Systems Acquisition and Enterprise Risk Analysis of Wildfire Detection and Monitoring Technologies

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***Abstract*—There is urgency for control and decision technologies to address the threat of wildfires as they endanger built and natural systems and lead to multifaceted consequences for ecosystem, human, societal, and economic well-being. Reliable early detection of new wildfires aids in reducing the impacts of this planetary emergency by enabling responses while fires remain small. With the development of new detection technologies, the variety of available technologies calls for a systems-level framework to effectively analyze the prioritization of technologies and sources of disruption to this prioritization. This paper applies a scenario-based multi-criteria decision analysis approach to assess priorities in detection and monitoring technologies under baseline and potentially disruptive scenarios. Sixteen categories of wildfire detection and monitoring technologies are evaluated under seven scenarios, including sociotechnical considerations, using nine success criteria.**

Keywords—wildfire detection, wildfire monitoring, systems analysis, scenario analysis, decision analysis, resilience

I. Introduction

The Global Wildfire Information System (GWIS) estimates that approximately 391 million hectares were burned globally by wildfires in 2024 [1]. In recent years, wildfires across the globe have been notable for their size, location, and compounding threats. Fires in the Amazon Rainforest have threatened important habitats while fires in the Arctic Circle emphasize the increase in fire activity in areas not typically prone to wildfires [2]. The Windy Deuce wildfire in 2024 required a nuclear weapons facility in Texas, United States to temporarily shut down, illustrating the potential for compounding disasters [3]. In Canada, the 2023 wildfire season more than doubled the record for area burned with over seventeen million hectares burned [4]. California, United States also experienced a doubling of the modern record for area burned with more than 1.7 million hectares burned in the 2020 wildfire season [5]. Compared to wildfire activity between 2010 and 2020, the United Nations projects a 9%-14% increase in catastrophic wildfires this decade, 20%-33% increase by mid-century, and 31%-52% by the turn of the century [2].

While wildfires can be a natural and essential phenomenon for maintaining system resilience, fuel bed changes, fire ignitions, and other factors have led to an increase in wildfire activity that threatens both natural and built systems [2], [6]. The impacts of wildfires are multifaceted. Beyond impacts to the landscape, wildfires affect water levels and decrease hydrologic quality. Ash enters bodies of water while a wildfire is actively burning, and sediment, heavy metals, and additional ash flow into water bodies during post-fire rainstorms, affecting aquatic and other life [7]. Issues also impact drinking water as facilities may not regularly test for these materials [7]. Additionally, vegetation loss and the increased water repellency of soil after a fire can accelerate erosion while also causing stream levels to rise with peak flows reaching up to one hundred times the prior records [8]. The corresponding impacts to the hydrological cycle present hazards for post-fire floods, mudslides, and other compounding disasters [8].

Wildfires also have numerous impacts on human health. Fine particulate matter (PM), including PM 2.5, is present in wildfire smoke [9]. Immediate impacts include difficulty breathing as well as irritation of the eyes, nose, and throat. Short-term exposure to wildfire smoke has been attributed to respiratory and cardiovascular effects, including decreased lung function, heart attacks, and strokes [10]. Fine particulate matter

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exposure has also been linked to a higher risk of premature mortality for populations with respiratory or cardiovascular conditions [10].

Sociotechnical systems are also affected by wildfires in a variety of ways. Large wildfires at the wildland-urban interface damage or destroy homes, businesses, and other structures. For instance, the Camp Fire in Paradise, California destroyed more than 18,800 structures [11]. A variety of factors, including costs, impact rebuilding: in the United States, only a quarter of homes that were affected by wildfires between 2000 and 2005 were rebuilt in five years [12].

The financial impacts of wildfires are significant. The United States spends approximately $3.35 billion annually for wildfire suppression, and suppression costs have been projected to increase by about 40% by mid-century [13]. The comprehensive economic burden in the United States is approximated at $71.1 to $347.8 billion annually [14].

Early detection and reliable monitoring of wildfires are vital for mitigating wildfire impacts as they improve response effectiveness by allowing resources to mobilize before the fire grows uncontrollably. Many technologies have been developed to aid in the early detection and monitoring of wildfires, and the technologies present an array of strengths and weaknesses in different use cases. A variety of satellites offer nearly global coverage while differing in resolution, latency, and performance in different observing conditions. Aerial-based systems, such as fixed wing aircraft, rotary wing aircraft, and drones, provide high-fidelity, near-real-time information, but operating costs typically limit deployment. Ground-based systems, such as sensor networks and camera systems, typically provide near-real-time regional coverage while differing in topographic limitations. This paper uses scenario-based multi-criteria decision analysis to assess sixteen categories of wildfire detection and monitoring technologies.

