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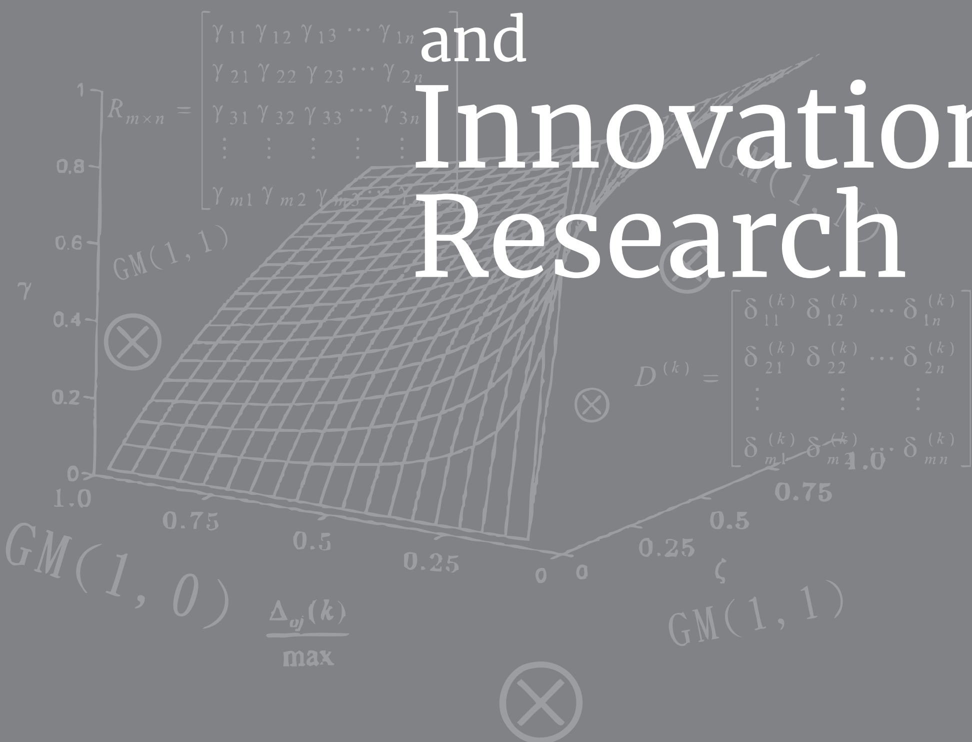

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Potential Threats of Megafires to Astronomical Observatories and an Optimal Protection Decision Model: Grey-System Trend Forecasting and Multi-Criteria Analysis

Hsien-Chuan Fan

Abstract

Against the backdrop of global warming, extreme weather is becoming increasingly frequent, and megafires are rising steadily in frequency, scale, and destructive power, posing a growing threat to immovable facilities such as astronomical observatories located deep within forests. The paper first describes the ecological role of wildfire and the drivers of megafires, and reviews cases in which observatories-Mount Stromlo, Siding Spring, Lick, Mount Wilson, the Allen Telescope Array, and Kitt Peak-were struck or threatened by wildfire. On this basis, and recognizing that fire records for any single site are characterized by small samples and poor information, a two-stage optimal protection decision model grounded in grey-system theory is constructed. In the first stage, a grey-prediction is built from the U.S. National Interagency Fire Center burned-area series, and the urgency of the threat is gauged from the exceedance frequency of megafire years and the roughly 30-year fire cycle of the Lulin Observatory site. In the second stage, criterion weights are determined objectively by grey entropy, and grey relational analysis is used to rank five protection strategies under multiple criteria. The results show that the "integrated prevention plus managed evacuation" strategy attains the highest grey relational grade(γ =0.91), markedly outperforming conventional aggressive suppression(γ=0.44); the ranking is robust to the distinguishing coefficient. The model provides a cardinal decision basis for wildfire protection at mountain observatories such as Lulin.

Keywords: Megafire, Ecological role, Grey predication, Grey entropy, Grey relational analysis, Cardinal decision

1. Introduction

In recent years, news of wildfires raging across the globe has become commonplace. Even in cold regions such as Alaska and Siberia, fires now spread readily, routinely consuming hundreds of hectares of forest. Scientists link this

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trend to global warming: as the number of extreme-weather days rises, intense heat and drought increase both the likelihood of ignition and the difficulty of suppression. Consequently, wildfires burn more fiercely and affect larger areas year after year, a phenomenon that scientists have termed the “megafire”[1,2].

