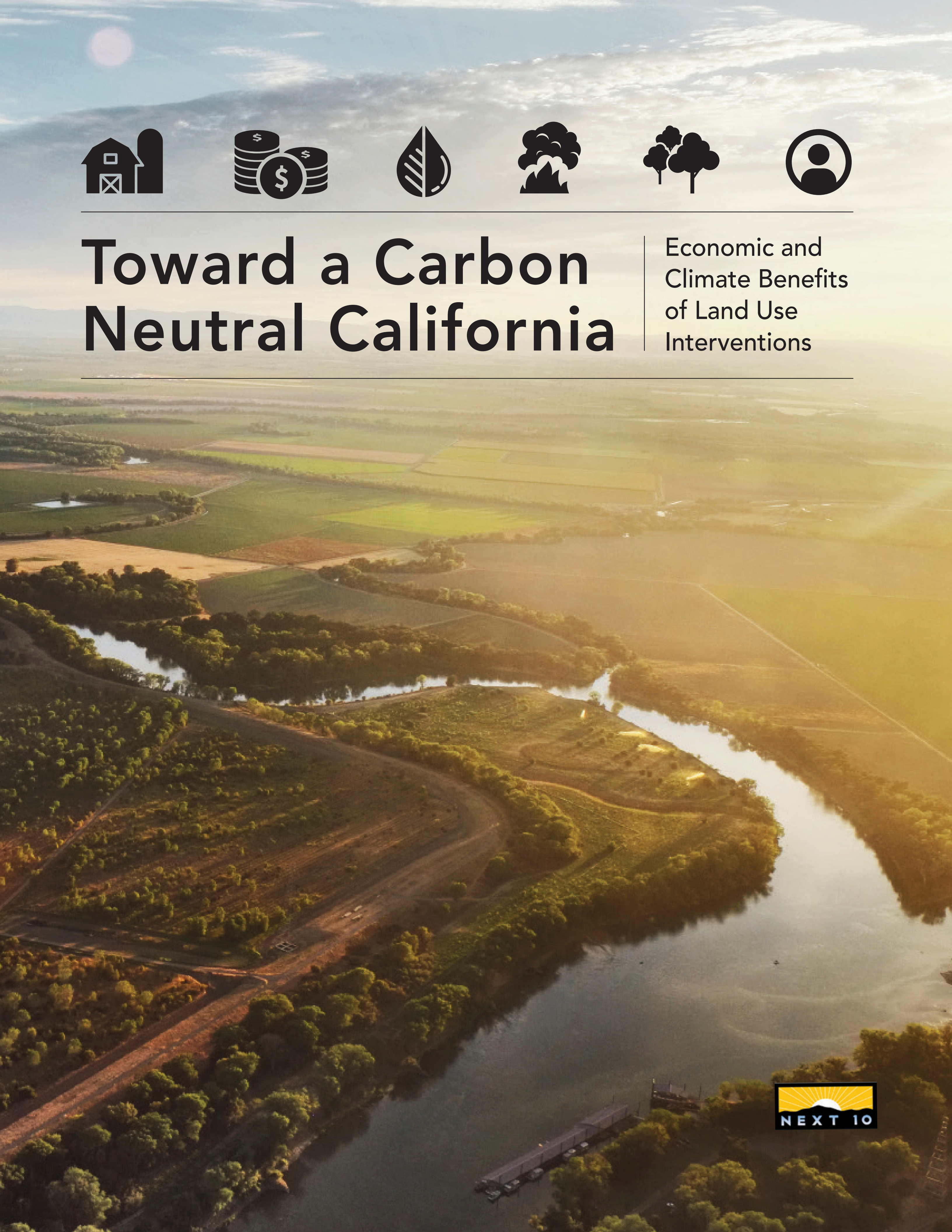

Toward a Carbon Neutral California

Economic and Climate Benefits of Land Use Interventions

NEXT 10

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TABLE OF CONTENTS

GLOSSARY

Biomass	The mass of live or dead vegetation, approximately half of biomass is water and half is carbon
Carbon dioxide (CO_2)	The main greenhouse gas in the atmosphere and used in photosynthesis by vegetation to grow by storing the carbon molecules as biomass. A molecule of CO_2 is 3.667 times the weight of a molecule of carbon.
Carbon Pool	A reservoir of carbon stored in a particular system, such as live vegetation, dead organic material, or soils.
Carbon Sequestration	The process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form. In this report, it is held in live vegetation, organic matter and soils.
Carbon Stock	Weight of carbon stored by a particular pool at one moment in time (expressed in units of carbon)
Carbon Flux	Weight of CO_2 that moves between carbon pools and the atmosphere between two time periods (expressed in units of CO_2)
Land use class	A type of land characterized by dominant vegetation, crop type, or use, such as forest, annual agriculture, and shrubland.
Net returns	The annual net returns to an economic activity measures the difference in annual revenue and annual cost. The net return to an economic activity over a series of years is given by the present value of the sum of annual net returns to the activity.
Tg	Teragram; equivalent to one million metric tons

I.

Executive Summary

BUILDING on its leadership to address climate change, the state of California increasingly recognizes the critical role that management of natural and agricultural ecosystems can play in helping to meet climate goals. Through the implementation of conservation, restoration, and management practices and policies, both public and private entities can reduce emissions and increase the sequestration capacity of the land. Collectively, these practices and policies are called “natural climate solutions” and have been shown to materially contribute at statewide and global scales.[1,2]

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California has already invested nearly $1 billion from its Greenhouse Gas Reduction Fund (GGRF) in land-based strategies to reduce emissions, building momentum to meet the state's 2030 greenhouse gas (GHG) reduction goal with an enhanced role for land-based climate strategies. In September 2018, Governor Brown released an Executive Order (B-55-18) setting a goal to make the state climate neutral, if not carbon negative, by 2045. This represents a significant opportunity to advance "negative emissions" strategies that can pull CO_2 out of the atmosphere, such as land conservation, restoration, and management. Indeed, the role of natural climate solutions becomes even more important when one considers that many of the other strategies suggested or piloted (e.g. direct air capture) to create "negative emissions" thus far rely on technologies that do not yet exist at scalable, cost-effective levels. Therefore, it's imperative the state invest heavily in this proven sector, while also exploring other opportunities. To help guide this investment, the state should create a roadmap to determine how land-based strategies might be implemented to help meet these goals. This need is sharpened by a growing risk that GHG emissions from wildfire will increase in the future due to trends in climate change and management history.

This study seeks to inform the state's GHG reduction goal for natural and working lands by providing an initial estimate of the climate mitigation benefits and costs of eight representative land management interventions under two alternative climate futures, using the LUCAS model. Climate mitigation from these interventions, or "net" emissions reductions, come from either "avoided emissions" and increased sequestration where atmospheric GHGs are stored in vegetation and soils (Table 1). These interventions or activities were selected based on their GHG reduction potential, their ability to be modeled using the LUCAS model, and because of the co-benefits they provide. They are also feasible to implement at broad scales given current technology. The effect on land-based carbon storage from these interventions is compared to a "control" run for each climate future in which interventions are not implemented. This study also quantifies the costs of implementing these interventions and provides an initial estimate of select economic benefits. Direct and implicit or opportunity costs of implementing interventions are presented to provide decision-makers with an initial estimate of the range of potential costs to integrate these activities into state climate policies.

To estimate the economic impacts associated with each intervention, one-time direct implementation expenditures and opportunity costs (foregone economic benefits due to an intervention) were calculated. All interventions except for **avoided conversion** and **changes to forest management** had direct costs. A subset of interventions had opportunity costs consisting of foregone returns to agricultural, forestry, or urbanization, including: **avoided conversion, changes to forest management, riparian restoration, and woodland restoration.**

To further capture the economic impacts of these interventions, the value of select opportunity benefits created by each intervention relative to the control scenario were calculated in addition to implementation and opportunity costs. First, the social cost of carbon (SCC) was used to estimate the economic benefit of avoided emissions as most interventions generate net emissions reductions relative to the control by 2050. Additionally, for two interventions—**avoided conversion** and **riparian restoration**— the social cost of nitrogen (SCN) was used to value the economic benefit of avoided nitrous oxide (a potent greenhouse gas) emissions and water quality impairment caused by reduced application of nitrogen fertilizer to agricultural fields. The avoided cost of flood damages associated with reduced urbanization in floodplains was estimated. Finally, the avoided cost of suppressing high severity wildfires was also calculated for the **reduced wildfire severity** intervention. It should be noted that this study does not attempt to provide economic analysis for many of the co-benefits resulting from the scenarios, nor does it calculate indirect economic benefits. It is likely that several scenarios would be even more cost-effective were these benefits considered, and further research could help quantify these benefits.

TABLE 1 Intervention Scenario Models and Land Cover Classes

MANAGEMENT TYPE	LAND COVER CLASS AFFECTED					
Forestry	**F**	**AA**	**AP**	**G**	**S**	**D**
1 **Reduced Wildfire Severity**[†] A variety of forest management practices are used to reduce fuel loading in forests.	●					
2 **Post-Wildfire Reforestation** Active replanting of trees in areas that burned under high severity fire.	●				●	
3 **Changes to Forest Management** Shifts in current forest management practices to increase carbon stocks and reduce harvest volumes.	●					
Restoration						
4 **Woodland Restoration** Planting native hardwoods in areas where they have been removed or lost due to land use change.				●		
5 **Riparian Restoration** Establishing forest cover along the banks of streams and rivers in agricultural and grassland regions.		●	●	●		
Agriculture						
6 **Agroforestry** The establishment of trees along agricultural field boundaries to act as a windbreak.		●	●			
7 **Cover Cropping** A rotation of non-cash crops when an agricultural field would normally lay bare to increase soil carbon.		●				
Conservation						
8 **Avoided Conversion** Reduced rates of land conversion due to urban or agricultural land use.	●	●	●	●	●	●

[†] assuming 10% & 30% high-severity fire

Note: F: forest, AA: agriculture-annual, AP: agriculture-perennial, G: grassland, S: shrubland, D: developed. Details and model assumptions are described in the Intervention Results section.

Key Findings

Despite naturally declining carbon stocks under both climate futures, the interventions collectively achieve emissions reductions: In total, the interventions analyzed resulted in net positive climate benefits by 2030, 2050, and 2100 despite a downward trend in carbon stocks (the amount of carbon stored in soils, dead organic matter, and vegetation) under the control run of each climate model. The largest reductions in net emissions resulted from avoided conversion of natural and agricultural land and changes to forest management on private timberland.

The aggregate emissions reductions from these interventions could help the state meet its 2050 climate targets and become carbon neutral by 2045: Their collective emissions reductions range from five to seven percent percent of the reductions the state needs to make in order to meet its GHG reduction goal for 2050. In both climate models, there is a reduction of over 260 million metric tons of CO_2 cumulatively (under 30% high severity fire scenario) by 2050. This is 2.5 times greater than the reductions expected to be produced by the residential and commercial sectors combined and 80 percent of both industrial and agricultural emissions reduction modeled to meet California's 2050 climate target. These interventions can also support efforts to become carbon neutral by 2045.

The economic benefits are significant, even with a limited scope: The cumulative economic benefits of these reductions are as high as $14.9 to $17.2 billion by 2050, and include the benefits of not emitting CO_2 or nitrogen-based greenhouse gases or pollutants, as well as the avoided costs of damages due to flooding urban areas and suppressing high severity wildfires. This includes a quantification of only a few of the environmental benefits associated with conservation or increased adaptation to climate impacts associated with the interventions modeled— the estimates could be significantly higher if they accounted for other direct and indirect economic benefits.

260 million

metric tons of CO_2 captured by these interventions

5-7 percent

of the emissions reductions the state needs to meet its 2050 climate goal

Economic benefits help balance opportunity cost: The cost of implementing these activities is driven by their opportunity costs. The opportunity cost of an activity is the economically-productive land use the activity prevents. Opportunity cost includes the present value of forgone net returns from residential and agricultural land use through perpetuity and the present value of forgone net returns from managed forest land use through 2050. Direct implementation and opportunity costs range from $32.6 to $35 billion for the "average" and "hot-dry" climate futures respectively from 2020 to 2050. This equals about $1.2 billion (2020-2050) a year for the high estimate. So, for every dollar spent on implementation and incurred as an opportunity cost, $0.49 is paid back in terms of benefits under the "hot-dry" and $0.46 under the "average" model.

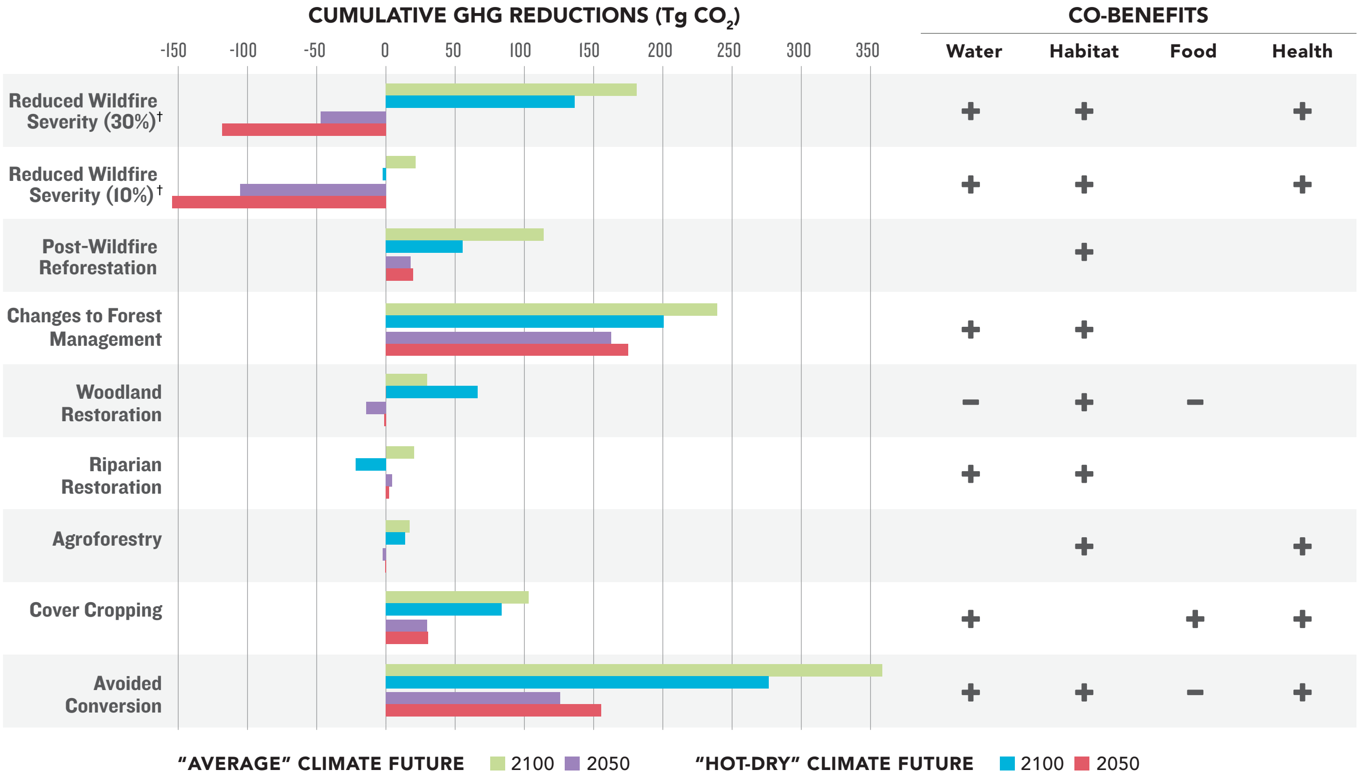
Yet, there are many benefits that are not included in this assessment that would certainly make the cost-effectiveness of these interventions even more favorable, including the increased amenity, recreation, and public health benefits of maintaining natural land near cities, the benefits of more compact growth patterns in terms of shorter commute times, less traffic, and associated social and environmental benefits. This study did not account for the indirect GHG emissions associated with urbanization and increases in cultivated agriculture, but by preventing those emissions, the avoided conversion intervention also provides indirect climate benefits.

For the benefits provided, these interventions are relatively cost-effective: When considering the price per ton of CO_2 emissions reductions compared to other sectors' activities, the majority of the activities for which there were net reductions by 2050 are relatively cost-competitive. For example, avoided conversion is the second most expensive intervention besides riparian restoration with a cost per ton of CO_2 reduced equal to $130 from 2020-2050 using discounted rates. Yet, this makes it cheaper than all but one of the eight programs administered by California Air Resources Board as part of the California Climate Investments Programs in 2017.[3]

The variable future risk of wildfire greatly impacts emissions savings potential, but conservative estimates show a net reduction by the end of century: Reduction of high-severity wildfire events by implementing thinning and prescribed burning projects reduces overall areas burned under high severity by over 1.5 million acres by the end of the century. Because this intervention removes carbon from the forest as part of the restoration action, it results in emissions until after 2060. After this point, both models under the 30 percent fire severity scenario start to result in net emissions reduction through the avoidance of high severity wildfire compared to the control model. By the end of the century, the "average" climate future results in a net reduction of 181 million metric tons of CO_2 cumulatively (under 30% high severity fire scenario) and 136 million metric tons of CO_2 under the "hot-dry" climate future. The reduction of high severity fire also reduces suppression costs from $57 to $240 million depending on the climate future for this fire scenario. The assumption of how much of future fire area will be high severity greatly affects the ability to achieve GHG reductions. For example, under a scenario in which only 10% of the future fire area burns under high severity conditions, the net climate effect is nearly neutral under the "hot-dry" climate future with a small amount (21 million metric tons) of reductions under the "average" climate future. On the other hand, if fire severity and frequency is underestimated, the savings could be far greater. Future improvements in harvested wood utilization will also greatly affect the climate benefit of this intervention.

Co-benefits improve attractiveness of intervention implementation: The interventions modeled in this study provide numerous co-benefits in terms of improved air quality, water quality, ecosystem resilience to climate change, and in some cases food production. By protecting and restoring natural vegetation cover in agricultural and rangeland systems (riparian restoration, agroforestry), water quality benefits accrue to downstream users through the retention of sediment and nutrient-rich runoff from fields. Reducing the frequency and intensity of timber harvest can provide increased habitat quality for wildlife that prefer older, more structurally complex forests, for example. Reducing the expansion of urban areas into natural habitats and agricultural lands provides numerous benefits, including bringing food production closer to markets and reduced traffic and air pollution due to shorter commute times. Finally, implementing projects to reduce wildfire risk provides numerous benefits in a climate-changed world through the protection of life and property. A characterization of these co-benefits can be found in Figure 1 and within each intervention's overviews later in the report.

FIGURE 1 Cumulative GHG Reductions by Intervention, Mid- and End-Century



CO-BENEFITS

	Water	Habitat	Food	Health
Reduced Wildfire Severity (30%)†	+	+		+
Reduced Wildfire Severity (10%)†	+	+		+
Post-Wildfire Reforestation		+		
Changes to Forest Management	+	+		
Woodland Restoration	−	+	−	
Riparian Restoration	+	+		
Agroforestry		+		+
Cover Cropping	+		+	+
Avoided Conversion	+	+	−	+

Note: Positive and negative effects on co-benefits including water quality and quantity (Water), habitat availability (Habitat), food production (Food), and public health and resilience (Health). †The same reduced wildfire severity scenario was run twice, each using a different assumption for the percentage of high severity fire that composes a wildfire in the model (30% vs 10%). See Intervention Results for more detail.

