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Systematic Review

How Does Fire Suppression Alter the Wildfire Regime? A Systematic Review

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Abstract: Fire suppression has become a fundamental approach for shaping contemporary wildfire regimes. However, a growing body of research suggests that aggressive fire suppression can increase high-intensity wildfires, creating the wildfire paradox. Whether the strategy always triggers the paradox remains a topic of ongoing debate. The role of fire suppression in altering wildfire regimes in diverse socio-ecological systems and associated research designs demands a deeper understanding. To reconcile these controversies and synthesize the existing knowledge, a systematic review has been conducted to screen 974 studies on the relationship between fire suppression and wildfire regimes. The rigorous screening process led to the selection of 37 studies that met our stringent criteria for inclusion. The selected literature was quantitatively analyzed in terms of study areas, study design and methods, and the impact of fire suppression on wildfire regimes. Several critical findings were revealed: 1. Numerous studies have focused on northern mid- and high-latitude biomes, neglecting tropical savannas where wildfires are frequent and intense. Further exploration in these regions is imperative. 2. Existing studies have predominantly employed methods such as difference analysis, regression analysis, and scenario simulations. Appropriate methods could be selected based on the study area, data availability, and understanding of fire regimes. 3. Despite the consensus that fire suppression reduces the total burned area, the emergence of the wildfire paradox remains controversial, with approximately equal amounts of the literature supporting and contradicting the wildfire paradox. A noteworthy pattern was observed: the wildfire paradox is more likely to occur in fuel-limited systems, specific vegetation types, and smaller scale and longer term studies. This systematic review highlights that the occurrence of the wildfire paradox is intricately tied to ecosystem feedback mechanisms for suppression and the research scale adopted. It is necessary to incorporate a comprehensive and multi-scale assessment of how local wildlands respond to suppression into wildfire management policy-making processes. This assessment will ensure a more informed and effective wildfire management strategy adapted to local conditions.

Keywords: fire suppression; wildfire regime; wildfire accidents; wildfire paradox; systematic review

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1. Introduction

Wildfires are global phenomena that elicit widespread concern worldwide. They not only directly threaten the assets and values of human societies in fire-prone regions [1–3], but also have detrimental effects on critical ecosystem services [4], including air pollution [5,6] soil erosion [7], and carbon loss [8–11]. Furthermore, these threats are exacerbated by the increasing probability and severity of wildfires caused by global warming [12–15], amplifying the significance of wildfires as a concern. To mitigate fire risks and prevent damage [2], it is essential to comprehend the factors driving fire regimes, which predominantly encompass climate [14] and human activities [16–19]. While climate has consistently played a predominant role by regulating vegetation productivity and moisture [19–21], in recent years, human factors, notably wildfire suppression, have gained prevalence on a global scale [22–24], emerging as another influential factor affecting fire regimes [25]. Wildfire suppression can directly halt the spread of fires upon ignition, potentially reducing fire frequency and constraining fire size [25,26]. Moreover, fire suppression can indirectly lead to alterations in fire intensity and size by modifying combustible fuels [27]. Therefore, there is a need for a deeper exploration of the relationship between wildfire suppression and wildfire regimes for a comprehensive understanding of wildfires.

While fire suppression has led to a significant decline in global fire activity in the 20th century [28], it has been suggested that fire suppression may lead to a paradox: the more effective the fire suppression, the more severe future fires [29–32]. This is known as the wildfire paradox [33]. The wildfire paradox has been illustrated in various fire-prone ecosystems globally, including North America [32,34,35], Africa [36], and China [37]. Theoretically, fire suppression can lead to larger fires by increasing fuel load and continuity. Specifically, the prolonged absence of wildfires may result in the significant accumulation of combustible biomass, such as dead wood, that should have been periodically burned [29–32], along with vegetation encroachment [38], especially in regions lacking fire prevention measures [39]. Over time, the increase in fuel load can create conditions for more intense fires. Additionally, while wildfires can create post-fire patches with insufficient fuel available for new fires across the landscape [38], acting as natural fire breaks and opportunistic fire suppressors [40], aggressive fire suppression can weaken the self-limiting nature of wildfires [41,42] by increasing fuel continuity and reducing natural fire breaks. This can create favorable conditions for the spread of wildfires, thereby resulting in increasing size of wildfires [39]. However, a few researchers insist that fire suppression remains crucial in reducing wildfire risk [40,43], and the occurrence of the wildfire paradox due to aggressive fire suppression remains contentious. Notably, there is a significant absence of a review of existing studies investigating the relationship between fire suppression and wildfire regimes across fire-prone ecosystems on a global scale. Given the high expenditure on fire suppression, the potential damage from extensive fires, and the important role of fire suppression in shaping fire regimes [44], it is imperative to validate the effectiveness of wildfire suppression across various studies and ecosystems for sustainable fire management. To achieve this validation, a comprehensive literature review is needed that encompasses a deep understanding of the wildfire paradox, a clear perception of the impacts of fire suppression on wildfire regimes, and a thorough comprehension of the variations among studies.

