Impacts of California’s climate-relevant land use policy scenarios on terrestrial carbon emissions (CO$_2$ and CH$_4$) and wildfire risk

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Abstract

Land-use and -cover change (LUCC) is globally important to climate change mitigation. However, using land-based strategies to support aggressive subnational greenhouse gas emissions reduction targets is challenging due to competing land use priorities and uncertainty in ecosystem carbon dynamics and climate change effects. We used the California natural and working lands carbon and greenhouse gas model to quantify the direct ecosystem carbon emissions (CO$_2$ and CH$_4$) impacts, trade-offs, and climate change interactions of two policy scenarios identified by the State of California for fulfilling multiple land use goals, including the competing goals of mitigating wildfire severity and landscape carbon emissions, among others. Here we show that emissions from desired forest management to reduce the amount of combustible biomass (fuel reduction) initially outweighed emissions reductions from other strategies (e.g. less intensive forest management, restoration, land conservation); however, avoided emissions and enhanced carbon sequestration from the other strategies gradually outweighed fuel reduction emissions. Thus, in jurisdictions with large-scale wildfire mitigation goals, practices that reduce emissions and/or increase carbon sequestration can simultaneously offset fuel reduction emissions. Our analysis highlights the complexities inherent in LUCC planning, underscoring the need for governments to begin the task now.

1. Introduction

Limiting global warming to 1.5°C above pre-industrial levels will require reducing global net carbon dioxide (CO$_2$) emissions to zero and dramatically reducing non-CO$_2$ greenhouse gases (GHGs), particularly methane (CH$_4$) by 2050 [1]. Land-use and -cover change (LUCC) is a key variable in most of the decarbonization modeling scenarios for achieving this goal (e.g. biomass energy with carbon capture and storage, afforestation, reforestation) [2–4], as it can be both a large source [5–7] and sink [8–10] of carbon emissions. However, decarbonization is just one of several, sometimes competing, values derived from land use, which complicates both the estimation of achievable carbon benefits and the development of regional policies for realizing those potentials.

Ranked globally as the fifth largest economy, with 39.5 million people [11], California became a leading entity in climate change mitigation efforts with the passage of the California Global Warming Solutions Act of 2006. Subsequent target-setting furthered the state’s commitment to reduce emissions by 40% and 80% below 1990 levels by 2030 and 2050, respectively. Natural and working lands (NWL) (e.g. forestlands, rangelands, and wetlands) have been deemed essential to realizing these goals [12]. Balancing the desire to secure NWL as a resilient carbon sink with the need for wildfire mitigation emerged as a focal point during development of the state’s climate change policy in 2016–2019 [13, 14]. In California, historical fire exclusion has resulted in conditions that, combined with climate change impacts, increase susceptibility to large, high severity wildfires [15–17]. However, the upfront emissions associated with reducing fuel loads (e.g. thinning, prescribed burning, understory treatment) are not necessarily offset by the reduction in wildfire emissions [18, 19].
Previous studies have estimated the technical potential of NWL to contribute to emissions reduction goals [16, 20–22], but few have evaluated the investment potential of subnational entities to reduce emissions through LUCC policies that meet a variety of land use goals, such as habitat restoration, agricultural production, and mitigation of high-severity wildfire, which can dominate the land carbon budget [23, 24]. Incorporating LUCC planning into climate change mitigation strategies is hampered by the lack of a cohesive framework that can simultaneously explore the effects of multiple practices (some with emissions trade-offs), inherent uncertainties in carbon stocks and fluxes, and climate change impacts.

We developed the California natural and working lands carbon and greenhouse gas model (CALAND) [14, 25] to overcome these limitations and examine the following key scientific questions: (a) What are the terrestrial carbon emissions and wildfire mitigation impacts of realistic LUCC policy scenarios designed to meet multiple land use priorities for California through the 21st century? (b) What are the trade-offs between wildfire mitigation activities and carbon? (c) How will climate change impact the mitigation potentials of land-based strategies? We simulated two portfolios of land-based strategies (Scenarios A and B) that represent moderate and high implementation levels of state-supported programs, respectively, under three climates (representative concentration pathways (RCP) 4.5 and 8.5, and historical climate). These scenarios included 14 mitigation pathways spanning land conservation, ecosystem restoration, forestry, and agriculture (table 1).

