Scientific Evidence for Investable Wildfire, Water, Energy and Ecological Resilience in California

A targeted review of recent academic literature and implications for outcomes-based finance and the proposed Optimization Bond

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Abstract

This paper reviews a targeted set of recent academic outputs relevant to California wildfire, water, energy, biodiversity, insurance and public-health resilience. It does not claim to be a full systematic review. Its purpose is to identify what the recent science supports, what it does not yet prove, and what follows for outcomes-based resilience finance. The central conclusion is that California now has a stronger scientific basis for prevention, preparedness and ecological restoration as sources of avoided loss and public-good value. However, the benefits are heterogeneous, distributed across many beneficiaries and often require local validation before they can support project-level financial claims. This creates the case for a disciplined finance architecture capable of translating scientifically plausible outcomes into investable, governable and equitable portfolios. The proposed Optimization Bond (OB) is considered in that context: as a potential mechanism for aligning beneficiaries, payers and capital providers around measurable wildfire, water, energy, ecological, insurance and community-resilience outcomes.

Executive conclusion

The recent literature points toward a single strategic conclusion: California's resilience problem is not only a project shortage, capital shortage or insurance-market problem. It is a coordination problem. Scientific evidence increasingly supports the proposition that well-targeted prevention and ecological restoration can reduce wildfire spread, structure loss, smoke exposure, water-system and energy-system disruption, and ecosystem degradation. Insurance, investor and governance literature add an equally important point: even where risk reduction is scientifically plausible, the value is difficult to capture because benefits are distributed across households, insurers, electric utilities, water agencies, local governments,

employers, public-health systems, ecosystems and future taxpayers. Conventional project finance struggles to capture this distributed value.

The OB approach is relevant because it asks how these distributed benefits can be organised into a measurable, investable and accountable structure. The evidence reviewed here supports the need for an outcomes-based mechanism, but it also imposes strict guardrails. Published estimates of avoided damages, mortality burden, insurance response or water-quality impacts should not be transposed directly into local transactions without evidence. Equity, Indigenous stewardship, livelihoods, community wellbeing and ecological uplift should be treated as core design constraints rather than secondary co-benefits.

The scientific case therefore strengthens the OB proposition, while also sharpening it. A credible OB should not promise easy monetisation of resilience. It should offer a disciplined way to decide what can be measured, what can be financed, who benefits, who should pay, what safeguards are required and where uncertainty remains. That distinction is practically important for public agencies, investors, insurers and communities: the OB is not merely another labelled bond, but a proposed architecture for turning best-available science, beneficiary logic and outcome governance into investable public-good resilience.

How to read this paper: the OB and the evidence-to-implementation architecture

The OB is best understood as an outcomes-based finance architecture for resilience portfolios where the benefits of prevention are material but distributed. It starts not with the bond instrument, but with the outcome architecture: what risk reduction or resilience outcome is scientifically plausible; who benefits; what evidence is sufficient; what safeguards are required; and how performance should be monitored over time.

The associated Toolkit is an applied evidence and transaction-readiness framework. Its role is to translate science into baselines, evidence thresholds, beneficiary maps, data-room requirements, claim guardrails and outcome-reporting logic. In this paper, the Toolkit is not treated as a subject of software documentation. It is treated as the practical discipline behind the OB: a way of ensuring that the finance proposition remains evidence-led, locally calibrated, socially legitimate and ecologically grounded.

The review therefore asks a deliberately narrow question: does the recent academic and policy-relevant evidence point toward the kind of multi-beneficiary, outcome-oriented structure that the OB is intended to provide? On balance, the evidence points toward such a structure, provided that it is locally calibrated, evidence-led and governed with appropriate safeguards. The science supports prevention, monitoring and multi-benefit resilience. It does not support casual extrapolation from broad studies to local financial claims. That is why an OB must combine investment ambition with scientific caution.

1. Purpose and scope

This paper is designed as a foundation piece for public thought leadership and commercial engagement. It reviews recent academic literature relevant to California's wildfire, water, energy, biodiversity, public-health, insurance and governance challenges, and draws implications for outcomes-based resilience finance. The review is deliberately targeted rather than exhaustive. Papers were selected for recency, relevance to California or the western United States, methodological usefulness, direct connection to avoided loss or resilience outcomes, and relevance to finance design.

The paper balances academic objectivity with a practical hypothesis: the latest science strengthens the case for a finance architecture such as the proposed OB, provided that the mechanism is evidence-led, locally calibrated, socially legitimate and ecologically grounded. The paper therefore does not treat the OB as an assumed conclusion. It asks whether the evidence points toward the kind of multi-beneficiary, outcome-oriented structure that the OB is intended to provide.

2. Method and selection criteria

This targeted narrative review focuses on a core group of California-relevant academic outputs from 2024-2026, supplemented by finance, insurance, investor, governance and policy-implementation literature. It also considers live California policy and market touchpoints, including SB 254, SB 1297, AB 1795, AB 1642 and SB 894, as non-academic indicators of policy direction. Those materials are not used as scientific evidence, but they are relevant to the commercial and implementation context in which the OB would operate.

- **Geography:** California or western-U.S. evidence was prioritised, with U.S.-wide evidence included where directly relevant to smoke, health, energy, insurance or finance architecture.
- **Recentness:** papers from 2024-2026 were prioritised to reflect the current state of science and policy debate.
- **Actionability:** papers were selected where findings could affect baselines, due diligence, monitoring, intervention targeting, beneficiary mapping, investment logic or safeguards.
- **Balance:** the review includes biophysical science, economics, public health, water quality, energy-system resilience, ecological monitoring, ecocultural stewardship, insurance, investor risk, governance and adaptation finance.
- **Guardrails:** each paper is interpreted for what it supports and what it does not support at project- or transaction-level.