As part of an evidence-based review, a systematic review synthesizes a well-articulated question [45] to identify the scope of existing research and research gaps [46]. The systematic review approach has already been applied to several wildfire ecology and management studies [47–50]. A systematic and explicit approach was employed to identify, select, and critically appraise relevant studies and collect and analyze their data [45]. This approach helps to highlight research disputes and their reasons. Therefore, this study collected and analyzed existing literature on the effects of wildfire suppression on wildfire regimes using a systematic review approach. The study aimed to answer the following questions: (1) Where are the study areas in the existing studies? (2) How did existing research quantify the relationship between fire suppression and wildfires? (3) What are the studies' responses to the research question, and why are the conclusions opposed? To address these questions, the research focused on: (1) extracting and tabulating background information on the study areas; (2) summarizing the study design and methods in the literature; and (3) quantitatively and qualitatively analyzing the trends in wildfire regimes influenced by fire suppression activities within the included literature.

2. Materials and Methods

This study adopted a systematic research approach (Figure 1). The procedure included identifying the research questions, formulating a research proposal, conducting a literature search, screening the literature, and extracting and analyzing data [51].

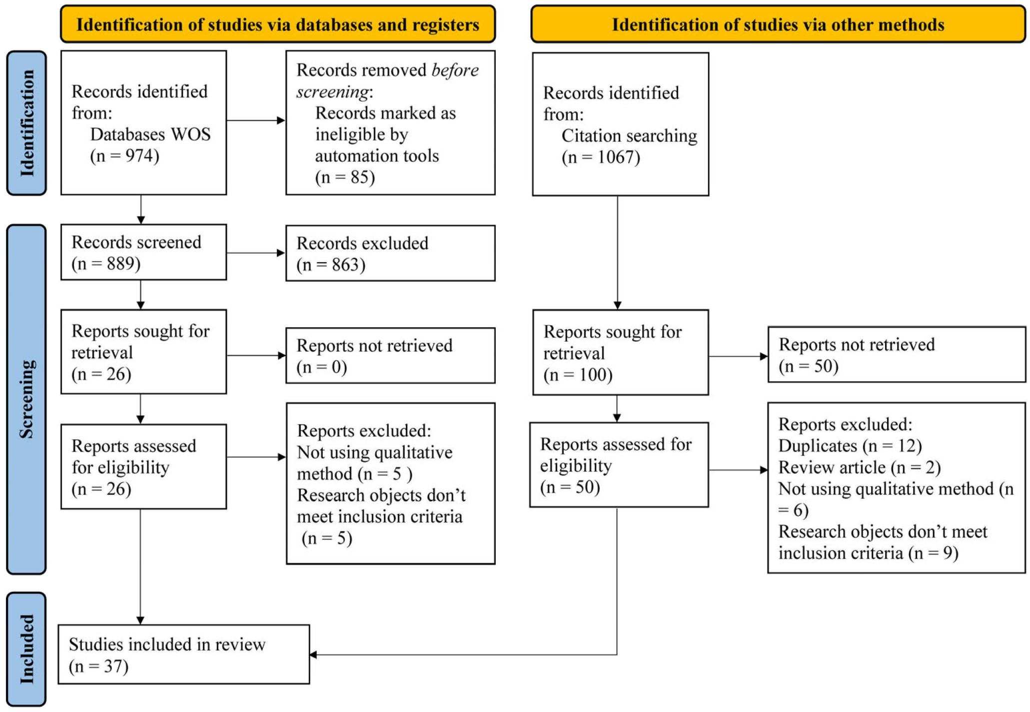

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 flow diagram.

2.1. Search Strategy

The dataset was extracted from published, peer-reviewed literature. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [52] were followed for keyword searches in the Web of Science (WOS) database, and forward and backward search methods were combined. The search terms used after several attempts were (suppression) AND (fire regime).

2.2. Screening Strategy

The screening was a two-step process. Firstly, the WOS web automatic exclusion tool was employed to exclude document types other than articles or letters and non-English documents, and, secondly, screen the title, abstract, and full text to include the literature that met the following criteria:

(1) Intervention: There are four phases of wildland fire management, including prevention, preparedness, response, and restoration [23]. We rigorously included studies that examined the impact of active fire suppression during the response phase in our analysis. Active fire suppression has been the dominant wildfire management practice worldwide since the early 20th century [53]. For the purpose of our study, we excluded research that examined the effects of measures during the prevention, preparedness, or restoration phases of wildfire management, such as education or regulation of fire prevention [54], prescribed burning, mechanical fuel treatments, silvicultural treatments [55–57], hazard-resistant construction, and so on. These studies were excluded because they do not address the relative impacts of fire suppression on wildfire regimes, and other review studies have been devoted to these topics [34,49,58].