Key Implementation Recommendations

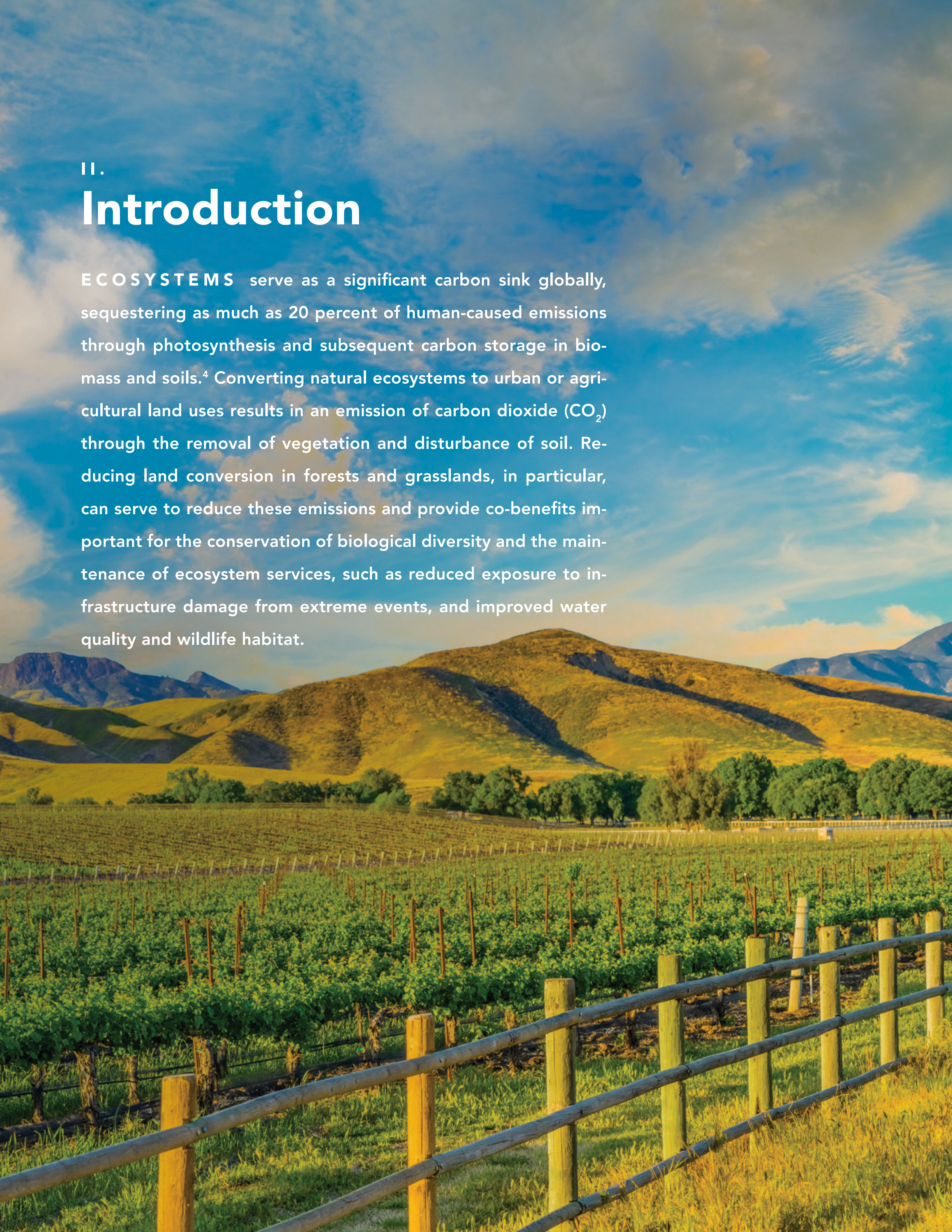
Establish an ambitious climate goal for the state's natural and working lands. Given the state's goal to become carbon neutral by 2045 and the potential for the state's natural and working lands to become an increasing net source of emissions, the state should establish an ambitious climate goal for its natural and working lands to ensure appropriate attention, accountability, and investment in these resources.

Early and aggressive implementation will provide larger climate benefits due to the time lags inherent in ecosystem response to interventions. Many of the interventions that rely on growing vegetation (mostly trees) will yield more substantial benefits the earlier they begin due to the compounding effect of tree growth—as trees grow larger their capacity to absorb more carbon dioxide increases. This is especially relevant given California's stated goal of having a climate neutral emissions profile by 2045. Natural and working lands interventions will be especially important in meeting that goal, given residual emissions likely in other economic sectors.

Dedicate sustained funding to natural and working lands for climate mitigation and associated benefits. While the state has dedicated some funding from its Greenhouse Gas Reduction Fund (GGRF) for natural and working lands investments, it has been relatively small and inconsistent compared to the scale and duration of climate investments in other sectors such as transportation and energy. While nearly $926 million has been invested in California's natural and working lands from the state's GGRF over the past six years through annual appropriations, this represents roughly 11 percent of the total $8.4 billion that has been invested across the economy.

Leverage existing programs and policies, while building new ones. In many cases, policies and programs already exist to enable implementation of the modeled interventions. In the near term, scaling up these programs using new funding sources will enable the rapid deployment of funding and technical expertise to ensure rapid implementation. Using existing landowner outreach tools and networks, such as those administered by RCDs, NRCS, CalFire, and the U.S. Forest Service can lead to increased adoption due to the legacy of trust and collaboration that underpins these programs. New programs could focus on planning at county and regional scales, and on implementation that can optimize greenhouse gas reductions across sectors as well as other important co-benefits.

Adopt a portfolio of solutions across land types, regions, economic sectors, and ownership types. Given the high uncertainty inherent in climate change scenarios, adopting an approach that spreads the risk across different land uses and geographic regions will make it more likely that place-based climate impacts and disturbances will not reverse beneficial actions. While forests certainly represent the largest opportunity to store carbon in aboveground biomass and grasslands represent a large potential belowground sink, there will be geographic differences in fire frequency, drought, and other processes that make investing in a diversity of implementation areas an effective risk management strategy.



II.

Introduction

ECOSYSTEMS serve as a significant carbon sink globally, sequestering as much as 20 percent of human-caused emissions through photosynthesis and subsequent carbon storage in biomass and soils.[4] Converting natural ecosystems to urban or agricultural land uses results in an emission of carbon dioxide (CO_2) through the removal of vegetation and disturbance of soil. Reducing land conversion in forests and grasslands, in particular, can serve to reduce these emissions and provide co-benefits important for the conservation of biological diversity and the maintenance of ecosystem services, such as reduced exposure to infrastructure damage from extreme events, and improved water quality and wildlife habitat.

In addition to reducing land conversion, changes to the way forests, grasslands, wetlands, and agricultural lands are managed can enhance the carbon sequestration potential in soil and vegetation through the implementation of specific management interventions, such as reducing the intensity and frequency of timber harvest, planting cover crops, and reforestation. These "natural climate solutions" include reducing land conversion and managing forests, grasslands, wetlands and agricultural lands to enhance their potential to store carbon. One global study found that they can provide as much as 37 percent of the cost-effective emissions reductions needed to hold global mean temperature increase to less than 2 degrees celsius.[1]

Building on its leadership to address climate change, California is increasingly recognizing the critical role that management of natural and agricultural ecosystems can play in helping to meet climate goals. California has adopted 2020, 2030 and 2050 goals to reduce greenhouse gas (GHG) emissions across the economy. While the state didn't rely heavily on ecosystem and agricultural land management to achieve its 2020 goal four years early—forest conservation activities have played a material role in reducing emissions through the state's cap and trade program. The state has invested nearly $1 billion from its Greenhouse Gas Reduction Fund (GGRF)—which is funded by cap-and-trade proceeds—in land-based strategies to reduce emissions, enhancing the role of land-based climate strategies to meet the state's 2030 goal.

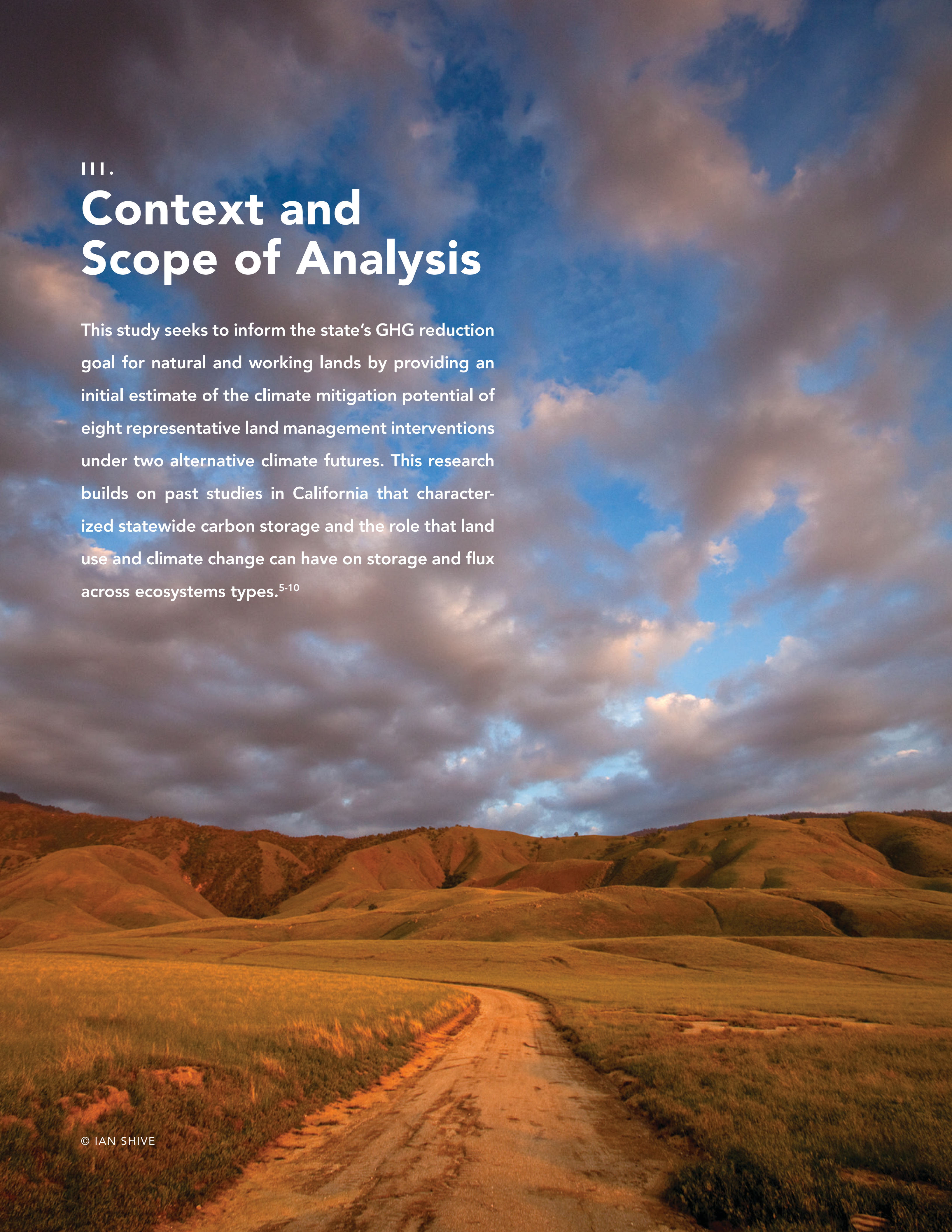
In September 2018, Governor Brown released an Executive Order (B-55-18) stating that the state will be climate neutral, if not carbon negative, by 2045. This represents a significant opportunity to advance "negative emissions" strategies such as land conservation, restoration, and management.

To meet these ambitious targets, California will increasingly need to enhance carbon sequestration or prevent emissions through the implementation of land-based strategies. This need is sharpened by a growing risk that GHG emissions from wildfire will increase in the future due climate change and management history. As a first step toward expanding the role of "natural and working lands" in its climate strategies, the California Air Resources Board (CARB) established an initial GHG reduction goal for its land sector (e.g., forests, urban forests, wetlands, rangelands, and agricultural lands). It plans to revisit this goal upon the completion and review of additional scientific research. This goal will likely inform the forthcoming statewide Natural and Working Lands Implementation Plan for the land sector.

III.

Context and Scope of Analysis

This study seeks to inform the state's GHG reduction goal for natural and working lands by providing an initial estimate of the climate mitigation potential of eight representative land management interventions under two alternative climate futures. This research builds on past studies in California that characterized statewide carbon storage and the role that land use and climate change can have on storage and flux across ecosystems types.[5-10]



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To date, a variety of analytical approaches have been used in California to quantify changes in ecosystem carbon storage and to attribute those changes to a variety of causes, including disturbances, mortality, harvest, or land use change. Studies looking at past trends typically rely on periodic inventories such as the Forest Inventory and Analysis (FIA) plot data administered by the U.S. Forest Service and supplement those sources with estimates from literature for non-forest cover types.[11] Inventory data have been combined with spatial data representing vegetation types to explore geographic patterns of carbon storage or change.[12-14] Future projections of carbon stock that incorporate alternative climate scenarios often rely on dynamic global vegetation models (DGVM) or other types of simulation models.

This study differs from previous analyses as it builds on this work by incorporating the use of the Land Use and Carbon Scenario Simulator (LUCAS) state and transition model developed by U.S Geological Survey and Apex Resource Management Solutions.[15-17] Recent research using LUCAS characterized the land use and carbon storage implications of 32 plausible future California scenarios representing combinations of four climate models, two emissions trajectories, and four land use change scenarios.[18]

This previous study used a representative set of climate models selected as part of the California Fourth Climate Change Assessment to illustrate the range of future outcomes for land cover, carbon storage, and controlling processes such as fire, drought, and changes in temperature and precipitation.[19] Those climate models were “hot-dry” (HadGEM2-ES), “warm-wet” (CNRM-CM5), “average” (CanESM2), and “complementary” (MIROC5). Combining climate futures with alternative scenarios of harvest, agricultural land change, and urbanization sampled from observed historical rates provides a comprehensive characterization of the range of potential outcomes for ecosystem carbon storage. Across the four models, total ecosystem carbon declined on average about 10 percent from early 21st century to 2100, though large variability characterized the scenario results. Based on this past work, this current study uses two climate models and one emissions trajectory, as described in the next section.

Analytical Approach

This study models the impact of eight land management and conservation interventions on carbon storage for two climate futures using the LUCAS model. The effect on land-based carbon from these interventions is compared to a “control” run for each climate future in which interventions are not implemented. This study also quantifies the costs of implementing these interventions and provides an initial estimate of select economic benefits. Direct and implicit or opportunity costs of implementing interventions are presented to provide decision-makers with an initial estimate of the range of potential costs to integrate these activities into state climate policies.

Understanding the influence of alternative climate change scenarios on the effectiveness of “natural climate solutions” is critical information for policymakers as they develop policies that incentivize particular activities. Designing programs that fund interventions that have consistent mitigation potential regardless of the climate future can be an effective risk management strategy. Being able to map and characterize the geographic patterns of the carbon change through LUCAS gives policymakers and land managers an opportunity to align these interventions with other ecological, social, and economic co-benefits. This set of scenarios will provide actionable information to guide climate policy development for activities covering natural and to a lesser degree, agricultural lands. Because the study only includes a subset of agricultural land management practices, it can be considered only as a partial assessment of the full potential of such practices.

To illustrate how different land management and conservation practices can be implemented at a smaller scale, a case study is presented on page 48 with two greenhouse gas reduction scenarios from a recently released report for Merced county, *Resilient Merced: A County Guide to Advance Climate Change Mitigation and Complementary Benefits through Land Management and Conservation.*[20] While these efforts share similar goals, the methods used to estimate greenhouse gas reductions are different, and the Merced effort focused on smaller scale implementation within a more proximate time frame. Nonetheless, the examples illustrate the types of activities counties and landowners might undertake to reduce emissions or sequester more carbon, while achieving other complementary benefits. The Merced research is presented in this report as a case study in how local governments can design and implement programs to integrate natural and working lands in local or regional climate action plans.

TABLE 2 Intervention Scenario Models and Land Cover Classes

MANAGEMENT TYPE	LAND COVER CLASS AFFECTED					
Forestry	**F**	**AA**	**AP**	**G**	**S**	**D**
1 Reduced Wildfire Severity[†]	●					
2 Post-Wildfire Reforestation	●				●	
3 Changes to Forest Management	●					
Restoration						
4 Woodland Restoration				●		
5 Riparian Restoration		●	●	●		
Agriculture						
6 Agroforestry		●	●			
7 Cover Cropping		●				
Conservation						
8 Avoided Conversion	●	●	●	●	●	●

[†] assuming 10% & 30% high-severity fire

Note: F: forest, AA: agriculture-annual, AP: agriculture-perennial, G: grassland, S: shrubland, D: developed. Details and model assumptions are described in the Intervention Results section.

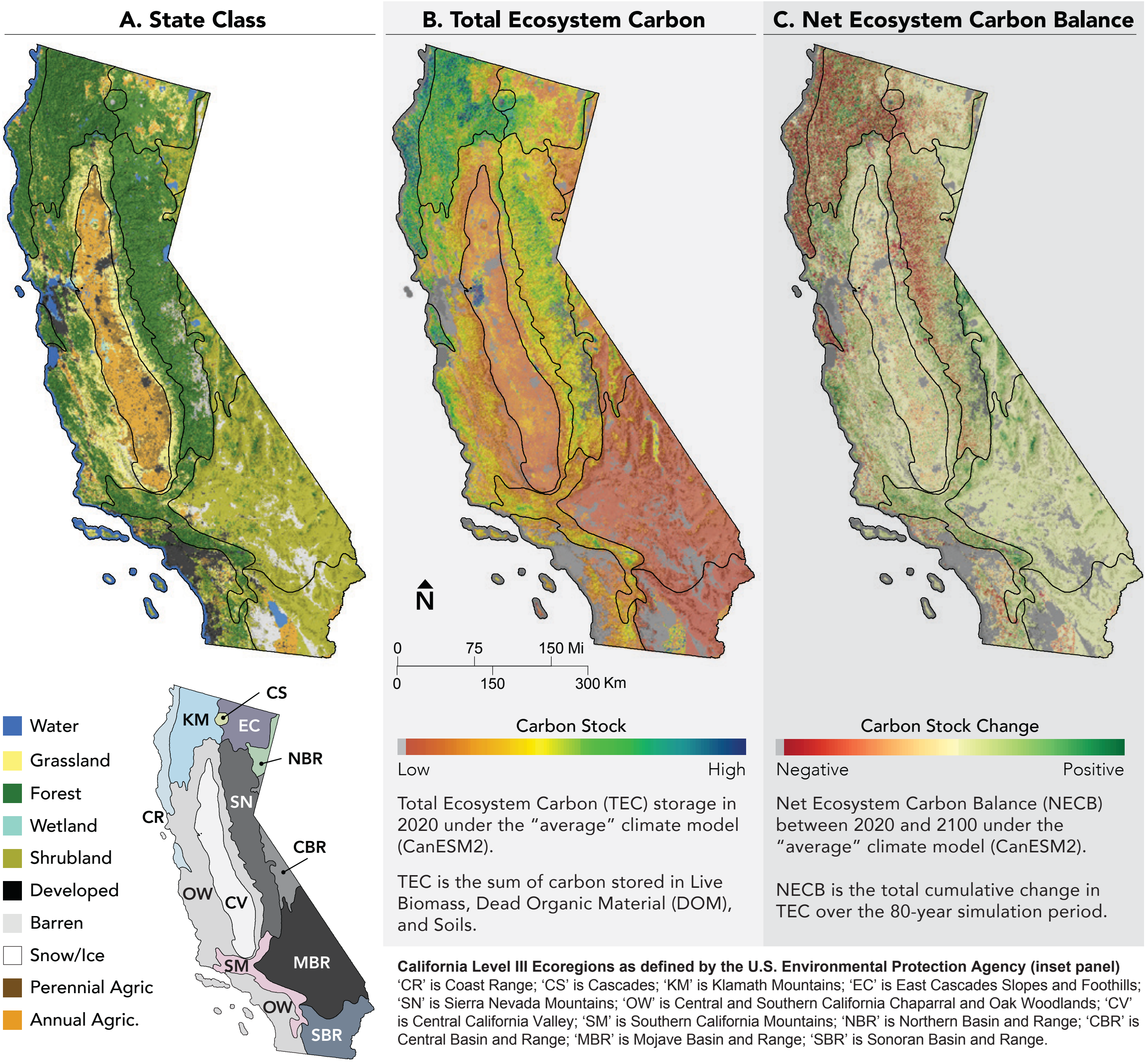
Methods Overview

LAND USE CHANGE AND CARBON

A recently developed modeling framework, LUCAS, was used to simulate vegetation growth, changes in land use, and the resulting emissions or uptake of carbon by ecosystems.[15,17] The model is capable of tracking spatial changes annually at 1 square kilometer (~0.6 square miles) spatial resolution over the period 2001-2100 across all of California. Data on historical land use, forest age, and ecosystem carbon stocks were used to develop the model (Figure 2). Additionally, two projections of future climate under an emissions trajectory (Representative Concentration Pathway [RCP] 8.5) roughly similar to taking little-to-no action to reduce global climate emissions were used to simulate ecosystem processes over the future time period (2016-2100). The first climate projection produces an "average" future climate relative to a wide range of other climate projections and the second produces a "hot-dry" future, as noted in the earlier section. Having two climate futures gave a basis for comparison of the intervention effects under different climate change scenarios.

