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COST-EFFECTIVENESS OF LARGE-SCALE FUEL REDUCTION FOR WILDFIRE MITIGATION IN CALIFORNIA

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EXECUTIVE SUMMARY

Intense wildfires in California impose significant economic impacts well beyond the insured losses of destroyed buildings and the costs of fighting fires. When impacts on health and overall disruption to the economy are taken into account, the total economic burden from wildfires in California is estimated to be on the order of $100 billion annually.

These impacts have been increasing over the past several decades due to a warming climate, more human encroachment into fire-prone areas, the rising value of exposed assets, and long-term fuel accumulation due to the over-suppression of fires.

In addition to addressing global warming, proactive fuel reduction treatments such as mechanical thinning and prescribed burning aim to reduce fuel loads to lower fire intensity and severity, thereby reducing the economic burden of wildfires.

Though fuel reduction has recently been embraced at both the federal and state levels, it necessitates substantial up-front investment, potentially amounting to billions of dollars annually, and it is not currently clear that these costs are justified from a cost-benefit perspective.

This report critically assesses whether the economic benefits derived from such fuel reduction treatments are sufficient to justify their costs.

We conducted an empirical evaluation of the effectiveness of fuel reduction treatments by using a novel methodology that quantifies the relationship between fire intensity and fuel loads via machine learning on a large and high-resolution dataset. Our analysis found that if fuel reductions are able to reduce economic losses proportionately to their observed effect on fire intensity, then the economic benefits of fuel reduction treatments are likely to far outstrip their costs.

The state of California has an articulated goal of reducing fuels on 1 million acres per year. If this reduction were to be conducted in order of cost-effectiveness (i.e., start with the 1 million acres that confer the highest net benefit), then, using our conservative central economic input parameters, meeting this goal would cost $3 billion annually but would confer a benefit of $10.9 billion annually for a benefit-to-cost ratio of 3.7-to-1 and a net benefit of $7.9 billion annually (Figure ES-1).

Furthermore, we quantified the cost of inaction and found that each year of delay in scaling up fuel treatment to 1 million acres per year results in a net loss of $4 billion.

We also estimated that the optimal rate of fuel reduction in California—the rate that maximizes the net annual economic benefit—is approximately 3.9 million acres per year or 3.9 times the state's articulated goal.

At a fuel reduction rate of 3.9 million acres per year, and using our conservative central economic input parameters, the annual cost of fuel reduction would be $10.5 billion, but it would confer a benefit of $22.2 billion annually for a benefit-to-cost ratio of 2.1-to-1 and a net benefit of $11.6 billion annually (Figure ES-1). The cost of each year of delay in scaling up fuel treatment to 3.9 million acres per year would be $5.8 billion.

We tested the robustness of these findings with a wide range of assumptions regarding the baseline economic burden of wildfires and the costs of fuel treatments. We found that if the economic burden from wildfires is substantially higher than third party estimates and the cost of treatment is relatively low, then the net benefit of fuel reduction can be as high as $50 billion per year, with costs of each year of delay reaching $25 billion. We also found that third part estimates of the economic burden from wildfires would have to be overestimated by three to five times, and third party estimates of the cost treatment would have to be substantially underestimated, for the net benefit of fuel reduction to not be on the order of at least $1 billion annually.

Overall, our results constitute strong evidence that the net benefits of fuel reduction and the cost of delay in scaling up fuel reduction are on the order of at least several billion dollars annually. Thus, these results support a clear economic rationale for the rapid scale-up of fuel reduction efforts in California to at least the state's articulated goal of 1 million acres per year, with greater benefits to be obtained with even more ambitious goals.

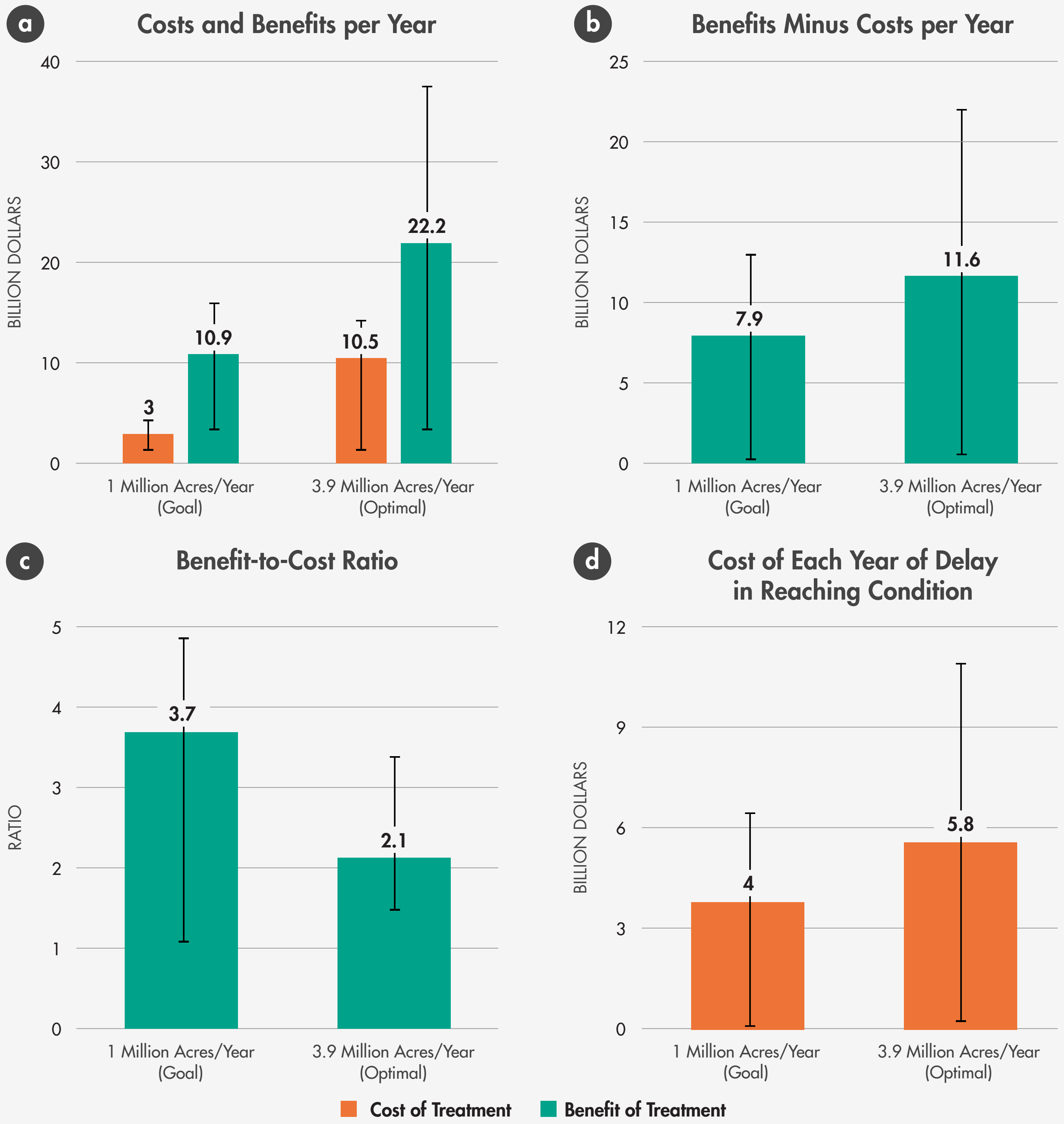

Figure ES-1: Costs and benefits of fuel reduction in California at articulated goal of 1 million acres per year and rate that maximizes net benefit, which is 3.9 million acres per year. a) Annual costs and benefits for each treatment rate. b) Annual net benefit for each treatment rate. c) Ratio of annual benefits to annual costs for each treatment rate. d) Cost of each year of delay in scaling up fuel treatments to their final condition. The error bars represent the 25th to 75th percentile confidence intervals of the values according to the joint sensitivity tests shown in Figure 10 and Figure 12.

Key Points:

- **Magnitude of Economic Losses from Wildfires:** When indirect effects are included, wildfires in California are estimated to impose economic losses of approximately $100 billion annually, which is several percent of California's GDP.
- **Costs of Fuel Reduction:** Implementing fuel reduction strategies across California's fire-prone areas is estimated to cost in the billions of dollars annually.
- **Location-Specific Costs vs. Benefits:** Our location-specific cost-benefit analysis showed that the most cost-effective regions are in the western foothills of the Sierra Nevada Mountains and produce approximately $10,000 in net benefits per acre treated per year.
- **Statewide Annual Costs vs. Benefits:** We found that, over a large range of assumptions for economic losses from wildfires and the costs of fuel reduction, the economic benefits of fuel reduction far exceed their costs.
- **Annual Costs vs. Benefits at a Rate of 1 Million Acres per Year:** At the state of California's articulated goal of reducing fuels on 1 million acres per year, costs would be $3 billion annually, and benefits would be $10.9 billion annually, for a net benefit of $7.9 billion annually and a benefit-to-cost ratio of 3.7-to-1 (Figure ES-1). These numbers also imply a cost for each year of delay in scaling up fuel treatment of $4 billion.
- **Rate of Treatment That Maximizes the Net Economic Benefit:** The optimal rate of fuel reduction in California—the rate that maximizes the net annual economic benefit—is approximately 3.9 million acres per year or 3.9 times the state's articulated goal.
- **Annual Costs vs. Benefits at a Rate of 3.9 Million Acres per Year:** At an optimal rate of 3.9 million acres per year, costs would be $10.5 billion annually, and benefits would be $22.2 billion annually, for a net benefit of $11.6 billion annually and a benefit-to-cost ratio of 2.1-to-1 (Figure ES-1). These numbers also imply a cost of each year of delay in scaling up fuel treatment of $5.8 billion.
- **Circumstances in Which Benefits Roughly Equal Costs:** The above estimates of the economic burden from wildfires would have to be overestimated by three to five times, and the estimates of the cost treatment would have to be substantially underestimated, for the net benefit of fuel reduction to not be at least $1 billion annually.

BACKGROUND

The annual area burned in California and the entire Western United States saw a precipitous decline from the 1800s to the 1980s,[1-3] but has since been on an ascent.[4-6] In addition to being exacerbated by climate change,[7-10] fire impacts are being enhanced by more direct human influences.[11,12] These include changes in where fires are ignited,[13-15] increases in the number of structures in harm's way,[16] and the long-term buildup of fuels,[17-19] which is partially due to the legacy of ill-advised policies that suppressed natural fires and eliminated the cultural burning practices of Indigenous people.[20-23]

Fires are natural and inevitable,[24] but proactive, intentional fuel reduction has the potential to reduce fire intensity and smoke emissions, decrease fire severity, increase ecosystem resilience and health, and make fires easier to contain.[25,26] Thus, one of the primary proposed strategies for addressing increases in wildfire danger in California is a substantial expansion of intentional fuel removal, which includes mechanical thinning and prescribed burning in forests[27,28] and prescribed burning and enhanced grazing[29] in shrublands and grasslands.[30]

New research has helped quantify the potential for fuel reduction to be effective and the degree to which it can offset climate change impacts on wildfire intensity.[31] This research uses an unprecedented combination of spatiotemporal resolution (0.5 km, hourly) and extent (48 million acres, nine years) to quantify the relationship between fuel characteristics and fire intensity via machine learning. It has found substantial potential for fuel reduction to be effective, adding to a large and growing body of literature reporting similar conclusions.[32-45]

However, scaling hazardous fuel reduction treatments to large areas in California will likely cost billions of dollars per year, and it is still unclear if the benefits are worth this cost. A recent comprehensive review suggested strong potential for net savings from fuel treatment, but highlighted the paucity of comprehensive, statewide assessments on the cost-effectiveness of fuel treatments in California.[46] The review also noted that the existing literature often relies on purely simulated wildfires that have little or no empirical grounding.

Thus, there is a critical need for empirically based quantitative estimates of fuel reductions' potential effectiveness for the state as a whole from a cost-benefit perspective. We address this need with the present report.