(2) Outcome: Specific wildfire characteristics representing wildfire regimes, including:

- Fire number: the total number of wildfires within a time period.
- Fire frequency: the inverse of the return period.
- Fire size: area of individual burn scars from each wildfire event.
- Fire intensity: the rate of energy released by the fire.
- Burned area: total surface area burned within regions per month or period.
- Extremely large wildfires (ELF): number, size, or burned area of extremely large wildfires.

(3) Assessment methods: Two types of quantitative research were included. Firstly, empirical studies providing insight into the effects of fire suppression on fire regimes based on historical fire regime data and fire suppression information were included. Furthermore, simulation studies using process-based wildfire behavior or risk simulation modeling to investigate changes in fire regimes under different suppression scenarios were also included.

2.3. Data Extraction

The following information was extracted to include relevant data and quantitatively describe the included literature:

Study setting: (I) Basic information about the literature, such as authors and journals. (II) Background information, including the main climate type, biome, and pyrome of each study area. The pyrome is the global fire regime syndrome and refers to global regions with similar wildfire characteristics [59]. To extract this information, the coordinates of the center of the study areas were overlaid on the world map of Köppen climate classification [60], the map of terrestrial ecoregions of the world [61], and the pyrome map of the world [59]. If the study area was on a large regional scale, the main type was extracted, representing the main context of the study area, and allowing a qualitative analysis of the papers.

Study design: spatial and temporal scale, research object, study design type, and research methods. The literature was divided into five spatial scales based on the size of the study area ($0–10^3$ km^2, $10^3–10^4$ km^2, $10^4–5 \times 10^4$ km^2, $5 \times 10^4–10^5$ km^2 and $>10^5$ km^2) and four temporal scales based on the time span of the study: 0–25 y, 25–50 y, 50–100 y, and >100 y. The research object refers to the wildfire characteristics and fire suppression variables under discussion. Research design type refers to the general strategy used to address the research question, divided into observational and experimental research designs [62]. In observational research, the researcher establishes relationships within a situation or phenomenon based on empirical data without any active intervention [63]. The experimental research design indicates that researchers actively modify a variable to investigate how the change affects other factors through field experiments, controlled experiments, or simulation models [62,63]. The specific statistical methods used by the included literature to explore the effects of fire suppression are described.

2.4. Study Assessment

The study settings and designs of the included literature were described based on the extracted data. The overall state of scientific evidence on the impact of fire suppression on fire regimes was then assessed based on an analysis of key findings from the included literature. The assessment process of key findings was divided into four steps (Figure 2).

Summary of key findings (Figure 2 (1)). Trends in wildfire characteristics under the influence of fire suppression were summarized across studies, and trends were labeled as either "+," indicating an increase in wildfire characteristics under the influence of fire suppression, "−" indicating a decrease, and "nosig" indicating that there was no significant change. This was a systematic review, not a meta-analysis; thus, effect sizes were not reported.

Assessment of the fire regime trends (Figure 2 (2)). The effects of fire suppression on each fire characteristic were clarified by counting the proportions of studies with increasing, decreasing, and nonsignificant trends for each wildfire characteristic under the impact of fire suppression.

