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

D. Richard Cameron[a,1], David C. Marvin[a,b], Jonathan M. Remucal[c], and Michelle C. Passero[a]

[a]The Nature Conservancy, San Francisco, CA 94105; [b]Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305; and [c]Jonathan Remucal Consulting, Madison, WI 53705

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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 $MMTCO_2e$ 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 $MMTCO_2e \cdot y^{-1}$ 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

Combatting 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 gasses (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/).

[1]To whom correspondence should be addressed. Email: dcameron@tnc.org.

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Here we present a scenario-based analysis of the annual and cumulative GHG reduction potential of a broad set of land conservation, management, and restoration activities for 2030 and 2050 time horizons in California. These benchmarks correspond to the state's longer term emissions goals—40% below 1990 levels by 2030 and 80% below 1990 levels by 2050. This study simulates the future GHG reduction potentials of these activities [e.g., changes to forest management (CFM), avoided conversion of grasslands to agriculture] when applied to California lands at three plausible rates of policy implementation relative to current efforts. Aggregate yearly reduction potentials are calculated for Limited (~50,000 $ha \cdot y^{-1}$), Moderate (~90,000 $ha \cdot y^{-1}$), and Ambitious (~125,000 $ha \cdot y^{-1}$) implementation scenarios (Tables S1 and S2). Empirical values from the literature are used to parameterize each activity's reduction rate, in terms of the emissions avoided when land conversion is prevented (for relevant activity types) and the ongoing net annual sequestration rate for a given intervention (for all activities) (Fig. 1 and Table S3). We use a Monte Carlo simulation to propagate the uncertainty of each activity and create confidence intervals for the potential reductions. We then compare the aggregate reduction potential of the activities against "business-as-usual" (BAU) emissions projections for California to highlight the contributions of these activities toward reaching the state's 2030 and 2050 GHG reduction targets.

