soil	Main canopy (above ground)	Main canopy (root)	Understory	Dead (standing)	Dead (downed)	Litter
Water	X						
Ice	X						
Barren	X	X	X				
Sparse	X	X	X				
Desert	X	X	X	X	X	X	X
Shrubland	X	X	X	X	X	X	X
Grassland	X	X	X	X	X	X	X
Savanna	X	X	X	X	X	X	X
Woodland	X	X	X	X	X	X	X
Forest	X	X	X	X	X	X	X
Meadow	X	X	X	X	X	X	X
Tidal Marsh	X	X					
Fresh Marsh	X						
Cultivated Land	X	X					
Urban Areas	X	X					

Figure 2 illustrates the relationships between modeled processes. The model starts with an initial carbon and land cover state in 2010 and simulates the following processes in order, on an annual time step:

1. The net landscape carbon exchange or loss (including adjustments based on climate and/or management activities),
2. The effects of forest management on carbon stocks, including carbon storage in wood products and carbon transfer to bioenergy feedstock (without changing the land type area),
3. The effects of wildfire on landscape carbon (with optional non-regeneration of some high severity burn area),
4. The effects of changes in land type area on landscape carbon (including restoration activities and wood products from forest to urban/agriculture conversion)

Management activities for Cultivated Land, Rangeland (Grassland, Savanna, Woodland), Forest (indirect effects on growth, mortality, and soil), and Urban Area (urban forest fraction) are implemented in step (1). Forest management (including dead removal from Urban Area) is directly implemented in step (2). Restoration, Land protection (i.e., avoided conversion to Urban Lands), and Forest expansion are implemented in step (4). The carbon densities for all pools are updated after each group of related processes (1)-(4). All landscape carbon, accumulated or emitted, and carbon stored or emitted by wood products, is accounted for (i.e., carbon is conserved). In general effects from land cover change, wildfire, climate, and management, on landscape carbon exchange are assumed to occur in the same year they occur. Some exceptions include delayed decay of wildfire-killed biomass, decay of logging residue that has been removed from the forest, and soil carbon loss due to land conversion. Additionally, carbon accumulation benefits associated with some forest management practices and rangeland compost extend for 10 to 30 years, depending on the practice. Partitioning of the annual land-atmosphere exchange of carbon into CO_2, CH_4, and BC, including carbon emissions pathways for discarded wood products and bioenergy generation from forest biomass, is computed once all years have been simulated.

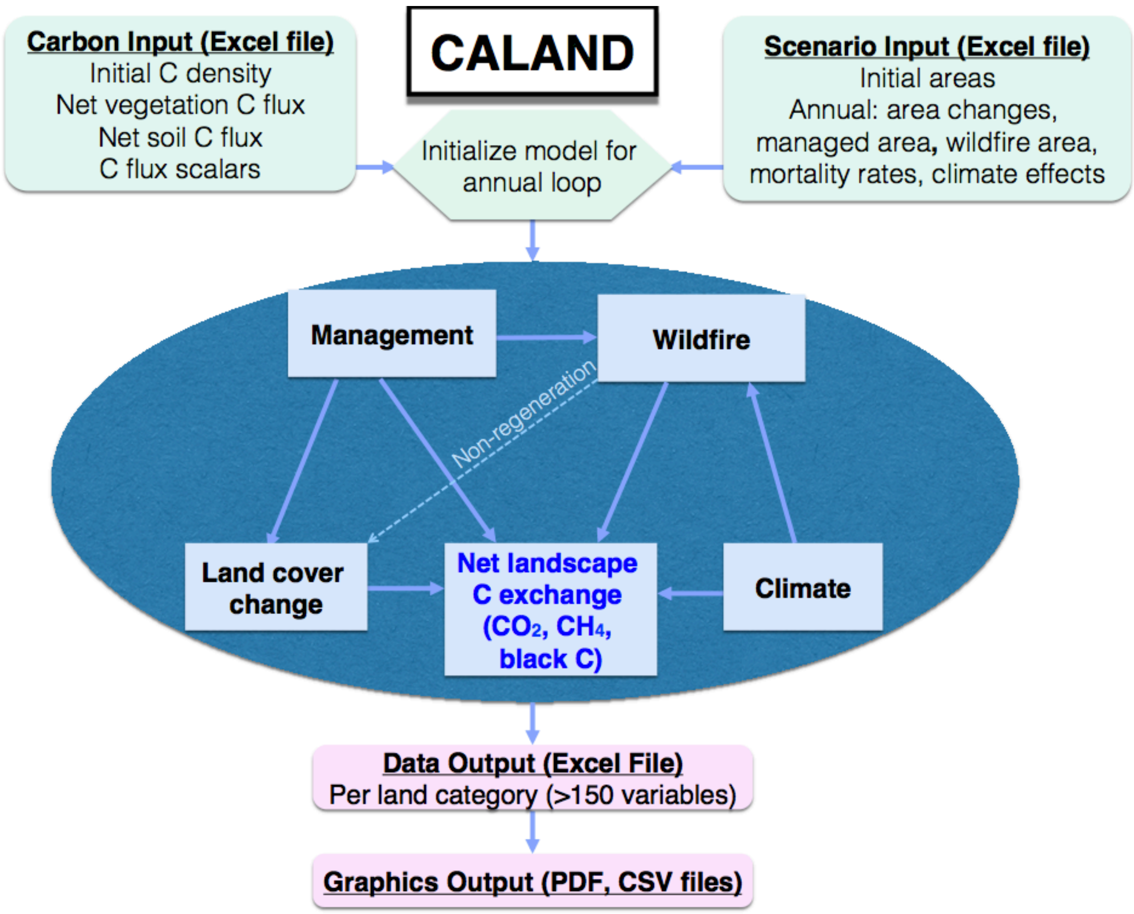


Figure 2: CALAND Model Operation

The CALAND model, located in the CALAND.r file, operates on an annual time step.

2.1 Initial state

The initial land cover and soil and vegetation carbon density state begins in 2010, which was derived from the California Air Resources Board (CARB) Greenhouse Gas Inventory for California Forests and Other Lands (Saah et al., 2016; Battles et al., 2014) and an urban forest assessment (McPherson et al., 2017). The initial soil carbon densities are derived from the NRCS gSSURGO database (USDA, 2014) and a review of California rangeland soil studies (Silver et al., 2010). These data were processed with the aid of a geographic information system so that they are geographically aligned[8] in order to obtain average carbon density values and associated uncertainty for the 940 land categories. The mean, standard deviation, maximum, and minimum carbon densities for each land category (for up to six biomass pools and one soil pool) are included in the carbon input file (carbon_input_nwl.xls). Uncertainty in the carbon inputs was characterized as the standard deviation of the calculated mean values for consistency, as not all data included explicit uncertainty.

2.1.1. Land categories

The land categories are the modeled units for which changes in landscape carbon are computed. These units are quasi-spatial, as the simulations do not occur on a spatial grid, but rather within non-spatially explicit land category areas within spatially-explicit region-ownership boundaries (i.e., as a fraction of each region-ownership area). They were defined by the intersection of the initial 2010 land cover and the static boundaries of spatial regions and ownership classes. The land cover data used to delineate the 15 land types in CALAND are based on remote sensing data from the LANDFIRE program[9] and are provided in the CARB Inventory database (Saah et al., 2016, Battles et al., 2014). The 204 LANDFIRE (2010) land cover types for California were aggregated into 15 CALAND land types based on the 2008 classification scheme provided in the CARB Inventory. These 15 land types were intersected spatially with nine ownership classes derived from a combination of CAL FIRE Fire Resource and Assessment Program (FRAP) ownership data,[10] the 2015 California Conservation Easement Database (CCED, 2015),[11] and USFS wilderness area data;[12] and nine spatial regions derived from a combination of the USFS Pacific Southwest Region[13] ecological sub-regions for the State

[8] GRASS GIS 7.0. All the spatial data have been transformed to CA Teale Equal Area Albers projection at 30 m resolution with extent: 736072.75860325 to 613987.24139675 south-north and -423161.42973785 to 586578.57026215 west-east.

[9] LANDFIRE data available online: https://www.landfire.gov

[10] CAL FIRE FRAP Mapping – FRAP Data available online: http://frap.fire.ca.gov/data/frapgisdata- sw-ownership13_2_download;
California Multi-Source Land Ownership available online: http://frap.fire.ca.gov/data/statewide/FGDC_metadata/ownership13_2.xml

[11] CCED, 2015

[12] USDA Forest Service FSGeodata Clearinghouse available online: https://data.fs.usda.gov/geodata/edw/datasets.php; https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.Wilderness.xml

of California, the Sacramento-San Joaquin Legal Delta boundary (as defined by the Delta Protection Act of 1959), and the Suisun Marsh as determined by soil carbon densities greater than 250 Mg C ha^{-1}. The spatial regions are the aggregation of Level 2 ecological sub-regions recommended by The California Department of Forestry and Fire Protection (CAL FIRE) (Figure A1 in Appendix A; also defined in the 2018 California Forest Carbon Plan[14]), with modifications to delineate the Legal Delta and Suisun Marsh. The Delta region was extracted from the Central Valley region, with some adjustments along the border with the Central Coast (<2 km) to ensure complete inclusion of the Legal Delta and distinct regions with contiguous area. This delineation facilitates modeling of wetlands management and restoration practices that are unique to the Delta region. Fresh Marsh is a unique land type that is not represented in the LANDFIRE data classification (i.e., initial area = 0), yet it is included in CALAND to track managed wetland restoration in the Sacramento-San Joaquin Delta. The initial area of offshore Seagrass is the midpoint value of the range reported by the West Coast Region of NOAA Fisheries (NOAA, 2014).

2.1.2 Biomass carbon

CALAND has six biomass carbon pools, including aboveground main canopy, belowground main canopy (root), understory, standing dead, downed dead, and litter (Table 2). The initial 2010 biomass carbon density input data for all land categories (except Urban Area) were derived from the CARB Inventory database (Saah et al., 2016, Battles et al., 2014). These source data are stored on a 30 m resolution grid, with distinct biomass values for each of the 204 LANDFIRE land cover types. They were calibrated to USFS FIA data and available literature. The biomass density values were converted to carbon density values using the recommended factor (carbon = 0.47*biomass; Saah et al., 2016). These gridded carbon values were used to calculate the area-weighted average of the grid cell values within each land category, which are the carbon density inputs to CALAND. The standard deviation, maximum, and minimum of these grid cells are also available in the carbon input file. The Urban Area input carbon densities come directly from the source data for the CARB Inventory database, with regional values split into aboveground (72%) and belowground (28%) main tree canopy carbon (McPherson et al., 2017).[15]

[13] USDA Forest Service Pacific Southwest Region State-Level Datasets available online: https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836; https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=fsbdev3_048133

[14] California Forest Carbon Plan available online; page 66: http://resources.ca.gov/wp-content/uploads/2018/05/California-Forest-Carbon-Plan-Final-Draft-for-Public-Release-May-2018.pdf

[15] Previous versions assigned all of the reported statewide value to aboveground carbon, across all regions.

Other sources were considered for gridded initial biomass carbon, but they only covered the forested area and were based on USFS FIA data. For example, a 250 m resolution data set (Wilson et al., 2013) was compared to the CARB Inventory data for 45 land categories. Relatively small differences were found between the Forest land types, but there was an apparent overestimation of carbon density for the other land types in the coarser data due to limited coverage and mixing of Forest with less vegetated area.

In most cases the biomass carbon density inputs are comparable to other reported estimates despite differences in aggregation and categories (Forest: Birdsey and Lewis, 2002; FRAP, 2010; Hudiburg et al., 2009; Pearson et al., 2009; Desert: Evans et al., 2014; Grassland: Ryals and Silver, 2013; Cultivated Land: Brown et al., 2004; Kroodsma and Field, 2006). Notable exceptions include a reported value for chaparral (Quideau et al., 1998) that is about four times the Shrubland values, and a reported oak woodland value (Hudiburg et al., 2009) that is about twice the Woodland values. Reported values for forest plantations can also be lower (e.g., Powers et al., 2013) or higher (e.g., Dore et al., 2016 and Quideau et al., 1998) than Forest values. **Overall, the CARB Inventory (Saah et al., 2016; Battles et al., 2014) was found to be the best match for CALAND requirements of complete spatial coverage, fine-resolution gridded data, and distinct component carbon pools for management purposes.** Furthermore, it is paired with a fairly detailed land cover database needed to delineate the landscape.

2.1.3 Soil organic carbon

CALAND has a single soil organic carbon pool. The initial 2010 soil organic carbon density values for all land categories, excluding Grassland, Savanna, and Woodland, were derived from the Gridded Soil Survey Geographic (gSSURGO) Database, a product from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (USDA, 2014). The gSSURGO database provides estimates of total soil organic carbon densities for 0 to 150 cm depth (or maximum reported depth) at both the original mapping unit level and disaggregated to a 10 m resolution grid. Rather than using the gridded data, the original mapping unit data was disaggregated to the same 30 m grid used for the biomass carbon data. Following the same method used for deriving biomass carbon density inputs, soil carbon data were aggregated to the land categories, excluding grid cells with missing data. Due to spatial gaps in the data, six land categories were not directly assigned soil carbon density values. Rather, they were estimated by extrapolating data from identical land types in other ownerships within the corresponding region.[16] The aggregated gSSURGO soil carbon density values for Grassland, Savanna, and Woodland were found to be about one-third of the values reported in a review of California rangeland studies that estimated total soil

[16] In Version 1, all the land categories were directly assigned values. In Version 2, the unassigned categories were Eastside Private Ice, Klamath USFS non-wilderness Ice, Deserts NPS Forest, Deserts State government Forest, Central Coast BLM Meadow, and Delta Department of Defense Sparse.

carbon density (Silver et al., 2010). Thus, the gSSURGO average values for these three land types were replaced with those reported in the review (across all ownerships and regions). Values for Forest, Urban Area, and Desert are comparable to other reported estimates (Forest: Birdsey and Lewis, 2002; Dore et al., 2016; Powers et al., 2013. Urban Area: Pouyat et al., 2006. Desert: Evans et al., 2014), while Coastal Marsh values are higher than reported values due to shallow measurements of soil carbon (e.g., Callaway et al., 2012). Values for Cultivated Land in the Delta region reflect average values for areas with (e.g., Hatala et al., 2012) and without peat soil types (e.g., Mitchell et al., 2015). One of the major challenges in obtaining accurate soil carbon data, beyond limited sampling of high spatial heterogeneity, is wide variation in the depth of soil measurements.

2.2. Projection Methods

CALAND projects California landscape carbon dynamics, including sequestration and emissions of CO_2, emissions of CH_4 and BC, and utilization of harvested and collected biomass carbon for wood products and bioenergy (Figures 4-5). The model is initialized in year 2010 (Section 2) and operates on an annual time step based on an input scenario and the following additional input parameters: (1) net ecosystem carbon exchange, (2) factors that adjust carbon exchange values due to management and climate, (3) mortality rates for perennial vegetation, and (4) fractions of carbon pools that are affected by land conversion, forest management, and wildfire. All of the carbon parameters except the climate scalars and mortality rates (fractions) are in the carbon input file. The climate scalars and mortality rates are in the scenario input files so that projected climate change and recent elevated rates of forest tree mortality can be emulated, respectively.

CALAND partitions the projected carbon dynamics into net ecosystem exchange of individual carbon-based GHGs (CO_2, CH_4 and BC) and their total GWP. Total GWP is calculated annually in units of CO_2-eq with a 100-yr time frame using a radiative forcing potential of 25 for CH_4 (Forster et al., 2007), and optionally a GWP of 900 for BC (Myhre et al., 2013). However, we recommended treating BC emissions as CO_2 (GWP = 1) as the current understanding is that BC does not behave like the main greenhouse gases. Ecosystem carbon accumulation is due to CO_2 uptake due to photosynthesis, whether stored in vegetation or the soil, while ecosystem carbon losses have the following emissions pathways: (1) CO_2 emissions due to decay of soil organic carbon, which can be enhanced by Forest management or land conversion; (2) CH_4 emissions from Fresh Marsh soils due to anaerobic decay processes; (3) CO_2 emissions due to decay of biomass (including roots) following land conversion, Forest management activities, and wildfire; (4) CO_2, CH_4, and BC emissions due to biomass burning from wildfire, prescribed burning, or bioenergy; and (5) CO_2 and CH_4 emissions due to decay of wood products in landfills. Wood products are counted as stored carbon, which decay incrementally after being discarded to landfills, releasing CO_2 and CH_4 to the atmosphere. Carbon emissions are split into burned and non-burned carbon pools. The burned carbon pool includes carbon emissions from wildfire, bioenergy, and controlled burns (either prescribed fire or for Forest management residue removal), which are partitioned into CO_2, CH_4, and optional BC. The partitioning fractions of total C emissions for controlled burns and wildfire are 0.9952, 0.0021, and 0.0027, respectively (Jenkins et al., 1996), while bioenergy emissions are partitioned using 0.9994, 0.0001, and 0.0005, respectively (Carreras-Sospedra et al., 2015). All carbon emissions, including decay and soil losses, are assumed to occur in the same year as the activity generating them, except for decay of biomass killed by wildfire. This has the effect of slightly front-loading some decay and soil emissions due to management and land conversion, which is relevant to annual accounting as the model does not assign all emissions to the years in which they may actually take place.

Figure 4: CALAND Land Type Carbon Dynamics

General depiction of carbon dynamics across all land types. Climate, wildfire, land cover change, and management can affect net vegetation and soil carbon fluxes and mortality rates. See Figure 5 for additional Forest management dynamics. See Table 2 for the carbon pools that exist for each land type.

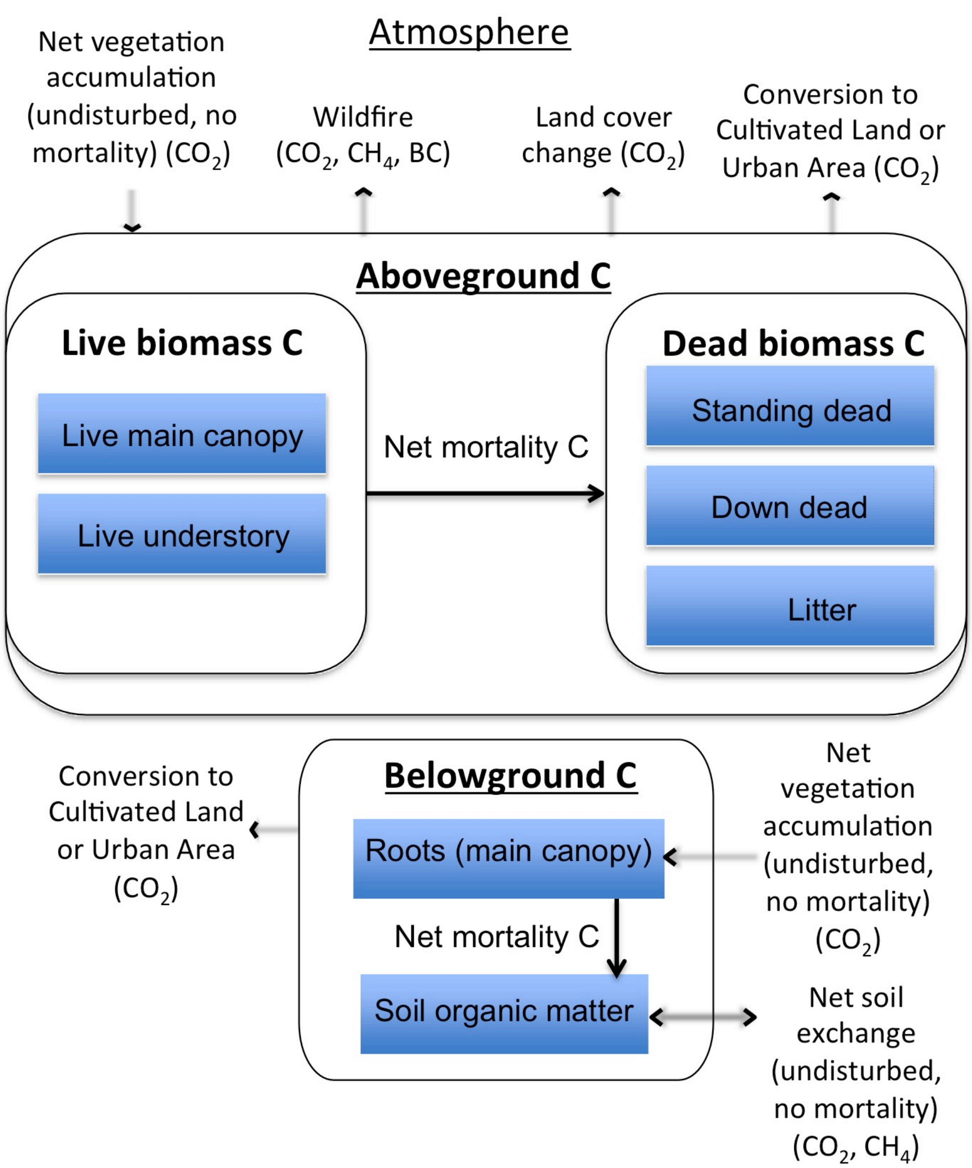
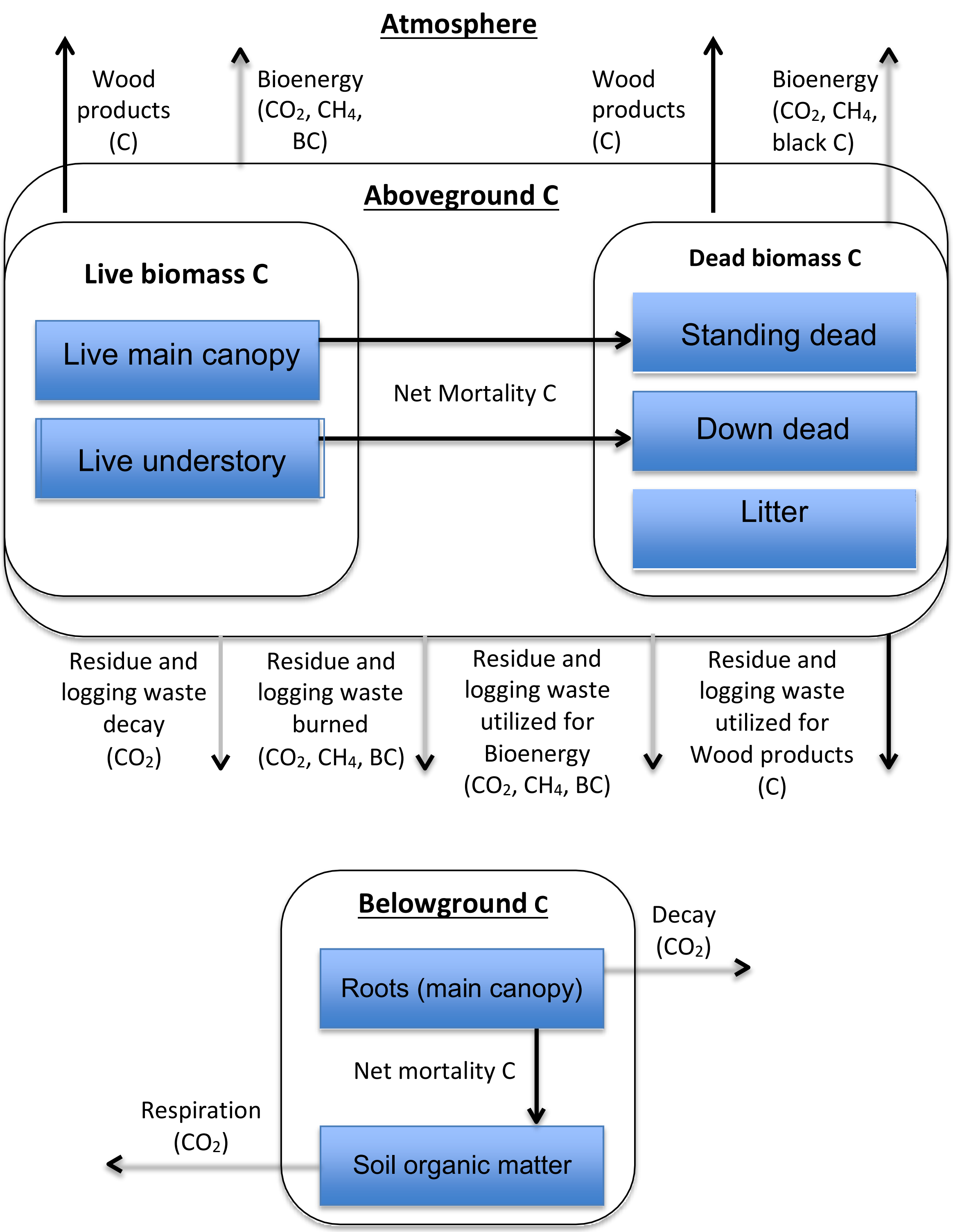


Figure 5: CALAND Forest Management Carbon Dynamics

These also apply when Forest is converted to Urban Area or Cultivated. Discarded wood products decay as CO_2 and CH_4. There are two separate pathways to wood and bioenergy: (1) the traditional harvest pathway and (2) a slash pathway from uncollected harvest residue and other debris (understory, downed, and litter).