2. Main findings

2.1. Ecosystem carbon emissions impacts of California State’s land use policy scenarios

We used the CALAND model to quantify the impacts of two subnational climate-relevant LUCC policy scenarios (Scenarios A and B) [14], developed in support of a variety of land use priorities in California (e.g. carbon sequestration, wildfire mitigation, habitat), on the statewide terrestrial GHG budget. The scenarios were developed through a novel process led by the California Natural Resources Agency, in partnership with other state agencies and public contributors (See Methods). In contrast to what is typically done in climate policy planning, state agencies included wildfire mitigation strategies with emissions tradeoffs (i.e. fuel reduction practices) in addition to emissions-reducing strategies (e.g. woodland restoration, avoided conversion, less intensive forest management), and did not target specific emissions reduction goals, but rather sought to represent the full, and in some cases, accelerated, implementation of existing natural resource management plans and programs based on a realistic scaling up of state funding and technical capacity, and a commensurate increase in landowner participation. Recent studies on the emissions mitigation potential of land stewardship practices at the global [21], U.S. national [22], and subnational [20] scales have used less constrained approaches on implementation areas, and the treatment areas proposed in some mitigation pathways in California far exceeded what the state elected to include in Scenarios A and B. Scenario A was considered moderate implementation, with areas that exceeded (up to two times) historical management levels on private and public lands but were feasible through increasing current projected state funding, while Scenario B was considered high implementation with areas that far exceeded Scenario A for certain practices, and would require substantial increases in projected state funding, and new programs and policies.

The simulated terrestrial GHG budget included all CO₂ and CH₄ fluxes from soil and vegetation, as well as areas in the ocean for seagrass restoration, including landfill and sawmill decay of forest wood products, and combustion of forest biomass from wildfire, controlled burning, and energy production (See Methods). We simulated Scenarios A and B with historical climate and with RCP 4.5 and RCP 8.5 spatially-explicit climate change effects on soil and vegetation carbon fluxes and wildfire areas, and compared the outputs to a baseline of no interventions with the respective climate (see Methods).

Compared to Scenario A, implementation areas in Scenario B included 44% more forest fuel reduction; a 40% increase in less intensive forest management; 184% more oak woodland restoration; 25% more seagrass restoration; 8% more coastal wetland restoration; and 50% more land protection from urban development (table 1). Both scenarios had some activities with approximately the same implementation areas (i.e. reforestation of non-regenerating forest, urban forest expansion, restoration of fresh wetland, coastal wetland, and montane meadow). In general, the temporal trends of the emissions impacts of management Scenarios A and B relative to the baseline were consistent across climates, with cumulative emissions greater than the baseline for the first 15–17 years following the onset of management interventions, followed by emissions reductions at increasing rates through 2100. Mean cumulative landscape emissions were reduced by 783 Tg CO₂ equivalents (CO₂e) over the long term (2019–2100) on average across the six combinations of climate (RCP 4.5, RCP 8.5, historical) and management Scenarios A and B (SD = 86.7 Tg CO₂e) relative to the baseline (figure 1 and table 2). However, in the short-term, during the period with the most management (2019–2030), cumulative emissions increased
by 33.3 Tg CO$_2$e on average across the six scenario-climate combinations (SD = 15.8 Tg CO$_2$e) relative to the baseline (table 2).

Averaged across climates, Scenario B generated 153% higher emissions than Scenario A from 2019 to 2030, but reduced cumulative emissions by 8.6% more than Scenario A by 2100. This demonstrates that immediate investments in emissions-reducing practices (2019–2030), many of which have long-term benefits, and ongoing wildfire mitigation practices (12 year repeat treatment interval through 2100) may eventually pay off in terms of carbon benefits. However, neither Scenarios A or B contributed positively ever, neither Scenarios A or B contributed positively
Table 2. Comparison of statewide impacts of two land use policy scenarios in California (Scenarios A and B) on baseline cumulative net carbon flux (CO$_2$ and CH$_4$) under historical climate and two future climate change projections: representative concentration pathways (RCP) 4.5 and 8.5. Values represent a change from the respective baseline of no interventions, across three climates and three time periods, where positive values are an increase in emissions and negative values are a decrease. Uncertainty bounds are in parentheses and were generated by simulating two combinations of initial carbon density inputs and historical carbon flux inputs:

| Climate | Scenario | 2019–2030 | 2019–2050 | 2019–2100 |
|---------|----------|-----------|-----------|-----------|
| Historical | A | 18.9$^c$ | (11.0–27.6)$^d$ | (−101.3 to −76.1) | (−791.5 to −651.1) |
| | B | 47.5 | (34.8–61.3) | (−93.7 to −53.6) | (−882.0 to −680.3) |
| RCP 4.5 | A | 19.8 | (11.8–28.7) | (−87.1 to −62.2) | (−760.6 to −622.9) |
| | B | 49.0 | (36.2–62.8) | (−74.5 to −34.5) | (−843.8 to −664.2) |
| RCP 8.5 | A | 17.7 | (9.4–26.7) | (−109.2 to −80.6) | (−909.7 to −778.6) |
| | B | 46.6 | (33.4–60.7) | (−102.6 to −58.5) | (−1016.9 to −835.7) |