Addressing this need requires estimating the costs of fuel reduction treatments, as well as the benefits of avoided economic losses associated with those treatments. In our study, we took independent third party estimates of the economic burden from wildfires and used our estimates of the effectiveness of fuel treatments at reducing fire intensity to calculate the effectiveness of fuel treatments in reducing economic losses. We also calculated the optimal area to treat and the rate of treatment that maximizes the net benefit. We investigated benefits and costs both for this optimal amount of area treated and for California's recently articulated goal of treating 1 million acres per year.[47]

Economic Losses from Wildfires

We estimated the economic benefits of fuel treatments by calculating how fuel treatments reduced Fire Intensity Potential[48] and associating that reduction with avoided economic losses. For this calculation, we required baseline estimates of the total economic losses associated with wildfires.

Because they are easy to document, increasing suppression costs are often given as a fiscal reason for concern regarding increasing wildfire costs. However, assessments of the total economic burden from wildfires indicate that suppression costs constitute on the order of 1% of the total burden.[49] Even direct damages to structures (e.g., insured losses) tend to be a small fraction of the total costs,[50] with much more of the total emanating from the cost of health impacts from smoke inhalation, loss of natural capital, effects on property values, and broader economic disruption.[51–58]

Estimates of the total economic burden of wildfires in the United States tend to be in the hundreds of billions annually, constituting several percent of US GDP. For instance, annual US economic burdens from wildfires were estimated at $406 billion for 2014,[59] $490 billion for 2007,[60] between $87 billion and $424 billion for 2016,[61] and between $394 billion and $893 billion per year over recent years[62] (all converted to 2022 dollars).

When the scope is restricted to the state of California, the economic burden for 2018 was estimated to be $148 billion.[63] An independent estimate for 2017 to 2021 placed annual economic losses at $117 billion,[64] constituting several percent of California's GDP. Also, since the California Department of Forestry and Fire Protection's suppression expenditure is now in the billions annually, and state-level suppression costs are estimated to represent as little as 1% of the full community costs of wildfire,[65] these numbers would also imply a total economic burden from California wildfires in the hundreds of billions of dollars annually.

These figures are roughly consistent with the aforementioned estimates for the US as a whole, given that California represents a significant portion of the US population exposed to wildfire impacts.

These studies informed our choice of the baseline economic burden of wildfires. Given that the $148 billion figure was based on 2018, which included the extraordinarily devastating Camp Fire (which destroyed the town of Paradise), and that the $117 billion per year estimate also sampled 2018 as well as the very destructive years of 2020 and 2021 (but not the milder years of 2022 and 2023), we have good reason to believe that the typical annual losses will be below these estimates.

Thus, for our central estimate, we used a substantially lesser value of $75 billion per year. However, we tested the sensitivity of all our primary results for the extensive range of $5 billion per year to $150 billion per year (Figures 10, 11, and 12), noting that the lower end of this range is almost certainly an underestimate given that it is below the mean reported insured losses of recent years.[66]

Avoided Economic Losses from Intense Wildfires via Fuel Reductions

To estimate avoided economic losses from wildfires, we used estimates of avoided Fire Intensity Potential via fuel reduction treatments described in Brown et al.'s study.[67] Fire Intensity Potential is based on satellite-observed Fire Radiative Power, which quantifies a fire's radiant energy release rate and is associated with the fire's size and fireline intensity (i.e., power per unit length of the firefront). It thus serves as a proxy for fire intensity[68] and biomass combustion rates[69] and a more indirect proxy for emissions of smoke and particulate matter,[70-72] fire spread rates,[73] and overall fire severity and impacts.[74,75] Fire Intensity Potential is a useful metric in our context because the aim of fuel management practices is not to eliminate fires but to reduce their intensity, spread rates (thereby making them easier to contain), and overall impacts when they do occur.

We estimated that the reduction in California statewide economic losses from wildfires is proportional to the reduction in California statewide Fire Intensity Potential achieved through fuel treatments. This can be justified by considering the established relationships between Fire Radiative Power and characteristics of wildfires that contribute strongly to economic impact (e.g., smoke production, difficulty in containment, spread rates, and ecosystem impacts).

Figure 1 shows the distribution of Fire Intensity Potential throughout the state of California and the effects of universal fuel reduction and climate warming on it. The bottom row shows the avoided Fire Intensity Potential from universal fuel treatments conducted both today (first column) and in 2050 (second column).[76]

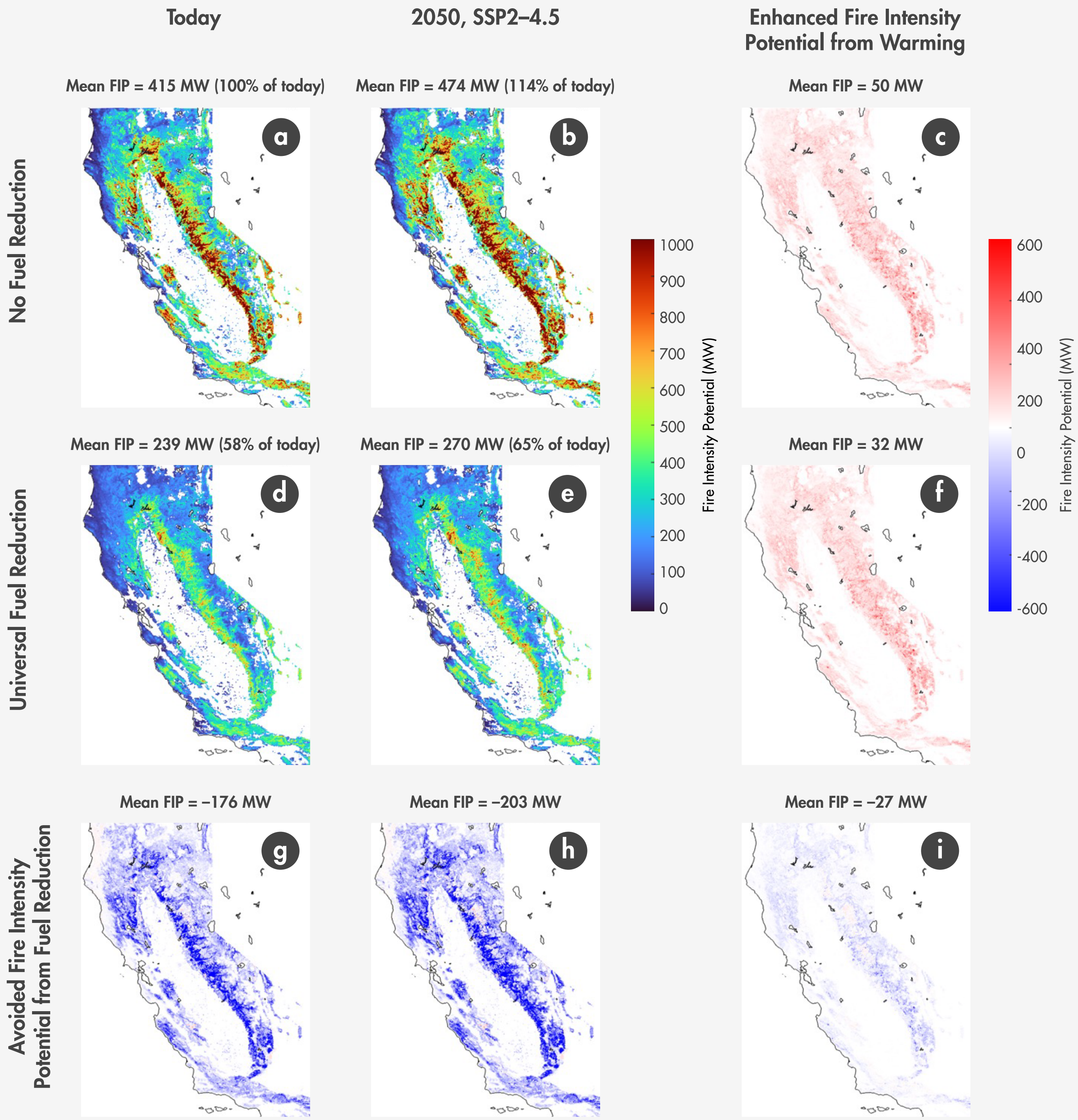

Figure 1: Mean Fire Intensity Potential (FIP) across all weather snapshots described in Brown et al[77] and effect of fuel reductions and warming associated with SSP2-4.5 emissions scenario. a) Mean FIP map in the current climate. b) Mean FIP map with 2050 warmth in the SSP2-4.5 scenario. d and e) Same as a and b but in the universal fuel reduction scenario. The 3rd row is the 2nd row minus the first row, and the 3rd column is the 2nd column minus the first column.

To estimate the spatial distribution of avoided economic losses from wildfires, we took the baseline $75 billion annual burden and allocated it across the state's 48 million acres of fire-prone area (all colored regions in Figure 1). We distributed this statewide economic burden proportionately according to local Fire Intensity Potential (Figure 2). This calculation resulted in local estimates of economic loss per acre per year, which sum to the state's overall burden of $75 billion per year. These numbers represent a long-term average (expected value) of each acre's contribution to the overall burden, much of which would not take place in any given year (since wildfires do not occur at any specific location in most years) and would be experienced non-locally (e.g., via remote impacts from smoke).

Overall, each acre in the state's fire-prone regions contributes, on average, $1,561 per year to the economic burden of wildfires. These contributions are quite unequal, with some acres along the north coast contributing in the $10s per acre per year and some acres in the western foothills of the Sierra Nevada contributing over $10,000 per acre per year (Figure 2).

Panels g and h in Figure 2 show the average avoided economic losses from universal fuel treatment, which would average $663 per acre per year in today's climate and $766 per acre per year in 2050 under an SSP2-4.5 emissions scenario. These avoided losses are also unequally distributed in space, with some locations showing no benefit from fuel treatment and others showing many thousands of dollars per acre per year in benefits from fuel treatment.