2.2.1. Net ecosystem carbon exchange

Overview of vegetation and soil carbon exchange inputs and climate options

Net ecosystem carbon exchange is composed of vegetation and soil carbon exchange, which is simulated for each land category under one of three possible climates (historical, RCP 4.5, and RCP 8.5). Management, wildfire, and land cover change interact with these input values to effect the final changes in carbon density in vegetation and soil carbon pools in each land category (Fig. 2). The vegetation carbon exchange is the annual net vegetation carbon flux (CO_2 uptake plus respiration) of an *undisturbed patch with no mortality*, while the soil values generally represent annual net changes in soil carbon density (plant-derived carbon inputs plus soil respiration). Each land category has literature-derived mean, maximum, minimum, and standard deviation input values for historical net annual vegetation and soil carbon exchange (Mg C ha^{-1} y^{-1}) (Appendix B). These values are constant over time, representing average historical climatic conditions. The user can select the historical climate setting or choose to apply the effects of projected climate change to the historical carbon exchange values (Section 2.2.3) when creating the input files using the function contained in the write_caland.r file.[17] Under projected climate change (RCP 4.5 or RCP 8.5), the vegetation and soil carbon exchange values change over time for each land category. Certain types of land management practices also directly modify the net carbon exchange rates (Appendices D and E). Most of the management effects have been determined from measurements of carbon density changes, while some are based on net CO_2 flux measurements.

Derivation and modeling of vegetation and soil carbon exchange inputs under historic climate

A variety of sources were used to derive the historical net vegetation and soil carbon exchange values, many of which have been converted from published data to the appropriate format for CALAND. The univariate statistics (mean, minimum, maximum, standard deviation) were derived from multiple data sources where available or from reported ranges within individual studies. Similar to the uncertainty range used for initial carbon density input values (Saah et al., 2016; Battles et al., 2014), the standard deviation of carbon flux measurements serves as a measure of their uncertainty. In some cases the minimum and maximum values have simply been calculated directly from the mean and standard deviation. In some cases, due to limited availability of complete data, the vegetation carbon exchange inputs represent a measurement of carbon accumulation in a particular live biomass pool (e.g., stem only versus whole plant). For these cases, the input values are scaled up proportionally to the whole plant based on the assumption that carbon densities in all of the plant component pools will increase in proportion to biomass carbon ratios (e.g., aboveground main canopy carbon to main canopy root carbon). Final live vegetation carbon density changes are computed by subtracting mortality from each vegetation pool. Vegetation carbon exchange is either zero (static carbon density) or positive (increasing carbon density), representing net carbon uptake

[17] Previous versions did not include the option to include climate change effects.

due to vegetation growth. Net carbon uptake is modeled in Shrubland, Savanna, Woodland, most Forest land categories, and Urban Area, while other land types are assumed to either not accumulate carbon (Water, Ice, Barren, Sparse) or to accumulate carbon primarily in the soil (Desert, Grassland, Meadow, Coastal Marsh, Fresh Marsh, Cultivated Land, Seagrass).[18]

Soil carbon exchange input values can also represent different biophysical processes depending on the availability (or lack thereof) of appropriate data. The type of measurement it represents determines how that value it used to compute the final net change in soil carbon density for each year of the simulation (Appendix B). Ultimately, final net change in soil carbon density includes carbon emissions from decay of soil organic matter plus plant-derived carbon inputs (i.e., mortality from main canopy root and litter pools). While litter and most root inputs to soil carbon are implicit in all land types, root carbon inputs are explicitly transferred to soil in two cases: Savanna and Woodland. For all other cases, annual root mortality is subtracted from roots but it is not added to the soil carbon unless mortality changes from the initial 2010 input value. A zero or positive value for soil carbon exchange represents static soil carbon density or net carbon accumulation, respectively. Soil carbon exchange can also be negative, indicating a net loss of soil carbon to the atmosphere (emissions) in the form of CH_4 and/or CO_2 due to decay of soil organic carbon. For example, Grassland, Savanna, Woodland, and Delta Cultivated Land all have negative soil carbon exchange values, resulting in decreasing soil carbon density and soil carbon emissions. On the other hand, Water, Ice, Barren, and Sparse have static vegetation and soil carbon exchange, meaning they do not accumulate or lose carbon over time (Appendix B).

Description of carbon dynamics and speciation (CO_2 and CH_4) by land type

Desert, Grassland, Meadow, Coastal Marsh, Fresh Marsh, and Seagrass have straightforward soil carbon exchange based on the literature. These values effectively represent net ecosystem carbon exchange, which is ultimately reflected in annual soil carbon density changes. In these cases, vegetation carbon pools are assumed to have static carbon densities (vegetation carbon uptake is implicitly transferred to the soil). Coastal Marsh is considered to have negligible CH_4 emissions due to its salinity. Thus, its carbon exchange of 1.44 ± 1.23 Mg C ha^{-1} y^{-1} represents CO_2 exchange only (aqueous carbon loss is not accounted for). The Grassland value of -2.22 ± 1.29 Mg C ha^{-1} y^{-1} is based on field CO_2 flux measurements, and reflects one of only two net ecosystem carbon losses across all land types. The Fresh Marsh soil carbon exchange value of 3.37 ± 0.33 Mg C ha^{-1} y^{-1} also represents net ecosystem carbon exchange, but in this case it is the sum of net CO_2 exchange and CH_4 emissions (aqueous carbon loss is not accounted for). The Fresh Marsh

[18] There is interest in adding perennial crop dynamics to CALAND, which would require adding a new, perennial-crop land cover type that would presumably have net carbon uptake in vegetation.

carbon exchange is partitioned between CO_2 and CH_4 to calculate the greenhouse gas balance.[19]

Cultivated Land has soil carbon exchange, but does not currently accumulate vegetation carbon in CALAND because annual and perennial crops are not segregated in the input land cover data and the implemented management practices apply only to annual crops. Thus, there is no basis for applying vegetation carbon accumulation rates in orchards and vineyards while maintaining fidelity with the rest of the Cultivated Land. Additional research is needed to understand how orchard and vineyard carbon storage is influenced by changes in crop types, crop area, age classes, management, and rotation periods. Soil carbon exchange values are estimated for crops grown under conventional management in peat soils in the Delta region (-2.82 ± 2.51 Mg C ha^{-1} y^{-1}) and in non-peat soils (0.19 ± 0.26 Mg C ha^{-1} y^{-1}). Root dynamics are not implemented for Cultivated Land due to lack of input root carbon data. The Cultivated input soil C flux value for non-peat soils is applied to all non-Delta regions. It is is derived from field experiments in three major growing regions: (1) San Joaquin Valley (8-year tomato-cotton, and 30-year chrono-sequence of alfalfa, wheat, maize, cotton, and sugar beets) (Mitchell et al., 2015; Wu et al., 2008); (2) Sacramento Valley (four 10-year systems in irrigated wheat and fallow, rainfed wheat and fallow, wheat-tomato, and maize-tomato) (Kong et al., 2005); and (3) Imperial Valley (90-year chrono-sequence of alfalfa, wheat, corn, and sugar beets, starting as uncultivated native soil) (Wu et al., 2008). The Cultivated input soil C flux value for peat soils is applied to the Delta region. It is derived from two rice systems (1-yr and 2-yr studies) and one corn system (1-year study) in the Delta region's Twitchell Island (Hatala et al., 2012; Knox et al., 2015).

In **Shrubland**, the vegetation carbon accumulation value represents the change in aboveground main canopy carbon. Thus, this is added annually to aboveground main canopy carbon density, and the other live vegetation carbon pools (i.e. belowground main canopy and understory) increase in proportion to biomass carbon ratios. Mortality is applied to the aboveground carbon and distributed to the dead carbon pools proportionally to existing density values. It is assumed that mortality transfers are net changes. Since the Shrubland soil carbon exchange value represents the net change in soil carbon density, it implicitly includes carbon emissions from decay of soil organic carbon and contributions from root mortality and litter. Thus, root mortality is subtracted from roots but it is not added to soil carbon unless there in a change in the initial 2010 mortality input value.

In **Savanna and Woodland**, net ecosystem carbon exchange values are split into net tree carbon exchange (represented by the vegetation carbon exchange value) and net understory-soil ecosystem carbon exchange (represented by the soil carbon exchange

[19] The average CO_2 and CH_4 carbon balance from Knox et al. (2015) is a net CO_2-eq emission, although net emissions differ with wetland age. The young wetland (~3 years old) is a net CO_2-eq source, while the older wetland (~15 years old) is barely a net CO_2-eq sink. Since we do not account for aqueous carbon loss in Fresh Marsh or Coastal Marsh, their net carbon flux rates may be slightly overestimated. It is unknown how much aqueous carbon loss is stored elsewhere or eventually emitted.

value), as measured by eddy covariance sans mortality. The sum of these two values represents total net carbon exchange. The vegetation carbon exchange is split between above- and below-ground main canopy in proportion to existing carbon densities. Due to lack of available data, Savanna and Woodland are currently assumed to have a Grassland understory with static carbon density even though initial carbon density values indicate that some of these lands have a woody understory. Thus, the understory in Savanna and Woodland is assumed to have no net vegetation carbon accumulation, and the soil carbon exchange is negative, representing net CO_2 emissions from the grass-soil system. Belowground main canopy mortality is added to soil carbon and main canopy mortality is added to the three dead carbon pools in proportion to existing carbon densities, but there is no direct transfer of carbon among the dead pools or to the soil. Savanna and Woodland are notable examples of where information is lacking to completely capture the carbon dynamics, as the distribution of woody versus grass understory and the carbon dynamics of a woody understory are unknown.

The **Forest** vegetation carbon accumulation values vary according to ownership and to region, with Private lands experiencing the highest management intensity. These values represent net aboveground main canopy stem (bole) volume changes (growing stock volume) (Christensen et al., 2017). Thus, additional carbon accumulation is calculated for main canopy leaf, bark, branch, and root in proportion to estimates of the proportion of carbon in different tree components (Jenkins et al., 2003). Carbon accumulates in the understory in proportion to the ratio of understory to main canopy stem carbon density. Mortality is applied to the main canopy and understory and distributed to the three dead carbon pools proportionally to existing density values, with implicit transfer of litter carbon to the soil. The soil carbon exchange value does not vary by ownership or region and represents net soil carbon density changes, including contributions from root mortality and litter and losses from respiration. Thus, root mortality is subtracted from roots, but is not added to soil carbon unless mortality changes from initial 2010 input values.

Urban Area (Developed_all) is parameterized such that vegetation carbon accumulation represents net above- and below-ground urban forest growth, sans mortality, on the area basis of Urban Area rather than urban forest area itself. Urban forest area is prescribed as a fraction of Urban Area and can remain constant at the initial 2010 value (15%) (McPherson et al., 2017), or it can be prescribed to change over time to meet a target fraction in a certain year. The effect of changing the urban forest fraction is implemented by linearly scaling the initial vegetation carbon accumulation rate for Urban Area proportionally to the change in urban forest fraction. The vegetation carbon accumulation rates are region-specific, with 72% allocated to aboveground and 28% allocated to belowground biomass (McPherson et al., 2017). There is no soil carbon exchange for Urban Area due to lack of input data. Aboveground mortality is transferred to a Dead removal management activity in order to control the destination of the removed material. The default is for all of this material to decay as CO_2 the same year as management. Belowground mortality is not transferred to soil carbon unless mortality changes from initial 2010 input values, in which case the difference is added to the soil.

2.2.2. Mortality rates

Mortality rates represent net fractions of existing live carbon that is transferred annually to dead carbon pools (aboveground main canopy and understory to standing, down dead, and litter) or to soil carbon from root mortality. The partitioning of the mortality carbon into the respective pools is generally in proportion to the existing carbon densities. The mortality rates are net transfers of carbon, as they implicitly include respiration of live and dead carbon. No carbon is transferred between the dead pools and they have implicit carbon transfer to the soil.[20] A fraction of root mortality goes to soil carbon, either implicitly or explicitly, based on the specific measurements underlying the carbon exchange values and whether the prescribed rates are different than the initial mortality rate. The initial 2010 mortality rate is 1% for all woody land types[21] except Forest. Land types with no net aboveground carbon accumulation will not incur mortality (e.g., Desert). Forest mortality values are calculated per region and ownership based on reported values (Christensen et al., 2017). Additionally, CALAND can simulate doubled forest mortality rates from 2015 through 2024 to emulate the ongoing die-off due to insects and drought, which is the default setting when creating the input files. The annual, aboveground main canopy and root mortality rates are prescribed in the scenario input file and can be land category specific, while the understory rate (1%) is a fixed parameter within the model. Additionally, Forest management activities change the mortality rates (Section 2.2.5).

2.2.3. Climate effects

CALAND can project landscape carbon dynamics based on historical or projected climatic conditions (RCP 4.5 and RCP 8.5 are available). The carbon fluxes under historical conditions are represented by the input carbon flux data. The effects of projected climate change on carbon fluxes are implemented by applying scaling factors calculated from global climate model outputs, while the wildfire area under projected climate change is generated from a combination of statistical methods and global climate model outputs (Section 2.2.6). The climatic conditions (i.e., historical, RCP 4.5, or RCP 8.5) for carbon accumulation and wildfire are the same within each CALAND simulation.

Outputs from the integrated Earth System Model (iESM; Collins et al. 2015), which is a variant of the Community Earth System Model (CESM, v1.1), were used to calculate RCP 4.5 and RCP 8.5 projected climate scaling factors for annual soil and vegetation carbon fluxes. The general process followed the iESM method (Bond-Lamberty et al., 2014). A ratio of a future annual value to the initial 2010 annual value was calculated in

[20] The mortality rates have been calculated based on net dead carbon pool accumulation values, which include respiration.

[21] This default rate is based on the ratio of literature-based net dead carbon pool accumulation to the initial CALAND carbon density, as calculated for Shrubland, and the average of the Forest mortality rates, and then rounded and made uniform across all land types.

each one-degree grid cell and vegetation type in iESM. This ratio was disaggregated to the spatial distribution of CALAND land categories in 2010, from which area-weighted averages were calculated for each land category. Different source variables and time-averaging window sizes were used for vegetation and soil factors. Using running averages of the source data reduced inter-annual fluctuations to better capture long-term climate effects. The ratios were also filtered for outliers before disaggregation in order to reduce the influence of non-climatic factors such as land cover change. The filtering method used median absolute deviation (Davies and Gather, 1993), which is the same approach used by the iESM (Bond-Lamberty et al., 2014). The last year of CALAND climate scaling inputs is 2086 due to the period of the iESM simulations and the soil time-averaging window. The climate scalar values in 2086 are extrapolated to each subsequent year simulated in CALAND. Seagrass bed carbon accumulation is not climate-adjusted due to lack of data.

Climate scaling factors for vegetation carbon fluxes were derived from the Net Primary Productivity (NPP) output from iESM, as it is directly comparable to the net vegetation carbon accumulation values used by CALAND, which do not include mortality or disturbance effects. The annual NPP values were calculated using a 5-year running average centered on the desired year. The iESM tree types were averaged together per grid cell to get one tree type that is distributed to CALAND's land types that contain trees (Forest, Woodland, Savanna, Urban Area). The iESM shrub types were processed similarly for CALAND's Shrubland type.

Soil carbon flux scaling factors were calculated from the annual change in the soil organic carbon content output from iESM, as it is most closely related to the net soil carbon accumulation values used by CALAND. The annual changes in soil organic carbon content were calculated using a 9-year running average centered on the desired year. There is only one soil column per grid cell in iESM, so the resulting ratio is calculated for all relevant CALAND land types in a given cell in 2010 (Desert, Shrubland, Grassland, Savanna, Woodland, Forest, Meadow, Coastal Marsh, Fresh Marsh, or Cultivated).

2.2.4. Management effects

(For restoration practices, see section 2.2.7.)

CALAND contains options for prescribing various management activities to Forest, Grassland, Savanna, Woodland, Urban Area and Cultivated Land that affect corresponding vegetation and/or soil carbon exchange values and Forest mortality rates (Table 3 and Appendices D, E, and F). These options are used to model management scenarios relative to a baseline. The parameters controlling the rate adjustments for each management activity are in the carbon input file. These parameters were derived from carbon exchange rates reported under different management activities. In brief, Forest management generally increases vegetation and soil carbon accumulation and decreases mortality, but these effects are highly dependent on region and ownership; Compost Amendment in Rangeland (Grassland, Savanna, and Woodland) reduces soil carbon loss in Grassland, Savanna, and Woodland; Soil Conservation on Cultivated Land reduces soil carbon loss in the Delta and increases soil carbon accumulation in all other regions;

and expansion of forest in Urban Area increases vegetation carbon accumulation. The Forest, Grassland, Savanna, and Woodland managed area is cumulative over time due to the long-term effects of management and the assumption that each year a new area will be managed, while benefits in Cultivated Land occur only for the area prescribed in a given year.

Forest management activities are described in detail in section 2.2.5. Each Forest management practice is assumed to affect carbon exchange rates equally across practices (except for Prescribed Burn, which is applied to previously managed land, and Afforestation and Reforestation, which do not affect these rates because they are land type changes).

Rangeland (Grassland, Savanna, and Woodland) management parameters include two levels of Compost Amendment application frequency that modify soil carbon exchange rates (Medium=10 or Low=30 year repeat period). The compost is applied once at the start of the period at a rate corresponding to 14.27 Mg C ha^{-1} with a C:N ratio of 11:1, and the annual benefits are in effect for the duration of the repeat period.

Cultivated Land management has a unique structure to implementing its Soil Conservation practice compared to the other land types. The Soil Conservation parameter for Cultivated Lands is the mean soil carbon flux under Soil Conservation management with an uncertainty range (mean ± standard deviation) that serves as a proxy for all practices intended as alternatives to conventional management, excluding practices involving land cover changes. The soil carbon flux of non-Delta cultivated land under Soil Conservation (0.59 ± 0.44 Mg C ha^{-1} y^{-1}) is based on a tomato-cotton rotation with cover crop and/or reduced tillage in San Joaquin Valley (Mitchell et al., 2015), and maize-tomato with cover crop or cover crop and composted manure in Sacramento Valley (Kong et al., 2005). The uncertainty ranges are the standard deviation of the individual treatment means, and represent the uncertainty of statewide average soil carbon fluxes from alternatively managed systems. Since there are no studies of cover crop, reduced tillage, or composting in the Delta region, the benefit or difference between managed and unmanaged soil carbon flux from the non-Delta regions (0.40 ± 0.2 Mg C ha^{-1} y^{-1}) was added to the Delta soil C flux (-2.82 ± 2.51 Mg C ha^{-1} y^{-1}) to estimate the managed soil carbon flux. The Delta uncertainty range represents the propagated error of the non-Delta benefit and Delta soil C flux.

Urban forest Dead removal is applied annually to the total Urban area, and includes Forest management options for disposing of the annual mortality fraction of the above ground biomass. The default is for all of this material to decay as CO_2. Urban forest fraction is prescribed as part of scenario definition, usually with a constant fraction for the baseline and an increasing fraction for alternative managment (See section 2.2.1).

Table 3. Management Practices Currently Implemented in CALAND version 3 and relationships to the Natural and Working Lands (NWL) Scenarios developed for the Draft California 2030 NWL Climate Change Implementation Plan (CA, 2019).
(See Section 4 for scenario descriptions and Appendices for detailed parameter values.)

Management Practice	Description/ Parameters
Practices that change ecosystem carbon exchange rate	
Cultivated land soil conservation	This is a proxy defined by a range of associated carbon fluxes that encompasses a wide variety of potential practices. This range is based on studies of cover crops and conservation tillage, and compared with biogeochemical modeling of other relevant practices. The desired extent of NWL implementation for these practices is not included in CALAND because it is modeled separately.
Rangeland compost amendment	10-year or 30-year repeat compost amendment for Grassland, Savanna, or Woodland The 30-year repeat treatment on Grassland is used for the two NWL alternative scenarios, but the desired extent of NWL implementation for these practices is not included in CALAND because it is modeled separately.
Urban forest expansion	Increase forest fraction of Developed area
Practices that change ecosystem carbon exchange rate and also explicitly transfer carbon among pools and can contribute to emissions	
Forest clearcut	Harvest of 66% of live and dead standing trees for wood products and bioenergy. 25% of slash is burned and 75% decays rapidly. Baseline: 36,884 acres per year.
Forest partial cut	Thinning of 20% of live and dead standing trees for wood products and bioenergy. 25% of slash is burned and 75% decays rapidly. Baseline: 114,833 acres per year.
Forest thinning	Clearing of ladder fuels and debris through thinning – includes removal of 20% of live and dead standing trees for wood products and bioenergy. 25% of slash is burned and 75% decays rapidly. Baseline: 164,884 acres per year.
Forest understory treatment	Understory clearing with 50% going to slash and 50% to downed dead material. 25% of slash is burned and 75% decays rapidly. Baseline: 6,664 acres per year.
Forest prescribed burn	Collecting and burning of understory and debris. About 50% of this goes to slash and the rest of the understory goes to downed dead. 100% of slash is burned. Baseline: 33,173 acres per year.
Extra Forest biomass utilization	Two levels of diversion of burned and decayed slash to energy and wood products. The high level (50% diverted, 50% decays) is used for state-funded thinning and understory treatment in the two NWL alternative scenarios.

Less Intensive forest management	Three options: 1) convert clearcut area to partial cut area, 2) convert clearcut area to reserve (no cut), 3) convert partial cut are to reserve
Removal of urban forest mortality	Offers flexibility in management and emissions of dead material in the urban forest. Currently parameterized to remove urban forest mortality and decay it rapidly.
Practices that involve land cover change and Seagrass	
Afforestation	Convert Grassland and Shrubland to Forest based on availability of these source land types. This cannot be prescribed at the same time as reforestation. This is not used in the two NWL alternative scenarios.
Reforestation	Convert Shrubland to Forest, often prescribed to match some portion of non-regenerated forest wildfire area. This cannot be prescribed at the same time as afforestation. The two NWL alternative scenarios include reforestation of all non-regenerated forest.
Meadow restoration	Convert Shrubland, Grassland, Savanna, and Woodland to Meadow, based on availability of these source land types.
Delta fresh wetlands restoration	Creation of managed fresh wetlands in Sacramento- San Joaquin Delta (from Cultivated land)
Coastal marsh restoration	Creation of saline tidal wetlands (from Cultivated land)
Land Protection	Reduction of baseline urban area growth rate
Seagrass restoration	Creation of offshore seagrass beds
Oak woodland restoration	Convert Cultivated and Grassland to Woodland, based on availability of these source types. This is also used a proxy for riparian restoration in the two NWL alternative scenarios.