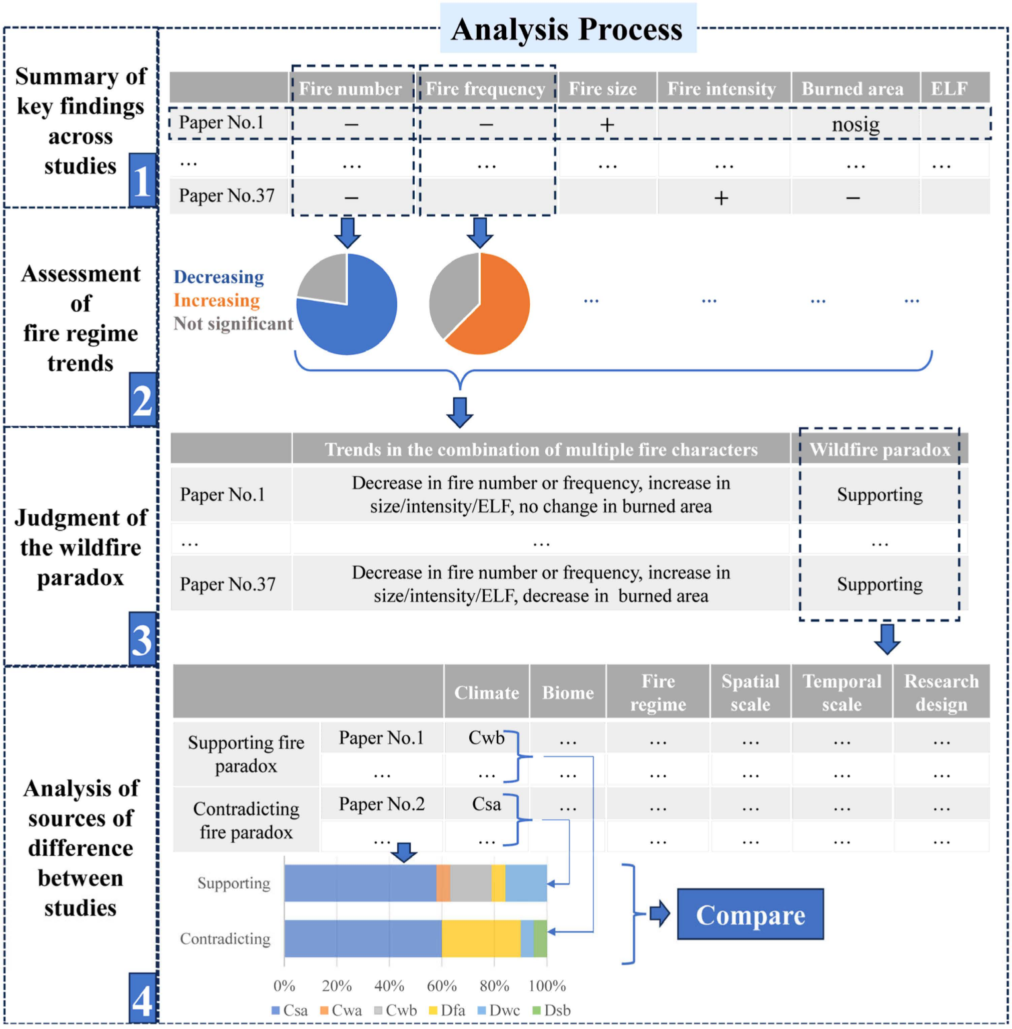

Figure 2. The analysis process of key findings from the included literature and its schematic diagram.

Appreciation of the wildfire paradox (Figure 2 (3)). Wildfire characteristics are not independent of each other [59], and focusing only on changes in individual wildfire characteristics risks missing hidden information regarding overall wildfire regime changes; therefore, information on changes in combinations of multiple wildfire characteristics was further synthesized across the literature. Based on the definition of the wildfire paradox and trends in wildfire size, intensity, or ELF, it was further determined whether the study supported the wildfire paradox. If the study concluded that fire suppression had led to increased fire size, intensity, or ELF, it would be described as supporting the paradox, and vice versa. If the literature failed to examine the variability in these characteristics, it was marked as unknown.

Analysis of sources of difference between studies (Figure 2 (4)). Whether studies supported the wildfire paradox would depend on the study area and design. To test this hypothesis, the study settings (climate, biome, and pyrome) and study designs (spatial and temporal scales and study design type) of the literature supporting and contradicting the wildfire paradox were summarized, respectively. The differences in the proportional composition of each variable between the two sets of studies were compared. The reasons for the differences between the results in the literature were identified by searching for variables for which the composition differed significantly between groups. Due to sample size limitations, differences between groups were investigated by observation and qualitative analysis only, without statistical testing.

3. Results

The database search identified 974 documents (Figure 1), and an automated tool was used to exclude 85 articles that failed to meet the criteria, 863 articles through title and abstract screening, and 10 articles through full-text screening (5 did not use quantitative analysis, 2 did not examine specific wildfire characteristics, and 3 focused on broad human interventions). In addition, 50 documents were identified from reference searching of the resulting articles that met the criteria, among which 29 articles were excluded through full-text screening (12 were duplicates, 2 were reviews rather than empirical studies, 6 were non-quantitative analyses, and 9 did not meet other inclusion criteria). A total of 37 studies were included in the analysis (Figure 1, Table 1).

