

# Ecosystem management and land conservation can substantially contribute to California's climate mitigation goals

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**Modeling efforts focused on future greenhouse gas (GHG) emissions from energy and other sectors in California have shown varying capacities to meet the emissions reduction targets established by the state. These efforts have not included potential reductions from changes in ecosystem management, restoration, and conservation. We examine the scale of contributions from selected activities in natural and agricultural lands and assess the degree to which these actions could help the state achieve its 2030 and 2050 climate mitigation goals under alternative implementation scenarios. By 2030, an Ambitious implementation scenario could contribute as much as 147 MMTCO<sub>2</sub>e or 17.4% of the cumulative reductions needed to meet the state's 2030 goal, greater than the individual projected contributions of four other economic sectors, including those from the industrial and agricultural sectors. On an annual basis, the Ambitious scenario could result in reductions as high as 17.9 MMTCO<sub>2</sub>e y<sup>-1</sup> or 13.4% of the state's 2030 reduction goal. Most reductions come from changes in forest management (61% of 2050 projected cumulative reductions under the Ambitious scenario), followed by reforestation (14%), avoided conversion (11%), compost amendments to grasslands (9%), and wetland and grassland restoration (5%). Implementation of a range of land-based emissions reduction activities can materially contribute to one of the most ambitious mitigation targets globally. This study provides a flexible, dynamic framework for estimating the reductions achievable through land conservation, ecological restoration, and changes in management regimes.**

land use change | avoided conversion | carbon sequestration | natural lands | agriculture

Over the past two decades, climate science and policy have increasingly recognized the role that forests and other terrestrial ecosystems could play in climate change mitigation. About 30% of global anthropogenic carbon dioxide emissions are absorbed through carbon sequestration from plant growth and associated ecological processes (1). However, clearing and degradation of ecosystems, particularly forests, represents an emissions source roughly equivalent to 9% of total emissions, or about half of the carbon dioxide released globally from the combustion of natural gas (1). Land conservation and changes in ecosystem management can reduce emissions that might otherwise occur from conversion to more intensive uses, land degradation, or natural disturbance, such as fire. In many cases, they can also promote increased sequestration (2, 3). Such interventions may enhance the resilience and adaptive capacity of species and ecosystems and serve to maintain the provision of ecosystem services in the face of accelerating environmental change (4–6).

Globally, many government jurisdictions have committed to reducing emissions [including the sequestration of more greenhouse gases (GHGs)] across natural and agricultural lands as part of their climate change targets under the Paris Agreement. As of 2016, 83% of Intended Nationally Determined Contributions submitted to the United Nations Framework Convention on Climate Change reference land use, land use change, and forestry as key parts of their mitigation contributions (7). However, there is

little consistent analysis of the mitigation potential across multiple land-based activities to help governments prioritize investments to reduce net emissions [though see Griscom et al. (8)], particularly at a subnational level where activities and funding can be more specifically directed and aligned.

Subnational jurisdiction commitments have become more common over the last decade as efforts to achieve binding multinational GHG goals languished. California is one such subnational jurisdiction that has been a leader in climate change policy through its early adoption of ambitious GHG reduction goals, as defined in the Global Warming Solutions Act of 2006, commonly known as Assembly Bill (AB) 32. More recently, California has adopted more aggressive GHG reduction goals for 2030 and maintains commitments to reduce emissions even further by 2050. Policies and investments to reduce emissions in the energy and transportation sectors have the state on track to meet its 2020 goal (emissions equal to the 1990 level), but earlier studies have shown that additional reductions are needed beyond existing policies to meet the 2030 and 2050 targets (9, 10). California has recognized the need to reduce emissions through the management and conservation of its “natural and working lands” (i.e., open space, wetlands, urban forests, agricultural lands, and forest lands) (11). To effectively include this sector to help meet the state's long-term climate goals, an assessment of the GHG reduction potential of the state's natural and agricultural lands is needed.