Sources are interpreted according to evidentiary role. Peer-reviewed empirical papers are used as scientific evidence; datasets are used as monitoring and measurement infrastructure; working papers and legal scholarship are used as finance or regulatory interpretation; and pending bills, agency reports and policy submissions are treated only as market and policy signals. This review therefore supports evidence-led finance design; it does not quantify an OB transaction, rank interventions for implementation, or treat broad literature values as locally validated cash-flow assumptions.

Table 1. Review logic and contribution of the selected literature

Evidence theme	Representative papers or sources	Contribution to the review
Avoided loss and intervention value	Strabo, Bryan and Reimer (2026); Zamanialaei et al. (2025); Hakkenberg et al. (2024)	Shows that mitigation and treatment can be linked to measurable differences in spread, severity, structure survival and avoided damages, while also requiring careful local calibration.
Dynamic risk baselines	Kumar et al. (2025); Madakumbura et al. (2025)	Shows that California wildfire risk is not well represented by static historical baselines because climate, fire season timing, human ignition and WUI expansion interact.
Monitoring and ecological function	Domenech et al. (2026); Power et al. (2024); Hankins (2024)	Shows that credible resilience finance needs ecological monitoring, process-based ecosystem understanding and legitimacy in stewardship governance.
Water and public health channels	Brucker et al. (2025); Qiu et al. (2025)	Shows that wildfire risk transmits into multi-year water-quality, smoke-health and economic productivity channels beyond burned acreage and structure loss.
Energy, grid and utility resilience	Vahedi et al. (2025); Warner, Callaway and Fowlie (2025); Singh, Ong and Sud (2025)	Shows that wildfire risk and energy-system resilience are coupled through power-line ignition, grid operations, reliability, mitigation cost and electricity affordability.
Finance, insurance and investor logic	Meraj and Hashimoto (2025); Motlagh et al. (2024); Boomhower et al. (2024); Sproul (2025); Bressan et al. (2024)	Shows why scientifically plausible resilience benefits do not automatically become investable cash flows or insurance-market responses.
Governance, legislation and implementation	County-level planning, adaptation-governance and adaptation-finance equity literature; SB 254, SB 1297, AB 1795, AB 1642 and SB 894	Shows that coordination, statutory pathways, evidence standards, equity and implementation capacity are central to resilience finance.

3. The emerging scientific picture

The literature does not reduce California's resilience challenge to a single variable. It presents a coupled system: climate change shifts fire timing and weather; WUI expansion increases exposure; fuel structure influences severity; household and community measures affect structure survival; wildfires degrade water quality for years; energy infrastructure can be both exposed asset and ignition source; smoke produces public-health consequences; freshwater ecosystems require process-based resilience; and Indigenous stewardship provides governance and ecological knowledge that conventional technocratic models often under-recognise.

This systems view is significant for finance. If risk and benefit are coupled across hazards, sectors and geographies, then financing should not be organised solely around isolated projects or single-benefit metrics. The science points toward portfolio design, cross-beneficiary logic, long time horizons and explicit safeguards against overclaiming.

4. Cross-cutting findings

4.1 Prevention is increasingly measurable, but not automatically bankable

Fuel-treatment economics, WUI structure-risk analysis and remote-sensing studies all strengthen the proposition that prevention can reduce losses. Yet none of these findings eliminates the need for local evidence. A statewide or western-U.S. benchmark is not a transaction-specific cash flow. It is a plausibility anchor that should trigger due diligence: What intervention is proposed? Where? At what scale? Against what counterfactual? With what treatment-effect evidence, monitoring and maintenance plan?

4.2 The right unit of intervention is often the portfolio

The WUI and water-quality papers suggest that resilience benefits operate through neighbourhood, basin and system effects. Structure spacing, defensible space, ember exposure and community uptake determine survival; wildfire impacts travel downstream through source-water systems; smoke exposure affects populations far beyond the burn perimeter. Financing therefore needs to bundle interventions where benefits are interdependent.

4.3 Dynamic risk requires dynamic baselines

The climate/WUI and fire-season-onset papers show that risk is moving. Historical average loss may understate the relevant counterfactual for prevention. This matters for finance because benefit-cost ratios, avoided expected annual loss and beneficiary allocations all depend on the baseline against which avoided risk is measured.

4.4 Water, health, biodiversity and livelihoods are not peripheral

Wildfire is not only a fire agency or insurance problem. It is also a water-quality, public-health, labour-productivity, ecological and community-wellbeing problem. The reviewed literature supports a broader resilience account in which avoided losses and positive outcomes include public-health protection, water-treatment cost reduction, source-water reliability, ecosystem function, biodiversity resilience and community livelihoods.

4.5 Equity and stewardship are design requirements

The ecocultural stewardship and adaptation-finance equity literature make a critical contribution. They remind finance designers that resilience is not merely a technical optimisation problem. Cultural burning, Indigenous stewardship, community governance, benefit-sharing and ecological relationships cannot be reduced to an instrumental add-on. In practice, however, these factors also affect delivery risk, legitimacy, maintenance and long-term performance. Equity is therefore both an ethical condition and a financial risk-control condition.