3.1. Study Setting

A total of 37 studies were highly clustered spatially and unevenly distributed. The earliest study was published in 1987, and the largest numbers of papers were published in 2007 and 2018. These 37 papers covered 50 study areas (Figure 3) across five continents: North America, Europe, Asia, South America, and Africa. The countries with the most publications were the USA (43.2%, n = 16), Canada (13.5%, n = 5), France (13.5%, n = 5), Spain (13.5%, n = 5), China (10.8%, n = 4), Brazil (5.4%, n = 2), Portugal (5.4%, n = 2), Greece (2.7%, n = 1), and Madagascar (2.7%, n = 1). Developed countries accounted for approximately 80% of the literature. The study area covered approximately 16 climate zones, 8 biomes, and 5 fire regime pyromes. Nearly 50% of the study areas were located in Mediterranean climate zones, more than 30% in subarctic climate zones, 14% in temperate humid continental climate zones, and the rest in tropical wet and dry savanna zones, cold semiarid zones, desert zones, and subtropical upland zones. The studies were conducted in eight different biomes: Mediterranean forest, woodland, and scrub (43.2%, n = 16), boreal forest (19%, n = 7), temperate coniferous forest (18.9%, n = 7), temperate grassland savannah and scrub (13.5%, n = 5), temperate broadleaf and mixed forest (10.8%, n = 4), tropical and subtropical grassland (5.4%, n = 2), tropical and subtropical grasslands, savannas, and shrublands (5.4%, n = 2), and desert and xeric shrublands (5.4%, n = 2). Although all five global pyromes were covered, the literature largely focused on two pyromes: rare-intense-large (RIL) (62.16%, n = 23) and rare-cool-small (RCS) (40.54%, n = 15). Only three papers discussed other pyromes: rare-cool-small (RCS), frequent-cool-small (FCS), and ICS (intermediate-cool-small). However, no studies were conducted on tropical savannahs in Australia and Africa, which are mainly dominated by FIL and FCS pyromes.

Researchers primarily focused on the relationship between burned areas and aggressive fire suppression. The study areas varied widely in terms of spatial and temporal scales (Figure 4). Most studies (70%) discussed burned areas, followed by the number of fires. In contrast, ELF, fire size, intensity, and frequency were discussed in less than 30% (Figure 4A). Approximately 50% of the studies did not simultaneously analyze changes in burned area or fire size, which hampers the understanding of fire regime dynamics. Nearly 60% of the studies examined the effects of aggressive fire suppression policies, 35% examined the effects of different fire suppression levels, and 5% examined the effects of different fire suppression strategies on wildfire regimes (Figure 4A). Landscape-scale (0–1000 km^2) studies constituted 50% of the research, whereas seven studies focused on regional scales larger than 100,000 km^2 (Figure 4B). Most studies were conducted for 25–50 years, with the second largest number of studies spanning over 100 years. The dynamics of wildfire data within the 0–1000 km^2 range over 100 years received the most attention (Figure 4B).

Table 1. ID value, citation, location, main biome, spatial scale, temporal scale, and outcome of each study included in the review. "BF" is boreal forest. "MFWS" is Mediterranean forest, woodland, and scrub. "TCF" is temperate coniferous forest. "TSGSS" is tropical and subtropical grassland, savanna, and shrubland. "DXS" is desert and Xeric shrubland. "TBMF" is temperate broadleaf and mixed forest. "TGSS" is temperate grassland, savanna, and shrubland. "TSMBF" is tropical and subtropical moist broadleaf forest. Studies with * considered non-forest fire regimes.

