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Comparing Wildfire Suppression Approaches: Insights from Different Scales

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Abstract**:** Effectively containing and controlling wildfires is a paramount goal for fire management agencies. This review, presented in two parts, delves into the complex realm of wildfire suppression effectiveness. The first part discusses research conducted at the flame and Fireline scales, shedding light on critical aspects of suppression efforts. The second part broadens the perspective, addressing effectiveness at incidents and scales of landscape and highlighting the motivation and implications of these studies. Recent findings reveal that wildfire suppression research encompasses various approaches. Laboratory experiments conducted at the flame size help evaluate the efficacy of suppression chemicals, aiding in resource selection. Field observations at the Fireline scale provide a realistic assessment of wildfire conditions, allowing for the examination of resource productivity and the impact of suppression efforts on fire behavior assessing wildfire suppression effectiveness is challenging due to diverse objectives, dynamic variables, and data acquisition hurdles. However, recent case studies underscore the advantages of fuel management in enhancing suppression effectiveness, while economic analyses offer insights into resource contributions during containment. Nevertheless, productivity models derived from non-wildfire data often overpredict operational production, and measuring wildfire suppression effectiveness varies depending on scale and purpose. From flames to landscapes, each scale presents unique opportunities and challenges. Despite the complexities, ongoing research illuminates key variables and contributes to a deeper understanding of effective wildfire suppression.

Keywords: Wildfire, Fire-Management, Suppression Effectiveness, Fuel-Management, Fire Behavior.

1. INTRODUCTION

Wildfires have far-reaching impacts on public safety, property, infrastructure, and the environment, prompting the need for effective management strategies encompassing prevention, preparedness, and response. Recent decades have witnessed significant advancements in wildfire management approaches, yet challenges have intensified due to climate shifts, evolving land use, fuel variations, and evolving societal expectations, resulting in more frequent and extreme wildfire events, escalating losses, and rising suppression costs [1-6]. These trends are expected to persist in the future. Therefore, comprehending the effectiveness of fire management activities, particularly suppression responses, holds paramount importance in mitigating these costs and consequences. Traditional wildfire suppression involves an array of actions aimed at controlling and extinguishing fires once detected, spanning offensive and defensive tactics, alongside essential pre-suppression activities like firefighter training, fuel management, equipment maintenance, resource positioning, dispatch protocols, and community education [7-12]. Evaluating suppression effectiveness proves indispensable in enhancing pre-suppression efforts and optimizing resource allocation during wildfire incidents, ultimately ensuring the safety of responders and communities. This review focuses on understanding suppression effectiveness across various spatial scales, ranging from controlled flame experiments and Fireline containment assessments to in-depth analyses of complete fire incidents and broad-scale landscape strategies, shedding light on the pivotal role of research in shaping informed fire management decisions [13-18].

Wildfire Suppression Approaches :

Wildfire suppression primarily involves extinguishing flames and establishing fuel-free barriers, often referred to as Fireline, or using moistened edges to confine the fire perimeter. This approach is essential in preventing further fire spread and involves detecting and eliminating residual combustion. It can be conceptualized as a race against time, as wildfires typically start small but can rapidly escalate [19]. Smaller fires are generally more manageable and cause less damage compared to larger ones [20-22].

The energy required for effective fire containment is influenced by several factors, including the rate of perimeter growth and fire intensity. Additionally, access challenges, such as the allocation of firefighting resources to defensive roles, can further complicate containment efforts [23-25].

To address these challenges, firefighting organizations develop strategies aimed at the prompt detection and immediate response to limit the growth of bushfires. While these strategies have proven effective in containing most wildfires within predefined boundaries, some fires have managed to evade initial containment efforts, resulting in extensive areas being affected by the fire [26-28]. It is worth noting that the effectiveness of these strategies may differ when applied to larger fires, which often involve different suppression objectives and longer durations [29-31].