2.2.5. Forest management

Forest management is defined here as activities with the primary goal of manipulating forest biomass without changing the long-term land type (regeneration is assumed[22]). Forest management activities modeled in CALAND include a set of treatments applied to Forest (Clearcut, Partial Cut, Thinning, Understory Treatment, Prescribed Burn) and a corresponding set with two available levels of additional slash (uncollected harvest residue) utilization (i.e., Clearcut Slash Utilization, Partial Cut Slash Utilization, Thinning Slash Utilization, Understory Treatment Slash Utilization, and Prescribed Burn Slash Utilization). Harvest and fuel reduction practices result in varying amounts of carbon lost from the main canopy, understory, standing dead, downed dead, and litter. Carbon losses that are not explicitly accounted for through removal for further processing (to wood products, bioenergy, and waste) are collected into a temporary slash pool that is cleared each year via storage in wood products or losses to the atmosphere from bioenergy, decay, or controlled burning. Detailed descriptions of parameters are in Appendices E, F1, and F2.

Reforestation (from Shrubland) and Afforestation (from Shrubland and Grassland) are implemented as a land type conversion, and only one or the other can be prescribed in the same simulation. Reforestation complements the optional non-regeneration of forest due to wildfire[23] (section 2.2.6)

---

[22] As detailed in the following footnote, regeneration is prevalent for these activities, and in the case of commercial harvest reforestation is mandated. Thus it is reasonable to assume that these activities do not change the land type.

[23] There are limited data available to specifically implement reforestation and non-regeneration in a landscape carbon model, and it is unclear whether reforestation practices significantly affect medium- to long-term landscape level carbon exchange in comparison with natural regeneration. Implicit forest regeneration is a reasonable assumption for forest management practices, as there are mandates and incentives to ensure such regeneration. Additionally, evidence suggests that natural regeneration is usually sufficient for stand replacing wildfire, with reforestation practices primarily determining species composition. However, severe fire and subsequent environmental conditions can affect regeneration rates of particular stands. The unknowns include whether and how much forest area will fail to regenerate to previous levels; how variability in regeneration success affects the long-term rate of stand or landscape carbon accumulation; the effects of reforestation practices on the long-term rate of stand and landscape carbon accumulation; and whether reforestation or environmental conditions ultimately drive regeneration. Furthermore, it is unclear whether reported data lump understory management into reforestation practices. Understory management has been shown to increase tree carbon accumulation, but it is often applied as a post-regeneration practice. In general, more detailed analyses of wildfire and forest regeneration data are needed to adequately parameterize the conditions for reforestation and non-regeneration in CALAND. The updated fire module does include optional non-regeneration with a model input argument that determines the extent of non-regeneration within high severity burn area. Changing this input argument allows the user to explore the uncertainty range of non-regenerated forest due to wildfire.

The ten Forest management activities are parameterized based on the literature except for the slash utilization pathways, which are aspirational targets that the CALAND user can adjust in the carbon input file (Appendix E). Each practice generates slash carbon, which is either lost to the atmosphere via decay and controlled burning in the five traditional treatments, or it can be collected and utilized in wood products or bioenergy in the five corresponding slash utilization activities. Changes to the slash parameters can be made in the carbon input file, but the sum of all slash fractions (Slash2Energy, Slash2Wood, Slash2Burn, Slash2Decay in Appendices F1 and F2) must add up to equal 1.

The carbon transfer parameters for each practice are the same across regions and ownerships. Clearcut and Partial Cut capture the average characteristics of commercial timber harvest practices in California. Clearcut represents practices such as clearcutting and leaving seed trees, while Partial Cut includes less intensive practices, such as selective tree harvest and commercial thinning (Stewart and Nakamura, 2012). The most common practice for fuel reduction is Thinning, so currently Thinning is parameterized identically to Partial Cut. Prescribed Burn and Understory Treatment are also fuel reduction activities with unique parameterizations due to unique sources and sinks for biomass carbon.

The wood products carbon pool is tracked using the IPCC Tier 2 guidelines (equation 12.1 in IPCC, 2006a) for estimating the next year's wood carbon stock from the current year's stock, the current year's addition, and the half-life of the wood products (52 years) (Stewart and Nakamura, 2012). Wood product carbon emissions are assumed to occur in landfills, and are split between CO_2 and CH_4 following IPCC Tier 2 methods (section 3.1 in IPCC, 2006b) and using CARB default values (Section IV, equation 89, in ARB, 2016).

The values for the amount of harvested and slash-utilized carbon going to bioenergy are aspirational both in terms of the amount of traditional slash (branches, tree-tops, bark) removed from the forest (only 4% of total harvested material is left in the forest) and the disposition of sawmill waste. Stewart and Nakamura (2012) report potential bioenergy feedstocks of 32% of Clearcut harvested biomass and 75% of Partial Cut harvested biomass, while an average USFS estimate is 53% (McIver et al., 2015). The proportions of slash utilization going to different end uses, and the emissions profiles of those end uses (e.g., energy production and emission control technologies used at bioenergy facilities) are expected to be critical to the net carbon emissions of Forest management and will continue to be investigated.

Forest management practices affect vegetation carbon accumulation, mortality rates, and fire severity (Appendix E) for a 20-year post-management period, except for Prescribed Burn, which affects only fire severity. Vegetation carbon accumulation and mortality rates can increase or decrease on managed land in relation to unmanaged land. These effects vary by region and ownership and were derived from USFS FIA data (Christensen et al., 2017). Forest management reduces the fraction of high severity fire on managed land (section 2.2.6, Table 4) (Lyderson et al., 2013). Cumulative managed area is tracked in order to implement these long-term effects, with the assumption that new area is treated each year within a 20-year window. Thus, to effectively emulate repeat treatments on the same land, repeat prescriptions must occur at least 20 years apart, otherwise they will affect carbon and mortality as if additional area has been treated. The cumulative managed area affected with respect to carbon accumulation and mortality during the 20-year benefit period does not necessarily equal the total cumulative managed area because Prescribed Burn is assumed to occur on land that has undergone Thinning or Understory Treatment within the previous 20 years. In other words, Prescribed Burn area does not contribute to the cumulative managed area that experiences carbon and mortality adjustments because the Prescribed Burn area has already been included due to previous management. This allows Prescribed Burn to be repeated at any interval without artificially inflating the effects of management on carbon and mortality. Conversely, cumulative Prescribed Burn area replaces cumulative Thinning and Understory Treatment area when adjusting fire severity because Prescribed Burn is assumed to have taken place more recently on that particular land (Section 2.2.6.).

The carbon emissions species (CO_2, CH_4, and BC) directly associated with each Forest management activity are specific to the three potential pathways of carbon transfer from land to atmosphere (controlled burn, bioenergy, and decay). All of these emissions occur within the model year and it is assumed that all carbon going to bioenergy is burned for electricity. The non-energy burned carbon emissions (i.e., prescribed burns and slash burning) are partitioned into CO_2, CH_4, and BC (i.e., 0.9952, 0.0021, and 0.0027, respectively) based on reported emissions fractions from burned biomass and the BC fraction of emission species (Jenkins et al., 1996), which are fixed parameters within the model. The burned carbon emissions from energy are currently partitioned into CO_2, CH_4, and BC (i.e., 0.9994, 0.0001, and 0.0005, respectively) based on average emissions fractions for California boiler plants (Carreras-Sospedra et al., 2015) and the same BC fractions of species for non-energy (which gives different BC emissions from energy because the species profile is different from non-energy). Other efforts are underway to examine potential emissions data from nascent bioenergy technologies, including those funded through the California Energy Commission's Electric Program Investment Charge (EPIC) Program, based on CALAND feedstock production estimates. Total annual non-burned carbon emissions are released within the model year as a result of decay of removed biomass (CO_2) and discarded wood products (CO2 and CH_4).

2.2.6. Wildfire

Spatially explicit wildfire area

Annual wildfire area is simulated in each Forest, Woodland, Savanna, Shrubland, and Grassland land category under one of three possible climates (historical, RCP 4.5, and RCP 8.5). The user chooses the wildfire option when creating the scenario input file with write_caland_inputs.r. The historical option is a constant, historical annual burn area, while the climate change options (RCP 4.5 and RCP 8.5) are projected-climate annual burn areas. The climate change data were derived from 1/16-degree gridded burn area estimates generated for the California Fourth Climate Change Assessment[24] (Westerling, 2018). Specifically, we used the burn area data for the "average" climate model (CanESM2) and central population scenario, and the annual, gridded burn area values were distributed to CALAND region-ownerships (the boundaries of which do not change over time). During simulation, each year the burn area is distributed proportionally to Forest, Woodland, Savanna, Shrubland, and Grassland land types (the areas of which do change over time) within each region-ownership. These land types were selected through visual overlay of the CAL FIRE fire perimeters data[25] with the land cover type data. The initial 2010 wildfire area for the climate change options is calculated as the 2001-2015 modeled average of the respective climate scenario when creating input files with write_caland_inputs.r. However, under a historical climate a constant annual burn value is used, which is the 2001-2015 modeled average for RCP 8.5 (185,237 ha statewide). Note that the RCP 4.5 initial area is similar (195,095 ha statewide), but both of these are lower than the non-spatial statewide area used in CALAND version 2 (243,931 ha statewide, 2001-2015 average). There is sufficient flexibility in the current scenario input file to prescribe a variety of fire cases, given the appropriate data.

Wildfire severity and non-regeneration

Wildfire severity is defined as the fraction of total burn area assigned to high, medium, and low severity burns, with corresponding amounts of carbon burned or transferred to dead biomass pools. The initial values and annual increase of high severity fraction are based on samples of California fires from 1984 to 2006 (Miller et al., 2009; Miller and Safford, 2012) (Table 4). The user can specify full regeneration or a threshold distance from burn edge beyond which a high severity patch will not regenerate (Collins et al., 2017) and will be converted to Shrubland. Non-regeneration is the default, with a minimum threshold of 120 m, which has been used to study California wildfire because it is the likely limit of California conifer seed dispersal (Collins et al., 2017; Stevens et al., 2017). A shorter distance increases non-regenerated area, and a longer distance decreases non-regenerated area.

Forest management for reduction of high severity wildfire

Forest management reduces the high severity fraction on managed land for a period of 20 years (equal to the carbon accumulation benefit period for forest management). These reductions are specified for three categories of fuel reduction treatments (Lyderson et al., 2013) (Table 4). As prescribed burn is assumed to occur on land that has been managed within the previous benefit period (20 years), it replaces the severity benefits of thinning and understory treatment. In other words, the cumulative prescribed burn area replaces the same area of thinning and understory treatment when calculating burn severity reduction. The area to which these adjustments are applied is calculated using the

---

[24] These data are available at: http://cal-adapt.org/data/wildfire/; a corresponding viewer is available at: http://cal-adapt.org/tools/wildfire/.

[25] CAL FIRE FRAP Date, Fire Perimeters, available online http://frap.fire.ca.gov/data/statewide/FGDC_metadata/fire15_1_metadata.xml

fraction of forest area burned multiplied by the fraction of forest area managed in order to maintain random spatial distributions of both processes within a land category.

Wildfire carbon dynamics

Wildfire carbon emissions are separated into an immediately burned pathway and a delayed, rapid decay pathway for wildfire-killed, non-burned biomass (Pearson et al., 2009). All burned wildfire carbon emissions are partitioned into CO_2, CH_4, and BC (i.e., 0.9952, 0.0021, and 0.0027, respectively) based on the same reported non-energy burned carbon emissions fractions (Jenkins et al., 1996) used for Forest management. The rapid decay pathway for wildfire-killed biomass assumes a fractional 0.09 per year decomposition rate based on recommended decay rates for non-solid-log material (Harmon et al., 1987). The corresponding CO_2 emissions result in 59% of wildfire-killed biomass decaying within 10 years of the fire, and 90% of fire-killed biomass decaying within 25 years.

Table 4. Management Effects on Wildfire Severity
Wildfire severity percent of total burn area and percent decreases/increases (negative/positive) in severity percent due to fuel reduction management. The initial 2010 high severity percent increases annually at a historic rate of 0.27%, with proportional decreases in medium and low severity fractions. The management adjustments are the percent change in the annual value of the respective severity class.

Wildfire Severity	Initial 2010 values without management	Management Effects on Wildfire Severity		
		Prescribed burn	Thinning, Partial cut, and Clearcut	Understory treatment
High	26%	-68%	-26%	-24%
Medium	29%	-13%	+10%	+30%
Low	45%	+94%	+19%	-6%

2.2.7. Land type conversion

Land type conversion is driven by three main levers in CALAND. First, there are baseline annual area changes that are applied to all land categories except for Water and Ice, which are assumed to remain constant. Second, several management practices effect land type conversion, including avoided conversion (Growth reduction), all the restoration practices, Afforestion (from Grassland and Shrubland), and Reforestation (from Shrubland; complementary to wildfire non-regeneration). Third, wildfire constrains land type conversion through optional non-regeneration (conversion to Shrubland) of some Forest area burned by high severity wildfire (Section 2.2.6).

Baseline annual area change inputs: options and methods of derivation

There are two options for baseline annual area change inputs: 1) remote sensing-based extrapolation, representing historical trends, and 2) model-based extrapolation, representing historical land-use driven trends of urban expansion and expansion/contraction of cultivated lands. One of these options is designated when creating the input files using write_caland_inputs.r.

The remote sensing-based option uses annual area change input data for each land category that were derived from changes in LANDFIRE remotely sensed land cover from 2001 to 2010. The calculation of these area changes include adjustments for slight differences in total area between years.[26] To calculate changes in area for each land category, the LANDFIRE raster datasets for 2001 and 2010 had to be spatially aligned with CALAND's geographic projection system and resolution of 30 m^2. Then the two LANDFIRE land type maps consisting of 158 and 204 land types in 2001 and 2010, respectively, were aggregated into CALAND's 15 land types (Section 2.1.1). The 15 land types were then intersected with CALAND's 9 ownership classes and 9 regional boundaries to define the spatial boundaries and areas of CALAND's 940 land categories. Lastly, the differences in total area for each land category were calculated.

The land-use driven modeling option uses annual area change input data for each land category that were derived from the business-as-usual projections of annual land cover changes in urban and cultivated lands from the Land Use and Carbon Scenario Simulator (LUCAS) of Sleeter et al. (2017). The LUCAS model simulated annual area changes of 11 discrete land cover categories, however only changes in Urban Area and Cultivated Land[27] areas were used. The reason for this is two-fold; first, the main drivers of land cover change in LUCAS were urban expansion and expansion/contraction of cultivated lands. Second, there are several land types in CALAND that are not represented in LUCAS. Thus, all other land type areas in each corresponding region-ownership combination, excluding water and ice, increase or decrease in proportion to their relative areas to offset the net change in urban and cultivated area, ensuring that area is conserved. A total of 92 years (2010-2101) of annual area changes were calculated at the 30 m^2 resolution using the LUCAS outputs. Using these data, a single average annual area change is calculated for each CALAND land category when generating input files with write_caland_inputs.r (the user can select 2010-2051 or 2010-2101 as the averaging period).

Implementation of baseline area changes

At the end of each simulation year the selected annual area changes are applied to the current land cover (Sections 2 and 2.1.1). The conversion areas are calculated independently for each ownership class within each region. The annual changes are first adjusted to account for land availability and to ensure that restored land type area

[26] For example, USFS Coastal Marsh is zero in 2010, but also shows a loss because it is 0.09 ha in 2001. Such losses are set to zero and redistributed among the other land types to ensure a net total area change of zero.

[27] Annual and perennial agriculture areas from LUCAS outputs were combined into a single cultivated land type to calculate annual area changes to correspond to the single cultivated land type in CALAND

persists. Conversion matrices are then calculated for each region-ownership combination to determine the areas of each land type being converted to (and from) another land type. These transition values are calculated by splitting individual land type gains proportionally across all available land type losses.

Permanence and uncertainty of baseline annual area change options

In contrast to the model-derived, land-use driven option, which only captures land type conversions caused by urban expansion and cultivated expansion/contraction, the remote sensing option captures all land type conversions (including those not driven by human activity). The land-use driven option may better capture Urban and Cultivated land cover change dynamics, but it does not capture potential land cover change due to non-anthropogenic disturbances, including permanent change due to severe disturbances, such as fire. On the other hand, the remote sensing option lacks information about the permanence of all land type changes due to having only two years to compare. For example, a forest fire or clearcut harvest may show up in the remote sensing data as Forest in one year and Grassland in another, but we do not know the cause of this change or if the land cover change is permanent. Forest regeneration periods can be longer than the 10 year-difference between remote sensing images, and there is evidence that some severely burned areas do not regenerate. Thus, CALAND's default assumptions include regeneration after Forest management and permanent land type conversion due to baseline trends, with optional non-regeneration of specified portions of high-severity wildfire patches (Section 2.2.6).

The large differences between the land cover change options indicate land cover change is a large source of uncertainty in CALAND. One approach to quantifying this uncertainty is to simulate all scenarios twice, once for each method, and to compare the range in outputs. Factors contributing to this uncertainty include non-permanence, misclassification, and crosswalk uncertainty (due to the combination of two different classification schemes). For example, in the remote-sensing based area changes, annual Grassland expansion and Shrubland contraction are an order of magnitude larger than the other land type changes. In this case the loss of Shrubland biomass contributes significantly to the California landscape being a net carbon source (i.e, loss) in the baseline projections. This is likely a trend in the ARB Inventory estimate as well. It is possible that the apparent Shrubland to Grassland conversion may actually represent large area shrub fires that occurred within a few years prior to 2010 and had not yet regenerated, giving the false impression that huge amounts of Shrubland were permanently converted to Grassland as part of a decadal trend. Furthermore, Water and Ice expansion in the remote sensing data could be due to unique weather patterns in 2001 and 2010 and/or different dates of the imagery used for each year. Misclassification error is inherent in remote sensing products. Particular misclassification errors have been identified in these data with respect to distinguishing orchards/vineyards (Cultivated Land) and vegetation in developed areas (Urban Area), such as parks, yards, and street trees. Combining this misclassification with uncertainty introduced by combining two different classification schemes into one (crosswalk uncertainty) provides some explanation why the remote-sensing option shows expansion of Cultivated Land in contrast to other analyses showing similar amounts of Cultivated Land contraction.

Additionally, the remote-sensing option may be capturing some land clearing and cultivation occurring outside the scope of the other analyses.

Due to these issues, the model-derived, land-use based data are the default land cover change inputs, which were used in the scenario simulations for the Draft California 2030 Lands Climate Change Implementation Plan (CA, 2019). This approach may better capture Urban Area and Cultivated Land cover change dynamics, but may miss potential land cover change due to non-anthropogenic sources, including permanent change due to severe disturbances, such as wildfire. A more complete approach would include a time-series remote sensing analysis of all land cover types and additional disturbance information. Nonetheless, uncertainty in absolute carbon projection of the mean carbon state in CALAND (i.e., for a single scenario) is significantly affected by uncertainty in land cover change, which is one reason why CALAND should be used to examine *differences* between alternative scenarios and a baseline scenario**.**

Management practice effects on land type conversion

The management practices that modify land type conversion in CALAND include Restoration (Woodland, Meadow, Coastal Marsh, Fresh Marsh, Seagrass), avoided conversion (labeled as Growth), Afforestation, and Reforestation. All restored areas persist throughout the simulation period. Avoided conversion reduces the growth rate of Urban Area. It is prescribed as an annually decreasing Urban growth rate, and simulated accordingly. The reduction in urbanization is applied to the baseline annual area growth rates for Urban Areas, which consequently reduces the loss of other land types. Thus, this option emulates conservation of natural and working lands. When using the remote sensing option for baseline annual area change, the Urban Area growth reduction will also increase the expansion of other expanding land type areas. Each simulation year, avoided conversion is applied first, followed by prescribed annual Restoration targets. The restoration targets are fulfilled to the extent that the land type areas from which restoration is programmed to occur on are available. Coastal Marsh and Fresh Marsh are restored from only Cultivated Land in CALAND, which aligns with current practices (Steve Deverel, personal communication). Restoration of seasonal wetlands and open water to Coastal Marsh also occurs in practice, but is not modeled by CALAND. Meadow is restored proportionally from existing Shrubland, Grassland, Savanna, and Woodland. Seagrass is restored from anything else in the ocean (i.e., non-Seagrass is not tracked). Afforestation proportionally converts Shrubland and Grassland to Forest and Reforestation converts Shrubland to Forest.

Land conversion effects on ecosystem carbon dynamics

There are two main ways that land type conversion affects carbon dynamics in CALAND. First, changes in the area trajectory of each land category relative to the baseline scenario will result in compounding carbon impacts (cost or benefit) based on the net difference in ecosystem carbon dynamics of the new area distribution of land categories. Not only can annual carbon exchange rates differ across the landscape with a new distribution of land category areas, but there can be new interactions with climate, wildfire, (non-)regeneration, and subsequent management. The second and most immediate impact of land conversion on carbon dynamics is the change in existing carbon stocks that occurs the same year as the converting land types.

The immediate changes in existing carbon stocks due to conversion between land types depend on the difference in carbon density between the exchanging land types, with the exception of land conversion to Urban Area or Cultivated Land. For these exceptions, all biomass carbon (above, dead, and roots) and a fraction of the soil carbon from the converting land type are removed and decay to the atmosphere within one year as CO_2 unless Forest is the land type converting to Urban Area or Cultivated Land, in which case some Forest management is applied to 100% biomass removal (see below). Input carbon transfer parameters for conversion to Urban Area or Cultivated land were derived from the academic literature (Appendix F3). In all other land type conversions, if aboveground carbon in the new land type is greater than in the original land type, all the carbon from the original land type is transferred to the new land type based on the assumption that it takes time for the converted land to gain enough carbon to match the average carbon density of the new land type. Conversely, if the new land type has less aboveground carbon than the original land type, the difference is emitted to the atmosphere the same year as conversion, and only the remaining portion is acquired by the new land type. This assumes that carbon loss is immediate upon conversion, which is often the case for this type of transition but can depend on how the conversion occurred. For belowground carbon (roots and soil), it is assumed that soil and root carbon losses are dictated by belowground carbon dynamics rather than the conversion. Thus, all belowground carbon is transferred from the old land type to the new land type (i.e., no carbon loss). Seagrass expansion initially dilutes carbon density because there is no initial gain in carbon due to unknown conditions of the new area. Seagrass contraction does not lose carbon to the atmosphere because it is assumed that the carbon is trapped in the ocean floor (carbon density does not change). All immediate carbon losses corresponding with land type conversions other than Forest to Urban Area or Cultivated Land occur as CO_2 emissions to the atmosphere.

Conversion to Urban Area or Cultivated Land is a special case because substantial alteration of the landscape is required. The carbon transfer parameter values are the same for conversion to Urban Area or to Cultivated Land. If the converting land type is Forest, a timber harvest is implemented that is parameterized similar to Clearcut with 100% of the biomass removed (Appendix F3). Only live main canopy and standing dead are available for wood products and bioenergy. All uncollected harvest residue and other vegetation carbon (understory, down dead, and litter) is assumed to decay to the atmosphere as CO_2. However, the new slash biomass utilization pathways are also available for this type of land conversion. Partitioning of the carbon emissions into CO_2, CH_4, and BC follows the same methods as described for Forest management (Section 2.2.5). Otherwise, all biomass carbon (above, dead, and roots) and a fraction of the soil carbon are removed and decay to the atmosphere as CO_2 the same year of conversion. The fraction of soil carbon lost to the atmosphere is based on a comprehensive review of adjacent-plot studies for agriculture, which shows that most of the soil carbon loss occurs within the first three years of conversion (Davidson and Ackerman, 1993).