$^a$ Based on global warming potential of CO$_2$ and CH$_4$, with black carbon counted as CO$_2$.

$^b$ Constant average climate.

$^c$ Mean value based on mean input values for land category carbon fluxes and initial 2010 carbon densities.

$^d$ Uncertainty range based on mean ± SD input values for historical carbon flux and initial 2010 carbon density.

This result can partly be attributed to the emissions from desired forest fuel reduction and associated bioenergy production far exceeding its benefit on enhanced forest growth and reduced wildfire emissions, as well as the carbon benefits from all of the other practices (e.g. land conservation, woodland restoration, less intensive forest management) during the first decade of management (figure 3). However, the limited implementation areas for the emissions-reducing practices were paramount in the scenarios’ limited emissions mitigation potential overall. For example, excluding the fuel reduction emissions from the net emissions impacts of Scenario B results in only 0.7% and 4.1% contribution to the state’s cumulative emissions reductions goals for 2030 and 2050, respectively (data not shown). These results highlight the complexity of LUCC planning; Scenarios A and B were not purely aiming to maximize carbon sequestration or avoid emissions. Rather, these scenarios were developed by the state to advance multiple state priorities (e.g. wildfire mitigation, carbon sequestration, ecosystem restoration) at implementation levels that were considered...
achievable. Clearly, more can be done to mitigate emissions from a technical point of view, particularly by treating more land area with the strategies demonstrated to avoid emissions or enhance carbon sequestration, but that would require more aggressive policies, resources, and landowner participation than was deemed feasible by the state.

Nevertheless, the carbon emissions metric alone does not represent the full ecological impact of these scenarios. Indeed, Scenarios A and B enabled the state to restore ecological function to 7.9% and 13% of forest lands, respectively, through management activities that reduce the severity of wildfire [15, 26–28], reduce mortality [29], and enhance productivity [29] and biodiversity [30]. Simultaneously, Scenarios A and B each partially offset fuel reduction emissions with emissions-reducing practices that have a variety of other co-benefits. For instance, in addition to avoiding land-clearing emissions through protection of forests, agriculture, and other lands from urban development, land conservation prevents environmental degradation [31] and loss of ecosystem services [32]. Furthermore, we acknowledge that the emissions benefits of some practices would be greater than modeled by CALAND if a life cycle assessment of each practice was taken into account. For example, although not included in CALAND, the emissions mitigation benefits of open space conservation would increase significantly if avoided transportation and energy emissions associated with low-density development of previously undeveloped land were included. Similarly, the largest source of emissions reductions due to compost application in rangelands is from the waste diversion from traditional high-emission waste management streams (e.g. slurry facilities or landfills without CH4 capture technologies) [33]. Finally, the identification and emissions assessment of different woody biomass utilization pathways (bioenergy, durable wood products) associated with fuels treatments elucidates opportunities for reducing emissions at the intersection of land use and energy or materials. For example, minimizing emissions from these pathways may be realized by optimizing some combination of the following alternatives to the existing direct combustion pathway for bioenergy: gasification systems or other, cleaner-burning technologies, bioenergy carbon capture and storage, or by diverting a larger portion of biomass to durable wood products.