In order to assess the effects of a particular land management intervention, a control – or a model simulation with no land management changes – scenario was completed. Each climate future was combined with a "business-as-usual" land use change scenario, and the model was run 100 times. By running each control model many times, an estimate of the future uncertainty of changes in carbon stocks was created. Separately, these same control models were simulated once but with alterations meant to make them directly comparable to each intervention model. Each intervention model started with this altered control model as its base and was changed to reflect a specific land management intervention. The results of the intervention scenario were then evaluated against the control scenario, and how the land management changes affected carbon and other model outputs were assessed. If the effect of the intervention did not diverge from the uncertainty bounds of the control, there was less confidence that the intervention will result in a net emissions reduction. See the Appendix for detailed explanation and assumptions on the land use and carbon modeling.

FIGURE 2 Study Area Overview



Total Ecosystem Carbon (TEC) storage in 2020 under the "average" climate model (CanESM2).

TEC is the sum of carbon stored in Live Biomass, Dead Organic Material (DOM), and Soils.

Net Ecosystem Carbon Balance (NECB) between 2020 and 2100 under the "average" climate model (CanESM2).

NECB is the total cumulative change in TEC over the 80-year simulation period.

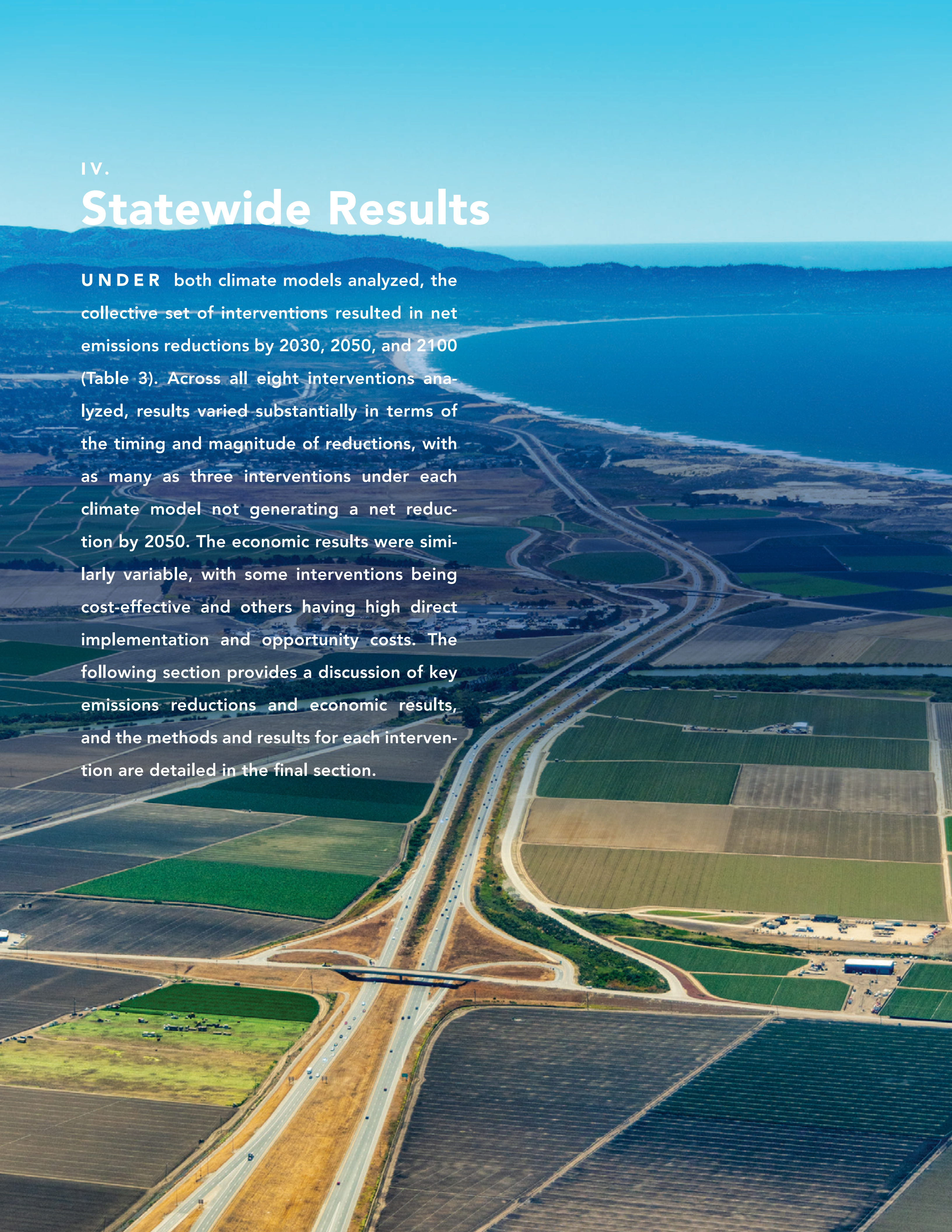
California Level III Ecoregions as defined by the U.S. Environmental Protection Agency (inset panel) 'CR' is Coast Range; 'CS' is Cascades; 'KM' is Klamath Mountains; 'EC' is East Cascades Slopes and Foothills; 'SN' is Sierra Nevada Mountains; 'OW' is Central and Southern California Chaparral and Oak Woodlands; 'CV' is Central California Valley; 'SM' is Southern California Mountains; 'NBR' is Northern Basin and Range; 'CBR' is Central Basin and Range; 'MBR' is Mojave Basin and Range; 'SBR' is Sonoran Basin and Range.

Note: All are shown for the "average" climate future and in the absence of any land management interventions.

ECONOMIC ASSESSMENT

To estimate the costs associated with each intervention, both the one-time direct expenditures and opportunity costs (foregone economic benefits due to an intervention) were calculated. All interventions except for **avoided conversion** and **changes to forest management** had direct costs. A subset of interventions had opportunity costs consisting of foregone agricultural, urbanization, or forestry net returns: **avoided conversion, changes to forest management, riparian restoration,** and **woodland restoration.**

To further capture the economic impacts of these interventions, the value of select opportunity benefits created by each scenario relative to the control scenario were also calculated. First, the social cost of carbon (SCC) was used to calculate the economic benefit of avoided emissions, as almost all interventions generate emissions reductions relative to the control by 2050.[21] Additionally, for two interventions,—**avoided conversion** and **riparian restoration**—the social cost of nitrogen (SCN) was used to value the economic benefit of avoided nitrous oxide (a potent greenhouse gas) emissions and water quality impairment caused by reduced application of nitrogen to agricultural fields.[22] The avoided cost of flood damages associated with avoided floodplain development was also estimated. Finally, the avoided cost of suppressing high severity wildfires was estimated for the reduced wildfire severity intervention. All costs and benefits are discounted to 2017 US$. See Appendix for detailed explanation of the economic assessment and underlying assumptions.

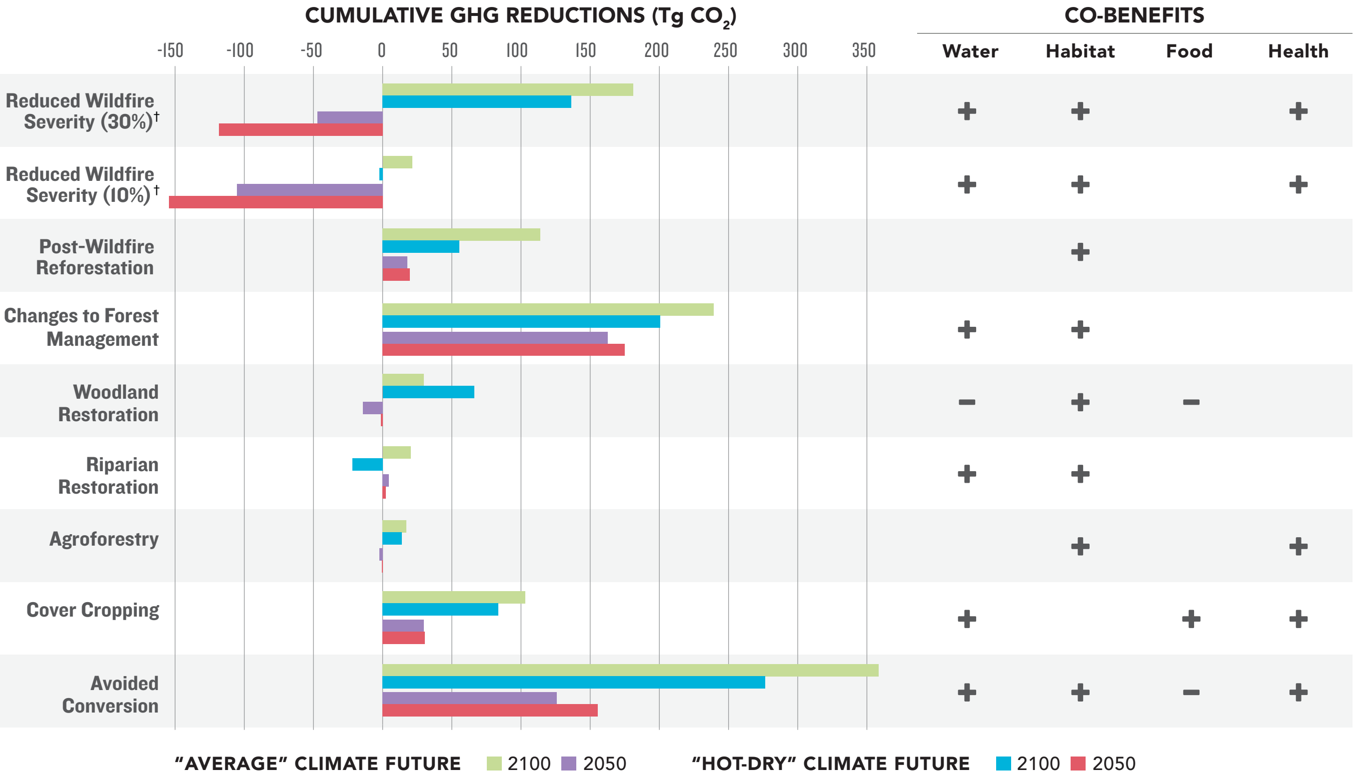


IV.

Statewide Results

UNDER both climate models analyzed, the collective set of interventions resulted in net emissions reductions by 2030, 2050, and 2100 (Table 3). Across all eight interventions analyzed, results varied substantially in terms of the timing and magnitude of reductions, with as many as three interventions under each climate model not generating a net reduction by 2050. The economic results were similarly variable, with some interventions being cost-effective and others having high direct implementation and opportunity costs. The following section provides a discussion of key emissions reductions and economic results, and the methods and results for each intervention are detailed in the final section.

FIGURE 3 Cumulative GHG Reductions by Intervention, Mid- and End-Century



	CO-BENEFITS			
	Water	Habitat	Food	Health
Reduced Wildfire Severity (30%)†	+	+		+
Reduced Wildfire Severity (10%)†	+	+		+
Post-Wildfire Reforestation		+		
Changes to Forest Management	+	+		
Woodland Restoration	−	+	−	
Riparian Restoration	+	+		
Agroforestry		+		+
Cover Cropping	+		+	+
Avoided Conversion	+	+	−	+

Note:. Positive and negative effects on co-benefits including water quality and quantity (Water), habitat availability (Habitat), food production (Food), and public health and resilience (Health). †The same reduced wildfire severity scenario was run twice, each using a different assumption for the percentage of high severity fire that composes a wildfire in the model (30% vs 10%). See Intervention Results for more detail.

Emissions Reduction Results

Both climate models resulted in declining carbon stocks – leading to a net increase in emissions – under the control scenario, relative to 2016, with the models diverging abruptly around 2060 (Subpanel D in Figures 7-15).[18] This downward trend in the land's ability to sequester carbon over time is due to both patterns in climate change as well as management history. Carbon storage in the "hot-dry" model steeply declined due to a persistent multi-year drought while the "average" model jumped above the 2016 reference amount briefly only to decline again. The end-of-century decrease in carbon storage was about 15 percent lower in the "hot-dry" climate compared to the "average" future under the control scenarios—showing the impact of different climate futures on carbon storage. Both models showed high interannual variability in carbon flux due to climate and disturbance effects, demonstrating that net carbon flux should be analyzed over multiple years when measured for climate policy.

The cumulative GHG reduction potential of each intervention by 2100 ranged from a high of over 350 Tg CO_2 for the **avoided conversion** intervention under the "average" climate model to a net emission of 21 Tg CO_2 under the "hot-dry" future for **riparian restoration** (Figure 3, Table 3). By 2050, **avoided conversion** was the second most effective intervention after **changes to forest management** in terms of overall GHG reduction potential under both climate models. The steep decline in urban and agricultural land expansion after 2050, plus the cessation of new additions to changes to forest management after 2050 lead to **avoided conversion** realizing larger reductions by 2100.

TABLE 3 GHG Reduction Potential From Each Intervention Scenario.

Intervention	Implementation Area (ac/yr)	CUMULATIVE EFFECT OF ACTIVITY (Tg CO_2)					
		"Hot-Dry" Climate			"Average" Climate		
		2030	2050	2100	2030	2050	2100
Forest							
Reduced Wildfire Severity (30% High Severity)[†]	forest thinning: 308,750 prescribed burn:123,500	-76.7	-118.2	136.3	-59.1	-47.0	181.1
Reduced Wildfire Severity (10% High Severity) [†]		-91.4	-154.5	-2.4	-75.6	-105.4	21.3
Post-Wildfire Reforestation	48,165	-2.9	19.5	55.4	-2.9	18.0	113.8
Changes to Forest Mgmt[†]	98,800	69.4	175.1	200.8	71.9	162.6	239.2
Restoration							
Woodland Restoration	12,597	1.5	-1.1	66.1	-4.8	-14.3	29.7
Riparian Restoration	4,940	1.8	2.2	-21.7	-11.4	4.4	20.2
Agriculture							
Agroforestry	7,904	-1.1	-0.7	13.9	-0.4	-2.2	17.2
Cover Cropping	56,563	6.2	30.5	83.7	4.8	29.7	103.1
Conservation							
Avoided Conversion	-55% Agricultural Expansion -75% Urbanization	47.7	155.6	276.4	27.2	125.9	358.6
Total Cumulative	(with 30% high severity wildfire)	45.9	262.9	810.9	25.3	277.1	1062.8
Total Annualized		4.6	10.8	11.0	2.5	12.6	15.7
Total Cumulative	(with 10% high severity wildfire)	31.2	226.6	672.2	8.8	218.7	903.1
Total Annualized		3.1	9.8	8.9	0.9	10.5	13.7

[†] Assumes 34% of the harvested wood products from these interventions are stored in a long-term pool (i.e., not immediately emitted to atmosphere or decayed). See *Intervention Results* for more detail.

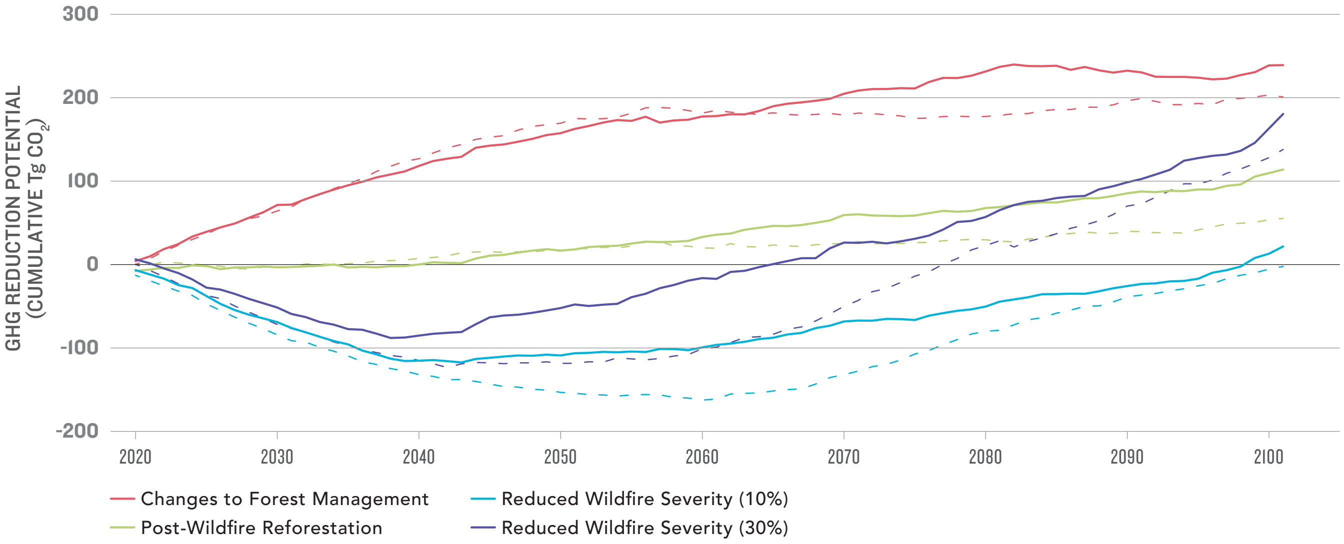
Note:. Negative numbers indicate a net emission to the atmosphere. Totals are calculated with the reduced wildfire severity scenario run with either 30% or 10% high severity fire. Annualized numbers are the average reduction potential over the preceding column (interventions started in 2020), actual annual reduction potentials vary from year-to-year

Cover cropping generated substantial reductions by both 2050 and 2100, far outpacing the other interventions available in cultivated agricultural land: **agroforestry** and **riparian restoration** (Figure 3). Smaller implementation areas certainly influenced the magnitude of reductions for these interventions (Table 3), but climate effects and ecosystem responses also had an impact.