## Significance

**Combating climate change will require using all available tools, especially those that contribute to other societal and economic goals, such as natural resource protection and energy security. Conserving and managing natural and agricultural lands to retain and absorb greenhouse gases (GHGs) are tools that have not been widely integrated into climate policy. Our analysis provides a quantification of potential climate benefits from multiple land-based activities for a jurisdiction with an emissions reduction target (up to 13.3% of the cumulative reductions needed to meet the 2050 target, or nearly three-fourths of a billion metric tons of GHGs). This approach provides a model that other jurisdictions can use to evaluate emissions reductions that might be achieved from conserving and restoring natural lands.**

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Data deposition: All data and simulation source code are available for download through the Open Science Framework repository (<https://osf.io/UHJCF>).

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**Table 1. Estimates of potential annual and cumulative emissions reductions from selected activities on natural and agricultural lands in California for the Moderate scenario, in 2030 and 2050 (MMTCO<sub>2</sub>e)**

Activity	2030			2050		
	Annual	Cumulative	Cumulative, % of total	Annual	Cumulative	Cumulative, % of total
Avoided emissions	<b>1.04</b> (0.72, 1.36)	<b>13.3</b> (8.98, 17.7)	<b>18.2%</b>	<b>1.25</b> (0.89, 1.61)	<b>36.4</b> (25.3, 47.6)	<b>10.1%</b>
Forests to development	0.27 (0.22, 0.33)	3.84 (3.07, 4.61)	5.2%	0.27 (0.22, 0.33)	9.31 (7.45, 11.2)	2.6%
Grasslands to annual row crops	0.08 (0.02, 0.13)	1.08 (0.31, 1.85)	1.5%	0.08 (0.02, 0.13)	2.63 (0.75, 4.5)	0.7%
Hardwood woodlands to developed use	0.64 (0.45, 0.83)	8.01 (5.38, 10.7)	10.9%	0.81 (0.6, 1.02)	22.7 (16.1, 29.4)	6.3%
Shrublands to annual row crops	0.02 (0, 0.03)	0.16 (0.05, 0.27)	0.2%	0.03 (0, 0.05)	0.58 (0.1, 1.06)	0.2%
Wetlands to pasture	0.03 (0.02, 0.04)	0.23 (0.18, 0.28)	0.3%	0.07 (0.05, 0.08)	1.20 (0.93, 1.47)	0.3%
Increased sequestration	<b>7.79</b> (0.44, 15.1)	<b>59.9</b> (2.79, 117)	<b>81.8%</b>	<b>17.7</b> (2.45, 33.0)	<b>323</b> (31.3, 614)	<b>89.9%</b>
CFM: mixed conifer	2.08 (−0.89, 5.01)	16.3 (−6.74, 39.3)	22.2%	4.16 (−1.78, 10.1)	81.3 (−34.1, 197)	22.6%
CFM: redwood	3.71 (1.31, 6.08)	29.0 (10.3, 47.8)	39.6%	7.48 (2.65, 12.3)	145 (51.4, 239)	40.5%
Compost amendments to grasslands	0.75 (−1.08, 2.61)	5.79 (−8.32, 20)	7.9%	1.66 (−2.4, 5.77)	31 (−44.2, 106)	8.6%
Reforestation—Disturbed sites	0.87 (0.79, 0.94)	5.94 (5.26, 6.62)	8.1%	3.52 (3.31, 3.74)	49.5 (45.8, 53.2)	13.8%
Restoration—Annual row crops to grasslands	0.02 (−0.01, 0.06)	0.17 (−0.08, 0.43)	0.2%	0.05 (−0.02, 0.12)	0.92 (−0.44, 2.28)	0.3%
Wetland restoration						
Corn to managed wetlands	0.06 (0.05, 0.06)	0.44 (0.4, 0.49)	0.6%	0.13 (0.11, 0.14)	2.35 (2.1, 2.6)	0.7%
Corn to tidal wetlands	0.23 (0.21, 0.24)	1.73 (1.59, 1.87)	2.4%	0.50 (0.46, 0.54)	9.19 (8.46, 9.91)	2.6%
Pasture to managed wetlands	0.02 (0.01, 0.03)	0.18 (0.1, 0.26)	0.2%	0.05 (0.03, 0.07)	0.96 (0.56, 1.36)	0.3%
Pasture to tidal wetlands	0.05 (0.04, 0.06)	0.39 (0.32, 0.46)	0.5%	0.11 (0.09, 0.13)	2.09 (1.7, 2.47)	0.6%
Total reductions	<b>8.82</b> (4.61, 13.0)	<b>73.3</b> (40.1, 106)		<b>19.0</b> (10.2, 27.6)	<b>359</b> (192, 526)	