2.2. The role of climate change

Although the three climate scenarios (RCP 4.5, RCP 8.5, historical) did not differ in their overall qualitative response to the emissions effects of Scenarios A and B, there was an apparent interaction between climate and management effects on changes in emissions relative to the baseline (figure 1 and table 2). Compared to historical climate, a higher reduction in cumulative emissions was simulated from 2019 to 2050 and from 2019 to 2100 under RCP 8.5, while lower benefits were simulated under RCP 4.5 during the same time periods. For example, averaged across Scenarios A and B, mean cumulative emissions reduction from baseline was 6.1 Tg CO2e higher
in 2050 under RCP 8.5 compared to historical climate, while under RCP 4.5 it was 17.0 Tg CO$_2$e lower than historical climate. Although both RCP 4.5 and RCP 8.5 reduced absolute ecosystem carbon accumulation of the nine individual scenarios relative to historical climate (table 3), the reduction from 2010 to 2100 was approximately twice as great under RCP 4.5 than RCP 8.5 (data not shown). This can partially be attributed to a higher absolute ratio of positive CO$_2$ fertilization effects to negative climate change effects on net primary productivity (NPP) and soil respiration (e.g. nitrogen limitation, high temperature, drought) under RCP 8.5 than RCP 4.5 due to the higher atmospheric CO$_2$ concentrations predicted under RCP 8.5. Indeed the enhanced ecosystem carbon benefits of Scenarios A and B relative to the baseline were greater under RCP 8.5 than RCP 4.5 (figure 3). The Integrated Earth System Model (iESM) [34] from which our climate scalars for vegetation and soil carbon fluxes were derived (see Methods) is consistent with the larger cohort of Earth System Models with respect to land carbon being more sensitive to changes in CO$_2$ concentration than to climate [35, 36]. Another important factor for the highest emissions reductions under RCP 8.5 is the higher emissions reduction payoff of fuel reduction activities in terms of avoided high-severity wildfire emissions under RCP 8.5 compared to RCP 4.5 due to the larger wildfire areas predicted under RCP 8.5 than RCP 4.5 (figure 3).

Understanding the statewide carbon impacts of implementing land-based strategies for mitigating emissions and wildfire under a changing climate is challenging due to the interconnectedness of the underlying processes. The outputs from this comprehensive landscape carbon model are complex, with up to five-way interactions (ecosystem carbon fluxes × climate × wildfire × management × LUCC). However, the overall trends in emissions impacts of Scenarios A and B were the same across climates,
indicating that the key constraint on the emissions mitigation potential of LUCC scenarios is the extent of the implementation areas, which in this case is a function of existing and potential state programs and funding availability.

2.3. Components of total net emissions impacts

The carbon impacts of land protection, less intensive forest management, improved agricultural lands management, and ecosystem restoration resulted in immediate, and in most cases, extended emissions reductions, while the activities undertaken to reduce high-severity wildfire increased net emissions during each treatment period (table 1 and figure 3). The net effect of all practices was a near-term increase in total net emissions in both Scenarios A and B relative to the baseline (figure 1). By the end of the first treatment period, from 2019 to 2030, the fuel reduction activities (understory treatment, prescribed burning, thinning) in Scenarios A and B reduced high-severity wildfire emissions by 1.6 Tg CO₂e and 3.5 Tg CO₂e, respectively, under RCP 8.5 climate, but the emissions from the treatment activities was 29.1 and 25.5 times greater, respectively (figure 3). It is perhaps not surprising that the emissions-producing effect of fuel reduction activities outweighed the emissions-sequestering effect of the other activities given that forest fuel reduction impacted 2.7 and 2.3 times more area than reforestation, less-intensive forest management, and oak woodland restoration combined in Scenarios A and B, respectively, from 2019 to 2030. This demonstrates the importance of simultaneously offsetting emissions-producing practices with practices that reduce emissions or increase carbon sequestration (e.g. reforestation, land protection, rangeland compost application). Otherwise, the landscape can become a net source of emissions compared to no management until the net increase in emissions is eventually offset by equal reductions in emissions over time (i.e. recovery period). The emissions recovery period following the first 12 years of fuel reduction treatments of Scenarios A and B was approximately 3 years and 5 years, respectively (figure 1). In general, the emissions recovery period is a function of the relative extents of implementation areas for emissions-reducing versus emissions-producing practices, and the magnitude and direction of the emissions impact of each practice.

Table 3. The nine individual scenarios simulated with CALAND. Carbon emissions (CO₂ and CH₄) impacts of Scenarios A and B were determined by subtracting the model output from the Baseline Scenario from Scenarios A and B model output with the corresponding climate.

| Climate   | Scenario |
|-----------|----------|
| Historical| A        |
|           | B        |
|           | Baseline |
| RCP 4.5   | A        |
|           | B        |
|           | Baseline |
| RCP 8.5   | A        |
|           | B        |
|           | Baseline |

The main sources of emissions reductions, in order of decreasing magnitude, were from enhanced ecosystem carbon storage, avoided urban expansion (i.e. land protection), and avoided high-severity wildfire (figure 2). Relative to the baseline of no state-supported interventions, ecosystem carbon storage increased under Scenarios A and B due to (a) enhanced vegetation growth and reduced mortality as a result of fuel reduction practices [29]; (b) avoided emissions from less intensive forest management (e.g. transition from even-age harvest to selective harvest); (c) CO₂ removal from ecosystem restoration (e.g. expanding the urban forest, restoring coastal wetlands, and reforestation of non-regenerating forest due to high-severity wildfire); and (d) enhanced soil carbon storage from agricultural soil conservation practices [37, 38].