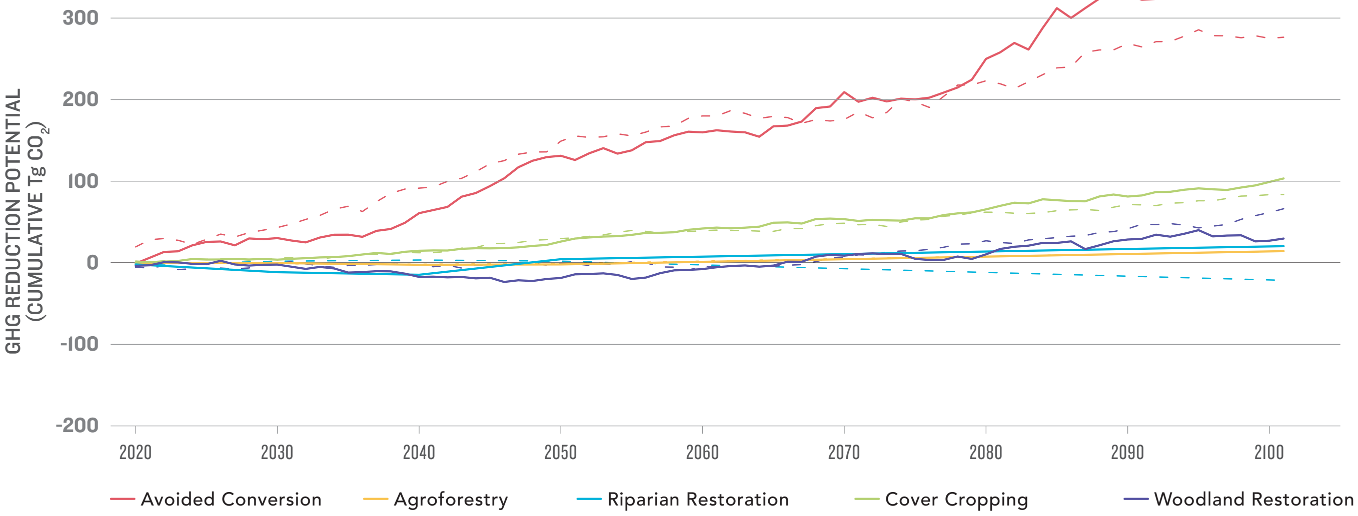
The interventions modeled in this study created co-benefits, and in some cases trade-offs, to natural and human systems. Figure 3 summarizes whether or not these co-benefits demonstrated positive or negative effects, including impacts to water quality and quantity (Water), habitat availability (Habitat), food production (Food), and public health and resilience (Health). For example, the **avoided conversion** intervention looks at the impacts of preventing the expansion of cities and the expansion of agricultural land into natural areas, which is important to protect and connect wildlife populations. Yet, by limiting the area for future agriculture, it may create a trade-off with food production. **Cover cropping** may be used as a water saving strategy, assuming a reduction in irrigation demand of cash crops that may provide benefits for future yields and reduce air pollution, due to the lack of bare ground that would be subject to wind erosion. Some of the co-benefit synergies and trade-offs for interventions in Figure 3 are debatable or have varying levels

FIGURE 4 Reduction Potential from Intervention Scenarios Over Time

A. Individual Intervention Scenarios for Forest-Related Interventions



B. All Other Interventions



Note: Solid lines refer to the "average" climate future and dotted lines to the "hot-dry" future.

of evidence to support categorization. Yet, to contextualize the rationale for these interventions beyond climate mitigation, they are presented as a plausible initial set of factors to consider.

Overall reductions were similar between the two climate futures until later in the century when the "hot-dry" model started trending lower than the "average" future (Table 3). This may be due to impacts from an extended mid-century drought that appears in the "hot-dry" future.[19] By 2100 the "average" climate future resulted in a 1063 Tg CO_2 cumulative reduction (i.e. additional ecosystem carbon) while the "hot-dry" climate future resulted in 811 Tg CO_2, a 31 percent difference.

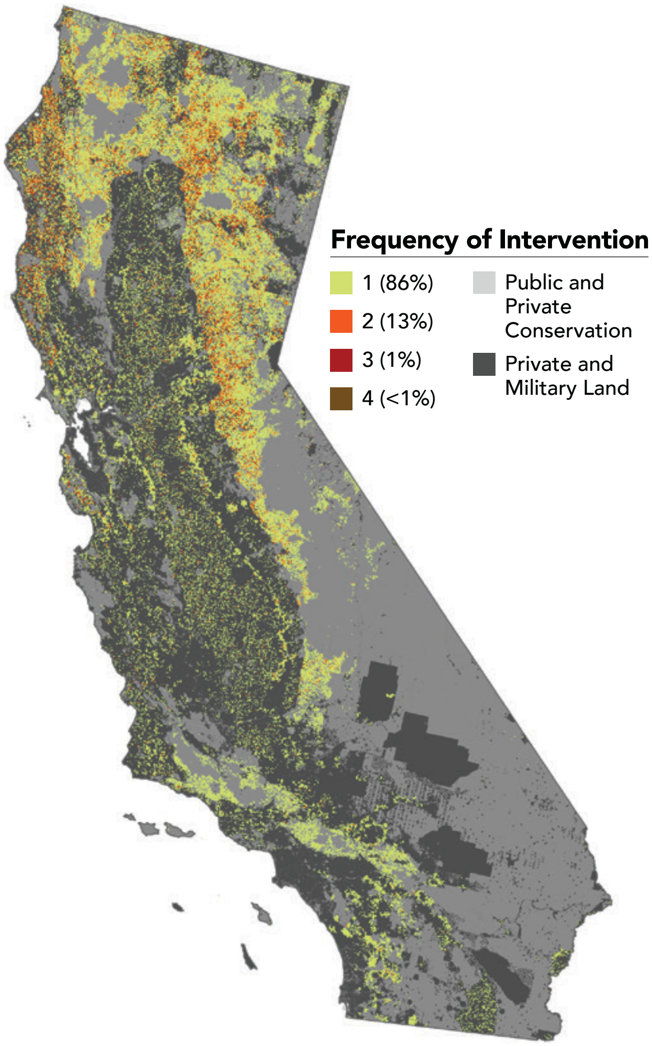
Over time, some interventions switched from being a net source of emissions to one that created net reductions. The **reduced wildfire severity** scenario resulted in large emissions from forest thinning and prescribed burning activities by 2050. To explore the uncertainty of future fire severity, two rates were used for the proportion of high severity fire (HSF) relative to total burned area –

10 percent, which is close to the observed historical rate in California, and 30 percent, to mimic fire regimes under a warming climate with reduced precipitation (Figure S1 in the Appendix). As larger areas are treated, the reduction of high severity fire resulted in avoided emissions relative to the control scenario. Essentially, the implementation of the intervention initially created a "carbon debt" on the landscape through forest thinning and prescribed burning that was slowly paid back through avoided HSF emissions. Ultimately this became a net reduction of emissions relative to the control (under 30% HSF). Under the "average" climate model, this intervention becomes net positive by around 2065 (Figure 4A) and the "hot-dry" model becomes positive about 10 years later in the 30 percent HSF scenario. The payback is much slower under the 10 percent HSF scenarios (Figure 4A) with the intervention resulting in a cumulative net neutral climate effect by 2100. Under a future with higher amounts of HSF, the intervention will reduce emissions more than a lower HSF future. This explains the stronger climate benefit observed under the 30 percent HSF scenario.

Interventions contributed to the relative carbon change differently over time with **avoided conversion** and **changes to forest management** yielding consistent reductions over time, and other interventions yielding a minimal reduction such as **woodland restoration,** or even negative such as **riparian restoration** (Table 3, Figure 4A, 4B). Intermittent disturbances affect the shape of the lines and, along with longer term climate changes, determined the spread between the two models. As discussed earlier, **reduced wildfire severity** results increased emissions resulting from the implementation of the fuel treatment activities, but then as those reached a critical extent on the landscape they started leading to reduced emissions relative to the control runs.

The lack of substantial reductions in the first half of the century from the **restoration** interventions and from the **agroforestry** intervention highlights the importance of early action for natural climate solutions. All three of these interventions involve adding trees to landscapes where trees are either absent or at very low density. Relative to the grassland and agricultural land they are replacing, the rate of input to soil carbon by these young forests is lower. This essentially yields a soil carbon storage "opportunity cost" during the early growth stages of these new forests. Eventually as the forests mature, both the above and belowground carbon inputs will exceed the rate of input of the non-forest lands they replaced. Additionally, there are climate effects that alter the response of these interventions. The majority of these three interventions occurred in the California Central Valley and the Chaparral and Oak Woodland ecoregions, which experienced substantially warmer temperatures under both climate futures than other ecoregions where interventions were modeled (Figure S1 in the Appendix).

FIGURE 5 Map of All Interventions Carried Out Over the 80-Year Modeling Period, 2020—2100



Note: Green areas represent areas where a single intervention was carried out and are strictly additive when combining interventions. Areas where more than one intervention was selected by the model (among independent scenarios) are shown in non-green colors and may not be additional.

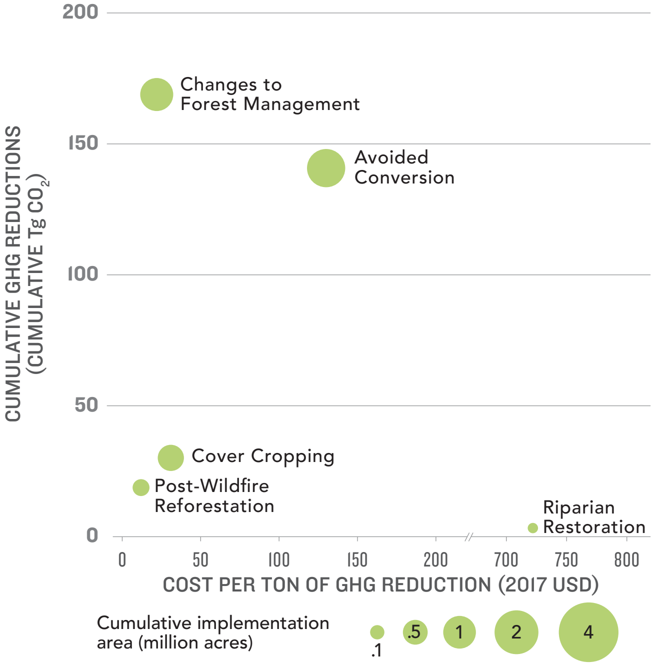
Interventions were located primarily in forest regions throughout the state due to three interventions being focused in conifer forests (**reforestation, reduced wildfire severity,** and **changes to forest management**) (Figure 5). The last two had very extensive implementation areas that likely overlap in places and constitute the majority of the cells that have two interventions occurring over the 80-year model period (these land areas are equivalent to 13 percent of all intervention cells). This may represent an interaction that wasn't captured in this study. A number of scattered cells throughout the Central Valley and foothills likely are the combination of **avoided conversion** and another intervention in agricultural and rangeland systems, and as such, can both be considered additive and complementary.

ECONOMIC RESULTS

The economic costs and benefits of the intervention impacts that occurred after 2050 were not measured due economic uncertainty more than 30 years from today. Direct implementation costs to 2050 varied substantially across interventions with **reduced wildfire severity** and **woodland restoration** having the highest overall costs, each over $4 billion (B) under both climate futures (Tables 4 and 5). The opportunity cost of foregone agricultural land net returns through perpetuity due to **avoided conversion** activities through 2050 was over $15B in the "average" model and nearly $17B under the "hot-dry" future (Table S1 in the Appendix). Additional foregone urbanization land net returns in perpetuity due to avoided conversion activities through 2050 were $2B and $2.2B under the "average" and "hot-dry" futures, respectively. **Changes to forest management** resulted in an opportunity cost of reduced timber returns of $5.3B and $5.6B under "average" and "hot-dry" futures (See Tables 4 and 5 for a detailed accounting of all costs and benefits).

In terms of economic benefits, the benefits created by activities on the landscape through 2050 are captured by the social cost of carbon (SCC) and social cost of nitrogen (SCN) values were highest, with combined benefits of over $13B (hot-dry) and over $10B (average) by 2050 using the medium SCC and assuming 10 percent HSF (Tables 4 and 5). Using the high SCC values and assuming 30 percent HSF, the economic benefits were equal to over $17B (hot-dry) and $14B (average). Additional benefits from avoided flood damage to newly urbanized areas of over $160M and $288M under the "hot-dry" and "average" futures respectively were realized. Reducing the extent of high severity fire also resulted in an avoided cost of suppressing these fires of over $240M (average) and $57M (hot-dry) under the 30 percent HSF scenario. See Appendix for more details on methods and calculations.

FIGURE 6 Cost per Ton of CO_2, Total Implementation Area, and GHG Reduction Potential in 2050 for Activities with a Net Reduction



Note: Three interventions are not shown because they did not produce cumulative reductions by 2050 (reduced wildfire severity, agroforestry, and woodland restoration), meaning a cost per ton is unable to be calculated. Note: broken x-axis is used to aid visualization of all valid interventions. For changes to forest management, the net present value of managed forest land rents is used here. Data for this chart averages across climate models.

Changes to forest management on private forest land represents a cost-effective intervention with an "average" cost per metric ton of carbon dioxide stored of $22 for the two climate models (Figure 6). This cost is derived from the difference in "rent streams" through 2050 from forest land under the **control** and **changes to forest management** scenario, or essentially the amount of money that would need to be spent through 2050 to offset

TABLE 4 Direct Intervention Implementation and Opportunity Costs, and Select Economic Benefits in 2017 USD, 2020 - 2051. Hot-Dry Future.

	ECONOMIC COST (2017 MILLION USD)						ECONOMIC BENEFIT (2017 MILLION USD)					
	Implementation Costs		Opportunity Costs (Urban + Ag + Forestry)				Medium SCC		Social Cost of Nitrogen		Avoided Flood Damages	Avoided Fire Suppression
	2030	2050	2030		2050		2030	2050	2030	2050	2050	2050
			Land Value	Rents	Land Value	Rents						
Forest												
Post-Wildfire Reforestation	152	209	–	–	–	–	-87	242	–	–	–	–
Reduced Wildfire Severity (30% High Severity)	2,072	4,069	–	–	–	–	-2,268	-3,026	–	–	–	57
Reduced Wildfire Severity (10% High Severity)	2,072	4,069	–	–	–	–	-2,702	-3,861	–	–	–	80
Changes to Forest Management	–	–	5,812	4,095	5,681	3,932	2,051	3,679	–	–	–	–
Restoration												
Woodland Restoration	1,572	4,586	18	13	36	20	43	-29	–	–	–	–
Riparian Restoration	446	789	837	590	1,393	801	54	69	1,083	1,528	–	–
Agriculture												
Agroforestry	32	61	–	–	–	–	-33	-34	–	–	–	–
Cover Cropping	569	902	–	–	–	–	184	498	–	–	–	–
Conservation												
Avoided Conversion	–	–	11,046	7,775	19,112	11,013	1,411	2,930	5,679	7,477	162	–
Total (30% high severity fire)	4,843	10,616	17,713	12,473	26,222	15,766	1,355	4,329	6,762	9,005	162	57
Total (10% high severity fire)	4,843	10,616	17,713	12,473	26,222	15,766	921	3,494	6,762	9,005	162	80

Note: Negative economic benefits indicate a cost. SCC is social cost of carbon.

the reduction in revenue associated with adopting a more selection-focused harvest regime. The intervention area needed to meet the estimated reduction is significant, totaling 2.9 million acres. **Avoided conversion** represents the reduction of urbanization and agricultural expansion on natural lands across 4.1 million acres and has a higher cost per ton due to the foregone increase in the perpetual stream of agricultural and urban net returns. **Riparian restoration** is costly without reliably yielding reductions across future climate scenarios. Both **cover cropping** and **post-wildfire reforestation** are low-cost interventions that yield moderate but reliable GHG reductions.

While this report doesn't capture all of the economic benefits associated with implementing these conservation and restoration activities, it is nonetheless helpful to characterize the initial economic cost and benefit to provide policymakers with a more comprehensive

TABLE 5 Direct Intervention Implementation and Opportunity Costs, and Select Economic Benefits in 2017 USD, 2020 - 2051 Under an "Average" Climate Future.

	ECONOMIC COST (2017 MILLION USD)						ECONOMIC BENEFIT (2017 MILLION USD)					
	Implementation Costs		Opportunity Costs (Urban + Ag + Forestry)				Medium SCC		Social Cost of Nitrogen		Avoided Flood Damages	Avoided Fire Suppression
	2030	2050	2030		2050		2030	2050	2030	2050	2050	2050
			Land Value	Rents	Land Value	Rents						
Forest												
Post-Wildfire Reforestation	161	231	–	–	–	–	-87	185	–	–	–	–
Reduced Wildfire Severity (30% High Severity)	2,090	4,081	–	–	–	–	-1,747	-1,777	–	–	–	241
Reduced Wildfire Severity (10% High Severity)	2,090	4,081	–	–	–	–	-2,236	-2,837	–	–	–	153
Changes to Forest Management	–	–	4,645	3,273	5,307	3,642	2,127	3,503	–	–	–	–
Restoration												
Woodland Restoration	1,577	4,501	19	13	36	20	-141	-332	–	–	–	–
Riparian Restoration	359	684	598	422	1,311	707	-336	-184	822	1,188	–	–
Agriculture												
Agroforestry	29	55	–	–	–	–	-11	-47	–	–	–	–
Cover Cropping	594	935	–	–	–	–	141	491	–	–	–	–
Conservation												
Avoided Conversion	–	–	11,046	7,775	19,112	11,013	803	2,166	4,278	5,827	288	–
Total (30% high severity fire)	4,810	10,487	14,577	10,264	23,857	14,080	749	4,005	5,100	7,015	288	241
Total (10% high severity fire)	4,810	10,487	14,577	10,264	23,857	14,080	260	2,945	5,100	7,015	288	153

Note: Negative economic benefits indicate a cost. SCC is social cost of carbon

picture of overall impacts. Some interventions have a relatively favorable ratio of costs to benefits including **cover cropping, changes to forest management,** reforestation (Table 6). Other interventions such as **riparian** and **woodland restoration** are costly and have negligible carbon sequestration benefits by 2050.

TABLE 6 Total Economic Cost in Comparison to Net Benefits of Social Cost of Carbon Under Low, Medium, and High Estimates and Other Economic Benefits in 2050

	Total Economic Cost (2017 Million USD)		Social Cost of Carbon Economic Benefit (2017 Million USD)						Other Economic Benefits (2017 Million USD)					
			Low		Medium		High		Social Cost of Nitrogen		Avoided Flood Damages		Avoided Fire Suppression	
	Avg	Hot Dry	Avg	Hot Dry	Avg	Hot Dry	Avg	Hot Dry	Avg	Hot Dry	Avg	Hot Dry	Avg	Hot Dry
Forest														
Post-Wildfire Reforestation	231	209	60	78	185	242	298	391	–	–	–	–	–	–
Reduced Wildfire Severity (30% High Severity)	4,081	4,069	-573	-976	-1,777	-3,026	-2,866	-4,881	–	–	–	–	241	57
Reduced Wildfire Severity (10% High Severity)	4,081	4,069	-915	-1,245	-2,837	-3,861	-4,576	-6,228	–	–	–	–	153	80
Changes to Forest Management[†]	3,642	3,932	1,130	1,187	3,503	3,679	5,650	5,934	–	–	–	–	–	–
Restoration														
Woodland Restoration	4,537	4,621	-107	-9	-332	-29	-536	-47	–	–	–	–	–	–
Riparian Restoration	1,995	2,181	-59	22	-184	69	-296	111	1,188	1,528			–	–
Agriculture														
Agroforestry	55	61	-15	-11	-47	-34	-75	-54	–	–	–	–	–	–
Cover Cropping	935	902	158	161	491	498	792	804	–	–	–	–	–	–
Conservation														
Avoided Conversion	17,203	19,112	699	945	2,166	2,930	3,493	4,725	5,827	7,477	288	162	–	–
Total (30% high severity fire)	32,679	35,087	1,293	1,397	4,005	4,329	6,460	6,983	7,015	9,005	288	162	241	57
Total (10% high severity fire)	32,679	35,087	951	1,128	2,945	3,494	4,750	5,636	7,015	9,005	288	162	153	80

[†] The opportunity cost for changes to forest management uses the NPV of forest land rents.

