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

Version 3, December 2018

Technical Documentation

Alan Di Vittorio and Maegen B. Simmonds
Lawrence Berkeley National Laboratory

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Contents

1. Summary

The California Natural and Working Lands Carbon and Greenhouse Gas Model (CALAND) is an empirically based, carbon accounting model that simulates the effects of various management practices and land use or land cover change on carbon dynamics in all California lands, including land-atmosphere carbon dioxide (CO_2) exchange, and emissions of methane (CH_4) and black carbon (BC, optional) associated with wetlands function and biomass burning, respectively, and the global warming potential (GWP) of net emissions of these three greenhouse gases (GHGs)[1]. Starting with historical carbon stock and flux data and two options for historical land use/cover change[2], CALAND simulates annual carbon stocks and fluxes, including material flow to wood products and bioenergy, for given land use/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.

CALAND's primary function is to quantify the difference between expected net GHG emissions from a historically grounded, baseline land use and management scenario and net GHG emissions arising from alternative land use and management activities pursued on a range of spatiotemporal scales. 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. The alternative management scenarios developed for the Natural and Working Lands Climate Change Implementation Plan were developed in 2018. Currently, CALAND should be used only to examine differences between GHG emissions arising from the baseline and alternative scenarios, as opposed to absolute GHG emissions[3].

CALAND operates statewide on 940 land type categories plus ocean seagrass (Table 1, Figure 1)[4]. CALAND simulates one scenario at a time to generate a single output file using two input data files and one processing script (caland.r). The output file is an Excel workbook containing several tables as individual sheets. The two input

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

[2] 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.

[3] Currently, the absolute outputs for any individual scenario are not robust due to extremely high uncertainty of historical baseline land use/cover change, combined with unknown distribution and carbon dynamics of savanna/woodland with woody versus grass understory. Planned updates to the historical baseline using a land use change driven approach may improve absolute carbon projections, but do 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.

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

files are also Excel workbooks, which contain the model data and scenario, respectively. The model data are constant across compared scenarios and comprise an integration of many data sources for carbon densities, fluxes, land management, land conversion, and fire. These data sources are described here and detailed in the appendices to this report. Each scenario 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. Each scenario is defined in its own input file. Due to the complexity of the input file, there is a function (write_caland_inputs.r) that reads raw data and generates the input file. Most of these raw data are given, but the user must create a raw scenario input file that defines one or more management scenarios. The raw scenario input file can use either acres or hectares as the area units, and these are converted to hectares by the write_caland_inputs function. There is a primary diagnostic plotting function (plot_caland.r) for creating figures from two or more scenario outputs, and two additional functions (plot_scen_types.r, plot_uncertainty.r) to create additional plots (see section 3). All functions are implemented in R (www.r-project.org).

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).

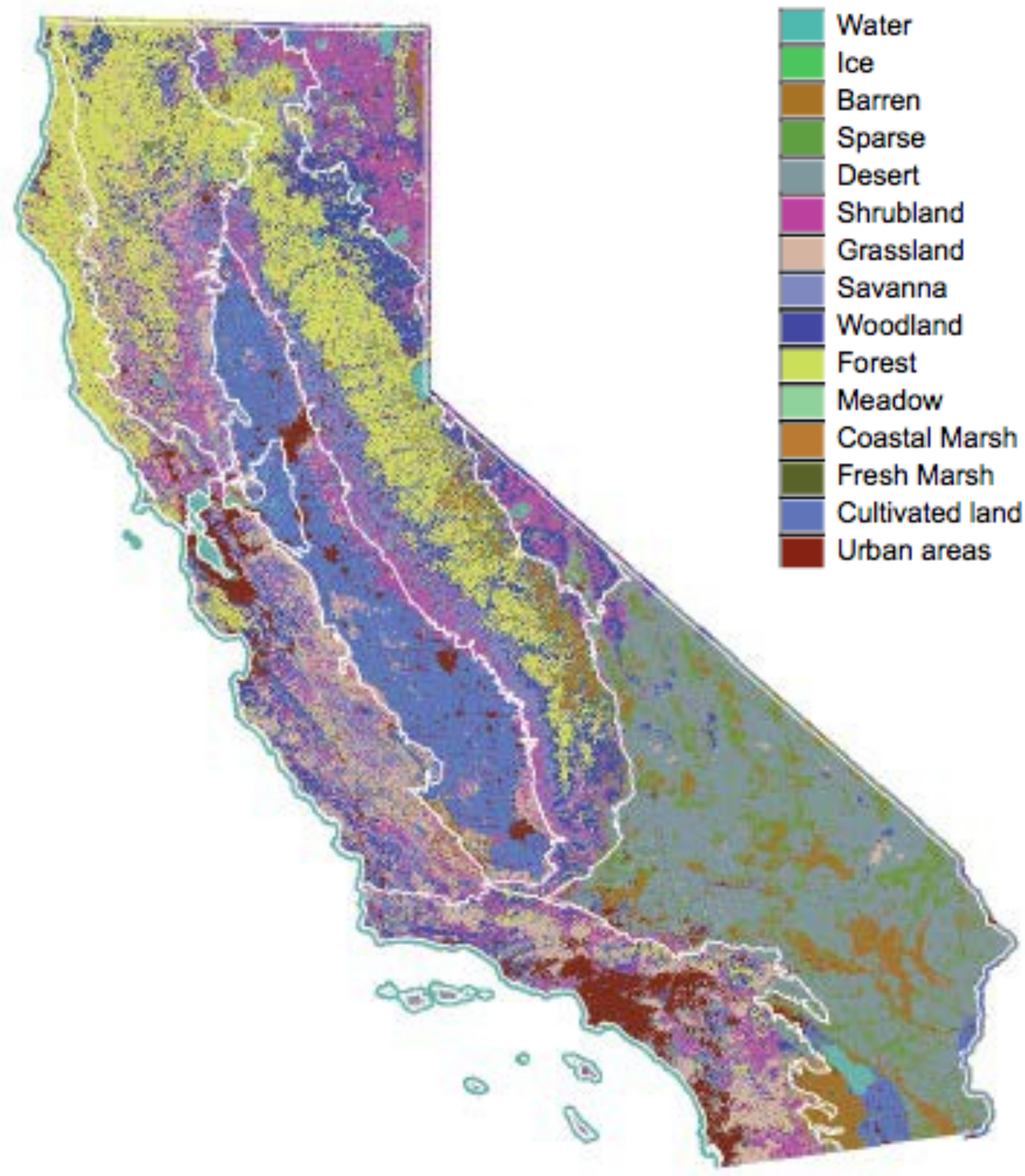
Spatial Regions	Ownership Classes	Land Cover Types	
Central Coast	U.S. Bureau of Land Management	Barren	Savanna
Central Valley	National Park Service	Cultivated Land	Seagrass
Sacramento-San Joaquin Delta	U.S. Department of Defense	Desert	Shrubland
Deserts	USDA Forest Service (non-wilderness)	Forest	Sparse
Eastside	Other Federal Government[5]	Fresh Marsh	Coastal Marsh
Klamath	State Government	Grassland	Urban Area
North Coast	Local Government	Ice	Water
Sierra Cascades	Private	Meadow	Woodland
South Coast	Conservation Easement Protected		