In responding to this trend, many developed countries have kept upgrading their firefighting technology, only to discover that most megafires are ultimately extinguished by heavy rainfall rather than human effort. The contribution of direct suppression is limited; forcing the issue not only incurs high costs but also exposes frontline firefighters to grave danger. Many experts have therefore called for a fundamental rethinking of the relationship between wildfire and nature, and of what a reasonable human response should be[1]. Building on existing qualitative discussion, this paper introduces grey-system theory to establish a quantitative optimal protection decision model, so that the question of how observatories should guard against wildfire can be answered with data rather than impression.

2. Wildfire Ecology and the Emergence of Megafires

2.1 The Ecological Role of Wildfire

In nature, wildfire long predates humankind. In any environment, combustion can occur whenever the three elements of the fire triangle are present: fuel, an oxidizer, and an ignition source. The abundant grasses and woody plants of primeval forests and grasslands provide excellent fuel; the oxygen that constitutes one-fifth of the atmosphere is an inexhaustible oxidizer; and lightning or the friction of dead wood can supply ignition. Over hundreds of millions of years, fire has shaped terrestrial ecosystems, and many plants have evolved strategies for coexisting with it[3].

Although humans tend to view fire as a hazard to be extinguished quickly, wildfire plays a legitimate ecological role. It constitutes an intermediate disturbance and is one of the mechanisms that maintain stable, rich biodiversity. This view rests on the ecological theory of succession, which holds that an ecosystem is not a fixed, unchanging system but one that changes dynamically under continual disturbance from physical factors such as volcanic eruptions, earthquakes, typhoons, and fire. Once such disturbances enter the system, it tends toward a new dynamic equilibrium, thereby preserving biodiversity[4,5].

For example, after a moderate fire in the ponderosa pine forests of the northwestern United States, the ground blooms with lupine, which promotes nutrient cycling, attracts diverse animals, and forms new food webs. The giant sequoia(Sequoiadendron giganteum), a tall, thick-barked tree, produces small,

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well-protected seeds that ordinarily will not germinate upon falling to the soil; instead they await a low-intensity fire that clears surface grasses without harming the thick-barked mature trees. The heat damages the seed coat and triggers germination, allowing seedlings to establish in the fertile, ash-rich soil and become the next generation of forest[4]. Fig. 1 depicts a roughly 200-year growth cycle observed in North American lodgepole pine (Pinus contorta) forests: a mature stand is ignited by a natural source, the fire clears surface vegetation and simultaneously cues the germination of seeds stored in the soil, and a new generation of forest grows, matures, becomes dense, and eventually meets a new ignition source-continuing the cycle[3].

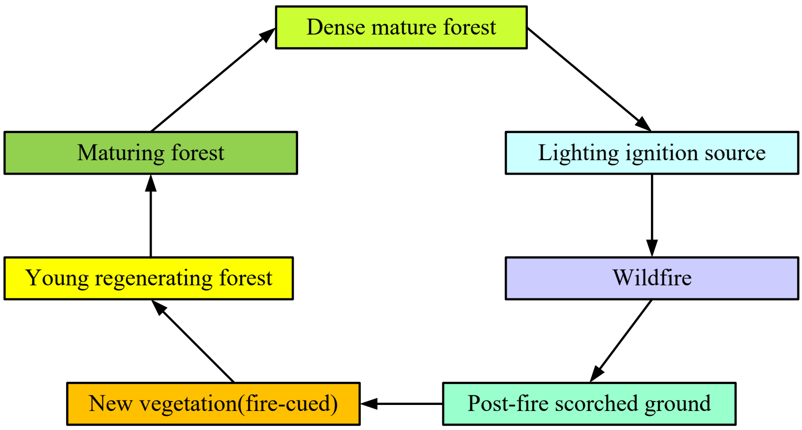

Fig. 1 Growth cycle model of forest under a natural fire regime

Thus, what appears in nature to be a merciless cycle of destruction in fact embodies a corresponding renewal design for the plant species that persist today, which are not threatened by the arrival of fire.

2.2 From Wildfire to Megafire

The difficulty now is that, whereas extreme weather was once uncommon and destructive fires occurred only at long intervals, wildfires today are more frequent, larger in scale, and greater in burned area. In some places a second fire arrives only a few years after the first, before surface vegetation can mature. The large quantities of carbon dioxide released-itself a greenhouse gas-further intensify the greenhouse effect and raise the likelihood of extreme weather, making megafires easier to ignite and more destructive. In boreal regions, fire can additionally thaw permafrost, producing unforeseen consequences and pushing the environment toward unknown extremes[1]. Nations have invested

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heavily in suppression, yet the cost is high, the effect limited, and the work dangerous; the decisive factor in extinguishing such fires is often heavy rain[1,6].