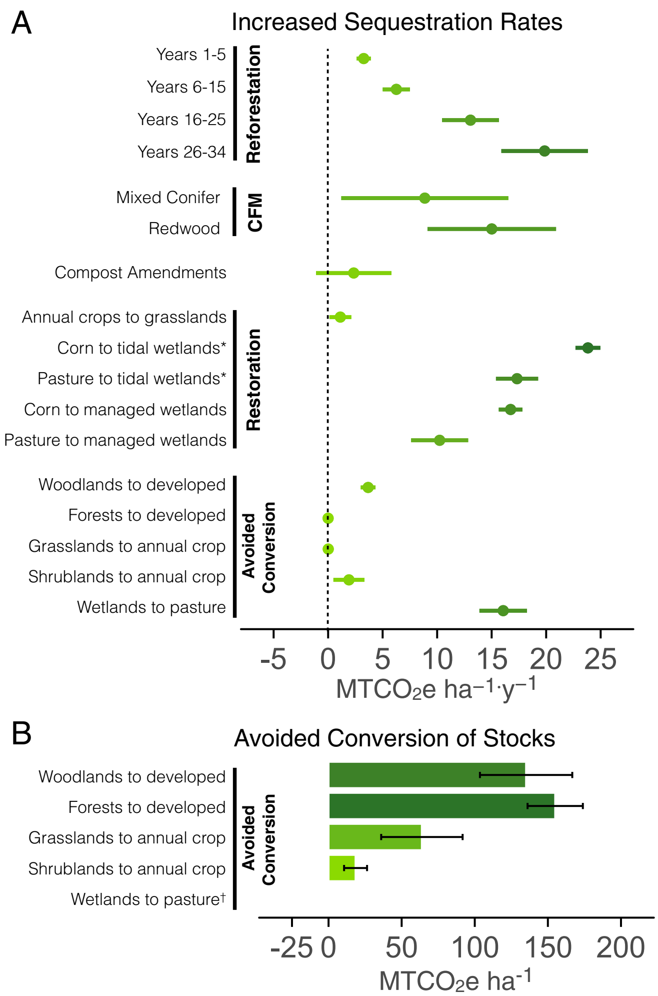

Fig. 1. Reductions used to parameterize the Monte Carlo simulations for (*A*) activities that increase sequestration of GHG and (*B*) activities that also have a reduction associated with the avoided conversion of their carbon stock. Reforestation is a single activity but has varying rates of sequestration based on forest age. Error bars represent the 90% confidence intervals. *The reduction rate of the tidal wetland activities may be overestimated because potential methane emissions after restoration are not included. †Estimate on one-time emissions from wetland to pasture conversion event unavailable. See Table S6 and *SI Methods* for a detailed description of all activities and the calculation of the associated reductions.

The analysis does not incorporate the full scope of potential land-based mitigation activities, especially those in agricultural lands but uses a diverse subset of activities to provide a conservative estimate of the magnitude of GHG reduction potential from the land base. To be included in the study, an activity must have (*i*) evidence of potential GHG reduction benefits and (*ii*) presumed cobenefits to ecosystems with natural or seminatural land cover present in California. We use the definition of cobenefits from Bain et al. (12) as the "community benefits resulting from mitigation behavior" such as reduced air pollution, hazard risk reduction, and natural resource provision. Many of the activities we analyze are currently being considered as fundable interventions to achieve California's climate change target. We assume that including cobenefits in the selection criteria will increase the likelihood that these activities ultimately will be adopted, especially where funding already exists to support the intervention described. For example, while there are many agricultural management practices that have been proposed to help meet climate goals, we include only compost amendments to managed grasslands as one such activity because it meets the selection criteria described above and there is demonstrated interest in adoption by the state as a key mitigation strategy.

The primary purpose of this assessment is to advance the understanding of the mitigation potential of California's natural and agricultural lands and to provide an initial range of estimates to compare ecosystem-based reductions to those for other sectors. While this study does not include all potential activities, it provides an example framework that could be used elsewhere to evaluate the potential for emissions reductions from implementing land use and conservation policies. In the shorter term, this study will help California better evaluate different policies to achieve climate goals and to align these goals with other social, economic, and ecological benefits, such as increased resiliency to drought and improved habitat conditions.

Results

Annual Reductions by 2030. In 2030, the projected total median annual reductions achieved across all 14 activities are $5.44_{2.74}^{8.13}$ (super/subscripts denote 90% confidence interval) and $12.1_{6.4}^{17.9}$ million metric tons (MT) of CO_2-equivalent ($MMTCO_2e$) for the Limited and Ambitious scenarios, respectively (Fig. 2 *A* and *C* and Tables S4 and S5). The Moderate scenario generates an estimated reduction of $8.82_{4.6}^{13.0}$ $MMTCO_2e$ (Fig. 2*B* and Table 1). These results for the Limited, Moderate, and Ambitious scenarios equate to 4.1%, 6.6%, and 9.1%, respectively, of California's total GHG annual reduction goal for 2030. Using the Limited scenario's lower bound and the Ambitious scenario's upper bound 90% confidence interval, we estimate the minimum and maximum potential annual reductions to be 2.0% and 13.4%, respectively, of the 2030 goal. Estimated reductions in 2030 from individual activities ranged from 0.008 $MMTCO_2e$ from avoided conversion of shrublands to agriculture under the Limited scenario to 4.95 $MMTCO_2e$ from changes to redwood forest management under the Ambitious scenario, with most activities producing <0.5 $MMTCO_2e$ under each scenario (Table 1 and Tables S4 and S5). CFM (redwood and mixed conifer combined), the most effective activity type in each scenario, accounted for 65.6% of the total reductions in 2030 under the Moderate scenario (Table 1) and has nearly seven times the annual reduction potential as the next highest activity, from reforestation of sites disturbed by wildfire. Activities based on increasing sequestration represented between 87% and 90% of the total reductions in 2030 under each scenario.

