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

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Technical Documentation

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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, emissions of methane (CH_4), and black carbon (BC) 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 remote sensing estimates and of land cover change between 2001 and 2010, CALAND simulates annual carbon stocks and fluxes, including material flow to wood products and bioenergy, for given land use/management scenarios from 2010 through 2050. The potential effects of climate change on carbon dynamics are not included in the model at present, although they will be incorporated in 2018 and CALAND will be run through 2100.

CALAND's primary function is to quantify the difference between expected net GHG emissions from a historically grounded, business-as-usual land use and management scenario and net GHG emissions arising from alternative land use and management activities pursued on a range of scales. This comparison will illustrate the change in net GHG emissions that is expected to arise from applied land conservation and management activities, relative to the business-as-usual case. The alternative management scenarios to be developed for the Natural and Working Lands Climate Change Implementation Plan will be identified in 2018. Currently, CALAND should be used only to examine *differences between* GHG emissions arising from the business-as-usual and alternative scenarios, as opposed to absolute GHG emissions. Planned improvements are expected to enhance the usability of this model for generating estimates of absolute GHG emissions across scenarios[2].

CALAND operates statewide on 940 land type categories and ocean seagrass (Table 1, Figure 1)[3]. CALAND simulates one scenario at a time to generate a single output file using two input data files and one processing function. The output file is an Excel workbook containing several tables as individual sheets. The two input files are

[1] Version 1 (November 2016) did not include these greenhouse gas outputs.

[2] 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.

[3] Version 1 had 45 land categories with 15 land types and three ownership classes (see Table A1).

also Excel workbooks which contain the model data and scenario, respectively. The model data are constant across all 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 annual mortality rates for vegetation. Each scenario is defined in its own input file. Two diagnostic plotting functions create figures from two or more scenario outputs, and an additional function is available to create new input files. 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).

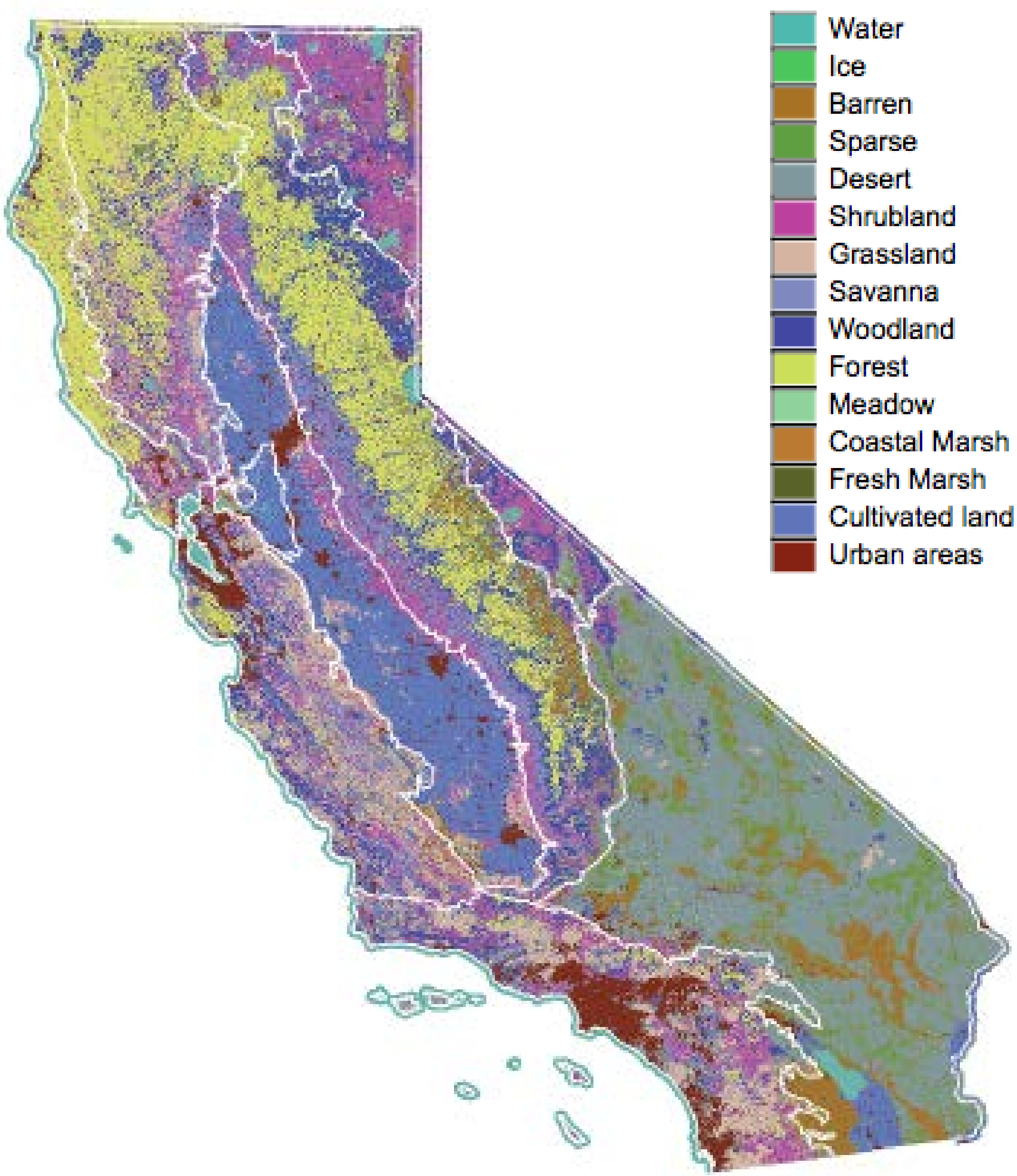
Spatial Regions	Ownership Classes	Land Cover Types	
Central Coast	U.S. Bureau of Land Management	Barren	Savanna
Central Valley	National Park Service	Cultivated Land	Seagrass
Sacramento-San Joaquin Delta	U.S. Department of Defense	Desert	Shrubland
Deserts	USDA Forest Service (non-wilderness)	Forest	Sparse
Eastside	Other Federal Government[4]	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		

[4] 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

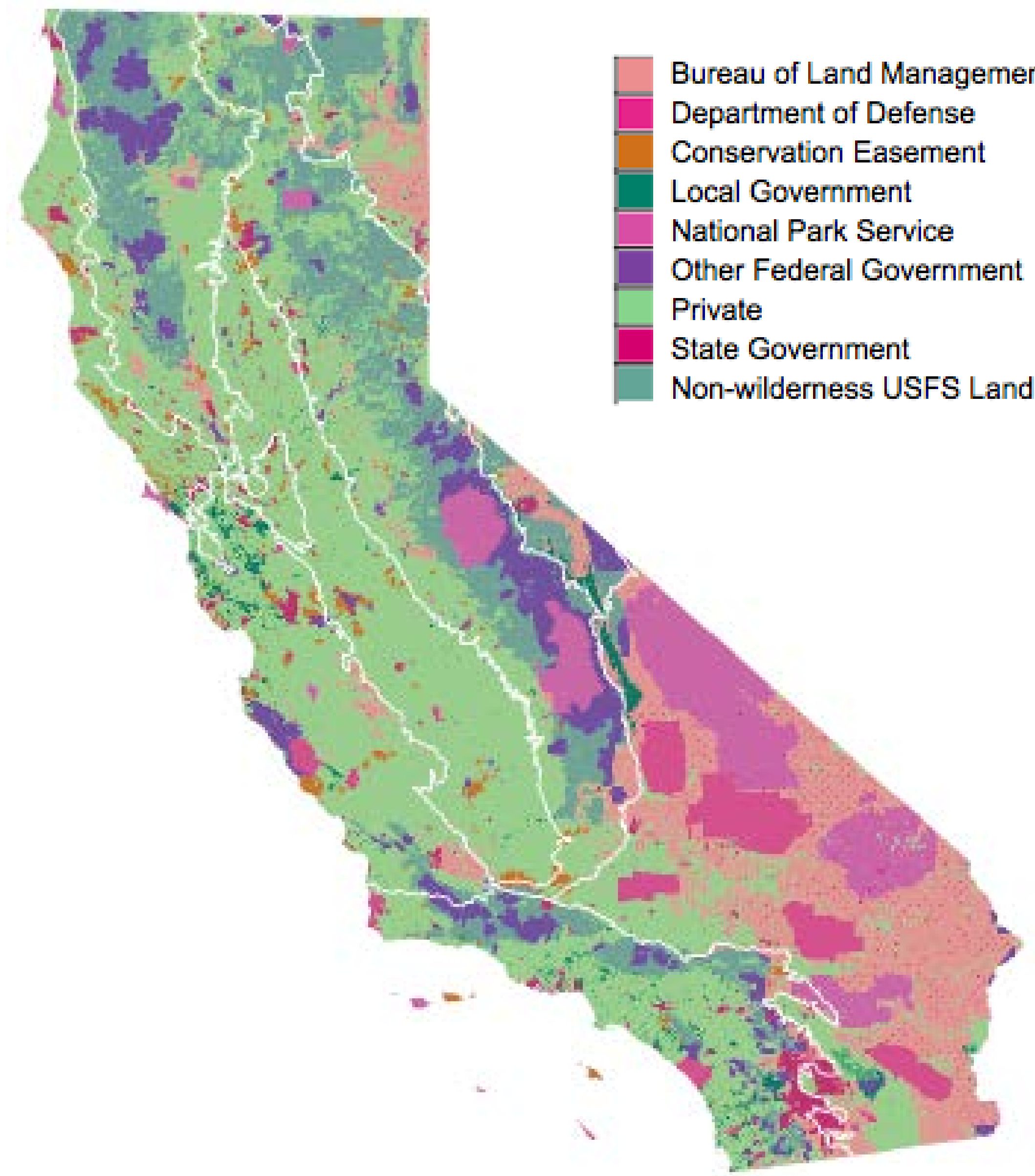
Figure 1: CALAND Land Categories

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 C 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. 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.