4.6 Insurance and investor response is not automatic

Insurance and investor literature complicates the simple claim that mitigation will automatically unlock private capital or lower premiums. Insurers differ in their ability to classify and price wildfire risk. Asset-level physical risk assessments reveal information that portfolio averages can miss. Regulation can improve access or create perverse incentives depending on design. These findings strengthen the OB case by showing that prevention value needs a mechanism for credible measurement, beneficiary alignment and governance, rather than assuming markets will convert risk reduction into finance unaided.

4.7 Wildfire resilience is also energy resilience

California's wildfire challenge is inseparable from energy-system resilience. Overhead power infrastructure can be an ignition source; wildfire, smoke and extreme weather can disrupt electricity delivery; public-safety power shutoffs impose community and economic costs; and hydropower, transmission corridors and critical facilities depend on resilient landscapes and watersheds. For outcomes-based finance, this widens the beneficiary map to include investor-owned utilities, public-power entities, community choice aggregators, hydropower operators, ratepayers, local governments and critical-service users. It also reinforces a central OB principle: resilience value must be measured across coupled systems, not isolated sectors.

Table 2. Synthesis of evidence streams, limits and OB implications

Literature stream	What it supports	What it does not prove	OB implication
Wildfire and WUI science	Prevention, hardening, defensible space, fuel treatment and targeting can reduce risk under specific conditions.	It does not turn statewide or regional benchmark results into project-level cash flow without local evidence.	Use local validation, dynamic baselines and counterfactual evidence before making transaction claims.
Water, energy, health and ecological science	Wildfire and climate risks transmit through water quality, energy reliability, smoke exposure, ecosystem function and community wellbeing.	It does not justify universal monetisation of every co-benefit or simple transfer of national estimates to local projects.	Broaden the beneficiary map while retaining conservative claim guardrails and local exposure evidence.

Insurance and investor literature	Granular risk information, risk classification and asset-level physical-risk assessment matter for capital allocation and insurance response.	It does not show that mitigation automatically lowers premiums, expands coverage or attracts investment.	Build insurer- and investor-usable evidence without assuming automatic market conversion.
Governance and policy literature	Planning quality, regional coordination, institutional capacity and equity influence resilience delivery.	It does not establish statutory certainty or guarantee that finance reaches the most vulnerable communities.	Embed governance, equity, capacity-building and implementation-readiness safeguards.
California policy and market touchpoints	SB 254, SB 1297, AB 1795, AB 1642 and SB 894 indicate policy interest in resilience finance, smoke standards and household mitigation support.	They are not academic evidence and, where pending, are not settled law.	Treat them as a market window for testing evidence-led, multi-beneficiary resilience finance.

5. Paper-by-paper review

5A. Core California resilience science

Table 3. Summary of reviewed core science papers and implications for outcomes-based finance

No.	Paper	Core evidence contribution	Implication for outcomes-based finance / OB architecture
i	Strabo, Bryan and Reimer (2026), Science	Large-scale empirical evaluation of U.S. Forest Service fuel treatments intersecting nearly 300 fires; public summaries report about $3.73-$3.75 avoided damage per $1 spent and about $2.8 billion in avoided losses.	Supports the proposition that prevention can be valued as avoided damage, but only as a benchmark unless locally calibrated.
ii	Zamanialaei et al. (2025), Nature Communications	California WUI analysis finds that structure spacing, exposure, hardening and	Moves the finance case from individual parcel measures toward

		defensible space interact; hypothetical mitigation scenario reports up to 52% structure-loss reduction.	community-scale mitigation, insurer relevance and neighbourhood spillover benefits.
iii	Kumar et al. (2025), npj Natural Hazards	Finds a 2.5-fold increase in high-risk fire weather and a 4.1-fold increase when WUI expansion is compounded with climate trend, with most extreme-impact fires originating near WUI.	Requires dynamic, forward-looking baselines rather than historical averages.
iv	Madakumbura et al. (2025), Science Advances	Attributes earlier fire-season onset across most California ecoregions to anthropogenic warming, with reported advancement of 6 to 46 days from 1992-2020.	Makes timing, implementation capacity and missed field seasons financially material.
v	Hakkenberg et al. (2024), Communications Earth & Environment	Uses GEDI lidar across 42 California fires and finds ladder-fuel indicators more consistently predict severity under extreme conditions than canopy volume indicators.	Improves targeting logic: finance should prioritize where manageable fuel structures are linked to severity reduction.
vi	Domenech et al. (2026), Scientific Data	Provides standardized prescribed-fire monitoring across 36 sites, 114 burn units, 972 plots and 1,838 surveys.	Supports ecological MRV and pre/post treatment verification rather than relying on treatment spend as a proxy for outcome.
vii	Brucker et al. (2025), Communications Earth & Environment	Finds multi-year water-quality degradation after wildfire across western U.S. watersheds, with carbon, nutrients and sediment remaining elevated for years.	Places water utilities, source-water protection and treatment costs within the same avoided-loss frame as wildfire mitigation.
viii	Power et al. (2024), PNAS	Argues for process-based understanding of California rivers, lakes and wetlands to recover degraded ecosystems and protect resilience, health and viability.	Expands outcomes beyond avoided asset loss to ecological function, water security and biodiversity resilience.

ix	Hankins (2024), PNAS	Frames California at the interface of climate, fire, water and ecocultural processes and highlights Indigenous stewardship as central to resilience.	Requires governance, equity, cultural burning, benefit-sharing and Indigenous stewardship to be part of the financial design.
x	Qiu et al. (2025), Nature	Projects wildfire-smoke PM2.5 could produce about 71,420 excess U.S. deaths per year by 2050 under a high-warming scenario, with mortality effects lasting up to three years.	Elevates smoke-health, labour productivity and fiscal-health channels as material resilience outcomes, with strong caution against simplistic monetisation.