On the basis of recent observations, many scientists argue that the role of wildfire-and the problem of megafires-should be examined from new perspectives. In February 2022, the United Nations Environment Programme released the report Spreading Like Wildfire, which examines the relationship between wildfire and climate change. Drawing on extensive scientific evidence, the report confirms a mutually reinforcing relationship: climate change intensifies drought, high temperatures, lightning, and strong winds while lowering relative humidity, producing hotter, drier, and longer fire seasons[1,7,8]. It is within this context that the concept of the megafire gradually took shape.

The term “megafire” was introduced in 2005 in the U.S. federal forest-fire policy literature, which noted that since the 1988 Yellowstone fires an unbroken series of uncontrollable conflagrations had emerged-most notably several extraordinary fires in the western United States in 2002-that conventional techniques could not contain[9]. A precise quantitative definition has remained contested in the scholarly literature; nonetheless, a working consensus has emerged that megafires can be characterized by two attributes: the scale of the burn and the magnitude of the damage[2]. More recent reviews have proposed a size-based criterion (for example, fires exceeding 10,000 ha), although debate over the term's precision and emotive connotations continues[10,11]. Comparative studies of megafires across the United States, Greece, Israel, Russia, and Australia identify common features: prolonged drought, excessive biomass accumulation, and fires that escape control, leading to longer burning periods, more intense combustion, and greater damage[2].

Such events were rare at the start of this century but have since grown ever more severe, with multiple occurrences each year. In 2022, for instance, a heatwave drove large, multi-front forest fires in the Gironde department of France from 18 July, destroying some 15,000 ha of forest and forcing the evacuation of more than 16,000 residents-an operation that included relocating a zoo to safeguard its animals. Greece and Spain likewise faced a combination of heat, drought, and strong winds in late July, with fires at numerous sites. Collectively, France, Spain, and Portugal had seen about 517,881 ha burned by late July that year, exceeding the full-year record for 2021. By the end of July, the United States had recorded more than 38,000 wildfires that had burned over five million acres (about 2.25 million ha), the largest figure in a decade. These observations are consistent with attribution studies showing that anthropogenic climate change has substantially increased burned area and fire-weather severity in recent decades[7,8,12,13], and with the most recent global assessments documenting the escalating wildfire crisis[14].

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It was once held that wildfires occurred only in summer, and that because the seasons are reversed between hemispheres, Northern and Southern Hemisphere fires would alternate rather than coincide. Today, however, wildfires occur in any season, and simultaneous fires in both hemispheres now break the old alternating pattern. This change is driven by global warming: as fires grow more probable and larger, they emit great quantities of carbon dioxide and other greenhouse gases, which in turn reinforce the warming trend-forming a vicious cycle[1].

3. Wildfire Threats to Observatories and Protection Strategies

3.1 A New Approach to Megafire Management

In confronting megafires, many countries have invested in improved firefighting equipment. The United States, for instance, has no road access to roughly 30% of its forest land and therefore relies heavily on aerial suppression, deploying dedicated firefighting helicopters, large air tankers, and light fixed-wing aircraft, alongside various wildland fire engines and trained aerial and ground crews, in an effort to build an integrated air-and-ground wildfire control system. Although such capabilities are impressive, their effectiveness against megafires is limited, the danger to frontline firefighters remains high, and the decisive factor in extinguishing a fire is still often heavy rainfall. Out of this experience has grown the view that, over the long term, prevention through advance management, together with managed evacuation when a fire strikes, may reduce losses more effectively than aggressive suppression. Indeed, recent research indicates that a century of fire exclusion has itself made wildfires more severe by allowing fuel to accumulate, accentuating the impacts of climate change [6].

Effective management must begin with a change of mindset: recognizing the ecological role of wildfire and not treating every forest fire as a disaster[15,16]. Aggressively suppressing small fires appears to protect the forest, but it allows large quantities of fuel to accumulate and thereby promotes megafires. A widely advocated framework for fuel management can be summarized as the “3R” approach[17].

1. Removal: removing fuel-such as dead trees and desiccated shrubs-on a regular, routine basis.
2. Reduction: reducing plant material, for example lower branches, dead portions of trees, and dry grasses.
3. Replacement: planting less flammable species to replace more flammable ones.