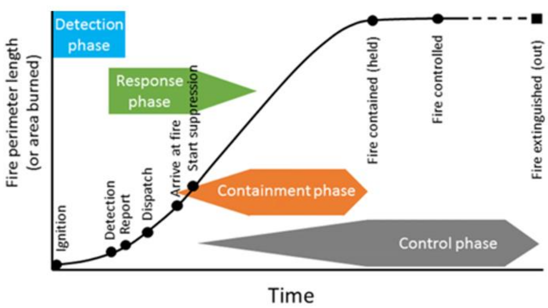

Fig 1: Fire Growth Model Established Over Time [32,33].

Adapted from Parks [32] and Martell [33], as shown in Figure 1 suppression response events, including fire spread and containment phases. Safety is crucial during suppression operations, and high-risk tactics are unacceptable. Containment tactics like flanking fire from anchor points and using safety-related acronyms are essential. Recent research focuses on reducing firefighter exposure to excessive risks [34-36].

Wildfire suppression uses diverse resources in various environments, locations, and tactical roles. Preventive suites adapt to local incidents and cultural influences, with heavy machinery in forestry and road construction potentially firefighting applications [34].

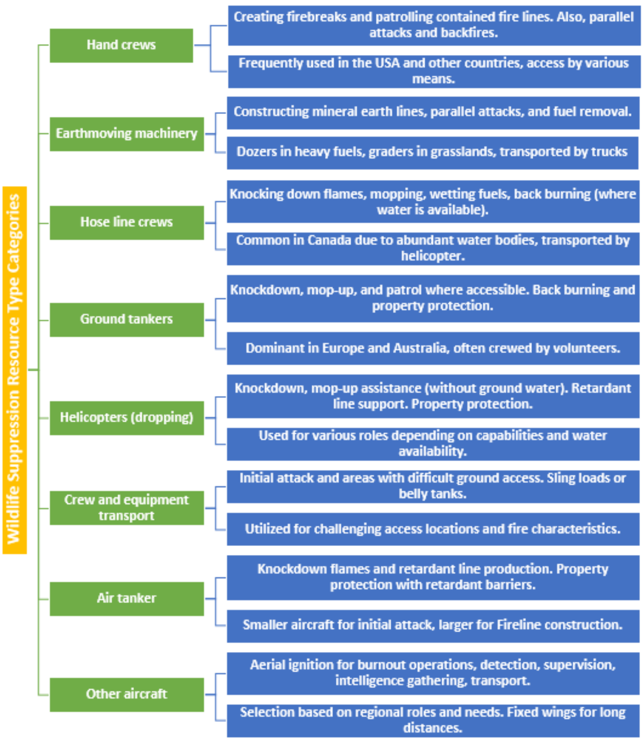

Fig 2:Types of Wildfire Suppression Resources and Their Typical Tactical Roles by author

Offensive suppression tactics are used to directly stop the spread of fire perimeters and to contain fires using control lines as shown in Figure 3.

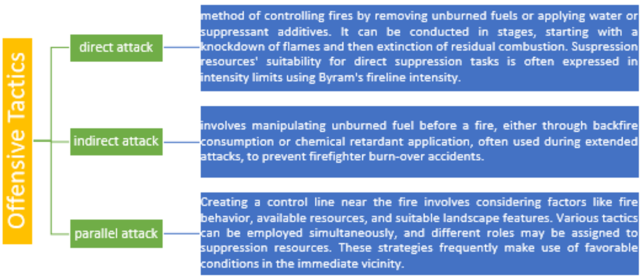

Fig 3: Offensive Suppression Tactics by author

The choice of tactics relies on fire behavior, the availability of resources, and appropriate landscape features. It's common to employ multiple tactics simultaneously, and suppression resources can be allocated to various roles. These tactics frequently make the most of favorable local conditions [37-44].

Fig 4: Some Examples Of Different Types Of Fireline And Suppression Tactics [46].