i. Wildfire fuel treatments: prevention as measurable avoided loss

Strabo, Bryan and Reimer (2026) provide the most direct recent evidence for the economic proposition that proactive wildfire treatment can generate measurable avoided damages. The paper is important because it evaluates real fires that encountered fuel treatments rather than relying only on simulation. Public summaries report approximately $3.73-$3.75 in avoided wildfire damages per $1 spent and about $2.8 billion in avoided losses across the studied fires. The result is material for policy and finance, but should be interpreted carefully. It supports fuel treatment as a high-value prevention class, but it does not make any single project automatically financeable. Treatment type, scale, location, counterfactual risk, exposure, maintenance, timing and monitoring all matter. For an OB, this paper is best used as a benchmark and evidence anchor: it helps establish that prevention can produce measurable avoided losses, while reinforcing the need for localised data before any project-level financial claim is made.

ii. WUI structure risk: from parcel measures to community spillovers

Zamanialaei et al. (2025) analyse five major California WUI fires using CAL FIRE post-fire data, remote sensing, fire reconstruction and machine learning. Their abstract reports that spacing between structures, exposure, hardening and defensible space work together to mediate structure risk, with an XGBoost classifier predicting structure survivability with 82% accuracy and a hypothetical scenario showing a 52% reduction in losses. This is highly relevant to California because insurance stress, household affordability and municipal fiscal exposure are concentrated in communities, not only individual parcels. The paper strengthens the argument that home hardening and defensible space should be financed and measured as community-scale risk-reduction systems. For an OB, it implies that the unit of finance should often be a neighbourhood, community, county or corridor portfolio rather than a collection of isolated household measures.

iii. Climate and WUI compounding: the inadequacy of static baselines

Kumar et al. (2025) introduce an Integrated Human-centric Wildfire Risk Index and find that climate trends increased high-risk fire weather by 2.5-fold, while the combination of climate

trend and WUI expansion produced a 4.1-fold increase in conditions conducive to extreme-impact wildfires from 1990 to 2022. More than three-quarters of extreme-impact wildfires originated within 1 km of the WUI. The financial implication is fundamental. If risk is rising because climate and exposure are moving together, historical average losses are an insufficient baseline for prevention finance. The counterfactual for a California resilience investment should be a dynamic baseline that considers future risk escalation, not only avoided repeat of the past. This supports an OB design in which avoided-loss logic, pricing, beneficiary allocation and performance monitoring are all forward-looking.

iv. Earlier fire-season onset: time as a financial variable

Madakumbura et al. (2025) link anthropogenic warming to earlier fire-season onset across California ecoregions, with reported onset advances of 6 to 46 days in 11 of 13 ecoregions during 1992-2020. This finding changes the interpretation of implementation delay: a project postponed by one field season may face a longer and earlier annual risk window than past planning assumptions would suggest. For the OB, this makes delivery capacity financially material. Permitting, contracting, burn windows, workforce capacity, predevelopment liquidity and local readiness are not administrative details; they influence whether capital actually reaches the ground before risk materialises. The paper therefore supports financing designs that include predevelopment capital, readiness gates and capacity-building budgets as core resilience components.

v. Ladder fuels and remote sensing: better treatment targeting

Hakkenberg et al. (2024) use GEDI spaceborne lidar across 42 California wildfires and find that vertical continuity metrics, especially ladder fuels, consistently predict severity under extreme topographic and weather conditions. Because fuels are the component of fire behaviour most amenable to management, this evidence is directly relevant to prioritisation. For outcomes-based finance, the implication is that capital should be allocated not merely to areas with high hazard, but to places where manageable biophysical factors are linked to material risk reduction. The paper strengthens the case for including remote-sensing provenance, fuel-structure indicators and treatment-targeting evidence in due diligence. It also supports the OB distinction between spend and outcome: what matters is not whether a treatment happened, but whether the treatment addresses the fuel structures associated with severity.

vi. Prescribed-fire monitoring: from treatment activity to verified ecological response

Domenech et al. (2026) describe the California Prescribed Fire Monitoring Program dataset covering 2019-2024: 36 sites, 114 burn units, 972 plots and 1,838 surveys. The dataset includes pre-fire, immediate post-fire and multi-year post-fire monitoring of forest structure, fuels, mortality, vegetation response and regeneration. This is valuable because prescribed fire is often discussed politically and operationally without a consistent evidence base for ecological response. For an OB, the dataset supports a move from accounting for prescribed fire as a cost line to treating it as a monitored intervention with risk, carbon, biodiversity and ecological resilience outcomes. It also reinforces a general principle: outcome finance is only credible when intervention logic is accompanied by monitoring logic.

vii. Wildfire and water quality: resilience beyond the burn perimeter

Brucker et al. (2025) analyse burned and unburned basins across the western United States and find multi-year water-quality degradation after wildfire, including elevated organic carbon, nutrients and sediment. The paper is central to California because it demonstrates that wildfire is also a water-security and utility-cost event. Avoided burn severity, source-water protection, reservoir sediment risk, treatment costs and service continuity can all form part of a physical-to-fiscal resilience case. In an OB structure, this broadens the beneficiary map beyond fire agencies and property insurers to water utilities, hydropower operators, municipalities, agricultural users and downstream communities.