ID	Authors	Source	Location	Main Biome	Temporal Range (yr)	Spatial Range (10^3 km^2)	Outcome
1	Alvarado et al., 2018 [36]	*Journal of Environmental Management*	Ibity and Itremo Protected Area, Madagascar Serra do Cipo National Park, Brazil	TSMBF TSGSS	25–50	0–1	Fire suppression resulted in a change in the fire size distribution, longer fire return periods, and a seasonal shift in burning toward later fires.
2	Brotons et al., 2013 [40]	*PLoS ONE*	Catalonia, Spain	MFWS	25–50	10–50	Active fire suppression had a large potential for compensation of the effects of climate change.
3	Calef, Varvak, McGuire, Chapin, and Reinhold, 2015 [64]	*Earth Interactions*	Interior Alaska, USA	BF	25–50	10–50	Fire suppression reduced the area burned over the past several decades and raised the burning rate of the burned area.
4	Chang et al., 2007 [37]	*International Journal of Wildland Fire*	Great Xing'an Mountains, China	TCF	>100	1–10	Fire suppression resulted in decreased fire frequency and increased fire severity, leading to catastrophic fires with return intervals ranging from 50 to 120 years.
5	Chapin et al., 2003 [65]	*Frontiers in Ecology and the Environment*	Alaskan boreal forest, USA	BF	>100	10–50	Short-term effectiveness of a given level of fire suppression in reducing burned areas declined over time. However, fire suppression areas experienced less fire than those with a natural fire regime even after 70 years.
6	Cumming, 2005 [66]	*Canadian Journal of Forest Research*	Northeastern Alberta boreal mixed wood forest, Canada	TSGSS	25–50	50–100	Change in fire management strategy resulted in a significant reduction in escape probability.
7 *	Curt and Frejaville, 2018 [67]	*Risk Analysis*	Southeastern France	MFWS	25–50	50–100	Fire suppression resulted in considerably decreased fire activity during the two following decades.
8 *	DeWilde and Chapin, 2006 [68]	*Ecosystems*	Interior Alaska, USA	BF	0–25	>100	Fire suppression resulted in smaller areas being burned.
9	Drury and Grissom, 2008 [69]	*Forest Ecology and Management*	Yukon Flats National Wildlife Refuge, USA	BF	0–25	10–50	Aggressive fire suppression did not result in significant fire return interval change.
10 *	Evin, Curt, and Eckert, 2018 [70]	*Natural Hazards and Earth System Sciences*	Southeastern France	MFWS	25–50	50–100	Despite aggressive fire suppression policy, massive fires could still occur.
11 *	Fernandes et al., 2016 [71]	*European Journal of Forest Research*	Portugal	MFWS	0–25	50–100	Allocating higher levels of fire-suppression resources did not considerably decrease fire size.
12 *	Frejaville and Curt, 2017 [72]	*Environmental Research Letters*	Southeastern France	MFWS	25–50	50–100	Fire suppression resulted in reducing fire activity.
13 *	Hanan et al., 2021 [73]	*Environmental Research Letters*	Johnson Creek, Idaho, USA Trail Creek, Idaho, USA	TBMF, TGSS	>100	0–1	Fire suppression increased larger fires early in the assessment period yet decreased mean wildfire size, frequency, and burned area throughout the entire assessment period.
14	Hansen et al., 2020 [74]	*Ecological Applications*	Grand Teton National Park, USA	DXS	>100	0–1	Strategies that emphasize managing wildfire use rather than suppressing it would not change climate-induced fire and forest change.
15	He et al., 2023 [75]	*Forests*	Great Xing'an Mountains, China	TCF	>100	0–1	Fire suppression resulted in higher fire intensity with less total burned area.
16 *	Keeley, Fotheringham, and Morais, 1999 [16]	*Science*	Brushland in California, USA	MFWS	50–100	10–50	Fire suppression did not result in more large fires.
17	Loepfe et al., 2012 [39]	*Climatic Change*	3 sites in Spain	MFWS	>100	0–10	Aggressive fire suppression reduced the burned area, resulting in a higher percentage of area burned in large fires.
18 *	Luciano Batista et al., 2018 [76]	*Journal of Environmental Management*	The Canastra National Park, Brazil	TSGSS	0–25	1–10	Strategies that emphasize managing wildfire use rather than suppressing it will not change climate-induced fire and forest change.
19	Martell and Sun, 2008 [77]	*Canadian Journal of Forest Research*	Ontario, Canada	BF	0–25	>100	Fire suppression resulted in a significant reduction in the area burned.

Table 1. *Cont.*

ID	Authors	Source	Location	Main Biome	Temporal Range (yr)	Spatial Range (10^3 km^2)	Outcome
20 *	Minnich, 1983 [78]	*Science*	Southern California to Baja California, USA	DXS	0–25	0–1	Fire suppression resulted in a decrease in fire numbers. However, fires consequently increased in size, spread rate, and intensity and became uncontrollable in severe weather conditions.
21 *	Ioannis Mitsopoulos and Mallinis, 2017 [43]	*Landscape and Urban Planning*	Greece	MFWS	0–25	>100	Once a fire occurs, large fire size generation is primarily affected by fire suppression.
22	Moritz, 1997 [79]	*Ecological Applications*	Los Padres National Forest, USA	MFWS	>100	1–10	Fire suppression did not change the distribution of extensive fires, resulting in fewer fires smaller than 4000 ha.
23 *	Moritz, 2003 [80]	*Ecology*	Los Padres National Forest, USA	MFWS	50–100	1–10	Fire suppression affected the characteristics of smaller fires much more than those of larger fires, resulting in a decrease in size and an increase in the number of smaller fires.
24	Parisien et al., 2020 [35]	*Nature Communications*	Boreal biomes, Canada	BF	25–50	>100	Fire suppression policies increased flammability in the wildland–urban interface.
25	Parks et al., 2015 [81]	*Ecosphere*	Western USA	MFWS	25–50	>100	Fire suppression reduced fire activity.
26	Pinol, Beven, and Viegas, 2005 [82]	*Ecological Modelling*	Tarragona, Spain Coimbra, Portugal	MFWS	>100	0–1	Increased firefighting capacity resulted in higher areas burned in large fires.
27	Pinol, Castellnou, and Beven, 2007 [83]	*Ecological Modelling*	2 sites in USA, 2 sites in France, 2 sites Spain	MFWS	0–25 25–50	0–1 1–10	The total area burned was the same whether suppression or prescribed fire policies were used or not; however, fire suppression enhanced fire intensity, and prescribed burning reduced it.
28	Podur and Martell, 2007 [84]	*International Journal of Wildland Fire*	Ontario, Canada	BF	25–50	>105	Fire suppression impacted areas burned, especially during severe fire weather years. Despite the impact of suppression, exceptionally severe weather would lead to high-area burns regardless of fire suppression efforts.
29	Reimer et al., 2019 [85]	*Fire-Switzerland*	Vermilion Valley of Kootenay National Park, Canada	TCF	50–100	0–1	Fire suppression resulted in an average burn probability reduction.
30	Riley, Thompson, Scott, and Gilbertson-Day, 2018 [86]	*Resources-Basel*	Sierra National Forest, USA	TGSS	0–25	1–10	No-suppression strategy produced large increases in the number, median size, and burn probability of large fires.
31	Roos et al., 2020 [87]	*Fire-Switzerland*	Wabakwa, USA	TCF	>100	0–1	Aggressive fire suppression resulted in higher fire intensity even in mild weather conditions.
32	Ruffault and Mouillot, 2015 [88]	*Ecosphere*	Southeastern France	MFWS	25–50	10–50	Active fire suppression resulted in a significant shift and abrupt decrease in fire activity.
33	Scheller et al., 2019 [89]	*Ecological Modelling*	Lake Tahoe Basin, USA	TGSS	>100	1–10	Active fire suppression resulted in a higher proportion of low-intensity fires and a lower total area burned.
34 *	Starrs et al., 2018 [90]	*Environmental Research Letters*	California, USA	MFWS	50–100	10–50	Aggressive fire suppression reduced fire probability.
35	Tian et al., 2020 [91]	*Canadian Journal of Forest Research*	Great Xing'an Mountains, China	TCF	25–50	>100	The improved fire suppression strategy greatly decreased the mean burn probability and affected the spatial distribution of fires.
36	Urbieta et al., 2019 [92]	*Annals of Forest Science*	Spain	MFWS	25–50	50–100	Fire suppression reduced fire activity.
37	Wang et al., 2007 [93]	*Landscape and Urban Planning*	Great Xing'an Mountains, China	TCF	>100	1–10	Compared with low fire suppression, high fire suppression would create a landscape with lower frequency and higher intensity wildfires.