Figure 4 displays various scenarios, including a slender hand trail within a parched eucalypt forest, a broad dozer trail that was readied for a major backburn as part of the Great Divide complex fires in 2006, a retardant line in mallee heath vegetation effectively stopping a head fire with a 5000-kW/m intensity during FuSE experiments, firefighters using light tankers to extinguish flames, and firefighters defending residential structures and sheds during the Mt Bolton fire. Controlled fire lines require extensive review work to prevent fuel re-igniting and spreading, requiring costly, time-consuming, and water-intensive ground-based suppression resources and monitoring, resulting in resource retention and longer firefighting exposure [45-46].

Effective fire suppression is influenced by various factors, including environmental conditions, firefighting resources, tactical decisions, and suppression chemicals. Factors like wind speed, vegetation type, fire intensity, flame height, wind speed, and terrain accessibility also play a role. Successful management and informed decisions are crucial for maximizing firefighting outcomes.

Wildfire suppression encompasses three primary elements, each influenced by numerous factors. The first element pertains to fire-related factors, including fire intensity and spread rates, which impact the feasibility of direct attack, resource selection, and the number of retardants or suppressants needed. The second element concerns the environment, encompassing variables such as dryness, wind conditions, temperature, and vegetation type, all of which influence tactical decisions, accessibility, and resource productivity. The third element revolves around the application aspect, encompassing resource availability, decision-making processes, experience, and specific suppression chemicals, all of which contribute to effective wildfire suppression. Understanding and effectively managing these elements and their associated factors are critical for successful wildfire suppression operations [45-47]

Flame Scale

Evaluating the effectiveness of wildfire suppression typically entails performing experiments within controlled settings like fuel beds and small field plots. These experiments offer distinct advantages, including the ability to collect precise data, cost-efficiency, and reduced risk. Researchers can strategically position measurement instruments, allowing for control over influential factors such as wind speed and fuel moisture content. This controlled environment facilitates in-depth investigations of specific variables and the ability to replicate factorial testing for thorough analysis.[48].

In the 1960s, the testing of wildfire retardants in laboratory settings was initiated with the aim of identifying chemicals suitable for field applications. These experiments typically entail the application of a wet retardant mixture onto a fuel bed, followed by allowing it to dry before igniting a fire. The effectiveness of the retardant is evaluated by analyzing fire spread rates and fuel consumption. During this process, an equation was developed to estimate the coverage provided by the fire retardant, which subsequently led to recommendations for its application in various fuel types [49-50].

Studies have been conducted to determine water coverage levels for extinguishing fires, using overhead sprays and simulations from aircraft. The first studies focused on pine litter fires in sheltered outdoor environments, assessing extinction effects, and predicting suppressant depth for low-intensity fires,

The results were used to test theoretical calculations estimating water requirements.

Recent research conducted in a combustion wind tunnel has introduced and validated a methodology for evaluating the efficacy of various gel and foam suppressants. This study has unveiled noteworthy variations in the volume of suppressant needed to extinguish flaming combustion in eucalypt litter fuels, with certain gel-based suppressants demonstrating a lower volume requirement than water- and foam-based alternatives [48].

Studies have indirectly investigated the use of suppressant mixes in small outdoor and laboratory settings. Taylor et al. [50] as shown in Figure 6,7 The study explored the use of gel suppressant control lines to prevent moving surface fires in pine needle litter plots, but adverse weather conditions limited the effectiveness of the results.