Primary results indicated are median values. The upper and lower 90% confidence interval bounds are shown in parentheses for each activity. CFM, changes to forest management.

ecological processes that enhance habitat quality and provide benefits to people. By maintaining wildlife habitat and watershed lands and reducing irrigation water demand, it is reasonable to assume that these conservation and management actions would foster socio-ecological resilience and promote adaptation to changing conditions.

Several considerations have bearing on the interpretation of the results of this study and the application to policy-making. Foremost among those is the assumption of a static effect of climate change on reduction and implementation rates. Vegetation composition and the stability of ecosystem carbon storage will be affected by warming temperatures and changes in precipitation (19, 20) as well as the increased frequency and intensity of mediating events such as fire (21). Climate change will likely affect the response of ecosystems to management and restoration activities modeled here. For example, a hot and dry future may limit the ability of forests and grasslands to store additional carbon, while a warm and wet future may lead to a more favorable response to management actions.

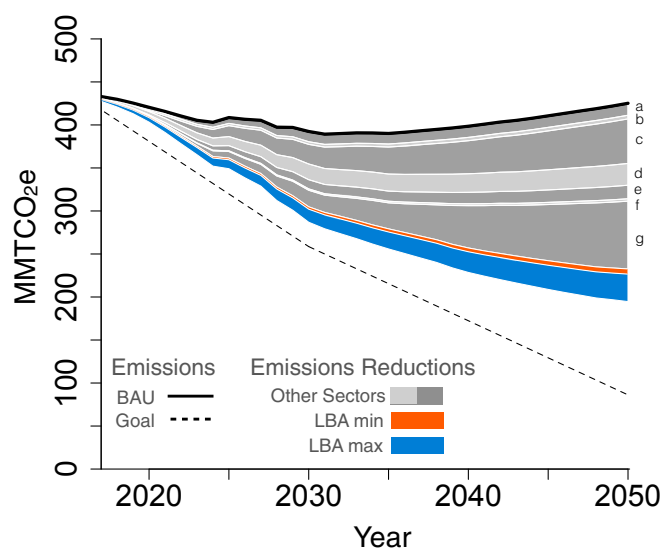
One recent study suggests California's ecosystems are a net source of GHGs due primarily to emissions from wildfire in forest and shrub ecosystems (22). These fires are presumed to burn with higher severity over larger areas than previously due to historic fire suppression, more frequent drought, and climate change (21, 23). Several studies have looked into the potential to reduce wildfire severity, and thus the GHG emissions and the ecological impact, by proactively implementing thinning and prescribed burning projects (20). We did not include such an activity type in this assessment due to the site-specific nature of relative fire risk and forest conditions, but these activities may lead to additional reductions, especially over longer time periods

and under more extreme fire severity scenarios and should be a priority for additional research.

Accounting for the interactions between the modeled activities would potentially yield different results. Some of these interactions may be sources of emissions "leakage" where implementation of reductions in one domain causes an increase in emissions from another domain. For example, as agricultural land is restored to wetland habitat or otherwise enrolled in conservation, resulting expansion of agricultural land into natural habitats such as grasslands may lead to increased global emissions. Accounting for and minimizing emissions leakage are key elements of climate policy development, however further research on the potential magnitude of leakage from the activities considered in this study could improve policy recommendations. Jenkins et al. (24) propose various policy approaches and project designs that may serve to minimize leakage from the implementation of new land-based emissions reduction programs.