Note: Negative economic benefits indicate a cost. SCC is social cost of carbon.

V.

Land Management Interventions: Methods & Results

1. Forest | Reduced Wildfire Severity

DEFINITION

A variety of forest management practices are used to reduce fuel loading and overcrowding in forests. This may involve thinning forest understories by removing underbrush and small-to-medium diameter trees (i.e., "thinning-from-below"), or thinning-from-below later followed by a prescribed burn to remove fallen dead wood and litter. This intervention is meant to address conifer-dominated forests and is restricted to ecoregions that have a high proportion of conifer-dominated forest cover (Sierra Nevada, Northern Basin, Klamath, Eastern Cascades, Coast Range, Central Basin, Cascades).

RATE

308,750 acres per year (ac/year) thinning, 123,500 ac/year prescribed burn (just on public land)

METHODS

Forest cells that received a thinning treatment (removal of small-to-medium diameter trees) were then set to zero probability of high severity fire for 15 years. Within 5 years 50 percent of those cells on public lands that receive thinning received a follow-on prescribed burn treatment. This further extended the zero probability of high severity fire an additional 20 years, after which the forest cell will return to the pre-treatment probability of high severity fire. This scenario was run under two different assumptions about the proportion of high severity fire that occurs during a wildfire in California: one that assumed 10 percent high severity fire and one that assumed 30 percent high severity fire. This was the only change made in the model run, with all other parameters staying the same. See Supplementary Methods in the Appendix for more detail.

Treatment locations were determined by a custom map that incorporates several legal and practical considerations. Suitable areas included lands outside of protected areas that prohibit mechanical treatment (Gap status 1 and 2; Protected Areas Data),[23] within lands that are considered "suitable" for timber harvest,[24] are priorities for fuel treatment by CalFire,[25] or have a >0.01 annual probability of future wildfire as predicted for the specific climate model.[26] The suitable areas for this intervention are selected based on the union of these factors, not solely lands that meet all criteria.

The overall rate of implementation was partitioned into 247,000 acres per year (ac/yr) thinning and 123,500 ac/yr prescribed burn on suitable public lands; 61,750 ac/yr thinning and no prescribed burning on private lands. The annual rates on public lands were reflective of the current United States Forest Service target for thinning, and the private land annual rate matches the CalFire Forest Carbon Plan.[27] A portion (34%) of the biomass removed from thinning was assumed to be converted to long-term hardwood products, which was then included in the calculation of net GHG reduction potential.[28]

RESULTS

Implementing thinning and prescribed burning interventions reduced flammable fuels by removing extra biomass that can create conditions for high severity wildfire. In the first several decades, this resulted in a net emission to the atmosphere even when accounting for avoided fire emissions and assuming 34 percent of the harvested wood products are stored in long-term pools. It is important to consider that if a larger share of the harvested wood products were used in long-term products or as an energy source to offset fossil fuel emissions, the net benefit would have increased substantially. The magnitude of emissions reduction grew over time to where this intervention provided a substantial net benefit over the intervention period of 2020-2100. This is especially important because by mid-century, this intervention was still producing net emissions due to the removal of forest biomass. Under the 30 percent high severity fire assumption, the intervention started to avoid wildfire emissions to a level where—in both climate futures—the intervention switched from net emissions to net reductions during the decade between 2065 and 2075 (Figure 7D). The cumulative reductions from 2050-2100 from the "hot-dry" future exceeded the "average" climate future, 254 Tg CO_2 vs. 228 Tg CO_2 (Table 3), resulting in the flip from an emissions source to a GHG reduction.

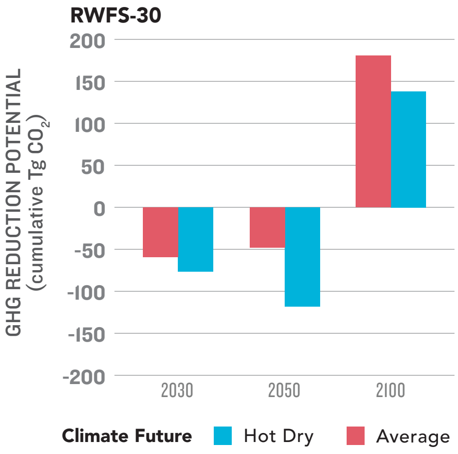
In contrast, the model that assumed 10 percent high severity fire was net neutral by the end of the century in the "hot-dry" climate future but had a small net reduction (21 Tg CO_2) under the "average" climate future (Table 3). However, the reductions under the 10 percent high severity fire assumption were not outside the uncertainty bounds of the control scenario, meaning the effectiveness of the intervention was not certain when accounting for variability in the system.

The geographic pattern of reductions under the 30 percent scenario (Figure 7B) is highly variable, with no detectable pattern other than a slight increase observable in the northwestern part of the state.

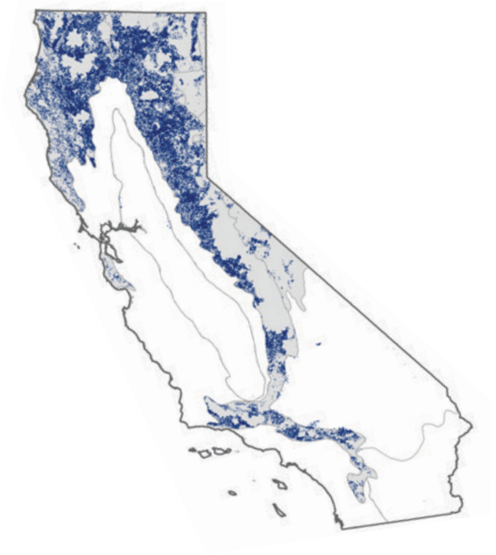
The average cost to implement reduced wildfire severity interventions over the period 2020-2050 totaled $4.1 billion. Savings from the reductions in lower wildfire suppression costs totaled $153 million under the 10 percent severity assumption and $241 million under the 30 percent severity assumption. The increased economic value of converting the harvested wood to useful products or fuels was not calculated.

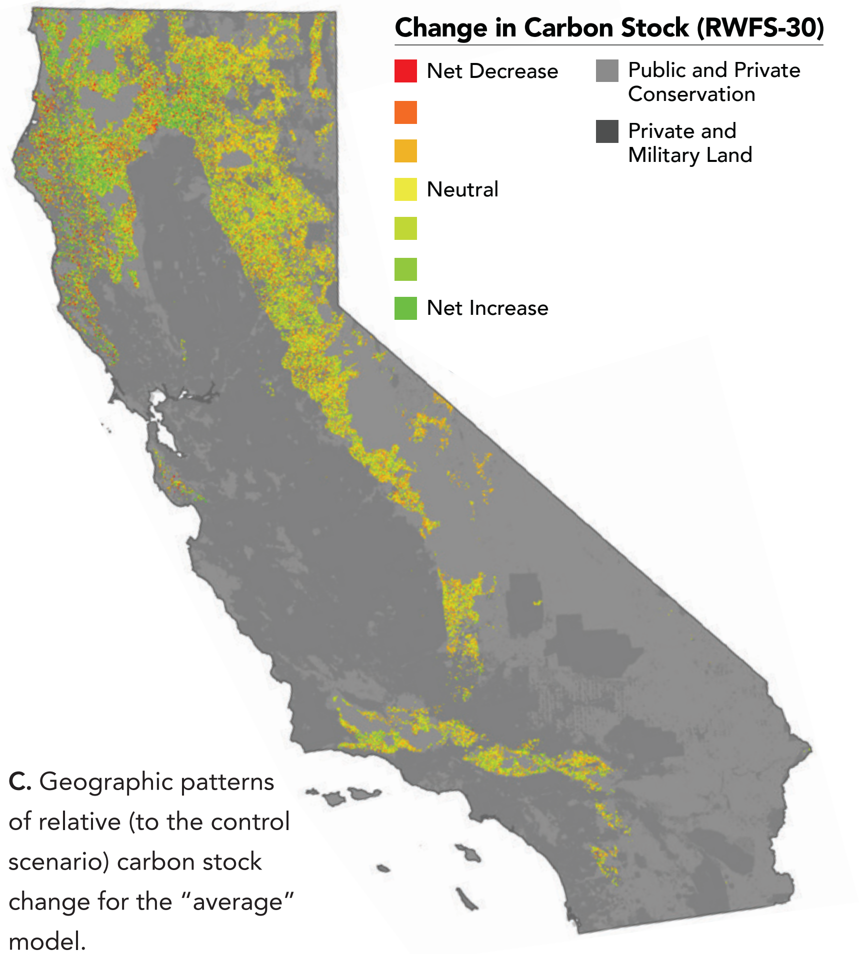
FIGURE 7 Overall Ecosystem Carbon Impact of Reduced Wildfire Severity (RWFS-30) Intervention, Assuming 30% High Severity Fire

A. Total net change in ecosystem and harvested wood products carbon storage at 2030, 2050, and 2100. This intervention yielded emissions reduction by the end of the century, but results in net emissions by 2030 and 2050.



B. Cells that experienced RWFS-30 intervention activity over the 80-year period for the "average" model.





C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by RWFS-30 intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.

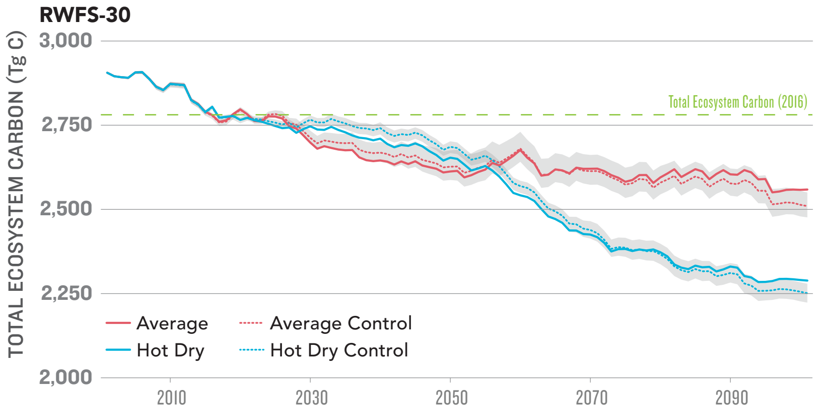
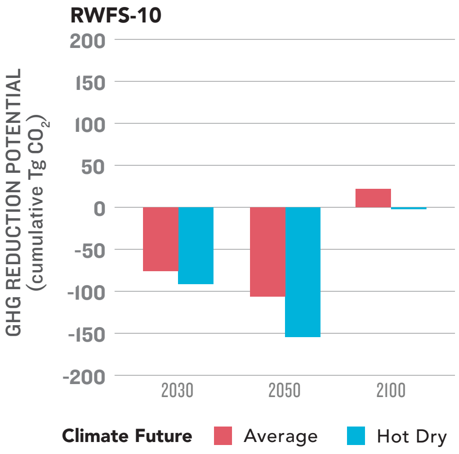
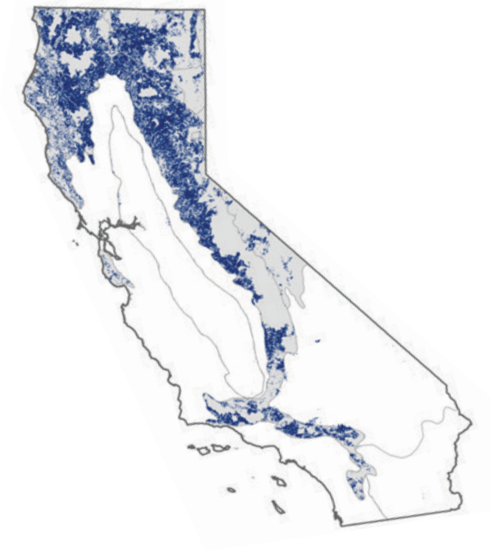


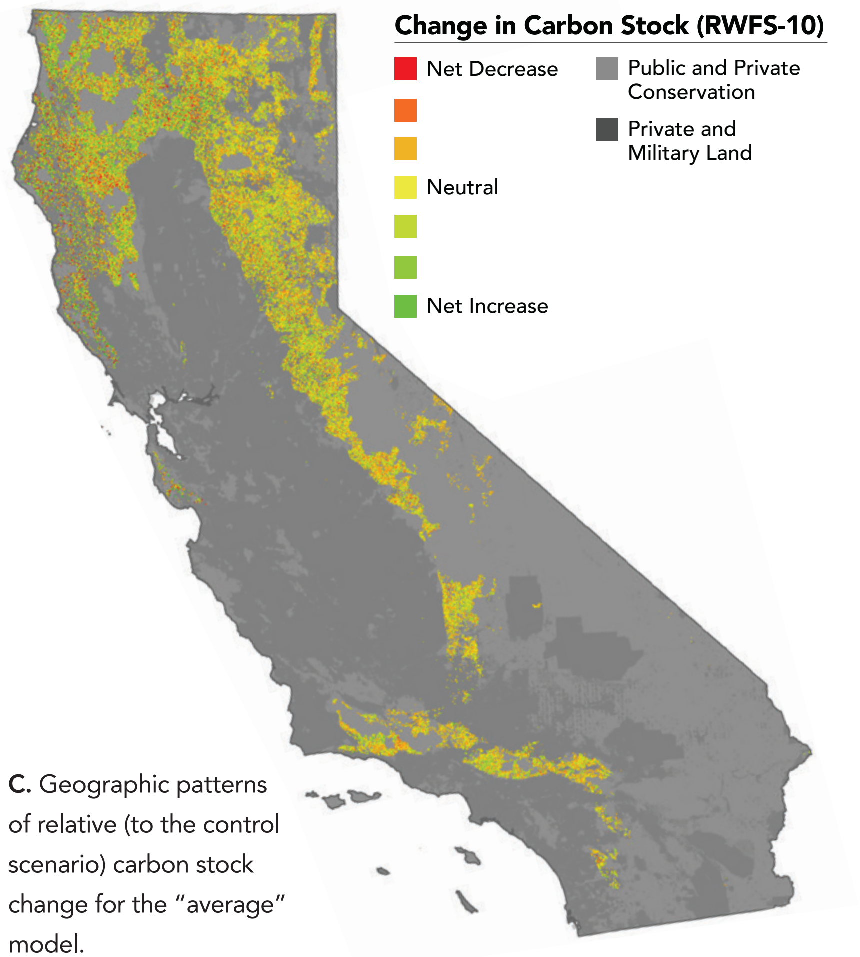
FIGURE 8 Overall Ecosystem Carbon Impact of Reduced Wildfire Severity (RWFS-10) Intervention, Assuming 10% High Severity Fire

A. Total net change in ecosystem and harvested wood products carbon storage at 2030, 2050, and 2100. This intervention is basically carbon neutral by the end of the century, but results in net emissions by 2030 and 2050.



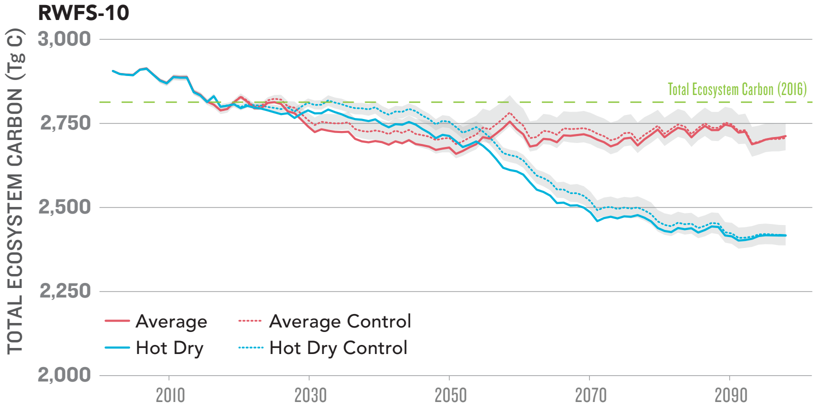
B. Cells that experienced RWFS-10 intervention activity over the 80-year period for the "average" model.





C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by RWFS-10 intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.



2. Forest | Post-Wildfire Reforestation

DEFINITION

This includes active replanting of trees in areas that burned under high severity fire.

METHODS

After a high severity wildfire event[26], the forest cell was moved into a post-fire state where 54 percent of the time, it recovered as forest and 46 percent of the time, it moved into an alternative state as shrubland, based on research from other western forests.[29] All cells in the post-fire state classified as forest were eligible for the reforestation intervention, except those that fall within areas with extreme "climate change exposure". These areas were identified as being greater than 95 percent unlikely to support the current vegetation type under future climate regimes and reforesting these areas was assumed to be unproductive.[30] Additionally, cells within protected areas were excluded from reforestation. The annual reforestation rate was partitioned among a subset of ecoregions based on the proportion of total forest area (Sierra Nevada, Northern Basin, Klamath, Eastern Cascades, Coast Range, Central Basin, Cascades). See Supplementary Methods in the Appendix for more detail.

RATE

48,165 ac/year on public or private land.

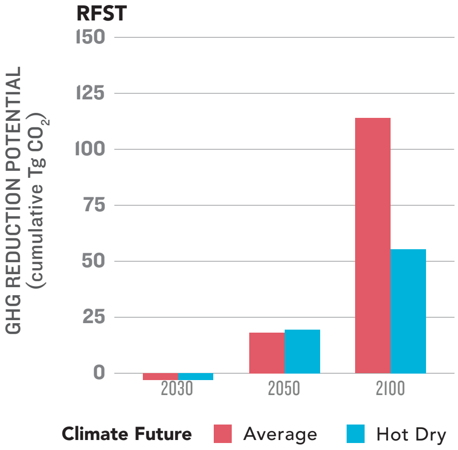
RESULTS

Reforestation was slow to yield net carbon gains, but by 2100 it ranked fourth among all interventions under the "average" climate future (Figure 3). Reductions under the "average" climate future were more than twice as large as under the "hot-dry" future (Figure 9A). This likely resulted from larger negative climate effects on forest growth and soil respiration, and the larger amount of wildfire and drought-induced forest mortality, under the "hot-dry" future. By 2100, approximately 1.5 million acres of forest land burned by high-severity fire is reforested, but with mixed effects on relative carbon stock change geographically (Figure 9B). This was the result of a "mismatch" between where wildfire occurred in the control scenario of the model compared to where it occurred in the reforestation intervention scenario. To account for this in the non-spatial results, the relative carbon stock change was summed across all forested areas in the ecoregions in which the intervention occurred.