Avoided urban expansion was the second largest source of benefits in Scenarios A and B (figure 3). By restricting projected business-as-usual urban growth [39] by 50% and 75% by the end of 2030 in Scenarios A and B, respectively, 245,000 ha and 367,500 ha of land were conserved, respectively (table 1). The emissions benefits were due to the immediate avoided CO₂ emissions from land clearing, particularly of woody biomass; the subsequent decay of vegetation and soil organic matter; and the long-term benefits of conserving ecosystems that accumulate carbon at higher rates than urban lands.

Avoided high-severity wildfire was the third largest source of emissions benefits in Scenarios A and B resulting from the fuel reduction treatments on 516,072 ha and 833,281 ha of forest lands, respectively (figure 2 and table 1). However, in the short-term the emissions produced from these activities through post-management decay, controlled burning, and associated bioenergy production outweighed the long-term emissions mitigation (20 years from a single treatment) from avoided high-severity wildfire, enhanced vegetation carbon accumulation, and reduced mortality.

2.4. Implications for land use and climate policy planning

Subnational governments have made collective commitments to mitigate climate change (e.g. U.S. Climate Alliance [40], Under2MOU [41]), yet development of land-based strategies to support these goals is challenging for a variety of reasons. First, it is uncertain whether land-based strategies will be effective at reducing carbon emissions under elevated CO₂ and associated climate change given the complexity of biophysical processes that interact with management activities to determine actual carbon benefits. Second,
quantifying the impacts of land-based strategies is challenging given the inherent uncertainties in the current status of ecosystem carbon stocks and fluxes [42]. Third, social, economic, political, and environmental factors influence land use priorities, which can result in competing interests and values derived from land-based activities, including agricultural production and wildfire risk mitigation, in addition to carbon storage and emissions reductions [43].

We have established a comprehensive framework of scenario exploration and quantification for regional LUCC policy planning that addresses these challenges by examining the carbon and fire implications of realistic portfolios of NWL strategies that inherently involve tradeoffs among different goals (e.g. carbon storage, wildfire mitigation, agricultural productivity), accounting for known uncertainties in carbon stocks and fluxes, and examining sensitivity to a range of possible future climate conditions. Further research in developing scenarios that explore the emissions impacts of NWL strategies with other constraints on implementation areas, such as market incentives, alternative policies (e.g. carbon neutrality by 2045), and land suitability is warranted. These scenarios would likely enable greater spatial scope for strategies that enhance ecosystem carbon capture and/or reduce emissions. Nevertheless, all of the NWL strategies in the two scenarios address climate change concerns, have multiple co-benefits, and in general, all but forest fuel reduction, reduce emissions or increase carbon sequestration, underscoring the important role that LUCC has in climate change mitigation.

3. Methods

3.1. Description of the CALAND model

CALAND version 3.0.0 [25] is an open-source stock and flow model that simulates carbon fluxes (CO₂, CH₄, and optional black C) from soil and vegetation, as well as from landfill and sawmill decay of forest wood products and combustion of forest biomass for energy production, across the entire state of California, including areas in the ocean for seagrass restoration. CALAND was designed for exploring the carbon and GHG impacts of LUCC, land conservation, and land management scenarios relative to an appropriate baseline [44]. Six key model dimensions (management, LUCC, wildfire, climate, ecosystem carbon exchange, and mortality) drive the simulated annual net carbon emissions from CALAND (figure 4).

CALAND has a hybrid modeling structure, linking California-specific empirical data with externally modeled data for wildfire [45], climate change effects on vegetation and soil carbon fluxes [46], and land cover change [39]. It uses a quasi-spatial approach in that its initial carbon and land cover state is spatially-explicit, derived from (a) 30 × 30 m² resolution land cover and vegetation carbon densities [47, 48]; (b) an urban forest inventory [49]; (b) soil carbon densities from the NRCS gSSURGO database [50]; and (c) a review of California rangeland soil studies [51] yet it does not simulate carbon dynamics within individual grid cells. Rather, cells representing the intersection of 15 land types within nine eco-regions and nine ownership combinations, as well as in restored marine seagrass, were aggregated into 940 discrete land categories, the areas of which are tracked and operated on over time.