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The emphasis of forest management is therefore not merely to leave nature to grow freely, but to remove and reduce fuel appropriately when too much has accumulated. Notably, under this paradigm even small fires can be regarded as a means of removing or reducing fuel; where natural wildfire cannot achieve the reduction target, prescribed fire may be planned[17]. Empirical evidence supports this approach: prescribed burning and mechanical thinning followed by burning substantially lower the severity of subsequent wildfires-by roughly 60 to 70% relative to untreated areas-and continue to buffer fire behavior even under severe fire weather[18~20]. Fig. 2 contrasts forest outcomes under the two paradigms.

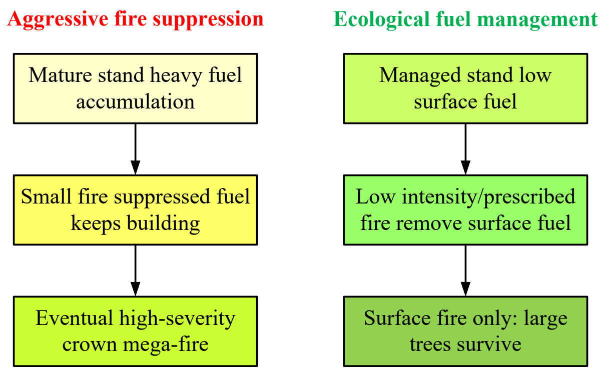

Fig. 2 Forest outcomes under aggressive fire suppression versus ecological fuel management

In 2022, the United Nations Environment Programme conducted a comprehensive scientific assessment of the drivers and management of wildfire. Beyond fuel, it considered factors such as climate and terrain, all of which must be understood and analyzed case by case to formulate an appropriate management strategy. When fire does occur, aggressive suppression is not the first priority; instead, a loss-mitigation mindset guides the response, and the approach is evaluated for its economic, environmental, and social effects, as summarized in Fig. 3[1,8].

Different countries currently emphasize different measures: Greece teaches residents evacuation routes and disaster preparedness; Portugal proactively clears fuel through official action; and southern France uses silvopastoral grazing to reduce fuel loads. All of these differ from the traditional approach of treating wildfire as a disaster to be aggressively suppressed, instead prioritizing prevention and managed evacuation-an approach worthy of attention and reference[4,5].

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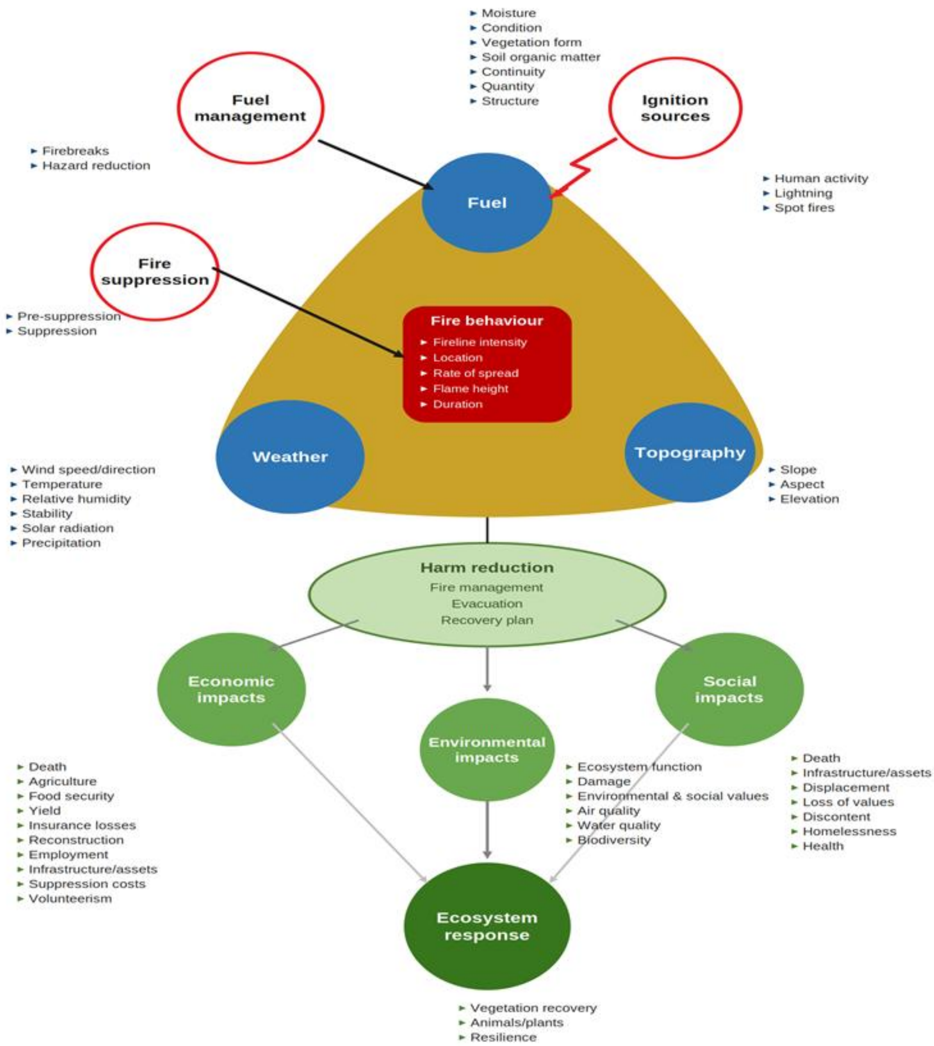

