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Collective Responsibility in Wildfire Mitigation: Optimizing Subsidies for Enhancing Community Resilience

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ABSTRACT

Wildfire poses an escalating threat to communities in the wildland-urban interface (WUI), where both government efforts and homeowner actions are critical for risk reduction. While actions such as home hardening, defensible space creation, and vegetation management are recognized as effective, homeowner adoption rates remain suboptimal. This highlights the need to better understand the drivers of homeowner mitigation behavior, the dynamic interactions with neighbors, and strategies to incentivize broader participation. Existing research largely examines individual decision-making in isolation, often neglecting the interdependence among homeowners inherent in wildfire mitigation as a collective action problem. Moreover, the role of government subsidies in promoting mitigation actions remains underexplored. This study develops a utility-based model that captures homeowners' mitigation decisions by incorporating income, homeownership tenure, wildfire risk, mitigation costs and benefits, and neighbor behaviors. Using Nash equilibrium analysis, we examine how homeowner strategies evolve under different levels of government subsidy and assess the collective utility outcomes for the community. Our results demonstrate the existence of a critical subsidy threshold necessary for wildfire mitigation to become the dominant homeowner strategy and highlight the importance of early-stage interventions and personal risk framing to overcome free-riding behavior and coordination failures. These results also underscore the importance of dynamic, targeted subsidy policies to foster collaborative mitigation efforts and strengthen WUI community resilience.

1 INTRODUCTION

The rapid expansion of the Wildland–Urban Interface (WUI) has significantly increased community exposure to wildfire risks, driven by accelerating urbanization and climate change (Guo et al., 2024). Although WUI areas account for only 4.7% of the global land surface, they accommodate nearly half of the global population, making wildfire resilience a critical concern for a substantial portion of society (Schug et al., 2023). Strengthening resilience in WUI communities is not only vital for individual homeowners but also for local governments, emergency response agencies, insurance companies, and national policymakers tasked with managing escalating disaster risks (Ma et al., 2011; Prince, 2022; Radeloff et al., 2018)

A primary strategy for enhancing wildfire resilience involves encouraging homeowner mitigation actions, such as creating defensible spaces and retrofitting homes with fire-resistant materials (Naser & Kodur, 2025). However, actual adoption rates remain low, constrained by financial limitations, risk perceptions, and social influences within communities (Auer, 2024; Lee et al., 2022). While government subsidies are widely regarded as effective tools to promote homeowners' mitigation investments, most existing studies and policy design tend to conceptualize these decisions as isolated, individual choices. However, this perspective overlooks the crucial role of interdependent dynamics between homeowners, as well as between homeowners and government authorities, in shaping risk management outcomes. In reality, homeowners' decisions are highly interdependent (e.g., depending on the anticipated or actual actions of neighboring property owners), with strategic complementarities and free-riding behavior significantly influencing participation levels (Reilly, 2015). Moreover, wildfire risk is collective in nature, with the vulnerability of any given home influenced by the preparedness and behaviors of neighboring properties.

This study aims to investigate the following research question: How can government subsidy strategies be optimally designed based on the interdependent behaviors of homeowners to maximize collective wildfire risk reduction in WUI communities? To address the question, this study considers three critical homeowner-level factors that influence their mitigation decisions: (1) cost sensitivity, which affects how financial incentives translate into actual investment behavior; (2) homeownership tenure, which influences long-term risk perception and the willingness to commit to mitigation costs; and (3) perceived wildfire risk, which varies across individuals and shapes the urgency and prioritization of mitigation efforts. By integrating these factors into a dynamic strategic modeling framework, this research seeks to offer new theoretical insights and practical guidance for the design of incentive policies that effectively promote proactive wildfire mitigation among WUI homeowners.

2 MODEL DEVELOPMENT

This section develops a utility-based decision model to characterize homeowners' wildfire mitigation behavior under the influence of neighbor mitigation actions and policy incentives. It lays the analytical groundwork for subsequent optimal strategy analysis and equilibrium analysis by formalizing utility functions, risk modeling, and investment cost structures.