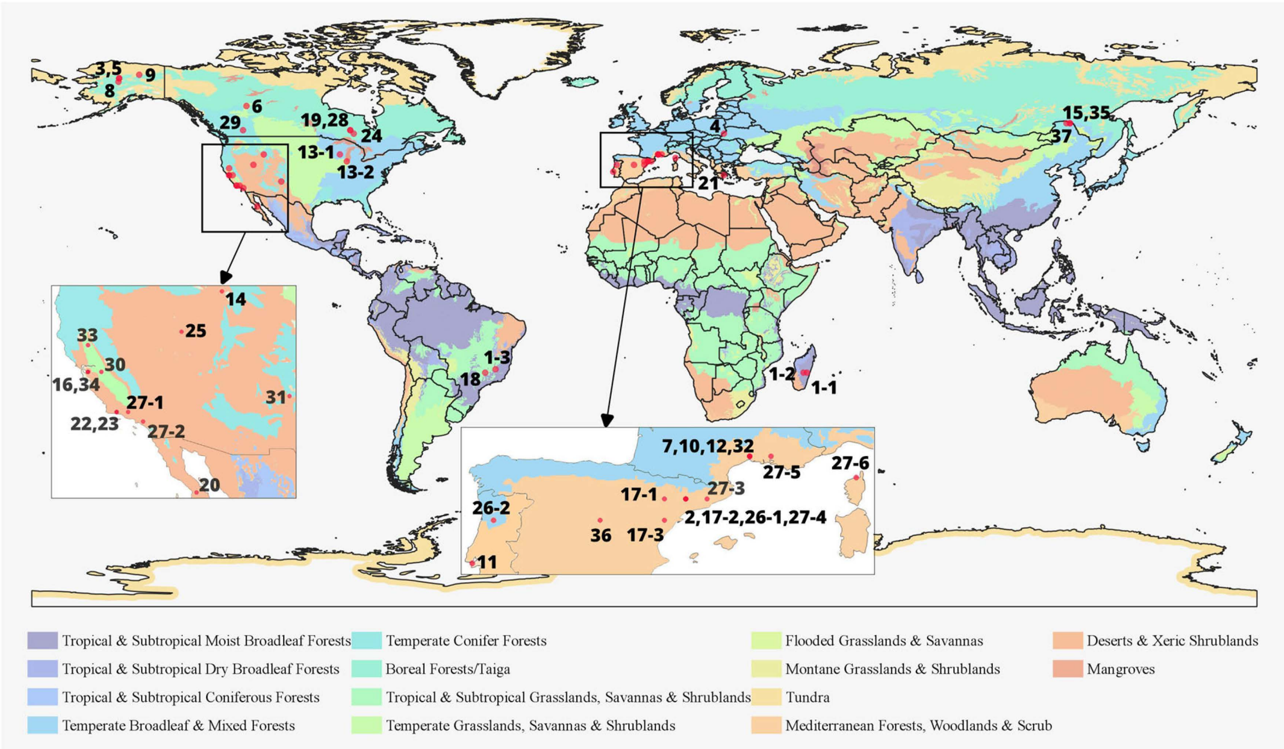

Figure 3. Geographical locations of studies included in this review and global biome map. Code numbers refer to the study ID values (Table 1). Code numbers such as "1-1" refer to the first study area of the first study.