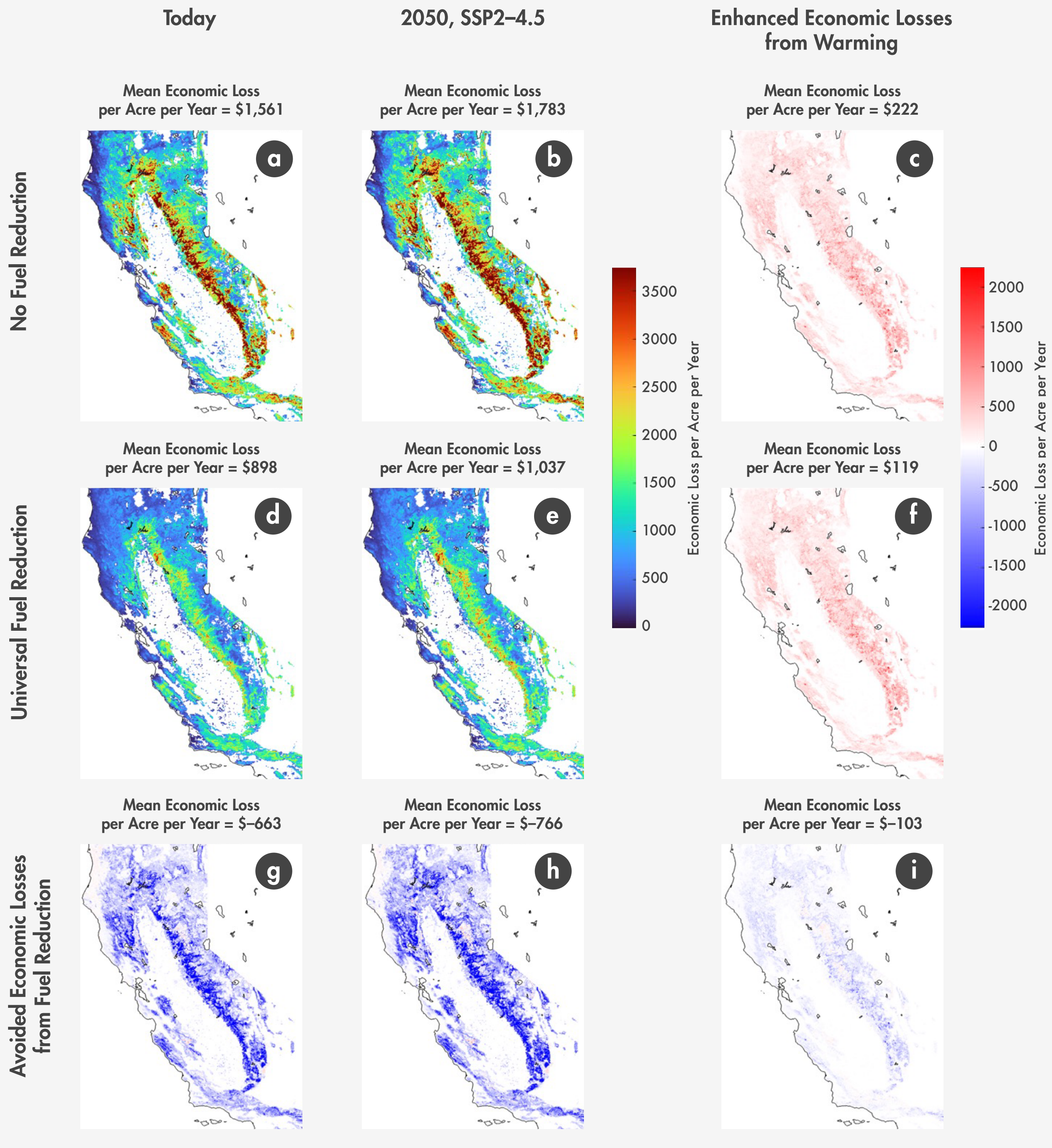

Figure 2: Same as Figure 1 but with estimates of local contribution (expected value over a long period of time) to total statewide economic burden of wildfires (baseline of $75 billion annually). Much of the local contribution to the economic burden would be experienced non-locally (e.g., via remote impacts from smoke).

Distributing the economic burden proportional to local Fire Intensity Potential, while speculative, is supported by the observation that most of the economic impacts of wildfires are calculated to be non-local (remote smoke impacts, effect on overall insurance rates, indirect reverberations throughout the economy, etc.). Thus, the local intensity of wildfires matters for overall economic impact, even if a fire does not directly threaten densely populated areas.

It is also plausible that avoided economic losses could exceed the decrease in Fire Intensity Potential. One reason for this is the fundamental dynamics of wildfires as a self-perpetuating chain reaction. The likelihood of containing wildfires early can prevent escalation of a fire and thus significantly mitigate its final size and total economic impact. Reduced Fire Intensity Potential can increase the likelihood of early containment, which would then have an outsized effect on the fire's total economic impact. Similarly, Fire Intensity Potential does not quantify the likelihood of ignition, but the extent to which lower Fire Intensity potential would result in a lower likelihood of ignition would then translate into an outsized reduction in economic losses, as there are zero economic losses from fires that are not ignited. Overall, these dynamics mean that it is quite plausible that reduced economic damage would be proportionally larger than reduced Fire Intensity Potential; thus, setting them as proportional constitutes a conservative assumption in our analysis. Nevertheless, we show results for a wide range of baseline economic losses, which is equivalent to holding economic losses constant, and investigating results for a wide range of proportionality factors between changes in Fire Intensity Potential and changes in economic losses.

Costs of Fuel Treatments

The costs of fuel reduction itself will depend on the technique,[78,79] the landscape,[80,81] proximity to resources,[82] potential revenue from wood products,[83,84] and less direct factors including agency management, project size, treatment goals, accessibility, permitting, and litigation. As a result, reported costs for mechanical thinning and prescribed burning vary widely, but a commonly cited figure for overall fuel reduction is $1,000 per acre, based on averages reported by the US Forest Service.[85] A recent meta-analysis reported a range of $306.75 to $1,736.51 per acre for mechanized whole-tree forest thinning.[86]

In another study, the California Wildfire and Forest Resilience Taskforce sponsored a survey of multiple land managers in the US Forest Service and the California Department of Forestry and Fire Protection (CalFire) to compile estimates of treatment costs as a function of vegetation (land surface) type and treatment method.[87] These estimates are shown in Table 1.

Table 1: Treatment cost estimates from Andreozzi et al.[88] for different land surface types and treatment techniques. Estimates are from a consultation with CalFire and the US Forest Service. All costs are per acre.

	Land Surface Type / Range	Mastication	Thinning		Piling		Lop and scatter	Pileburn
			Manual	Mechanical	Manual	Mechanical		
CalFire	Herbaceous / Shrubland	$1,813.00	$1,851.00	–	–	–	–	$3,125.00
	Woodland	$1,198.00	$2,683.00	$2,807.00	–	–	$1,217.00	–
	Grassland / Brush	$1,669.00	$2,534.00	$2,500.00	$2,551.00	$1,521.00	$1,263.00	$2,303.00
	Forest	$1,788.00	$1,461.00	$957.00	$1,071.00	$640.00	$1,616.00	$810.00
	Mean	$1,617.00	$2,132.25	$2,088.00	$1,811.00	$1,080.50	$1,365.33	$2,079.33
USFS	Low	$800.00	$450.00	$945.00	$400.00	$800.00	–	$250.00
	High	$1,700.00	$950.00	$1,800.00	$1,200.00	$1,200.00	–	$450.00
	Mean	$1,250.00	$700.00	$1,372.50	$800.00	$1,000.00	–	$350.00

For our central cost estimates, we sought numbers that can represent the average across a variety of circumstances. For this purpose, we averaged the manual and mechanical thinning estimates for the four landscapes reported by CalFire. We then added prescribed fire cost estimates on top of this, assuming that both thinning and prescribed fire are conducted during treatments. For grasslands, we assumed that no thinning is done and only prescribed fire is necessary. For simplicity, we chose not to consider potential revenue from wood products as an offsetting factor on the costs of fuel reduction in forests. Our resulting mean cost of treatment is over $2,000 per acre (Table 2), more than double the $1,000 per acre average reported by the US Forest Service hedging our results in the conservative direction.[89]

Table 2: Treatment costs and treatment frequency used as central estimates of our study. Thinning values are simple averages of CalFire's estimates for manual and mechanical thinning in Table 1. Sensitivity rates of the study's main results are shown for a range of 30% to 230% of these central estimates (Figures 10, 11, and 12).

Land Surface Type	Thinning per acre	Rx Fire per acre	Thinning + Rx Fire per acre	Frequency (years)	Cost per acre per year
Herbaceous / Shrubland	$1,851.00	$600.00	$2,451.00	3	$817.00
Woodland	$2,745.00	$600.00	$3,345.00	4	$836.25
Grassland / Brush	–	$600.00	$600.00	1	$600.00
Forest	$1,209.00	$600.00	$1,809.00	5	$361.80
Mean	$1,451.25	$600.00	$2,051.25	3.25	$653.76

For the purpose of our calculation, we required *annualized* cost, which incorporate both a cost per acre of treatment and a lifetime of treatment. Treatments will be longer lasting in, for example, forests than in grasslands because grass regrows much more quickly than surface vegetation in forests. Fuel reduction should be effective in forests for at least six years,[90] but still has substantial impact after 10 years[91] and could last for 20 years.[92] In shrublands, the effect should last at least five years.[93] In grasslands, prescribed fire would likely need to be conducted annually. For our baseline calculation, we used retreatment frequencies of once every five years for forests, four years for woodlands, three years for shrublands, and one year for grasslands.

Overall, our cost estimates can be considered conservative (i.e., hedged in the expensive direction). This, along with the economic burden hedged in the low direction, means that our primary reported results on net benefits are likely to be conservative. Regardless, the sensitivities of our primary results are reported for all mean costs between 30% and 230% of the central per acre estimates (Figures 10, 11, and 12).

The frequency of treatment needed and the associated costs per acre per year are combined in Figure 3, which shows the cost per acre per year as a function of the land surface type. Under the stated assumptions, the state average treatment cost would be $717 per acre per year across California's fire-sensitive regions.

This calculation assumes all land within each 2km by 2km pixel is treated, but studies have shown that much of the wildfire mitigation benefits of fuel reduction can be achieved by treating only a strategic portion of the land,[94-101] which indicates that the desired effect could be achieved by treating less land and thus incurring less cost.

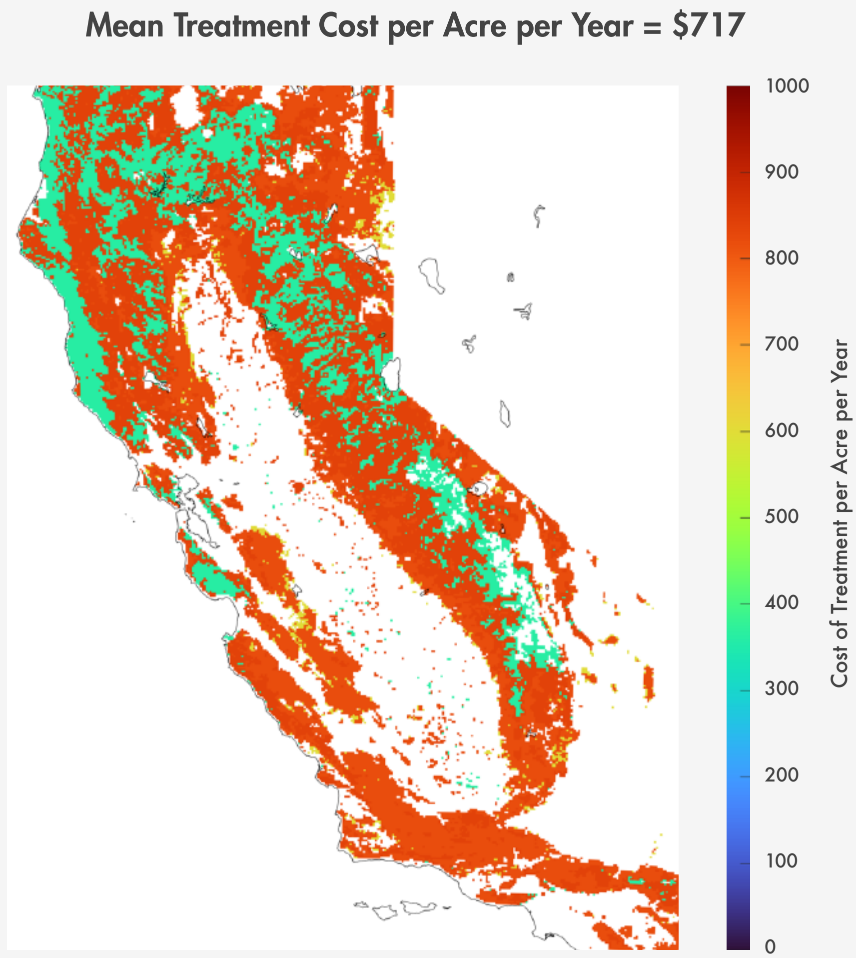

Figure 3: Estimates of local treatment costs per acre per year. Costs were derived from estimates of costs per acre divided by estimates of necessary retreatment intervals (Table 2).

Net Benefit of Fuel Treatments

With the estimates of the benefits of avoided economic losses from intense wildfires (Figure 4, panels a and b) and the costs of treatment (Figure 4, panels c and d), we were able to calculate the net benefits (benefit-cost) of statewide fuel treatments (Figure 4, panels e and f) for both the current climate and a future warmer climate.