viii. Freshwater ecosystems: ecological process as resilience infrastructure

Power, Chandra, Gleick and Dietrich (2024) argue that California needs a process-based understanding of river, lake and wetland ecosystems to forecast responses to climate change and interventions. They stress recovery of degraded ecosystems and protection of existing ecosystem resilience, health and viability. This paper guards against a narrow interpretation of resilience finance as asset-loss reduction alone. Wetlands, rivers, floodplains and lakes are not only environmental amenities; they regulate hydrologic extremes, sustain biodiversity, support livelihoods and create social value. For the OB, this means ecological uplift should be treated as part of the outcome architecture, not a cosmetic co-benefit appended to a financial model.

ix. Ecocultural stewardship: legitimacy and justice as resilience conditions

Hankins (2024) places California at the interface of climate, fire, water and ecocultural processes and argues that Indigenous stewardship has sustained social-ecological resilience through past climate variability. The paper emphasises that climate resilience and biodiversity conservation are part of broader ecocultural relationships and responsibilities. This is important for the OB because outcomes-based finance must not reduce Indigenous stewardship, cultural burning or community wellbeing to monetised externalities. The finance architecture should respect sovereignty, governance rights, free, prior and informed consent where applicable, data rights, benefit-sharing and long-term stewardship. The paper strengthens the argument that equity and legitimacy are not only ethical requirements; they are also delivery and risk-management conditions.

x. Wildfire smoke and mortality: public health as a material outcome channel

Qiu et al. (2025) quantify U.S. wildfire-smoke PM2.5 mortality under climate change and project about 71,420 excess deaths per year by 2050 under a high-warming scenario, with evidence that mortality impacts can persist up to three years after exposure. The paper also monetises damages and concludes that smoke-health impacts may be among the most costly consequences of warming in the United States. For California, smoke converts wildfire from a perimeter-loss problem into a statewide and even interstate public-health problem. For the OB, it supports inclusion of smoke exposure, vulnerable populations, labour productivity and health-system burden in the outcome frame. At the same time, it requires caution: national mortality projections should not be used mechanically as local avoided-loss values. Local exposure, demographic, health and attribution evidence are necessary before using smoke-health benefits in a transaction case.

5B. Finance, insurance and investor literature

These papers explain why scientifically credible risk reduction does not automatically become investable finance, lower premiums or market participation. They are therefore central to the OB thesis.

Table 4. Finance, insurance and investor papers relevant to the OB proposition

No.	Paper	Core contribution	Implication for outcomes-based finance / OB architecture
xi	Meraj and Hashimoto (2025), Sustainability Science	Reviews the adaptation-finance gap and argues for greater use of nature-based solutions where they reduce future adaptation costs and deliver biodiversity and livelihood co-benefits.	Supports the OB emphasis on resilience portfolios that combine avoided-loss value with nature, livelihoods and public-good outcomes.
xii	Motlagh et al. (2024), International Journal of Disaster Risk Reduction	Reviews bonds for disaster resilience and finds that existing resilience-oriented bond practice varies widely, with many examples concentrated in flood and hurricane resilience.	Helps distinguish the OB from generic labelled bonds by foregrounding outcome architecture, beneficiary alignment and evidence governance.
xiii	Boomhower, Fowlie, Gellman and Plantinga (2024), NBER Working Paper 32625	Uses parcel-level wildfire risk and insurer filings to examine risk classification, pricing and supply in homeowners insurance.	Shows that mitigation value enters insurance markets through complex risk-selection and pricing channels, not automatically through aggregate risk reduction.
xiv	Sproul (2025), Stanford Environmental Law Journal	Uses law-and-economics reasoning to examine California's Safer from Wildfires regulation and potential adverse-selection or market-distortion effects.	Supports careful design of any mitigation-to-insurance link, including avoidance of free-rider problems and credible verification.
xv	Bressan, Duranovic, Monasterolo and Battiston (2024), Nature Communications	Shows why asset-level assessment of physical climate risk matters for adaptation policy, investment and finance tools.	Supports granular, asset- and portfolio-level evidence rather than relying on coarse regional averages.

xi. Adaptation finance and nature-based solutions

Meraj and Hashimoto (2025) frame nature-based solutions as a response to the adaptation-finance gap. Their contribution is not California-specific, but it is relevant because it connects climate resilience, ecosystem services, disaster-risk reduction, biodiversity and livelihoods to the problem of mobilising finance. For the OB, the paper supports a broader value frame: wildfire, water and ecological interventions should not be justified only as avoided-damage instruments. They should also be evaluated for ecological and social value, provided that claims are evidenced and not overstated.

xii. Disaster resilience bonds and the gap between label and outcome

Motlagh et al. (2024) review literature and practice on bonds for disaster resilience. The paper is useful because it demonstrates that the resilience-bond field is heterogeneous: instruments differ in project scope, governance, issuer type, risk-transfer function and outcome connection. This helps clarify what should set the OB apart. The OB should not be presented merely as a bond with a resilience label, but as a coordinating architecture for evidence-backed, multi-beneficiary outcomes. The instrument matters, but the outcome architecture comes first.

xiii. Homeowners insurance, wildfire risk and risk classification

Boomhower, Fowlie, Gellman and Plantinga (2024) use proprietary parcel-level wildfire risk data and insurer regulatory filings to examine how wildfire risk is priced and provided in homeowners insurance. Their findings point to variation in insurers' risk classification and pricing strategies. For the OB, the implication is that insurance value cannot be assumed from mitigation spend alone. A mitigation portfolio may reduce physical risk, but insurers need credible, sufficiently granular and regulatorily acceptable evidence before that risk reduction can affect pricing, coverage or participation. This strengthens the case for an evidence architecture that links community-scale mitigation to insurer-relevant verification.