Because this study accounts primarily for the direct ecosystem carbon storage implications of different activities, it does not include the potential indirect emissions or indirect reductions that may be associated with implementing a GHG reduction activity. For example, vehicle emissions associated with reforestation activities are not included. Likewise, the avoided emissions from farming operations associated with preventing conversion to row crops are also not included. In a subnational accounting system, indirect emissions and reductions could be captured in the accounting for other sectors, such as energy and transportation.

This study considers only activities that presumably provide ecosystem cobenefits to natural land cover types and, as such, is a conservative estimate of the full mitigation potential of land-based



**Fig. 3.** California BAU emissions (28) (solid line) compared with the 2030 and 2050 goal (dashed line). Each polygon is a wedge of emissions reductions coming from the energy and transportation sectors (gray shading) and the land-based activity (LBA) sector. The LBA minimum is the lower 90% confidence interval of the Limited scenario, and the LBA maximum is the upper 90% confidence interval of the Ambitious scenario. Letters denote the emissions reductions ( $\text{MMTCO}_2\text{e y}^{-1}$ ) from sectors evaluated in the CARB scoping plan (29) with estimates for 2030 and 2050 in parentheses, respectively: (a) agriculture (11.9, 13.9), (b) residential and commercial (3.1, 4.3), (c) electric power (22.8, 51.8), (d) high GWP (18.2, 25.3), (e) industrial (10.7, 15.7), (f) recycling and waste (1.6, 2.8), and (g) transportation (19.3, 78.8). LBA min (2.7, 6.0), LBA max (17.9, 37.9).

interventions. Modeling a full set of agricultural management practices, for example, is beyond the scope of this study but represents a complementary set of interventions to those considered here. Activities that may promote increased carbon sequestration in agricultural soils (25), limit methane and  $\text{N}_2\text{O}$  emissions in crop systems (26), and adapt grazing practices to promote sequestration (27) were not included here but may contribute substantial additional reductions.

## Conclusion

Meeting climate change targets at a subnational and national scale will require full implementation of known mitigation strategies as well as investment in new areas that show potential. The framework demonstrated here can be used as an initial method to estimate the GHG reduction potential of alternative land-based strategies. Notably, in the case of California, land-based potential is material to the debate about alternative policy options. This study highlights the important role that land management and restoration, and forest management in particular, can have in achieving climate change goals.

## Methods

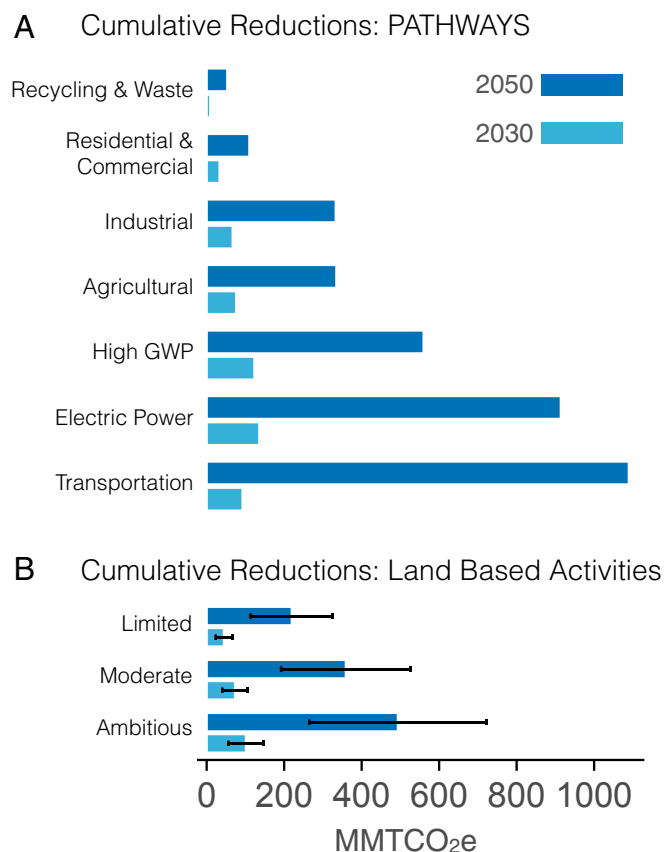
This study portrays three potential future GHG reduction scenarios, named Ambitious, Moderate, and Limited, along with the associated uncertainty of each scenario. Each scenario includes 14 individual land management, conservation, and restoration activities described in [Table S6](#), with variable rates of yearly activity implementation. We treat the different scenarios as plausible alternatives for rate of policy implementation relative to current efforts to use conservation and ecosystem management for GHG reduction efforts. Together, the Limited and Ambitious scenarios are intended to bracket the reductions that could be achieved in California from conservation and changes in land use or management through 2050.