The net benefit (benefit-cost) maps (Figure 4, panels e and f) show where the benefits of treatment exceed their costs (green), justifying them from a society-wide economic perspective, and where they do not (red). The areas where benefits exceed costs most dramatically are in the western Sierra Nevada foothills near the transition between forests and shrublands because this is where fuel treatment is calculated to have the largest leverage on Fire Intensity Potential.[102]

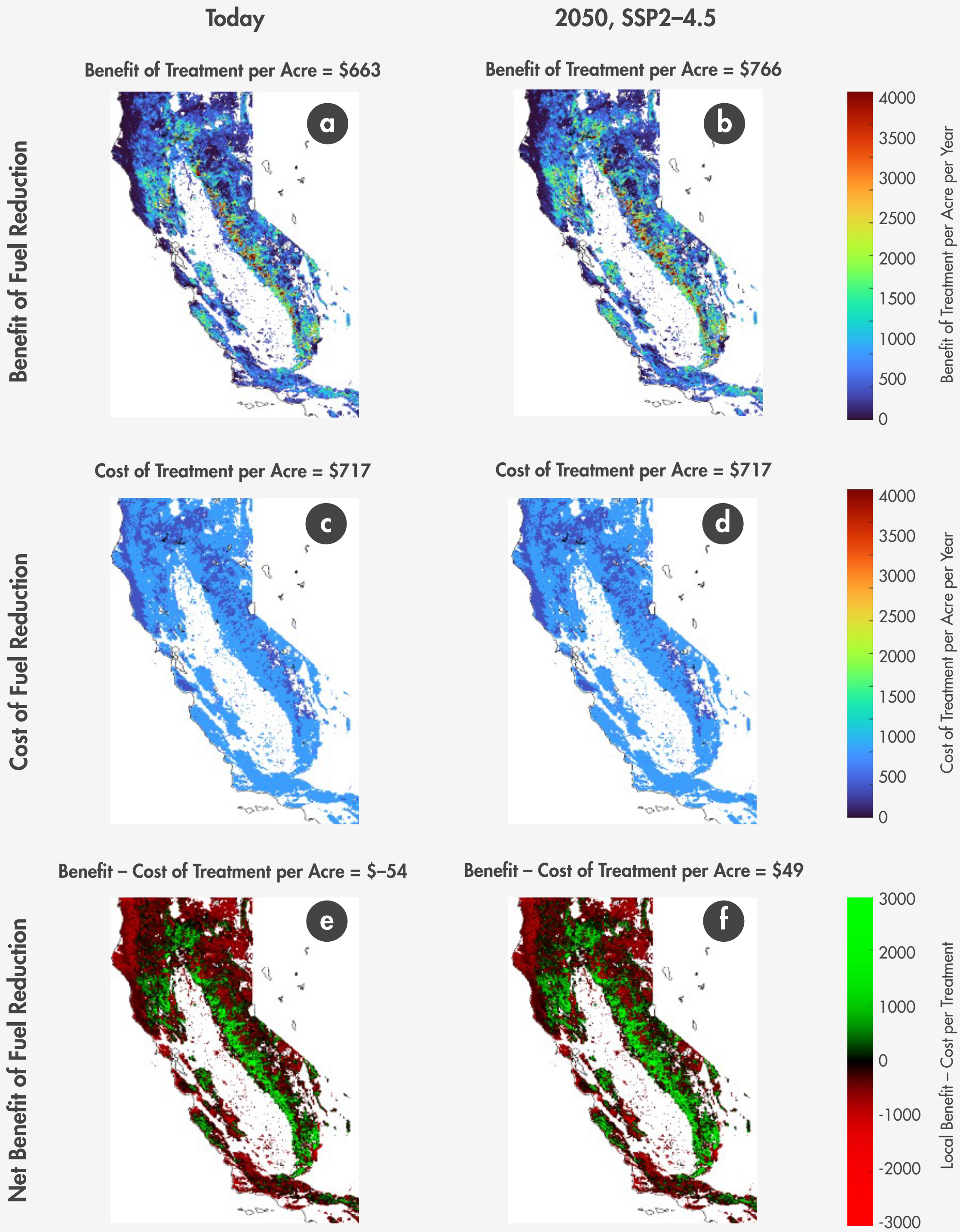

Figure 4: Estimates of local benefits, costs, and net benefits (benefit-cost) of fuel reduction across California if the entire state were treated.

The maps in Figure 4, panels e and f raise the question of how much area the state should treat if its goal is to maximize the net benefit of those treatments.

By rank-ordering locations based on net benefits per acre, the nonlinear nature of the effect of treatment on different locations is evident (Figure 5, panel a). The most effective locations yield net benefits of $10,000 per acre per year, but the drop-off is steep. The relative influence of the benefit versus the cost side of the ledger can be seen in Figure 5, panel b, showing that the reason for the drop-off in net benefits as more area is treated is primarily a drop-off in benefits rather than an increase in costs.

The optimal area that should be undergoing fuel reduction (and rate of fuel reduction in acres per year) occurs when marginal benefits equal marginal costs (vertical black line in Figure 5, panels a and b; this is also the area of positive values in Figure 4, panel e). This area is roughly 15 million acres (out of 48 million acres in our analysis). Our area-weighted mean treatment frequency is approximately four years, which indicates that the rate of treatment that maximizes the net benefit is roughly 3.9 million acres per year or 8.3% of our domain.

The articulated goal for the state of California is to scale up fuel reduction treatments to 1 million acres per year (vertical yellow line in Figure 5, panels a and b),[103] which is equivalent to roughly 4 million acres under perpetual treatment (at a mean four-year return interval). This is about a quarter of the 15 million acres under perpetual treatment that would maximize the net benefit.

Figure 6 shows the local contribution to the total economic burden from wildfires under the two fuel reduction scenarios (the articulated 1 million acres per year goal and the optimal 3.9 million acres per year scenario). The blue area in Figure 6, panels e and f is the area that would undergo fuel reduction in the optimal 3.9 million acres per year scenario but not under the articulated goal of 1 million acres per year.

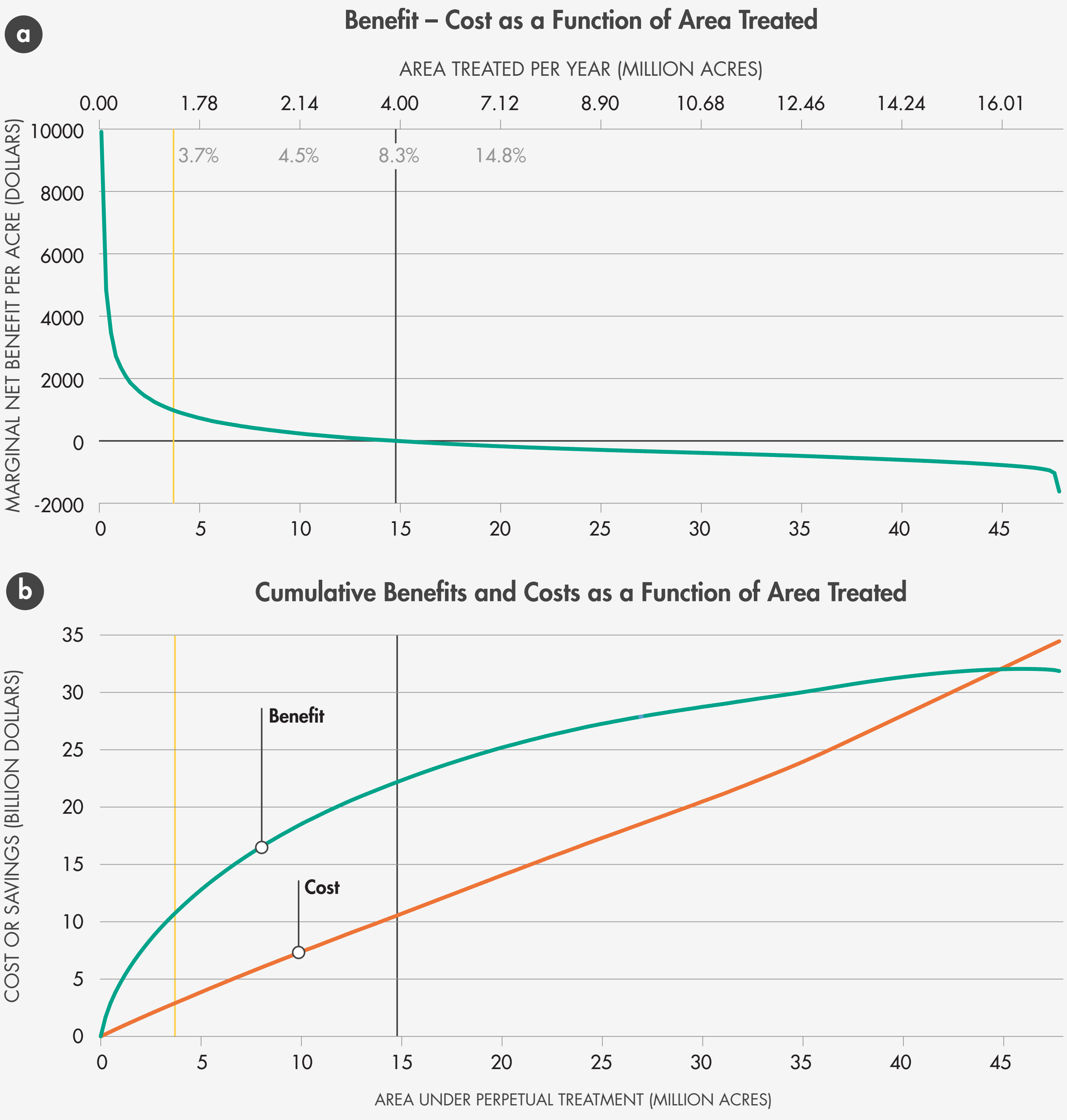

Figure 5: Marginal net benefit, benefit, and cost of fuel reduction as a function of area undergoing fuel reduction treatment. The vertical yellow line delineates the articulated 1 million acres per year goal, and the vertical black line delineates the optimal 3.9 million acres per year scenario.

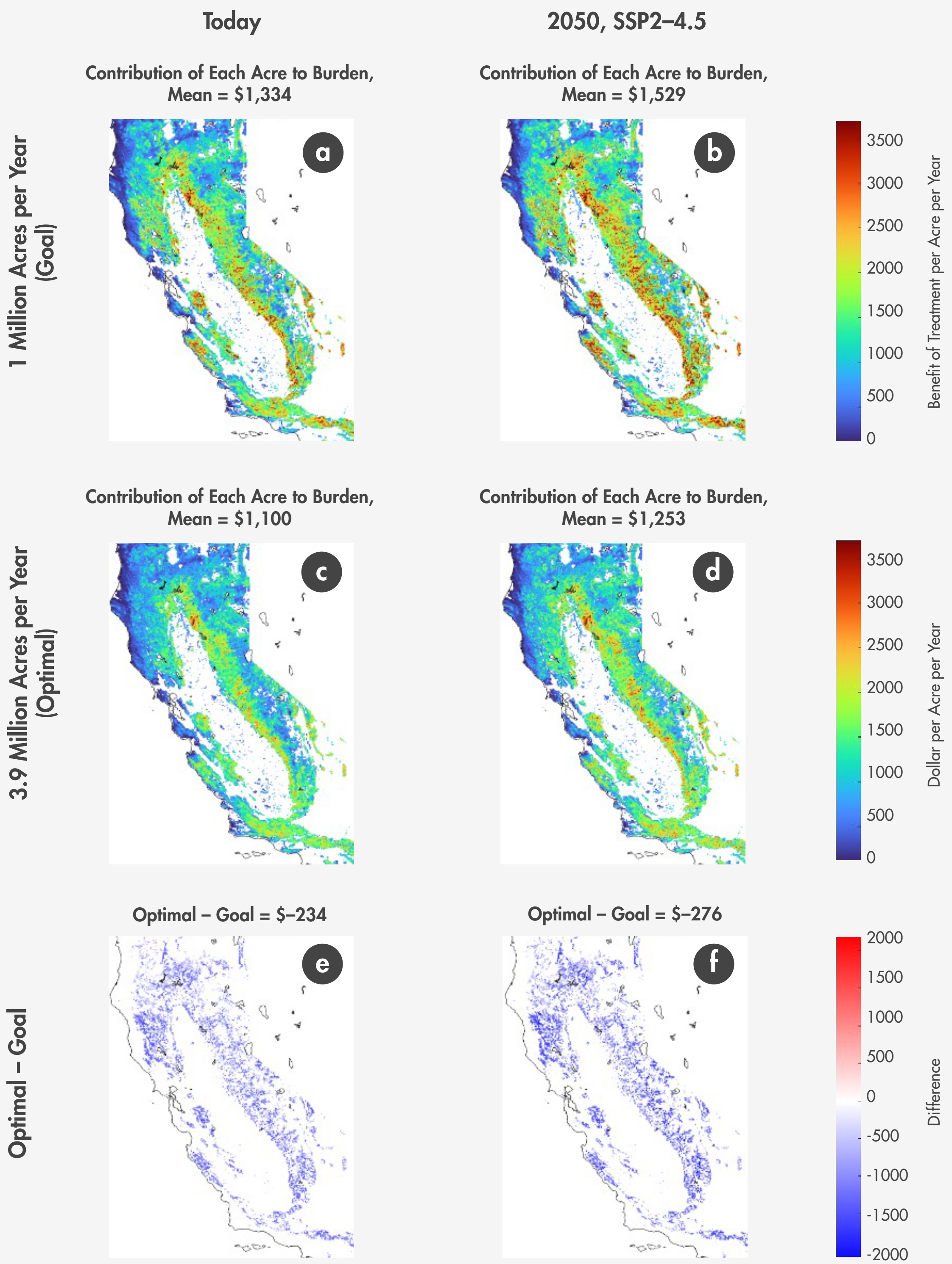

Figure 6: Local contribution to total economic burden of wildfires under the articulated 1 million acres per year goal (top row), the optimal 3.9 million acres per year scenario (middle row), and the difference between the two (bottom row).