2.1 Main Symbols

The primary symbols used in the models are summarized in Table 1.

Table 1. Key Symbols and Their Descriptions

Symbols	Definition
V_h	The property value of the homeowner, $V_h > 0$
c_h	Homeowner's wildfire mitigation effort level, $c_h > 0$
c_n	Neighbor's wildfire mitigation effort level, $c_n > 0$
p_0	Baseline probability that a given home will be damaged by wildfire, $p_0 \in (0,1)$
p'	Probability that a given home will be damaged by wildfire after mitigation measures, $p' \in (0,1)$

θ	Homeowners' cost sensitivity (related to income level)
s	Government subsidy, $s > 0$
$C_h(t)$	Time-discounted economic cost of mitigation investment
t	Homeownership tenure (years)
λ	Time discount rate
a	A time-equivalent constant reflecting the government-mandated minimum wildfire protection requirements
α	Effectiveness coefficient of the homeowner's direct mitigation effort
β	Effectiveness coefficient of the neighbor's mitigation effort

2.2 Model assumptions

Based on these definitions, several fundamental assumptions are established to characterize the homeowners' decision-making process: (1) homeowners are assumed to behave rationally, seeking to maximize their expected utilities (Gary S. Becker, 1976); (2) wildfire mitigation decisions are influenced by both individual-level characteristics (e.g., financial capacity, tenure duration) and the observed behaviors of neighbors (Brenkert-Smith, 2010); (3) government subsidies are only granted to those who actively invest in appropriate wildfire risk mitigation actions; (4) the effectiveness of mitigation efforts follows a diminishing return pattern (i.e., initial actions yield large risk reductions, but incremental benefits decrease with continued investment); and (5) the economic burden of investment is discounted over the expected homeownership (Timothy W. Collins, 2008).

2.3 Utility formulation

Each homeowner faces two strategic choices: invest (Y) or not invest (N) in wildfire mitigation.

The utility functions under four possible strategy combinations are defined as follows, where the first subscript indicates the neighbor's action, and the second subscript indicates the homeowner's action:

Scenario I: Both the homeowner and the neighbor invest:

$$U_{YY} = V_h - p'_{YY}V_h - \theta c_h - C_h(t) + s \tag{1}$$

Scenario II: The homeowner invests, the neighbor does not:

$$U_{NY} = V_h - p'_{NY}V_h - \theta c_h - C_h(t) + s \tag{2}$$

Scenario III: The neighbor invests, the homeowner does not:

$$U_{YN} = V_h - p'_{YN}V_h \tag{3}$$

Scenario IV: Neither invests:

$$U_{NN} = V_h - p'_{NN}V_h \tag{4}$$

where $s > 0$ denotes the government subsidy received only if the homeowner invests.

2.4 Wildfire Risk Modeling

The probability that a given home will be damaged by wildfire after adopting mitigation actions depends on the mitigation efforts of both the homeowner and the neighbor and is modeled as:

$$p'_{YY} = p_0 e^{-\alpha c_h - \beta c_n} \tag{5}$$

$$p'_{YN} = p_0 e^{-\beta c_n} \tag{6}$$

$$p'_{NY} = p_0 e^{-\alpha c_h} \tag{7}$$

$$p'_{NN} = p_0 \tag{8}$$

where $\alpha > 0, \beta > 0$ capture the relative effectiveness of direct and neighbor's mitigation efforts. We assume that the benefit from homeowner's direct wildfire mitigation effort is greater than that of the neighbor's wildfire mitigation effort, which means $\alpha > \beta$. The exponential function reflects diminishing returns: initial mitigation investments significantly reduce risk, but additional investments yield progressively smaller reductions.