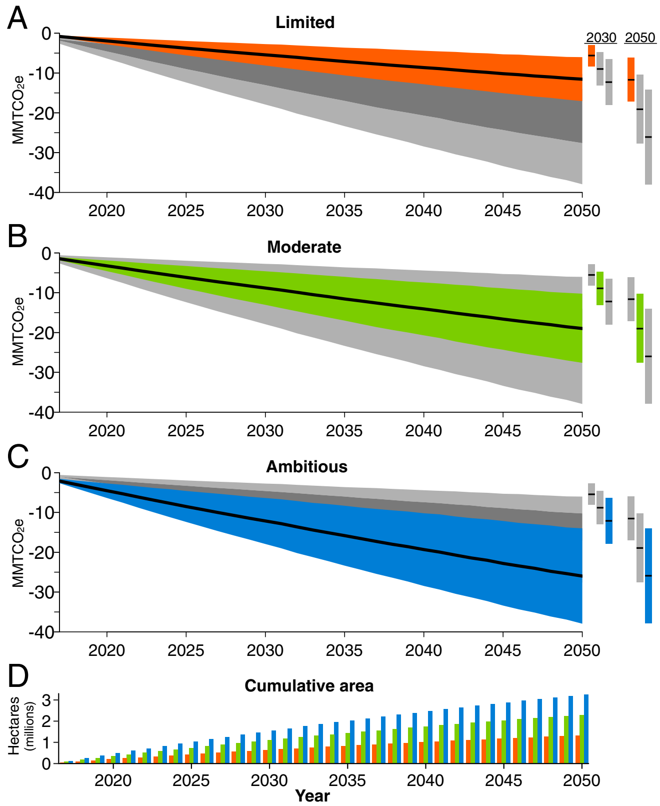

Fig. 2. Median GHG reductions (black line) with 90% confidence interval (colored area) over time for the (*A*) Limited, (*B*) Moderate, and (*C*) Ambitious implementation scenarios. *A–C* use the same plot with different colored shading for better visualization of the scenarios while still showing their overlap (gray shading). Side bar chart shows the median with 90% confidence interval of the reduction potential at 2030 and 2050. (*D*) Cumulative area of implementation by year for each implementation scenario, with colors matching the scenarios presented in *A–C*.

Annual Reductions by 2050. By 2050, projected total annual reductions range from $11.6_{6.0}^{17.1}$ under the Limited scenario to $26.0_{14.0}^{38.0}$ $MMTCO_2e \cdot y^{-1}$ under the Ambitious scenario, accounting for 3.4% and 7.7%, respectively, of the state's emissions reduction goal for that year. The Moderate scenario produced $19.0_{10.2}^{27.6}$ $MMTCO_2e \cdot y^{-1}$ of reductions in 2050, or 5.6% of the state's goal. Reductions from individual activities ranged from 0.013 $MMTCO_2e \cdot y^{-1}$ for the avoided conversion of shrublands to agriculture under the Limited scenario to 9.95 $MMTCO_2e \cdot y^{-1}$ for changes to redwood forest management under the Ambitious scenario. CFM (redwood and mixed conifer combined) accounted for 61.3% of the total reductions in 2050 under the Moderate scenario (Table 1). This was over three times more than the reductions from reforestation of sites disturbed by wildfire, the next highest activity. Reforestation accounted for 18.5% of the total in 2050, up from 9.8% in 2030; this increase in the proportion of total reductions reflects the increasing rate of sequestration by reforested sites as earlier tree cohorts transition from sapling to adult stages, sequestering more carbon annually. Activities based on increased sequestration continued to dominate the reductions achieved, accounting for at least 93% of the total under each scenario in 2050.