Figure 7 expresses these findings in terms of locations that should be included in a given fuel reduction plan as a function of the total amount of area designated to undergo fuel reduction (assuming fuel reduction is prioritized to maximize net economic benefit and considering no other factors). The darkest red areas should be included in a 1 million acres per year plan, while the lighter red, orange, yellow areas should be included in a 3.9 million acres per year plan. Maps like this can serve as a useful point of comparison for tracking where real world fuel reduction projects are taking place to monitor if they are occurring at roughly the locations where they will yield the highest net benefits.

Should be Included in a Given Acre per Year Treatment Plan

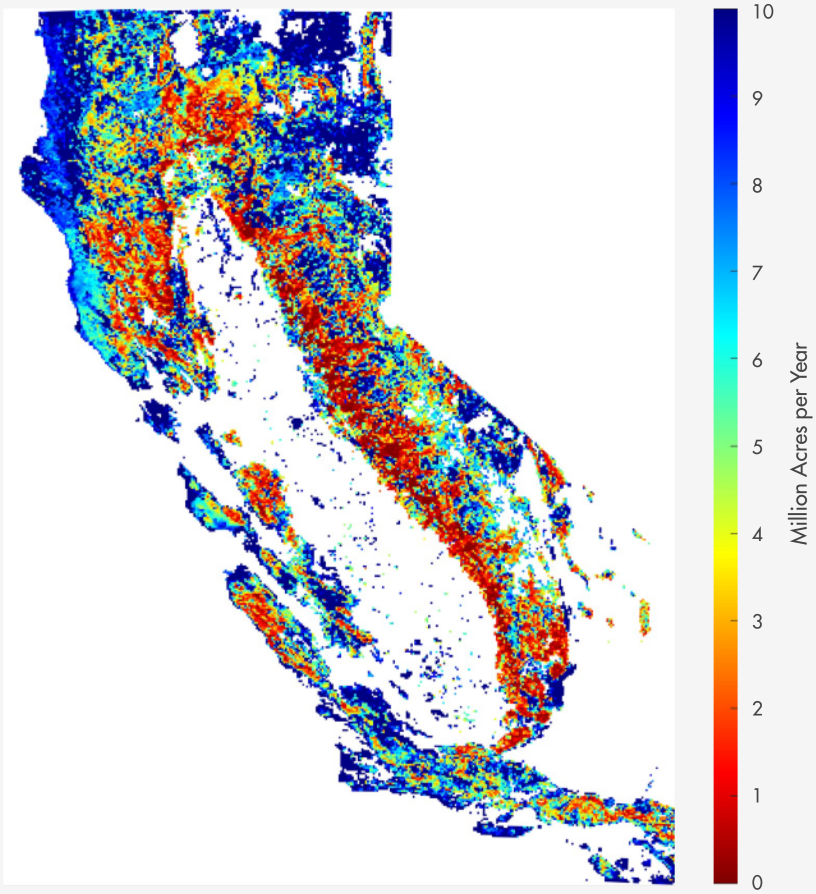

Figure 7: Locations that should be included in an X million acres per year fuel reduction plan (where X is the displayed variable) if locations are prioritized based on net economic benefit of fuel reduction.

Figure 8 (which also appeared as Figure ES-1) summarizes these findings. Under the articulated goal of fuel reduction on 1 million acres per year, the total statewide costs would amount to $3 billion annually, with anticipated benefits of $10.9 billion annually, for a net benefit of $7.9 billion annually and benefit-to-cost ratio of 3.7-to-1.

If the net benefit were maximized and 3.9 million acres were treated per year, total fuel reduction costs would increase to $10.5 billion annually, but benefits would increase to $22.2 billion annually, resulting in a net benefit of $11.6 billion annually and a benefit-to-cost ratio of 2.1-to-1 (Figure 8).

Figure 8: Costs and benefits of fuel reduction in California at the articulated goal rate of 1 million acres per year and the rate that maximizes the net benefit, which is 3.9 million acres per year. a) Annual costs and benefits for each treatment rate. b) Annual net benefit for each treatment rate. c) Ratio of annual benefits to annual costs for each treatment rate. d) Cost of each year of delay in scaling up fuel treatments to their final condition. The error bars represent the 25th to 75th percentile confidence intervals of the values according to the joint sensitivity tests shown in Figure 10 and Figure 12.

Cost of Delay in Scaling Up Fuel Reductions

We also calculated the loss associated with a delay in scaling up fuel treatments to their final condition while simultaneously considering the exacerbation of wildfire danger from climate change. This calculation is informative in the current context where issues associated with permitting procedures have been identified as causing multi-year delays in conducting fuel reduction projects.[104]

Figure 9 demonstrates the calculation of the cost of delay results shown in Figure 8, panel d. The baseline economic impact of wildfires in our analysis is $75 billion annually and is projected to increase by 14% to $86 billion annually by 2050 under SSP2-4.5 due to warmer conditions (orange line in Figure 9, panel a). If the 1 million acres per year treatment plan was fully scaled up, the economic burden of wildfires today would be $64 billion annually; in 2050, it would be $73 billion annually. Under a fully scaled-up reduction plan of 3.9 million acres per year, the burden today would be $53 billion annually; in 2050, it would be $60 billion annually. The annual costs of each level of treatment (Figure 9, panel b) can be added to the economic burdens to get a net economic burden of each situation that includes the cost of treatment (Figure 9, panel c).

This can then be expressed as the difference from the no-treatment scenario (Figure 9, panel d), which can be interpreted as the cost of not performing fuel reduction or, equivalently, the foregone benefit of not being in the final treatment condition. From here, we calculated the forgone benefit as a function of the time it takes to reach the final condition, which can be expressed as the cost of each year of delay in reaching the final state.

Each year of delay in reaching the articulated goal of 1 million acres per year would incur an additional economic burden of $4 billion, and each year of delay in reaching the optimal 3.9 million acres per year scenario would incur an additional economic burden of $5.8 billion. (The cost of delay is larger for the 3.9 million acres per year scenario than the 1 million acres per year scenario because there are more benefits on the table in the 3.9 million acres per year scenario.) These figures underscore the importance of timely action in wildfire mitigation strategies.

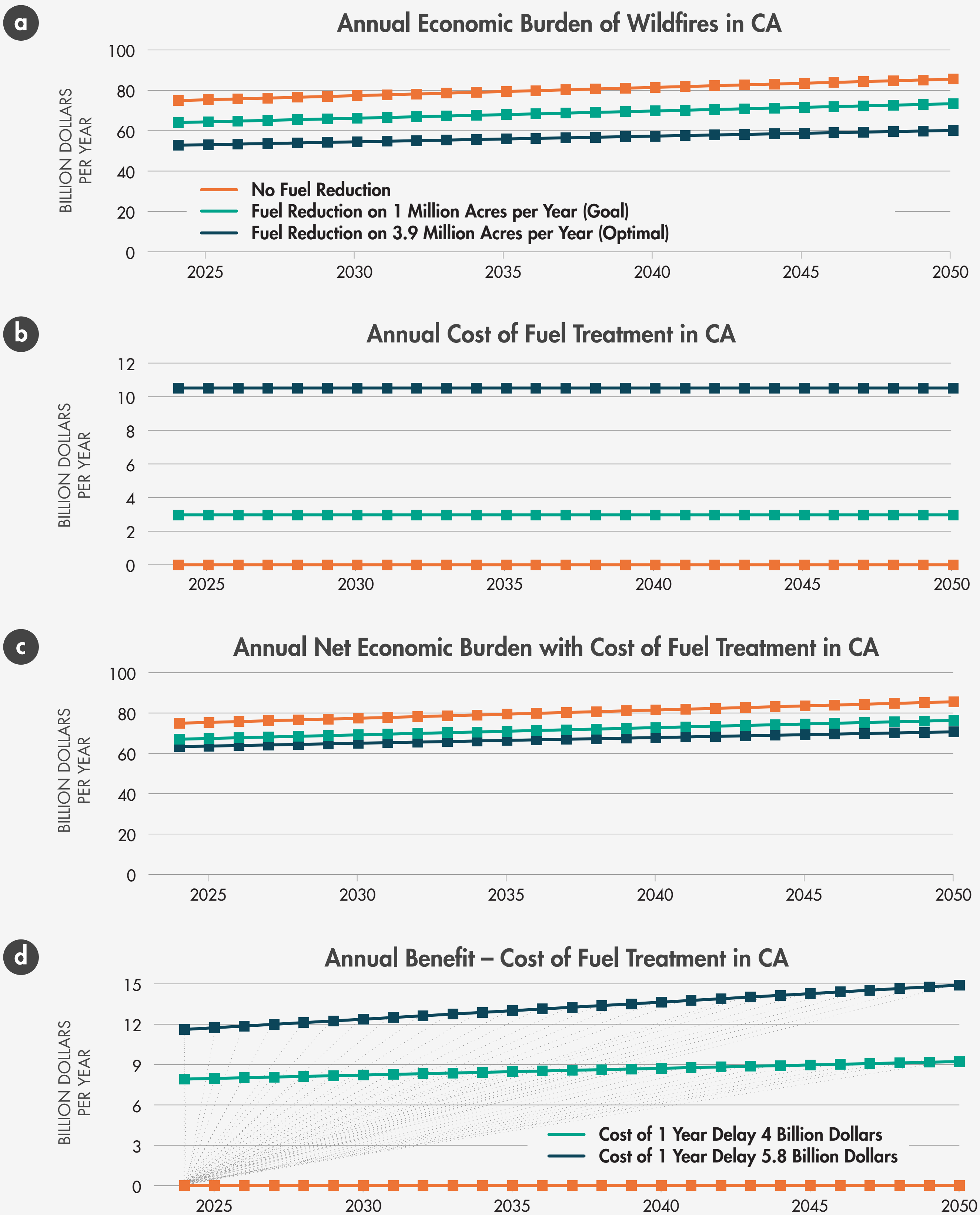

Figure 9: Trajectories of economic burden from wildfires, costs of fuel reduction, net burden, and net benefits of fuel reduction. The orange line is a no-fuel reduction scenario. The green line represents the articulated 1 million acres per year goal, and the dark blue line represents the optimal 3.9 million acres per year scenario.

Confidence Ranges for Primary Results

The costs, benefits, and costs of delay in reaching the final condition calculations all have confidence ranges based on a range of possible values used as input parameters. The primary drivers of those ranges are a) uncertainty in the baseline economic burden from wildfires, b) uncertainty in the proportionality between changes in Fire Intensity Potential and changes in the economic burden from wildfires, and c) uncertainty in the costs of treatment.