2.5 Time-Discounted Investment Cost

Considering the time value of money, we use a time-discounted cost function to calculate the homeowner's actual cash outflow cost over the property holding period t, which can be expressed as follows:

$$C_h(t) = c_h \cdot \frac{1 - e^{-\lambda(t+a)}}{\lambda(t + \mathrm{a})} \tag{9}$$

where $t =$ the expected homeownership period; λ = the discount rate; and a = a time-equivalent constant reflecting the government-mandated minimum wildfire protection requirement. Both long-term and short-term homeowners are required to bear this cost. When $t \to 0$, then $C_h(t) \approx c_h$. When $t \to \infty$, then $C_h(t) \approx \frac{c_h}{t+a}$, which shows that the longer the homeownership tenure, the more the investment cost is amortized over time, allowing long-term homeowners to benefit from the cost-sharing effect (Lee et al., 2022).

3 OPTIMAL MITIGATION STRATEGY ANALYSIS: FROM THE HOMEOWNER PERSPECTIVE

We analyze wildfire mitigation investment from the perspective of an individual homeowner, assuming their neighbor's decision is fixed. We derive the conditions under which a homeowner will choose to invest based on a comparison of utilities between the "invest" and "not invest" strategies, conditional on the neighbor's behavior. The utility comparison can be represented by a game tree, as illustrated in Figure 1.

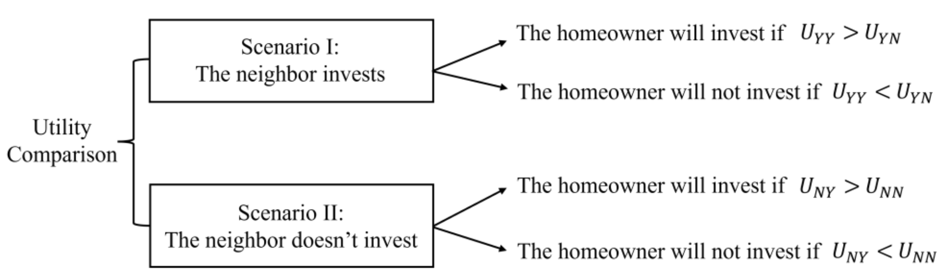

Figure 1. Utility comparison tree

3.1 Scenario I: Neighbor invests

To evaluate the effectiveness of the homeowner investment strategy U_{YY} compared to the strategy that the homeowner does not invest U_{YN} given that the neighbor has already invested in mitigation actions, the net benefit of investment can be denoted as ΔU:

$$\Delta U_1 = V_h p_0 e^{-\beta c_n}(1 - e^{-\alpha c_h}) - \theta c_h - c_h \cdot \frac{1 - e^{-\lambda(t+a)}}{\lambda(t+a)} + s \tag{10}$$

where $V_h p_0 e^{-\beta c_n}(1 - e^{-\alpha c_h})$ = the monetary benefit from reducing the risk of wildfire damage to the property due to the homeowner's wildfire mitigation investment and their neighbor's investment; θc_h = the homeowner's sensitivity to costs, which tends to be higher for low-income homeowners; and $c_h \cdot \frac{1-e^{-\lambda(t+a)}}{\lambda(t+a)}$ = the time-discounted investment cost, which reflects the actual perceived financial burden over the ownership period, considering time discounting and regulatory minimum wildfire mitigation standards.

Lemma 1. A homeowner invests if $\theta < \theta^*$, where:

$$\theta_1^* = \frac{V_h p_0 e^{-\beta c_n}(1 - e^{-\alpha c_h})}{c_h} + \frac{s}{c_h} - \frac{1 - e^{-\lambda(t+a)}}{\lambda(t+a)} \tag{11}$$

Lemma 1 shows the cost sensitivity threshold for homeowners' investment decisions, denoted as θ_1^*. As θ_1^* increases, a greater proportion of homeowners satisfy the condition $\theta < \theta_1^*$, and more homeowners find it optimal to invest in wildfire mitigation.

Proposition 1. The threshold θ_1^* increases with homeownership tenure t, facilitating wildfire mitigation investment.