II. Methods

A scenario-based multi-criteria decision analysis is developed to prioritize wildfire detection and monitoring technologies under baseline and disruptive scenarios. The approach recognizes risk as a change of priorities caused by a disruptive scenario. The method is adapted from [15]-[19].

Three sets are used to develop the multi-criteria decision analysis: criteria, initiatives, and scenarios. The criteria $C = \{c_1, \dots, c_m\}$ are first developed from stakeholder and system objectives: the criteria assess the ability of the initiatives to achieve the desired goals. Additionally, each criterion is determined to have low, medium, or high relevance, and a numeric relevance score is assigned accordingly. This paper adopts relevance scores of one, two, and four for low, medium, and high relevance, respectively. A numeric weight, w_{j0}, for the relevance of each criterion c_j in the baseline, or zeroth, scenario is subsequently determined by normalizing the relevance scores. Table I lists the nine criteria used in this study and their baseline relevance. The criteria and baseline relevance are selected in collaboration with stakeholders and personnel experienced in wildfire incident response. Accuracy is not explicitly included as a success criterion as each technology exhibits high accuracy under the correct conditions; that is, the performance of each technology is better assessed by considering other criteria such as data latency, resolution, and resilience to poor observing conditions.

TABLE I. Success Criteria for Wildfire Detection and Monitoring Systems and Their Relevance in the Baseline Scenario

Index	Criterion	Baseline Relevance
c.01	Pre-Fire Utility	Medium
c.02	Incipient Fire Utility	High
c.03	Active Burning Utility	High
c.04	Data Latency	High
c.05	Coverage Area	Medium
c.06	Observing Condition Resilience	Medium
c.07	Operational Complexity	Medium
c.08	Cost	Medium
c.09	Resolution	High

Next, the set of initiatives $X = \{x_1, \dots, x_n\}$ is defined as the set of detection and monitoring technologies under consideration. Table II lists the sixteen initiatives considered in this paper which are selected from the technologies reviewed in [6] and discussion with stakeholders.

TABLE II. Wildfire Detection and Monitoring Technology Initiatives

Index	Initiative
x.01	Satellites: NASA FIRMS
x.02	Satellites: Infrared Imaging
x.03	Satellites: Spectral Imaging
x.04	Satellites: Synthetic Aperture Radar
x.05	Satellites: CubeSat
x.06	Satellites: Geostationary
x.07	Aerial-Based: Fixed Wing Aircraft
x.08	Aerial-Based: Rotary Wing Aircraft
x.09	Aerial-Based: Night Vision-Enabled Rotary Wing Aircraft
x.10	Aerial-Based: High-Level Drones
x.11	Aerial-Based: Drones Combined with Ground Sensors
x.12	Ground-Based: Passive Sensor Arrays
x.13	Ground-Based: Visual Camera Systems
x.14	Ground-Based: AI-Enabled Visual Camera Systems
x.15	Ground-Based: Fixed Infrared Detection
x.16	Ground-Based: Portable Infrared Detection

A criteria-initiative (C-I) assessment characterizes how well each initiative achieves each criterion. A four-point scale is used to describe the achievement with scores of "very well", "well", "somewhat," and "minimally" mapped to values of one, two-thirds, one-third, and zero, respectively. Table III provides the C-I assessment of the wildfire detection and monitoring technologies with the following symbols used to improve visual understanding of the assessment: a filled circle denotes "very well," a partially filled circle represents "well," an empty circle indicates "somewhat," and a dash signifies "minimally." The C-

I assessment values are determined from [6], [20]-[48], stakeholder consultation, and discussions with technology experts. Reported values are used in the assessment, but actual technology performance may differ by application.