We explicitly show the primary results as a function of wide ranges in uncertainties a) and c) that should certainly encompass their true values (Figures 10, 11, and 12). These ranges are $5 billion to $150 billion per year for economic burden and 30% to 230% of the baseline values for cost of treatment (Table 2, holding the treatment frequency constant). This calculation effectively results in a range of $800 to $6,000 of treatment cost per acre.

We also note that testing the results as a function of the range in uncertainty a) is equivalent to testing the results' sensitivity to the proportionality between changes in Fire Intensity Potential and changes in economic burden from wildfires (uncertainty b). For example, comparing an economic burden of $75 billion per year to $20 billion per year is equivalent to holding the economic burden at $75 billion per year and testing the sensitivity of the results to Δ(Economic Burden)Δ(Fire Intensity Potential)=($20 billion per year)/($75 billion per year)=0.27.

Ten numbers are expressed as bars in Figure 8. Figures 10 and 12 show the range of these numbers as a function of ranges in uncertainties a) and c).

For the 1 million acres per year fuel reduction plan, the net benefit ranges can be as high as $21 billion per year if the economic burden is high and the cost of treatment is low. The black line in Figure 10, panel c shows overall net benefit from overall net cost and indicates that, for the 1 million acres per year plan to have a negative benefit-cost ratio, the costs of treatment would need to be over approximately $3,000 per acre (about triple US Forest Service estimates), and the net economic burden would need to be below $20 billion per year (less than 20% of its assessed value in two recent analyses[105,106]).

For the optimal area-treated scenario (the area of which adjusts with the ranges of the other parameters), the net benefit ranges can be as high as $55 billion per year if the economic burden is high and the cost of treatment is low. The red line in Figure 12, panel c delineates $1 billion in net benefit and indicates that, for treatment to confer below $1 billion in net benefit, the costs would need to be over approximately $3,000 per acre (about triple US Forest Service estimates), and the net economic burden would need to be below $30 billion per year (less than 30% of its assessed value in two recent analyses[107,108]).

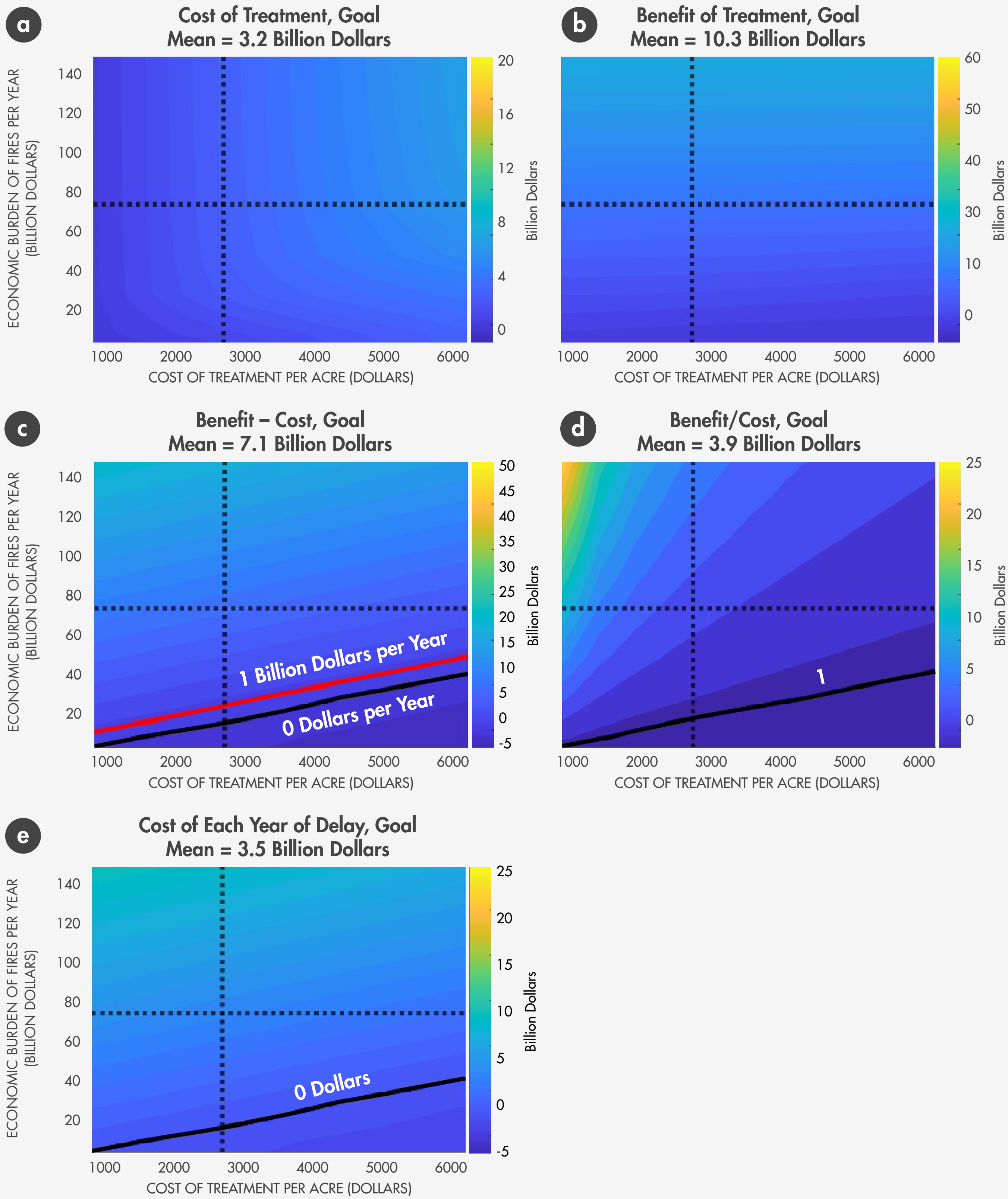

Figure 10: Confidence ranges as function of both costs of treatment and economic burden of wildfires for five primary results associated with the 1 million acres per year goal shown in Figure 8. The joint 25th to 75th percentiles of the values shown here inform the error bars in Figure 8. Dashed lines represent the central input parameters.

Figure 11 shows the endogenously calculated fuel reduction treatment rates as a function of the uncertainty ranges in the costs of treatment and the economic burden of wildfires. When costs of treatment are low and the economic burden from wildfires is high, these calculations suggest fuel reductions on over 10 million acres per year are optimal, which would put approximately 40 million acres (out of 48 million acres in our domain) under perpetual fuel treatment (Figure 5). The black line shows the 1 million acres per year contour, which indicates that the state's articulated goal would be sufficient to maximize net benefit only under relatively high costs of treatments and low economic burdens from wildfires.

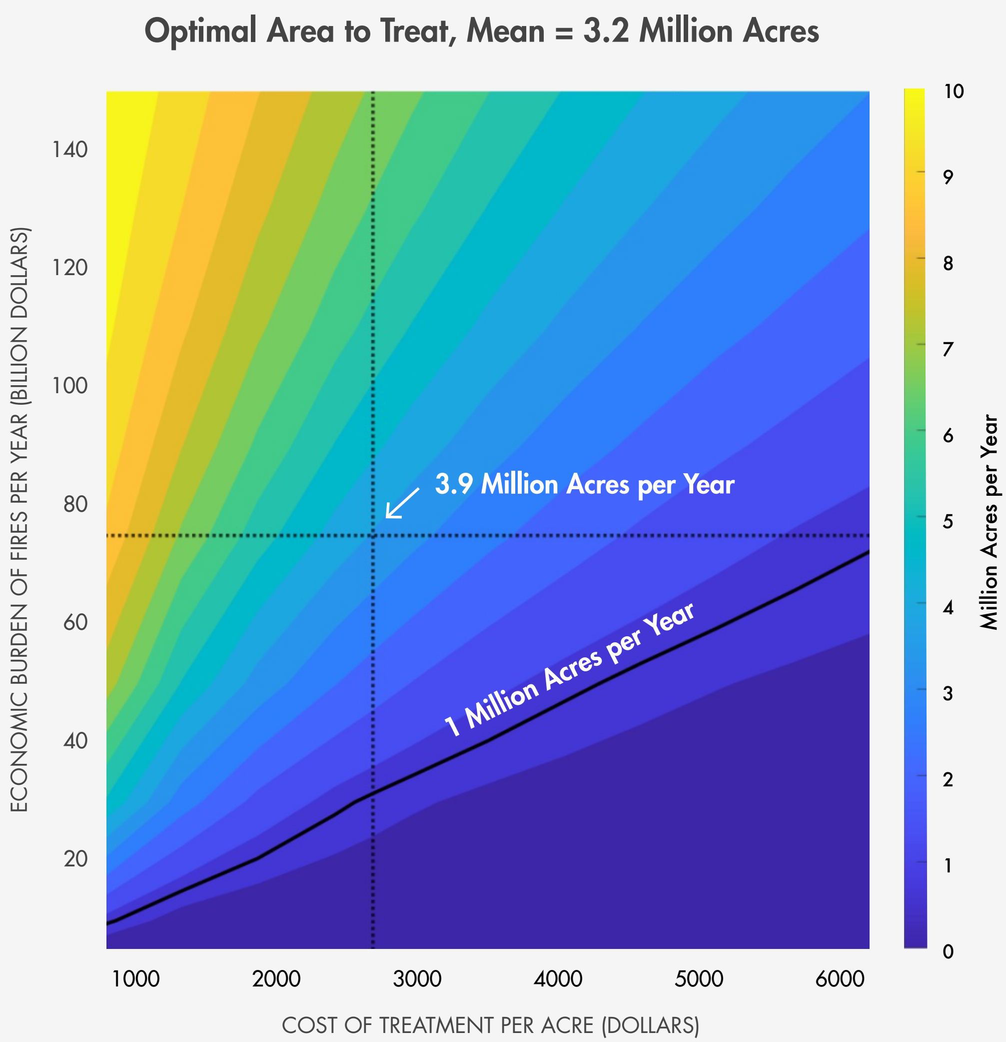

Figure 11: Calculated optimal area that should undergo fuel reduction if goal is to maximize net benefit as function of input assumptions for both costs of treatment and economic burden of wildfires. Dashed lines represent the central input parameters.