To further illustrate the impact of homeownership tenure on mitigation decisions, we conduct a numerical simulation based on the following parameter settings: $\alpha = 0.5, \beta = 0.3, V_h = 1, p_0 = 0.5, c_n = 0.2, \lambda = 0.1$, and $a = 2$. The government subsidy is fixed at $s = 0.2$. The homeowner's wildfire mitigation investment cost c_h varies from 0.05 to 1.0, and the homeownership tenure t takes values of 5, 10, 15, and 20 years, as shown in Figure 2.

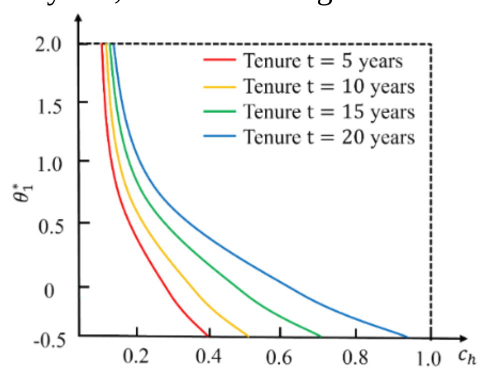

Figure 2. Impact of homeownership tenure on θ_1^*

This result confirms that homeowners with longer expected tenure are more likely to invest in wildfire mitigation, as the investment costs are effectively amortized over a longer period, making the mitigation investment more attractive even when the upfront cost is relatively high. This finding highlights the importance of considering homeownership tenure when designing wildfire mitigation incentive policies.

Proposition 2. The threshold θ_1^* increases with government subsidies s, encouraging cost-sensitive homeowners.

Figure 3 illustrates how government subsidies influence θ_1^*. Parameter settings are the same as Figure 2, but with government subsidies $s \in \{0.1, 0.2, 0.3, 0.4\}$.

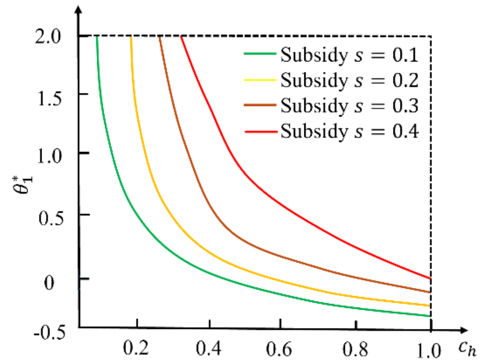

Figure 3. Effect of government subsidy on θ_1^*

The results show that: (1) for a given investment cost c_h, a higher government subsidy consistently results in a higher threshold θ_1^*; (2) the positive relationship between s and θ_1^* confirms the analytical findings that government subsidies make wildfire mitigation investments viable for a broader range of cost-sensitive homeowners; and (3) particularly when the investment cost c_h is high, the role of subsidies becomes even more critical to maintain a sufficiently high threshold to incentivize participation.

3.2 Scenario II: Neighbor doesn't invest

To evaluate the effectiveness of the homeowner investment strategy U_{NY} compared to the strategy that the homeowner does not invest U_{NN}, we analyze the net benefit of investing, denoted as ΔU:

$$\Delta U_2 = V_h p_0 (1 - e^{-\alpha c_h}) - \theta c_h - c_h \cdot \frac{1 - e^{-\lambda(t+a)}}{\lambda(t+a)} + s \tag{12}$$

We further derive the cost sensitivity threshold to understand homeowners' investment decisions while neighbors don't invest.

Lemma 2. A homeowner invests if $\theta < \theta_2^*$, where:

$$\theta_2^* = \frac{V_h p_0 (1 - e^{-\alpha c_h})}{c_h} + \frac{s}{c_h} - \frac{1 - e^{-\lambda(t+a)}}{\lambda(t+a)} \tag{13}$$

Proposition 3. Homeowners with longer tenures are more likely to invest in wildfire mitigation in the absence of neighborhood mitigation. Specifically, the threshold θ_2^* still increases with homeownership tenure t, as longer-term homeowners are better positioned to amortize the cost of wildfire mitigation over an extended period and internalize long-term risk reduction.

To further illustrate Proposition 3, we conduct a numerical simulation based on similar parameter settings to those in Figure 2, but neighbor investment effort $c_n = 0$, as shown in Figure 4. This indicates that even without neighbor cooperation, longer homeownership tenures reduce financial pressure and promote investment in wildfire mitigation.