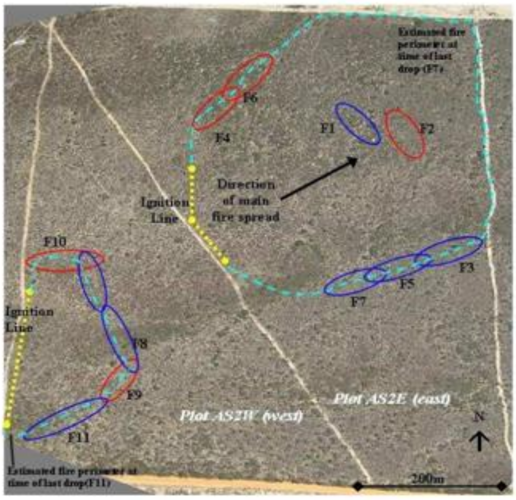

Fig 5: Foam Drop Locations in Plot AS2 [50].

Foam drop locations in plot AS2 are superimposed over a pre-fire geo-rectified aerial photograph, with blue and red ovals indicating bomber 580 and 583 drops, respectively, without a post-fire aerial image.

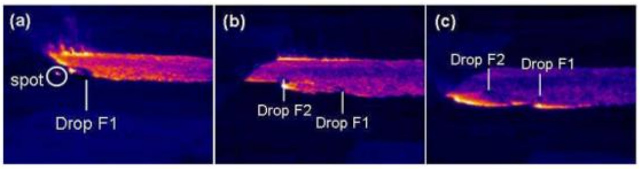

Fig 6: Infrared Sequence Showing Drops F1 And F2 In Plot AS2E. (A) Spot Fire Ahead of Drop F1 (15:11), (B) Drop F2 Being Burnt Around (15:14), (C) Drops F1 And F2 Completely Burnt Around (15:17) [50].

Gibos and Ault's study on pre-treated litter fuels in field settings faced challenges due to unfavorable weather conditions. Refai et al.'s study Water was discovered on fire intensity in tiny beds both with radiant heat panels. Coverage decreased intensity but varied depending on fuel bed retention. Only one study investigated suppression effectiveness during mop-up [52-55].

Fireline Scale

Wildfire suppression observations are conducted to examine the productivity of suppression resources and their impact on fire behavior. The Fireline scale provides a realistic representation of wildfire conditions, allowing for a close examination of suppression effectiveness.

Resource Productivity

Productivity is crucial for incident planning, containment simulation, firefighter exposure estimation, and suppression efficiency. However, fundamental productivity research has declined, leaving issues like resource performance and environmental variables unresolved [46]. Two productivity studies on hand crews, published since Hirsch and Martell's review, found that firefighters in Australia produce 512 meters of Fireline per hour, declining with fatigue as shown in Table 1 [56,57].

Table 1: Some Recent Study Productivity Rates as Examples

Source and Methodology	Resource Type	Fuel/Weather Conditions	Productivity (m/h)	Average	Range
Broyles (2011) [58]	Type 1 hotshot crew (Direct Attack)	Grass, Chaparral, Brush, Timber	342, 133, 332, 211	101	422
Broyles (2011) [58]	Type 1 hotshot crew (Indirect Attack)	Grass, Chaparral, Brush, Timber, Wildfire Responses	191, 101, 99, 139	54	227
McCarthy et al. 2003 [59]	6-person hand crew	Dry eucalypt forest, Wildfire Responses (Various Incidents)	102, 350, 700, 350, 170	45	1200
McCarthy et al. 2003 [59]	Small dozer (D4)	Dry eucalypt forest, Wildfire Responses (Various Incidents)	350	200	1000
McCarthy et al. 2003 [59]	Large dozers (D6–D9)	Dry eucalypt forest, Wildfire Responses (Various Incidents)	700	250	1000
McCarthy et al. 2003 [59]	Tanker	Dry eucalypt forest, Wildfire Responses (Various Incidents)	350	100	800
McCarthy et al. 2003 [59]	Single-engine air tanker	Dry eucalypt forest, Wildfire Responses (Various Incidents)	170	80	300
Hirsch et al. (2004) [60]	Initial attack crew (4 people)	Coniferous forests, Mixed wood, Grass, Slash	341, 274, 813, 263	163	1220