Land Type: / Carbon Pool:	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					

One carbon input file assigns all the carbon densities, fluxes, and management effects, while a scenario input file prescribes the annual area of land cover, land management, fire, and vegetation mortality, delineated by the 940 categories as appropriate. The business-as-usual (BAU) scenario extrapolates historical patterns into the future based on remote sensing data and reported statistics[5] from 2000 to 2015. The alternative scenario files include additional management and conservation practices and corresponding acreages for implementation over a designated period. The initial alternative scenarios used in Version 1 (2016) were provided by the California Natural Resources Agency and the California Department of Food and Agriculture, and included a variety of additional practices during 2017-2050. Ultimately, to inform the Natural and

[5] BAU annual management areas, wildfire, ecosystem carbon fluxes.

Working Lands Implementation Plan, management and conservation practices and their geographic extent will be compiled into new alternative scenarios to be modeled. At this stage of CALAND development, LBNL and state agencies seek to identify and define, or develop parameters for, the full suite of management and conservation practices to be investigated and refined for use in alternative scenario planning. These practices will be incorporated into the model structure described here.

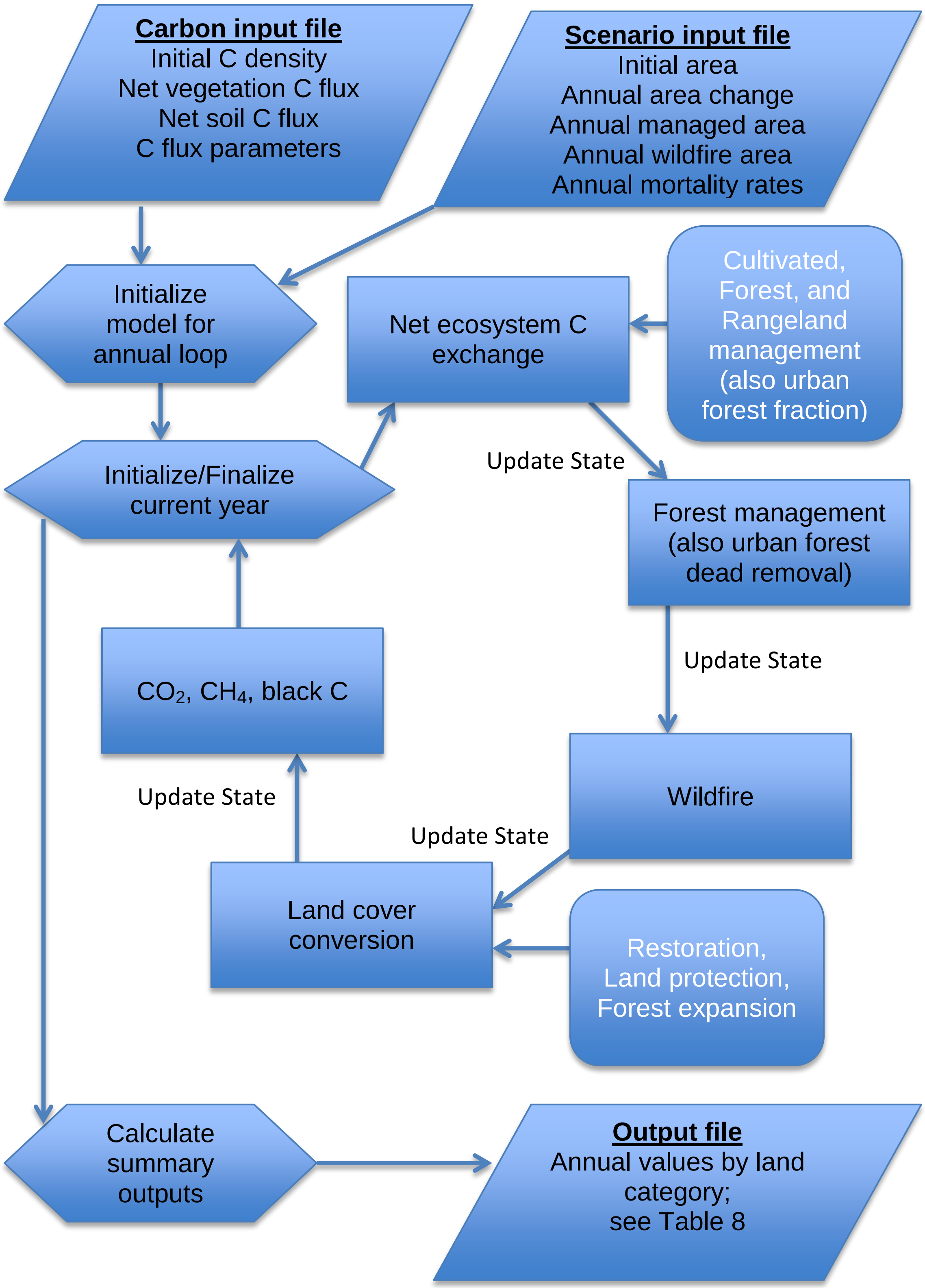
Figure 2 illustrates CALAND's annual time step operation. The model starts with an initial carbon and land cover state in 2010 and simulates the following processes on an annual time step:

1. The net ecosystem carbon accumulation or loss (including adjustments based on 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 (without changing land type 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), and
5. Land-atmosphere exchange of CO_2, CH_4, and BC, including carbon emission pathways for discarded wood products and bioenergy generation from forest biomass.

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 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.

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 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 (Bjorkman et al, 2015). 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[6] 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 from the LANDFIRE program[7] and are provided in the CARB Inventory database (Saah et al., 2016, Battles et al., 2014). These data also define the BAU land cover change from 2001 to 2010, which informs the land cover change in the BAU input scenario file.

The 158 (2001) to 204 (2010) land cover types for California are aggregated into 15 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[8], the 2015 California Conservation Easement Database (CCED)[9], and USFS wilderness area data[10]; and nine spatial regions derived from a combination of the USFS

[6] 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.

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

[8] 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

[9] CCED, 2015

[10] 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[11] 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 MgC/ha. 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 ARB database (Bjorkman et al. 2015), and the same statewide values of aboveground tree carbon density are used for all ownership classes[12]. Belowground (root) carbon data are not available for Urban Area and Cultivated Land types. Thus, these root carbon pools contain no carbon throughout the simulations. 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

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[11] 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

[12] This may be improved for Version 3 by aggregating the city or county values to the spatial regions.

resolution data set (Wilson et al., 2013) was compared to the CARB Inventory data at the aggregation of 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., 2011. 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 that is about four times the Shrubland values (Quideau et al. 1998), and a reported oak woodland value that is about twice the Woodland values (Hudiburg et al., 2009). 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[13]. 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

[13] 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.

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), 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. Business-as-Usual and Alternative Land Use and Management Scenarios

The business-as-usual scenario consists of land cover change plus historic rates of forest management, urban forest expansion, wildfire, Delta marsh restoration, and an estimated 10 years of doubled Forest tree mortality from 2015-2025[14]. These doubled mortality rates have been included in the business-as-usual scenario because they are associated with observed impacts of insects and drought that are not captured by the data used to initialize and parameterize the model[15]. The land cover change is implemented as the annualized net difference in land category (Table 1, Figure 1) area between 2001 and 2010[16]. The forest management values are annual average areas reported in the CAL FIRE Draft Vegetation Treatment Program Environmental Impact report (VTPEIR) (2004-2013; CAL FIRE, 2016) and obtained from the USFS Pacific Southwest Region office (2008-2015; PSR, Jason Ko, personal communication). The split in area between Clearcut and Partial Cut on Private land was based on an analysis associated with the first version of the CARB Inventory (Robards and Nickerson, 2013). Applying these forest management areas to the initial state gives a reasonable estimate of annual wood production from USFS land when compared with values supplied by the PSR office (Jason Ko, personal communication). A business-as-usual trend was also implemented for urban forest area expansion as demonstrated by CARB analysis (John Dingman, personal communication). Business-as-usual wildfire area is implemented as the annual average of 2000-2015 burned area from the CALFIRE fire perimeters data

[14] On a biomass/carbon basis. The most 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.

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

[16] An update using California Department of Conservation Farmland Mapping and Monitoring Program land use data is planned for a future version. See section 2.3.5 for more detail on land cover change.

set[17]. Business-as-usual Delta marsh restoration assumes successful completion of the EcoRestore 2020 target (3,500 acres by the end of 2020), which is based on evidence that this activity is on track to meeting the target.[18]

The alternative scenario(s) consist of the addition of a suite of activities for land use (conservation/ avoided conversion) and land management and restoration (see Table 3) to the business-as-usual scenarios. Each activity is applied to the appropriate land type(s) at a given extent (i.e., acreage) over the 2017-2030 timeframe. After 2030, the management practices return to business-as-usual levels (acres/year). The activities to be modeled and extent of implementation are directed by State agencies, with input and judgment from LBNL researchers regarding feasibility and state of the science. Table 3 contains a listing of management practices currently implemented in CALAND Version 2; the parameters currently used for modeling; and management practices that State agencies have directed LBNL to review for potential inclusion in Version 3.