Fig. 3 Factors influencing wildfire and the corresponding management responses (after UNEP, 2022)

3.2 How Can an Immovable Observatory Avoid Wildfire Damage?

Adopting a new fire-management mindset helps reduce wildfire losses, but how should one respond when a building or facility in the forest cannot be moved? Here we take astronomical observatories as a case study. Traditionally, observatory site surveys have prioritized conditions such as distance from artificial light pollution, good atmospheric transparency, a high proportion of clear nights, and high elevation, so observatories are usually located deep in

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remote, densely forested mountains. In the past this signified a pleasant natural environment; today, however, it raises the concern that surrounding forest may draw wildfire to the site and reduce the observatory to ashes. This is no idle worry, as the following cases illustrate.

1. In 2003, the Mount Stromlo Observatory near Canberra, Australia, was engulfed by wildfire, losing at least five telescopes; reconstruction took roughly a decade [21].
2. In 2013, the Siding Spring Observatory was threatened by wildfire; mindful of the 2003 catastrophe, crews mounted an all-out defense and, aided by extensive aerial water drops, escaped destruction, though observations were suspended for about two weeks.
3. In August 2020, California wildfires threatened the Lick Observatory, severely damaging the main buildings and equipment.
4. In September 2020, wildfire threatened the 116-year-old Mount Wilson Observatory in southern California; the U.S. Forest Service deployed more than a hundred wildland firefighters who used large bulldozers to cut firebreaks, conducted backburns, and applied aerial retardant, greatly limiting the losses.
5. In September 2021, California wildfire advanced toward the Allen Telescope Array-a 42-antenna array dedicated to the search for extraterrestrial life; crews cleared brush near the antennas and pruned low branches, and the array survived, though it was offline for about a month.
6. Kitt Peak National Observatory in Arizona is one of the largest concentrations of astronomical instruments in the Northern Hemisphere. On 11 June 2022, the Contreras Fire, ignited by dry lightning, burned more than 11,000 acres; it reached the summit on 17 June, personnel were evacuated, and several non-scientific buildings were destroyed. Although the domes were not directly damaged, the surrounding destruction was striking[22,23].

These examples make clear that the threat of wildfire to observatories is real, urgent, and deserving of serious attention.

Taiwan's Lulin Observatory is a key base for optical astronomy in Taiwan. Located at an elevation of 2,862 m on Front Lulin Mountain within Yushan National Park, it revealed traces of past fires during the site survey of the 1990s-remnants of fires in 1930, 1960, and 1990. According to expert investigation, local fuel accumulates to a critical level over a span of several decades; combined with climatic and environmental factors, this yields a fire cycle of roughly 30 years[6,17,24]. The next potential fire window is again approaching, and the dense surface vegetation ought to be managed; yet, because the site lies within a national park, regulations forbid the casual removal of so much as a

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single plant, making it difficult to eliminate the wildfire hazard. To remedy the shortcomings of the existing qualitative discussion, this paper introduces grey-system theory to establish an optimal decision model for observatory wildfire protection.

4. A Grey Optimal Protection Decision Model

The cases above show that the threat of wildfire to observatories is real and pressing, yet the question of which protection strategy to adopt has remained at the level of qualitative discussion. The fire sample obtainable for any single site is extremely limited(Lulin, for instance, has only three recorded fires), the influencing factors are numerous, and the data are incomplete-precisely the small-sample, poor-information decision problem at which grey-system theory excels[25,26]. The paper therefore constructs a two-stage grey decision model: first assessing the threat, then selecting the optimal strategy.