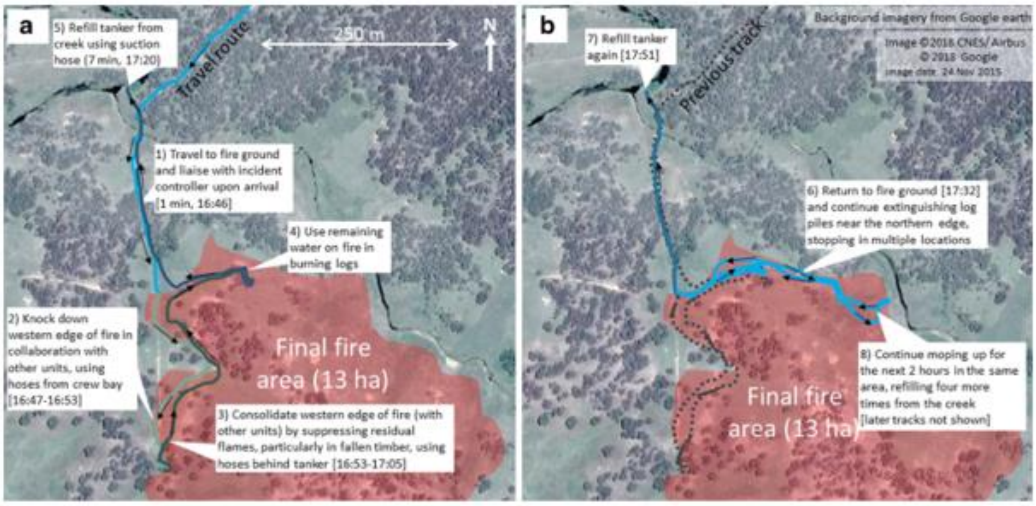

Fig 7:EXAMPLE of TRACKING DATA SHOWING THE MOVEMENTS OF A MEDIUM TANKER [61].

A US productivity study revealed lower hand crew productivity rates due to unplanned and complex wildfire suppression operations. Tracking systems could provide reliable data for resource types without affecting performance or suppression outcomes. Interpreting tracking data requires complementary data on tasking and objectives, tactics, and effectiveness assessments [58].

As shown in figure 7 illustration of tracking data that illustrates the trajectory of a medium tanker (1100 liters) engaged in firefighting operations during a grassfire near Bungendore, New South Wales, on January 5, 2013, is presented. This data was obtained through a global positioning system carried by the author while performing firefighting duties. Panel A displays the final segment of the journey and the suppression activities involving the first load of water. Panel B depicts the movements during the mop-up phase. It's worth noting that this tanker was one of ten vehicles involved in combatting the fire, which occurred on a day characterized by a high grassland fire danger rating [61-62].

Fire Incident Scale

Wildfire suppression observations serve as a valuable tool for evaluating the efficiency of suppression resources and their impact on fire behavior. The Fireline scale offers an authentic representation of wildfire conditions, facilitating a thorough assessment of suppression resources. Examining suppression operations encompassing entire fire incidents offers valuable insights, particularly in the context of large and intricate incidents. Traditionally, this area of study has relied on case studies. Additionally, economic modeling methods have been employed to gauge productivity and minimize losses resulting from extensive wildfires. Assessing suppression effectiveness presents challenges due to diverse operational goals and tactics, requiring incident controllers to continually make decisions regarding objectives and strategies [63-67].

Wildfire case studies frequently encompass inquiries from both the public and agencies, with a primary focus on assessing fire impacts, safety measures, fuel management strategies, and fire behavior. Some of these case studies delve into the intricacies of suppression effectiveness.

The findings of these studies indicate that mechanically treated forest fuels play a pivotal role in enhancing various aspects of firefighting operations. These treatments improve access for firefighters, facilitate better communication, and enhance situational awareness, thus simplifying the detection and suppression of spot fires. Moreover, the reduction in canopy density resulting from these treatments aids in the penetration of retardant drops to surface fuels.