3. Model outputs and diagnostics

The CALAND() function (defined in the CALAND.r file) is the carbon and greenhouse gas accounting model. A single scenario file is simulated each time CALAND() is run, producing a single main output .xls file that summarizes outputs for 214 variables including annual and cumulative metrics, each in an individual worksheet (Appendix G). Each worksheet is a table of annual values, as well as total change values, for a single variable (Appendix G). The change values are the differences between the final and initial year values. Each record (row) is for a specific land category (i.e., landtype-region-ownership combination), or for varying levels of aggregation of regions (All_region), land types (All_land), and ownerships (All_own). There are seven main categories of output table, including area, carbon stock, carbon density, land-atmosphere carbon exchange, wood products, GHG species partitioning, and CO_2-equivalent GHG emissions. Land category area, carbon stock, carbon density, and cumulative gain/loss variables represent absolute values at, or net changes from the initial year simulated (i.e., 2010) up to, the beginning of the labeled year, while managed and burned areas and annual gain/loss variables represent activities or fluxes during the labeled year. The output records are labeled with the identification number corresponding to the land category raster map for the initial 2010 land cover state. These values can be displayed by land category or by related spatial aggregation (e.g., region-ownership) using a Geographic Information System.

The plot_caland() function (defined in plot_caland.r file), compares outputs from the CALAND() model. It is designed to compare the CALAND() output .xls file for a baseline scenario to any number of alternative scenarios (a total of at least two scenarios required), and will output a suite of individual data tables (.csv files) and corresponding graphics (.pdf files) that summarize various variables at the user's desired level of spatial aggregation of region, land type, and ownership combination(s). The plot_caland() function has many options for summarizing the data. Here are a few examples: (1) the aggregation level can be zoomed out to the entire State of California (summing across all regions, land types, and ownerships) or as granular as a specific region, land type, and ownership combination (i.e., land category), such as North Coast, Forest on Private lands; (2) a cutoff year can be selected to zoom in on a desired time period; and (3) the area units can be acres or hectares.

The plot_caland() function has two modes: (1) general diagnostics as described above and (2) individual practice evaluation. The general diagnostics mode produces a variety of time series and snapshot plots for regular scenario simulations, while the individual practice mode is designed to calculate per-area statistics for a single practice from a pair of simulations carefully constructed to isolate the desired practice.

There are two additional diagnostic functions, plot_scen_types() and plot_uncertainty() (defined in plot_scen_types.r and plot_uncertainty.r), that use the .csv output files from plot_caland(). These secondary diagnostic functions allow the user to generate tailored figures for specified variables, scenarios, and land categories (with optional aggregation of all regions, ownerships, and land types). The plot_scen_types() function plots multiple land types within a single scenario on a single plot, while the plot_uncertainty() function generates shaded uncertainty plots from a set of three appropriate simulations (e.g., mean, maximum, and minimum emission configurations).

4. Baseline and alternative land use and management scenarios for the Draft California 2030 Natural and Working Lands Climate Change Implementation Plan

The Draft California 2030 Natural and Working Lands Climate Change Implementation Plan (CA, 2019) focuses on the carbon and GHG consequences of two portfolios of State-supported land-use and land management goals with varying levels of intensity (moderate and high intensity). We used the CALAND model to simulate three scenarios (a baseline and the two alternatives) under RCP 8.5 projected climate change. However, the scenarios can also be simulated under historical climate (no climate change) or RCP4.5.

The baseline scenario included ecosystem carbon fluxes with RCP8.5 climate effects (Section 2.2.3), wildfire area under RCP 8.5 (Section 2.2.6), constant urban forest fraction of 15% (McPherson et al., 2017), and land-use driven land cover change (Sleeter et al., 2017) (Section 2.2.7), but excluded all state-funded management practices. Some non-state-funded practices were included in the baseline, which included the following: historical forest harvest areas for even-age and uneven-age management on private land (Robards and Nickerson, 2013); historical (2004-2015) USFS-funded fuel reduction areas on USFS and private land (CAL FIRE, 2016; J. Ko, USFS, personal communication) (Table 3); and removal of mortality from urban forest as immediate CO_2 emissions to the atmosphere. The USFS-funded fuel reduction areas were the same for the baseline and alternative scenarios because they are outside the scope of state-funded intervention. A doubling of forest tree mortality was also prescribed for the baseline and alternative scenarios from 2015 to 2025[28] to emulate observed impacts of insects and drought, which are not captured by the mortality data from Christensen et al. (2017).[29]
The two alternative scenarios included additional suites of land use changes (e.g., avoided conversion of natural and working lands to Urban Areas), management practices (e.g., forest fuel reduction), and restoration activities (e.g., fresh marsh) (Table 3). Each activity was applied annually to the appropriate land type(s) and specified areas from 2019 to 2030, or longer for repeat fuel reduction treatments, avoided conversion, and

[28] On a biomass carbon basis. Recently published tree mortality numbers indicate that the annual average number of trees that died in 2015-2016 is about 20 times the 2010-2014 annual average. Tree Mortality Task Force, Tree Mortality Facts and Figures (April 2017) Available online: http://www.fire.ca.gov/treetaskforce/downloads/TMTFMaterials/Facts_and_Figures_April_201 7.pdf. Accessed Aug. 15, 2017.

[29] The primary effect of increasing mortality in CALAND is carbon transfer from the live to dead pool.

urban forest expansion. After 2030 the management practices return to baseline with three exceptions: 1) state-funded forest fuel reduction practices repeat every 20 years for maintenance (i.e., the 12-year block starts again in 2039); 2) the resulting growth rate for 2030 is held constant, 3) urban forest fraction continues to expand at the same rate as in previous years.

The alternative scenarios were developed cooperatively by many state agencies and represent goals for California land management, excluding expectations for the Healthy Soils program, which were simulated separately by another model. The primary difference between the two alternative scenarios was the magnitude of the implementation of the various practices. For example, Alternative A had a 50% reduction in urban growth rate by 2030, while Alternative B had a 75% reduction by 2030. Full details of the alternative scenarios are reported in the Natural and Working Lands Implementation Plan (CA, 2019).

The two alternative scenarios were compared to the baseline to estimate the effects of different land management suites on California's landscape carbon budget (Figure 6). Uncertainty of these estimates is based only on uncertainties in land carbon flux values and initial carbon densities. The uncertainty envelope is defined by a low emission configuration (high land carbon uptake rates and low initial carbon densities) and a high emission configuration (low land carbon uptake rates and high initial carbon densities). While less intensive forest management reduced carbon emissions, increased forest fuel reduction dramatically increased carbon emissions. Longer-term benefits of forest and restoration practices, combined with temporal gaps in forest fuel reduction implementation, eventually compensate for early fuel reduction emissions to provide cumulative reductions in landscape greenhouse gas emissions. The recovery periods vary by scenario, with the less intensive scenario (Scenario A) recovering sooner than the more intensive scenario (Scenario B).

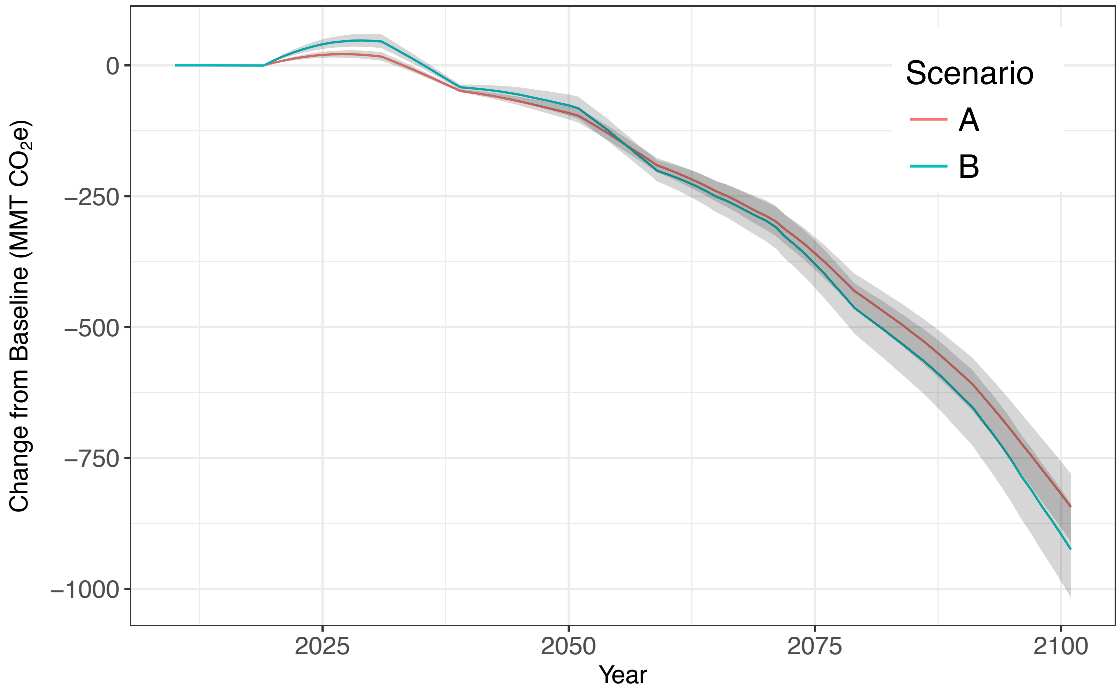


Figure 6. Total cumulative greenhouse gas emission impacts of two portfolios of land use and land management goals with moderate and high intensity (Scenarios A and B, respectively), developed for the Draft California 2030 Natural and Working Lands Climate Change Implementation Plan (CA, 2019) under RCP 8.5. Positive values represent an increase in emissions relative to the baseline, while negative values represent a decrease in emissions.

5. Looking Ahead

CALAND continues to evolve to better serve the needs of the State and other stakeholders. In addition to minor upgrades there are four main avenues for further development: 1) Improve land use and land cover change to provide better absolute carbon budget estimates; 2) Develop additional land/vegetation management practices for Cultivated Land, Woodland, Savanna, Shrubland, and Grassland; 3) Integration with bioenergy pathway tools such as those being developed in the CEC-funded California Biopower Impacts project; and 4) Disaggregation to finer spatial scales. To pursue any one of these updates will require additional resources and considerable effort.

Appendices

Appendix A: Land Category components identified for use in CALAND

Each land category is a unique combination of spatial region, ownership class, and land type. Variable terms used in the model are in parenthesis.

Spatial Regions	
Key Terms	**Definition**
Central Coast (Central_Coast)	See Figures 1 and A1
Central Valley	See Figure 1 and A1
Delta	Legal Delta plus Suisun Marsh, see Figure 1
Deserts	See Figures 1 and A1
Eastside	See Figures 1 and A1
Klamath	See Figures 1 and A1
North Coast (North_Coast)	See Figures 1 and A1
Sierra Cascades (Sierra_Cascades)	See Figures 1 and A1
South Coast (South_Coast)	See Figures 1 and A1
Ownership Classes	
Key Terms	**Definition**
Bureau of Land Management (BLM)	Bureau of Land Management
Department of Defense (DoD)	Department of Defense
Easement	Conservation easement, regardless of ownership, and Non-Profit Conservancies and Trusts
Local Government (Local_gov)	Local government (e.g., city, county)
National Park Service (NPS)	National Park Service
Other Federal Government Land (Other_fed)	Bureau of Indian Affairs, Bureau of Reclamation, US Fish and Wildlife Service, Other Federal Lands, USFS Wilderness area (81% of this class)
Private	All land under private ownership that is not in the Easement category
State Government (State_gov)	CA Dept. of Fish and Wildlife, CA Dept. of Forestry and Fire Protection, CA Dept. of Parks and Recreation, Other State Lands

Appendix A: Land Category components identified for use in CALAND

Each land category is a unique combination of spatial region, ownership class, and land type. Variable terms used in the model are in parenthesis.

Non-wilderness United States Forest Service Land (USFS_nonwild)	All Forest Service land that is not designated as Wilderness area
Land Types	
Key Terms	**Definition**
Water	Open water
Ice	Ice, permanent snow
Barren	Little to no vegetation
Sparse	Sparse vegetation
Desert	Desert vegetation
Shrubland	Shrubs, chaparral
Grassland	Grassland
Savanna	Grass with sparse trees
Woodland	Scattered trees with grass
Forest	Trees are the dominant vegetation
Meadow	Inland seasonally wet grassland
Tidal Marsh (Coastal_Marsh)	Tidal marsh
Fresh Marsh (Fresh_Marsh)	Restored and managed Delta wetlands
Cultivated Land (Cultivated)	Annual and perennial crops, including hay and cultivated pasture
Urban Area (Developed_all)	Developed land, including associated vegetation such as parks and yards
Seagrass (Ocean, Other_fed)	Offshore seagrass beds

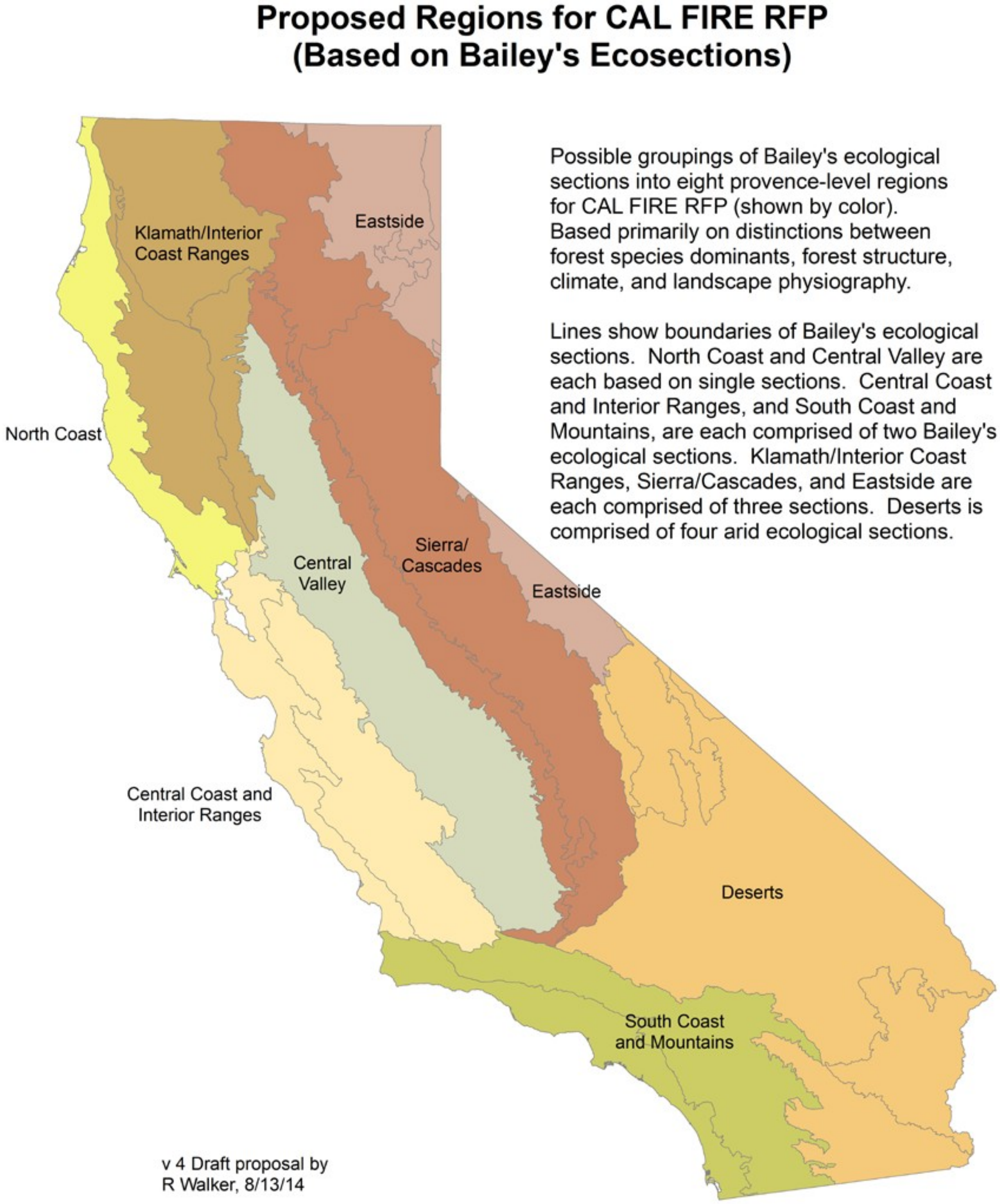


Figure A1: Aggregation of USFS California Level 2 ecological sub-regions recommended by The California Department of Forestry and Fire Protection (CAL FIRE) and used in CALAND. The Delta region was delineated primarily from the Central Valley region (boundary not shown; see Fig. 1).

Appendix B: Annual net carbon exchange in live vegetation and soil (sans mortality) without interventions and under historic climate.
Net carbon exchange values are the amount of carbon (Mg C ha^{-1}) that is sequestered (positive) or emitted (negative) each year based on historic climatic conditions without any intervention. Annual mortality losses from vegetation or gains in soil are not included unless otherwise noted. Data are presented as mean plus and minus SD.

Land Type	Region	Ownership	Net Carbon Exchange Vegetation (Mg C ha^{-1} y^{-1})	Net Carbon Exchange Soil (Mg C ha^{-1} y^{-1})	Source
Water	All	All	NA[1]	0[2]	
Ice	All	All	NA[1]	0[2]	
Barren	All	All	0[2]	0[2]	
Sparse	All	All	0[2]	0[2]	
Desert	All	All	0[2]	0.76 ± 0.07	Hastings et al., 2005, and Wohlfahrt et al., 2008 (soil)
Shrubland	All	All	0.93 ± 0.31[3]	0.28 ± 0.08	Quideau et al., 1998 (vegetation and soil)
Grassland	All	All	0[2]	-2.22 ± 1.29	Ma et al., 2007, and Ryals and Silver, 2013 (soil)
Savanna	All	All	3.67 ± 0.68[4]	-2.69 ± 0.47[5]	Ma et al., 2007 (vegetation and soil)
Woodland	All	All	3.67 ± 0.68[4]	-2.69 ± 0.47[5]	Ma et al., 2007 (vegetation and soil)
Meadow	All	All	0[2]	0.95 ± 0.25	Drexler et al., 2015 (soil)
Coastal Marsh	All	All	0[2]	1.44 ± 1.23	Callaway et al., 2012, and Chmura et al., 2003 (soil)
Fresh Marsh	All	All	NA[1]	3.37 ± 0.33	Knox et al., 2015 (soil)
Cultivated	Non-Delta	All	0[2]	0.19 ± 0.26	Mitchell et al., 2015, Wu et al., 2008, and Kong et al., 2005 (soil)
Cultivated	Delta	All	0[2]	-2.82 ± 2.51	Hatala et al., 2012, and Knox et al., 2015 (soil)
Urban	Central Coast	All	1.45 ± 0.04[6]	0[2,7]	McPherson et al., 2017 (vegetation)
Urban	Central Valley	All	0.95 ± 0.006[6]	0[2,7]	McPherson et al., 2017 (vegetation)
	Delta		0.95 ± 0.006[6]	0[2,7]	
	Deserts		0.20 ± 0.01[6]	0[2,7]	
	Eastside		0.70 ± 0.01[6]	0[2,7]	
	Klamath		0.70 ± 0.01[6]	0[2,7]	
	North Coast		1.96 ± 0.07[6]	0[2,7]	
	Sierra Cascades		0.70 ± 0.01[6]	0[2,7]	

Appendix B: Annual net carbon exchange in live vegetation and soil (sans mortality) without interventions and under historic climate. Net carbon exchange values are the amount of carbon (Mg C ha^{-1}) that is sequestered (positive) or emitted (negative) each year based on historic climatic conditions without any intervention. Annual mortality losses from vegetation or gains in soil are not included unless otherwise noted. Data are presented as mean plus and minus SD.

Land Type	Region	Ownership	Net Carbon Exchange Vegetation (Mg C ha^{-1} y^{-1})	Net Carbon Exchange Soil (Mg C ha^{-1} y^{-1})	Source
Forest	All	Other federal	1.82 ± 0.12[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
Forest	Central Coast	U.S. Bureau of Land Management	0.44 ± 0.26[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	0.44 ± 0.26[8,9]	0.71 ± 0.30[10]	
		Conservation Easement Protected	1.85 ± 0.42[8,9]	0.71 ± 0.30[10]	
		Local Government	2.62 ± 0.82[8,9]	0.71 ± 0.30[10]	
		National Park Service	0.44 ± 0.26[8,9]	0.71 ± 0.30[10]	
		Private	2.03 ± 0.39[8,9]	0.71 ± 0.30[10]	
		State Government	2.62 ± 0.82[8,9]	0.71 ± 0.30[10]	
		USFS (non-wilderness)	0.74 ± 0.35[8,9]	0.71 ± 0.30[10]	
Forest	Central Valley	U.S. Bureau of Land Management	0[2]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
Forest	Central Valley	U.S. Department of Defense	0[2]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		Conservation Easement Protected	1.26 ± 0.80[8,9]	0.71 ± 0.30[10]	
		Local Government	0.79 ± 0.95[8,9]	0.71 ± 0.30[10]	
		Private	1.15 ± 0.74[8,9]	0.71 ± 0.30[10]	
		State Government	0.79 ± 0.95[8,9]	0.71 ± 0.30[10]	
Forest	Delta	U.S. Bureau of Land Management	0.00 ± 0.00[2]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	0[2]	0.71 ± 0.30[10]	
		Conservation Easement Protected	1.26 ± 0.80[8,9]	0.71 ± 0.30[10]	
		Local Government	0.79 ± 0.95[8,9]	0.71 ± 0.30[10]	
		Private	1.15 ± 0.74[8,9]	0.71 ± 0.30[10]	
		State Government	0.79 ± 0.95[8,9]	0.71 ± 0.30[10]	
Forest	Deserts	U.S. Bureau of Land Management	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)

Appendix B: Annual net carbon exchange in live vegetation and soil (sans mortality) without interventions and under historic climate. Net carbon exchange values are the amount of carbon (Mg C ha^{-1}) that is sequestered (positive) or emitted (negative) each year based on historic climatic conditions without any intervention. Annual mortality losses from vegetation or gains in soil are not included unless otherwise noted. Data are presented as mean plus and minus SD.

Land Type	Region	Ownership	Net Carbon Exchange Vegetation (Mg C ha^{-1} y^{-1})	Net Carbon Exchange Soil (Mg C ha^{-1} y^{-1})	Source
Forest	Deserts	U.S. Department of Defense	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		Conservation Easement Protected	0.32 ± 0.14[8,9]	0.71 ± 0.30[10]	
		Local Government	0.41 ± 0.35[8,9]	0.71 ± 0.30[10]	
		National Park Service	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	
		Private	0.27 ± 0.11[8,9]	0.71 ± 0.30[10]	
		State Government	0.41 ± 0.35[8,9]	0.71 ± 0.30[10]	
		USFS (non-wilderness)	0.65 ± 0.15[8,9]	0.71 ± 0.30[10]	
Forest	Eastside	U.S. Bureau of Land Management	0.20 ± 0.05[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	0.20 ± 0.05[8,9]	0.71 ± 0.30[10]	
		Conservation Easement Protected	0.50 ± 0.21[8,9]	0.71 ± 0.30[10]	
		Local Government	1.32 ± 1.52[8,9]	0.71 ± 0.30[10]	
		National Park Service	0.20 ± 0.05[8,9]	0.71 ± 0.30[10]	
		Private	1.21 ± 0.30[8,9]	0.71 ± 0.30[10]	
		State Government	1.32 ± 1.52[8,9]	0.71 ± 0.30[10]	
		USFS (non-wilderness)	0.74 ± 0.11[8,9]	0.71 ± 0.30[10]	
Forest	Klamath	U.S. Bureau of Land Management	3.00 ± 0.85[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	3.00 ± 0.85[8,9]	0.71 ± 0.30[10]	
Forest	Klamath	Conservation Easement Protected	2.38 ± 0.30[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		Local Government	1.36 ± 0.79[8,9]	0.71 ± 0.30[10]	
		National Park Service	3.00 ± 0.85[8,9]	0.71 ± 0.30[10]	
		Private	2.74 ± 0.24[8,9]	0.71 ± 0.30[10]	
		State Government	1.36 ± 0.79[8,9]	0.71 ± 0.30[10]	

Appendix B: Annual net carbon exchange in live vegetation and soil (sans mortality) without interventions and under historic climate.
Net carbon exchange values are the amount of carbon (Mg C ha^{-1}) that is sequestered (positive) or emitted (negative) each year based on historic climatic conditions without any intervention. Annual mortality losses from vegetation or gains in soil are not included unless otherwise noted. Data are presented as mean plus and minus SD.