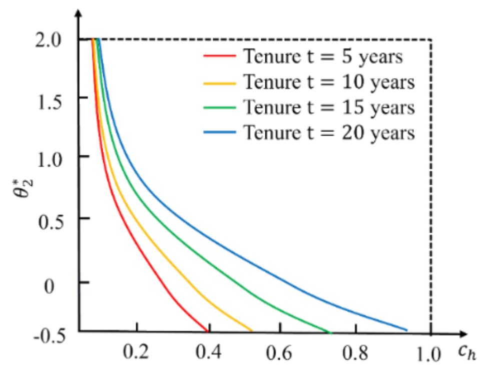

Figure 4. Effect of homeownership tenure on θ_2^*

Proposition 4. Government subsidies play a compensatory role in the absence of neighborhood cooperation.

Figure 5 illustrates how government subsidies influence θ_2^*. Parameter settings are the same as Figure 4, while government subsidies $s \in \{0.1, 0.2, 0.3, 0.4\}$. It is found that, in the absence of neighbor action, government subsidies play a critical role in enabling investment by cost-sensitive homeowners.

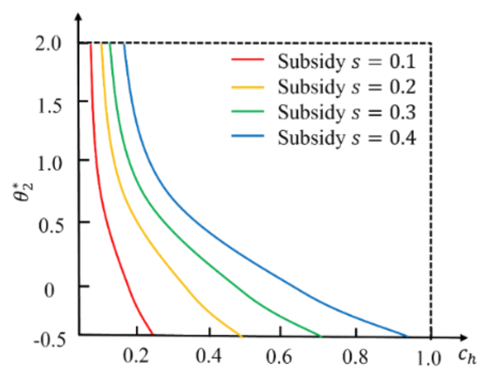

Figure 5. Effect of government subsidy on θ_2^*

3.3 Free Riding Dynamics

The difference between the thresholds obtained from the first two scenarios illustrates the impact of neighbor mitigation action on individual mitigation decisions:

$$\theta_1^* - \theta_2^* = \frac{V_h p_0 (1 - e^{-\alpha c_h})}{c_h} \left(e^{-\beta c_n} - 1\right) \tag{14}$$

Neighbor mitigation decreases the incentives for homeowners to invest, potentially leading to free-riding behavior.

Proposition 5. Neighbor investment reduces marginal benefits and lowers θ^*.

To further illustrate Proposition 5, we conduct a numerical simulation based on the following parameter settings: $\alpha = 0.5, \beta = 0.3, V_h = 1, p_0 = 0.5, c_n = 0.2, \lambda = 0.1, a = 2, s = 0.2,$ and $t = 8$. The homeowner's wildfire mitigation effort level c_h varies from 0.05 to 1.0, as shown in Figure 6. The results demonstrate that for any given c_h, the threshold θ_1^* is consistently lower than θ_2^*. It indicates that fewer homeowners will invest when their neighbors already have, because the incentive for personal effort declines when neighborhood mitigation reduces overall wildfire risk. This can be evidence of free-riding behavior.

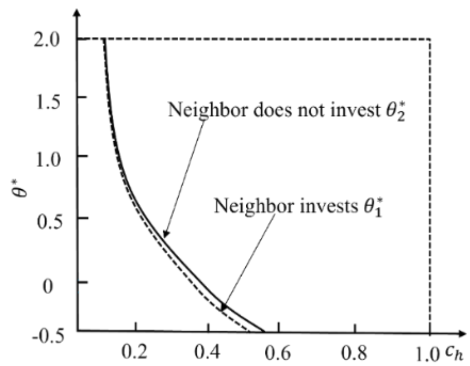

Figure 6. Comparison of cost sensitivity thresholds: θ_1^* vs. θ_2^*

4 STRATIGIC EVOLUTION IN COMMUNITY WILDFIRE MITIGATION

Building on the individual utility comparison framework, we extend the analysis to dynamic strategic interactions between homeowners under wildfire risk externalities. To capture strategic interdependence in wildfire risk management, we model a two-player symmetric game, where each homeowner decides whether to invest.