Furthermore, these case studies have highlighted the significant influence of the fuel types present in large fires on suppression effectiveness. These insights serve as valuable resources for fire managers, contributing to a deeper understanding of effective wildfire suppression strategies [68-72].

Researchers used incident reports to analyze Fireline construction and perimeter growth, finding reduced fuels reduced fire spread and improved suppression effectiveness. They suggest further wildfire case studies to explore suppression effectiveness across various vegetation types and fire behavior as shown in Table 2.

Table 2: Fire Behavior and Suppression Effectiveness Across Various Vegetation Types

Author(s) and Year	**Experiment Details**	**Key Results**
Finney et al. [73]	Daily fire perimeter spread rates and containment probability of 455 large fires across the United States	During periods of moderated fire behavior, large fires are contained opportunistically.
Calkin et al. [78]	During periods of moderate fire behavior, large fires are contained opportunistically.	Low EI values indicate unproductive resource use or ineffective Fireline construction on large fires. High EI values suggest parts of the fire perimeter are allowed to burn freely.
Stonesifer et al. [78]	Developed the aircraft exposure index specifically for firefighting aircraft	The aircraft exposure index considers aircraft type, flight time, and long-term accident rate to assess exposure to hazards.
Holmes and Calkin [64]	Developed relative productivity functions based on the length of held Fireline	Estimated productivity of large wildfire firefighting resources (hand crews, dozers, engines, and helicopters). Because of a variety of factors, actual efficiency rates were lower than standard rates.
Katuwal et al. [63]	Studied determinants of inefficiencies in containment production using geospatial data	Geospatial data was used to observe controlled Fireline productivity. Factors affecting productivity include bulldozers, tankers, fuel features, weather, landscape, and fire conditions.
O'Connor et al. [79,80]	Developed spatial models for control line planning, using the Suppression Difficulty Index	Predicted suitable locations for control lines based on distances from roads and landscape features. The Suppression Difficulty Index is used to quantify the difficulty of suppression efforts.
Rodríguez y Silva and González-Cabán (75)	Introduced area contraction factor, a metric for estimating suppression effectiveness	Between detection and control, the area contraction component compares the actual fire area to the prospective area affected by a free-burning unsuppressed fire.
Thompson et al. [77]	Key performance indicators (KPIs) have been compiled for analyzing suppression tool use and effectiveness.	KPIs included resource use estimation, incident management team impact, Fireline effectiveness, and environmental conditions for air tankers.