xiv. California insurance regulation and the risk of perverse incentives

Sproul (2025) examines California's Safer from Wildfires regulation through a law-and-economics lens. The paper is useful because it shows how mitigation-discount regimes can produce unintended consequences if risk classification, insurer incentives and consumer behaviour are not carefully aligned. For the OB, the lesson is not that mitigation discounts are wrong. It is that finance and insurance mechanisms must be designed around credible verification, community uptake, fairness and market behaviour. Without that discipline, resilience policy can unintentionally shift rather than reduce risk.

xv. Asset-level physical risk and adaptation finance

Bressan, Duranovic, Monasterolo and Battiston (2024) show why asset-level assessment of climate physical risk matters for adaptation finance. The relevance to California is methodological. Wildfire, water and WUI risks are geographically specific and often depend on local exposure, infrastructure, terrain, vegetation, building characteristics and governance capacity. For the OB, this supports a granular portfolio approach: risk and benefit should be assessed at the level at which interventions, beneficiaries and outcomes can be credibly linked.

5C. Governance, legislation and policy-implementation literature

A further category is needed because the science and finance literature both point to the same implementation problem: outcomes depend on governance. Regional coordination, statutory authority, social vulnerability, local planning capacity, data standards and equity all shape whether resilience investment reaches the right places and produces durable public value.

Table 5. Governance and policy-implementation literature relevant to California resilience finance

No.	Paper	Core contribution	Implication for outcomes-based finance / OB architecture
xvi	Zhang, Lambrou, Kolden and Loukaitou-Sideris (2025), International Journal of Disaster Risk Reduction	Assesses California county General Plans, Hazard Mitigation Plans and Community Wildfire Protection Plans against fire-adapted community and social-vulnerability frameworks.	Supports the need for planning-quality, social-vulnerability and implementation-readiness screens in resilience finance.
xvii	Gori Nocentini et al. (2024), Urban Climate	Systematic review of climate adaptation governance in metropolitan regions, where administrative boundaries and inequalities can inhibit adaptation.	Supports regional and portfolio governance rather than isolated municipal or project-by-project finance.
xviii	Venner, Garcia-Lamarca and Olazabal (2024), Current Climate Change Reports	Critical review showing that adaptation finance accessibility is often shaped by institutional capacity and political/financial interests rather than vulnerability alone.	Strengthens the requirement that OB design embed equity, community benefit and capacity support rather than assuming finance will flow to the most exposed communities.

xvi. County wildfire planning and social vulnerability

The county-level wildfire planning study evaluates California counties' General Plans, Hazard Mitigation Plans and Community Wildfire Protection Plans. Its relevance lies in showing that formal planning instruments do not automatically produce comprehensive, equitable wildfire resilience. Recovery planning and social vulnerability can be overlooked even where hazard planning exists. For the OB, this supports due diligence on planning quality, social vulnerability, recovery capacity and local implementation readiness before capital is committed.

xvii. Metropolitan and regional adaptation governance

The systematic review of metropolitan climate adaptation governance is not wildfire-specific, but it is highly relevant to California because risk and benefit rarely respect jurisdictional boundaries. Wildfire corridors, watersheds, smoke pathways, insurance markets and utility systems operate regionally. The paper supports the OB's regional and portfolio logic: coordination institutions matter because they determine whether interventions are bundled, prioritised and maintained across administrative boundaries.

xviii. Adaptation-finance inequity and capacity

Venner, Garcia-Lamarca and Olazabal (2024) argue that climate vulnerability is often not the primary determinant of adaptation finance access; institutional capacity and political or financial interests can dominate. This is a critical warning for any investable resilience model. An operationally effective OB would still fail its public-purpose test if it systematically favoured places with the greatest capacity to transact rather than those with the greatest need. The paper therefore supports explicit equity screens, technical assistance, community benefit logic and capacity-building components.

5D. Energy, grid and utility resilience literature

Energy-system resilience is a necessary additional category because wildfire risk and power infrastructure are interdependent. Utility infrastructure can contribute to ignition risk, wildfire can damage or constrain grid operations, and mitigation choices can affect reliability, affordability and the pace of electrification. These papers connect the OB thesis to grid planning, hydropower and ratepayer affordability.

Table 6. Energy, grid and utility literature relevant to California resilience finance

No.	Paper	Core contribution	Implication for outcomes-based finance / OB architecture
xix	Vahedi et al. (2025), Nature Reviews Electrical Engineering	Reviews the bidirectional wildfire-power-grid nexus, including power-line ignitions, infrastructure damage, operational risk, vegetation management and funding risks.	Positions grid resilience as a coupled wildfire, community-safety and infrastructure-finance outcome rather than a standalone utility issue.
xx	Warner, Callaway and Fowlie (2025), Nature Climate Change	Evaluates costs, reliability implications and risk-reduction benefits of utility wildfire mitigation and finds dynamic grid management can reduce risk at lower cost than some conventional approaches.	Supports cost-effective adaptation logic: OB portfolios should compare intervention cost, avoided risk and reliability effects rather than assuming capital-intensive measures are always optimal.

xxi	Singh, Ong and Sud (2025), The Electricity Journal	Examines wildfire investment, transmission and distribution costs, and electricity affordability across California IOUs, POUs and CCAs.	Adds ratepayer affordability and provider-type differences to the beneficiary and payer map, especially where wildfire mitigation costs are passed through to customers.