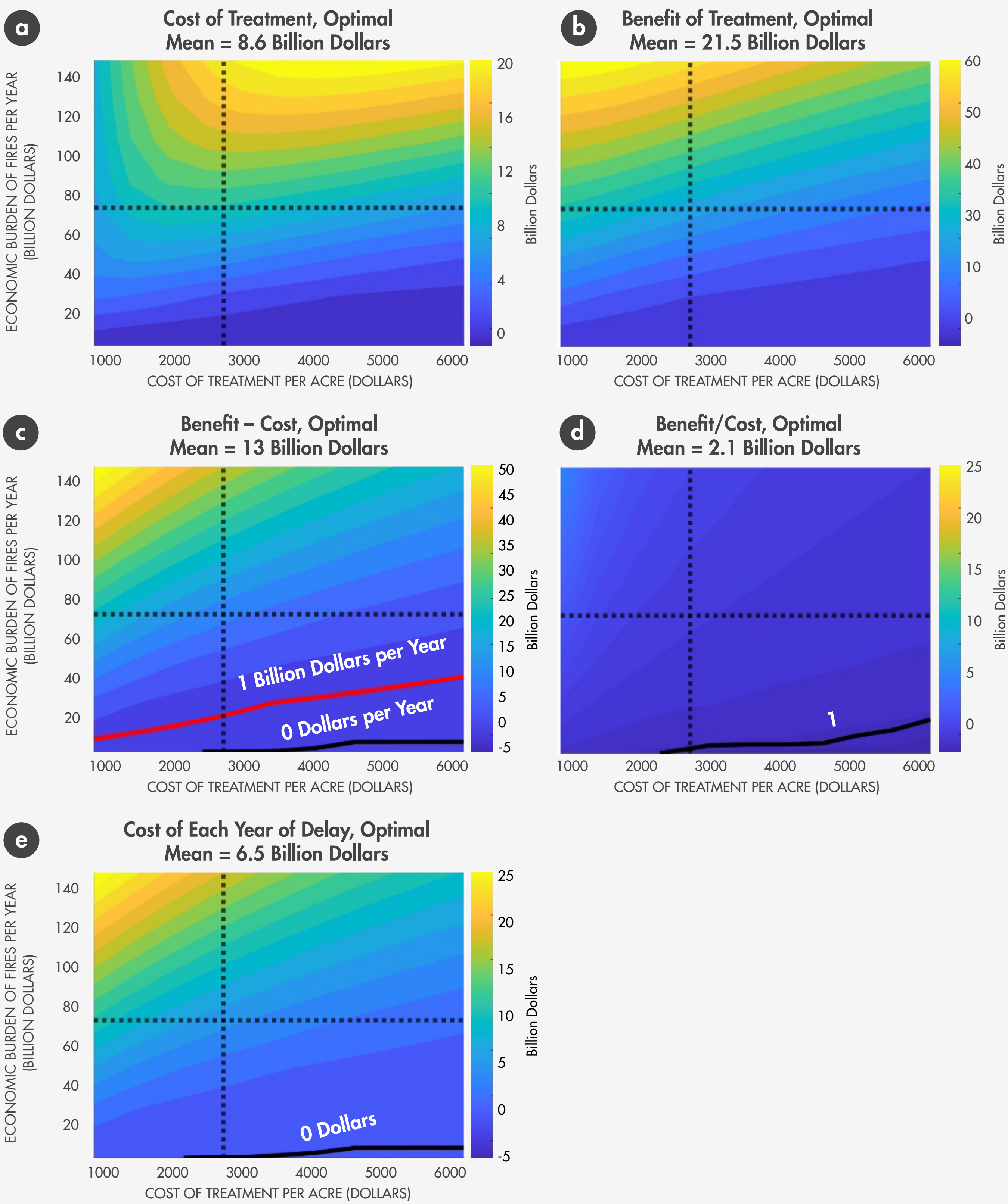

Figure 12: Confidence ranges as a function of both costs of treatment and economic burden of wildfires for five primary results associated with optimal acres per year scenario (calculated endogenously, Figure 11). The joint 25th to 75th percentiles of the values shown here inform the error bars in Figure 8. Dashed lines represent the central input parameters.

CONCLUSION

Overall, this analysis indicates that the economic benefits of fuel reduction treatments are likely to be far larger than their costs. Under our central input parameters, the state of California's articulated goal of reducing fuels on 1 million acres per year would cost $3 billion annually but would confer a benefit of $10.9 billion annually for a net benefit of $7.9 billion annually.

We also found that the optimal rate of fuel reduction in California—the rate that maximizes the net annual economic benefit—is approximately 3.9 million acres per year, or 3.9 times the state's articulated goal. At this rate of fuel reduction, the annual cost would be $10.5 billion, but it would confer a benefit of $22.2 billion annually and a net benefit of $11.6 billion annually.

Our analysis demonstrates that inaction is costly. The cost of *each year* of delay in scaling up fuel treatment to 1 million acres per year is calculated to be $4 billion, and the cost of each year of delay in scaling up fuel treatment to 3.9 million acres per year would be $5.8 billion (Figure 8).

We also investigated the confidence intervals around these results as a function of a wide range of assumptions on the economic burden of wildfires as well as the costs of fuel reduction. We found that the net benefit of scaling up fuel reductions may be many 10s of billions of dollars annually and that the only way for the 1 million acres per year scenario to *not* confer large net benefits would be if the third party estimates of the economic burden from wildfires were overestimated by a factor of several and the third party estimates of the cost of treatment were underestimated by a substantial margin.

Thus, these results demonstrate a clear economic justification for the rapid scale-up of fuel reduction efforts in California to at least the state's articulated goal of 1 million acres per year, with greater economic benefits likely to be achieved with larger rates of fuel reduction.

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REFERENCES

1 Scott L. Stephens, Robert E. Martin, and Nicholas E. Clinton, "Prehistoric Fire Area and Emissions from California's Forests, Woodlands, Shrublands, and Grasslands," *Forest Ecology and Management* 251(2007): 205-16, https://doi.org/10.1016/j.foreco.2007.06.005.

2 David M. J. S. Bowman et al., "Vegetation Fires in the Anthropocene," *Nature Reviews Earth & Environment* 1(2020): 500-15, https://doi.org/10.1038/s43017-020-0085-3.

3 Jennifer R. Marlon et al., "Long-Term Perspective on Wildfires in the Western USA," *Proceedings of the National Academy of Sciences* 109(2012): E535-E543, https://doi.org/10.1073/pnas.1112839109.

4 Marshall Burke et al., "The Changing Risk and Burden of Wildfire in the United States," *Proceedings of the National Academy of Sciences* 118(2021): e2011048118, https://doi.org/10.1073/pnas.2011048118.

5 Gavin M. Jones et al., "Forest Restoration Limits Megafires and Supports Species Conservation Under Climate Change," *Frontiers in Ecology and the Environment* 20(2022): 210-16, https://doi.org/10.1002/fee.2450.

6 Marco Turco et al., "Anthropogenic Climate Change Impacts Exacerbate Summer Forest Fires in California," *Proceedings of the National Academy of Sciences* 120(2023), https://doi.org/10.1073/pnas.2213815120.

7 Piyush Jain et al., "Observed Increases in Extreme Fire Weather Driven by Atmospheric Humidity and Temperature," *Nature Climate Change* 12(2022): 63-70, https://doi.org/10.1038/s41558-021-01224-1.

8 John T. Abatzoglou and A. Park Williams, "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests," *Proceedings of the National Academy of Sciences* 113(2016): 11770-75, https://doi.org/10.1073/pnas.1607171113.

9 Patrick T. Brown et al., "Climate Warming Increases Extreme Daily Wildfire Growth Risk in California," *Nature* 621(2023): 760-66, https://doi.org/10.1038/s41586-023-06444-3.

10 A. Park Williams et al., "Observed Impacts of Anthropogenic Climate Change on Wildfire in California," *Earth's Future* 7(2019): 892-910, https://doi.org/10.1029/2019ef001210.

11 Carlin Frances Starrs et al., "The Impact of Land Ownership, Firefighting, and Reserve Status on Fire Probability in California," *Environmental Research Letters* 13(2018): 034025, https://doi.org/10.1088/1748-9326/aaaad1.

12 Alexandra D. Syphard et al., "Human Presence Diminishes the Importance of Climate in Driving Fire Activity across the United States," *Proceedings of the National Academy of Sciences* 114(2017): 13750-55, https://doi.org/10.1073/pnas.1713885114.

13 Jennifer K. Balch et al., "Warming Weakens the Night-Time Barrier to Global Fire," *Nature* 602(2022): 442-48, https://doi.org/10.1038/s41586-021-04325-1.

14 R. Chelsea Nagy et al., "Human-Related Ignitions Increase the Number of Large Wildfires across U.S. Ecoregions," *Fire* 1(2018): 4, https://doi.org/10.3390/fire1010004.

15 Volker C. Radeloff et al., "Rapid Growth of the US Wildland-Urban Interface Raises Wildfire Risk," *Proceedings of the National Academy of Sciences* 115(2018): 3314-19, https://doi.org/10.1073/pnas.1718850115.

16 Volker C. Radeloff et al., "Rising Wildfire Risk to Houses in the United States, Especially in Grasslands and Shrublands," *Science* 382(2023): 702-7, https://doi.org/10.1126/science.ade9223.

17 D. H. Safford and D. V. M. K. Water, *Using Fire Return Interval Departure (FRID) Analysis to Map Spatial and Temporal Changes in Fire Frequency on National Forest Lands in California* (Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2014).

18 Brandon M. Collins et al., "A Quantitative Comparison of Forest Fires in Central and Northern California Under Early (1911–1924) and Contemporary (2002–2015) Fire Suppression," *International Journal of Wildland Fire* 28(2019): 138, https://doi.org/10.1071/WF18137.

19 Gabrielle F. S. Boisramé, Timothy J. Brown, and Dominique M. Bachelet, "Trends in Western USA Fire Fuels Using Historical Data and Modeling," *Fire Ecology* 18(2022), https://doi.org/10.1186/s42408-022-00129-4.

20 Forest Service, U.S. Department of Agriculture, *Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests*, January 2022, https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Confronting-the-Wildfire-Crisis.pdf.

21 T. R. Graham, S. Mccaffrey, and B. T. Jain, *Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity* (Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2004).

22 Clarke A. Knight et al., "Land Management Explains Major Trends in Forest Structure and Composition over the Last Millennium in California's Klamath Mountains," *Proceedings of the National Academy of Sciences* 119(2022), https://doi.org/10.1073/pnas.2116264119.

23 Mark R. Kreider et al., "Fire Suppression Makes Wildfires More Severe and Accentuates Impacts of Climate Change and Fuel Accumulation," *Nature Communications* 15(2024), https://doi.org/10.1038/s41467-024-46702-0.

24 Elizabeth D. Reinhardt et al., "Objectives and Considerations for Wildland Fuel Treatment in Forested Ecosystems of the Interior Western United States," *Forest Ecology and Management* 256(2008): 1997-2006, https://doi.org/10.1016/j.foreco.2008.09.016.

25 Forest Service, *Confronting the Wildfire Crisis.*

26 Graham, Mccaffrey, and Jain, *Science Basis for Changing Forest Structure.*

27 Forest Service, *Confronting the Wildfire Crisis.*

28 Governor's Forest Management Task Force, *California's Wildfire and Forest Resilience Action Plan*, January 2021, https://wildfiretaskforce.org/action-plan/.

29 Patrick E. Clark et al., "Evaluating the Efficacy of Targeted Cattle Grazing for Fuel Break Creation and Maintenance," *Rangeland Ecology & Management* 89(2023): 69-86, https://doi.org/10.1016/j.rama.2023.02.005.

30 G. R. Beebe et al., *Smoke, Goats, and Oaks: Effects of Goat Browsing and Prescribed Fire on Woodland Structure and Floristic Composition in Ozark Hardwoods* (Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2022).

31 Patrick T. Brown et al., "The Potential for Fuel Reduction to Offset Climate Warming Impacts on Wildfire Intensity in California," *EarthArXiv [Preprint]* (2024), https://doi.org/10.31223/X5BT49.

32 Jones et al., "Forest Restoration Limits Megafires."

33 Jeffrey E. Ott, Francis F. Kilkenny, and Theresa B. Jain, "Fuel Treatment Effectiveness at the Landscape Scale: A Systematic Review of Simulation Studies Comparing Treatment Scenarios in North America," *Fire Ecology* 19(2023), https://doi.org/10.1186/s42408-022-00163-2.

34 Alan H. Taylor, Lucas B. Harris, and Carl N. Skinner, "Severity Patterns of the 2021 Dixie Fire Exemplify the Need to Increase Low-Severity Fire Treatments in California's Forests," *Environmental Research Letters* 17(2022): 071002, https://doi.org/10.1088/1748-9326/ac7735.

35 Samuel G. Evans et al., "Modeling the Risk Reduction Benefit of Forest Management Using a Case Study in the Lake Tahoe Basin," *Ecology and Society* 27(2022), https://doi.org/10.5751/ES-13169-270218.

36 Nicole M. Vaillant et al., "Effect of Fuel Treatments on Fuels and Potential Fire Behavior in California, USA, National Forests," *Fire Ecology* 5(2009): 14-29, https://doi.org/10.4996/fireecology.0502014.

37 Jolie Pollet and Philip N. Omi, "Effect of Thinning and Prescribed Burning on Crown Fire Severity in Ponderosa Pine Forests," *International Journal of Wildland Fire* 11(2002): 1, https://doi.org/10.1071/WF01045.

38 James K. Agee and M. Reese Lolley, "Thinning and Prescribed Fire Effects on Fuels and Potential Fire Behavior in an Eastern Cascades Forest, Washington, USA," *Fire Ecology* 2(2006): 3-19, https://doi.org/10.4996/fireecology.0202003.