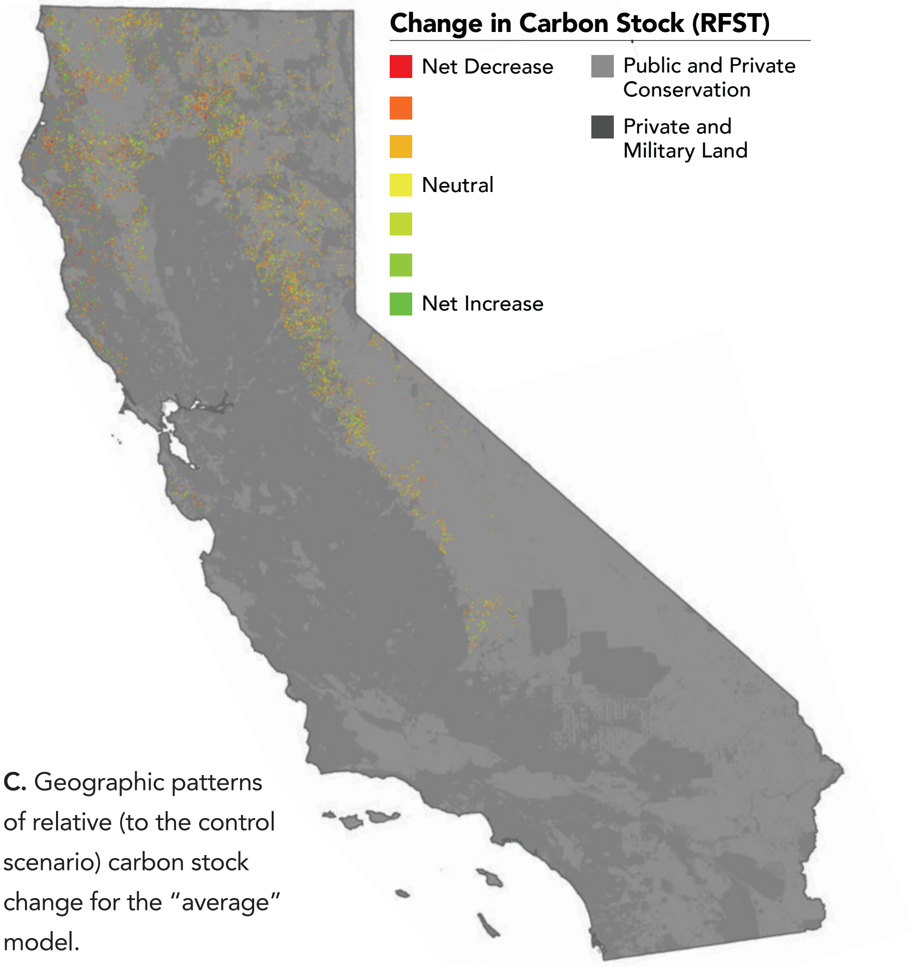
By 2050, the total cost to reforest 593,000 acres was on average \$220 million and yields 18.8 Tg of CO_2 reductions. The resulting cost of reforestation was on average \$12 per ton of CO_2 reduced, one of the lowest cost interventions assessed here. In addition, the economic benefits from accounting for the social cost of carbon range from \$68.9 million to \$245.6 million.

FIGURE 9 Overall Ecosystem Carbon Impact of Reforestation (RFST) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100. The "average" model results in twice the amount of reductions compared to the "hot-dry" future by the end of the century.

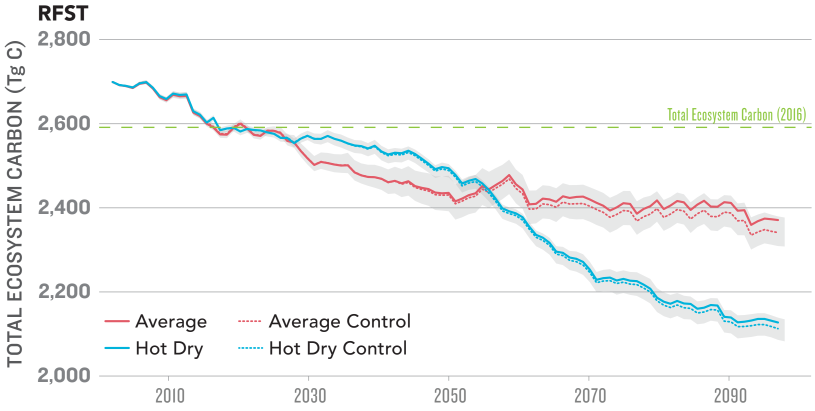


B. Cells that experienced RFST intervention activity over the 80-year period for the "average" model.



C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by reforestation intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.



3. Forest | Changes to Forest Management

DEFINITION

This intervention shifts current forest management practices to increase carbon stocks and reduce harvest volumes. This is achieved by both increasing the rotation age of forest clearcuts and shifting harvest practices away from clearcutting and other even-aged harvest toward selection harvest practices. In this report, the term "clearcut" is used to refer to many types of various canopy-removing even-aged harvest.

RATE

98,800 ac/year for 30 years (until 2050).

METHODS

Only private forest lands were eligible for changes to forest management (CFM). Fifty percent of the overall annual harvest area was automatically allocated to lands that were enrolled in the CFM class. Forest cells that were selected for CFM will have a minimum age of clearcut harvest (extended rotation length) increased by 50% above the control minimum age. Overall harvest in the CFM class will be shifted away from a current 60:40 ratio of clearcut to selection harvest, to a 30:70 clearcut:selection ratio. Enrollment of new forest cells in this intervention ended in 2050, but lands already enrolled in the CFM regime stayed enrolled until the end of the century. See Supplementary Methods in the Appendix for more detail.

This intervention was restricted to any private forest lands classified as suitable for timber harvest[24] in ecoregions that have a high proportion of forest cover (Sierra Nevada, Northern Basin, Klamath, Eastern Cascades, Coast Range, Central Basin, Cascades). In calculating the reductions, 34 percent of the carbon that ended up as harvested wood products[28] was assumed to be stored in a long-term pool (not emitted) through 2100 in both the control and the intervention scenarios.

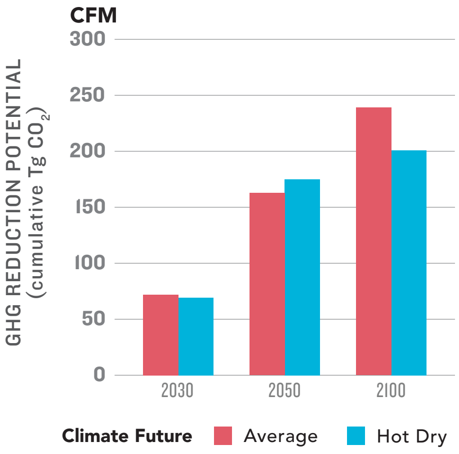
RESULTS

Changes to forest management resulted in one of the largest reduction potentials of all interventions assessed, ranking first by 2050 and dropping down to second by 2100. There were differences between climate futures in the reduction potential, but not as drastic as in other interventions (Figure 10A). This intervention yielded large and consistent net reductions over the entire study period, even after enrollment of lands ended in 2050. Over time the magnitude of the reductions increased, clearly exceeding the uncertainty of the control scenario. By 2050, 2.9 million acres were enrolled in changes to forest management practices, meaning these practices would continue indefinitely on those lands. The effect is two-fold: first, carbon stocks increase on those lands as more selection harvest was used in place of clearcut and the rotation age is higher on lands where clearcut harvest was still used. Second, because half of the annual harvest was allocated to lands in the changes to forest management program, there was less overall clearcut harvest that occurred statewide in comparison to the control scenario.

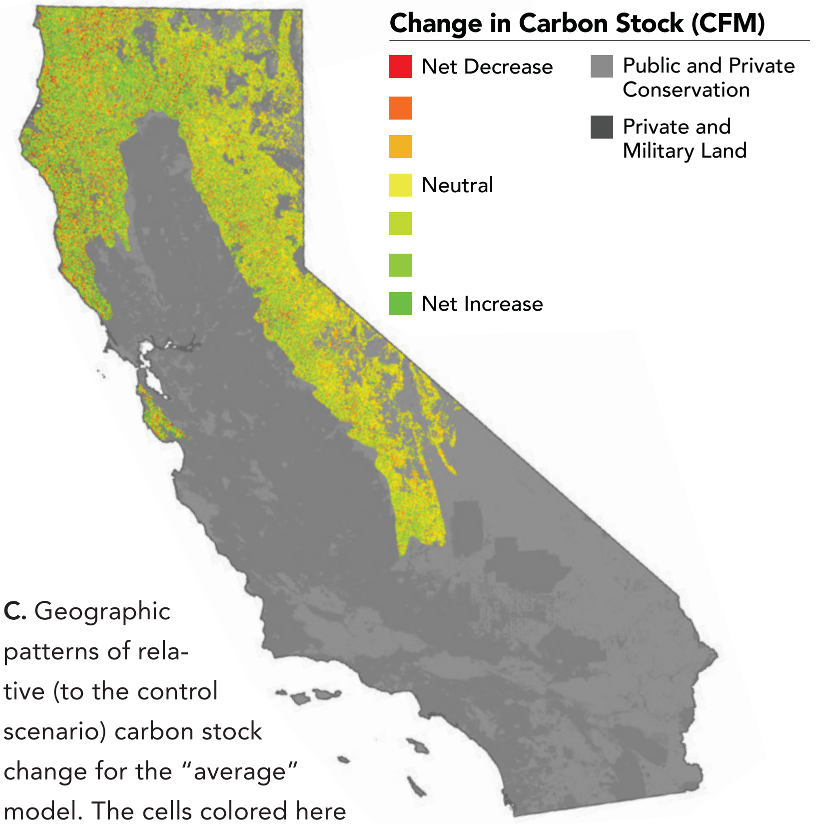
By 2050 the total cost (opportunity cost of reduced timber land rents) of this intervention averaged $3.75 billion, netting an average of 168.8 Tg of CO_2 reductions. This made changes to forest management the most impactful intervention, with a cost of $22 per ton of CO_2 reduced. In addition, the economic benefits from accounting for the social cost of carbon ranged from $1.2 to $5.9 billion.

FIGURE 10 Overall Ecosystem Carbon Impact of Changes to Forest Management (CFM) Intervention

A. Total net change in ecosystem and harvested wood products carbon storage at 2030, 2050, and 2100. The magnitude of reduction benefits grows over time even though the land enrolled in this intervention stops by 2050.

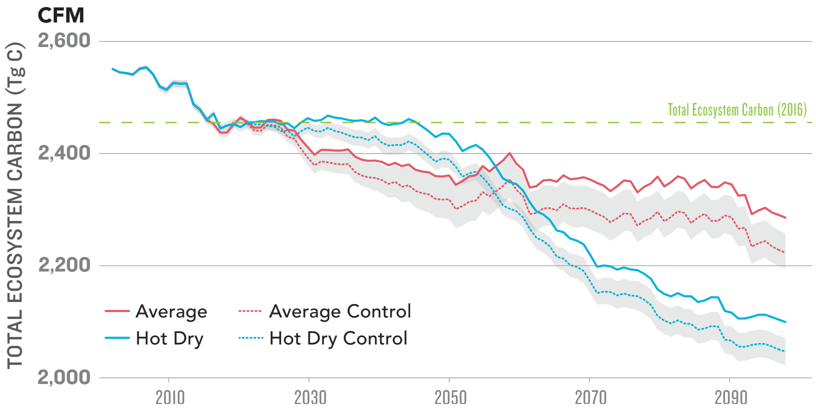


B. Cells that experienced CFM intervention activity over the 80-year period for the "average" model.



C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model. The cells colored here are the geographic scale for which net reductions are calculated because the CFM scenario influenced the harvest regime beyond just the cells enrolled.

D. Total ecosystem carbon in ecoregions and state classes affected by changes to forest management intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line. This intervention provides reductions that are clearly outside the uncertainty range in the control runs.



4. Restoration | Woodland Restoration

DEFINITION

Planting native oak species to 30 percent density in areas where they have been removed or lost due to wildfire.

RATE

12,597 ac/year

METHODS

Only grassland cells in the Oak Woodland and Chaparral ecoregion were eligible for this restoration intervention. When a cell was selected for restoration the state class was changed to forest. An implementation area mask was created so that only cells falling in areas that were considered historical oak woodland are eligible for restoration.[31] The planting density (30%) is intended to still permit grazing on these woodlands. See Supplementary Methods in the Appendix for more detail.

RESULTS

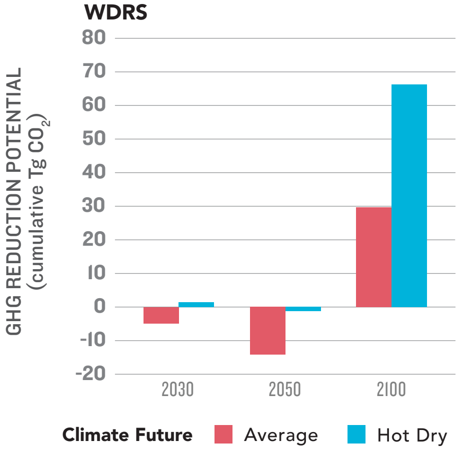
Like **agroforestry, woodland restoration** only resulted in net reductions relative to control by the last half of the century (Figure 11A) and only in the last 20 years of the century did it depart from the uncertainty bounds of the control (Figure 11D). Interestingly, the end of century reductions were higher in the "hot-dry" scenario than they were in the "average" scenario (twice as much) (Figure 11A). This was counter to the results for all other interventions, and indicated that some effect on forest in the Central Valley and Oak Woodlands ecoregions was more pronounced for the "hot-dry" than it was for the "average" climate future. Or, conversely, some disturbances such as a fire or mortality may have impacted the restored forest in the "average" future and not the "hot-dry" future.

Areas that were restored had a larger increase in sequestration in the northern half of the state than in the southern half (based on the brighter green cells in Figure 11C). This may indicate that there were more favorable growing conditions in the north either in terms of climatic factors or in terms of lack of disturbance. **Woodland restoration** did yield 66 Tg CO_2 reduction potential under the "hot-dry" model and 29 Tg CO_2 under the "average" model by the end of the century and so represents a potentially beneficial activity for long-term climate mitigation, but is expensive to implement. Yet, by 2050 the intervention did not achieve a net benefit, with the direct implementation costs averaging $4.5 billion by 2050 under both climate futures, using the cost of nearly $15,000 per acre (Table 4, 5, Appendix Table S1).

Further research is needed to understand the mechanisms by which this intervention results in a net source of emissions relative to the control scenario. Like **riparian restoration** and **agroforestry** it may be driven by a decline in soil carbon, relative to the control. Shifting from a grassland to a young forest in the model means carbon inputs to soil have a relative decrease for a period of time, leading to less soil carbon under the intervention in early years. As such, specific parameters for interventions that better reflect the site-specific impacts of planting trees in grasslands should be evaluated as a model refinement.

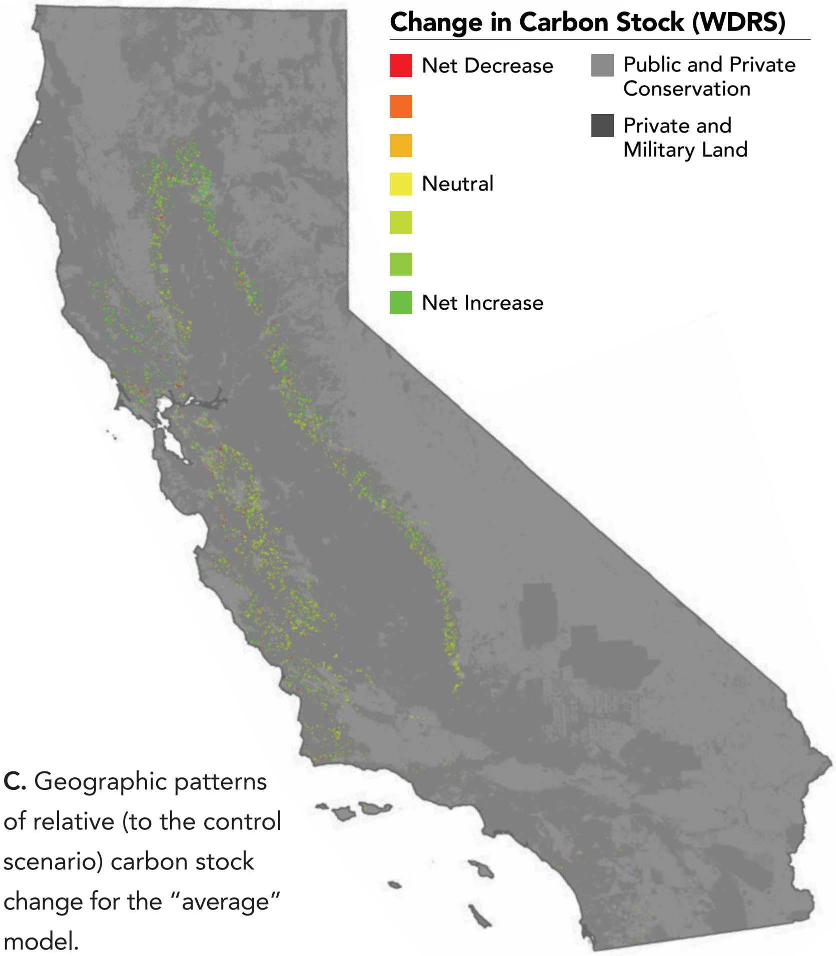
FIGURE 11 Overall Ecosystem Carbon Impact of the Woodland Restoration (WDRS) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100.

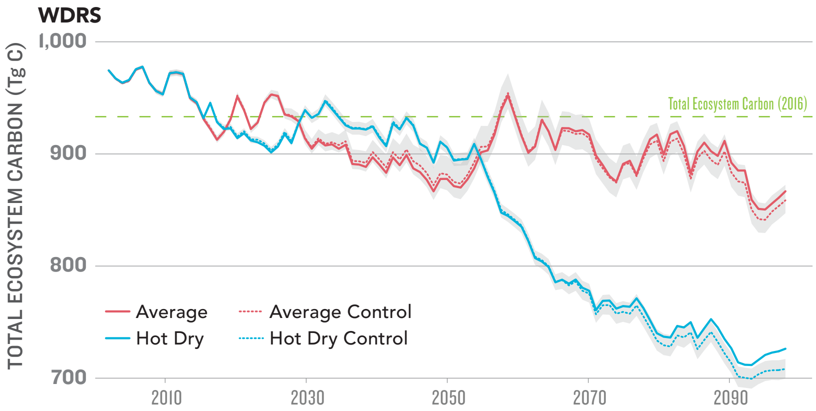


B. Cells that experienced WDRS intervention activity over the 80-year period for the "average" model.

C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.



D. Total ecosystem carbon in ecoregions and state classes affected by changes to woodland restoration intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.



5. Restoration | Riparian Restoration

DEFINITION

Establishing forest cover along the banks of streams and rivers in agricultural and grassland regions.

RATE

4,940 ac/year

METHODS

Riparian restoration was only permitted on agriculture (annual and perennial) and grassland cells that are directly adjacent to major waterways[32], excluding canals. Existing riparian areas were excluded from the potential cells for this intervention.[33] The target rate was approximately 25 percent higher than the annual rate calculated from a study that assessed the total potential restorable riparian area in just the Central Valley.[34] See Supplementary Methods in the Appendix for more detail.

RESULTS

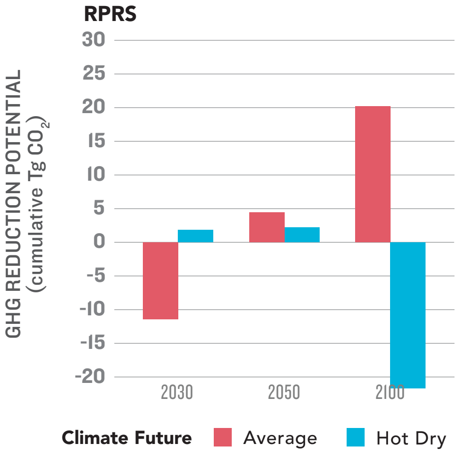
This intervention showed striking differences in reduction potential depending on the climate future. Under the "average" climate future, by 2030 **riparian restoration** resulted in a large (11 Tg) emission of CO_2 relative to the control (Figure 12A). By 2100 this was completely reversed and a net emissions reduction of 20 Tg was achieved. On the other hand, under the "hot-dry" future nearly the opposite occurred, with a small net reduction by 2030 and then a steady decline to a net emission of 22 Tg by 2100.

The relatively poor performance of this intervention is likely explained by two factors. First, **riparian restoration** had the lowest implementation rate of all interventions assessed here, a result of the constrained land area on which it can be implemented. Second, as with **woodland restoration,** there is relatively less soil carbon input to soil in the model for young forests than for grassland or agriculture land use classes. This lead to a soil carbon deficit that may have reduced the effectiveness of the intervention. Further research is needed to assess the performance of this intervention in the model.