TABLE III. CRITERIA-INITIATIVE ASSESSMENT FOR WILDFIRE DETECTION AND MONITORING SYSTEMS

	c.01	c.02	c.03	c.04	c.05	c.06	c.07	c.08	c.09
x.01	●	●	◐	○	●	◐	●	●	◐
x.02	●	●	◐	—	●	◐	●	●	◐
x.03	●	●	◐	○	●	◐	●	●	○
x.04	—	●	—	—	●	●	●	●	●
x.05	●	●	◐	○	●	◐	●	◐	◐
x.06	●	●	●	◐	◐	◐	●	●	○
x.07	○	●	●	●	○	○	○	—	●
x.08	○	—	●	●	○	◐	○	—	●
x.09	—	—	●	●	○	—	—	—	●
x.10	●	●	◐	●	○	◐	○	—	●
x.11	●	—	○	◐	—	◐	◐	◐	—
x.12	●	●	—	●	—	●	●	◐	●
x.13	●	●	—	●	○	○	◐	○	◐
x.14	●	●	—	●	○	○	◐	○	◐
x.15	●	●	○	●	—	○	◐	○	◐
x.16	—	—	○	●	—	○	●	◐	◐

Then, the baseline score or value of each initiative is calculated using (1):

$$V_0(x_i) = \sum_{j=1}^{m} w_{j0} a_{ij}, \quad (1)$$

where $V_0(x_i)$ denotes the value of initiative x_i under the baseline scenario, w_{j0} is the baseline weight of criterion c_j, and a_{ij} is the assessment of the extent to which initiative x_i achieves criterion c_j from the C-I assessment. The baseline rankings are determined by sorting the baseline scores such that the initiative with the highest score receives a ranking of one. The rankings represent the priority order of the initiatives under the current baseline scenario.

Next, disruption is considered. The set of disruptive scenarios $S = \{s_1, \ldots, s_p\}$ is determined. Each scenario is a potential future scenario that has the capacity to disrupt priorities. Table IV lists the six disruptive scenarios considered in this study. The selection of scenarios is informed by literature review and stakeholder consultation. Changes in engagement could include changes in funding, mitigation and prevention efforts, or related education. Changes in conditions affecting fire threat may consist of changes in temperature, rainfall, or humidity. Changes affecting fire spread could include variations in wind or fuel bed conditions.

A criteria-scenario (C-S) assessment identifies how the scenarios disrupt the importance of each criterion. A five-level Likert scale is used to describe how the importance of a criterion may change under a disruptive scenario. The reweighting of criteria under each disruptive scenario allows stakeholder insight and experience to be leveraged to make judgments of the relative changes in criteria importance without requiring the criteria-initiative assessment to be reconsidered for potential future scenarios [19]. Table V presents the C-S assessment for the wildfire detection technology criteria with the following symbols used to aid visual comprehension: an upward, filled triangle denotes "increases," an upward, empty triangle represents "increases somewhat," a dash signifies "remains unchanged," a downward, empty triangle indicates "decreases somewhat," and a downward filled triangle depicts "decreases." The C-S assessment scores are selected from literature review and stakeholder consultation. A multiplicative factor u_{jk} that describes the change in importance of criterion c_j due to scenario s_k compared to the baseline is determined based on the C-S assessment with "increases" and "decreases" inversely proportional, "remains unchanged" equal to one, and "increases somewhat" and "decreases somewhat" inversely proportional according to (2):

$$u_{jk} = \begin{cases} \beta_1, & \text{increases} \\ \beta_2, & \text{increases somewhat} \\ 1, & \text{remains unchanged} \\ 1/\beta_2, & \text{decreases somewhat} \\ 1/\beta_1, & \text{decreases} \end{cases}, \quad (2)$$

where β_1 and β_2 are constants such that $\beta_1 > \beta_2 > 1$. This paper adopts $\beta_1 = 8$ and $\beta_2 = 6$.

TABLE IV. DISRUPTIVE SCENARIOS WITH POTENTIAL TO IMPACT THE PRIORITIZATION OF WILDFIRE DETECTION AND MONITORING TECHNOLOGIES

Index	Scenario
s.01	Engagement Increases
s.02	Engagement Decreases
s.03	Conditions for Fire Threat Improve
s.04	Conditions for Fire Threat Worsen
s.05	Conditions for Fire Spread Improve
s.06	Conditions for Fire Spread Worsen

After conducting the C-S assessment, the numeric weights of the criteria are updated for each scenario according to (3):

$$w_{jk} = \frac{u_{jk} w_{j0}}{\sum_{j=1}^{m} u_{jk} w_{j0}}, \quad (3)$$

where w_{jk} is the normalized numeric weight of criterion c_j under scenario s_k and u_{jk} is the multiplicative factor that corresponds to the change in importance of criterion c_j under scenario s_k.