[5] 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

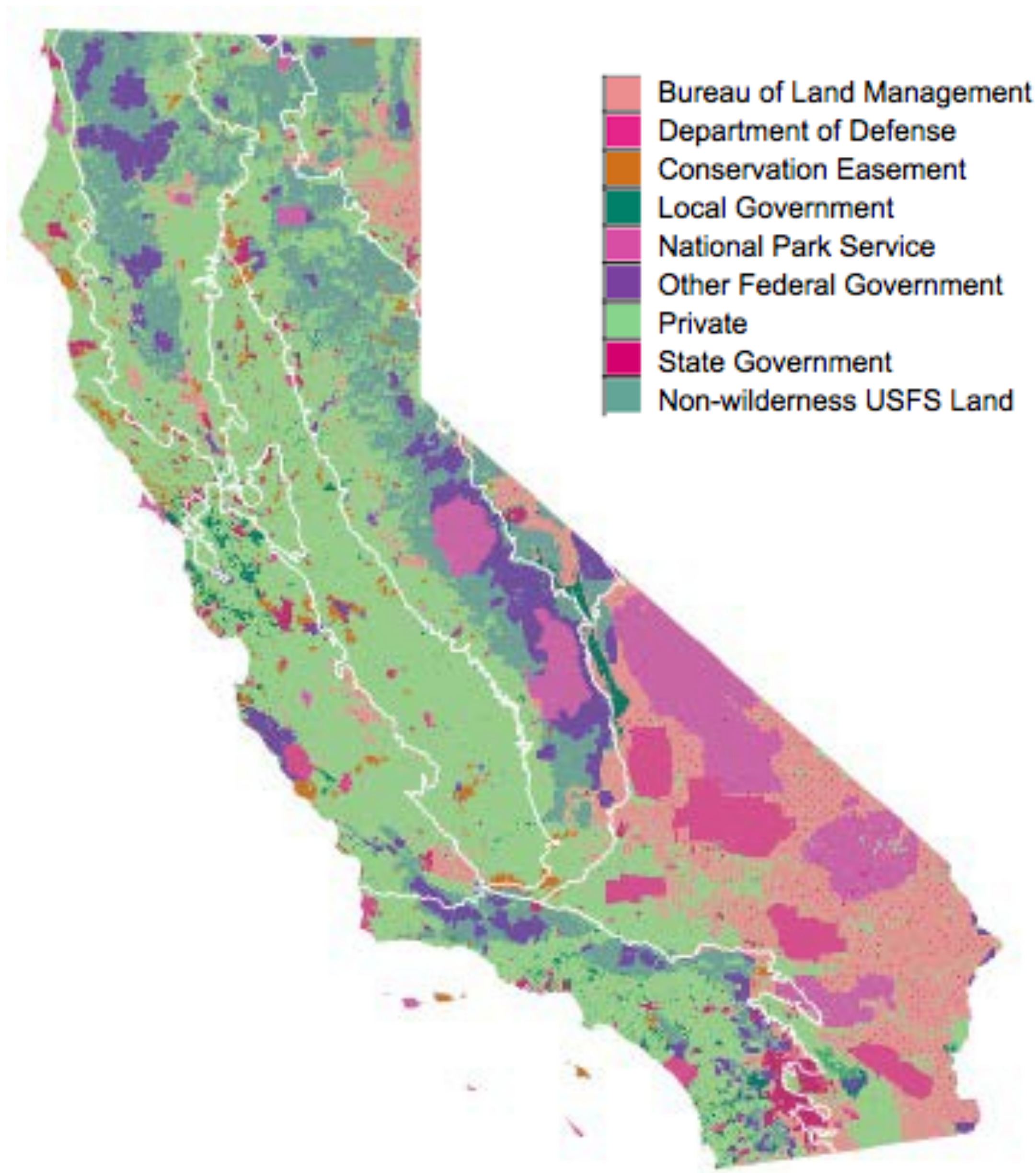
Figure 1: CALAND Land Categories

Corresponding to Table 1. The land categories are defined by the intersection of nine spatial regions (delineated by white lines), a) 15 land cover types, and b) nine ownership classes. Seagrass is considered separately.

a) 15 land cover types



b) Nine ownership classes



2. Model structure

CALAND is an empirically-based, database model that projects the accumulation and fate of above- and below-ground carbon in up to seven carbon pools (Table 2); carbon flow to wood products and bioenergy; and emissions of CO_2, CH_4, and BC, for a given set of land categories, under a variety of management activities. 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). Optionally, BC can be emitted separately with its corresponding GWP of 900. CALAND relies on California-specific data from academic literature, state institutions, and state partner organizations. It simulates carbon stocks and fluxes among several pools based on explicit environmental and human processes, and as such it is an IPCC Tier 3 approach for estimating landscape carbon dynamics. The data consist of carbon densities, rates of net carbon accumulation or emissions to the atmosphere, the proportion of CO_2, CH_4, and BC in carbon emissions from burned biomass, and the effects of forest management, land conversion, and fire on carbon stocks and fates. These data are provided in various formats and represent places ranging from specific study sites to general land types (e.g., Forest). As such, these data are processed into averages or characteristic values for each of 940 land categories--the intersection of 15 land types, nine ownership classes, and nine regions (Table 1, Figure 1)--and one Seagrass category, along with uncertainty ranges for the carbon data.

Table 2: Carbon Pools Represented in CALAND

Boxes marked by "X" are 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					

The impacts of management on landscape carbon are estimated by taking the difference between a management scenario and a baseline scenario simulated by CALAND. Baseline scenarios are often extrapolations of recent trends, but can also represent non-management[6] to estimate the total effects of a management scenario. The California Natural Resources Agency has provided two management scenarios and one non-management baseline scenario that are in accordance with the Natural and Working Lands Implementation Plan (section 2.2). Each simulation starts from an initial condition in 2010 and calculates one year at a time based on the given scenario.

[6]Includes only wildfire, mortality, ecosystem carbon fluxes, historical land use and cover change, and optional climate change effects.