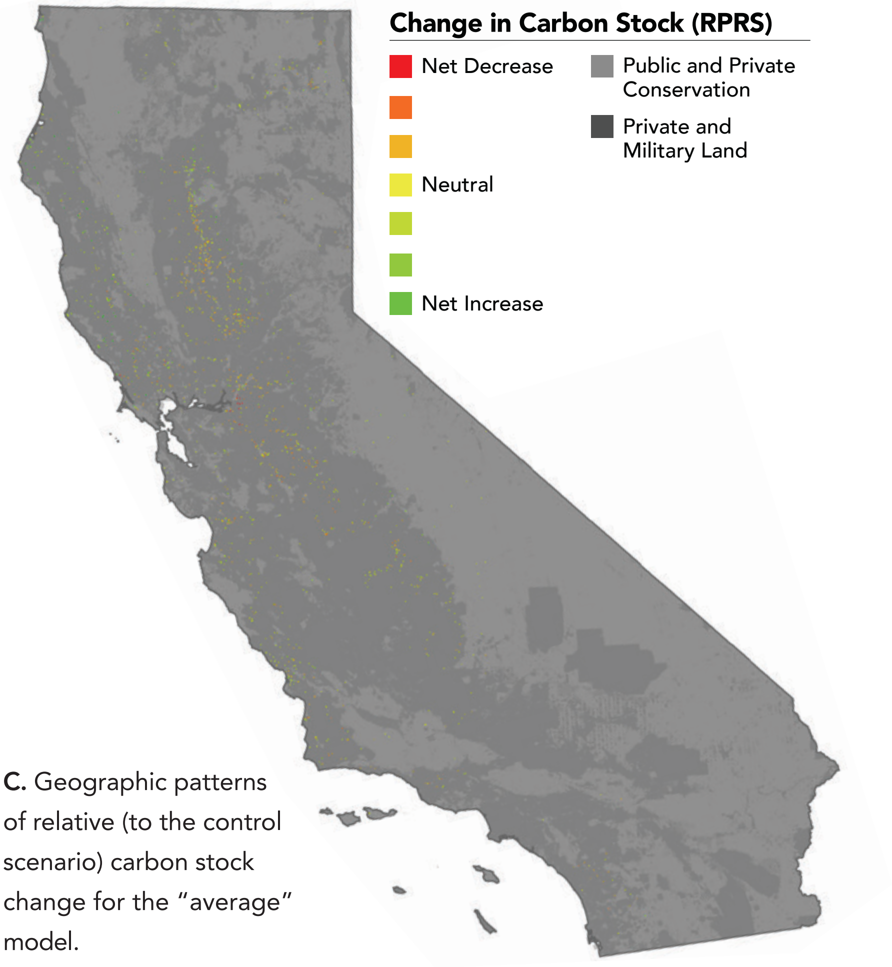
Riparian restoration had a total average cost of $2.1 billion by 2050, with the majority of the costs (65%) due to loss of the agricultural revenue of the lands that are being restored to riparian corridors. This opportunity cost ($1.352 billion) was completely offset by the monetary benefit associated with the avoided cost of nitrogen ($1.358 billion).

FIGURE 12 Overall Ecosystem Carbon Impact of the Riparian Restoration (RPRS) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100.

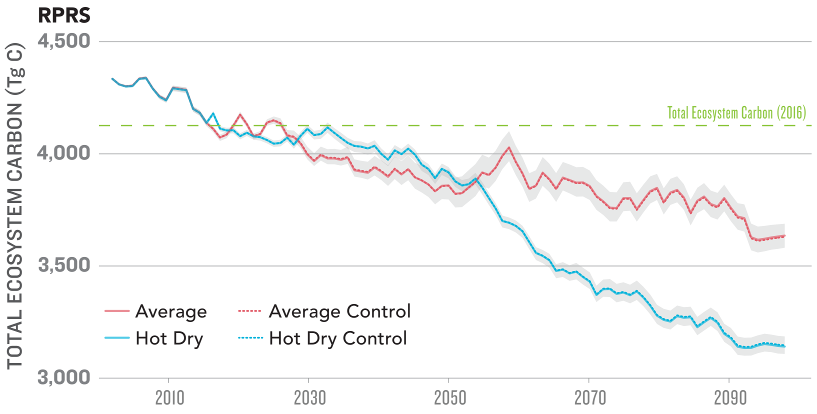


B. Cells that experienced RPRS intervention activity over the 80-year period for the "average" model.



C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by the riparian restoration intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.



Note: Control line is masked by the intervention line.

6. Agriculture | Agroforestry

DEFINITION

The intervention models the establishment of trees along agricultural field boundaries to act as a windbreak. This represents a substantial increase in carbon on landscapes that currently do not hold large quantities of woody above and belowground carbon.

RATE

7,904 ac/year

METHODS

Both annual and perennial agriculture cells were eligible for **agroforestry** establishment. The state class was changed from agriculture to forest on cells selected for this intervention. This intervention only occurs in the Central Valley ecoregion—thereby limiting the growth rate and carbon flows to the parameters specific to the Central valley ecoregion. These plantings were assumed to occur at the margins of agricultural fields and other non-productive areas, resulting in no loss to agricultural productivity. It was calculated that 7 percent of the area of agricultural lands could be planted with windbreaks. This intervention aimed to plant windbreaks on 80 percent of all potential area by 2100. See Supplementary Methods in the Appendix for more detail.

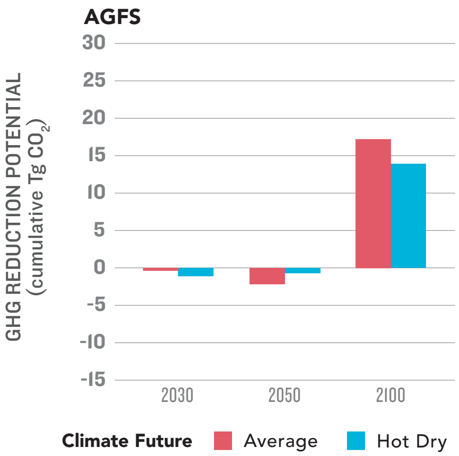
RESULTS

Agroforestry took a while to show net carbon benefits, but by the end of the century was able to sequester between 14 and 17 Tg of CO_2. In earlier years, this intervention swung between having no impact (net neutral) to a small negative impact (emissions source) (Figure 13A). The increased carbon sequestration from this intervention did not have a major effect on the overall trend of Central Valley lands that received the **agroforestry** intervention (Figure 13D). As with woodland and **riparian restoration,** a combination of low implementation rates and low soil carbon inputs of young forests relative to grassland and agriculture lands led to a lag in the emissions reduction potential.

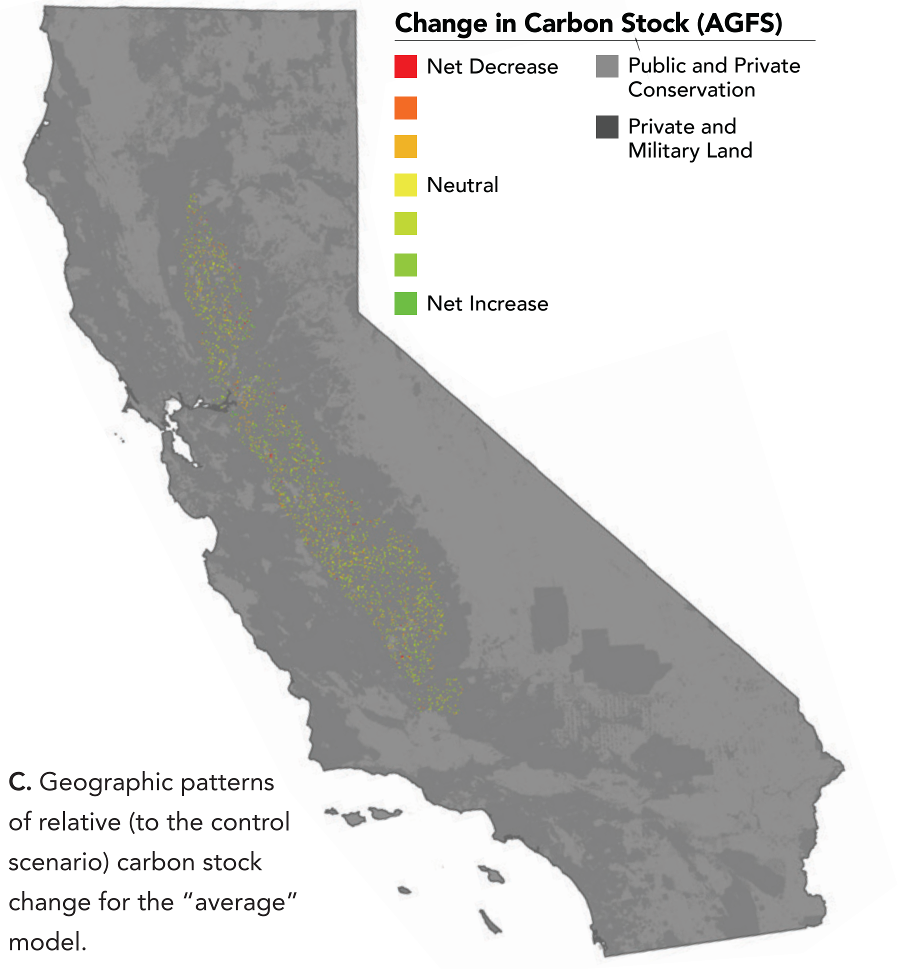
By 2050, **agroforestry** was expected to cost on average $58 million, by far the lowest total cost intervention assessed. However, by 2050 the net carbon benefit was essentially neutral or negative depending on the climate future (Figure 13A).

FIGURE 13 Overall Ecosystem Carbon Impact of the Agroforestry (AGFS) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100.

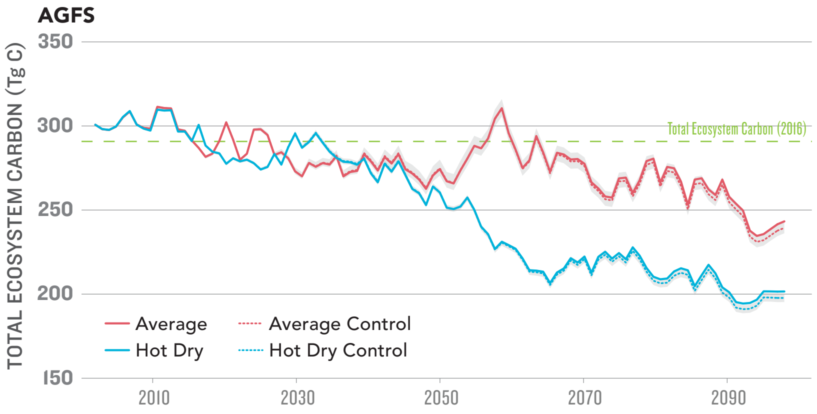


B. Cells that experienced AGFS intervention activity over the 80-year period for the "average" model.



C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by agroforestry intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line.



7. Agriculture | Cover Cropping

DEFINITION

This intervention models a rotation of non-cash crops (often planted during winter months) when an agricultural field would normally lay bare. Prior to cash crop planting the cover crop is plowed under, increasing the amount of organic material incorporated into the soil. Soil carbon is increased through the breakdown of organic material (both roots and above ground components of the plant) after incorporation into the soil. The contribution of the cover crop organic material can substantially increase inputs to the soil carbon pool.

RATE

56,563 ac/year.

METHODS

Annual agriculture cells anywhere in the state were eligible for this intervention. The intervention simulated a scenario where cover crops were grown for 4 months of the year (during winter) and 100 percent of the cover crop live carbon was moved to the litter pool. The result was an increase in soil carbon compared to non-cover crop annual agriculture cells. The rate was 200 percent of the current rate of cover crop adoption in California (NRCS database).[35] See Supplementary Methods in the Appendix for more detail.

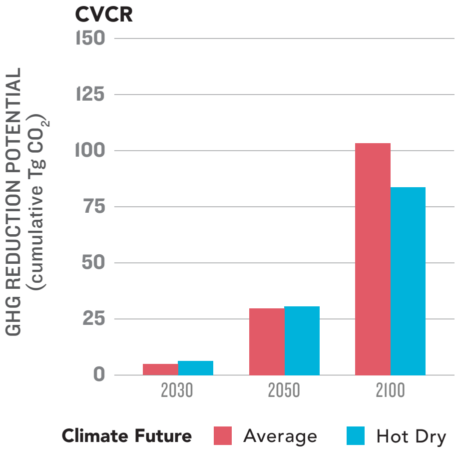
RESULTS

Cover cropping led to large and consistent reductions over time, on par with the magnitude of reductions from **post-wildfire reforestation.** Future climate conditions did not appear to have a major impact on the reduction potential of **cover cropping,** however end of century reduction potential was 18 percent lower under a "hot-dry" climate future (Figure 14A). The positive effects of building soil carbon through the use of cover crops did not vary widely geographically (Figure 14C). Although the overall amount of carbon stored in annual crop systems across California was projected to steadily decline (Figure 14D) throughout the remainder of the 21st century, the addition of cover crops as a management practice can at least help buffer some of this decline.

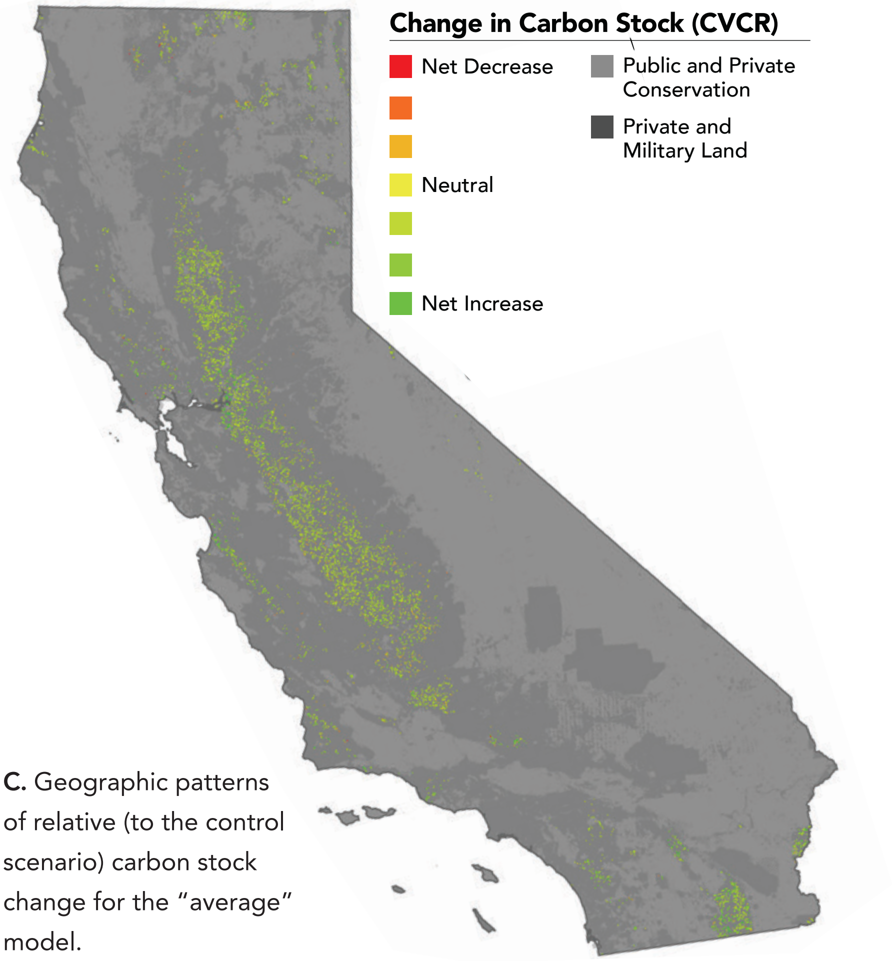
The total cost to implement **cover cropping** at this rate was on average $918.5 million by 2050, while absorbing 30 Tg of CO_2. This puts **cover cropping** at an average of $22 per ton of CO_2 reduced. The economic benefits calculated from the social cost of carbon ranged from $160 million to $636 million, potentially offsetting a large portion of the cost of implementing **cover cropping** at these rates.

FIGURE 14 Overall Ecosystem Carbon Impact of the Cover Crop (CVCR) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100.

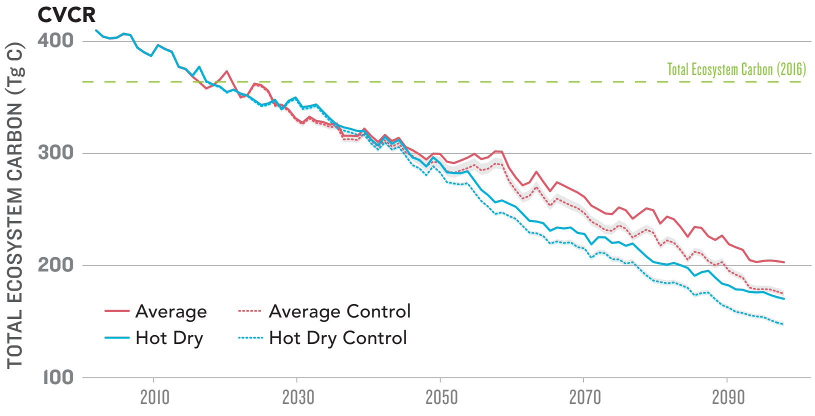


B. Cells that experienced CVCR intervention activity over the 80-year period for the "average" model.



C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by cover cropping intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line. This intervention provides reductions that are clearly outside the uncertainty range in the control runs.



8. Conservation | Avoided Conversion

DEFINITION

Reduced rates of natural land conversion to urban or agricultural land use.

RATE

75 percent reduction in urbanization, 55 percent reduction in agricultural expansion

METHODS

Following the methods of a recent paper[16], a low population growth scenario was used to set the annual urban growth rate at the county level. This resulted in an average urbanization reduction of 75 percent from 2020-2100. To reduce agricultural expansion, an annual conversion rate was sampled from a historical period with relatively low annual ag expansion (1993-1996), which resulted in a 55 percent reduction in agricultural expansion compared to sampling from the full historical period (1993-2012).

RESULTS

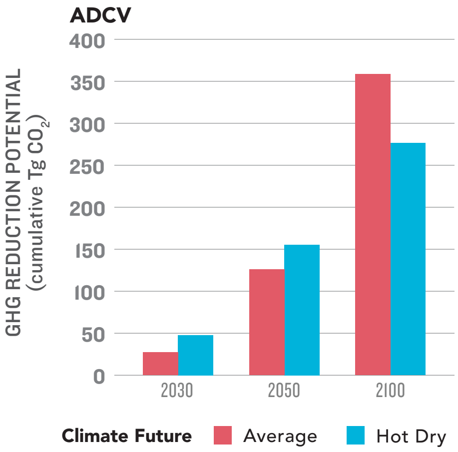
Avoided conversion resulted in consistent reductions that eventually became the largest contributor of reductions by the end of the century (Figure 3, Figure 15A). The combination of reduced emissions from reduced rates of urbanization and agricultural expansion yielded over 125 Tg CO_2 by 2050 for both climate models. Because **avoided conversion** immediately results in avoided emissions by definition, it is an example of a pathway that should be considered for immediate implementation.

The geographic pattern of reductions relative to the control (Figure 15C) suggests that the areas east of the Central Valley in the foothills that were converted to perennial agriculture in the control runs have less carbon storage in the **avoided conversion** run. This may indicate a trade-off between woody biomass stored in orchards that provide climate mitigation benefits above the existing grasslands. More investigation is needed to verify this hypothesis.