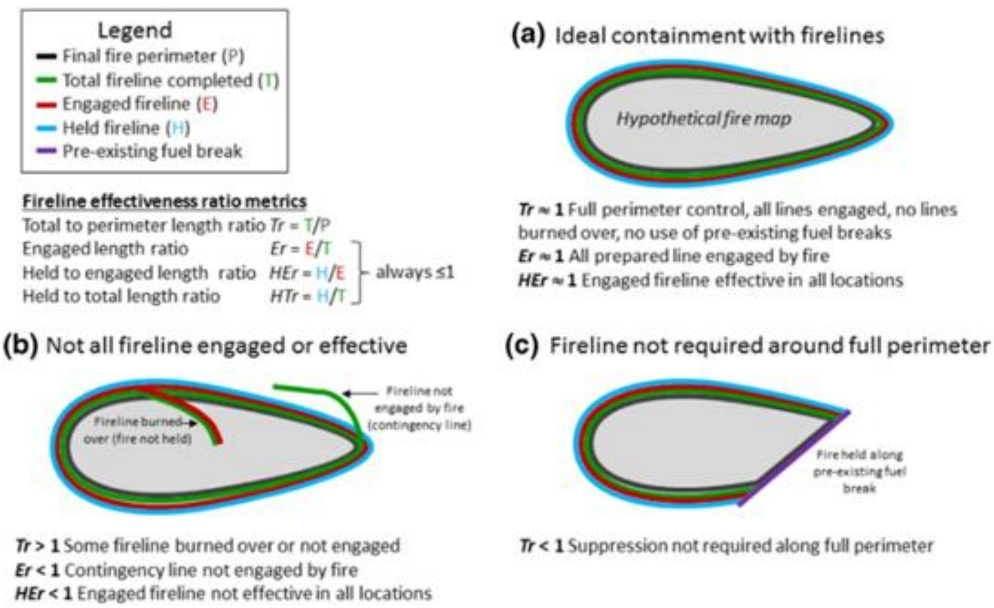

Fig 8: Examples of Fireline Effectiveness Metrics Based on Ratios of Fire Line, and Perimeter Length [75].

Thompson et Al. [75-78], research project established a set of key performance indicators (KPIs) designed for the evaluation of suppression resource utilization and efficiency at the incident scale. These KPIs have been categorized into four distinct groups: the estimation of resource utilization, the evaluation of incident management impact, the assessment of Fireline effectiveness, and the summarization of environmental conditions. Among these KPIs, certain ones involve comparing productivity rates against established benchmarks and utilizing Fireline completion estimates to generate metrics that quantify Fireline effectiveness.

Landscape Scale

Research has investigated wildfire suppression effectiveness on a regional scale by leveraging fire agency databases and compiled datasets. These studies adopt various metrics, such as the annual area burned, success rates in initial attack efforts, and occurrences of large fires. They aim to discern the influential factors impacting the success of suppression operations, including response times and the time required for fuel treatment to achieve containment [81,82]. To account for spatial variability in land use and fire conditions, these studies employ diverse threshold values for burned area and containment time. Notably, urban fires exhibit swifter suppression responses, leading to lower initial attack success thresholds. Additionally, some studies have introduced the concept of "area growth" representing the difference between the final and initial attack areas, as an alternative measure of effectiveness.

These investigations assess the effectiveness of initial attack operations and fire incidents by considering factors such as burned area, containment time thresholds, and area growth. They account for spatial disparities, acknowledge the quicker responses observed in urban fire scenarios, and introduce innovative metrics to gauge suppression performance [84].

Table 3 Objectives, Data, Metrics, And Findings of Some Landscape Scale Suppression Studies

Study and Objective	Methodology	Key Findings
Finney et al. (1997) [73] - Containment of large fires	Generalized linear mixed models	In studies, different burned area and prevention time threshold values are used to account for initial strike success and large fire occurrence due to path variations in land use and fire ecosystem.
McCarthy et al. (2003) [93] - Resourcing and suppression	Data from incident-related interviews	Prevention progress is more likely if a bushfire is on low slopes, has low fuel hazards, is small when noticed, and has more firefighters on the scene on the day they are noticed.
Plucinski (2012) [39] - Initial attack success and large fires	Dataset of Australian forest and shrubland fires with aircraft deployment	The number of initial attack escapes and large fires increase with fire size at initial attack, fuel hazard, and fire danger. The number of initial attack escapes and large fires increase with fire size at the original attack, fuel hazard, and fire hazard.
Plucinski et al. (2012) [83] - Aircraft impact on initial attack containment	Data from Australian forest and shrubland fires with aircraft involvement	In difficult conditions such as fuel hazard, climate, slope, response time, and area burning during the initial attack, aircraft reduce containment time.
Plucinski (2013) [85] - Predicting grassfires escaping initial attack	Australian grassfire data with aircraft deployment	Larger fires with higher vegetation fire danger countries are more likely to evacuate the initial attack.
Fernandes et al. (2016) [74] - Assistance in the suppression of large fires in Portugal	Dataset of extremely large forest fires	Large fires are brought under control by increased suppression resource base, milder seasonal changes, and low fuel areas. Gains in containment occur during periods of reduced fire weather.
Beverly (2017) [95] - Time since last fire on initial attack suppression	Organization statistics on lightning-caused fires in black woody forests	The probability of initial attack escape increases with time since fire, initial fire size, and the Initial Spread Index.