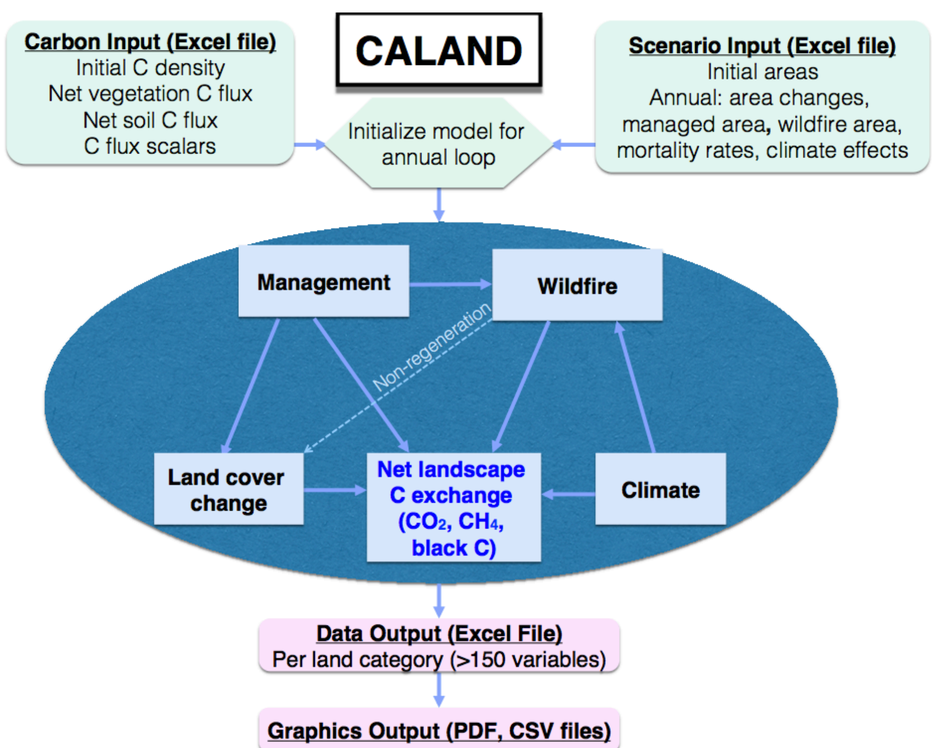
Figure 2 illustrates the relationships between model components. The model starts with an initial carbon and land cover state in 2010 and simulates the following processes on an annual time step:

1. The net ecosystem carbon accumulation 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 (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, 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). All landscape carbon exchange, except for decay of wildfire-killed biomass, is assumed to occur within the same year of the driving activity. This includes, for example, decay of logging residue that has been removed from the forest and soil carbon loss due to land conversion. Land-atmosphere exchange of CO_2, CH_4, and BC, including carbon emission pathways for discarded wood products and bioenergy generation from forest biomass, are calculated from the carbon dynamics after all years have been processed.

Figure 2: CALAND Model Operation

The CALAND model operates on an annual time step.



2.1 Initial state

The initial land cover and biomass carbon state begins in 2010 and is derived from the improved California Air Resources Board (CARB) greenhouse gas inventory for California forests and other lands (CARB Inventory; Saah et al., 2016; Battles et al., 2014) and an urban forest assessment (McPherson et al, 2017). The initial soil carbon state is derived from the NRCS gSSURGO database (USDA, 2014) and a review of California rangeland soil studies (Silver et al., 2010). These data have been processed with the aid of a geographic information system so that they are geographically aligned[7] 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. Uncertainty in CALAND inputs is consistently characterized as the standard deviation of the calculated mean values because not all data include explicit uncertainty.

2.1.1. Land categories

The land categories are the spatial units for which changes in landscape carbon are calculated, and are defined by the intersection of land cover types, ownership classes, and spatial regions. The land cover data used to delineate the 15 land types in CALAND are based on remote sensing data from the LANDFIRE program[8] and are provided in the CARB Inventory database (Saah et al., 2016, Battles et al., 2014). The 204 (2010) LANDFIRE land cover types for California are aggregated into 15 CALAND land types based on the 2008 classification scheme provided in the CARB Inventory. These 15 land types are intersected spatially with nine ownership classes derived from a combination of CAL FIRE Fire Resource and Assessment Program (FRAP) ownership data[9], the 2015 California Conservation Easement Database (CCED)[10], and USFS wilderness area data[11]; and nine spatial regions derived from a combination of the USFS

[7] 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.

[8] Available online: https://www.landfire.gov

[9] 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

[10] CCED, 2015

[11] 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

Pacific Southwest Region[12] ecological subregions for the state 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 subregions recommended by CAL FIRE (Figure A1 in Appendix A; and also defined in the 2017 Draft Forest Carbon Plan), modified to delineate the Legal Delta and Suisun Marsh. The Delta region has been extracted from the Central Valley region, with some adjustments along the border with the Central Coast (<2km), to ensure complete inclusion of the Legal Delta and distinct regions with contiguous area. This delineation will facilitate modeling of wetlands management and restoration practices that are unique to the Delta region. Fresh Marsh is a unique category that is not represented in the LANDFIRE data classification (i.e. area = 0), yet it is included in order 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

The initial 2010 biomass carbon density values for all land categories (except Urban Area) are from the CARB Inventory database (Saah et al., 2016, Battles et al., 2014), which does not include soil carbon. These source data are stored on a 30 m resolution grid, with distinct biomass values for each of the 204 LANDFIRE land cover types, and are calibrated to USFS FIA data and available literature. The biomass values were converted to carbon values using the recommended factor (carbon = 0.47*biomass; Saah et al., 2016). These carbon values were used to calculate the area- weighted average of the grid cell values within each land category, which is the primary input carbon density 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)[13]. The six biomass carbon pools are aboveground main canopy, belowground main canopy (root), understory, standing dead, downed dead, and litter (Table 2).

Other sources were considered for gridded initial biomass carbon, but they covered only the forested area and were based on USFS FIA data. Specifically, a 250 m resolution data set (Wilson et al., 2013) was compared to the CARB Inventory data for

[12] 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

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

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, CALAND's average, aggregated carbon density values are comparable to other reported estimates, especially considering the differences in aggregation and categories (Forest: Birdsey et all, 2002; FRAP, 2010; Hudiburg et al., 2009; Pearson et al., 2009. Desert: Evans et al., 2014. Grassland: Ryals et al. 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 CALAND Forest averages. **Overall, the CARB Inventory 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

The initial 2010 soil organic carbon density values for all land types except Grassland, Savanna, and Woodland are from the USDA NRCS gSSURGO database (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 method used for the biomass carbon data, 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 values. Rather, they were filled by extrapolating data from identical land types in other ownerships within the respective region[14]. The aggregated, gSSURGO, soil organic carbon density values for Grassland, Savanna, and Woodland land types were found to be about one-third of the values reported in a review of California rangeland studies that estimated total soil carbon density (Silver et al., 2010). As a result, 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 et al., 2002; Dore et al., 2016; Powers et al., 2013. Urban Area: Pouyat et al., 2006. Desert: Evans et al., 2014),

[14] In Version 1, all the land categories were directly assigned values. In version 2, the unassigned categories were Eastside and Klamath Ice, two Forest ownerships in Deserts, Central Coast Meadow, and Delta Sparse.

while Coastal Marsh values are higher than reported because of shallow soil carbon measurements (e.g., Callaway et al., 2012). Cultivated Land values in the Delta region reflect average values for areas with (e.g., Hatala et al., 2012) and without peat substrates (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, CH_4 and BC, and utilization of harvested and collected biomass carbon for wood products and energy (Figures 4-5). The model is initialized to 2010 as described above 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, (3) mortality rates for perennial vegetation, and (4) fractions of carbon pools that are affected by land conversion, forest management, and wildfire. All parameters except the mortality rates are in the carbon input file. The mortality rates are in the scenario input files so that recent elevated rates of forest tree mortality can be emulated.