Land Type	Region	Ownership	Net Carbon Exchange Vegetation (Mg C ha^{-1} y^{-1})	Net Carbon Exchange Soil (Mg C ha^{-1} y^{-1})	Source
Forest	North Coast	USFS (non-wilderness)	2.61 ± 0.17[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Bureau of Land Management	5.18 ± 1.88[8,9]	0.71 ± 0.30[10]	
		U.S. Department of Defense	5.18 ± 1.88[8,9]	0.71 ± 0.30[10]	
		Conservation Easement Protected	4.11 ± 0.62[8,9]	0.71 ± 0.30[10]	
		Local Government	5.98 ± 1.53[8,9]	0.71 ± 0.30[10]	
		National Park Service	5.18 ± 1.88[8,9]	0.71 ± 0.30[10]	
		Private	4.91 ± 0.45[8,9]	0.71 ± 0.30[10]	
		State Government	5.98 ± 1.53[8,9]	0.71 ± 0.30[10]	
		USFS (non-wilderness)	7.94 ± 5.15[8,9]	0.71 ± 0.30[10]	
Forest	Sierra Cascades	U.S. Bureau of Land Management	1.48 ± 0.18[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	1.48 ± 0.18[8,9]	0.71 ± 0.30[10]	
		Conservation Easement Protected	1.20 ± 0.12[8,9]	0.71 ± 0.30[10]	
		Local Government	2.55 ± 0.82[8,9]	0.71 ± 0.30[10]	
		National Park Service	1.48 ± 0.18[8,9]	0.71 ± 0.30[10]	
		Private	2.09 ± 0.14[8,9]	0.71 ± 0.30[10]	
		State Government	2.55 ± 0.82[8,9]	0.71 ± 0.30[10]	
		USFS (non-wilderness)	2.45 ± 0.11[8,9]	0.71 ± 0.30[10]	
Forest	South Coast	U.S. Bureau of Land Management	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	Christensen et al., 2017, and Jenkins et al., 2003 (vegetation); Quideau et al., 1998 (soil)
		U.S. Department of Defense	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	
		Conservation Easement Protected	0.32 ± 0.14[8,9]	0.71 ± 0.30[10]	
		Local Government	0.41 ± 0.35[8,9]	0.71 ± 0.30[10]	
		National Park Service	0.05 ± 0.03[8,9]	0.71 ± 0.30[10]	
		Private	0.27 ± 0.11[8,9]	0.71 ± 0.30[10]	
		State Government	0.41 ± 0.35[8,9]	0.71 ± 0.30[10]	

Appendix B: Annual net carbon exchange in live vegetation and soil (sans mortality) without interventions and under historic climate.

Net carbon exchange values are the amount of carbon (Mg C ha^{-1}) that is sequestered (positive) or emitted (negative) each year based on historic climatic conditions without any intervention. Annual mortality losses from vegetation or gains in soil are not included unless otherwise noted. Data are presented as mean plus and minus SD.

Land Type	Region	Ownership	Net Carbon Exchange (Mg C ha^{-1} y^{-1}) Vegetation	Soil	Source
Forest	South Coast	USFS (non-wilderness)	0.65 ± 0.15[8,9]	0.71 ± 0.30[10]	
Seagrass	Ocean	Other Federal	NA[1]	0.45 ± 0.45	Mcleod et al., 2011 (soil)

[1] Carbon pool is not represented in CALAND.

[2] Due to lack of data, static carbon density is assumed (i.e., net carbon exchange is 0 Mg C ha^{-1} y^{-1}) based on expert opinion.

[3] Only includes aboveground main canopy net carbon exchange; root main canopy and understory carbon exchange are additional and are calculated annually as follows:

(a) $\boldsymbol{CO_{2\,root}} = \frac{f_{root}}{f_{stem}} \cdot \boldsymbol{CO_{2\,stem}}$, where $\boldsymbol{CO_{2\,root}}$ is the C accumulation in the root (Mg C ha^{-1} y^{-1}), $\boldsymbol{CO_{2\,stem}}$ is the CO_2 uptake in the stem (bole) (Mg C ha^{-1} y^{-1}), $\boldsymbol{f_{root}}$ is the ratio of root to aboveground main canopy carbon density (fraction), and $\boldsymbol{f_{stem}}$ is the constant fraction (0.66) of stem to aboveground main canopy.

(b) $\boldsymbol{CO_{2\,understory}} = \boldsymbol{f_{understory}} \cdot \boldsymbol{CO_{2\,above\,main}}$, where $\boldsymbol{CO_{2\,understory}}$ is the CO_2 uptake in the understory (Mg C ha^{-1} y^{-1}), $\boldsymbol{f_{understory}}$ is a constant fraction (0.1) of understory to above main canopy, and $\boldsymbol{CO_{2\,above\,main}}$ is the CO_2 uptake in aboveground main canopy (Mg C ha^{-1} y^{-1}).

[4] Based on measured net carbon flux of total main canopy (above and below), and an assumed grassland understory with static carbon density. Net vegetation carbon exchange value (sans mortality) is partitioned into below- and above-ground main canopy based on the existing ratio of root to aboveground biomass carbon.

[5] Based on soil surface CO_2 flux, which excludes carbon inputs from roots. Thus, root carbon inputs to soil are additional and are calculated each year as follows: $\boldsymbol{below2dead\_flux\_vals} = \boldsymbol{D_{root}} \cdot \boldsymbol{f_{mortality}}$, where below2dead_flux_vals is the root-derived carbon inputs to soil (Mg C ha^{-1} y^{-1}), $\boldsymbol{D_{root}}$ is main canopy root carbon density (Mg C ha^{-1}) and $\boldsymbol{f_{mortality}}$ is the annual mortality fraction of live aboveground main canopy (fraction).

[6] Net vegetation carbon exchange (sans mortality) in Urban Area is partitioned to above- and belowground main canopy pools with 72% allocated based on initial 2010 ratio of above- to aboveground and 28% is allocated to belowground biomass (McPherson et al., 2017) below-ground main canopy carbon.

[7] If belowground mortality rates increase in Urban Area from the initial 2010 values, the difference in root carbon mortality is added to the net soil carbon exchange.

[8] Total aboveground main canopy net carbon exchange based on scaled up measurements of carbon accumulation in stem (bole) (Christensen et al., 2017) and component fractions of leaf (0.05), bark (0.12), branch (0.17), and stem (0.66) (Jenkins et al., 2003).

[9] Excludes net carbon exchange in understory and belowground main canopy, which are calculated each year as follows:

(a) $\boldsymbol{CO_{2\,root}} = \boldsymbol{CO_{2\,stem}} \frac{f_{root}}{f_{stem}}$, where $\boldsymbol{CO_{2\,root}}$ is carbon accumulation in the belowground main canopy (Mg C ha^{-1} y^{-1}), $\boldsymbol{CO_{2\,stem}}$ is the CO_2 uptake in the stem (bole) (Mg C ha^{-1} y^{-1}), $\boldsymbol{f_{root}}$ is the ratio of root to aboveground main canopy carbon density (fraction), and $\boldsymbol{f_{stem}}$ is the constant fraction (0.66) of stem to aboveground main canopy.

(b) $\boldsymbol{CCO_{2\,understory}} = \boldsymbol{CO_{2\,stem}} \cdot \frac{D_{understory}}{D_{stem}}$, where $\boldsymbol{CO_{2\,understory}}$ is the CO_2 uptake in aboveground understory (Mg C ha^{-1} y^{-1}), $\boldsymbol{CO_{2\,stem}}$ is the CO_2 uptake in the main canopy stem (bole) (Mg C ha^{-1} y^{-1}), $\frac{D_{understory}}{D_{stem}}$ is the ratio of understory to main canopy stem carbon density (fraction), which is constrained to a maximum value of 1.

[10] Based on measured historical changes in soil organic carbon density, which implicitly includes root-derived carbon inputs. However, if mortality rates increase from initial 2010 values, the difference in root carbon mortality is added to the soil.

Appendix C: Annual net mortality fractions of live biomass carbon without intervention.

Annual mortality fractions are the net fractions (unitless) of each living biomass pool (Mg C ha^{-1}) that die each year. The dead biomass is transferred to dead aboveground carbon pools or to soil as indicated for each land type. It is assumed that the amount of biomass that dies each year is a net value, with the assumption that emissions have already been subtracted. This is consistent with net carbon exchange values (Appendix B), from which emissions have also been subtracted. The annual mortality flux is computed as follows: $M_i = f_{mortality,i} \cdot D_i$, where M_i is the mortality flux from the live biomass pool i (Mg C ha^{-1} y^{-1}), $f_{mortality,I}$ is the mortality fraction of live biomass carbon pool i (fraction), and D_i is the carbon density (Mg C ha^{-1}) of live biomass carbon pool i.

Land Type	Region	Ownership	Annual Mortality Fractions (unitless)			Source
			Main canopy		Understory	
			Aboveground	Belowground		
Water	All	All	NA[1]	NA[1]	NA[1]	NA
Ice	All	All	NA[1]	NA[1]	NA[1]	NA
Barren	All	All	0[2]	0[2]	NA[1]	Based on expert opinion due to lack of available data.
Sparse	All	All	0[2]	0[2]	NA[1]	
Desert	All	All	0[2]	0[2]	0[2]	
Shrubland	All	All	0.01[3]	0.01[4]	0.01[3]	
Grassland	All	All	0[2]	0[2]	0[2]	
Savanna	All	All	0.01[4]	0.01[5]	0.01[6]	
Woodland	All	All	0.01[4]	0.01[5]	0.01[6]	
Meadow	All	All	0[2]	0[2]	0[2]	
Coastal Marsh	All	All	0[2]	0[2]	0[2]	
Fresh Marsh	All	All	0[2]	0[2]	0[2]	
Cultivated	All	All	0[2]	0[2]	0[2]	
Urban	All	All	0.01[7]	0.01[4]	NA[1]	
Forest	Central Coast	U.S. Bureau of Land Management	0.013[8,9]	0.013[4,9]	0.01[8]	Christensen et al., 2017 (main canopy), and expert opinion for understory mortality due to lack of available data.
Forest	Central Coast	U.S. Department of Defense	0.013[8,9]	0.013[4,9]	0.01[8]	
Forest	Central Coast	Easement	0.0076[8,9]	0.0076[4,9]	0.01[8]	
Forest	Central Coast	Local Government	0.0043[8,9]	0.0043[4,9]	0.01[8]	
Forest	Central Coast	National Park Service	0.0130[8,9]	0.0130[4,9]	0.01[8]	
Forest	Central Coast	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	

Appendix C: Annual net mortality fractions of live biomass carbon without intervention.

Annual mortality fractions are the net fractions (unitless) of each living biomass pool (Mg C ha^{-1}) that die each year. The dead biomass is transferred to dead aboveground carbon pools or to soil as indicated for each land type. It is assumed that the amount of biomass that dies each year is a net value, with the assumption that emissions have already been subtracted. This is consistent with net carbon exchange values (Appendix B), from which emissions have also been subtracted. The annual mortality flux is computed as follows: $M_i = f_{mortality,i} \cdot D_i$, where M_i is the mortality flux from the live biomass pool i (Mg C ha^{-1} y^{-1}), $f_{mortality,I}$ is the mortality fraction of live biomass carbon pool i (fraction), and D_i is the carbon density (Mg C ha^{-1}) of live biomass carbon pool i.

Land Type	Region	Ownership	Annual Mortality Fractions (unitless)			Source
			Main canopy		Understory	
			Aboveground	Belowground		
Forest	Central Coast	Private	0.0069[8,9]	0.0069[4,9]	0.01[8]	Christensen et al., 2017 (main canopy), and expert opinion for understory mortality due to lack of available data.
Forest	Central Coast	State Government	0.0043[8,9]	0.0043[4,9]	0.01[8]	
Forest	Central Coast	USFS (non-wilderness)	0.0241[8,9]	0.0241[4,9]	0.01[8]	
Forest	Central Valley	U.S. Bureau of Land Management	0[2]	0[2]	0.01[8]	
Forest	Central Valley	U.S. Department of Defense	0[2]	0[2]	0.01[8]	
Forest	Central Valley	Easement	0.0089[8,9]	0.0089[4,9]	0.01[8]	
Forest	Central Valley	Local Government	0.0001[8,9]	0.0001[4,9]	0.01[8]	
Forest	Central Valley	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Central Valley	Private	0.0080[8,9]	0.0080[4,9]	0.01[8]	
Forest	Central Valley	State Government	0.0001[8,9]	0.0001[4,9]	0.01[8]	
Forest	Delta	U.S. Bureau of Land Management	0[2]	0[2]	0.01[8]	
Forest	Delta	U.S. Department of Defense	0[2]	0[2]	0.01[8]	
Forest	Delta	Easement	0.0089[8,9]	0.0089[4,9]	0.01[8]	
Forest	Delta	Local Government	0.0001[8,9]	0.0001[4,9]	0.01[8]	
Forest	Delta	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Delta	Private	0.0080[8,9]	0.0080[4,9]	0.01[8]	
Forest	Delta	State Government	0.0001[8,9]	0.0001[4,9]	0.01[8]	
Forest	Deserts	U.S. Bureau of Land Management	0.041[8,9]	0.041[4,9]	0.01[8]	
Forest	Deserts	U.S. Department of Defense	0.041[8,9]	0.041[4,9]	0.01[8]	

Appendix C: Annual net mortality fractions of live biomass carbon without intervention.

Annual mortality fractions are the net fractions (unitless) of each living biomass pool (Mg C ha^{-1}) that die each year. The dead biomass is transferred to dead aboveground carbon pools or to soil as indicated for each land type. It is assumed that the amount of biomass that dies each year is a net value, with the assumption that emissions have already been subtracted. This is consistent with net carbon exchange values (Appendix B), from which emissions have also been subtracted. The annual mortality flux is computed as follows: $M_i = f_{mortality,i} \cdot D_i$, where M_i is the mortality flux from the live biomass pool i (Mg C ha^{-1} y^{-1}), $f_{mortality,I}$ is the mortality fraction of live biomass carbon pool i (fraction), and D_i is the carbon density (Mg C ha^{-1}) of live biomass carbon pool i.

Land Type	Region	Ownership	Annual Mortality Fractions (unitless)			Source
			Main canopy		Understory	
			Aboveground	Belowground		
Forest	Deserts	Easement	0.0105[8,9]	0.0105[4,9]	0.01[8]	Christensen et al., 2017 (main canopy), and expert opinion for understory mortality due to lack of available data.
Forest	Deserts	Local Government	0.0267[8,9]	0.0267[4,9]	0.01[8]	
Forest	Deserts	National Park Service	0.041[8,9]	0.041[4,9]	0.01[8]	
Forest	Deserts	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Deserts	Private	0.0097[8,9]	0.0097[4,9]	0.01[8]	
Forest	Deserts	State Government	0.0267[8,9]	0.0267[4,9]	0.01[8]	
Forest	Deserts	USFS (non-wilderness)	0.042[8,9]	0.042[4,9]	0.01[8]	
Forest	Eastside	U.S. Bureau of Land Management	0.0013[8,9]	0.0013[4,9]	0.01[8]	
Forest	Eastside	U.S. Department of Defense	0.0013[8,9]	0.0013[4,9]	0.01[8]	
Forest	Eastside	Easement	0.0018[8,9]	0.0018[4,9]	0.01[8]	
Forest	Eastside	Local Government	0.0002[8,9]	0.0002[4,9]	0.01[8]	
Forest	Eastside	National Park Service	0.0013[8,9]	0.0013[4,9]	0.01[8]	
Forest	Eastside	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Eastside	Private	0.0106[8,9]	0.0106[4,9]	0.01[8]	
Forest	Eastside	State Government	0.0002[8,9]	0.0002[4,9]	0.01[8]	
Forest	Eastside	USFS (non-wilderness)	0.0053[8,9]	0.0053[4,9]	0.01[8]	
Forest	Klamath	U.S. Bureau of Land Management	0.0083[8,9]	0.0083[4,9]	0.01[8]	
Forest	Klamath	U.S. Department of Defense	0.0083[8,9]	0.0083[4,9]	0.01[8]	
Forest	Klamath	Easement	0.0059[8,9]	0.0059[4,9]	0.01[8]	
Forest	Klamath	Local Government	0.0161[8,9]	0.0161[4,9]	0.01[8]	

Appendix C: Annual net mortality fractions of live biomass carbon without intervention.

Annual mortality fractions are the net fractions (unitless) of each living biomass pool (Mg C ha^{-1}) that die each year. The dead biomass is transferred to dead aboveground carbon pools or to soil as indicated for each land type. It is assumed that the amount of biomass that dies each year is a net value, with the assumption that emissions have already been subtracted. This is consistent with net carbon exchange values (Appendix B), from which emissions have also been subtracted. The annual mortality flux is computed as follows: $M_i = f_{mortality,i} \cdot D_i$, where M_i is the mortality flux from the live biomass pool i (Mg C ha^{-1} y^{-1}), $f_{mortality,I}$ is the mortality fraction of live biomass carbon pool i (fraction), and D_i is the carbon density (Mg C ha^{-1}) of live biomass carbon pool i.

Land Type	Region	Ownership	Annual Mortality Fractions (unitless)			Source
			Main canopy		Understory	
			Aboveground	Belowground		
Forest	Klamath	National Park Service	0.0083[8,9]	0.0083[4,9]	0.01[8]	Christensen et al., 2017 (main canopy), and expert opinion for understory mortality due to lack of available data.
Forest	Klamath	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Klamath	Private	0.007[8,9]	0.007[4,9]	0.01[8]	
Forest	Klamath	State Government	0.0161[8,9]	0.0161[4,9]	0.01[8]	
Forest	Klamath	USFS (non-wilderness)	0.011[8,9]	0.011[4,9]	0.01[8]	
Forest	North Coast	U.S. Bureau of Land Management	0.0031[8,9]	0.0031[4,9]	0.01[8]	
Forest	North Coast	U.S. Department of Defense	0.0031[8,9]	0.0031[4,9]	0.01[8]	
Forest	North Coast	Easement	0.0033[8,9]	0.0033[4,9]	0.01[8]	
Forest	North Coast	Local Government	0.0072[8,9]	0.0072[4,9]	0.01[8]	
Forest	North Coast	National Park Service	0.0031[8,9]	0.0031[4,9]	0.01[8]	
Forest	North Coast	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	North Coast	Private	0.0035[8,9]	0.0035[4,9]	0.01[8]	
Forest	North Coast	State Government	0.0072[8,9]	0.0072[4,9]	0.01[8]	
Forest	North Coast	USFS (non-wilderness)	0.0069[8,9]	0.0069[4,9]	0.01[8]	
Forest	Sierra Cascades	U.S. Bureau of Land Management	0.0081[8,9]	0.0081[4,9]	0.01[8]	
Forest	Sierra Cascades	U.S. Department of Defense	0.0081[8,9]	0.0081[4,9]	0.01[8]	
Forest	Sierra Cascades	Easement	0.0063[8,9]	0.0063[4,9]	0.01[8]	
Forest	Sierra Cascades	Local Government	0.0038[8,9]	0.0038[4,9]	0.01[8]	

Appendix C: Annual net mortality fractions of live biomass carbon without intervention.

Annual mortality fractions are the net fractions (unitless) of each living biomass pool (Mg C ha^{-1}) that die each year. The dead biomass is transferred to dead aboveground carbon pools or to soil as indicated for each land type. It is assumed that the amount of biomass that dies each year is a net value, with the assumption that emissions have already been subtracted. This is consistent with net carbon exchange values (Appendix B), from which emissions have also been subtracted. The annual mortality flux is computed as follows: $M_i = f_{mortality,i} \cdot D_i$, where M_i is the mortality flux from the live biomass pool i (Mg C ha^{-1} y^{-1}), $f_{mortality,I}$ is the mortality fraction of live biomass carbon pool i (fraction), and D_i is the carbon density (Mg C ha^{-1}) of live biomass carbon pool i.

Land Type	Region	Ownership	Annual Mortality Fractions (unitless)			Source
			Main canopy		Understory	
			Aboveground	Belowground		
Forest	Sierra Cascades	National Park Service	0.0081[8,9]	0.0081[4,9]	0.01[8]	Christensen et al., 2017 (main canopy), and expert opinion for understory mortality due to lack of available data.
Forest	Sierra Cascades	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	Sierra Cascades	Private	0.0069[8,9]	0.0069[4,9]	0.01[8]	
Forest	Sierra Cascades	State Government	0.0038[8,9]	0.0038[4,9]	0.01[8]	
Forest	Sierra Cascades	USFS (non-wilderness)	0.0117[8,9]	0.0117[4,9]	0.01[8]	
Forest	South Coast	U.S. Bureau of Land Management	0.041[8,9]	0.041[4,9]	0.01[8]	
Forest	South Coast	U.S. Department of Defense	0.041[8,9]	0.041[4,9]	0.01[8]	
Forest	South Coast	Easement	0.0105[8,9]	0.0105[4,9]	0.01[8]	
Forest	South Coast	Local Government	0.0267[8,9]	0.0267[4,9]	0.01[8]	
Forest	South Coast	National Park Service	0.041[8,9]	0.041[4,9]	0.01[8]	
Forest	South Coast	Other federal	0.0146[8,9]	0.0146[4,9]	0.01[8]	
Forest	South Coast	Private	0.0097[8,9]	0.0097[4,9]	0.01[8]	
Forest	South Coast	State Government	0.0267[8,9]	0.0267[4,9]	0.01[8]	
Forest	South Coast	USFS (non-wilderness)	0.042[8,9]	0.042[4,9]	0.01[8]	
Seagrass	Ocean	Other Federal	NA[1]	NA[1]	NA[1]	NA

[1]Carbon pool is not represented in CALAND.

[2]Due to lack of available mortality data and modeled static C density, mortality fraction is set to 0 (i.e., net carbon exchange is 0 Mg C ha^{-1} y^{-1}).

[3]Dead C flux (Mg C ha^{-1} y^{-1}) is transferred to dead C pools in proportion to the existing proportions of standing dead, down dead, and litter carbon densities unless there are non-existing dead pools, in which case the missing proportions are replaced with default values for standing dead (0.11), down dead (0.23), and/or litter (0.66).