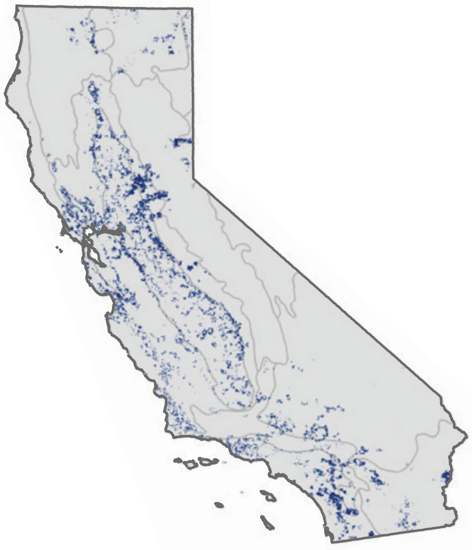
The economic implications of implementing policies and actions to prevent conversion are relatively favorable when considering the full set of benefits, such as the Social Cost of Carbon (SCC) and Social Cost of Nitrogen (SCN). The medium SCC values were $2.9 billion (B) and $2.1B through 2050 for the "hot-dry" and "average" climate futures, respectively. Using the high SCC values were $4.7B and $3.5B for the "hot-dry" and "average" models respectively. The SCN values added an additional $7.4B for "hot-dry" future and $5.8B for the "average" future by 2050. Accounting for the opportunity costs with this intervention in terms of foregone urban or agricultural net returns provides a full picture of the economic implications. The 2050 urban and agricultural opportunity costs, in terms of foregone increase in land values, for the "average" model were $17.1B and $19.1B for the "hot-dry" future by 2050. Using the high SCC and SCN values, the total benefits resulting to society from this intervention were $12.1B compared to costs of $17.1B under the "hot-dry" future, and $9.3B for the "average" future compared to costs of $19.1B. Avoiding conversion to developed uses also reduces flood damages when the reduction occurs in floodplain area. The present value of avoided flood damages over the 2021-2051 period ranged from $0.16B to $0.25B. This analysis obviously does not fully capture the full range of costs and benefits, but given the many benefits associated with protected natural lands such as recreation, public health, and water supply benefits, these comparisons can help contextualize the conservation and climate opportunities associated with this intervention.

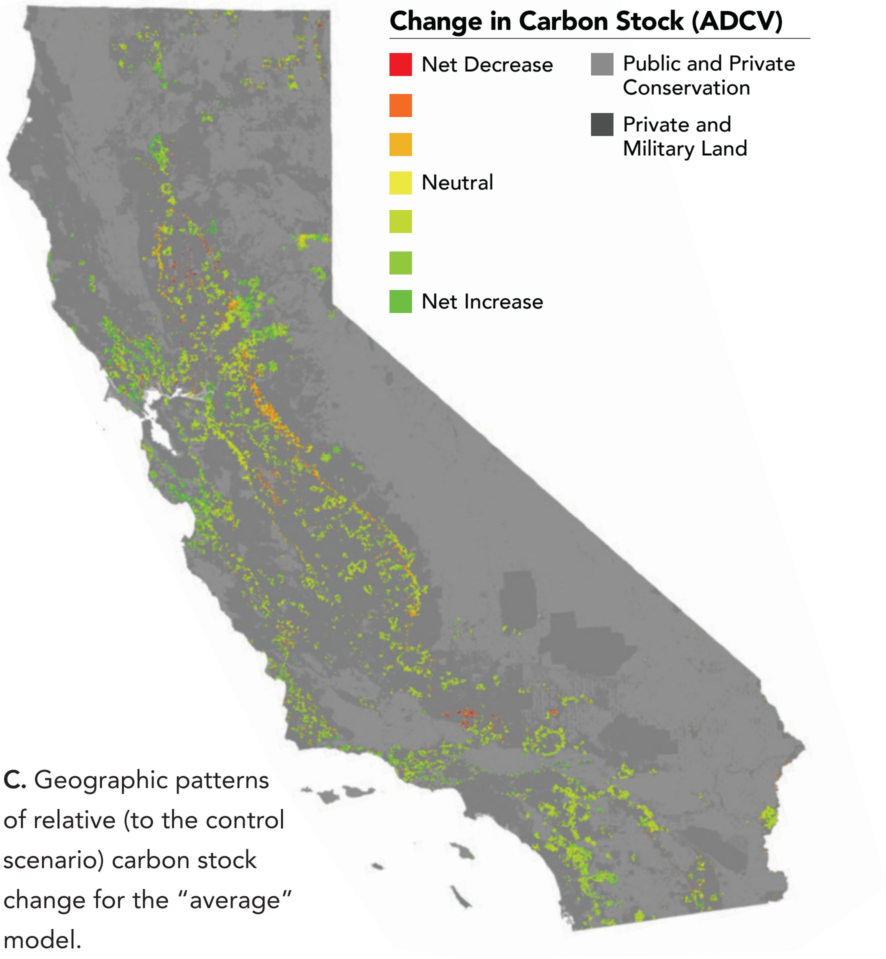
FIGURE 15 Overall Ecosystem Carbon Impact of the Avoided Conversion (ADCV) Intervention

A. Total net change in ecosystem carbon storage at 2030, 2050, and 2100. Similar to other interventions, the "average" climate future resulted in higher reductions.



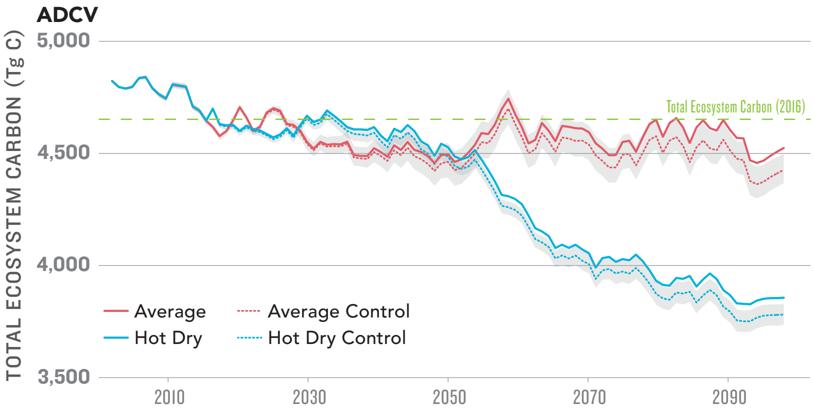
B. Cells that experienced ADCV intervention activity over the 80-year period for the "average" model.





C. Geographic patterns of relative (to the control scenario) carbon stock change for the "average" model.

D. Total ecosystem carbon in ecoregions and state classes affected by cover cropping intervention. The 95% confidence interval of the control run is shown in grey shading and the 2016 reference carbon storage is shown in the green-dashed line. This intervention provides reductions that are clearly outside the uncertainty range in the control runs.



VI.

Implementation Considerations & Recommendations

THESE interventions demonstrate potential to increase sequestration or avoid emissions relative to a future without such interventions. Further research and investment in field trials and programs to validate reduction potential and accelerate adoption will position California well to achieve the carbon neutrality by 2045 goal. While it may seem counterintuitive to invest in a sector that shows an increase in emissions due to factors mostly outside the realm of California's influence or control, these interventions can significantly reduce those losses – providing an important, and proven, climate mitigation strategy.

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If California ends up experiencing the future of the "hot-dry" climate model, the carbon storage potential of the land will be further reduced due to warming and increased wildfire and tree mortality. Indeed, the "average" future model generated 31 percent more cumulative reductions than the "hot-dry" future by the end of the century (under the 30% HSF scenario). Yet, in many ways, this "macro trends vs. interventions" tension is not unlike most sectors. For example, the price of gas (something the state has little control over) may well be one of the main factors in whether California meets emissions reductions in the transportation sector, if one were to assume that inexpensive gas would delay adoption of low and zero emissions vehicles.

The interventions analyzed in this study provide a number of co-benefits that make implementation more attractive. Many of the interventions provide ecosystem or economic benefits that will serve to reduce climate

IMPLEMENTATION AT A LOCAL LEVEL:

Merced County and Landowner Intervention Case Studies

The purpose of this section is to illustrate the potential climate and complementary benefits of land management and restoration activities at a smaller geographic scale, specifically the county and landowner scales. In this example, Merced County is used to describe potential greenhouse gas reductions and co-benefits that could result from riparian restoration, and increased use of hedgerows and cover crops.

Merced County is located in the Central Valley of California. More than 95 percent of the county's 1.27 million acres are devoted to food and fiber production, and agricultural revenues totaled $3.45 billion in 2016. Merced County is also developing rapidly—its population is expected to increase 50 percent by 2040. Given this rapid rate of growth, local governments, and landowners will face important land use and management decisions regarding residential and industrial development, and natural and working lands. In turn, this will also impact the ability of these lands to sequester carbon and provide other public and environmental benefits. Merced County is currently developing a climate action plan for the county.

A countywide assessment was conducted by a team led by the Nature Conservancy and funded by the California Department of Conservation to better understand the potential for Merced County's natural and working lands to support its climate and sustainability goals. Resilient Merced: A County Guide to Advance Climate Change Mitigation and Complementary Benefits through Land Management and Conservation (see end of feature for link) estimated the greenhouse gas reduction potential of different land use, restoration and management activities, as well as corresponding co-benefits and cost benefits. The accounting methods used to estimate the greenhouse gas reduction potential and co-benefits for Merced County, while conceptually similar to the methods used to estimate statewide GHG reduction potential in this study, are different due to the scale.

This project and the tool used for report serves as a guide for other counties and is designed to help other local governments and regions to plan, implement, and account for greenhouse gas reductions and co-benefits associated with different land use, land management and conservation activities. It can also help the state and local governments prioritize climate policies and investments, track progress toward goals, and understand tradeoffs among different land use and land management scenarios.

County Example: Cover Cropping and Hedgerow Planting in Merced County

In cover cropping, grasses and forbs (broad-leaved, herbaceous, flowering plants) are planted for seasonal vegetative cover. The practice promotes soil health as the cover crops' root system stabilizes soil, increases soil porosity, and encourages beneficial soil organisms. Since cover crops contribute to soil carbon sequestration, they help to reduce net greenhouse gas emissions.

Table 1. Cumulative combined emission reductions and carbon removals, costs and benefits, 2014–2030, for maximum adoption countywide of hedgerow planting and cover cropping

Activity	Cumulative Net Carbon Removal and Reductions ($MTCO_2e$)	Estimated Cost of Implementation (2016$)	Social Cost of Carbon Benefits (2016$)
Cover cropping	114,839	$5,230,000	
Hedgerow planting	680,235	$91,520,000	
Total	796,771	$96,750,000	$13,100,000

Hedgerow planting, as it is applied in Merced County, involves planting rows of woody vegetation (shrubs and small trees) along field borders and in gaps between blocks of vineyards and orchards. Hedgerow plants provide habitats for pollinators and wildlife, and sequester carbon in their roots, branches, and stems.

Merced County scenario

In the model, cover cropping and hedgerow planting were initiated in 2014 with a steady 6-year phase-in period for all suitable acres. This countywide scenario includes an adoption cap for implementation of agricultural activities based on a survey of experts in the county to assess the likelihood and extent of adoption of this practice. The adoption cap is intended to set a realistic limit on acreage of implementation—20 percent of all suitable acres for cover cropping and 30 percent for hedgerow planting. With these caps, cover cropping is implemented on just over 54,000 acres, and hedgerow planting on 5,500 acres. (In the assumptions built into the modeling, 10% of the area within any vineyard or orchard is available for hedgerow canopy.)

The annual net greenhouse gas emissions reduction rates for both interventions were calculated using COMET-Planner (a GHG estimation tool for agriculture used by the Natural Resource Conservation Service.) For hedgerow planting, the rate is 8.23 metric tons of CO_2e per acre, per year ($MTCO_2e$/ac/yr) and based on the 10-year rate used in COMET-Planner. For cover cropping, the rate of sequestration is 0.21 $MTCO_2e$/ac/yr and the scenario relied on an average of COMET-Planner reduction rates for several different kinds of cover cropping. The cumulative net increase in landscape carbon stocks (carbon removals) calculated for this scenario (2014-2030) is 796,771 $MTCO_2e$ when compared with the reference scenario.

Cover cropping and hedgerow planting: Estimated costs and benefits

The estimated cost associated with implementing countywide cover cropping and hedgerow planting scenario (based on estimates from the U.S.D.A. Natural Resources Conservation Service) is $96,750,000. The estimate reflects the approximate direct costs of labor, equipment, and materials required to 1) establish permanent vegetation, such as grass and legumes, in the alleyways and between tree and vine rows in the case of cover crops; and 2) establish a single row of woody vegetation. No opportunity costs are foreseen, and there is no land use change in this scenario.

The carbon benefits of this scenario, compared with the reference case, are estimated to be $13,100,000. The carbon benefits are based on average estimates of the social cost of carbon by the California Air Resources Board, which is estimated as the present discounted value of damages from a metric ton of carbon dioxide emissions. The benefit is the avoided damage from not emitting a ton of emissions (or sequestering a ton of carbon). A number of other benefits associated with cover cropping and hedgerow planting can't easily be assigned a dollar value and are not included in the valuation above. These co-benefits include, but are not limited to, enhanced soil quality and stabilization, habitat for wildlife species such as birds, and an increase in pollinators. Greater detail on the assessment, its methods, and findings can be found at https://maps.conservation.ca.gov/TerraCount/downloads/

change impacts and promote adaptation (e.g. through a reduction of high severity fire or reduction in demand for irrigation water), providing additional advantages in a climate changed-world. While the scope of economic costs and benefits analyzed in this study was limited, all eight interventions studied proved to be cost-effective when compared to other sectors' solutions. Further research could help policymakers better understand more comprehensive net economic benefits that would flow from implementing these interventions. Perhaps most importantly, many of these interventions are an attractive climate solution as they have the potential to remove greenhouse gases from the atmosphere—unlike emissions reduction in other sectors.

Models are useful tools for understanding and studying the future behavior of a system like California's lands and their carbon stocks and flows. However, the models and simulations developed here should not be taken as a prediction or representation of the future. They are simply one of many possible trajectories the state may follow. By running the same simulation twice but making changes only relevant to a particular intervention, the effect is similar to running a controlled experiment. This allows a reasonable assessment of the effect that a land management intervention would have, even if the overall results of a particular simulation do not play out in reality. That being said, every effort was taken to make this model as realistic—if simplified—a representation of California's statewide carbon stocks and flows on its lands that available data, time, and resource constraints would allow.

Specific limitations of the current model include its spatial resolution and coarse growth data. The model was run at one-kilometer resolution, which reflected a tradeoff between the resolution of the available data and the computing resources required to run the model. A higher (sharper) resolution would improve the results because the size of each intervention is typically less than one square kilometer. The growth parameters used in the model were calibrated using data summarized at the ecoregional level for each land use class. Therefore, the results do not take into account the many complexities of ecosystem processes that occur within an ecoregion.

While eight different land management interventions were assessed for this report, many other interventions exist that lead to GHG reductions. The methods and results presented here are not meant to be comprehensive, rather they are meant provide a useful framework to evaluate the effects of changes to land management in the context of ecosystem carbon over the scale of an entire state.

Implementation Recommendations

To optimize the potential for greenhouse gas reductions through land-based interventions in the state and help expand California's toolkit for carbon negative strategies, policymakers could consider the following implementation recommendations:

Establish an ambitious climate goal for the state's natural and working lands. Given the state's ambitious goals to reduce emissions and become carbon neutral by 2045 and the potential for the state's natural and working lands to become an increasing net source of emissions, absent interventions to alter this trajectory, the state should establish an ambitious climate goal for its natural and working lands to ensure appropriate attention, accountability, and investment in these resources.

Early and aggressive implementation will provide larger climate benefits due to the time lags inherent in ecosystem response to interventions. Many of the interventions that rely on growing vegetation (mostly trees) will yield more substantial benefits the earlier they begin due to the compounding effect of tree growth; as trees grow larger their capacity to absorb more carbon dioxide increases. This is especially relevant given California's stated goal of having a climate neutral emissions profile by 2045. Natural and working lands interventions will be especially important in meeting that goal, given residual emissions likely in other economic sectors.

Dedicate sustained funding to natural and working lands for climate mitigation and associated benefits. While the state has dedicated some funding from its Greenhouse Gas Reduction Fund for natural and working lands investments, it has been relatively small and inconsistent compared to the scale and duration of climate investments in other sectors such as transportation and energy. While nearly $926 million has been invested in California's natural and working lands from the state's Greenhouse Gas Reduction Fund over the past six years through annual appropriations, this represents roughly 11 percent of the total $8.4 billion that has been invested across the economy—with 60 percent continuously appropriated to transportation-oriented programs.

Leverage existing programs and policies, while building new ones. In many cases, policies and programs already exist to enable implementation of the modeled interventions. In the near term, scaling up these programs using new funding sources will enable the rapid deployment of funding and technical expertise to ensure rapid implementation. Using existing landowner outreach tools and networks, such as those administered by RCDs, NRCS, CalFire, and the U.S. Forest Service can lead to increased adoption due to the legacy of trust and collaboration that underpins these programs. New programs could focus on planning at county and regional scales and implementation that can optimize greenhouse gas reductions across sectors as well as other important co-benefits.

Adopt a portfolio of solutions across land types, regions, economic sectors, and ownership types. Given the high uncertainty inherent in climate change scenarios, adopting an approach that spreads the risk across different land uses and geographic regions will make it more likely that place-based climate impacts and disturbances will not reverse beneficial actions. While forests certainly represent the largest opportunity to store carbon in aboveground biomass and grasslands represent a large potential belowground sink, there will be geographic differences in fire frequency, drought, and other processes that make investing in a diversity of implementation areas an effective risk management strategy.

Align climate mitigation goals with other social, economic, and environmental goals. Given the potential co-benefits associated with many of these interventions considered here, implementation should incorporate other factors, many of which are spatially-explicit when setting priorities areas. For example, preventing agricultural expansion into areas that are already experiencing groundwater overdraft or reforesting lands within an ecological corridor for wildlife can help to further align climate mitigation with other goals. A large component of this in the future will be related to preventing or minimizing impacts to people from extreme events such as wildfire, flooding, or mudslides. Prioritizing reforestation in lands that have recently burned and are in the upper watershed of an urbanized area is another example of increasing risk reduction co-benefits through strategic implementation.

Develop consistent methods for monitoring progress over time. While an important first step is to understand the scale and nature of opportunity to mitigate climate change through different land management activities, it is also important for the state to develop consistent methods to account for and monitor progress over time at different scales. To minimize potential burdens to landowners, these methods could be designed to operate at a programmatic level or regional scale.

VII.

Conclusion

THIS report illustrates an approach to modeling the climate mitigation and economic impacts of a diverse set of interventions in natural and agricultural lands, which could support California's efforts to reduce emissions and achieve carbon neutrality. The effect of varied climate futures was a significant factor in the overall cumulative climate mitigation effect, with a "hot-dry" future showing lower emissions reduction potential than an "average" future. The mid-century and end of century reduction potential was substantial and shows that natural and working lands can be an essential part of climate solutions.

This work should inform state climate change solutions and lead to additional research into the feasibility of scaling up beneficial conservation and restoration interventions that also provide numerous ecological, social, and economic benefits. California policymakers have set ambitious climate change mitigation targets, and this report can provide practical information to help evaluate opportunity to use natural and working lands to help meet those targets. The LUCAS model is a flexible, adaptable tool to explore opportunities and trade-offs in aligning land conservation and restoration with climate goals. This report should generate support for a process to engage stakeholders in additional discussions regarding scenario development, intervention definition, economic analysis and technical and policy needs so that California can show the world that restoring and protecting land can be a key climate solution.

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