CALAND translates the projected carbon dynamics into net ecosystem exchange of carbon-based GHGs and their total GWP in terms of CO_2 equivalent (CO_2-eq) emissions. Net ecosystem carbon accumulation is counted as CO_2 uptake due to photosynthesis, whether stored in vegetation or the soil, while net ecosystem carbon loss from soil to the atmosphere is counted as CO_2 emissions due to decomposition of organic matter (except for Fresh Marsh, for which the carbon exchange is partitioned between CO_2 uptake and CH_4 emission). Wood products are considered as stored carbon for accounting purposes, while the incremental decay of discarded wood products in landfills generates CO_2 and CH_4 emissions. Additional pathways for carbon emissions include wildfire and associated biomass decay, prescribed burning, bioenergy, decay of cleared vegetation biomass (including roots) following Forest management activities or land conversion, and soil carbon loss due to Forest management or land conversion. These 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 or for residue removal), and is partitioned among CO_2, CH_4, and optional BC (bioenergy emissions are partitioned differently from other burned biomass). Total GWP from net exchange of CO_2, CH_4, and BC is calculated annually in units of CO_2-eq with a 100-yr time frame using radiative forcing potentials of 25 for CH_4 (Forster et al., 2007) and 900 for BC (Myhre et al., 2013). 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 emissions to the year in which they are actually projected to 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.

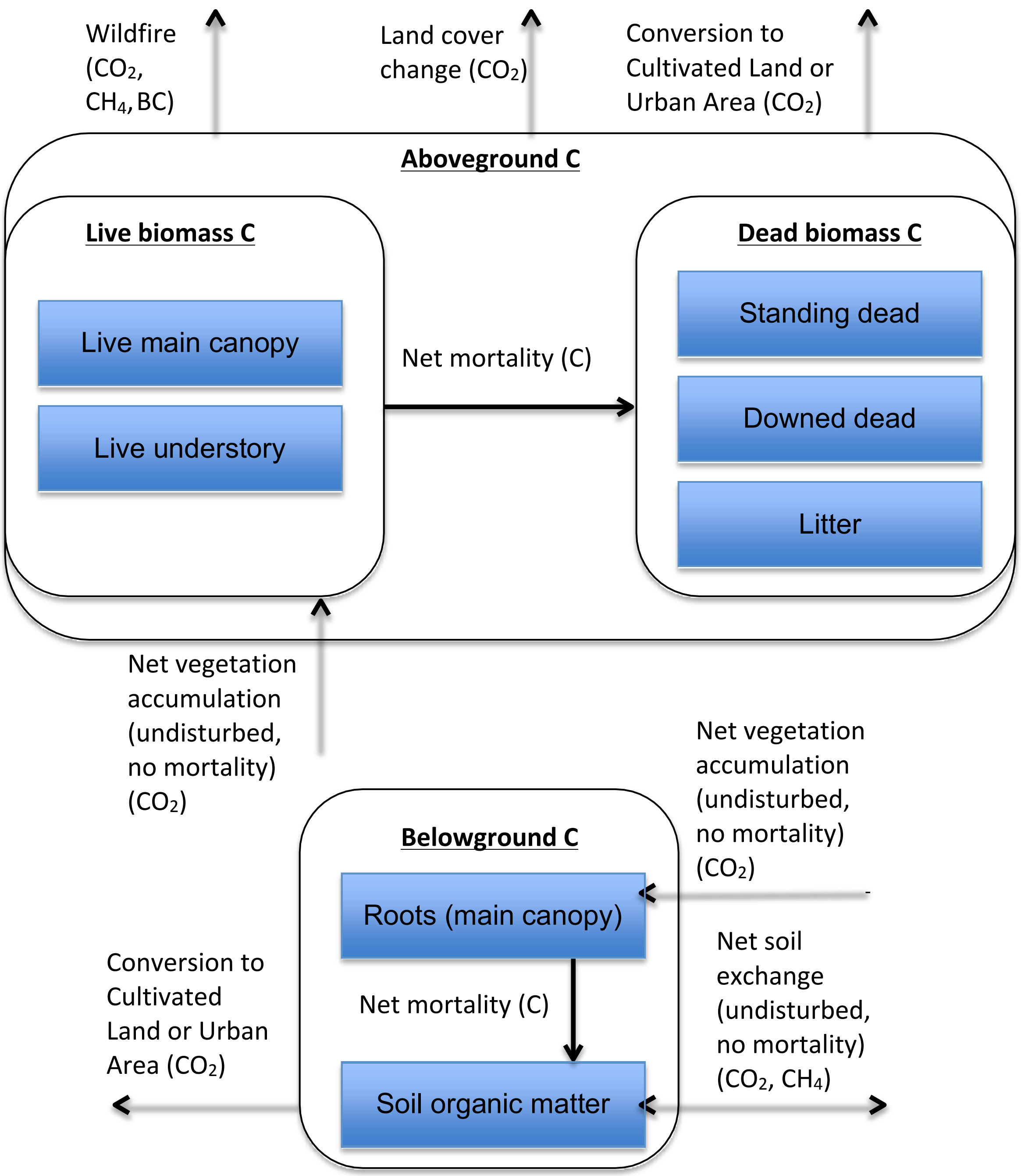
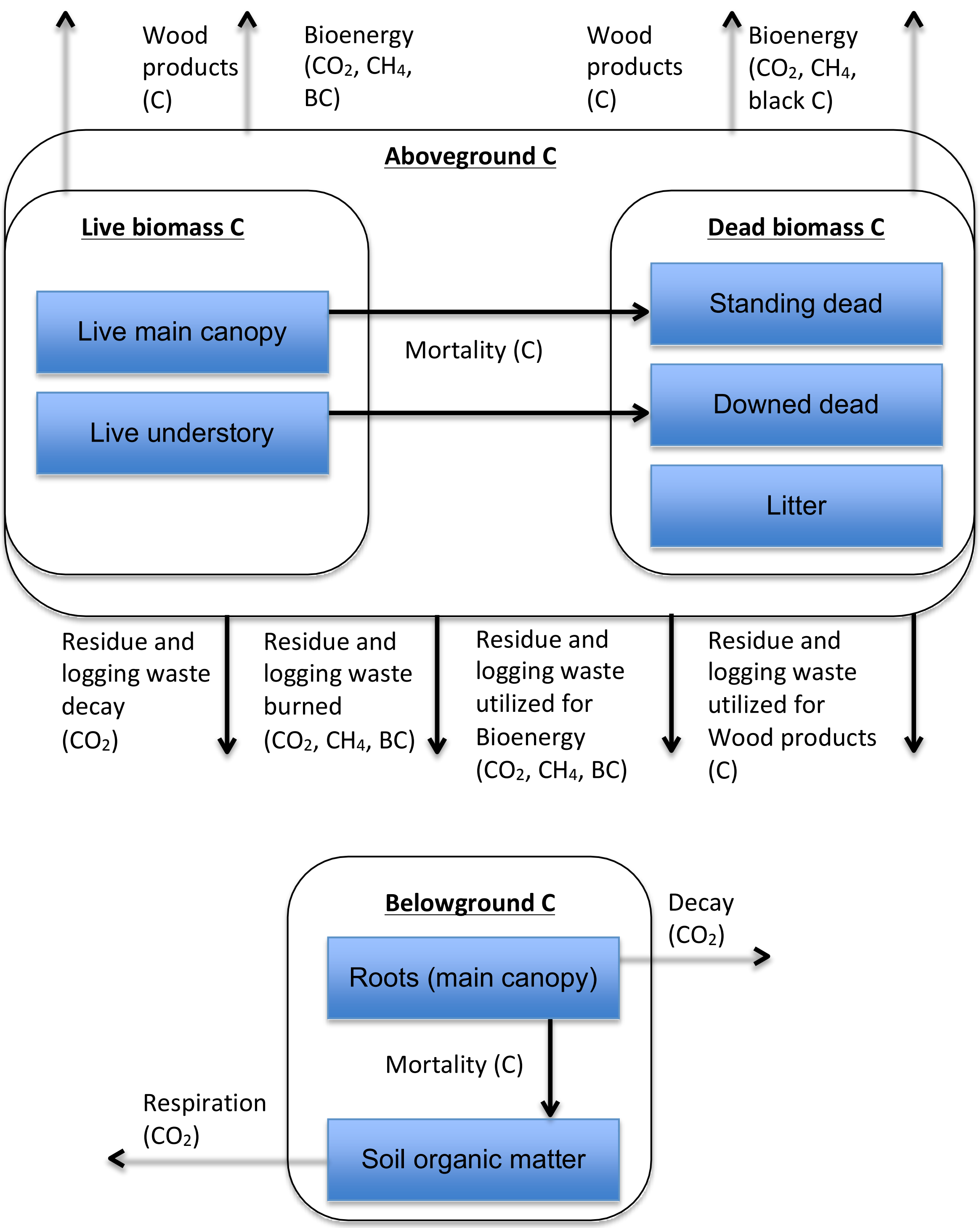