Table 3: Management Practices Currently Implemented in CALAND and Planned for Potential Inclusion

Italics indicate activities that they have not been implemented in Version 2 and are undergoing review for potential inclusion in CALAND Version 3.

Activity	Description/ Parameters
Practices that (may) change ecosystem carbon exchange rate	
Cultivated land soil conservation	Cover-crops, conservation tillage practices
Rangeland compost amendment	10-year or 30-year repeat compost amendment for Grassland, Savanna, or Woodland
Urban forest expansion	Increase forest fraction of Developed area
Rotational grazing	*Reviewing COMET-Planner and other sources for supplemental data and methods*
Conservation crop rotation on Cultivated lands	
Mulching of Cultivated lands	
Practices that can change ecosystem carbon exchange rate and may 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
Forest partial cut	Thinning of 20% of live and dead standing trees for wood products and bioenergy

[17] CAL FIRE FRAP Data Fire Perimeters, Available online: http://frap.fire.ca.gov/data/statewide/FGDC_metadata/fire15_1_metadata.xml

[18] California Natural Resources Agency. EcoRestore Progress Report. April 2017. Available online: http://resources.ca.gov/docs/ecorestore/ECO-FS-ProgressY2-V11-FINAL-20170601.pdf. Accessed Sept. 14, 2017.

Forest fire fuel reduction	Clearing of ladder fuels and debris through thinning – includes removal of 20% of live and dead standing trees for wood products and bioenergy
Forest understory treatment	Understory clearing and removal
Forest prescribed burn	Collecting and burning of understory and debris
Extra Forest biomass utilization	Diversion of burned and decayed understory and debris to energy and wood products
Improved forest management	*Need input parameters to define practices*
Restoration of natural fire regimes	*Need input parameters, e.g., annual burned areas at different severities if available*
Practices that involve land cover change (plus seagrass)	
Forest area expansion	Increase forest area
Meadow restoration	Creation of meadows
Delta wetlands restoration	Creation of managed 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	*Afforestation/restoration of oaks trees on suitable land types*
Conversion of Cultivated land and other agricultural lands to other land cover types, undertaken for whole-farm carbon, habitat, productivity, and other improvements (e.g., installation of hedgerows, riparian area restoration)	*Reviewing COMET-Planner and other sources for supplemental data and methods*

The following section – 2.3: Projection Methods – describes the structure of both the business-as-usual and alternative scenarios in greater detail.

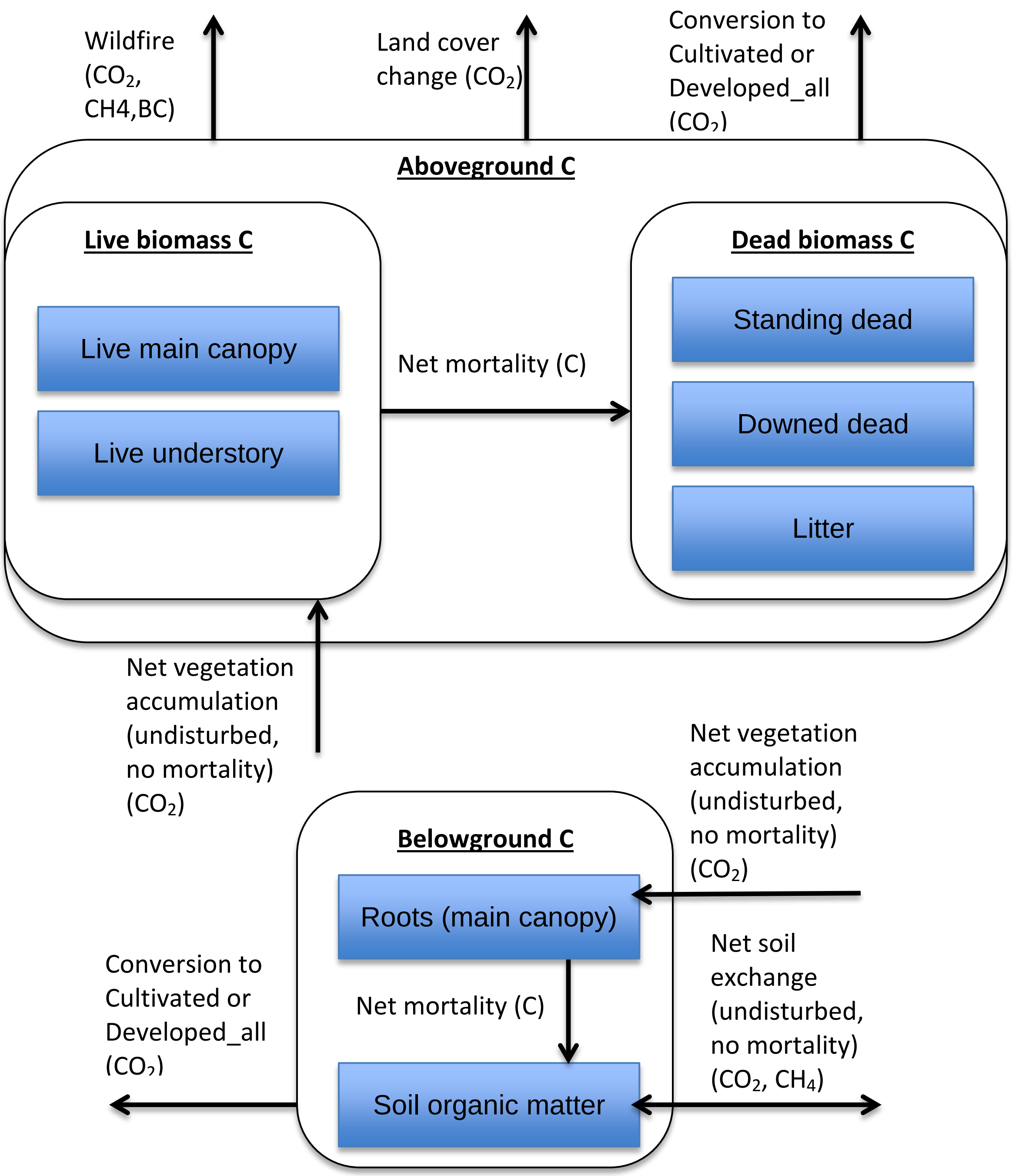
2.3. Projection Methods

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 2-4). 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 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 global warming potential in terms of CO_2 equivalent 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, 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 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 equivalents 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. This has the effect of front-loading those emissions, 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 3: CALAND Land Type Carbon Dynamics

Savanna and Woodland do not accumulate understory carbon. Management practices can affect net vegetation and soil carbon accumulation and mortality rates. See Figure 4 for additional Forest management dynamics. See Table 2 for the carbon pools that exist for each land type.



2.3.1. Mortality rates

Mortality rates represent net fractions of existing live carbon that is transferred annually to dead carbon pools (aboveground and understory to standing, downed, litter) or to soil carbon in the case of root mortality, generally in proportion to the existing carbon pool densities. These are net rates in that 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[19]. A fraction of root mortality goes to soil carbon either implicitly or explicitly, based on the nature of 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[20] except Forest. Land types with no net above ground carbon accumulation will not incur mortality (e.g., Desert). Forest mortality values (Private = 0.5%, USFS non-wilderness = 1.1%, Other = 0.8%) are calculated based on reported values (Christensen et al., 2016) and the initial carbon densities of the land categories. The annual, main canopy/root mortality rates are set in the scenario file and can be land category specific, while the understory rate (1%) is a fixed parameter within the model. Additionally, management activities in Forest reduce the mortality rate (see section 2.3.2).

2.3.2. Net ecosystem carbon exchange

Each land category has literature-derived values for net annual vegetation carbon exchange and soil carbon exchange on a per area basis. Appendix B lists these values and their sources by land category. The vegetation data represent the net ecosystem carbon exchange (combined carbon assimilation and respiration) of an *undisturbed patch with no mortality*, while the soil data generally include root mortality and litter contributions as sources (except for Savanna and Woodland). These values are constant over time and therefore exclude potential effects of climate change[21]. On the other hand, certain types of land management can change the net carbon exchange rate. Most of these values have been determined from carbon stock change measurements, while some are based on net CO_2 flux measurements. With the exception of negative soil carbon exchange rates in Grassland, Savanna, Woodland, and Delta Cultivated Land (assumed to be peatland), which represent carbon release to the atmosphere, all input values for soil and vegetation carbon exchange rates are either zero (no change in carbon density) or positive, representing net carbon accumulation

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

[20] 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 Forest, and then rounded and made uniform across all land types.

[21] One of the goals for Version 3 is to implement climate change effects on the ecosystem carbon exchange based on data generated for the California Fourth Climate Change Assessment.

due to vegetation growth. Note that Savanna and Woodland soil carbon exchange input parameters represent a grass understory. Water, Ice, Barren, and Sparse do not accumulate carbon in vegetation or soil.

These input values have been gleaned from a variety of sources and many of them have been converted from published data to the appropriate format for CALAND. The univariate statistics (mean, minimum, maximum, standard deviation) are derived from multiple data sources where available, or from reported ranges within individual studies. As with the carbon density data, the standard deviation serves as a measure of uncertainty. In some cases the minimum and maximum values have simply been calculated directly from the mean and standard deviation.