Then, the score of each initiative under each scenario is calculated using (4):

$$V_k(x_i) = \sum_{j=1}^{m} w_{jk} a_{ij}, \quad (4)$$

where $V_k(x_i)$ is the score or value of initiative x_i under disruptive scenario s_k, w_{jk} is the weight assigned to criterion c_j

under scenario s_k, and a_{ij} is the C-I assessment score that describes the extent to which initiative x_i achieves criterion c_j. For each scenario, the initiative rankings are determined by sorting the scores in decreasing order with the highest scoring initiative achieving a rank of one.

TABLE V. CRITERIA-SCENARIO ASSESSMENT OF CHANGES IN CRITERIA RELEVANCE FOR WILDFIRE DETECTION AND MONITORING TECHNOLOGIES UNDER DISRUPTIVE SCENARIOS

	s.01	**s.02**	**s.03**	**s.04**	**s.05**	**s.06**
c.01	—	△	▽	▲	—	—
c.02	—	—	—	—	▽	▲
c.03	—	—	—	—	▽	▲
c.04	—	—	▽	▲	▽	▲
c.05	—	—	—	—	▽	▲
c.06	—	—	▽	▲	▽	▲
c.07	▽	△	—	△	—	△
c.08	▽	▲	—	—	—	—
c.09	—	—	▽	▲	▽	△

Finally, the disruptiveness of each scenario is considered as the change in priority order of the initiatives compared to the rankings under the baseline. The disruptiveness score d_k of scenario s_k is quantified by subtracting the Spearman rank correlation coefficient of the rankings under the baseline scenario and scenario s_k from one. A higher disruptiveness score indicates a more significant shift in rankings.

III. RESULTS AND DISCUSSION

Fig. 1 summarizes the rankings of the sixteen initiatives across the baseline scenario and six disruptive scenarios. The black rectangles represent the system order prioritization of the initiatives under the baseline scenario. The red rectangles signify the degree to which the initiatives can fall in priority under the disruptive scenarios. Conversely, the blue rectangles depict the extent to which the initiatives can improve in ranking when accounting for the disruptive scenarios. For example, while initiative x_4 is ranked tenth in the baseline scenario, it falls to rank fifteen and rises to rank six under the disruptive scenarios.

Geostationary satellites and NASA FIRMS satellites are ranked first and second in the baseline scenario, respectively. However, both initiatives demonstrate the potential to fall significantly in priority under the disruptive scenarios considered. As a result, other technologies should also be considered for wildfire detection to improve resilience to disruption. Conversely, although drones combined with ground sensors and portable infrared detection are ranked last and next-to-last in the baseline scenario, respectively, the technologies can both rise to eleventh priority.

The change in ranking of an initiative across the scenarios, which is represented by the length of the blue and red bars, is a measure of the resilience of the initiative to disruption: initiatives with less significant ranking changes demonstrate higher resilience. For example, night vision-enabled rotary wing aircraft exhibit the greatest resilience to disruption; however, the technology remains in the bottom quarter of the rankings. On the

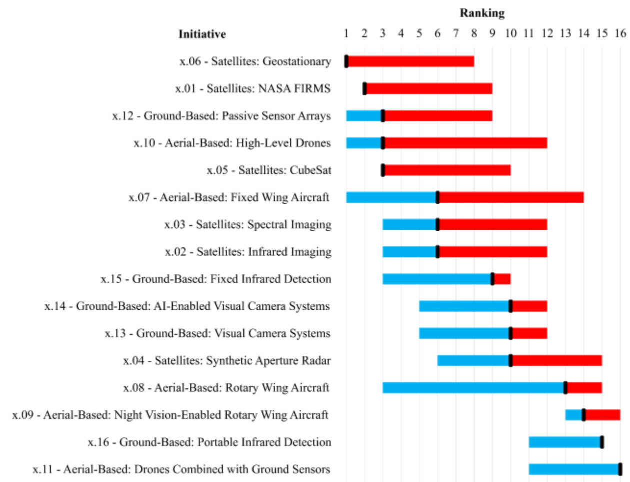

Fig. 1. Rankings of wildfire detection and monitoring technologies under baseline and disruptive scenarios.

other hand, fixed wing aircraft exhibit the least resilience to disruption as the technology ranges from first to fourteenth rank. The result aligns with the practice of deploying fixed wing aircraft during periods of increased fire danger or other conditions that necessitate their use. Significant changes in priority also suggest further evaluation of the resilience of the technologies. Collectively, disruption has a significant impact on the priority order of the wildfire detection and monitoring technologies: the relative instability, or low resilience, of the technologies aligns with the current focus on development of new detection technologies and highlights the need for an integrated system of technologies as advocated by [6].