To simplify the model, we assume that all neighbors exert identical influence on an individual homeowner, regardless of their spatial distance. Given that a proportion $x \in [0,1]$ of the population chooses to invest, the expected payoff for a homeowner who chooses to invest, given that a proportion x of the population also invests, is defined as follows.

$$\pi_Y(x) = xU_{YY} + (1-x)U_{YN} \tag{15}$$

The expected payoff for a homeowner who chooses not to invest, under the same investment rate x, is defined as follows.

$$\pi_N(x) = xU_{NY} + (1-x)U_{NN} \tag{16}$$

The evolutionary dynamics of the system follow the replicator equation:

$$\dot{x} = x(1-x)[\pi_Y(x) - \pi_N(x)] \tag{17}$$

where $\dot{x}$ denotes the rate of change in the proportion of investors.

In the wildfire mitigation investment game, the stationary points $\dot{x} = 0$ correspond to the Nash equilibria of the underlying static game. Specifically, pure strategy Nash equilibria arise at the boundary points, $x = 0$ (no investment) and $x = 1$ (full investment), depending on the payoff structure, while mixed strategy Nash equilibria occur at an interior point $x^* \in (0,1)$, satisfying $\pi_Y(x^*) = \pi_N(x^*)$.

Based on the definitions of the payoff differentials, $\Delta U_1 = U_{YY} - U_{YN}$ (when the neighbor invests) and $\Delta U_2 = U_{NY} - U_{NN}$ (when the neighbor does not invest), the equilibrium structure of the system can be fully characterized. When x is close to 0, where investors are rare and most neighbors do not invest, the replicator dynamics can be approximated by:

$$\dot{x} \approx x\Delta U_2 \tag{18}$$

Thus, the sign of ΔU_2 determines the stability at $x = 0$: if $\Delta U_2 > 0$, then $\dot{x} > 0$ and the system departs from $x = 0$, making no investment unstable; and if $\Delta U_2 < 0$, then $\dot{x} < 0$, and the system converges to $x = 0$, stabilizing at no investment. Similarly, when x is close to 1, where almost all neighbors invest, the dynamics approximate:

$$\dot{x} \approx (1 - x)\Delta U_1 \tag{19}$$

Here, the sign of ΔU_1 governs the stability at $x = 1$: if $\Delta U_1 > 0$, then $\dot{x} < 0$ as $x \to 1$, indicating that full investment is stable; if $\Delta U_1 < 0$, then $\dot{x} > 0$, and the system moves away from full investment.

When ΔU_1 and ΔU_2 have opposite signs ($\Delta U_1 \cdot \Delta U_2 < 0$), individual investment decisions depend on the neighbor's behavior, creating a path-dependent structure. In this case, there exists a unique unstable interior equilibrium at

$$x^* = \frac{\Delta U_2}{\Delta U_2 - \Delta U_1}, x^* \in (0,1) \tag{20}$$

If the initial proportion of investors $x_0 > x^*$, the system evolves toward full investment $x = 1$; and if $x_0 < x^*$, it evolves toward no investment $x = 0$. Therefore, whether widespread community investment emerges ultimately depends on the initial level of participation.

Although replicator dynamics describe an evolutionary process over time, the stationary points precisely correspond to the Nash equilibria of the original wildfire mitigation game. The signs and relative magnitudes of ΔU_1 and ΔU_2 fully determine the final equilibrium outcome—universal investment, universal free-riding, or coordination failure requiring external intervention to overcome critical thresholds.

Building upon the above analysis of equilibrium structures under replicator dynamics, we now formally characterize the effects of external factors, such as subsidies, property value, cost sensitivity, and risk parameters, on investment behavior and equilibrium outcomes.