CALAND consists of several algorithms [25], programmed using R statistical software, version 3.3.3 [52]. The model simulates carbon dynamics for an individual scenario on an annual time step. The emissions differences between alternative scenario simulations and a baseline simulation are computed using CALAND’s diagnostic software. The CALAND model operates on individual land category units using values in lookup tables of California-specific initial land cover areas and carbon densities; annual land cover area changes; historical ecosystem carbon fluxes (i.e. vegetation carbon accumulation and soil carbon fluxes); mortality rates; climate-specific wildfire areas; wildfire severity temporal trends; climate change scalars for soil and vegetation carbon fluxes; and prescribed annual management areas and associated carbon flux scalars and carbon transfer parameters. Scenarios that are simulated with historical climate are prescribed constant annual soil and vegetation carbon flux to each land category, derived from published field measurements and remote sensing products. Management parameters, derived from the literature, are applied to these fluxes on an area-weighted basis. Sensitivity tests of each individual practice and of combined practices are described by Di Vittorio et al [44].

Scenarios that are simulated with projected climate change (RCP 4.5 or RCP 8.5) are prescribed climate scalar multipliers for soil and vegetation carbon fluxes, as well as climate-specific annual wildfire areas. We derived the climate scalars using model outputs from the iESM [34] Community Earth System Model (CESM) version 1.1.2 [46]. We generally followed the iESM method [53], and then mapped the scalars from iESM’s 1° grid to CALAND’s land categories based on the initial 30 × 30 m² land data for 2010. Specifically, annual NPP and annual changes in soil organic carbon density outputs from iESM were used to derive the climate scalars for vegetation and soil carbon fluxes, respectively. Running averages of these data were used to reduce interannual variability in order to better capture the long-term climate effects. The NPP values are directly comparable to CALAND’s net vegetation carbon accumulation values, which exclude mortality and disturbance effects, while the changes in soil carbon density correspond to the net soil carbon flux input values used by CALAND. Only NPP values for the
Tree and shrub plant functional types in iESM were used in this calculation, as the only land types in CALAND with vegetation carbon accumulation are those with trees or shrubs (i.e. forest, urban forest, woodland, savanna). Thus, the scalars were calculated for the tree or shrub plant functional types within each one-degree grid cell in iESM as the 5 year running average NPP, centered on the current year, divided by the 5 year average NPP from 2008 to 2012, centered on 2010—the initial simulation year in CALAND. An area-weighted average was calculated if there were multiple tree types per grid cell. Since there is only a single soil carbon pool per grid cell in iESM, the climate scalars for soil carbon flux were calculated per grid cell as the 9 year running average annual change in soil carbon density, centered on the current year, divided by the 9 year average from 2006 to 2014.

Prior to mapping the iESM climate scalars to CALAND, we performed two steps. First, to reduce the influence of non-climatic factors such as land cover change, we filtered both sets of scalars using the median absolute deviations as a threshold above which the data were omitted \[54\]. This was the same approach as the iESM method \[53\]; however our thresholds of 2 SD and 1 SD for the soil and vegetation averaging window, respectively, were more conservative than the iESM threshold (~3.3 SD). Second, we calculated iESM climate scalars only from 2010 to 2086 due to the period of the iESM simulations and the soil time-averaging window. Thus, we extrapolated the climate scalar values in 2086 to each subsequent year simulated in CALAND (i.e. 2087 through 2100).

Next, we disaggregated the iESM climate scalars (RCP 4.5 and RCP 8.5) for vegetation (tree or shrub plant functional types) and soil (single type) carbon fluxes at 1° resolution to the CALAND initial 2010 land cover gridded dataset at 30 × 30 m² resolution. If the land cover in each 30 × 30 m² cell was a land type with trees (i.e. forest, urban forest, woodland, or savanna) or shrubs (i.e. shrubland), it was assigned the corresponding iESM climate scalar for tree or shrub carbon accumulation, respectively. We did not climate-adjust any other land types for vegetation carbon accumulation, as we made the assumption of static carbon density due to lack of data. Similarly, all cells corresponding to a CALAND land type with a non-zero soil carbon flux (i.e. desert, shrubland, grassland, savanna, woodland, forest, meadow, coastal marsh, fresh marsh, or cultivated) were assigned the corresponding non-land type specific iESM climate scalar for soil carbon flux, with the exception of seagrass. Seagrass was not climate-adjusted due to lack of data. Lastly, we calculated the area-weighted average of both sets of climate scalars for each land category and climate forcing (RCP 4.5 and RCP 8.5).