Cumulative Reductions. Though our primary focus was the scale of reductions the land base could contribute toward achieving the annual emissions goals established by California, cumulative emissions are considered a more reliable indicator of peak global temperatures (13, 14). Cumulative reductions are the difference between the BAU emissions (those that would occur in the absence of intentional interventions to reduce emissions or sequester more carbon) and the straight-line emissions pathway to meet 2030 and 2050 targets. To translate California's annual emissions reductions goals to cumulative emissions reductions, we assumed linear reductions in annual emissions to 2050 (15), with benchmarks at 2030 and 2050. Starting in 2017, cumulative reductions that would need to be achieved across all sectors to meet the 2030 and 2050 goals would total 843 and 5,430 $MMTCO_2e$, respectively. Cumulative reductions across all activities modeled here through 2030 ranged from $44.6_{23.5}^{65.7}$ $MMTCO_2e$ under the Limited scenario to 102_{56}^{147} $MMTCO_2e$ under the Ambitious scenario, with the Moderate scenario producing 73.3_{40}^{106} $MMTCO_2e$ (Table 1 and Tables S4 and S5). By 2050, cumulative reductions were 220_{113}^{326} $MMTCO_2e$ under the Limited scenario, 359_{192}^{526} $MMTCO_2e$ under the Moderate scenario, and 494_{264}^{722} $MMTCO_2e$ under the Ambitious scenario. These reductions amount to 5.3% (Limited), 8.7% (Moderate), and 12.0% (Ambitious) of the cumulative reductions needed across all sectors by 2030, reaching a maximum of 17.4% (upper limit of the Ambitious scenario). By 2050, these reductions meet 4.0% (Limited), 6.6% (Moderate), and 9.1% (Ambitious) of the cumulative reductions needed, with a maximum contribution of 13.3%. The proportional decrease reflects both increasing BAU emissions after 2031 and the attenuation of reductions by the discount rate in our simulation.

Discussion

We find that GHG reductions pursued through aggressive implementation of conservation, restoration, and management activities has the potential to contribute up to 17% of California's cumulative 2030 GHG emissions reduction goal. Even a less ambitious approach will help speed the attainment of these goals, while contributing a broad set of ecological, economic, and social benefits. This provides a compelling example for how land-based reductions can, at a minimum, help jurisdictions to meet climate mitigation targets. Comparing the magnitude of land-based reductions to those projected through other pathways provides useful policy context for how select land conservation, restoration, and management activities can contribute to California's climate change goals. Recent studies have projected the emissions reduction potential from various sectors in California under different policy scenarios (9, 10, 16, 17). These studies have either placeholder values for emissions or reductions related to the land base (9), or they included no values for natural and agricultural lands.

Comparison with Other Sectors' Contributions. Using an updated version of the California PATHWAYS model described by Williams et al. (17), the California Air Resources Board quantified the contribution by end use sector to 2030 overall emissions reduction goals (18). The minimum potential (lower 90% confidence interval of Limited scenario) of land-based activities is comparable to the residential and commercial sector and greater than the recycling and waste sector (Fig. 3). Under the best case (upper 90% confidence interval of Ambitious scenario), annual land-based reductions rank fourth and third of eight sectors in terms of potential magnitude of reductions, for 2030 and 2050, respectively. The median results for cumulative reductions by scenario compete well with other sectors for 2030 and 2050 (Fig. 4), with the Ambitious scenario ranking fourth among all sectors in terms of cumulative reductions. Incorporating the activity-based estimates in the study from the Moderate and Ambitious scenarios would help ensure that the state can make up any potential shortfalls in emissions reductions achieved by 2030 and to potentially exceed its goal. Moreover, the implementation of many of these activities also contributes to maintenance and restoration of

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 ($MMTCO_2e$)

Activity	2030 Annual	2030 Cumulative	2030 Cumulative, % of total	2050 Annual	2050 Cumulative	2050 Cumulative, % of total)
Avoided emissions	**1.04** (0.72, 1.36)	**13.3** (8.98, 17.7)	**18.2%**	**1.25** (0.89, 1.61)	**36.4** (25.3, 47.6)	**10.1%**
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	**7.79** (0.44, 15.1)	**59.9** (2.79, 117)	**81.8%**	**17.7** (2.45, 33.0)	**323** (31.3, 614)	**89.9%**
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	**8.82** (4.61, 13.0)	**73.3** (40.1, 106)		**19.0** (10.2, 27.6)	**359** (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