xix. Wildfire and the power-grid nexus

Vahedi et al. (2025) review the wildfire-power-grid nexus in a changing climate. Their contribution is to show that wildfire and power systems are bidirectionally linked: power lines can ignite fires, fires can damage infrastructure, and risk management involves operations, vegetation, modelling, funding and recovery. For the OB, the implication is straightforward. Energy resilience should sit inside the wildfire-water-community resilience frame, not outside it.

xx. Dynamic grid management and adaptation cost

Warner, Callaway and Fowlie (2025) evaluate utility wildfire mitigation in the electric power sector, including cost, reliability and risk-reduction trade-offs. Their analysis supports a core OB principle: capital should be allocated to interventions that can demonstrate cost-effective risk reduction, not merely to the most visible or capital-intensive measures. Dynamic grid management, grid hardening, vegetation management and undergrounding should therefore be assessed through comparable outcome and affordability logic.

xxi. Electricity affordability and wildfire mitigation costs

Singh, Ong and Sud (2025) connect wildfire investment to electricity affordability across California power providers. This matters because resilience finance can shift costs onto ratepayers if payer logic is poorly designed. For the OB, the paper reinforces the need to distinguish beneficiaries, payers and exposed communities, and to consider ratepayer affordability alongside utility risk reduction, grid reliability and community protection.

6. California policy and market touchpoints

Although this paper is primarily an academic review, California's current policy environment is important because it shows that the state is beginning to legislate around the same coordination problem identified by the literature. The following touchpoints should be treated as policy and market signals, not as academic evidence. Bill language may change as measures move through the legislative process. Policy materials were reviewed as of 12 May 2026; bill language and status may change as measures move through the legislative process.

6.1 SB 254 Natural Catastrophe Resiliency Study

California's SB 254 Natural Catastrophe Resiliency Study provides an important non-academic market and policy touchpoint. The California Wildfire Fund describes SB 254 as requiring a comprehensive assessment of long-term reforms to protect access to insurance, reduce litigation costs, provide fair and expeditious compensation, support wildfire mitigation, safety

and community resilience, and ensure large electrical corporations remain accountable for safety while maintaining financial health to attract low-cost capital for ratepayers.

The SB 254 report, released in April 2026, is described by the California Wildfire & Forest Resilience Task Force as evaluating policy options to reduce damage to life and property, accelerate post-disaster recovery and equitably allocate the costs of natural catastrophes, including catastrophic wildfires. Its broad policy pathways - community wildfire risk reduction, equitable allocation of catastrophe burdens and state roles in catastrophe resiliency - closely mirror the finance problem identified by the scientific literature.

The Darwin Fund's published stakeholder contribution proposed a California Forest & Water Management Optimization Bond as a coordinating architecture for forests, headwaters and high-risk WUI. In the context of this academic review, the significance of SB 254 is not that it validates any particular transaction. Rather, it shows that California's policy debate is now focused on the same coordination problem highlighted by the science: how to connect prevention, mitigation, insurance affordability, utility risk, water resilience, public finance and community protection in a durable and equitable model.

6.2 SB 1297: regional wildfire partnerships and performance-based finance

SB 1297 is especially relevant because its current bill text explicitly uses the language of regional wildfire partnerships, beneficiary alignment, revenue bonds, catalytic state investment and performance-based financing. The bill finds that effective wildfire risk reduction requires landscape-scale, regionally coordinated investment strategies integrating vegetation management, structure hardening, community preparedness and infrastructure resilience. It also states that sustainable wildfire-resilience finance requires aligning the financial interests of beneficiaries including local governments, water agencies, electrical corporations, insurers, reinsurers and state and federal agencies.

For the OB, SB 1297 is important as a policy signal. It suggests that California may be moving toward the statutory and institutional conditions needed for regional, multi-beneficiary wildfire finance. The bill's reference to performance-based financing supported by multiyear revenue commitments from beneficiary entities tied to verified wildfire-risk and loss reductions is closely aligned with the OB's organising logic. The bill should therefore be referenced cautiously but clearly: not as enacted law, and not as validation of the OB, but as evidence that California's legislative debate is converging on similar concepts.

6.3 AB 1795 and AB 1642: smoke, contamination and evidence standards

AB 1795, the Smoke Damage Recovery Act, and AB 1642, concerning wildfire contamination standards, are relevant because they move smoke and post-fire contamination from general concern toward evidence standards, testing protocols, remediation, claims handling and habitability. The California Department of Insurance explains that AB 1795 is intended to establish uniform statewide standards for inspection, testing and remediation of smoke-damaged residential properties and to require insurers to follow consistent remediation protocols. AB 1642 similarly points toward science-informed, health-based standards for investigation, environmental testing and clearance after wildfire contamination.

These bills matter for the OB because the smoke-health and remediation channel cannot be treated as a vague co-benefit. If California is creating legal and regulatory standards for testing, clearance, remediation and claims handling, an outcomes-based finance structure should be capable of recognising those standards in its data and evidence architecture. The same point applies in reverse: a credible OB should not monetise smoke benefits without local exposure, health, testing and claims evidence.

6.4 SB 894: household capital, home hardening and defensible space

SB 894 would establish a California Wildfire Resilience Loan Program to provide financial assistance for projects and activities to reduce wildfire-related risks and losses, including home hardening and defensible space improvements. The bill recognises that wildfire risk-reduction investments provide public benefits beyond individual property owners and that lack of affordable upfront capital is a barrier to widespread adoption.