Figure 5: CALAND Forest management carbon dynamics

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 comprised 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. The vegetation values represent 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 carbon exchange 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 (see section 2.3.5)[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 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 its uncertainty. In some cases the minimum and maximum values have simply been calculated directly from the mean and standard deviation. The vegetation carbon exchange inputs represent a measurement of carbon accumulation in a particular live biomass pool (e.g., stem only versus whole plant). This is due to limited availability of complete data. 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

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

live vegetation carbon density changes are computed by subtracting mortality from each vegetation carbon pool. Vegetation carbon exchange is either zero (static carbon density) or positive (increasing carbon density), representing net carbon uptake 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 (see 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 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 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 matter. For example, Grassland, Savanna, Woodland, and Delta Cultivated Land all have negative soil carbon exchange values historically, 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 (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 is based on field CO_2 flux measurements, and reflects one of only two net ecosystem carbon losses across all land types (-2.22 ± 1.29 Mg C ha^{-1} y^{-1}). The Fresh Marsh soil carbon exchange value (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).

[18] There is interest in adding perennial crop dynamics to CALAND.

The Fresh Marsh 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. 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, 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 soil C flux applied to all non-Delta regions is derived from field experiments in 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), 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 Imperial Valley (90-year chrono-sequence of alfalfa, wheat, corn, and sugar beets, starting as uncultivated native soil) (Wu et al., 2008). The Cultivated soil C flux in the Delta region is derived from two rice systems (1-yr and 2-yr studies) and one corn system (1-year study) in Twitchell Island (Hatala et al., 2012, and 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 matter and contributions from root mortality and litter. Thus, root mortality is subtracted from roots but is not added to soil carbon unless there in a change in the initial 2010 mortality.

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 value), as measured by eddy covariance sans mortality. The sum of these two values represents total net carbon exchange. The vegetation carbon exchange is

[19] The average CO_2 and CH_4 carbon balance from Knox et al. (2015) gives a net CO_2eq emission, although net emissions differ with 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.

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, with respect to both the distribution of woody versus grass understory and the carbon dynamics of a woody understory.

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 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 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. Belowground mortality is not transferred to soil carbon unless mortality changes from initial 2010 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). CALAND simulations by default include doubled forest mortality rates from 2015 through 2024 to emulate the ongoing die-off due to insects and drought. 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, management activities in Forest change the mortality rates (see section 2.3.3).

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 historical conditions are those derived directly from the input data, the effects of projected climate on carbon accumulation rates are implemented by applying scaling factors calculated from global climate model outputs, and the wildfire area under projected climate is generated from a combination of historical data and global climate model outputs (see section 2.3.4 for wildfire description). 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), are used to calculate RCP 4.5 and RCP 8.5 projected climate scaling factors for annual soil and vegetation carbon accumulation. The general process follows the iESM method (Bond-Lamberty et al., 2014) and takes the ratio of a future annual value to an initial annual value (2010) at each one-degree grid cell and vegetation type from iESM, disaggregates this ratio to the spatial

[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.

distribution of CALAND land categories, and then calculates area-weighted averages for each land category. Different source variables and time-averaging window sizes are used for vegetation and soil factors. Using running averages of the source data reduces inter-annual fluctuations to better capture long-term climate effects. The ratios are also filtered for outliers before disaggregation in order to reduce the influence of non-climatic factors such as land cover change. The filtering method uses median absolute deviation (Davies and Gather, 1993), and is the same one 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, and these 2086 values are applied to CALAND years beyond 2086. Seagrass bed carbon accumulation is not climate-adjusted due to lack of data.

Vegetation carbon accumulation scaling factors are calculated from the Net Primary Productivity (NPP) output from iESM because 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 are calculated using a 5-year running average centered on the desired year. The iESM tree types are 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 are processed similarly for CALAND's Shrubland type.

Soil carbon flux scaling factors are calculated from the annual change in the soil organic carbon content output from iESM because it is most closely related to the net soil carbon accumulation values used by CALAND. The annual changes in soil organic carbon content are 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 applied to the relevant CALAND land types in a given cell (Desert, Shrubland, Grassland, Savanna, Woodland, Forest, Meadow, Coastal Marsh, Fresh Marsh, Cultivated).