The vegetation carbon accumulation values for each land category represent a measurement of carbon accumulation in a particular live biomass pool (e.g., stem only vs. whole plant). This is a result of limited availability of complete data. Consequently, total live vegetation carbon accumulation is calculated based on the assumption that carbon densities in all of the component pools will increase in proportion to existing biomass carbon ratios (e.g., aboveground main canopy carbon to main canopy root carbon). CALAND models accumulation of carbon in vegetation only in Shrubland, Savanna, Woodland, Forest, and Urban Area, while other land types are considered 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). There is interest among state agencies in incorporating accumulation of carbon in biomass on Cultivated Land with perennial crops, particularly orchards and vineyards.

Similar to the input parameters for vegetation carbon accumulation, the soil carbon exchange values for each land type can represent different physical processes depending on the availability (or lack thereof) of appropriate data. If a land type has vegetation carbon uptake, the net soil carbon uptake is assumed to come from mortality of main canopy root biomass, plus carbon transfer from litter, minus the ecosystem respiration of the understory-soil system. If there is no vegetation carbon exchange, the soil carbon uptake (or loss) is assumed to represent total net ecosystem carbon exchange, regardless of whether the vegetation is annual (e.g., Grassland) or perennial (e.g., Desert). It is assumed that these soil values correspond with the initial mortality rate of 1%. Thus, if the prescribed mortality rate differs from the initial value, the contribution to soil carbon is adjusted by the corresponding difference in root mortality, except for Urban Area, where the prescribed mortality is directly transferred to the dead removal management practice. Soil carbon exchange applies to Desert, Shrubland, Grassland, Savanna, Woodland, Forest, Meadow, Coastal Marsh, Fresh Marsh, Cultivated Land, and Seagrass.

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, the non-soil 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 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 (on a per area, annual basis). The Fresh Marsh soil carbon exchange value also represents net ecosystem carbon exchange, but in this case it is the sum of net CO_2 exchange (i.e. uptake) and CH_4 emissions (aqueous carbon loss is not accounted for). The Fresh Marsh carbon exchange is partitioned between CO_2 and CH_4 to calculate the greenhouse gas balance[22].

Cultivated Land has soil carbon exchange, but does not accumulate vegetation carbon in CALAND currently 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. Furthermore, 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 in peat soils (soil carbon loss, in the Delta region; Hatala et al., 2012; Knox et al., 2015) and for crops grown in non-peat soils (the rest of the state)[23]. Root dynamics are not implemented for Cultivated Land due to lack of input root carbon data.

In **Shrubland**, the vegetation carbon accumulation value represents the change in standing biomass carbon (i.e. aboveground main carbon). Thus, this is added annually to aboveground main canopy carbon, and the other live vegetation carbon pools (i.e. live understory and roots) increase in proportion to existing biomass carbon ratios. Mortality is applied to the aboveground carbon and distributed to the dead carbon pools proportionally to existing density values, assuming that these are net changes and there is implicit transfer of litter carbon to the soil. The soil carbon exchange value represents the net change in soil carbon density, including contributions from root mortality, litter, and respiration, so root mortality is subtracted from roots and implicitly counted in soil carbon accumulation.

In **Savanna and Woodland**, net ecosystem carbon exchange values are split into net tree carbon exchange (represented by the vegetation carbon accumulation value) and net understory 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 net tree accumulation is split between aboveground and root proportionally to existing carbon densities. Due to lack

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[22] The average CO_2 and CH_4 carbon balance from Knox et al. (2015) gives a net CO_2e emission, although net emissions differ with age. The young wetland (~3 years old) is a net CO_2e source, while the older wetland (~15 years old) is barely a net CO_2e sink. Since we do not account for aqueous carbon loss in Fresh Marsh or Coastal Marsh, their net carbon accumulation rates may be slightly overestimated. It is unknown how much aqueous carbon loss is stored elsewhere or eventually emitted.

[23] All Cultivated Land in the Delta is currently assumed to be on peatland and is assigned the appropriate soil carbon accumulation value in the input file. This may overestimate absolute soil carbon loss because not all Delta Cultivated Land is peatland, but it allows direct estimation of the benefits of restoring Delta wetlands.

of data, Savanna and Woodland are currently assumed to have no woody understory carbon dynamics even though initial carbon density values indicate that some of these lands do have a woody understory. This woody understory is static in CALAND, and the understory carbon dynamics are modeled as Grassland. 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. Tree root mortality is added to soil carbon and main canopy mortality is added to the three dead carbon pools proportionally 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.

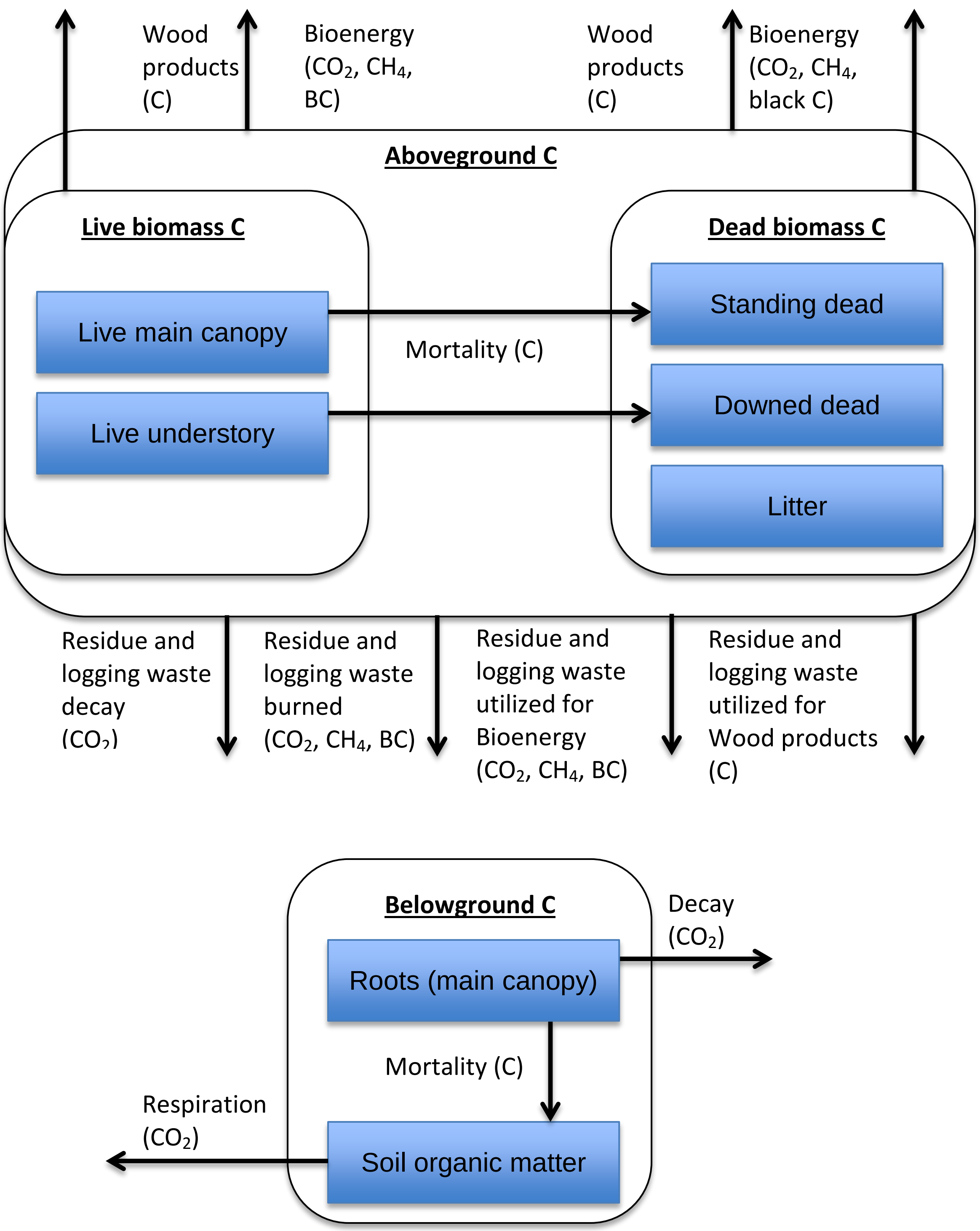
The **Forest** vegetation carbon accumulation values vary according to ownership and to region, with Private lands experiencing the highest management intensity. These values represent net aboveground wood volume changes (growing stock volume). Thus, additional carbon accumulation is calculated for foliage, branch, bark, root, and understory proportionally to existing amounts in the vegetation carbon pools and estimates of the proportion of carbon in different tree elements (Jenkins et al., 2003). 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 and implicitly counted in soil carbon accumulation.

Urban Area is parameterized such that vegetation carbon accumulation represents net aboveground urban forest growth including mortality and its management, but on the area basis of Urban Area. Urban forest area is a fraction of Urban Area that changes over time either at a historical rate (John Dingman, personal communication), or to meet a target fraction in a certain year. Thus, the vegetation carbon accumulation rate for Urban Area is linearly scaled from its initial value proportionally to the linear change in urban forest fraction. This carbon accumulates in aboveground biomass only because there is no soil carbon exchange or root dynamics for Urban Area due to lack of input data. Mortality is transferred to a dead removal management activity in order to control the destination of the removed material.