Similarly, climate-specific annual wildfire areas were applied in each scenario. Under historical climate, a constant burn area was applied annually within each region-ownership combination and distributed across grassland, shrubland, savanna, woodland, and forest in proportion to each land type’s area each year. Under projected climate change, total burn areas within each region-ownership combination varied each year. These areas were derived from empirically modeled burn areas from the ‘average’ climate model (CanESM2) among the four climate models chosen in California’s Fourth Climate Change Assessment, and central population scenario at 1/16° resolution for RCP 4.5 and RCP 8.5 \[45\]. In order for
the initial burn areas to be consistent across the three climates, the modeled average annual burn areas from 2001 to 2015 under RCP 8.5 (185,237 ha statewide) were used for the initial 2010 simulation year for all climates, and for all years under historical climate. Wildfire areas were partitioned into low, medium, and high severity with increasing levels of ecosystem carbon that are burned, or are transferred to dead biomass pools that rapidly decay [17]. Specifically, low, medium, and high severity wildfire results in 20%, 40%, and 60% of above-ground living biomass, and 28%, 55%, and 85% of dead biomass, to burn and emit to the atmosphere, respectively. Additionally, low, medium, and high severity wildfire results in a transfer of 8%, 15%, and 25% of carbon from living to dead biomass pools, respectively. The initial severity fractions and annual increases in the high severity fraction were derived from historical California wildfire data from 1984 to 2006 [55, 56].

Land type conversion was controlled by three processes: (a) business-as-usual land-use driven area changes derived from historical rates of urban area expansion and changes in cultivated land areas [39]; (b) management practices that involve land conversion (i.e. avoided conversion to urban areas, reforestation, and all restoration practices); and (c) user-defined levels of forest non-regeneration following high-severity wildfire [57].

3.2. Scenario development and simulations
In collaboration with state agencies (California Natural Resources Agency, California Strategic Growth Council, California Air Resources Board, California Environmental Protection Agency, and the Governor’s Office of Planning and Research), we developed two portfolios of land use and land management strategies (Scenarios A and B) (table 1). State agencies sought to develop scenarios that reflected full, and in some cases, accelerated, implementation of existing natural resource management plans and programs; a realistic scaling up of state funding and technical capacity; and a commensurate increase in landowner participation. Scenarios A and B each comprised the same suite of land management, conservation, and restoration practices, but with implementation areas that were scaled to two levels of state investment and landowner participation (moderate and high, respectively), which were informed by the following: (a) a California Natural Resources Agency-led survey of its internal departments, boards, and regional conservancies (e.g. California Department of Conservation, California Department of Fish and Wildlife, California Department of Forestry and Fire Protection, California Department of Parks and Recreation, California Department of Water Resources, California Ocean Protection Council, Sacramento-San Joaquin Delta Conservancy, San Diego River Conservancy, San Gabriel and Lower Los Angeles Rivers and Mountains Conservancy, Santa Monica Mountains Conservancy, Sierra Nevada Conservancy, State Coastal Conservancy, and Wildlife Conservation Board); (b) ten state-led regional meetings with public stakeholders; (c) existing statewide and regional natural resource management plans (e.g. California Forest Carbon Plan, State Wildlife Action Plan, Central Valley Joint Venture, San Francisco Bay Joint Venture, Sierra Meadows Strategy); and (d) the per area CO₂e impacts (cost or benefit) and co-benefits of individual practices. The implementation rates included in these scenarios were not constrained by expected cost, labor or equipment availability, or permitting. Ultimately, Scenario A was considered moderate implementation, with areas that exceeded (up to two times) historical management levels on private and public lands but were feasible through increasing current projected state funding, while Scenario B was considered high implementation with areas that far exceeded Scenario A for certain practices, and would require substantial increases in projected state funding, and new programs and policies. Agricultural soil health practices were limited in the state’s scenarios, but future CALAND versions and model runs could be modified as more California-based empirical data becomes available. The state indicated a desire to grow the extent of soil health practice utilization far beyond the area included in Scenarios A and B, but opted to use the COMET-Planner tool, developed by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) and Colorado State University, in policy projections [14].