4.1 Stage One: Assessment of the Threat Trend

1. GM(1,1) model: Let the series $X(k)=(x(1),x(2),x(3),\cdots,x(n))$ denote the historical burned area by year. After a first-order accumulated generating operation (1-AGO), the grey differential equation (1) is established; its whitenization (time-response) solution is given by equation (2), and the predicted values are recovered by inverse accumulation via equation (3).

$$\frac{dx^{(1)}}{dx}+ax^{(1)}=b \tag{1}$$

$$\hat{x}^{(1)}(k+1)=[x^{(0)}(1)-\frac{b}{a}]e^{-ak}+\frac{b}{a} \tag{2}$$

$$\hat{x}^{(0)}(k+1)=\hat{x}^{(1)}(k+1)-\hat{x}^{(1)}(k) \tag{3}$$

Model accuracy is examined by the posterior-error ratio C and the small-error probability P, as in equation (4), where S_2 and S_1 are the standard deviations of the original series and of the residuals, respectively, and $\varepsilon(k)$ is the residual.

$$C=\frac{S_2}{S_1},\ p=prob\{|\varepsilon(k)-\bar{\varepsilon}|<0.6745S_1\} \tag{4}$$

Using the NIFC-reported nationwide U.S. burned area for 2014-2025 (in million acres), the model yields a development coefficient a=0.041 and a grey input b =9.27. The mean absolute relative error is 35.1%, the posterior-error ratio C=0.84, and the small-error probability P=0.50, placing the model in the "unqualified (Grade IV)" category of grey accuracy. The result is itself meaningful: nationwide burned area is a strongly fluctuating, information-poor process for which single-series trend extrapolation cannot yield a reliable point forecast (see Fig. 4); although its central forecast for 2026-2030 falls in the range of about 4.8 to 5.7 million acres, the confidence is low and it should not serve as the sole basis for decisions.

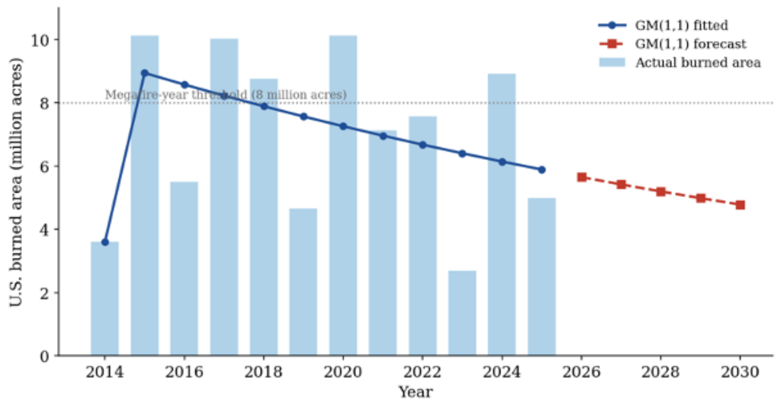

Fig. 4 GM(1,1) grey prediction of U.S. annual burned area (data source: NIFC)

2. Exceedance frequency of megafire years: Because the point forecast is unreliable, the exceedance frequency offers a more robust characterization of the threat. From 2014 to 2025, five years exceeded eight million acres burned (2015, 2017, 2018, 2020, and 2024), giving an empirical frequency of megafire years as high as 0.42-that is, a megafire year occurs on average once every two to three years. The extreme has become the norm rather than the exception.
3.The Lulin fire cycle: At the site level, the Lulin Observatory location has three recorded fires-in 1930, 1960, and 1990-implying an average recurrence interval of about 30 years and hence a next high-risk window around 2020. As of 2026, the site has entered and passed its historical recurrence window; after decades of accumulation, fuel is approaching the critical threshold and fire risk is markedly elevated.
4. Stage summary: The threat cannot be precisely predicted at the macro scale yet remains persistently high, and at the site scale Lulin is within its recurrence window. Because the timing and scale of a fire are highly uncertain, the optimal response should not rely on the passive “predict-then-suppress” paradigm but should shift toward robust, proactive protection-precisely the premise of the second-stage decision.