The activities fall into one of two categories—increased sequestration (e.g., reforestation) and avoided emissions (e.g., avoiding conversion of wetlands to cultivated crops)—covering a range of natural and agricultural

land use types in California: irrigated cropland, forests, shrublands, grasslands, and wetlands. Given the selection criteria for activities stated above, not all potential land-based reduction activities were included in our analysis, especially in agricultural lands, and some meeting the criteria were not included due to data limitations (e.g., urban forestry).

**Activity Area Implementation, GHG Reduction Rates, and Discount Rate.** We conducted a literature review to identify area implementation and GHG reduction rates to estimate potential yearly emissions reductions for each activity type. Reduction and implementation rates applicable specifically to California were used, except a few cases requiring the use of rates applicable to a broader area (Tables S2 and S3). Preference was given to peer-reviewed sources unless the most relevant information was in technical reports. In general, justifications for implementation rates were drawn from a single reference (Table S2). We varied the implementation rate—the annual area of additional land on which an activity is implemented (in hectares per year)—of each activity to design the Ambitious, Moderate, and Limited scenarios (Table S1). Implementation rates were assumed to remain constant over time within a scenario.

Based on estimates from the literature, we assigned a mean and SD value for the annual GHG reduction rate to each activity as a measure of the net annual flux associated with implementation of each activity (in MT of CO<sub>2</sub>e·ha<sup>-1</sup>·y<sup>-1</sup>). The avoided conversion activities have an additional value for the emitted carbon stock (in MT CO<sub>2</sub>e·ha<sup>-1</sup>). In cases where multiple sources reported reduction rates or a single source reported multiple rates across time or space, the mean and pooled SD was used to construct the distribution. We converted SEs and confidence intervals from the literature to SD when necessary. Unless the literature indicated a change over time for a given activity type, reduction rate mean values were



**Fig. 4.** Comparison among reductions from various economic sectors and those from LBAs used in this study. Cumulative reductions in 2030 and 2050 (A) for the energy and transportation sectors from a modeling study of long-term decarbonization scenarios undertaken by the State of California (i.e., PATHWAYS) (28) and (B) for the LBA sector implementation scenarios in this study. The error bars are 90% confidence intervals; the PATHWAYS study did not assess uncertainty.

assumed to remain constant. For forests and woodlands, reduction rates and carbon stocks are for aboveground carbon only (Table S3). All other ecosystem types account for soil GHG budget or stocks. See *SI Methods* for details specific to the calculation of each activity's reduction rate and discount rate.

**Scenario Simulations and Uncertainty.** We used a Monte Carlo simulation to account for the uncertainty associated with sequestration rates and stock changes. For each activity in every simulation year (2017–2050), we pulled 50,000 samples from a normal distribution created from the mean and SD of the activity's net sequestration rate (Fig. 1A and Table S3). Because an ecosystem continues to sequester carbon after an activity has been implemented, each activity's total implementation area grows yearly by the implementation rate less than the discount rate. The product of the Monte

Carlo samples and the total implementation area yielded a probability distribution of potential GHG reductions. Additional details on the simulation are available in *SI Methods*. Simulations and subsequent analyses were performed in R (version 3.3.2).

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