For the OB, SB 894 reinforces the household-capital side of the finance problem. Community-scale risk reduction depends on uptake by many owners, including those who may lack liquidity. A portfolio finance architecture should therefore be able to combine regional landscape investment, community hardening, credit enhancement, technical assistance, verification and equity safeguards. Household-level finance and regional outcomes-based finance are not substitutes; they are complementary layers of the same resilience system.

7. Implications for the proposed Optimization Bond

Taken together, the literature supports the rationale for the OB, but in a way that should be framed carefully. The science does not say that every resilience project is investable or that every benefit can be confidently monetised. It says that several important outcome channels are now sufficiently evidenced to justify a more disciplined finance architecture: one that can screen interventions, allocate capital, map beneficiaries, monitor results and distinguish evidence-backed claims from aspirational claims.

The proposed OB is therefore best positioned not as a generic green bond or a rebranded resilience bond, but as a coordinating architecture for measurable, multi-beneficiary resilience. Its distinctive contribution is to combine portfolio prioritisation, avoided-loss evidence, insurance and investor relevance, ecological and social outcomes, beneficiary/payer logic, governance safeguards and outcome reporting in a single structure.

Design principles implied by the evidence

- **Use dynamic risk baselines.** California wildfire, WUI and water risk should be assessed against a changing climate and changing exposure base, not solely historical averages.
- **Treat prevention as a portfolio.** Fuel treatment, home hardening, defensible space, water-system protection, prescribed fire, ecological restoration and community preparedness interact across landscapes.
- **Separate benchmark evidence from transaction evidence.** Published ROI and risk-reduction figures should guide screening and plausibility, but local data should support project-level claims.

- **Map all material beneficiaries.** Benefits may accrue to households, insurers, water utilities, municipalities, energy and infrastructure operators, public-health systems, employers, ecosystems and future taxpayers.
- **Recognise energy-system resilience as a material outcome channel.** Wildfire mitigation should consider ignition risk, grid reliability, hydropower exposure, public-safety power shutoff burdens and ratepayer affordability where energy assets or users are material beneficiaries.
- **Make equity and ecological uplift core design constraints.** The highest-return portfolio is not necessarily the best public-interest portfolio unless distributional impacts, community wellbeing, livelihoods and ecological integrity are explicitly included.
- **Invest in monitoring.** Outcome finance cannot rely on spending as a proxy for resilience; it needs pre/post evidence, counterfactual logic and monitoring at appropriate time horizons.
- **Build implementation capacity into the finance case.** Workforce, burn windows, permits, contracting, governance and maintenance capacity affect whether resilience capital can produce real outcomes before the next event.
- **Design for insurance and investor usability.** Evidence should be granular enough to inform insurer, utility, municipal and investor decisions without overstating what current science can support.

What sets the OB apart

The review suggests that California's need is not simply another bond label. Existing instruments can finance projects, transfer risk or fund public expenditure, but the hard problem is coordination: beneficiaries are dispersed, benefits are probabilistic, costs occur upfront, evidence quality varies and the highest-value interventions often cross jurisdictional and ownership boundaries. The OB is distinctive because it starts with the outcome architecture rather than the instrument. It asks what risk and resilience outcomes are scientifically plausible, who benefits from them, what evidence is sufficient to support payment or investment, and how social and ecological safeguards are embedded before capital is structured.

In this sense, the OB is not an alternative to public funding, insurance reform, utility mitigation, Forest Resilience Bonds, municipal bonds, green bonds or philanthropy. It is a means of coordinating these tools into investable portfolios where prevention value, affordability, ecological function and community wellbeing can be made more visible, measurable and governable.

Limitations

This paper is a targeted narrative review rather than a systematic review or meta-analysis. It does not claim to identify every relevant paper, quantify the full California resilience opportunity, rank intervention classes, or provide a transaction-ready valuation for any specific portfolio.

Its purpose is more limited: to identify where recent science, finance and governance literature supports an evidence-led outcomes-based finance architecture, and where local evidence,

community consent, legal authority, monitoring and uncertainty disclosure remain necessary before investment or payment claims can be made.

8. Conclusion: from evidence to investable public-good resilience

The reviewed literature supports a clear conclusion: California's resilience challenge is no longer simply a matter of whether wildfire, water, ecological and public-health risks are serious. The science now provides increasingly specific evidence about where risk is changing, where interventions can work, how benefits propagate through water, energy, health, infrastructure and insurance systems, and why ecological and cultural stewardship are essential to durable resilience.

At the same time, the literature also cautions against simplistic finance narratives. Avoided damages are real but probabilistic. Intervention effects are heterogeneous. Insurance responses depend on risk classification, regulation and market behaviour. Smoke, water and ecological outcomes require local evidence. Indigenous stewardship cannot be reduced to a monetised co-benefit. Equity is not solved by aggregate benefit-cost ratios. These cautions are not obstacles to finance; they are design requirements for credible finance.

The proposed Optimization Bond is promising because it is responsive to these requirements. It offers a way to translate distributed avoided losses and co-benefits into an investable, accountable structure while keeping science, equity, community wellbeing, livelihoods and ecological uplift visible in the design. Its commercial value lies in solving a problem that ordinary project finance often cannot solve: many actors benefit from resilience, but no single actor can easily justify or fund the whole prevention portfolio alone.

California can lead globally if it treats resilience as investable public-good infrastructure: scientifically grounded, locally validated, socially legitimate and financially structured around measurable outcomes. The latest science does not remove the hard work of governance, data, implementation and capital formation. It does, however, make the direction of travel unmistakable: prevention finance must become more integrated, more evidence-based, more insurable, more investable and more equitable. That is the space in which the proposed OB is intended to operate.

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