[4]Dead belowground main canopy C flux (Mg C ha^{-1} y^{-1}) is only transferred to the soil C pool if there is an increase in the initial 2010 dead belowground main canopy (Mg C ha^{-1} y^{-1}).
[5]Dead belowground main canopy C flux (Mg C ha^{-1} y^{-1}) in Savanna and Woodland is transferred to the soil C pool because in these land types soil C exchange represents an annual net ecosystem carbon exchange which does not explicitly include a net change in soil C density.
[6]Due to the data available for Savanna and Woodland, which are based on a grass understory, the understory mortality reflects the same understory mortality fraction as in Grassland (i.e., 0).
[7]Dead aboveground main canopy C flux (Mg C ha^{-1} y^{-1}) in Urban Area is transferred to harvest pathways, which is prescribed in the input file (i.e., durable wood products and/or bioenergy).
[8]Dead aboveground main canopy C (Mg C ha^{-1} y^{-1}) in Forest is transferred to dead pools according to the following:
Standing dead: $\boldsymbol{dC_{standing\ dead} = 0.66 \cdot M_{above}}$, where $\boldsymbol{dC_{standing\ dead}}$ is the annual accumulation of carbon in the standing dead pool (Mg C ha^{-1} y^{-1}), 0.66 is the constant fraction of main canopy stem (bole) relative to total aboveground main canopy (fraction), $\boldsymbol{M_{above}}$ is the total dead carbon lost from aboveground main canopy (Mg C ha^{-1} y^{-1});
Down dead: $\boldsymbol{dC_{down\ dead} = \frac{D_{down}}{D_{down}+D_{litter}} \cdot 0.44 \cdot M_{above}}$, where $\boldsymbol{dC_{down\ dead}}$ is the annual accumulation of carbon in the down dead pool (Mg C ha^{-1} y^{-1}), $\boldsymbol{\frac{D_{down}}{D_{down}+D_{litter}}}$ is the fraction of down dead carbon density relative to down dead and litter, 0.44 is the constant fraction of main canopy leaf, bark, and branch relative to total aboveground main canopy (fraction), $\boldsymbol{M_{above}}$ is the total dead carbon lost from aboveground main canopy (Mg C ha^{-1} y^{-1});
Litter: $\boldsymbol{dC_{litter} = \frac{D_{litter}}{D_{down}+D_{litter}} \cdot 0.44 \cdot M_{above}}$, where dC_{litter} is the annual accumulation of carbon in the litter pool (Mg C ha^{-1} y^{-1}), $\boldsymbol{\frac{D_{litter}}{D_{down}+D_{litter}}}$ is the fraction of litter carbon density relative to down dead and litter, 0.44 is the constant fraction of main canopy leaf, bark, and branch relative to total aboveground main canopy (fraction), $\boldsymbol{M_{above}}$ is the total dead carbon lost from aboveground main canopy (Mg C ha^{-1} y^{-1}).
[9]Doubled mortality from 2015 to 2024 to represent ongoing die-off of trees due to insects and drought.

Appendix D1: Rangeland compost scalars (unitless) for enhancing annual soil carbon exchange rates (Mg C ha^{-1} y^{-1}) in rangelands **(**Grassland, Savanna, and Woodland) due to applications of compost at medium (10 year) and low (30 year) retreatment frequencies.

The annual net soil carbon exchange rates without management (Appendix B) are multiplied by the rangeland compost scalars for a period equivalent to the repeat frequency level in the treated areas. Note that all soil carbon exchange rates without management are negative for Grassland, Savanna, and Woodland, indicating net soil carbon emissions each year. Rangeland compost application adds carbon to the soil carbon pool (benefit) with the net effect of deceasing emissions.

Region	Land type	Ownership	Rangeland Compost Scalars		Net soil carbon exchange without management[1] (Mg C ha^{-1} y^{-1})	Net soil carbon exchange with rangeland compost application (Mg C ha^{-1} y^{-1})		Net increase (benefit) in soil carbon due to management (Mg C ha^{-1} y^{-1})	
			Low frequency	Medium Frequency		Low frequency	Medium Frequency	Low Frequency	Medium Frequency
All	Grassland	All	0.94[1]	0.77[1]	-2.22[2]	-2.09	-1.71	0.13	0.51
All	Savanna	All	0.94[1]	0.77[1]	-2.69[3]	-2.53	-2.07	0.16	0.62
All	Woodland	All	0.94[1]	0.77[1]	-2.69[3]	-2.53	-2.07	0.16	0.62

[1]Average values from Appendix B.
[2]Ryals et al., 2015.
[3]Ma et al., 2007, and Ryals and Silver, 2013.
[4]Ma et al., 2007.

Appendix D2: Comparison of annual soil carbon exchange rates (Mg C ha^{-1} y^{-1}) in Cultivated Lands with and without soil conservation management. Positive net exchange rates represent carbon sequestration.

The uncertainty range (mean ± SD) of the annual soil carbon exchange rate with soil conservation management can be modeled as a proxy for a range of possible practices known to sequester carbon in croplands, summarized here as the minimum and maximum effects.

Region	Land type	Ownership	Net soil carbon exchange without management[1] (Mg C ha^{-1} y^{-1})	Net soil carbon exchange with soil conservation management (Mg C ha^{-1} y^{-1})	Net change in soil carbon due to management (*positive value is benefit*) (Mg C ha^{-1} y^{-1})	
					Minimum Effect	Maximum Effect
Non-Delta	Cultivated	All	0.19[2]	0.59 ± 0.44[3]	-0.04	0.84
Delta	Cultivated	All	-2.82[3]	-2.42 ± 2.56[4]	-2.16	2.96

[1]Average values from Appendix B.
[2]Mitchell et al., 2015; Wu et al., 2008; and Kong et al., 2005
[3]Mitchell et al., 2015 and Kong et al., 2005
[3]Hatala et al., 2012, and Knox et al., 2015.
[4]Due to lack of data on cover crop, reduced tillage, or composting in the Delta region, we applied the net changes in soil carbon in the non-Delta regions to the net soil carbon flux without management in the Delta region.

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

		Forest Management[1] Enhancement/Reduction Factors (fraction)					
		Fuel reduction practices			Harvest practices		
Parameter	Ownership	Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	Source
Forests in Central Coast							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	7.01	7.01	7.01	7.01	Christensen et al., 2017
	U.S. Department of Defense	1	7.01	7.01	7.01	7.01	
	Conservation Easement Protected	1	1.65	1.65	1.65	1.65	
	Local Government	1	1.16	1.16	1.16	1.16	
	National Park Service	1	7.01	7.01	7.01	7.01	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.5	1.5	1.5	1.5	
	State Government	1	1.16	1.16	1.16	1.16	
	USFS (non-wilderness)	1	4.11	4.11	4.11	4.11	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	0.32	0.32	0.32	0.32	Christensen et al., 2017
	U.S. Department of Defense	1	0.32	0.32	0.32	0.32	
	Conservation Easement Protected		0.55	0.55	0.55	0.55	
	Local Government	1	0.96	0.96	0.96	0.96	
	National Park Service	1	0.32	0.32	0.32	0.32	
	Other Federal	1	0.43	0.43	0.43	0.43	
	Private	1	0.6	0.6	0.6	0.6	
	State Government	1	0.96	0.96	0.96	0.96	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Central Coast (Cont.)							
Mortality fraction	USFS (non-wilderness)	1	0.17	0.17	0.17	0.17	Christensen et al., 2017
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in Central Valley							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	1	1	1	1	Christensen et al., 2017
	U.S. Department of Defense	1	1	1	1	1	
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	1.59	1.59	1.59	1.59	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.1	1.1	1.1	1.1	
	State Government	1	1.59	1.59	1.59	1.59	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	1	1	1	1	Christensen et al., 2017
	U.S. Department of Defense	1	1	1	1	1	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Mortality fraction	Conservation Easement Protected	1	0.9	0.9	0.9	0.9	Christensen et al., 2017
	Local Government	1	69.99	69.99	69.99	69.99	
	Other Federal	1	0.43	0.43	0.43	0.43	
	Private	1	1	1	1	1	
	State Government	1	69.99	69.99	69.99	69.99	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in Delta							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	1	1	1	1	Christensen et al., 2017
	U.S. Department of Defense	1	1	1	1	1	
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	1.59	1.59	1.59	1.59	
Net vegetation C exchange (sans mortality)	Other Federal	1	2.08	2.08	2.08	2.08	Christensen et al., 2017
	Private	1	1.1	1.1	1.1	1.1	
	State Government	1	1.59	1.59	1.59	1.59	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Delta (Cont.)							
Mortality fraction	U.S. Bureau of Land Management	1	1	1	1	1	Christensen et al., 2017
	U.S. Department of Defense	1	1	1	1	1	
	Conservation Easement Protected	1	0.9	0.9	0.9	0.9	
	Local Government	1	69.99	69.99	69.99	69.99	
	Other Federal	1	1	1	1	1	
	Private	1	69.99	69.99	69.99	69.99	
	State Government	1	69.99	69.99	69.99	69.99	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in Deserts							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	6.42	6.42	6.42	6.42	Christensen et al., 2017
	U.S. Department of Defense	1	6.42	6.42	6.42	6.42	
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	0.77	0.77	0.77	0.77	
	National Park Service	1	6.42	6.42	6.42	6.42	
	Other Federal	1	2.08	2.08	2.08	2.08	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

		Forest Management[1] Enhancement/Reduction Factors (fraction)					
		Fuel reduction practices			Harvest practices		
Parameter	Ownership	Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	Source
Forests in Deserts (Cont.)							
Net vegetation C exchange (sans mortality)	Private	1	1.2	1.2	1.2	1.2	Christensen et al., 2017
	State Government	1	0.77	0.77	0.77	0.77	
	USFS (non-wilderness)	1	0.49	0.49	0.49	0.49	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	0.26	0.26	0.26	0.26	Christensen et al., 2017
	U.S. Department of Defense	1	0.26	0.26	0.26	0.26	
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	0.39	0.39	0.39	0.39	
	National Park Service	1	0.26	0.26	0.26	0.26	
	Other Federal	1	0.43	0.43	0.43	0.43	
	Private	1	1.08	1.08	1.08	1.08	
	State Government	1	0.39	0.39	0.39	0.39	
	USFS (non-wilderness)	1	0.25	0.25	0.25	0.25	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Eastside							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	9.79	9.79	9.79	9.79	Christensen et al., 2017
	U.S. Department of Defense	1	9.79	9.79	9.79	9.79	
	Conservation Easement Protected	1	3.93	3.93	3.93	3.93	
	Local Government	1	1.5	1.5	1.5	1.5	
	National Park Service	1	9.79	9.79	9.79	9.79	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.63	1.63	1.63	1.63	
	State Government	1	1.5	1.5	1.5	1.5	
	USFS (non-wilderness)	1	2.65	2.65	2.65	2.65	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	13.84	13.84	13.84	13.84	Christensen et al., 2017
	U.S. Department of Defense	1	13.84	13.84	13.84	13.84	
	Conservation Easement Protected	1	9.52	9.52	9.52	9.52	
	Local Government	1	84.96	84.96	84.96	84.96	
	National Park Service	1	13.84	13.84	13.84	13.84	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Eastside (Cont.)							
Mortality fraction	Other Federal	1	0.43	0.43	0.43	0.43	Christensen et al., 2017
	Private	1	1.64	1.64	1.64	1.64	
	State Government	1	84.96	84.96	84.96	84.96	
	USFS (non-wilderness)	1	3.31	3.31	3.31	3.31	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in Klamath							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	1.1	1.1	1.1	1.1	Christensen et al., 2017
	U.S. Department of Defense	1	1.1	1.1	1.1	1.1	
	Conservation Easement Protected	1	1.39	1.39	1.39	1.39	
	Local Government	1	2.42	2.42	2.42	2.42	
	National Park Service	1	1.1	1.1	1.1	1.1	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.21	1.21	1.21	1.21	
	State Government	1	2.42	2.42	2.42	2.42	
	USFS (non-wilderness)	1	1.27	1.27	1.27	1.27	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Klamath (Cont.)							
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	1.03	1.03	1.03	1.03	Christensen et al., 2017
	U.S. Department of Defense	1	1.03	1.03	1.03	1.03	
	Conservation Easement Protected	1	1.45	1.45	1.45	1.45	
	Local Government	1	0.53	0.53	0.53	0.53	Christensen et al., 2017
	National Park Service	1	1.03	1.03	1.03	1.03	
	Other Federal	1	0.43	0.43	0.43	0.43	
	Private	1	1.23	1.23	1.23	1.23	
	State Government	1	0.53	0.53	0.53	0.53	
	USFS (non-wilderness)	1	0.78	0.78	0.78	0.78	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in North Coast							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	1.08	1.08	1.08	1.08	Christensen et al., 2017
	U.S. Department of Defense	1	1.08	1.08	1.08	1.08	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in North Coast (Cont.)							
Net vegetation C exchange (sans mortality)	Conservation Easement Protected	1	1.36	1.36	1.36	1.36	Christensen et al., 2017
	Local Government	1	0.93	0.93	0.93	0.93	
	National Park Service	1	1.08	1.08	1.08	1.08	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.14	1.14	1.14	1.14	
	State Government	1	0.93	0.93	0.93	0.93	
	USFS (non-wilderness)	1	0.7	0.7	0.7	0.7	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	1.19	1.19	1.19	1.19	Christensen et al., 2017
	U.S. Department of Defense	1	1.19	1.19	1.19	1.19	
	Conservation Easement Protected	1.1	1.1	1.1	1.1	1	
	Local Government	0.5	0.5	0.5	0.5	1	
	National Park Service	1.19	1.19	1.19	1.19	1	
	Other Federal	0.43	0.43	0.43	0.43	1	
	Private	1.04	1.04	1.04	1.04	1	Christensen et al., 2017
	State Government	0.5	0.5	0.5	0.5	1	
	USFS (non-wilderness)	0.53	0.53	0.53	0.53	1	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

		Forest Management[1] Enhancement/Reduction Factors (fraction)					
		Fuel reduction practices			Harvest practices		
Parameter	Ownership	Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	Source
Forests in North Coast (Cont.)							
Medium severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	Lyderson et al., 2017
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in Sierra Cascades							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	2.25	2.25	2.25	2.25	Christensen et al., 2017
	U.S. Department of Defense	1	2.25	2.25	2.25	2.25	
	Conservation Easement Protected	1	2.79	2.79	2.79	2.79	
	Local Government	1	1.32	1.32	1.32	1.32	
	National Park Service	1	2.25	2.25	2.25	2.25	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.6	1.6	1.6	1.6	
	State Government	1	1.32	1.32	1.32	1.32	
	USFS (non-wilderness)	1	1.37	1.37	1.37	1.37	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.
Mortality fraction	U.S. Bureau of Land Management	1	0.93	0.93	0.93	0.93	Christensen et al., 2017
	U.S. Department of Defense	1	0.93	0.93	0.93	0.93	
	Conservation Easement Protected	1	1.2	1.2	1.2	1.2	
	Local Government	1	1.97	1.97	1.97	1.97	
	National Park Service	1	0.93	0.93	0.93	0.93	

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in Sierra Cascades (Cont.)							
Mortality fraction	Other Federal	1	0.43	0.43	0.43	0.43	Christensen et al., 2017
	Private	1	1.09	1.09	1.09	1.09	
	State Government	1	1.97	1.97	1.97	1.97	
	USFS (non-wilderness)	1	0.64	0.64	0.64	0.64	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	0.87	1.10	1.3	1.10	1.10	
Low severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Forests in South Coast							
Net vegetation C exchange (sans mortality)	U.S. Bureau of Land Management	1	6.42	6.42	6.42	6.42	Christensen et al., 2017
Net vegetation C exchange (sans mortality)	U.S. Department of Defense	1	6.42	6.42	6.42	6.42	Christensen et al., 2017
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	0.77	0.77	0.77	0.77	
	National Park Service	1	6.42	6.42	6.42	6.42	
	Other Federal	1	2.08	2.08	2.08	2.08	
	Private	1	1.2	1.2	1.2	1.2	
	State Government	1	0.77	0.77	0.77	0.77	
	USFS (non-wilderness)	1	0.49	0.49	0.49	0.49	
Net soil C exchange (sans mortality)	All	1	1	1	1	1	Due to lack of data no effect is assumed.

Appendix E: Direct effects of specific forest management practices on vegetation and soil C exchange (sans mortality), mortality fractions, and wildfire severity.

With respect to the Forest land type, the management-specific factors summarized here directly scale the forest carbon parameters for unmanaged lands: annual net vegetation carbon exchange rates without management (Appendix B), mortality fractions without management (Appendix C), and wildfire severity fractions without management (Table 4). Benefits are applied for 20 years for each year of management in the treated areas. Parameter factors equal to 1 indicate the management practice has no effect (assumed due to lack of data), while >1 and <1 indicate an enhancement and reduction, respectively.

Parameter	Ownership	Forest Management[1] Enhancement/Reduction Factors (fraction)					Source
		Fuel reduction practices			Harvest practices		
		Prescribed Burn	Thinning	Understory treatment	Clear cut	Partial cut	
Forests in South Coast (Cont.)							
Mortality fraction	U.S. Bureau of Land Management	1	0.26	0.26	0.26	0.26	Christensen et al., 2017
	U.S. Department of Defense	1	0.26	0.26	0.26	0.26	
	Conservation Easement Protected	1	1	1	1	1	
	Local Government	1	0.39	0.39	0.39	0.39	
	National Park Service	1	0.26	0.26	0.26	0.26	
	Other Federal	1	0.43	0.43	0.43	0.43	
	Private	1	1.08	1.08	1.08	1.08	
	State Government	1	0.39	0.39	0.39	0.39	
	USDA Forest Service (non-wilderness)	1	0.25	0.25	0.25	0.25	
High severity wildfire fraction	All	0.32	0.84	0.76	0.84	0.84	Lyderson et al., 2017
Medium severity wildfire fraction	All	1.94	1.19	0.94	1.19	1.19	
Low severity wildfire fraction	All	0.87	1.1	1.3	1.1	1.1	

[1]Not all management practices presented; afforestation and reforestation are assigned a value of 1 for all parameters (no effect), and high and medium level extra slash utilization paired with any of the fuel reduction or harvest activities are identical to the practice without extra slash utilization.

Appendix F1: Direct transfers of Forest carbon due to specific harvest practices.

The carbon transfer fractions (unitless) are the fractions of the existing carbon densities (Mg C ha^{-1}) associated with each of the pools specified by the parameter that are transferred from one pool to another, to wood products, or to the atmosphere via decay, burning, or bioenergy due to harvest practices. The carbon transfers occur in the areas managed by the specific practice in the same year management occurs. These values apply across Forests in all regions and ownerships. See table footnotes for definitions of some of the parameter terminology.

Parameter	Carbon transfer fractions due to harvest						Source
	Partial cut harvest			Clear cut harvest			
	Extra Slash Utilization			Extra Slash Utilization			
	None	Medium	High	None	Medium	High	
Aboveground Main Canopy & Standing Dead[1] to Harvest	0.2	0.2	0.2	0.66	0.66	0.66	Stewart and Nakamura, 2012; Saah et al., 2016; and Battles et al., 2014.
Harvest to Wood	0.2	0.2	0.2	0.63	0.63	0.63	Stewart and Nakamura, 2012.
Harvest to Energy	0.75	0.75	0.75	0.32	0.32	0.32	
Harvest to Sawmill Decay	0.01	0.01	0.01	0.01	0.01	0.01	
Harvest to Slash	0.04	0.04	0.04	0.04	0.04	0.04	
Understory to Slash	0.7	0.7	0.7	0.9	0.9	0.9	Based on expert opinion due to lack of available data.
Down Dead to Slash	0.42	0.42	0.42	0.62	0.62	0.62	Dore et al., 2016.
Litter to Slash	0.42	0.42	0.42	0.62	0.62	0.62	Stewart and Nakamura, 2012 (Harvest)
Slash to Energy	0	0.125	0.25	0	0.125	0.25	“None” extra slash utilization based on expert opinion. “Medium” and “High” extra slash utilization are aspirational exploratory values and not based on feasibility.
Slash to Wood	0	0.125	0.25	0	0.125	0.25	
Slash to Burning	0.25	0	0	0.25	0	0	
Slash to Decay	0.75	0.75	0.5	0.75	0.75	0.5	
Aboveground Main Canopy to Standing Dead	0	0	0	0	0	0	Based on expert opinion due to lack of available data.
Understory to Down Dead	0.3	0.3	0.3	0.1	0.1	0.1	
Soil Decay to Atmosphere	0.13	0.13	0.13	0.2	0.2	0.2	Birdsey and Lewis, 2002.
Belowground Main Canopy Decay to Atmosphere	0.03[2]	0.03[2]	0.03[2]	0.13[2]	0.13[2]	0.13[2]	
Belowground Main Canopy Decay to Soil	0.17[2,3]	0.17[2,3]	0.17[2,3]	0.53[2,3]	0.53[2,3]	0.53[2,3]	

[1]Standing dead assumed to have same fraction harvested as aboveground main canopy.

[2]Loss of belowground main canopy to the atmosphere and soil is based on the transfer fractions for aboveground main canopy, while the partitioning to atmosphere and soil is based on Birdsey and Lewis, 2002.

[3]The loss to soil is subtracted from roots but not added to soil, as it is assumed to be implicit in the baseline net soil C flux.

Definitions: _**Harvest**_: cut/cleared above ground canopy and standing dead biomass; _**Wood**_: durable wood products; _**Slash**_: cut/cleared biomass left in the forest; this includes contributions from harvested above ground canopy and standing dead, understory, downed dead, and litter; _**Energy**_: feedstock pathway to electricity produced by biomass combustion; _**Sawmill**_: processing plant for harvested biomass; _**Decay**_: biomass decay to the atmosphere; _**Understory**_: All non-main-canopy vegetation, including small trees less than 12.5 cm in diameter; _**Downed dead**_: ground level fuel load (i.e., dead twigs, branches, and stems on the ground); _**Litter**_: Ground duff layer, including fallen pine needles and other small, dead, biomass particles; _**Burning**_: Setting fire to dead biomass in piles and/or spread out via broadcast burning.

Appendix F2: Direct transfers of Forest carbon due to specific fuel reduction practices.

The carbon transfer fractions (unitless) are the fractions of the existing carbon densities (Mg C ha^{-1}) associated with each of the pools specified by the parameter that are transferred from one pool to another, to wood products, or to the atmosphere via decay, burning, or bioenergy due to fuel reduction practices. The carbon transfers are fractions of the pool specified by the parameter and occur in the areas managed by the specific practice in the same year management occurs. These values apply across Forests in all regions and ownerships.

	Carbon transfer fractions due to fuel reduction practices									
	Prescribed Burn			Thinning			Understory Treatment			
	Extra Slash Utilization			Extra Slash Utilization			Extra Slash Utilization			
Parameter	**None**	**Medium**	**High**	**None**	**Medium**	**High**	**None**	**Medium**	**High**	**Source**
Aboveground Main Canopy & Standing Dead to Harvest	0	0	0	0.2	0.2	0.2	0	0	0	Prescribed burn and understory treatment do not involve harvest. Thinning is assigned same values as partial cut (Appendix F1).
Harvest to Wood	0	0	0	0.2	0.2	0.2	0	0	0	
Harvest to Energy	0	0	0	0.75	0.75	0.75	0	0	0	
Harvest to Sawmill Decay	0	0	0	0.01	0.01	0.01	0	0	0	
Harvest to Slash	0	0	0	0.04	0.04	0.04	0	0	0	
Understory to Slash	0.55	0.55	0.55	0.7	0.7	0.7	0.5	0.5	0.5	Pearson et al., 2009 (prescribed burn); Thinning is assigned same values as partial cut (Appendix F1); Understory treatment based on expert opinion.
Down Dead to Slash	0.53	0.53	0.53	0.42	0.42	0.42	0	0	0	Wiechmann et al., 2015; (prescribed burn) Thinning is assigned same values as partial cut (Appendix F1); Understory based on expert opinion.
Litter to Slash	0.6	0.6	0.6	0.42	0.42	0.42	0	0	0	
Slash to Energy	0	0.125	0.25	0	0.125	0.25	0	0.125	0.25	"None" extra slash utilization based on expert opinion. Medium and high extra slash utilization are aspirational, exploratory values and not based on feasibility.
Slash to Wood	0	0.125	0.25	0	0.125	0.25	0	0.125	0.25	
Slash to Burning	1	0.75	0.5	0.25	0	0	0.25	0	0	
Slash to Decay	0	0	0	0.75	0.75	0.5	0.75	0.75	0.5	
Aboveground Main Canopy to Standing Dead	0.03	0.03	0.03	0	0	0	0	0	0	Prescribed burn is based on Wiechmann et al., 2015; Thinning is assigned same values as partial cut (Appendix F1); Understory treatment based on expert opinion.
Understory to Down Dead	0.45	0.45	0.45	0.3	0.3	0.3	0.5	0.5	0.5	Prescribed burn is based on medium intensity fire from Pearson et al., 2009; Thinning is assigned same values as partial cut (Appendix F1); Understory treatment based on expert opinion.