CALAND and its complete technical description, diagnostic software, user guide, and all the scenario and carbon input files used in this analysis are publicly available at: https://zenodo.org/record/3256727 [25]. The carbon and emissions dynamics of Scenarios A and B were simulated under three climates (historical climatic conditions, RCP 4.5, and RCP 8.5) from 2010 to 2100 using CALAND (version 3.0.0) [25]. In addition, a reference baseline scenario that represented the absence of all state-supported interventions was simulated under the three climates (table 3). Furthermore, the ongoing increase in forest mortality due to insects and drought [58] were emulated in CALAND by doubling the forest mortality rates from 2015 through 2024 in each of the nine simulations [25]. The only management activity implemented in the baseline scenario was forest management in federal and private lands, derived from historical levels of management. The purpose of the private managed forest land in the baseline was to provide a reference for the two levels of less intensive forest management in the two alternative scenarios. This multi-dimensional modeling framework allowed for integration of CO₂e impacts of multiple objectives and land use considerations across a changing climate and landscape.
The mean initial 2010 carbon density inputs and mean historical carbon fluxes for vegetation and soil in each land category were the model inputs used to generate the average cumulative emissions outputs for each scenario and climate combination.

3.3. Quantification of carbon emissions impacts and uncertainty

The total net global warming potential of carbon-based GHG emissions were calculated in units of CO$_2$e for each of the nine scenarios (table 3) with a 100 year time frame using a radiative forcing potential of 25 for CH$_4$ relative to CO$_2$ [59]. Although CALAND tracks black carbon emissions, the global warming potential of black carbon was calculated equivalent to CO$_2$. We decided to make this simplification due to high uncertainty in black carbon emissions factors, atmospheric residence time, and counteractive radiative effects with organic carbon.

To quantify the impacts of the land-based strategies of Scenarios A and B on total emissions, the Baseline average cumulative emissions outputs for the three climates were subtracted from the average cumulative emissions outputs for Scenarios A and B with the corresponding climate (table 3). Uncertainty bounds for the average changes in cumulative emissions for each scenario were calculated by first simulating each scenario and climate combination two additional times using two combinations of carbon inputs to generate minimum and maximum emissions: (a) mean – s.d. for initial carbon density and mean + s.d. historical carbon fluxes (lower bounds), and (b) mean + s.d. for initial carbon density and mean − s.d. historical carbon fluxes (upper bounds). Second, the changes from baseline under Scenarios A and B were calculated for each scenario-climate combination for lower and upper uncertainty bounds.

The individual components of total cumulative emissions impacts were quantified by aggregating categories of CALAND outputs according to the source of emissions. The key groupings in this analysis were related to emissions changes from baseline due to changes in (a) ecosystem carbon stocks, (b) urban area expansion, (c) controlled burning of forest biomass, (d) wildfire severity (e) post-management decay of forest biomass (f) biomass combustion for bioenergy, and (g) landfill decay of durable wood products. This aggregation and visualization (figure 2) was useful to policymakers in identifying additional opportunities for GHG mitigation associated with forest biomass utilization pathways. Identifying and activating alternative forest biomass utilization pathways was a policy goal [60] concurrent with development of CALAND. For example, emissions associated with bioenergy could be reduced by transitioning away from direct combustion technology, towards gasification, or by diverting a larger share of biomass to durable wood products.

3.4. Comparison to California’s 2030 and 2050 greenhouse gas emissions reduction goals

To assess the level of contributions from land use and land management strategies to the statewide direct emissions reduction goals, we compared the simulated annual emissions change from baseline due to Scenarios A and B, to a stepwise linear regression of annual emissions reductions that would achieve the state’s direct emissions reduction targets for 2030 and 2050 (40% and 80% below 1990 emissions, respectively). To calculate the direct emissions reductions trajectory, we used the statewide annual emissions in 1990 as the baseline. We assumed the 2020 target of 1990 emissions was met (431 Tg CO$_2$e), effectively zeroing out the change in emissions in 2020. Annual emissions targets were 258.6 Tg CO$_2$e yr$^{-1}$ and 86.2 Tg CO$_2$e yr$^{-1}$ in 2030 and 2050, respectively.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.3256727.

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Author contributions

M.S. and A.D. designed the study, developed the model and scenarios, and performed the simulations for each scenario. All authors contributed to the conceptual framework of the model. C.I. and E.J. surveyed state agencies and public input and provided the activity scope, target management areas and timeline for the two scenarios. M.S. wrote the manuscript with contributions from all the co-authors.

Conflict of interest

The authors declare no competing interests.

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