2.2.4. Management effects

(For restoration practices, see section 2.3.6.)

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 alternative scenarios relative to a baseline. The parameters controlling the rate adjustments for each management activity are in the carbon input file. These parameters are derived from carbon exchange rates reported under different management activities. In brief, Forest management increases vegetation and soil carbon accumulation and decreases mortality; 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 2.3.5. 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}) (Hatala et al., 2012; Knox et al., 2015) 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 area of Urban, 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.

Table 3: Management Practices Currently Implemented in CALAND version 3 and relationships to the Natural and Working Lands (NWL) Scenarios.
(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.
Practices that change ecosystem carbon exchange rate and also explicitly transfer carbon among pools and can contribute to emissions (continued)	
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 Rorest, 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)
Practices that involve land cover change and Seagrass (continued)	
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[23]). 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 utilization (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 understory, downed dead, litter, and uncollected harvest residue. These carbon losses 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[24] (section 2.3.4), and can also include removal of slash for bioenergy and wood products. These parameters are the same ones as defined in Appendices F1 and F2.

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

[24] 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). All ten practices generate 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 these slash fractions (Slash2Energy, Slash2Wood, Slash2Burn, Slash2Decay in Appendices F1 and F2) must add to 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, with Clearcut representing practices such as clearcutting and leaving seed trees, and Partial Cut representing 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 (IPCC, 2006a; equation 12.1) 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 (IPCC, 2006b; section 3.1) and using CARB default values (ARB, 2016; Section IV, eq 89). The values for the amount of harvested and slash-utilized carbon going to energy 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 32% of harvested biomass could go to energy for Clearcut and 75% for Partial Cut, 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 and mortality rates (Appendix E) for a 20-year post-management period. Vegetation carbon accumulation increases on managed land, while mortality rate can increase or decrease. These effects vary by region and ownership and are derived from USFS FIA data (Christensen et al., 2017). These long-term effects are implemented by applying adjustments to cumulative managed area over the previous 20 years. 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 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 (see section 2.3.4).

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 energy 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 as 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 as CO_2 within the model year as a result of decay of removed biomass or wood products.

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 using 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 (see section 2.3.5 for climate description). The climate change data are derived from 1/16-degree gridded burn area estimates generated for the California Fourth Climate Change Assessment[25] (Westerling, 2018). Specifically, they are the burn area data for the "average" climate model (CanESM2)

[25] These data are available at http://cal-adapt.org/data/wildfire/, with a corresponding viewer at http://cal-adapt.org/tools/wildfire/

and central population scenario. The gridded burn area values were distributed to CALAND region-ownerships, and within each region-ownership (the boundaries of which do not change over time) the burn area was distributed proportionally to Forest, Woodland, Savanna, Shrubland, and Grassland land types (the areas of which do change over time). These land types were selected through visual overlay of the CAL FIRE fire perimeters data[26] 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. For the historical climate run the constant annual value is the RCP 8.5 initial area (185,237 ha statewide). Note that the RCP 4.5 initial area is similar (195,095 ha statewide), but that both of these are lower than the non-spatial statewide area used in CALAND v2 (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 CA fires from 1984 to 2006 (Miller et al., 2009 and Miller et al., 2012) (Table 4). The user can specify either 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 threshold of 120m, 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 fraction of forest area burned

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

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 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. Wildfire severity percent of total burn area and percent decreases/increases (negative/positive) in severity percent due to fuel reduction management. The initial high severity percent is increased annually by 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.

		Management Effects on Wildfire Severity		
Wildfire Severity	Initial value	Prescribed burn	Thinning, Partial cut, and Clearcut	Understory treatment
High	26%	-68%	-26%	-24%
Medium	29%	-13%	+10%	+30%
Low	45%	+94%	+19%	-6%

2.3.7. 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, forest area expansion (Afforestion), and Reforestation (complementary to wildfire non-regeneration) (see 2.3.4). Third, wildfire constrains land type conversion through optional non-regeneration (conversion to Shrubland) of some Forest area burned by high severity wildfire (see 2.3.6).

Baseline annual area change inputs: options and methods of derivation

There are two options for baseline annual area change inputs: remote sensing-based extrapolation, representing historical trends, and model-based extrapolation, representing 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.r.

The remote sensing-based option is derived from LANDFIRE remote sensing data, and it is based on the difference in land cover between 2001 and 2010 with adjustments for slight differences in total area between years[27]. 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 landtype maps consisting of 158 and 204 land types in 2001 and 2010, respectively, were aggregated into CALAND's 15 land types (see 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 is based on 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). LUCAS simulates annual area changes of 11 discrete land cover categories, however only changes in Urban Area and Cultivated Land[28] areas were used. The reason for this is two-fold; first, the main drivers of land cover change in LUCAS are 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, from which a single average annual area change was calculated for each CALAND land category.

Implementation of baseline area changes

At the end of each model 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 persists. Conversion matrices are then calculated for each region-ownership combination to determine the areas of each land type being converted to (and from)

[27] 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.

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

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 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 for comparison. For example, a forest fire or clear cut 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 long 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 2.3.4).

The land cover change inputs are highly uncertain, based on the large differences between the two options and this uncertainty is not quantified. Sources of 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 change data, annual Grassland expansion and Shrubland contraction are an order of magnitude larger than the other land type changes, with the loss of shrub biomass contributing significantly to a net California landscape carbon source in our baseline projections (not only in CALAND projections, but likely for the ARB Inventory estimate as well). This 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 could be due to unique weather patterns in 2001 and 2010 and/or different dates of the imagery used for each year. While there is always some misclassification error in remote sensing products, particular problems in distinguishing between orchards/vineyards (Cultivated Land) and vegetation in developed areas (Urban Area; i.e., parks, yards, street trees, etc.) have been found. Combining this misclassification with uncertainty introduced by combining two different classification schemes into one (crosswalk uncertainty) provides some explanation of why the remote-sensing based data estimate expansion of Cultivated Land (which is small relative to other land type changes), in contrast to other analyses showing similar amounts of Cultivated Land contraction. Additionally, the remote-sensing based data may be capturing some land clearing and cultivation occurring outside the scope of the other analyses.

Due to these issues, the land-use based data are the default land cover change inputs. 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 state in CALAND is significantly affected by uncertainty in land cover change, which is one reason why CALAND currently should be used only to examine differences between alternative scenarios and the business-as-usual scenario**.**

Management practice effects on land type conversion

The management practices that modify land type conversion in CALAND include Restoration (Meadow, Coastal Marsh, Fresh Marsh, Seagrass), avoided conversion (labeled as Growth, which reduces the growth rate of Urban Area), Afforestation and Reforestation. Avoided conversion is prescribed and implemented as an annually decreasing Urban growth rate. The reduction is applied to the baseline annual area growth rates for Urban Areas, which consequently reduces the loss of other land types. When using the remote sensing option for baseline annual area change, the Urban Area growth reduction will also increase the expansion of other growing land type areas. After avoided conversion is applied, prescribed annual Restoration targets are fulfilled to the extent that land types areas are available. Coastal Marsh and Fresh Marsh are restored only from Cultivated Land. This land conversion aligns with current practices (Steve Deverel, personal communication), although Coastal Marsh can also be restored from seasonal wetlands and open water. 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. All restored areas persist throughout the simulation period.