The balance of the potentials for an initiative to rise and fall, which is visually examined by comparing the lengths of the blue and red bars, should also be considered by stakeholders as it provides a representation of the potential upside or downside of investing in the initiative if disruption occurs. For instance, fixed infrared detection achieves a middle rank in the baseline scenario, but it demonstrates significant potential to rise in rank while exhibiting little demotion potential.

Notably, the three main technology modalities (satellites, aerial-based, and ground-based) each include technologies that are highly ranked in the baseline scenario as well as technologies that rise and fall significantly in priority under disruption. As a result, multimodal systems of technologies are suggested for further research and development to balance their strengths and weaknesses in the baseline scenario as well as their promotion and demotion potentials under disruption.

The scenario disruptiveness scores are displayed in Fig. 2. A worsening of conditions for wildfire threat is the most disruptive scenario. An increased wildfire threat requires more emphasis on pre-fire monitoring, low latency, and high resolution to improve early detection of new fire ignitions. In turn, technologies such as sensor arrays, rotary wing aircraft, and visual and infrared camera systems are prioritized although they are ranked near the middle in the baseline scenario. Decreased engagement, the second most disruptive scenario, may reduce available funding and labor, resulting in the prioritization of lower cost technologies that are simple to operate. A change in conditions that reduces wildfire spread, the third most disruptive scenario, prioritizes satellite technologies such as infrared and spectral imaging that were not initially ranked as highly due to their more significant delays in data transmission. Overall, the most disruptive scenarios highlight the volatility of wildfire detection priorities to a variety of changes.

On the other hand, increased engagement and a worsening of conditions with respect to wildfire spread are the least disruptive scenarios. While increased awareness is important for public support of detection efforts and improvements in wildfire prevention efforts at the society level, the change in prioritization of technologies is less significant.

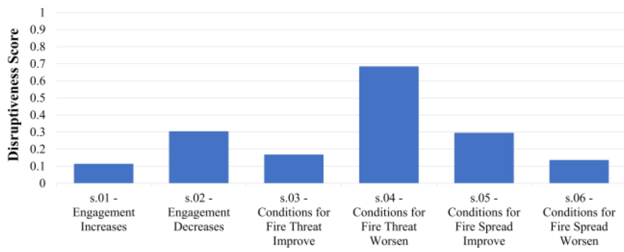

Fig. 2. Disruptiveness of scenarios impacting the prioritization of wildfire detection and monitoring technologies.

IV. CONCLUSION

This paper uses scenario-based multi-criteria decision analysis to evaluate sixteen categories of wildfire detection and monitoring technologies. The technologies are analyzed under a baseline scenario as well as six possible future scenarios, and the effect of disruption of the scenarios on the prioritization of technologies is determined. Systems and risk analyses are integrated to guide prioritization of detection technologies for research, development, and investment. Understanding how wildfire detection and monitoring technologies are prioritized assists with procurement, supply chain management, and deployment. Table VI summarizes the results of the multi-criteria decision analysis of wildfire detection and monitoring technologies.

TABLE VI. SUMMARY OF RESULTS OF MULTI-CRITERIA DECISION ANALYSIS FOR WILDFIRE DETECTION AND MONITORING TECHNOLOGIES

Result	**Description**
Most disruptive scenarios	*s.04 – Conditions for Fire Threat Worsen* is the most disruptive. *s.02 – Engagement Decreases* and *s.05 – Conditions for Fire Spread Improve* are the next most disruptive.
Least disruptive scenarios	*s.01 – Engagement Increases* is the least disruptive. *s.06 – Conditions for Fire Spread Worsen* and *s.03 – Conditions for Fire Threat Improve* are the next least disruptive.
Initiative resilience	The disruptive scenarios induce high variability in system prioritization, highlighting the need for development of additional resilient technologies.
Technology modality	No single technology modality outperforms the others. Initiatives of different modalities rise and fall in priority under different scenarios, emphasizing the importance of developing multimodal technology systems.

The described analysis is an iterative method that should be repeated as new detection and monitoring technologies emerge, stakeholder perspectives evolve, or conditions relevant to wildfires change. Future work includes extending the analysis to consider the differences in detection and monitoring approaches in remote and urban areas. Additionally, as technology performance and availability differ significantly by location, future work will incorporate regional considerations to develop a tool that produces a tailored prioritization of technologies for localities of stakeholder interest.

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