Appendix F2: Direct transfers of Forest carbon due to specific fuel reduction practices.

The carbon transfer fractions (unitless) are the fractions of the existing carbon densities (Mg C ha^{-1}) associated with each of the pools specified by the parameter that are transferred from one pool to another, to wood products, or to the atmosphere via decay, burning, or bioenergy due to fuel reduction practices. The carbon transfers are fractions of the pool specified by the parameter and occur in the areas managed by the specific practice in the same year management occurs. These values apply across Forests in all regions and ownerships.

Parameter	Carbon transfer fractions due to fuel reduction practices									Source
	Prescribed Burn			Thinning			Understory Treatment			
	Extra Slash Utilization			Extra Slash Utilization			Extra Slash Utilization			
	None	Medium	High	None	Medium	High	None	Medium	High	
Soil Decay to Atmosphere	0	0	0	0.13	0.13	0.13	0	0	0	Thinning is assigned same values as partial cut (Appendix F1); Prescribed burn and understory treatment based on expert opinion.
Belowground Main Canopy Decay to Atmosphere	0	0	0	0.03	0.03	0.03	0	0	0	Thinning is assigned same values as partial cut (Appendix F1); Prescribed burn and understory treatment based on expert opinion.
Belowground Main Canopy Decay to Soil	0	0	0	0.17	0.17	0.17	0	0	0	

Appendix F3: Direct transfers of carbon due to conversion of Forest and non-Forest Lands to Cultivated Land or Urban Area.

These are the fractions (unitless) of carbon densities (Mg C ha^{-1}) associated with each of the pools specified that are transferred from one pool to another, to wood products, or to the atmosphere via decay, burning, or bioenergy due to land conversion to Cultivated Land or Urban Area. For non-Forest conversion to Cultivated Land or Urban Area all harvested biomass decays. The transfers occur in the areas converted during the same year of conversion. These values apply across all regions and ownerships.

Parameter	Carbon transfer fractions due to land conversion		Source
	Forest to Cultivated or Urban Area	Non-Forest Lands to Cultivated or Urban Area	
Aboveground Main Canopy & Standing Dead to Harvest	1		Assumed all biomass is removed or decays due to conversion; Gonzalez et al., 2015.
Harvest to Wood	0.63	0	Stewart and Nakamura, 2012.
Harvest to Energy	0.32	0	
Harvest to Sawmill Decay	0.01	0	
Harvest to Slash	0.04	1	
Understory to Slash	1		Assumed all biomass is removed or decays due to conversion.
Down Dead to Slash	1		
Litter to Slash	1		
Slash to Energy	0		
Slash to Wood	0		
Slash to Burning	0		
Slash to Decay	1		
Soil Decay to Atmosphere	0.31		Davidson and Ackerman, 1993.
Belowground Main Canopy Decay to Atmosphere	1		Belowground biomass loss based on transfer fractions for aboveground main canopy; based on personal communication with Bruce Gwynne.

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Area (ha)	
Area	Land category area
Managed_area	Simulated managed area – this may be different than the prescribed managed area due to land availability
Wildfire_area	Simulated wildfire area – this is the wildfire area as distributed across land categories, and the totals may be different than prescribed due to land availability
Carbon density (Mg C ha^{-1})	
All_orgC_den	Total organic carbon density (sum of the seven C pools)
All_biomass_C_den	Living and dead vegetation carbon density (All_orgC_den – Soil_orgC_den)
Above_main_C_den	Main live canopy carbon density
Below_main_C_den	Main live root carbon density
Understory_C_den	Understory live carbon density
StandDead_C_den	Standing dead carbon density
DownDead_C_den	Downed dead carbon density
Litter_C_den	Litter carbon density
Soil_orgC_den	Soil organic carbon density
Carbon stock (Mg C)	
All_orgC_stock	Total organic carbon stock (sum of the seven C pools)
All_biomass_C_stock	Living and dead vegetation carbon stock (All_orgC_den – Soil_orgC_den)
Above_main_C_stock	Main live canopy carbon stock
Below_main_C_stock	Main live root carbon stock
Understory_C_stock	Understory live carbon stock
StandDead_C_stock	Standing dead carbon stock
DownDead_C_stock	Downed dead carbon stock
Litter_C_stock	Litter carbon stock
Soil_orgC_stock	Soil organic carbon stock
Wood product carbon stock (Mg C)	

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Total_Wood_C_stock	Persistent wood product carbon stock
Wood product carbon stock (Mg C) (Cont.)	
Total_Wood_CumGain_C_stock	Cumulative gain in wood product carbon stock
Total_Wood_CumLoss_C_stock	Cumulative loss in wood product carbon stock from decay in landfills
Total_Wood_AnnGain_C_stock	Annual gain in wood product carbon stock
Total_Wood_AnnLoss_C_stock	Annual loss in wood product carbon stock from decay in landfills
Manage_Wood_C_stock	Persistent wood product carbon stock from forest management
Manage_TotWood_CumGain_C_stock	Cumulative gain in wood product carbon stock sourced from forest management (harvest plus extra slash utilization)
Manage_Harv2Wood_CumGain_C_stock	Cumulative gain in wood product carbon stock sourced from forest management harvest
Manage_Slash2Wood_CumGain_C_stoc k	Cumulative gain in wood product carbon stock sourced from forest management slash
Manage_Wood_CumLoss_C_stock	Cumulative loss in wood product carbon stock sourced from forest management, from decay in landfills
Manage_TotWood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from forest management (harvest plus extra slash utilization)
Manage_Harv2Wood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from forest management harvest
Manage_Slash2Wood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from forest management slash
Manage_Wood_AnnLoss_C_stock	Annual loss in wood product carbon stock sourced from forest management, from decay in landfills
LCC_Wood_C_stock	Persistent wood product carbon stock sourced from land cover change
LCC_TotWood_CumGain_C_stock	Cumulative gain in wood product carbon stock sourced from land cover change (harvest plus extra slash utilization)
LCC_Harv2Wood_CumGain_C_stock	Cumulative gain in wood product carbon stock sourced from land cover change harvest
LCC_Slash2Wood_CumGain_C_stock	Cumulative gain in wood product carbon stock sourced from land cover change slash
LCC_Wood_CumLoss_C_stock	Cumulative loss in wood product carbon stock sourced from land cover change, from decay in landfills
LCC_TotWood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from land cover change (harvest plus extra slash utilization)

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	Definition
LCC_Harv2Wood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from land cover change harvest
Wood product carbon stock (Mg C) (Cont.)	
LCC_Slash2Wood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from land cover change slash
LCC_Wood_AnnLoss_C_stock	Annual loss in wood product carbon stock sourced from land cover change, from decay in landfills
Land-Atmosphere carbon exchange (Mg C)	
Eco_CumGain_C_stock	Cumulative net gain in ecosystem carbon stock from atmosphere
Total_Atmos_CumGain_C_stock	Cumulative emissions of carbon from forest management, wildfire, land cover change, and landfill wood product decay
Manage_Atmos_CumGain_C_stock	Cumulative emissions of carbon from forest management
Fire_Atmos_CumGain_C_stock	Cumulative emissions of carbon from wildfire
LCC_Atmos_CumGain_C_stock	Cumulative emissions of carbon from land cover change
Wood_Atmos_CumGain_C_stock	Cumulative emissions of carbon from landfill wood product decay
Total_Energy2Atmos_C_stock	Cumulative emissions of carbon from biomass energy associated with forest management and land cover change
Eco_AnnGain_C_stock	Annual net gain in ecosystem carbon stock from atmosphere
Total_Atmos_AnnGain_C_stock	Annual emissions of carbon from forest management, wildfire, land cover change, and landfill wood product decay
Manage_Atmos_AnnGain_C_stock	Annual emissions of carbon from forest management
Fire_Atmos_AnnGain_C_stock	Annual emissions of carbon from wildfire
LCC_Atmos_AnnGain_C_stock	Annual emissions of carbon from land cover change
Wood_Atmos_AnnGain_C_stock	Annual emissions of carbon from landfill wood product decay
Total_AnnEnergy2Atmos_C_stock	Annual emissions of carbon from biomass energy associated with forest management and land cover change
Partitioning of land-atmosphere carbon exchange (Mg C) (all carbon emissions)	

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Manage_Atmos_CumGain_FireC	Cumulative emissions of carbon from controlled burning due to forest management (prescribed burns and slash burning)
Partitioning of land-atmosphere carbon exchange (Mg C) (all carbon emissions) (Cont.)	
Manage_Atmos_CumGain_TotEnergyC	Cumulative emissions of carbon from total bioenergy due to forest management (harvest plus extra slash utilization)
Man_Atmos_CumGain_Harv2EnergyC	Cumulative emissions of carbon from bioenergy due to Forest management harvest
Man_Atmos_CumGain_Slash2EnergyC	Cumulative emissions of carbon from bioenergy due to Forest management extra slash utilization
Manage_Atmos_CumGain_NonBurnedC	Cumulative emissions of carbon from in situ and sawmill decay due to forest management (excludes wood product decay in landfills)
Fire_Atmos_CumGain_BurnedC	Cumulative emissions of carbon from burning due to wildfire
Fire_Atmos_CumGain_NonBurnedC	Cumulative emissions of carbon from decay due to wildfire
LCC_Atmos_CumGain_FireC	Cumulative emissions of carbon from slash burning due to land cover change (default is 0)
LCC_Atmos_CumGain_TotEnergyC	Cumulative emissions of carbon from total bioenergy due to conversion of Forest to Urban Area or Cultivated Land (harvest plus extra slash utilization)
LCC_Atmos_CumGain_Harv2EnergyC	Cumulative emissions of carbon from bioenergy due to harvest due to conversion of Forest to Urban Area or Cultivated Land
LCC_Atmos_CumGain_Slash2EnergyC	Cumulative emissions of carbon from bioenergy due to extra slash utilization associated with conversion of Forest to Urban Area or Cultivated Land (default is 0)
LCC_Atmos_CumGain_NonBurnedC	Cumulative emissions of carbon from in situ and sawmill decay due to forest management (excludes wood product decay in landfills)
Manage_Atmos_AnnGain_FireC	Annual emissions of carbon from controlled burning due to forest management (prescribed burns and slash burning)
Manage_Atmos_AnnGain_TotEnergyC	Annual emissions of carbon from total bioenergy due to forest management (harvest plus extra slash utilization)
Man_Atmos_AnnGain_Harv2EnergyC	Annual emissions of carbon from bioenergy due to Forest management harvest
Man_Atmos_AnnGain_Slash2EnergyC	Annual emissions of carbon from bioenergy due to Forest management extra slash utilization

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Manage_Atmos_AnnGain_NonBurnedC	Annual emissions of carbon from in situ and sawmill decay due to forest management (excludes wood product decay in landfills)
Partitioning of land-atmosphere carbon exchange (Mg C) (all carbon emissions) (Cont.)	
Fire_Atmos_AnnGain_BurnedC	Annual emissions of carbon from burning due to wildfire
Fire_Atmos_AnnGain_NonBurnedC	Annual emissions of carbon from decay due to wildfire
LCC_Atmos_AnnGain_FireC	Annual emissions of carbon from slash burning due to land cover change (default is 0)
LCC_Atmos_AnnGain_TotEnergyC	Annual emissions of carbon from total bioenergy due to conversion of Forest to Urban Area or Cultivated Land (harvest plus extra slash utilization)
LCC_Atmos_AnnGain_Harv2EnergyC	Annual emissions of carbon from bioenergy due to harvest associated with conversion of Forest to Urban Area or Cultivated Land
LCC_Atmos_AnnGain_Slash2EnergyC	Annual emissions of carbon from bioenergy due to extra slash utilization associated with conversion of Forest to Urban Area or Cultivated Land (default is 0)
LCC_Atmos_AnnGain_NonBurnC	Annual emissions of carbon from in situ and sawmill decay due to land cover change (excludes wood product decay in landfills)
Man_Atmos_AnnGain_SawmillDecayC	Annual emissions of carbon from sawmill decay due to forest management harvest
Man_Atmos_AnnGain_InFrstDecayC	Annual emissions of carbon from in situ decay due to forest management
Man_Atmos_CumGain_SawmillDecayC	Cumulative emissions of carbon from sawmill decay due to forest management harvest
Man_Atmos_CumGain_InFrstDecayC	Cumulative emissions of carbon from in situ decay of carbon due to forest management
LCC_Atmos_AnnGain_SawmillDecayC	Annual emissions of carbon from sawmill decay associated with conversion of Forest to Urban Area or Cultivated Land
LCC_Atmos_AnnGain_OnSiteDecayC	Annual emissions of carbon from in situ decay due to land cover change
LCC_Atmos_CumGain_SawmillDecayC	Cumulative emissions of carbon from sawmill decay associated with conversion of Forest to Urban Area or Cultivated Land
LCC_Atmos_CumGain_OnSiteDecayC	Cumulative emissions of carbon from in situ decay due to land cover change
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative)	

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Eco_CumCO2	Cumulative ecosystem CO_2 exchange (includes management and climate effects on soil and vegetation C exchange and mortality)
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
Eco_CumCH4eq	Cumulative ecosystem CH_4 exchange (includes management and climate effects on soil and vegetation C exchange and mortality)
ManTotEnergy_CumCO2	Cumulative CO_2 emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManTotEnergy_CumCH4eq	Cumulative CH_4 emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManTotEnergy_CumBCeq	Cumulative BC emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManHarv2Energy_CumCO2	Cumulative CO_2 emissions from bioenergy due to Forest management harvest
ManHarv2Energy_CumCH4eq	Cumulative CH_4 emissions from bioenergy due to Forest management harvest
ManHarv2Energy_CumBCeq	Cumulative BC emissions from bioenergy due to Forest management harvest
ManSlash2Energy_CumCO2	Cumulative CO_2 emissions from bioenergy due to Forest management extra slash utilization
ManSlash2Energy_CumCH4eq	Cumulative CH_4 emissions from bioenergy due to Forest management extra slash utilization
ManSlash2Energy_CumBCeq	Cumulative BC emissions from bioenergy due to Forest management extra slash utilization
ManFire_CumCO2	Cumulative CO_2 emissions from controlled burning due to forest management (prescribed burns and slash burning)
ManFire_CumCH4eq	Cumulative CH_4 emissions from controlled burning due to forest management (prescribed burns and slash burning)
ManFire_CumBCeq	Cumulative BC emissions from controlled burning due to forest management (prescribed burns and slash burning)
ManNonBurn_CumCO2	Cumulative CO_2 emissions from in situ and sawmill decay due to forest management (excludes wood product decay in landfills)
ManSawmillDecay_AnnCO2	Annual CO_2 emissions from sawmill decay due to Forest management
ManForestDecay_AnnCO2	Annual CO_2 emissions from in situ decay due to Forest management

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
ManSawmillDecay_CumCO2	Cumulative CO_2 emissions from sawmill decay due to Forest management
ManForestDecay_CumCO2	Cumulative CO_2 emissions from in situ decay due to Forest management
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
LCCTotEnergy_CumCO2	Cumulative CO_2 emissions from total bioenergy due to conversion of Forest to Urban Area or Cultivated Land (harvest plus extra slash utilization)
LCCTotEnergy_CumCH4eq	Cumulative CH_4 emissions from total bioenergy due to conversion of Forest to Urban Area or Cultivated Land (harvest plus extra slash utilization)
LCCTotEnergy_CumBCeq	Cumulative BC emissions from total bioenergy due to conversion of Forest to Urban Area or Cultivated Land (harvest plus extra slash utilization)
LCCHarv2Energy_CumCO2	Cumulative CO_2 emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCHarv2Energy _CumCH4eq	Cumulative CH_4 emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCHarv2Energy_CumBCeq	Cumulative BC emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCSlash2Energy_CumCO2	Cumulative CO_2 emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCSlash2Energy_CumCH4eq	Cumulative CH_4 emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCSlash2Energy_CumBCeq	Cumulative BC emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCFire_CumCO2	Cumulative CO_2 emissions from slash burning due to land cover change (default is 0)
LCCFire_CumCH4eq	Cumulative CH_4 emissions from slash burning due to land cover change (default is 0)
LCCFire_CumBCeq	Cumulative BC emissions from slash burning due to land cover change (default is 0)
LCC_NonBurn_CumCO2	Cumulative CO_2 emissions due land cover change, including in situ and sawmill decay (excludes

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
	landfill decay of wood products)
LCCSawmillDecay_AnnCO2	Annual CO_2 emissions from sawmill decay due to land cover change associated with conversion from Forest to Urban Area or Cultivated Land
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
LCCOnSiteDecay_AnnCO2	Annual CO_2 emissions from in situ decay due to land cover change associated with land cover change
LCCSawmillDecay_CumCO2	Cumulative CO_2 emissions from sawmill decay due to land cover change associated with conversion from Forest to Urban Area or Cultivated Land
LCCOnSiteDecay_CumCO2	Cumulative CO_2 emissions from in situ decay due to land cover change
Wildfire_Decay_AnnCO2	Annual CO_2 emissions from decay due to wildfire
Wildfire_Decay_CumCO2	Cumulative CO_2 emissions from decay due to wildfire
TotalEnergy_CumCO2	Cumulative CO_2 emissions from all bioenergy
TotalEnergy_CumCH4eq	Cumulative CH_4 emissions from all bioenergy
TotalEnergy_CumBCeq	Cumulative BC emissions from all bioenergy
TotalCntlFire_CumCO2	Cumulative CO_2 emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
TotalCntlFire_CumCH4eq	Cumulative CH_4 emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
TotalCntlFire_CumBCeq	Cumulative BC emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
Wildfire_CumCO2	Cumulative CO_2 emissions from wildfire (decay plus burning)
Wildfire_CumCH4eq	Cumulative CH_4 emissions from wildfire
Wildfire_CumBCeq	Cumulative BC emissions from wildfire
Wood_CumCO2	Cumulative CO_2 emissions from all landfill decay of wood products (forest management and land cover change)

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
Wood_CumCH4eq	Cumulative CO_2 emissions from all landfill decay of wood products (forest management and land cover change)
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
Eco_AnnCO2	Annual ecosystem CO_2 exchange (includes management and climate effects on soil and vegetation C exchange and mortality)
Eco_AnnCH4eq	Annual ecosystem CH_4 exchange (includes management and climate effects on soil and vegetation C exchange and mortality)
ManTotEnergy_AnnCO2	Annual CO_2 emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManTotEnergy_AnnCH4eq	Annual CH_4 emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManTotEnergy_AnnBCeq	Annual BC emissions from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManHarv2Energy_AnnCO2	Annual CO_2 emissions from bioenergy due to Forest management harvest
ManHarv2Energy_AnnCH4eq	Annual CH_4 emissions from bioenergy due to Forest management harvest
ManHarv2Energy_AnnBCeq	Annual BC emissions from bioenergy due to Forest management harvest
ManSlash2Energy_AnnCO2	Annual CO_2 emissions from bioenergy due to Forest management extra slash utilization
ManSlash2Energy_AnnCH4eq	Annual CH_4 emissions from bioenergy due to Forest management extra slash utilization
ManSlash2Energy_AnnBCeq	Annual BC emissions from bioenergy due to Forest management extra slash utilization
ManFire_AnnCO2	Annual CO_2 emissions from from controlled burning due to forest management (prescribed burns and slash burning)
ManFire_AnnCH4eq	Annual CH_4 emissions from controlled burning due to forest management (prescribed burns and slash burning)
ManFire_AnnBCeq	Annual BC emissions from controlled burning due to forest management (prescribed burns and slash burning)
ManNonBurn_AnnCO2	Annual CO_2 emissions from in situ and sawmill decay due to forest management (excludes wood product decay in landfills)

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
LCCTotEnergy_AnnCO2	Annual CO_2 emissions from bioenergy due to conversion from Forest to Urban Area or Cultivated Land from Forest (harvest plus extra slash utilization)
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
LCCTotEnergy_AnnCH4eq	Annual CH_4 emissions from bioenergy due to conversion from Forest to Urban Area or Cultivated Land from Forest (harvest plus extra slash utilization)
LCCTotEnergy_AnnBCeq	Annual BC emissions from bioenergy due to conversion from Forest to Urban Area or Cultivated Land from Forest (harvest plus extra slash utilization)
LCCHarv2Energy_AnnCO2	Cumulative CO_2 emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCHarv2Energy_AnnCH4eq	Cumulative CH_4 emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCHarv2Energy_AnnBCeq	Cumulative BC emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCSlash2Energy_AnnCO2	Cumulative CO_2 emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCSlash2Energy_AnnCH4eq	Cumulative CH_4 emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCSlash2Energy_AnnBCeq	Cumulative BC emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
LCCFire_AnnCO2	Cumulative CO_2 emissions from slash burning due to land cover change (default is 0)
LCCFire_AnnCH4eq	Cumulative CH_4 emissions from slash burning due to land cover change (default is 0)
LCCFire_AnnBCeq	Cumulative BC emissions from slash burning due to land cover change (default is 0)
LCC_NonBurn_AnnCO2	Annual CO_2 emissions due land cover change, including in situ and sawmill decay (excludes landfill decay of wood products)

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
TotalEnergy_AnnCO2	Annual CO_2 emissions from all bioenergy
TotalEnergy_AnnCH4eq	Annual CH_4 emissions from all bioenergy
TotalEnergy_AnnBCeq	Annual BC emissions from all bioenergy
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
TotalCntlFire_AnnCO2	Annual CO_2 emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
TotalCntlFire_AnnCH4eq	Annual CH_4 emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
TotalCntlFire_AnnBCeq	Annual BC emissions from total controlled burning (prescribed burns and slash burning) associated with forest management and land cover change
Wildfire_AnnCO2	Annual CO_2 emissions from wildfire (decay plus burning)
Wildfire_AnnCH4eq	Annual CH_4 emissions from wildfire
Wildfire_AnnBCeq	Annual BC emissions from wildfire
Wood_AnnCO2	Annual CO_2 emissions from all landfill decay of wood products (forest management and land cover change)
Wood_AnnCH4eq	Annual CO_2 emissions from all landfill decay of wood products (forest management and land cover change)
Total_CumCO2	Cumulative CO_2 exchange from all sources
Total_CumCH4eq	Cumulative CH_4 exchange from all sources
Total_CumBCeq	Cumulative BC exchange from all sources
Total_AnnCO2	Annual CO_2 exchange from all sources
Total_AnnCH4eq	Annual CH_4 exchange from all sources
Total_AnnBCeq	Annual BC exchange from all sources
TotalWood_CumCO2eq_all	Cumulative emissions of CO_2 and CH_4 from landfill decay of wood products
TotalWood_AnnCO2eq_all	Annual emissions of CO_2 and CH_4 from landfill decay of wood products

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	**Definition**
TotalNonBurn_CumCO2eq_all	Cumulative exchange of CO_2 and CH_4 from all sources excluding controlled burning and wildfire
TotalFire_CumCO2eq_all	Cumulative emissions of CO_2, CH_4, and BC from controlled burning (prescribed burn and slash burning) and wildfire
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (Cont.)	
TotalEnergy_CumCO2eq_all	Cumulative emissions of CO_2, CH_4, and BC from all bioenergy (forest management and land cover change)
TotalNonBurn_AnnCO2eq_all	Annual exchange of CO_2 and CH_4 from all sources excluding all controlled burning and wildfire
TotalFire_AnnCO2eq_all	Annual emissions of CO_2, CH_4, and BC from controlled burning (prescribed burn and slash burning) and wildfire
TotalEnergy_AnnCO2eq_all	Annual emissions of CO_2, CH_4, and BC from all bioenergy (forest management and land cover change)
TotalBurn_CumCO2eq_all	Cumulative exchange of CO_2, CH4, and BC from all controlled burning and wildfire
TotalBurn_AnnCO2eq_all	Annual exchange of CO_2, CH_4, and BC from all controlled burning and wildfire
Total_CumCO2eq_all	Cumulative exchange of CO_2, CH_4, and BC from all sources
Total_AnnCO2eq_all	Annual exchange of CO_2, CH_4, and BC from all sources
Additional partitioning of BC-C emissions (Mg C)	
ManFire_CumBCC	Cumulative emissions of BC from controlled burning due to Forest management (prescribed burn and slash burning)
ManTotEnergy_CumBCC	Cumulative emissions of BC from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManHarv2Energy_CumBCC	Cumulative emissions of BC from bioenergy due to Forest management harvest
ManSlash2Energy_CumBCC	Cumulative emissions of BC from bioenergy due to Forest management extra slash utilization
LCCFire_CumBCC	Cumulative BC emissions from slash burning due to land cover change (default is 0)
LCCTotEnergy_CumBCC	Cumulative BC emissions from bioenergy due to conversion from Forest to Urban Area or Cultivated Land from Forest (harvest plus extra slash utilization)

Appendix G: CALAND Output variables and definitions (214 variables)

These outputs are generated by running the CALAND() function defined in the CALAND.r file. The data are stored in an individual Excel workbook (.xls) for each scenario. Each variable corresponds to an individual worksheet within the file (in order below). There are values for each land category and each year simulated, as well as aggregated values by land type, ownership, and region at the bottom of each table.