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4.2 Stage Two: Selection of the Optimal Protection Strategy

1. Candidate strategies and evaluation criteria: Synthesizing the domestic and international experience of Section 3, we identify five feasible protection strategies: S1, conventional aggressive suppression; S2, 3R fuel management; S3, prescribed burning; S4, firebreaks plus aerial retardant; and S5, integrated prevention plus managed evacuation. Six evaluation criteria are adopted: C1, mitigation effectiveness; C2, economic cost; C3, personnel safety; C4, ecological compatibility; C5, regulatory feasibility; and C6, long-term sustainability. Of these, C2 is a cost-type criterion (smaller is better) and the rest are benefit-type (larger is better). In the absence of a directly measurable unified metric, and following the standard grey-decision practice of quantifying qualitative information, each strategy is scored against each criterion on a 1-9 scale using the documentary evidence reviewed above, forming the decision matrix (Table 1 and Table 2). It should be noted that these scores represent structured expert judgement grounded in the literature rather than measured data, and may be further calibrated by an expert panel in practical application[27~29].

Table 1 Decision matrix (1-9 scale; C2 is cost-type)

Strategy\Criterion	C1 effect.	C2 cost	C3 safety
S1 Aggressive suppression	5	9	3
S2 3R fuel management	7	5	7
S3 Prescribed burning	6	4	5
S4 Firebreak + retardant	8	7	6
S5 Integrated prevention + evac.	9	5	8

Table 2 Decision matrix (1-9 scale; C2 is cost-type)-cont.

Strategy\Criterion	C4 ecology	C5 regul.	C6 sustain.
S1 Aggressive suppression	2	7	2
S2 3R fuel management	6	5	8
S3 Prescribed burning	8	3	7
S4 Firebreak + retardant	4	6	5
S5 Integrated prevention + evac.	7	7	9

2. Objective weighting by grey entropy: To avoid subjectivity, the criterion weights are determined objectively by the information (grey) entropy method [27,28], as in equation(5): the decision matrix is first normalized according to benefit/cost orientation, after which the entropy value e_j and weight ω_j of each criterion are computed (m is the number of alternatives, n is the number

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of criteria, and p_{ij} the normalized proportion).

$$e_j = \frac{-1}{\ln m}\sum_{i=1}^{m} p_{ij} \ln p_{ij},\ \omega_j \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \tag{5}$$

The resulting weights are listed in Table 3, mitigation effectiveness (C1, 0.195) carries the highest weight, while the remaining criteria are relatively balanced.

Table 3 Objective weights by grey entropy

Criterion	Type	Entropy	Weight
C1 Mitigation effectiveness	Benefit	0.795	0.195
C2 Economic cost	Cost	0.833	0.160
C3 Personnel safety	Benefit	0.829	0.163
C4 Ecological compatibility	Benefit	0.820	0.172
C5 Regulatory feasibility	Benefit	0.840	0.153
C6 Long-term sustainability	Benefit	0.835	0.157

3. Grey relational ranking: Taking the optimal normalized value of each criterion to form the reference series, the relational coefficient is computed by equation (6) (distinguishing coefficient ρ=0.5, where Δ_{min} and Δ_{max} are the global minimum and maximum of the differences among each comparison series and the reference series), the weighted sum then gives the grey relational grade, and also in equation (6).

$$\xi_{ij} = \frac{\Delta_{\min.} + \rho\Delta_{\max.}}{\Delta_{ij} + \Delta_{\max.}},\ \gamma_{\mathrm{i}} = \sum_{j=1}^{n}\omega_j\xi_{ij} \tag{6}$$

The results are shown in Table 4 and Fig. 5, for S5(0.912)>S3(0.635)≈S2 (0.630)>S4(0.542)>S1(0.435). "Integrated prevention plus managed evacuation" is the optimal strategy, whereas conventional aggressive suppression is the least favorable.

Table 4 Grey relational ranking of the five protection strategies

Rank	Protection strategy	Grey relational grade(γ)
1	S5 Integrated prevention + managed evacuation	0.912
2	S3 Prescribed burning	0.635
3	S2 3R fuel management	0.630
4	S4 Firebreak + aerial retardant	0.542
5	S1 Conventional aggressive suppression	0.435