CALAND contains options for prescribing various management activities to land area in Forest, Grassland, Savanna, Woodland, Urban Area and Cultivated Land that affect corresponding carbon exchange values and Forest mortality rates. These options are engaged to model the alternative scenarios. See Appendix C for management effects on net ecosystem carbon accumulation. The parameters controlling the rate adjustments for each management activity are set in the carbon input file. These parameters are derived from carbon exchange rates reported under different management activities. Specific Forest management activities are covered in the next section, and each Forest management practice is assumed to affect carbon exchange equally across practices (except for Afforestation, which does not affect these rates because it is a land type change). 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 MgC/ha with a C:N ratio of 11:1. The Low compost amendment frequency is recommended for the 50-year period of this study so as to not introduce treated area additional to that prescribed in a given year (due to repeated amendments), and to ensure benefits for this period without necessarily expecting repeat amendments to occur. The Cultivated Land management parameter represents soil conservation that modifies the soil carbon exchange rates based on combined data for cover crop and no-till practices. 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 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 adjustments to Cultivated Land rates occur only for the area prescribed in a given year. **In brief, Forest management increases vegetation and soil carbon accumulation and decreases mortality; compost amendment reduces soil carbon loss in Grassland, Savanna, and Woodland; and soil conservation on Cultivated Land reduces soil carbon loss in the Delta and increases soil carbon accumulation elsewhere.**

Figure 4: 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/bioenergy: (1) the traditional harvest pathway and (2) a slash pathway from uncollected harvest residue and other debris (understory, downed, and litter).



2.3.3. 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[24]). Forest management activities modeled in CALAND include a set of treatments applied to Forest lands (Clearcut, Partial Cut, Fuel Reduction, Understory Treatment, Prescribed Burn) and a corresponding set with additional slash utilization (Clearcut Slash Utilization, Partial Cut Slash Utilization, Fuel Reduction 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, and litter pools, 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. The parameters that define these activities are in Appendix E. Afforestation (i.e., forest area expansion) is implemented as a land type conversion (see below). Reforestation is not implemented in CALAND because of lack of data, and because it would be redundant in automatically regenerating ecosystems (Forest management and wildfire do not change the land type).[25] Forest clearing activities associated with conversion from Forest to Urban Area or Cultivated Land are implemented as part of the land type conversion

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[24] 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.

[25] There are not sufficient data to specifically implement reforestation in a landscape carbon model, nor is it clear that reforestation practices significantly affect landscape level carbon exchange. 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 replacement, with reforestation practices primarily determining species composition. However, severe fire can affect regeneration rates and other environmental factors associated with 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 statistics 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 fire and forest regeneration data are needed to adequately parameterize the conditions for reforestation in CALAND, in addition to a more detailed fire module. Provided these data exist and show that forest area may not regenerate naturally, the implemented Afforestation activity could be used to emulate reforestation practices. Given the lack of data and the high uncertainty of the associated processes, it is reasonable to assume in the current version that forest (and other ecosystems) implicitly regenerate after fire. This assumption will be investigated in future development of CALAND.

routine in CALAND (see below), and can also include removal of slash for bioenergy and wood products. These parameters are the same ones as defined in Appendix E.

The ten Forest management activities are parameterized based on the literature except for the potential 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 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 Appendix E) must add to 1.

The carbon transfer parameters are the same across ownerships, but the adjustments to ecosystem carbon accumulation rates vary across ownerships because the non-adjusted rates vary across ownerships. Clearcut and Partial Cut capture the average characteristics of nearly all commercial timber harvest practices in California, with Partial Cut representing commercial thinning (Stewart and Nakamura, 2012). The most common practice for fuel reduction is thinning, so currently Fuel Reduction is parameterized identically to Partial Cut. Prescribed Burn is also a fuel reduction activity, but is parameterized separately because it has 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. 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 are will therefore be areas of inquiry in the coming months and a component of alternative scenarios developed for the NWL Implementation Plan.

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). We assume that all carbon going to energy is burned for electricity. All of these emissions occur within the model year. The non-energy burned carbon emissions are partitioned into CO_2, CH_4, and BC 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 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. Upcoming research will seek to incorporate emissions data from nascent bioenergy technologies, including those funded through the California Energy Commission's Electric Program Investment Charge (EPIC) Program. 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.

2.3.4. Wildfire

Wildfire transfers carbon from the landscape to the atmosphere, and from live to dead biomass, without changing land type (regeneration is assumed, see Section 2.3.3 footnote). Wildfire is parameterized for three severity levels in the wildfire table in the carbon input file, based on Pearson et al. (2009) (Appendix E). The annual wildfire area is prescribed in the scenario files, with one case prescribed for all scenarios. The area burned each year is the 2000-2015 average annual burned area calculated from the CAL FIRE fire perimeters data set[26]. This statewide area is distributed proportionally; first to the 2010 ownership areas within each region (which do not change over time), and then each year to the Forest, Woodland, Savanna, Shrubland, and Grassland land types (which do change over time) within each ownership and region. These land types were selected through visual overlay of the fire perimeters data with the land cover type data. There is sufficient flexibility in the current scenario file to prescribe a variety of fire cases, and to modify the format to accept land-category-specific and/or year-specific areas (similar to the managed area and mortality inputs). Currently, the main limitation in projecting the effects of fire on landscape carbon is the data processing required to generate detailed inputs[27]. All wildfire carbon emissions are partitioned into CO_2, CH_4, and BC based on the same reported non-energy burned carbon emissions fractions (Jenkins et al., 1996) used for Forest management.

2.3.5. Land type conversion

Land type conversion is driven by historical, business-as-usual trends and by specified conservation targets. The annual conversion area is 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 to determine the areas of each land type being converted to another land type. These transition values are calculated by splitting individual land type gains proportionally across all available land type losses.

The business-as-usual values were calculated as the annual area changes required to match the net land category area differences between 2001 and 2010, as

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

[27] One of the goals for Version 3 is to implement the use of the spatially explicit wildfire area that is being developed for the California Fourth Climate Change Assessment.

determined from the LANDFIRE remote sensing data, with adjustments for slight differences in total area between years[28]. **While this method captures all land type changes (including those not driven by human activity), the main limitation of using only two land cover endpoints is that this method cannot determine the permanence of the land type changes, and thus cannot determine the actual annual rates of change over time.** For example, a forest fire or clearcut 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, which of these two types persists due to the long regeneration periods of forests, or what fraction of burned forest may not regenerate naturally. Thus, CALAND assumes that land type regeneration occurs after fire or harvest for all land types, and that the baseline trends represent permanent land type conversion.

Non-permanence may be the largest source of land cover change uncertainty in the current business-as-usual trends, but misclassification and crosswalk uncertainty (due to the combination of two different classification schemes) also contribute to this uncertainty. 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 CALAND's estimated expansion of Cultivated Land (which is small relative to other land type changes) differs from other analyses showing similar amounts of Cultivated Land contraction. Additionally, the remote sensing data used in CALAND may be capturing some land clearing and cultivation occurring outside the scope of the other analyses. Nonetheless, uncertainty in absolute carbon projection of the mean state in CALAND is dominated by uncertainty in Grassland/Shrubland cover changes, which is one reason why CALAND *currently* should be used only to examine *differences* between alternative scenarios and the business-as-usual scenario**.**

An update to business-as-usual land cover change is planned for a future version of CALAND, using a land use change driven approach that incorporates data from the

[28] For example, in Version 1 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.

California Department of Conservation Farmland Mapping and Monitoring Program (FMMP)[29]. This future approach may better capture Urban Area and Cultivated Land cover change dynamics, but would miss potential land cover change due to non-anthropogenic sources, including permanent change due to severe disturbances, such as fire. A more complete approach would include a time-series remote sensing analysis of all land cover types and additional disturbance information.

The management practices that drive land type conversion in CALAND include Restoration (Meadow, Coastal Marsh, Fresh Marsh, Seagrass), land protection (labeled as Growth, which defines the Urban Area growth rate), and Afforestation. These targets are applied on top of the business-as-usual changes. Areas that have been restored persist throughout the simulation period. Coastal Marsh and Fresh Marsh are restored only from Cultivated Land, which aligns with current practices (Steve Deverel, personal communication), although technically Coastal Marsh can also be restored from seasonal wetland (which is not distinguished in the land cover classification) 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). Land protection is implemented as an annually prescribed, decreasing Growth rate for Urban Area. This growth rate prescription supersedes the historical value input from the remote sensing data. Afforestation is restored proportionally from existing Shrubland and Grassland.

The effects of land type conversion on existing carbon stocks are based on differences in carbon density between the land types, with the exceptions 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

[29] One of the goals for Version 3 is to implement the land use scenarios developed for the CA Fourth Climate Change Assessment.

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

Each output table in the output file provides annual values for a single variable (Appendix D), 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. 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.

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. The diagnostic script “plot_caland.r” makes summary plots comparing different scenarios for many of these output tables. An additional diagnostic script (plot_scen_types.r) makes land-type comparison plots from the outputs of “plot_caland.r”.

4. Looking Ahead

CALAND continues to evolve to better serve the needs of the State and other stakeholders. Planned improvements for Version 3 include: 1) updated land use and land cover change, 2) updated wildfire area and severity, 3) addition of potential climate change impacts on vegetation growth, and 4) development of additional management practices. Updates to the land use and cover change (1) and wildfire (2) components are expected to be completed by the end of 2017. The addition of climate impacts (3) and some new management practices (4) are expected to be completed by the end of March 2018, pending data availability.