Parameter	Definition
LCCHarv2Energy_CumBCC	Cumulative BC emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
LCCSlash2Energy_CumBCC	Cumulative BC emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)
Additional partitioning of BC-C emissions (Mg C) (Cont.)	
Wildfire_CumBCC	Cumulative emissions of BC from wildfire
ManFire_AnnBCC	Annual emissions of BC from wildfire
ManTotEnergy_AnnBCC	Annual emissions of BC from controlled burning due to Forest management (prescribed burn and slash burning)
ManHarv2Energy_AnnBCC	Annual emissions of BC from total bioenergy due to Forest management (harvest plus extra slash utilization)
ManSlash2Energy_AnnBCC	Annual emissions of BC from bioenergy due to Forest management harvest
LCCFire_AnnBCC	Annual emissions of BC from bioenergy due to Forest management extra slash utilization
LCCTotEnergy_AnnBCC	Annual BC emissions from slash burning due to land cover change (default is 0)
LCCHarv2Energy_AnnBCC	Annual BC emissions from bioenergy due to conversion from Forest to Urban Area or Cultivated Land from Forest (harvest plus extra slash utilization)
LCCSlash2Energy_AnnBCC	Annual BC emissions from bioenergy due to harvest associated with conversion from Forest to Urban Area or Cultivated Land
Wildfire_AnnBCC	Annual BC emissions from bioenergy due to extra slash utilization associated with conversion from Forest to Urban Area or Cultivated Land (default is 0)

References

Battles, J.J., Gonzalez, P., Robards, T., Collins, B.M., and Saah, D.S., (2014). California forest and rangeland greenhouse gas inventory development final report. California Air Resources Board Agreement 10-778, Jan 2014.

Birdsey, R.A., and Lewis, G.M. (2002). Carbon in U.S. forests and wood products, 1987-1997: state-by-state estimates. General Technical Report NE-310, USFS, Northeastern Research Station.

Bond-Lamberty, B., Calvin, K., Jones, A.D., Mao, J., Patel, P., Shi, X.Y., Thomson, A., Thornton, P., Zhou, Y. (2014). On linking an Earth system model to the equilibrium carbon representation of an economically optimizing land use model. Geoscientific Model Development, 7:2545-2555. DOI: 10.5194/gmd-7-2545-2014.

Brown, S., Pearson, T., Dushku, A., Kadyzewski, J., and Qi, Y. (2004). Baseline greenhouse gas emissions for forest, range, and agricultural lands in California. Winrock International, for the California Energy Commission. PIER Energy-Related Environmental Research. 500-04-069F.

CA (2019) Draft: California 2030 Natural and Working Lands Climate Change Implementation Plan. https://www.arb.ca.gov/cc/natandworkinglands/draft-nwl-ip-040419.pdf

CAL FIRE (2016). Program Environmental Impact Report for the Vegetation Treatment Program. Chapter 5: Cumulative effects analysis. Draft, March 2016.

Callaway, J.C., Borgnis, E.L., Turner, R.E., and Milan, C.S. (2012). Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands. Estuaries and Coasts, 35:1163-1181. DOI: 10.1007/s12237-012-9508-9.

CARB, (2016). California's 2000-2014 Greenhouse Gas Emission Inventory: Technical Support Document. State of California Air Resources Board, Air Quality Planning and Science Division, September 2016.

Carreras-Sospedra, M., MacKinnon, M., Dabdub, D., and Williams, R., (2015). Assessment of the emissions and energy impacts of biomass and biogas use in California, California Air Resources Board, Agreement #11-307, Feb. 27, 2015.

CCED (2015). California Conservation Easement Database, version 2015a: Database manual, April 2015. Greeninfo Network.

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., and Lynch, J.C. (2003). Global carbon sequestration in tidal, saline wetland soils. Global Biogeochemical Cycles, 17(4):1111. DOI: 10.1029/2002GB001917.

Christensen, G.A, Grray, A.N., Kuegler, O., Tase, N.A., Rosenburg, M. (2017). AB 1504 California forest ecosystem and harvested wood product carbon inventory: 2006-2015. Final Report. California Department of Forestry and Fire Protection agreement no. 7CA02025. Sacramento, CA: California Department of Forestry and Fire Protection and California Board of Forestry and Fire Protection. 390p.

CNRA (2017). California Forest Carbon Plan: Managing our forest landscapes in a changing climate. Draft, January 20, 2017. CNRA, CALFIRE, CAL EPA. http://www.fire.ca.gov/fcat/downloads/California%20Forest%20Carbon%20Plan%20Draft%20for%20Public%20Review_Jan17.pdf.

Collins, W.D., Craig, A.P., Truesdale, J.E., Di Vittorio, A.V., Jones, A.D., Bond-Lamberty, B., Calvin, K.V., Edmonds, J.A., Kim, S.H., Thomson, A.M., Patel, P., Zhou, Y., Mao, J., Shi, X., Thornton, P.E., Chini, L.P., Hurtt, G.C. (2015). The integrated Earth system model version 1: formulation and functionality. Geoscientific Model Development, 8:2203-2219. DOI: 10.5194/gmd-8-2203-2015.

Collins, B.M., Stevens, J.T., Miller, J.D., Stephens, S.L., Brown, P.M., North, M.P. (2017). Alternative characterization of forest fire regimes: incorporating spatial patterns. Landscape Ecology, 32:1543-1552. DOI: 10.1007/s10980-017-0528-5.

Davidson, E.A., and Ackerman, I.L. (1993). Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry, 20(3):161-193.

Davies, L., and Gather, U. (1993). The identification of multiple outliers. Journal of the American Statistical Assoication, 88(423):782-792. DOI: 10.2307/2290763.

Deverel, S., personal communication, Principal Hydrologist, Hydrofocus, Inc. Dingman, J., personal communication, Staff, California Air Resources Board.

Dore, S., Fry, D.L., Collins, B.M., Vargas, R., York, R.A., Stephens, S.L. (2016). Management impacts on carbon dynamics in a Sierra Nevada mixed conifer forest. PLOS ONE, 11(2):e0150256. DOI: 10.1371/journal.pone.0150256.

Drexler, J.Z., Fuller, C.C., Orlando, J., and Moore, P.E. (2015). Recent rates of carbon accumulation in montane fens of Yosemite National Park, California, U.S.A. Arctic, Antarctic, and Alpine Research, 47(4):657-669. DOI: 10.1657/AAAR0015-002.

Evans, R.D., Koyama, A., Sonderegger, D.L., Charlet, T.N., Newingham B.A., Fenstermaker, L.F., Harlow, B., Jin, V.L., Ogle, K., Smith, S.D., and Nowak R.S. (2014). Greater ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO_2. Nature Climate Change. DOI: 10.1038/NCLIMATE2184.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R. (2007). 2007: Changes in atmospheric constituents and in radiative forcing, in: Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor, and H.L. Miller Cambridge Univ. Press, Cambridge, UK, and New York. p. 129–234.

FRAP (2010). Chapter 1.2: Sustainable working forests and rangelands. In: California's forests and rangelands: 2010 assessment. CALFIRE FRAP.

Gonzalez, P., Battles, J.J., Collins, B.M., Robards, T., Saah, D.S. (2015). Aboveground live carbon stock changes of California wildland ecosystems, 2001- 2010. Forest Ecology and Management, 348:68-77. DOI: 10.1016/j.foreco.2015.03.040.

Gwynne, B., personal communication, Senior Environmental Scientist, California Department of Conservation.

Harmon, M.E., Cromack, K., Smith, B.G. (1987). Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Canadian Journal of Forest Research, 17:1265-1272.

Hastings, S.J., Oechel, W.C., and Muhlia-Melo, A. (2005). Diurnal, seasonal and annual variation in the net ecosystem CO_2 exchange of a desert shrub community (Sarcocaulescent) in Baja California, Mexico. Global Change Biology, 11:927-939. DOI: 10.1111/j.1365-2486.2005.00951.x.

Hatala, J.A., Detto, M., Sonnentag, O., Deverel, S.J., Verfaillie, J., Baldocchi, D.D. (2012). Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. Agriculture, Ecosystems, and Environment, 150:1-18. DOI: 10.1016/j.agee.2012.01.009.

Hudiburg, T., Law, B., Turner, D.P., Campbell, J., Donato, D., and Duane, M. (2009). Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. Ecological Applications, 19(1):163-180.

IPCC (2006a). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land use. Chapter 12: Harvested Wood Products.

IPCC (2006b). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. Chapter 3: Solid Waste Disposal.

Jenkins, B.M. et al. (1996) Atmospheric Pollutant Emission Factors from Open Burning of Agricultural and Forest Biomass by Wind Tunnel Simulations, Vol. 1-3. Final Report, ARB contract A932-126. University of California, Davis, CA.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., and Birdsey, R.A. (2003). National- scale biomass estimators for United States tree species. Forest Science, 49(1):12-35.

Knox, S.H., Sturtevant, S., Matthes, J.H., Koteen, L., Verfaillie, J., and Baldocchi, D. (2015). Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH_4) fluxes in the Sacramento-San Joaquin Delta. Global Change Biology, 21:750-765. DOI: 10.1111/gcb.12745.

Ko, J., personal communication, Climate Change and Ecosystem Services Program Lead, U.S. Forest Service.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C. (2005). The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Science Society of America Journal, 69:1078-1085 doi: 10.2136/sssaj2004.0215.

Kroodsma, D.A. and Field, C.B. (2006). Carbon sequestration in California agriculture, 1980-2000. Ecological applications, 16(5):1975-1985.

Sleeter, B. M., Wilson, T. S., Sharygin, E., and Sherba, J. (2017). Future Scenarios of Land Change Based on Empirical Data and Demographic Trends, Earth's Future, 5, 1068–1083, https://doi.org/10.1002/2017EF000560.

Ma, S., Baldocchi, D.D., Xu, L., and Hehn, T. (2007). Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. Agricultural and Forest Meteorology, 147:157-171. DOI: 10.1016/j.agrformet.2007.07.008.

McIver, C.P., Meek, J.P., Scudder, M.G., Sorenson, C.B., Morgan, T.A., Christensen, G.A. (2015). California's forest products industry and timber harvest, 2012. Gen. Tech. Rep. PNW-GTR-908. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 49p.

McPherson, E.G., Xiao, Q., van Doorn, N.S., de Geode, J., Bjorkman, J., Hollander, A., Boynton, R.M., Quinn, J., Thorne, J.H., (2017). The structure, function and value of urban forests in California communities. Urban Forestry and Urban Greening, 28:43-53.

Miller, J.D., and Safford, H.D. (2012). Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Cascades, California, USA. Fire Ecology, 8(3):41-57. DOI: 10.4996/fireecology.0803041.

Miller, J.D., Safford, H.D., Crimmins, M., and Thode, A.E. (2009). Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade mountains, California and Nevada, USA. Ecosystems, 12:16-32. DOI: 10.1007/s10021-008-9201-9.

Mitchell, J.P., Shrestha, A., Horwath, W.R., Southard, R.J., Madden, N., Veenstra, J., and Munk, D.S. (2015). Tillage and cover cropping affect crop yields and soil carbon in the San Joaquin Valley, California. Agronomy Journal, 107:588-596. DOI: 10.2134/agronj14.0415.

Mcleod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Bjork, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Frontiers in Ecology and the Environment, 9(10):552-560. DOI: 10.1890/110004.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang (2013), 2013: Anthropogenic and Natural Radiative Forcing, in: Climate Change 2013: The Physical Science Basis.

NOAA (2014). California eelgrass mitigation policy and implementing guidelines. NOAA Fisheries, West Coast Region, Oct. 2014.

Pearson, T., Brown, S., and Netzer, N. (2009). Baseline greenhouse gas emissions and removals for forests and rangelands in California. Winrock International, for the California Energy Commission. PIER Energy-Related Environmental Research.

Pouyat, R.V., Yesilonis, I.D., and Nowak, D.J. (2006). Carbon storage by urban soils in the United States. Journal of Environmental Quality, 35:1566-1575. DOI: 10.2134/jeq2005.0215.

Powers, R.F., Busse, M.D., McFarlane, K.J., Zhang, J., and Young, D.H. (2013). Long-term effects of silviculture on soil carbon storage: does vegetation control make a difference? Forestry, 86:47-58. DOI: 10.1093/forestry/cps067.

Quideau, S.A., Graham, R.C., Chadwick, O.A., and Wood, H.B. (1998). Organic carbon sequestration under chaparral and pine after four decades of soil development. Geoderma, 83:227-242.

Robards, T. and Nickerson J. (2013). Appendix 3: Carbon dioxide (CO_2) emissions estimates associated with silviculture applications for California forests. In: Battles, J.J., Gonzalez, P., Robards, T., Collins, B.M., and Saah, D.S., California forest and rangeland greenhouse gas inventory development final report. California Air Resources Board Agreement 10-778, Jan 2014.

Ryals, R. and Silver, W.L. (2013). Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. Ecological Applications, 23(1):46-59.

Ryals, R., Hartman, M.D., Parton, W.J., DeLonge, M.S., and Silver, W.L. (2015). Long-term climate change mitigation potential with organic matter management on grasslands. Ecological Applications, 25(2):531-545.

Saah D., J. Battles, J. Gunn, T. Buchholz, D. Schmidt, G. Roller, and S. Romsos. 2016. Technical improvements to the greenhouse gas (GHG) inventory for California forests and other lands. Submitted to: California Air Resources Board, Agreement #14-757. 55 pages.

Silver, W.L., Ryals, R., and Eviner, V. (2010). Soil carbon pools in California's annual grassland ecosystems. Rangeland Ecology and Management, 63(1):128- 136. DOI: 10.2111/REM-D-09-00106.1.

Stevens, J.T., Collins, B.M., Miller, J.D., North, M.P., Stephens, S.L. (2017). Changing spatial patterns of stand-replacing fire in California conifer forests. Forest Ecology and Management, 406:28-36.

Stewart, W.C. and Nakamura, G.M. (2012). California: Linking harvests to the US greenhouse gas inventory. Forest Products Journal, 62(5):340-353.

Turk, J.K. and Graham, R.C. (2009). Soil carbon and nitrogen accumulation in a forested debris flow chronosequence, California. Soil Science Society of America Journal, 73:1504-1509. DOI: 10.2136/sssaj2008.0106.

USDA (2014). Gridded soil survey geographic (gSSURGO) database: User guide. Version 1.1, April 2014, National Soil Survey Center, National Geospatial Center of Excellence, Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p 2_053628.

Westerling, A.L. (2018). Wildfire simulations for California's Fourth Climate Change Assessment: Projecting changes in extreme wildfire events with a warming climate. California's

Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC-2018-014.

Wiechmann, M.L., Hurteau, M.D., North, M.P., Koch, G.W., Jerabkova, L. (2015). The carbon balance of reducing wildfire risk and restoring process: an analysis of 10-year post-treatment carbon dynamics in a mixed-conifer forest. Climatic Change, 132:709-719. DOI: 10.1007/s10584-015-1450-y.

Wilson, T., Woodall, C.W., and Griffith, D.M. (2013). Imputing forest carbon stock estimates from inventory plots to a nationally continuous coverage. Carbon Balance and Management, 8:1. http://www.cbmjournal.com/content/8/1/1.

Wohlfahrt, G., Fenstermaker, L.F., and Arnone, J.A. III (2008). Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. Global Change Biology, 14:1475:1487. DOI: 10.1111/j.1365-2468.2008.01593.x.

Wu, L., Wood, Y., Jiang, P., Li, L., Pan, G., Lu, J., Change, A.C., and Enloe, H.A. (2008). Carbon sequestration and dynamics of two irrigated agricultural soils in California. Soil Science Society of America Journal, 72:808-814. DOI: 10.2136/sssaj2007.0074.

Extended Bibliography for CALAND

The following references were reviewed during the development of CALAND, but the data were ultimately not used:

Black, T.A., J.W. Harden (1995). Effect of timber harvest on soil carbon storage at Blodgett Experimental Forest, California. Canadian Journal of Forest Research, 25:1385-1396.

Blankinship, J.C., S.C. Hart (2014). Hydrological control of greenhouse gas fluxes in a Sierra Nevada subalpine meadow. Arctic, Antarctic, and Alpine Research, 46(2):355-364.

Byrnes, R., V. Eviner, E. Kebreab, W.R. Horwath, L. Jackson, B. Jenkins, S. Kaffka, A. Kerr, J. Lewis, F. Mitloehner, J. Mitchell, K. Scow (2016). Leveraging research to inform California climate scoping plan: agriculture and working lands sectors. UC Davis World Food Center report to CA ARB.

De Gryze, S., A. Wolf, S.R. Kaffka, J. Mitchell, D.E. Rolston, S.R. Temple, J. Lee, J. Six (2010). Simulating greenhouse gas budgets of four California cropping systems under conventional and alternative management. Ecological Applications, 20(7):1805-1819.

DeLonge, M.S., Ryals, R. and Silver, W.L. 2013. A Lifecycle Model to Evaluate Carbon Sequestration Potential and Greenhouse Gas Dynamics of Managed Grasslands. Ecosystems, 16: 962–979.

Drexler, J.Z., C.C. Fuller, J.Orlando, P.E. Moore (2015). Recent rates of carbon accumulation in montane fens of Yosemite National Park, California, USA. Arctic, Antarctic, and Alpine Research, 47(4):657-669.

Gaman, T. (2008). Oaks 2040: Carbon resources in California oak woodlands. An inventory of carbon and California oaks. California Oak Foundation.

Gaman, T., J. Firman (2006). Oaks 2040: The status and future of oaks in California. General Technical Report PSW-GTR-217.

Jasoni, R.L., S.D. Smith, J.A. Arnone III (2005). Net ecosystem CO_2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO_2. Global Change Biology, 11:749-756.

Koteen, L.E., N. Raz-Yaseef, D.D. Baldocchi (2015). Spatial heterogeneity of fine root biomass and soil carbon in a California oak savanna illuminates plant functional strategy across periods of high and low resource supply. Ecohydrology, 8:294-308.

Luo, H., Oechel, W.C., Hastings, S.J., Zulueta, R., Qian, Y. and Kwon, H. 2007. Mature semiarid chaparral ecosystems can be a significant sink for atmospheric carbon dioxide. Glob. Chang. Biol., 13: 386–396.

McIntyre, P.J., J.H. Thorne, C.R. Dolanc, A.L. Flint, L.E. Flint, M. Kelley, D.D. Ackerly (2015). Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks. Proceedings of the National Academy of Sciences Early Edition, 6pp. doi: 10.1073/pnas.1410186112.

McPherson, E.G., Q. Xiao, E. Aguaron (2013). A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests. Landscape and Urban Planning, 120:70-84.

Norton, J.B., L.J. Jungst, U. Norton, H.R. Olsen, K.W. Tate, W.R. Horwath (2011). Soil carbon and nitrogen storage in upper montane riparian meadows. Ecosystems, 14(8):1217-1231.

Norton, J.B., H.R. Olsen, L.J. Jungst, D.E. Legg, W.R. Horwath (2014). Soil carbon and nitrogen storage in alluvial wet meadows of the southern Sierra Nevada mountains, USA. Journal of Soils Sediments, 10pp. doi: 10.1007/s11368-013-0797-9.

Smith, J.E., L.S. Heath, J.C. Jenkins (2003). Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests. General Technical Report NE-298. USDA FS.

Smith, J.E., L.S. Heath, K.E. Skog, R.A. Birdsey (2006). Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. General Technical Report NE-343. USDA FS.

Smukler, S.M., S. Sanchez-Moreno, S.J. Fonte, H. Ferris, K. Klonsky, A.T. O'Geen, K.M. Scow, K.L. Steenwerth, L.E. Jackson (2010). Biodiversity and multiple ecosystem functions in an organic farmscape. Agriculture, Ecosystems and Environment, 139:80-97.

Stephens, S.L., R.E.J. Boerner, J.J. Modhaddas, E.E.Y. Moghaddas, B.M. Collins, C.B. Dow, C. Edminster, C.E. Fiedler, D.L. Fry, B.R., Hartsough, J.E. Keeley, E.E. Knapp, J.D. McIver, C.N. Skinner, A. Youngblood (2012). Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. Ecoshpere, 3(5):38.

Teh, Y.A., W.L. Silver, O. Sonnentag, M. Detto, M. Kelly, D.D. Baldocchi (2011). Large greenhouse gas emissions from a temperate peatland pasture.
Ecosystems, 14(2):311-325.

Welch, K.R., H.D. Safford, T.P. Young (2016). Predicting conifer establishment post wildfire in mixed conifer forests of the North American Mediterranean- climate zone. Ecospere, 7(12):e01609.

Williams, J.N., A.D. Hollander, A.T. O'Geen, L.A. Thrupp, R. Hanifin, K. Steenwerth, G. McGouty, L.E. Jackson (2011). Assessment of carbon in woody plants and soil across a vineyard-woodland landscape. Carbon Balance and Management, 6:11.

Wohlfahrt, G., L.F. Fensermaker, J.A. Arnone III (2008). Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. Global Change Biology, 14:1475-1487.

Wu, L., A.C. Chang, B. McCullough-Sanden, K.M. Bali (2006). Quantitative and qualitative assessment of soil organic carbon in native and cropland soils in California. Kearny Foundation of Soil Science: Soil carbon and California's Terrestrial Ecosystems, Final Report: 2001033.

Xu, L., D.D. Baldocchi (2004). Seasonal variation in CO_2 exchange over a Mediterranean annual grassland in California. Agricultural and Forest Meteorology, 1232:79-96.