Land conversion effects on ecosystem carbon dynamics

There are two main modes in which 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 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 initial changes in existing carbon stocks are based on differences in carbon density between the exchanging land types, with the exception of land conversion to Urban Area or Cultivated Land. For these exceptions, carbon transfer parameters from the academic literature are used instead (see Appendix E for parameters). In all other cases, if aboveground carbon in the new land type is greater than in the old land type, all the carbon from the old 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 old land type, the difference is emitted to the atmosphere within the year and only the remaining portion is transferred to 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 carbon losses corresponding with conversion to land types other than Urban Area and 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 for conversion to Urban Area and Cultivated Land are identical (see Appendix E for parameters). If the old land type is Forest, the conversion involves a timber harvest that is currently parameterized as a Clearcut with 100% of the biomass removed. This means that only live main canopy and standing dead are available for wood products and bioenergy, and that all uncollected harvest residue and other vegetation carbon (understory, down dead, and litter) is currently 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 above for Forest management (section 2.3.3). Otherwise, all biomass carbon (above, dead, and roots) and a fraction of the soil carbon are removed and decay to the atmosphere within one year as CO_2. 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 Ackerson, 1993).

3. Model outputs and diagnostics

Each output table in the output file provides annual values for a single variable (Appendix G), by land category, with additional records for aggregated regions and/or land types. Change values, which are the differences between the final and initial year values, are also included in these tables. 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 emissions. Land category area, carbon stock, carbon density, and cumulative gain/loss variables represent (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 so that values can be displayed by land category using a Geographic Information System.

There is a primary diagnostic function (defined in plot_caland.r) that plots several variables (see appendix G for variables) from the model output file, and two secondary diagnostic functions (defined in plot_scen_types.r and plot_uncertainty.r?) that use files generated by the plot_caland function. Plot_caland compares one or more scenarios with a baseline scenario, and has two modes: 1) general diagnostics 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. Plot_caland supports CALAND outputs with and without black carbon, plots for aggregate and individual land categories, a cutoff year for time series, and a selection for acres or hectares as the diagnostic area units.

The secondary diagnostic functions allow a user to generate some tailored figures for specified variables, scenarios, and land categories (with optional aggregation of all regions/ownerships/land types). Plot_scen_types co-plots multiple land types within a single scenario, and plot_uncertainty 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 Natural and Working Lands Climate Change Implementation Plan

The California Natural and Working Lands Climate Change Implementation plan focuses on the carbon consequences of state interventions to land management. The three associated scenarios (a baseline and two alternatives) can be run using historical (no climate effects), RCP4.5, and RCP8.5 climate effects on ecosystem fluxes (2.3.5) and wildfire areas (2.3.4). The baseline scenario includes ecosystem carbon fluxes, wildfire area, historical forest harvest areas for even-age and uneven-age management on private land, historical USFS-funded fuel reduction areas on USFS and private land (Table 3), a constant urban forest fraction of 15% (McPherson et al., 2017), and historical land use and cover change based on Sleeter et al. (2018) (see section 2.3.6). Additionally, mortality in urban forest is removed from the system and decays to the atmosphere, and forest tree mortality is doubled from 2015-2025[15] to emulate the observed impacts of insects and drought that are not captured by the data used to initialize and parameterize the model[16]. The forest harvest rates are derived from

Robards and Nickerson (2013) and the forest fuel reduction rates are derived from the CAL FIRE Draft Vegetation Treatment Program Environmental Impact report (VTPEIR) (2004-2013; CAL FIRE, 2016) and the USFS Pacific Southwest Region office (2008-2015; PSR, Jason Ko, personal communication). These USFS-funded fuel reduction areas are the same for the baseline and alternative scenarios because they are outside the scope of state-funded intervention. No state-funded forest management activities are included in the baseline scenario.

The two alternative scenarios each consist of the addition of a suite of activities (Table 3) for land use (e.g., conservation/avoided conversion), land management (e.g., fuel reduction), and restoration (e.g., fresh marsh) to the baseline scenario. Each activity is applied annually to the appropriate land type(s) at a given extent (i.e., acreage) over the 2019-2030 timeframe. After 2030 the management practices return to baseline with three exceptions: 1) the resulting growth rate for 2030 is held constant, 2) urban forest fraction continues to expand at the same rate as in previous years, and 3) state-funded forest fuel reduction practices repeat every 20 years for maintenance (i.e., the 12-year block starts again in 2039). These scenarios have been developed cooperatively by many state agencies and represent goals for California land management, excluding expectations for the Healthy Soils program, which are simulated separately by another model. The primary difference between the two alternative scenarios is the area of implementation of the various practices. For example, Alternative A has a 50% reduction in urban growth rate by 2030, while Alternative B has a 75% reduction by 2030. Full details of the alternative scenarios are reported in the Natural and Working Lands Implementation Plan.

The two alternative scenarios have been compared with the baseline to estimate the effects of different land management suites on California's landscape carbon budget (Figure 3). 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 reduces carbon emissions, increased forest fuel reduction dramatically increases 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 carbon emissions after a scenario-dependent time period.

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[15] 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_2017.pdf. Accessed Aug. 15, 2017.