39 Susan J. Prichard, David L. Peterson, and Kyle Jacobson, "Fuel Treatments Reduce the Severity of Wildfire Effects in Dry Mixed Conifer Forest, Washington, USA," *Canadian Journal of Forest Research* 40(2010): 1615-26, https://doi.org/10.1139/X10-109.

40 Xiao Wu et al., "Low-Intensity Fires Mitigate the Risk of High-Intensity Wildfires in California's Forests," *Science Advances* 9(2023), https://doi.org/10.1126/sciadv.adi4123.

41 Susan J. Prichard et al., "Fuel Treatment Effectiveness in the Context of Landform, Vegetation, and Large, Wind-Driven Wildfires," *Ecological Applications* 30(2020), https://doi.org/10.1002/eap.2104.

42 H. D. Safford et al., "Fuel Treatment Effectiveness in California Yellow Pine and Mixed Conifer Forests," *Forest Ecology and Management* 274(2012): 17-28, https://doi.org/10.1016/j.foreco.2012.02.013.

43 Scott L. Stephens et al., "The Effects of Forest Fuel-Reduction Treatments in the United States," *BioScience* 62(2012): 549-60, https://doi.org/10.1525/bio.2012.62.6.6.

44 M. P. North et al., "Pyrosilviculture Needed for Landscape Resilience of Dry Western United States Forests," *Journal of Forestry* 119(2021): 520-44, https://doi.org/10.1093/jofore/fvab026.

45 Kimberley T. Davis et al., “Tamm Review: A Meta-Analysis of Thinning, Prescribed Fire, and Wildfire Effects on Subsequent Wildfire Severity in Conifer Dominated Forests of the Western US,” *Forest Ecology and Management* 561(2024): 121885, https://doi.org/10.1016/j.foreco.2024.121885.

46 Teresa J. Feo et al., *The Costs of Wildfire in California: An Independent Review of Scientific and Technical Information* (Sacramento: California Council on Science and Technology, 2020). https://ccst.us/wp-content/uploads/The-Costs-of-Wildfire-in-California-FULL-REPORT.pdf.

47 Governor’s Forest Management Task Force, *California’s Wildfire and Forest Resilience Action Plan.*

48 Brown et al., “Potential for Fuel Reduction to Offset Climate Warming Impacts.”

49 James Paci, Matthew Newman, and Tim Gage, *The Economic, Fiscal, and Environmental Costs of Wildfires in California* (Palo Alto, CA: Gordon and Betty Moore Foundation, 2023), https://www.moore.org/docs/default-source/default-document-library/the-economic-fiscal-and-environmental-costs-of-wildfires-in-ca.pdf.

50 Feo et al., *Costs of Wildfire in California.*

51 Feo et al., *Costs of Wildfire in California.*

52 Paci, Newman, and Gage, *Economic, Fiscal, and Environmental Costs of Wildfires in California.*

53 Daoping Wang et al., “Economic Footprint of California Wildfires in 2018,” *Nature Sustainability* 4(2020): 252-60, https://doi.org/10.1038/s41893-020-00646-7.

54 Kimiko Barrett, *Full Community Costs of Wildfire*, Headwaters Economics, May 2018, https://headwaterseconomics.org/wp-content/uploads/full-wildfire-costs-report.pdf.

55 “Climate-Exacerbated Wildfires Cost the U.S. between $394 to $893 Billion Each Year in Economic Costs and Damages,” U.S. Congress Joint Economic Committee, October 2023, https://www.jec.senate.gov/public/_cache/files/9220abde-7b60-4d05-ba0a-8cc20df44c7d/jec-report-on-total-costs-of-wildfires.pdf.

56 J. Zhuang et al., *Total Cost of Fire in the United States* (Buffalo, NY: Fire Protection Research Foundation, 2017).

57 J. R. Hall, *The Total Cost of Fire in the United States* (Quincy, MA: National Fire Protection Association, 2014).

58 Douglas S. Thomas et al., *The Costs and Losses of Wildfires: A Literature Survey* (Gaithersburg, MA: National Institute of Standards and Technology, 2017).

59 Zhuang et al., *Total Cost of Fire in the United States.*

60 Hall, *Total Cost of Fire in the United States.*

61 Thomas et al., *Costs and Losses of Wildfires.*

62 “Climate-Exacerbated Wildfires Cost the U.S.”

63 Wang et al., “Economic Footprint of California Wildfires.”

64 Paci, Newman, and Gage, *Economic, Fiscal, and Environmental Costs of Wildfires in California.*

65 Barrett, *Full Community Costs of Wildfire.*

66 Feo et al., *Costs of Wildfire in California.*

67 Brown et al., "Potential for Fuel Reduction to Offset Climate Warming Impacts."

68 Balch et al., "Warming Weakens the Night-Time Barrier."

69 M. J. Wooster et al., "Retrieval of Biomass Combustion Rates and Totals from Fire Radiative Power Observations: FRP Derivation and Calibration Relationships between Biomass Consumption and Fire Radiative Energy Release," *Journal of Geophysical Research: Atmospheres* 110(2005), https://doi.org/10.1029/2005jd006318.

70 Charles Ichoku et al., "Global Characterization of Biomass-Burning Patterns Using Satellite Measurements of Fire Radiative Energy," *Remote Sensing of Environment* 112(2008): 2950-62, https://doi.org/10.1016/j.rse.2008.02.009.

71 C. Ichoku and L. Ellison, "Global Top-Down Smoke-Aerosol Emissions Estimation Using Satellite Fire Radiative Power Measurements," *Atmospheric Chemistry and Physics* 14(2014): 6643-67, https://doi.org/10.5194/acp-14-6643-2014.

72 W. Tang and A. F. Arellano, "Investigating Dominant Characteristics of Fires across the Amazon during 2005–2014 through Satellite Data Synthesis of Combustion Signatures," *Journal of Geophysical Research: Atmospheres* 122(2017): 1224-45, https://doi.org/10.1002/2016jd025216.

73 Pierre Laurent et al., "Varying Relationships between Fire Radiative Power and Fire Size at a Global Scale," *Biogeosciences* 16(2019): 275-88, https://doi.org/10.5194/bg-16-275-2019.

74 Wu et al., "Low-Intensity Fires Mitigate the Risk."

75 William J. Bond and Jon E. Keeley, "Fire as a Global 'Herbivore': The Ecology and Evolution of Flammable Ecosystems," *Trends in Ecology & Evolution* 20(2005): 387-94, https://doi.org/10.1016/j.tree.2005.04.025.

76 Brown et al., "Potential for Fuel Reduction to Offset Climate Warming Impacts."

77 Brown et al., "Potential for Fuel Reduction to Offset Climate Warming Impacts."

78 José J. Sánchez et al., "Do Fuel Treatments in U.S. National Forests Reduce Wildfire Suppression Costs and Property Damage?," *Journal of Natural Resources Policy Research* 9(2019): 42-73, https://doi.org/10.5325/naturesopolirese.9.1.0042.

79 Heesol Chang et al., "The Cost of Forest Thinning Operations in the Western United States: A Systematic Literature Review and New Thinning Cost Model," *Journal of Forestry* 121(2023): 193-206, https://doi.org/10.1093/jofore/fvac037.

80 Chang et al., "Cost of Forest Thinning Operations in the Western United States."

81 Alison H. Berry and Hayley Hesseln, "The Effect of the Wildland-Urban Interface on Prescribed Burning Costs in the Pacific Northwestern United States," *Journal of Forestry* 102(2004): 33–37, https://doi.org/10.1093/jof/102.6.33.

82 Chang et al., "Cost of Forest Thinning Operations in the Western United States."

83 Chang et al., "Cost of Forest Thinning Operations in the Western United States."

84 David Wear, Matthew Wibbenmeyer, and Emily Joiner, *The Economics of Forest Fuel Removals on Federal Lands*, Resources for the Future, June 2023, https://media.rff.org/documents/WP_23-27_v3.pdf.

85 Cecilia Clavet et al., *Wildfire Resilience Funding: Building Blocks for a Paradigm Shift*, The Nature Conservancy, June 2021, https://www.nature.org/content/dam/tnc/nature/en/documents/WildfireResilienceFunding_TNC_6-30-21.pdf.

86 Chang et al., "Cost of Forest Thinning Operations in the Western United States."

87 Chelsea L. Andreozzi, Jennifer B. Smith, and Steven M. Ostoja, *Central Coast Regional Profile*, a report prepared by the Science Advisory Panel for the California Wildfire and Forest Resilience Task Force, May 2023, https://wildfiretaskforce.org/wp-content/uploads/2023/05/CentralCoast_RegionalProfile_May2023_V2.pdf.

88 Andreozzi, Smith, and Ostoja, *Central Coast Regional Profile.*

89 Clavet et al., *Wildfire Resilience Funding.*

90 Wu et al., "Low-Intensity Fires Mitigate the Risk."

91 Davis et al., "Tamm Review."

92 Brandon M. Collins et al., "Modeling Hazardous Fire Potential within a Completed Fuel Treatment Network in the Northern Sierra Nevada," *Forest Ecology and Management* 310(2013): 156-66, https://doi.org/10.1016/j.foreco.2013.08.015.

93 José Manuel Fernández-Guisuraga and Paolo M. Fernandes, "Prescribed Burning Mitigates the Severity of Subsequent Wildfires in Mediterranean Shrublands," *Fire Ecology* 20 (2024), https://doi.org/10.1186/s42408-023-00233-z.

94 Ott, Kilkenny, and Jain, "Fuel Treatment Effectiveness at the Landscape Scale."

95 Prichard et al., "Fuel Treatment Effectiveness."

96 Ana M. G. Barros et al., "Improving Long-Term Fuel Treatment Effectiveness in the National Forest System through Quantitative Prioritization," *Forest Ecology and Management* 433(2019): 514-27, https://doi.org/10.1016/j.foreco.2018.10.041.

97 Daniel J. Krofcheck et al., "Prioritizing Forest Fuels Treatments Based on the Probability of High-Severity Fire Restores Adaptive Capacity in Sierran Forests," *Global Change Biology* 24(2018): 729-37, https://doi.org/10.1111/gcb.13913.

98 Fermin Alcasena et al., "Contrasting the Efficiency of Landscape versus Community Protection Fuel Treatment Strategies to Reduce Wildfire Exposure and Risk," *Journal of Environmental Management* 309(2022): 114650, https://doi.org/10.1016/j.jenvman.2022.114650.

99 Carmen L. Tubbesing et al., "Strategically Placed Landscape Fuel Treatments Decrease Fire Severity and Promote Recovery in the Northern Sierra Nevada," *Forest Ecology and Management* 436(2019): 45-55, https://doi.org/10.1016/j.foreco.2019.01.010.

100 David A. Schmidt, Alan H. Taylor, and Carl N. Skinner, "The Influence of Fuels Treatment and Landscape Arrangement on Simulated Fire Behavior, Southern Cascade Range, California," *Forest Ecology and Management* 255(2008): 3170-84, https://doi.org/10.1016/j.foreco.2008.01.023.

101 Young-Hwan Kim, Pete Bettinger, and Mark Finney, "Spatial Optimization of the Pattern of Fuel Management Activities and Subsequent Effects on Simulated Wildfires," *European Journal of Operational Research* 197(2009): 253-65, https://doi.org/10.1016/j.ejor.2008.05.025.

102 Brown et al., "Potential for Fuel Reduction to Offset Climate Warming Impacts."

103 Forest Service, *Confronting the Wildfire Crisis.*

104 Eric Edwards and Sara Sutherland, *Does Environmental Review Worsen the Wildfire Crisis?*, PERC Policy Brief, June 2022, https://www.perc.org/wp-content/uploads/2022/06/PERC-PolicyBrief-NEPA-Web.pdf.

105 Paci, Newman, and Gage, *Economic, Fiscal, and Environmental Costs of Wildfires in California.*

106 Wang et al., "Economic Footprint of California Wildfires."

107 Paci, Newman, and Gage, *Economic, Fiscal, and Environmental Costs of Wildfires in California.*

108 Wang et al., "Economic Footprint of California Wildfires."

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