Theorem 1. There exists a government subsidy threshold s^* such that if $s \geq s^*$, investment becomes the dominant strategy, and the unique Nash equilibrium is full investment (Y, Y). The expression for s^* is derived as follows.

$$s^* = max\{\theta c_h + C_h(t) - (p'_{YN} - p'_{YY})V_h, \theta c_h + C_h(t) - (p'_{NN} - p'_{NY})V_h\} \tag{21}$$

Proposition 6. Subsidies and higher property values positively influence the payoff differentials, making investment more attractive.

Proposition 7. Cost sensitivity and mitigation costs reduce the marginal payoff differentials.

Proposition 8. Increasing α boosts ΔU_2, enhancing the personal effectiveness of investment and promoting cooperation. Increasing β reduces ΔU_1, increasing the incentives for free-riding behavior.

5 POLICY DISCUSSION

This study provides practical insights into wildfire mitigation policy design by examining the dynamic decision-making of homeowners. Results show that cost sensitivity thresholds, influenced by subsidies, property value, mitigation costs, and homeownership tenure, are critical to investment behavior. Setting subsidy levels above the critical threshold is essential to ensure that mitigation investment becomes the dominant strategy, independent of neighbor actions.

Targeted strategies are necessary to address cost-sensitive homeowners who are less likely to invest, especially those with lower incomes or shorter expected tenure. Differentiated and conditional subsidies can enhance participation while reducing equity gaps. Additionally, the presence of unstable interior equilibria highlights the need for early interventions. Pilot programs subsidizing early adopters, coupled with public campaigns, can help communities overcome coordination failures.

Risk perception framing also significantly impacts behavior. Policies should focus on enhancing homeowners' perception of personal benefit from mitigation rather than emphasizing collective advantages, thereby reducing free-riding tendencies. As community mitigation progresses and overall risk declines, maintaining high participation levels requires coordination mechanisms, such as minimum participation thresholds, community agreements, and collective insurance models.

6 CONCLUSIONS

This study develops a dynamic game-theoretical framework to analyze homeowner wildfire mitigation investment decisions under the influence of government subsidy policies. By explicitly modeling cost sensitivity, homeownership tenure, and perceived wildfire risk, and incorporating dynamic interactions among homeowners through replicator dynamics, the study derives critical thresholds that govern individual and collective mitigation behavior.

The results highlight three main findings. First, there exists a critical subsidy threshold such that only when government subsidies meet or exceed this level, wildfire mitigation becomes the dominant strategy for homeowners across the community. This finding directly informs the design of effective public financial interventions to overcome cost barriers and ensure widespread participation. Second, the presence of unstable interior equilibria in the replicator dynamics demonstrates the importance of early-stage interventions. If the initial proportion of investors fails to exceed critical mass, the system tends to converge toward a no-investment equilibrium, suggesting that seeding early adopters is essential for breaking coordination failures. Third, the analysis reveals that strengthening homeowners' perceived personal benefits from mitigation (as captured by the risk reduction parameter α) is more effective than emphasizing collective benefits in sustaining voluntary participation and minimizing free-riding behavior.

These findings are relevant not only for fire-prone regions in the United States but also for global contexts where WUI expansion and wildfire risk are intensifying, such as Australia, Mediterranean Europe, and parts of South America. Designing dynamic, differentiated, and behaviorally informed subsidy strategies can provide a scalable blueprint for improving wildfire resilience in diverse socio-economic and environmental settings worldwide.

However, the present research is subject to several limitations. The model assumes homogeneous homeowner populations with symmetric payoff structures, whereas in reality, significant heterogeneity exists in income, risk perception, social influence, and property characteristics. Moreover, the model abstracts from the spatial distribution of properties and the localized nature of wildfire risk. In practice, the proximity between homes and spatial patterns of risk propagation can significantly alter incentives, as neighboring investments or non-investments directly affect an individual's exposure and strategic choices. Future research should extend the framework by incorporating heterogeneous agent models, spatial interactions, and endogenous evolution of risk perceptions over time based on environmental feedback. Empirical validation using household-level mitigation data and surveys will also be critical to refining the proposed theoretical thresholds and policy recommendations.

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