Collins et al. (2018) [84] - Factors influencing forest and grass fire suppression	The agency analyzed information from forest and tree and bushfires in New South Wales, Australia.	Peak number of resources per hectare of fire, fuel load, slope, and weather conditions influence containment probability.
Tremblay et al. (2018) [86] - Suppression intervention and fire size	Information from lightning-caused fires in the boreal forests of northeastern Alberta	Fire area growth is linked with the Canadian Forest Fire Weather Index.

Suppression success analyses utilize agency datasets, weather, topographic data, and surveys. Influential variables include initial fire size, weather, fuel, and suppression response, with accuracy based on first-comer crew experience [82-92].

Weather, fuel age, fuel load, and fuel hazard all influence fire danger indices and suppression outcomes. Timing variables, resource type, capabilities, and the number of resources used also impact suppression response. Quick fires have smaller perimeters and intensities, while resource scarcity can impact containment probability [93-105].

Few studies have identified the impact of terrain variables, such as slope, on suppression, possibly due to initial attack studies in flat areas. McCarthy et al.'s study found that steep terrain fires were less resourced and more likely to escape initial attack efforts.

According to two Australian studies, aircraft are most beneficial for initial attack success when environmental conditions make firefighting more difficult and when deployed quickly. Aircraft may not be required if the fire behavior is mild or if ground resources can quickly access the ignition. If suppression success is unlikely, aircraft should be repurposed or rested until conditions improve Fernandes et al. collected data from 100 "extremely large" Portuguese fires to investigate the role of suppression forces in reducing fire duration and growth rate. They discovered that more resources are assigned to higher-risk areas, but there is no evidence that resource quantity influences fire duration.

Studies have examined the impact of suppression policy changes on fire prevention using long-term agency datasets and comparing areas with similar environments. Results show positive outcomes, including more effective policies, faster responses, and increased resources. However, quantifying the effects of specific changes is challenging due to the influence of other changes in firefighting technology [106-110].

A study on lightning-caused forest fires in Ontario by Martell and Sun discovered a significant relationship between the average annual percentage of burned area, vegetation, weather, and fire control effort, supporting the idea that fire suppression prevents burned areas in boreal forests [110]. According to landscape studies, suppression effectiveness is influenced by response time and fuel mitigation, with the initial attack fire area being critical. Probabilistic models ignore indirect tactics and resources, making comparisons difficult [111-112]

Conclusions

Wildland fire suppression effectiveness research is crucial for informed planning and response decisions, but evaluation is challenging due to various variables and measurement scales, despite the growing demand for comprehensive knowledge. At the flame scale, Controlled experiments evaluate wildfire suppression chemicals' effectiveness in halting fire spread and reducing fuel consumption, but they provide a limited representation of actual wildfire scenarios. Moving to the fire line scale, Observations on fire perimeters and Fireline construction reveal resource productivity, suppression impact, hand crew productivity, and aerial resource effectiveness, providing valuable insights into wildfire contexts. Fire suppression research at the fire incident scale and recent economic analyses highlight the need for more accurate data in productivity models, highlighting the need for economic modeling and case studies of specific wildfire events. Lastly, landscape-scale studies rely on incident databases. Analyses of fire outcomes reveal critical variables, but gaps persist, necessitating datasets beyond routine records and collaboration between researchers and fire managers. In conclusion, research conducted at the flame and Fireline scales has provided essential evidence for decision-making regarding suppression chemicals and firefighting resources. Future investigations at these scales should delve deeper into specific chemical and resource types and explore mop-up roles. Incorporating tracking systems and diverse data sources during wildfire resource deployments will help create realistic operational datasets for model development. Ultimately, a multi-scale approach to suppression effectiveness research is vital to addressing the evolving challenges of wildfire management comprehensively.

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