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

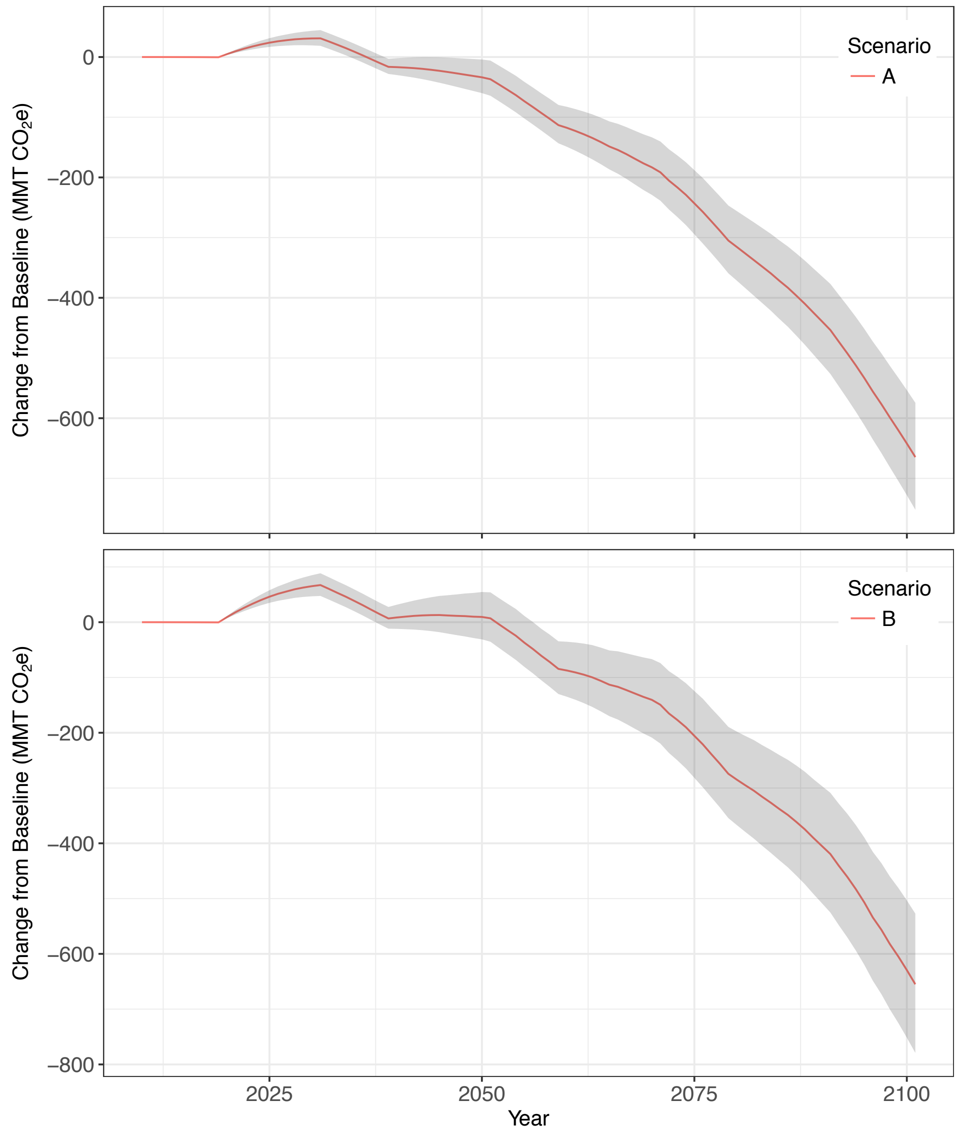

Figure 3. Total cumulative CO_2 equivalent impacts of two Natural and Working Lands scenarios on landscape carbon emissions under RCP 8.5.

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/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 main tasks will require additional resources and considerable effort.

Appendices

Appendix A: Land Categories identified for use in CALAND

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
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
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

Appendix A: Land Categories identified for use in CALAND

Variable terms used in the model are in parenthesis.

Land Types (Cont.)	
Key Terms	**Key Terms**
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

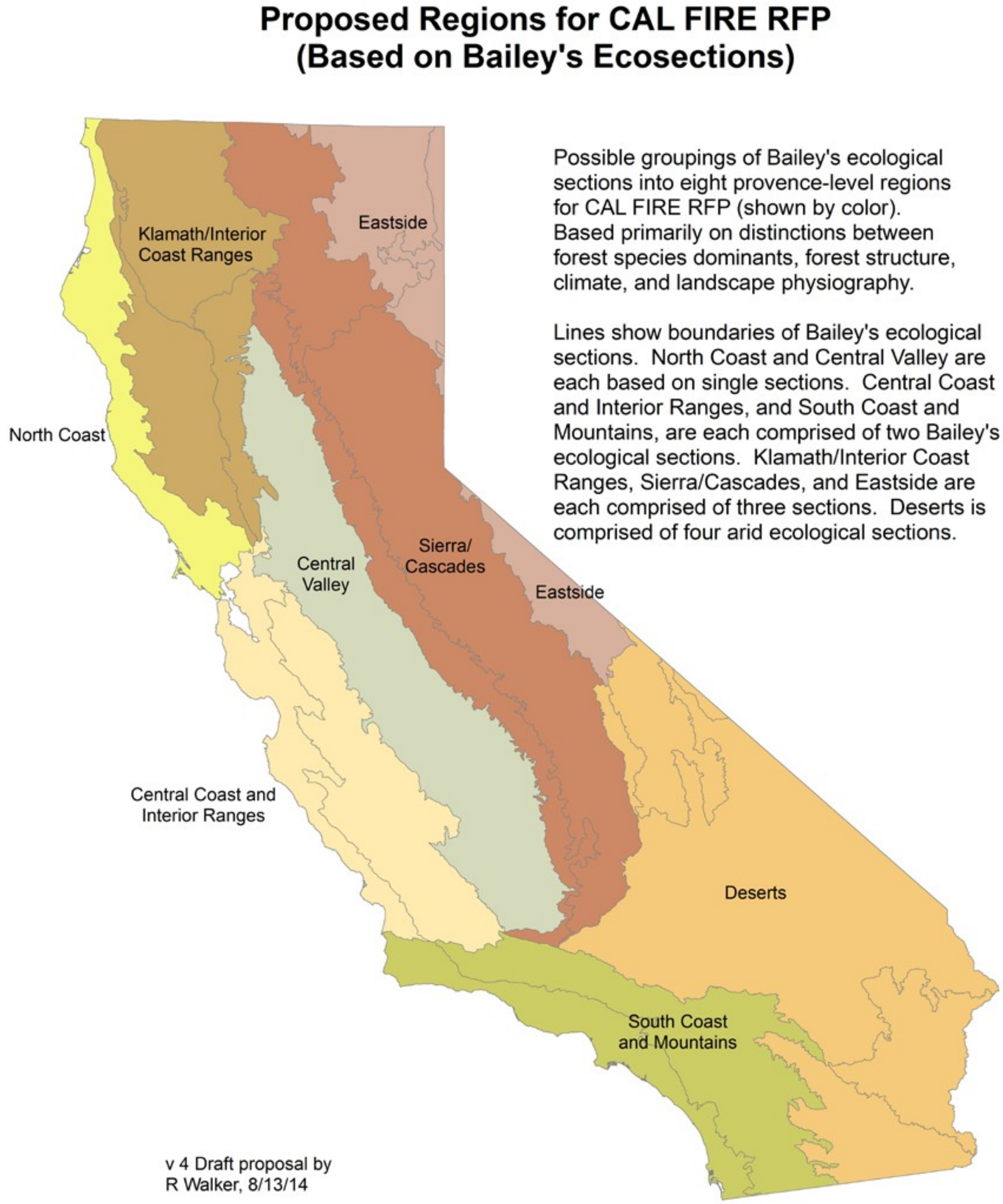

Figure A1: Recommended aggregation of USFS California Level 2 ecological subregions. The Delta region has been delineated primarily from the Central Valley region.