The current, business-as-usual land use and land cover change data are going to be replaced with a newly generated data set that incorporates California Department of Conservation FMMP data. The USGS has generated land use and land cover change scenarios--based on FMMP agricultural and urban land use data--for the California Fourth Climate Change Assessment (Fourth Assessment). These scenarios include business-as-usual and alternative projections for population growth. These USGS data use a different land cover map than CALAND, and so only the changes in agricultural and urban areas will be applied to CALAND's initial land cover map to determine the new land use and land cover change trajectories. This will improve Urban Area and Cultivated land cover change dynamics and reduce uncertainty associated with the currently used high rate of Shrubland loss, but it will miss permanent, non-anthropogenic land cover change. A comprehensive land use and land cover change study would be required to provide more complete information on California landscape dynamics.

Business-as-usual and alternative-climate wildfire scenario maps that have also been developed for the Fourth Assessment will be used to improve CALAND wildfire carbon dynamics. Currently, statewide average burned area is distributed proportionally across the regions to Forest, Woodland, Savanna, Shrubland, and Grassland land types, at medium severity. The new wildfire data include annual burned area (available) and severity (not yet available), and will be spatially assigned to CALAND land categories. CALAND will also be modified to use these new data. This development will be an important expansion of the wildfire component that will facilitate potential implementation of wildfire-management interactions, including restoration of pre-suppression fire regimes.

Implementing potential climate impacts on vegetation growth requires both model development and additional data processing. The current carbon accumulation values are from field studies and represent growth and respiration under historical climate conditions. New data inputs will be generated that adjust the BAU accumulation values by climate scenario. The USGS is using a mechanistic ecosystem model to generate these new data in conjunction with the Fourth Assessment. These data will be transformed into CALAND inputs, and CALAND will be modified to apply these climate impact scenarios to its vegetation and soil carbon accumulation values. This development will facilitate exploration and understanding of climate-management interactions.

Depending on the desired management practice, addition of practices requires varying degrees of data acquisition, practice parameterization, and model development. While the current set of practices in Version 2 represents the available data, with the exception of the newly implemented slash utilization pathway, it does not represent the complete set that the State is currently pursuing through existing climate change mitigation programs, expects to pursue as part of its Natural and Working Lands Strategy going forward, or expects to include in the Natural and Working Lands Implementation Plan. The particular practices and the order in which they are added to

CALAND will depend on data availability, ease and reliability of parameterization, magnitude of model development, and priority.

The new slash utilization pathway is a good example of how new practices may be implemented in CALAND. The model has recently been modified to allow removal and use (i.e., energy and wood products) of harvest residue that is usually burned or left in the forest to decay. There are no data for this practice because it is not traditionally done, and the next step is to develop appropriate parameterizations that define the amount removed and what happens to it. Once defined, the practice can be applied in CALAND to estimate its effect on the landscape carbon budget.

Additional Forest management practices are under consideration for implementation in CALAND. Improved forest management can take many forms. Alternative fuel reduction strategies can be added by developing new parameterizations for harvest and biomass disposition. Lengthening cutting cycles, however, would require data on the relative increase in long-term, average carbon density with respect to the business-as-usual cycle, and model development to accommodate this new input and its effect on the carbon budget.

There is growing interest in carbon management on Cultivated and grazed (Grassland, Savanna, Woodland) lands, but there are few data available. The USDA-NRCS has recently developed a California-specific version of COMET-Planner, which is a modeling tool designed to estimate GHG benefits of particular agricultural practices. These practices include various tillage, cover crop, crop rotation/pattern, amendment, pasture, grazing, and nutrient management options for both cropland and grazed land. As many of these practices have overlapping uncertainty ranges, the goal is to explore ways to reduce the set of COMET-Planner practices into a few key categories that could then be parameterized as inputs to CALAND.

The largest number of COMET-Planner practices for Cultivated land are actually changes in land cover, such as riparian restoration and hedgerow planting. Adding these practices to CALAND would require data acquisition (including what fraction of a field would likely be converted), new parameterizations, and model development to accommodate this more specific type of land cover change that comes only from Cultivated land and has a finite length of time during which it accumulates carbon.

Adding a more general restoration of a common land type, such as Woodland, also requires model development, and the template for this type of expansion and persistence exists in CALAND for other land types (e.g., Forest expansion).

Appendices

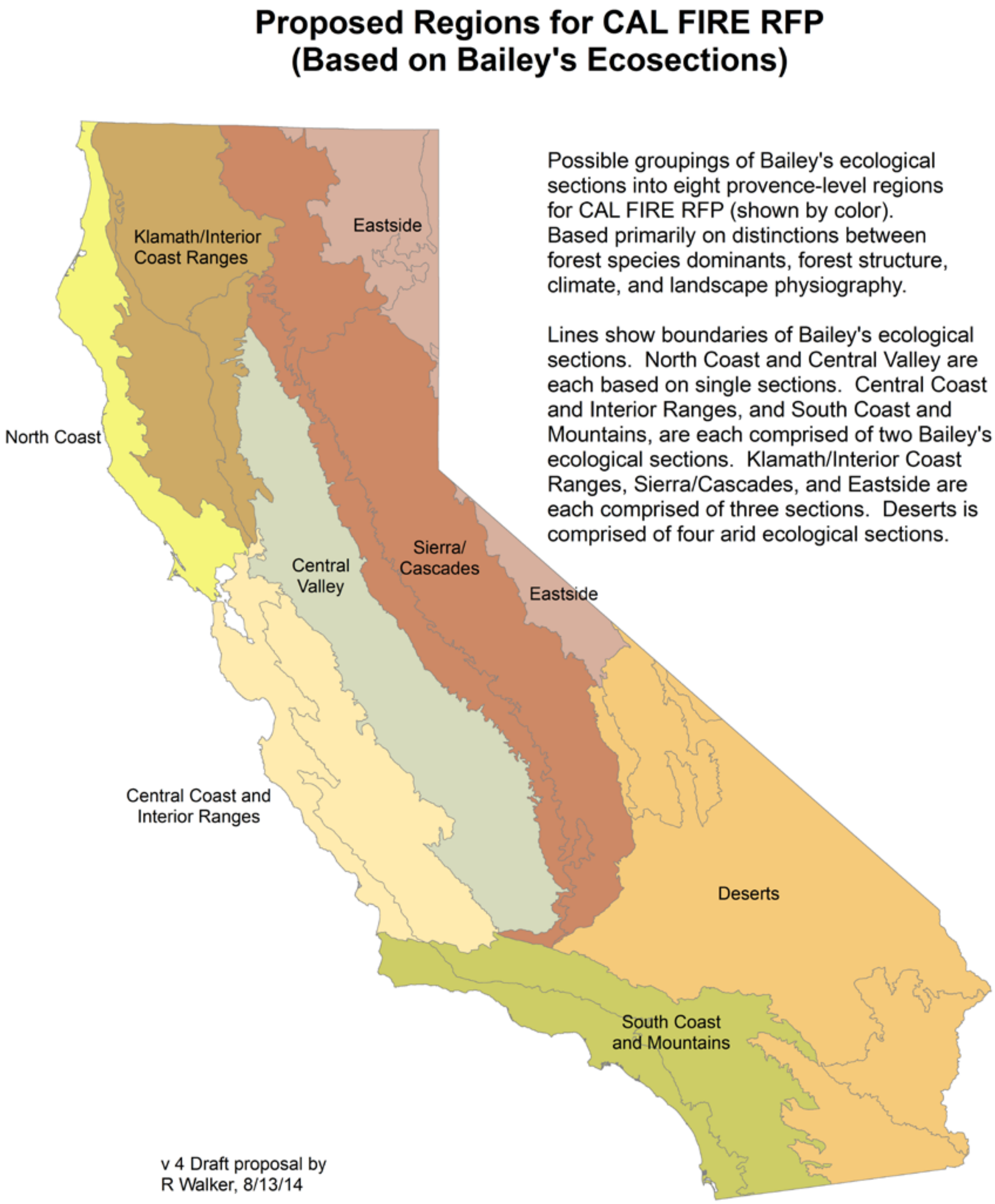
Appendix A: Land Categories identified for use in CALAND

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
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
Coastal 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 Areas (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.



Appendix B: Mean Net Ecosystem Carbon Accumulation Rates

Positive values indicate land uptake.

Land Category	**Vegetation** MgC/ha/yr	**Soil** MgC/ha/yr	**Source**
Water	NA	NA	NA
Ice	NA	NA	NA
Barren	NA	NA	NA
Sparse	NA	NA	NA
Desert	NA	0.76	Hastings et al., 2005 Wohlfahrt et al., 2008
Shrubland	0.93	0.28	Quideau et al., 1998
Grassland	NA	-2.22	Ma et al., 2007 (Table 2) Ryals and Silver, 2013 (appendix)
Savanna	3.67	-2.69	Ma et al., 2007 (Table 2)
Woodland	3.67	-2.69	Ma et al., 2007 (Table 2)
Forest[30], Private	2.1	0.71	Christensen et al., 2016 (growth, mortality) Quideau et al., 1998 (soil, litter) Turk and Graham, 2009 (litter)
Forest, other	1.4	0.71	Christensen et al., 2016 (growth, mortality) Quideau et al., 1998 (soil, litter) Turk and Graham, 2009 (litter)
Forest, USFS non-wilderness	1.37	0.71	Christensen et al., 2016 (growth, mortality)

[30] These state average Forest values within each ownership are disaggregated to the regions based on relative productivity (Hudiburg et al., 2009) and Forest area.