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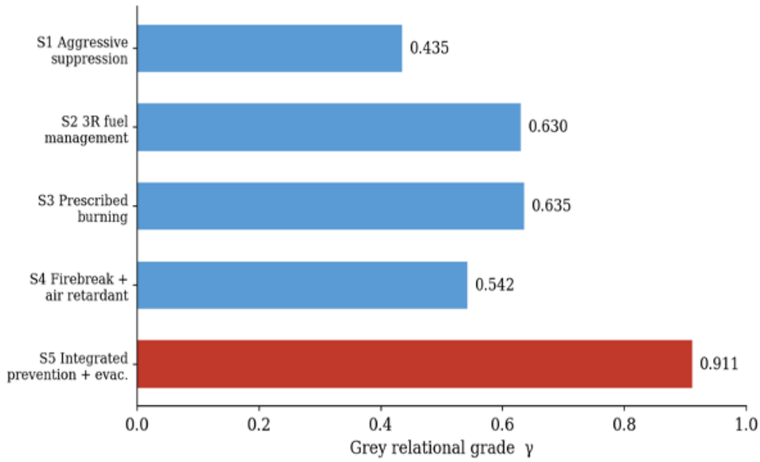

Fig. 5 Grey relational ranking of the five protection strategies (red=optimal)

4. Sensitivity analysis

Varying the distinguishing coefficient ρ over the interval from 0.1 to 0.9, the grades of all strategies shift accordingly, but the ranking remains unchanged (Fig. 6), indicating that the optimality of S5 is robust to the choice of parameter.

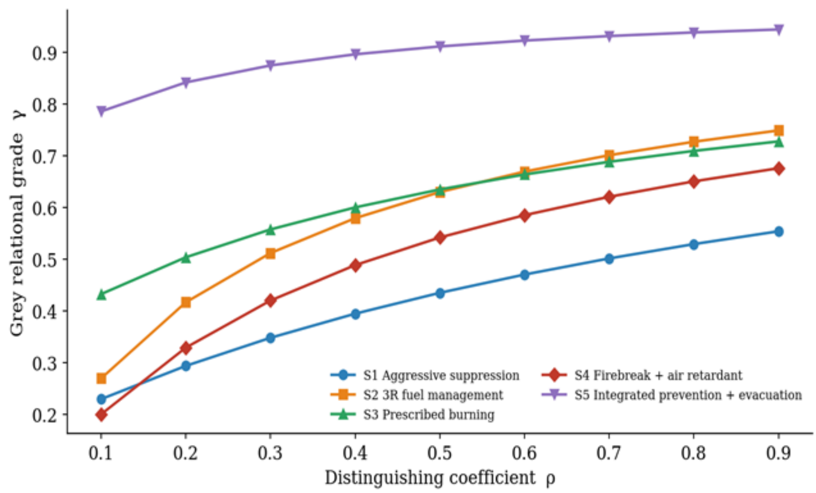

Fig. 6 Sensitivity of the grey relational grades to the distinguishing coefficient ρ (ranking is stable)

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4.3 Model Conclusions and Recommendations for the Lulin Observatory

The model yields clear conclusions consistent with the qualitative analysis: in facing megafires, reliance on after-the-fact aggressive suppression(S1) is the least effective, most costly, and most dangerous option, whereas an integrated strategy centered on advance fuel reduction and supplemented by evacuation planning(S5) is optimal. For the Lulin Observatory, located within Yushan National Park and constrained by regulation from removing vegetation, we recommend

1. Seeking regulatory flexibility to designate a limited fuel-management zone around the site, with periodic clearing of dead branches and understory shrubs (corresponding to the removal and reduction of the 3R approach).
2. Establishing firebreaks on the perimeter and pre-arranging support agreements for aerial water and retardant drops (the Mount Wilson model).
3. Formulating and rehearsing contingency plans for personnel evacuation and equipment protection.
4. Using modern information technology to continuously monitor fuel load, climate, and terrain and to update the risk assessment dynamically. Only in this way can the site move from a passive to a proactive posture before the next fire-risk window arrives.

5. Conclusion

The paper has described the ecological role of wildfire in an attempt to rehabilitate its image as a purely destructive force. Yet because global warming has increased the probability of extreme weather, wildfires have grown larger, more frequent, more damaging, and harder to extinguish. Under these conditions, prevention cannot rely on the traditional mindset of aggressive suppression, which only accumulates more fuel and adds kindling for the next fire. The new fire-management thinking should consider how to reduce fuel in advance and remove some dead material; in high-risk areas, evacuation plans should be prepared ahead of time with regard to climate and terrain; and for buildings that cannot be evacuated, such as observatories, more proactive protection measures should be devised. Going further, this paper has used a two-stage grey-system decision model to translate these qualitative judgements into a quantifiable, testable, and generalizable decision basis: the threat assessment shows that fire risk is high and that Lulin is within its recurrence window, while the strategy selection quantitatively confirms that integrated prevention plus managed evacuation outperforms conventional aggressive suppression-thereby providing a scientific decision framework for wildfire protection at mountain observatories.

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4. References

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