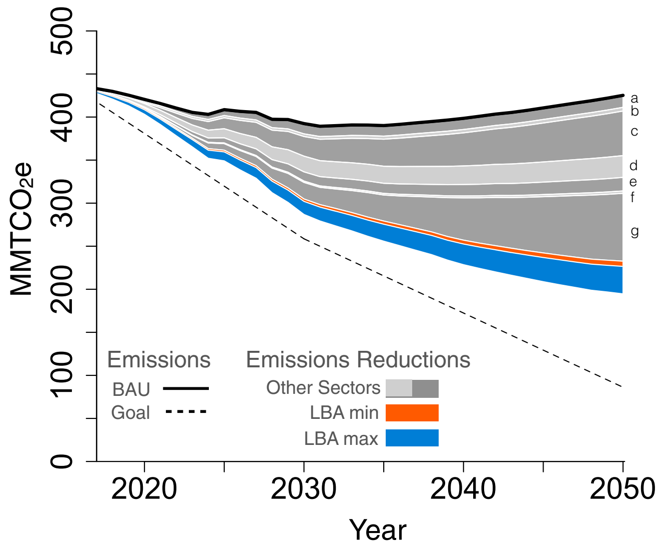

Fig. 3. California BAU emissions (28) (solid line) compared with the 2030 and 2050 goal (dashed line). Each polygon is a wedge of emissions reductions coming from the energy and transportation sectors (gray shading) and the land-based activity (LBA) sector. The LBA minimum is the lower 90% confidence interval of the Limited scenario, and the LBA maximum is the upper 90% confidence interval of the Ambitious scenario. Letters denote the emissions reductions ($MMTCO_2e \cdot y^{-1}$) 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 N_2O 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 $CO_2e \cdot ha^{-1} \cdot y^{-1}$). The avoided conversion activities have an additional value for the emitted carbon stock (in $MTCO_2e \cdot ha^{-1}$). 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

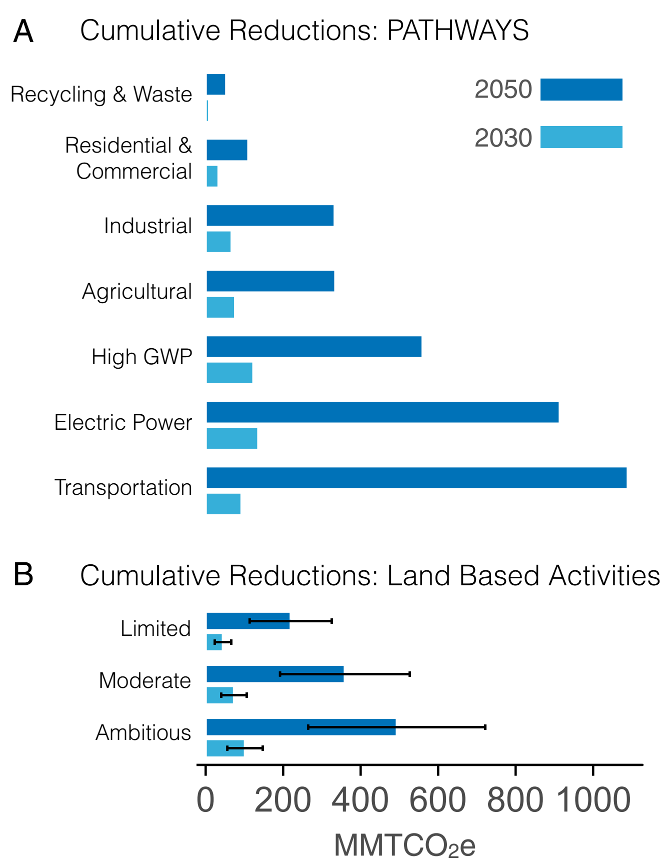

Fig. 4. Comparison among reductions from various economic sectors and those from LBAs used in this study. Cumulative reductions in 2030 and 2050 (*A*) for the energy and transportation sectors from a modeling study of long-term decarbonization scenarios undertaken by the State of California (i.e., PATHWAYS) (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. 1*A* 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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