			Quideau et al., 1998
			(soil, litter)
			Turk and Graham, 2009
			(litter)
Meadow	NA	0.95	Drexler et al., 2015 (Table 2)
Coastal Marsh	NA	1.44	Callaway et al., 2012
			Chmura et al., 2003 (Table 1)
Fresh Marsh	NA	3.37	Knox et al., 2015 (Appendix D)
Cultivated Land, non-Delta	NA	0.31	Mitchell et al., 2015 (Appendix D)
			Wu et al., 2008 (Table 2)
Cultivated Land, Delta	NA	-2.18	Hatala et al., 2012
			Knox et al., 2015
Urban Area	0.93	NA	Bjorkman et al., 2015
Seagrass (Ocean)	NA	0.45	Mcleod et al., 2011 (Table 1, the minimum range value)

Appendix C: Management Effects on Net Ecosystem Carbon Accumulation

The prescribed mortality rates in Appendix B are multiplied by the following factors for the managed area.

Land Category	Vegetation factor	Soil factor	Mortality factor	Source
Forest, private	1	1.79	1	Powers et al., 2013 (soil, Table 4)
Forest, protected	1.2	1.79	0.67	Christensen et al., 2016 (growth, mortality; in relation to private values) Powers et al., 2013 (soil, Table 4)
Forest, USFS	1.2	1.79	0.56	Christensen et al., 2016 (growth, mortality; in relation to private values) Powers et al., 2013 (soil, Table 4)
Rangeland, medium frequency	NA	0.77	NA	Ryals et al., 2015
Rangeland, low frequency	NA	0.94	NA	Ryals et al., 2015
Cultivated Land, non-Delta, no-till/cover crop	NA	2.58	NA	Mitchell et al., 2015 (Appendix D)
Cultivated Land, Delta, no-till/cover crop	NA	0.85	NA	Based on the C exchange from Hatala et al., 2012 and Knox et al., 2015, using the absolute benefit from Mitchell et al., 2015

Appendix D: CALAND Output Variables and Definitions (158 variables)

Output variable:	Definition:
Area (ha) (3)	
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 per ha) (9)	
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) (9)	
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) (23)	
Total_Wood_C_stock	Persistent wood product carbon stock
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 slash)
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 slash)
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 slash)
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 slash)
LCC_Harv2Wood_AnnGain_C_stock	Annual gain in wood product carbon stock sourced from land cover change harvest
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) (14)	
Eco_CumGain_C_stock	Cumulative net gain in ecosystem carbon stock from atmosphere
Total_Atmos_CumGain_C_stock	Cumulative gain in atmosphere carbon stock from forest management, wildfire, land cover change, and landfill wood product decay
Manage_Atmos_CumGain_C_stock	Cumulative gain in atmosphere carbon stock from forest management
Fire_Atmos_CumGain_C_stock	Cumulative gain in atmosphere carbon stock from wildfire
LCC_Atmos_CumGain_C_stock	Cumulative gain in atmosphere carbon stock from land cover change
Wood_Atmos_CumGain_C_stock	Cumulative gain in atmosphere carbon stock from landfill wood product decay

Total_Energy2Atmos_C_stock	Cumulative gain in atmosphere carbon stock 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 gain in atmosphere carbon stock from forest management, wildfire, land cover change, and landfill wood product decay
Manage_Atmos_AnnGain_C_stock	Annual gain in atmosphere carbon stock from forest management
Fire_Atmos_AnnGain_C_stock	Annual gain in atmosphere carbon stock from wildfire
LCC_Atmos_AnnGain_C_stock	Annual gain in atmosphere carbon stock from land cover change
Wood_Atmos_AnnGain_C_stock	Annual gain in atmosphere carbon stock from landfill wood product decay
Total_AnnEnergy2Atmos_C_stock	Annual gain in atmosphere carbon stock from biomass energy associated with forest management and land cover change
Partitioning of land-atmosphere carbon exchange (Mg C) (land uptake is negative) (30)	
Manage_Atmos_CumGain_BurnedC	Cumulative gain in atmosphere carbon stock from burning due to forest management, including bioenergy
Manage_Atmos_CumGain_NonBurnedC	Cumulative gain in atmosphere carbon stock from decay due to forest management
Fire_Atmos_CumGain_BurnedC	Cumulative gain in atmosphere carbon stock from wildfire
Fire_Atmos_CumGain_NonBurnedC	Cumulative gain in atmosphere carbon stock from decay following wildfire (default is 0)
LCC_Atmos_CumGain_TotEnergyC	Cumulative gain in atmosphere carbon stock from bioenergy due to land cover change (harvest plus slash)
LCC_Atmos_CumGain_Harv2EnergyC	Cumulative gain in atmosphere carbon stock from bioenergy due to land cover change harvest
LCC_Atmos_CumGain_Slash2EnergyC	Cumulative gain in atmosphere carbon stock from bioenergy due to land cover change slash
LCC_Atmos_CumGain_NonBurnC	Cumulative gain in atmosphere carbon stock from decay due to land cover change
LCC_Atmos_CumGain_FireC	Cumulative gain in atmosphere carbon stock from slash burning due to land cover change
Manage_Atmos_AnnGain_BurnedC	Annual gain in atmosphere carbon stock from burning due to forest management, including bioenergy
Manage_Atmos_AnnGain_NonBurnedC	Annual gain in atmosphere carbon stock from decay due to forest management
Fire_Atmos_AnnGain_BurnedC	Annual gain in atmosphere carbon stock from wildfire
Fire_Atmos_AnnGain_NonBurnedC	Annual gain in atmosphere carbon stock from decay following wildfire (default is 0)
LCC_Atmos_AnnGain_TotEnergyC	Annual gain in atmosphere carbon stock from bioenergy due to land cover change (harvest plus slash)
LCC_Atmos_AnnGain_Harv2EnergyC	Annual gain in atmosphere carbon stock from bioenergy due to land cover change harvest

LCC_Atmos_AnnGain_Slash2EnergyC	Annual gain in atmosphere carbon stock from bioenergy due to land cover change slash
LCC_Atmos_AnnGain_NonBurnC	Cumulative gain in atmosphere carbon stock from decay due to land cover change
LCC_Atmos_AnnGain_FireC	Annual gain in atmosphere carbon stock from slash burning due to land cover change
Manage_Atmos_CumGain_TotEnergyC	Cumulative gain of atmosphere carbon stock from biomass energy due to forest management (harvest plus slash; this is part of Manage_Atmos_CumGain_BurnedC)
Man_Atmos_CumGain_Harv2EnergyC	Cumulative gain of atmosphere carbon stock from biomass energy due to forest management harvest
Man_Atmos_CumGain_Slash2EnergyC	Cumulative gain of atmosphere carbon stock from biomass energy due to forest management slash
Manage_Atmos_CumGain_FireC	Cumulative gain (from prescribed burns and residue burning due to forest management) of atmosphere carbon stock (this is part of Manage_Atmos_CumGain_BurnedC)
Manage_Atmos_AnnGain_TotEnergyC	Annual gain of atmosphere carbon stock from biomass energy due to forest management (harvest plus slash; this is part of Manage_Atmos_AnnGain_BurnedC)
Man_Atmos_AnnGain_Harv2EnergyC	Annual gain of atmosphere carbon stock from biomass energy due to forest management harvest
Man_Atmos_AnnGain_Slash2EnergyC	Annual gain of atmosphere carbon stock from biomass energy due to forest management slash
Manage_Atmos_AnnGain_FireC	Annual gain (from prescribed burns and residue burning due to forest management) of atmosphere carbon stock (this is part of Manage_Atmos_AnnGain_BurnedC)
Eco_AnnCO2C	Annual ecosystem C emitted as CO_2, due to net ecosystem C exchange (no wildfire, management, or land conversion effects)
Eco_AnnCH4C	Annual ecosystem C emitted as CH_4, due to net ecosystem C exchange (no wildfire, management, or land conversion effects)
Eco_CumCO2C	Cumulative ecosystem C emitted as CO_2, due to net ecosystem C exchange (no wildfire, management, or land conversion effects)
Eco_CumCH4C	Cumulative ecosystem C emitted as CH_4, due to net ecosystem C exchange (no wildfire, management, or land conversion effects)
Global warming potential of land-atmosphere carbon exchange (Mg CO_2 eq) (land uptake is negative) (70)	
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
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
ManTotEnergy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with Forest management slash
ManTotEnergy_CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with Forest management slash
ManTotEnergy_CumBCeq	Cumulative BC exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_CumBCeq	Cumulative BC exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_CumBCeq	Cumulative BC exchange from bioenergy associated with Forest management slash
ManSlash2Fire_CumCO2	Cumulative CO_2 exchange from burning (residue and prescribed burns) associated with Forest management
ManSlash2Fire_CumCH4eq	Cumulative CH_4 exchange from burning (residue and prescribed burns) associated with Forest management
ManSlash2Fire_CumBCeq	Cumulative BC exchange from burning (residue and prescribed burns) associated with Forest management
LCCTotEnergy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus slash)
LCCHarv2Energy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy_CumCO2	Cumulative CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest slash
LCCTotEnergy _CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus slash)
LCCHarv2Energy _CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy _CumCH4eq	Cumulative CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest slash
LCCTotEnergy _CumBCeq	Cumulative BC exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus slash)
LCCHarv2Energy _CumBCeq	Cumulative BC exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy _CumBCeq	Cumulative BC exchange from bioenergy associated

	with conversion to ag/urban from Forest slash
LCC_NonBurn_CumCO2	Cumulative CO_2 exchange associated with land cover change
LCCFire_CumCO2	Cumulative CO_2 exchange from slash burning associated with land cover change
LCCFire_CumCH4eq	Cumulative CH_4 exchange from slash burning associated with land cover change
LCCFire_CumBCeq	Cumulative BC exchange from slash burning associated with land cover change
TotalEnergy_CumCO2	Cumulative CO_2 exchange from all bioenergy
TotalEnergy _CumCH4eq	Cumulative CH_4 exchange from all bioenergy
TotalEnergy _CumBCeq	Cumulative BC exchange from all bioenergy
Wildfire_CumCO2	Cumulative CO_2 exchange from wildfire
Wildfire_CumCH4eq	Cumulative CH_4 exchange from wildfire
Wildfire_CumBCeq	Cumulative BC exchange from wildfire
ManTotEnergy_AnnCO2	Annual CO_2 exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_AnnCO2	Annual CO_2 exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_AnnCO2	Annual CO_2 exchange from bioenergy associated with Forest management slash
ManTotEnergy_AnnCH4eq	Annual CH_4 exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_AnnCH4eq	Annual CH_4 exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_AnnCH4eq	Annual CH_4 exchange from bioenergy associated with Forest management slash
ManTotEnergy_AnnBCeq	Annual BC exchange from bioenergy associated with Forest management (harvest plus slash)
ManHarv2Energy_AnnBCeq	Annual BC exchange from bioenergy associated with Forest management harvest
ManSlash2Energy_AnnBCeq	Annual BC exchange from bioenergy associated with Forest management slash
Man Slash2Fire_AnnCO2	Annual CO_2 exchange from burning (residue and prescribed burns) associated with Forest management
Man Slash2Fire_AnnCH4eq	Annual CH_4 exchange from burning (residue and prescribed burns) associated with Forest management
Man Slash2Fire_AnnBCeq	Annual BC exchange from burning (residue and prescribed burns) associated with Forest management
LCCTotEnergy_AnnCO2	Annual CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus slash)
LCCHarv2Energy_AnnCO2	Annual CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy_AnnCO2	Annual CO_2 exchange from bioenergy associated with conversion to ag/urban from Forest slash
LCCTotEnergy _AnnCH4eq	Annual CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus

	slash)
LCCHarv2Energy _AnnCH4eq	Annual CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy _AnnCH4eq	Annual CH_4 exchange from bioenergy associated with conversion to ag/urban from Forest slash
LCCTotEnergy _AnnBCeq	Annual BC exchange from bioenergy associated with conversion to ag/urban from Forest (harvest plus slash)
LCCHarv2Energy _AnnBCeq	Annual BC exchange from bioenergy associated with conversion to ag/urban from Forest harvest
LCCSlash2Energy _AnnBCeq	Annual BC exchange from bioenergy associated with conversion to ag/urban from Forest slash
LCC_NonBurn_AnnCO2	Annual CO_2 exchange associated with land cover change
LCCFire_AnnCO2	Annual CO_2 exchange from slash burning associated with land cover change
LCCFire_AnnCH4eq	Annual CH_4 exchange from slash burning associated with land cover change
LCCFire_AnnBCeq	Annual BC exchange from slash burning associated with land cover change
TotalEnergy_AnnCO2	Annual CO_2 exchange from all bioenergy
TotalEnergy_AnnCH4eq	Annual CH_4 exchange from all bioenergy
TotalEnergy_AnnBCeq	Annual BC exchange from all bioenergy
Wildfire_AnnCO2	Annual CO_2 exchange from wildfire
Wildfire_AnnCH4eq	Annual CH_4 exchange from wildfire
Wildfire_AnnBCeq	Annual BC exchange from wildfire

Appendix E: Forest management (and conversion to Urban Area/Cultivated Land) carbon transfer parameters

These are the fractions of carbon moved from one pool to another, to wood products, or to the atmosphere via decay, burning, or bioenergy.

Parameter	Definition	Source
Above_harvested_frac	Fraction of main canopy carbon ultimately removed from Forest	Harvest based on Stewart and Nakamura, 2012 (Table 2 divided by CALAND initial carbon density); Conversion based on Gonzalez et al., 2015
StandDead_harvested_frac	Fraction of standing dead carbon ultimately removed from forest	Harvest based on Stewart and Nakamura, 2012 (same fraction as for main canopy); Conversion based on Gonzalez et al., 2015 (same as for main canopy)
Harvested2Wood_frac	Fraction of total harvested carbon going to wood products	Stewart and Nakamura, 2012 CALFIRE FRAP ownership: http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download; http://frap.fire.ca.gov/data/statewide/FGDC_metadata/ownership13_2.xml 2015 California Conservation Easement Database: CCED, 2015 USFS Wilderness Area: https://data.fs.usda.gov/geodata/edw/datasets.php; https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.Wilderness.xml USFS PSR ecological subregions for the state of California: https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836; https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586 Legal Delta: https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586 Suisun Marsh, delineated by high soil C density: gSSURGO (USDA, 2014)
Harvested2Energy_frac	Fraction of total harvested carbon going to atmosphere	Stewart and Nakamura, 2012

	via energy generation (burned for electricity)	CALFIRE FRAP ownership: http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download; http://frap.fire.ca.gov/data/statewide/FGDC_metadata/ownership13_2.xml
		2015 California Conservation Easement Database: CCED, 2015
		USFS Wilderness Area: https://data.fs.usda.gov/geodata/edw/datasets.php; https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.Wilderness.xml
		USFS PSR ecological subregions for the state of California: https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836; https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586
		Legal Delta: https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586
		Suisun Marsh, delineated by high soil C density: gSSURGO (USDA, 2014)
Harvested2SawmillDecay_frac	Fraction of total harvested carbon decaying to atmosphere at the sawmill	Stewart and Nakamura, 2012
		CALFIRE FRAP ownership: http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download; http://frap.fire.ca.gov/data/statewide/FGDC_metadata/ownership13_2.xml
		2015 California Conservation Easement Database: CCED, 2015
		USFS Wilderness Area: https://data.fs.usda.gov/geodata/edw/datasets.php; https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.Wilderness.xml
		USFS PSR ecological subregions for the state of California: https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836; https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586

		Legal Delta: https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586
		Suisun Marsh, delineated by high soil C density: gSSURGO (USDA, 2014)
Harvested2Slash_frac	Fraction of total harvested carbon that is left on site	Stewart and Nakamura, 2012
		CALFIRE FRAP ownership: http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download; http://frap.fire.ca.gov/data/statewide/FGDC_metadata/ownership13_2.xml
		2015 California Conservation Easement Database: CCED, 2015
		USFS Wilderness Area: https://data.fs.usda.gov/geodata/edw/datasets.php; https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.Wilderness.xml
		USFS PSR ecological subregions for the state of California: https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836; https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586
		Legal Delta: https://catalog.data.gov/dataset/legal-delta-boundary-2001-dwr-ds586
		Suisun Marsh, delineated by high soil C density: gSSURGO (USDA, 2014)
Understory2Slash_frac	Fraction of understory carbon transferred to slash (temporary C pool that transfers to atmosphere via bioenergy or burning, or to wood products)	Burn is based on medium intensity fire from Pearson et al. 2009;
		Weed/brush treatment is conservatively split
DownDead2Slash_frac	Fraction of down dead carbon transferred to slash (temporary C pool that transfers to atmosphere via bioenergy or burning, or to wood products)	Harvest is from Dore et al., 2016 (Table 2, based on litter);
		Burn is from Wiechmann et al. 2015

Litter2Slash_frac	Fraction of litter carbon transferred to slash (temporary C pool that transfers to atmosphere via bioenergy or burning, or to wood products)	Harvest is from Dore et al., 2016 (Table 2) Burn is from Wiechmann et al. 2015
Slash2Energy_frac	Fraction of slash carbon going to atmosphere via energy generation (burned for electricity) (default is 0.25 and 0.0 with and without slash utilization, respectively)	Aspirational target for slash utilization
Slash2Wood_frac	Fraction of slash carbon going to wood products (default is 0.0)	Aspirational target for slash utilization
Slash2Burn	Fraction of slash carbon burned in the forest (default is 0.0 and 0.25 with and without slash utilization, respectively, for non-Prescribed_burn; default is 1.0 for Prescribed_burn)	Assumed minimum fraction of carbon emitted from pile burns
Slash2Decay	Fraction of slash carbon decaying to the atmosphere (default is 0.75)	Assumed maximum fraction of carbon left to decay
Soil2Atmos_frac	Fraction of soil carbon decaying to atmosphere	Harvest based on Birdsey et al., 2002;
		Conversion based on Davidson et al., 1993
Under2DownDead_frac	Fraction of understory carbon going to down dead	Burn is based on medium intensity fire from Pearson et al. 2009;
		Weed/brush treatment is conservatively split
Above2StandDead_frac	Fraction of main canopy carbon going to standing dead	Burn based on Wiechmann et al., 2015

Below2Atmos_frac	Fraction of main root carbon decaying to atmosphere	For conversion to developed/ cultivated: Based on personal communication with Bruce Gwynne
Below2Soil_frac	Fraction of main root carbon going to the soil	For conversion to developed/ cultivated: Based on personal communication with Bruce Gwynne

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