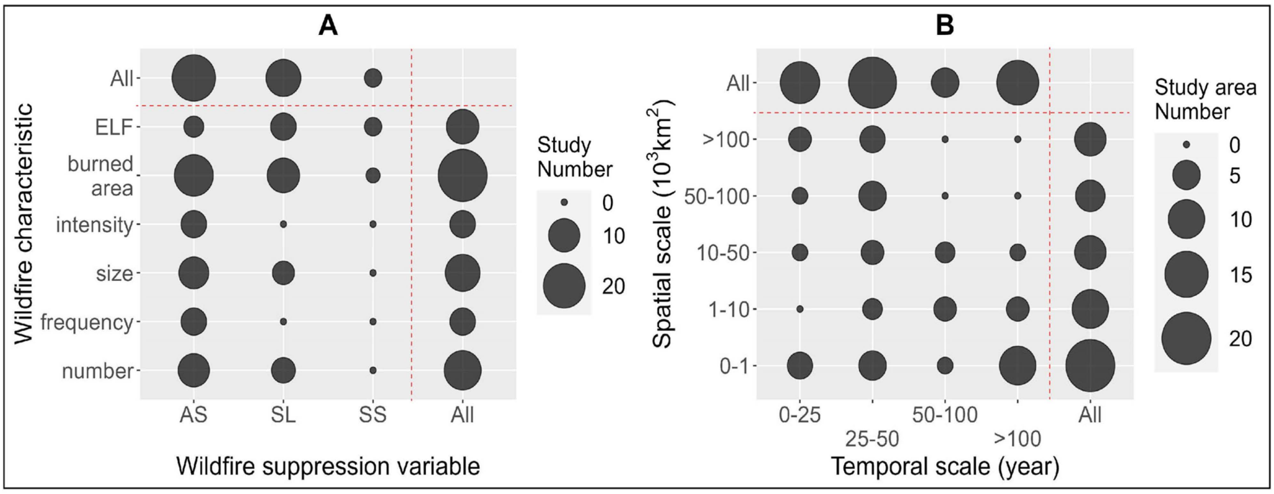

Figure 4. (**A**) Number of studies by wildfire characteristic and suppression variable. (**B**) Number of study areas by spatial and temporal scale. "AS" is active wildfire suppression. "SL" is wildfire suppression level. "SS" is wildfire suppression strategy.

3.2. Study Design

A total of 45.9% of the studies used an observational research design. In comparison, 54.1% used an experimental research design, with no significant preference for researcher selection. Observational studies analyze empirical observations and explore the correlations between variables [94] through collecting and comparing historical fire data, including the analysis of differences and regression analysis. The experimental study design primarily analyzed simulated values predicted by the mechanistic model; however, it was inherently an analysis of differences.

Table 2 illustrates that most observational studies (n = 13, 65%) used difference analysis methods. The study population was characterized into two groups based on the presence or absence of fire suppression and statistically examined to determine whether there were differences in wildfire characteristics between the groups. This analysis aimed to determine whether fire suppression factors could explain the variations in wildfire characteristics. The grouping scheme included a spatial dimension comparing wildfire characteristics in areas with and without wildfire suppression or varying suppression levels, and a temporal dimension comparing wildfire characteristics in the same area. One study used Fisher's exact test to analyze the difference between temporal trends in fire suppression resources and fire risk factors [92], which combined both temporal and spatial perspectives. Most studies employed hypothesis testing to quantify the differences, such as the Wilcoxon signed rank test [36], one-way analysis of variance (ANOVA) [16,64,69], Bhattacharyya coefficient [70], bootstrapping [67], Friedman's test [76], permutation test [76], chi-square test [76], sequential F-test [88], and OLS-based CUSUM test [88]. However, a few studies [68,78–80] formed conclusions by directly comparing examples of narrative statistical values without statistical significance, which may have led to errors.

Table 2. Summary of research designs used by the included studies.

Research Design			Research Method	Strength	Weakness
Observational study	Difference analysis	Comparison of wildfire data in different fire suppression contexts	Wilcoxon signed-rank test (1), one-way ANOVA (3, 9, 16), bootstrapping (7), Friedman's test (18), permutation test (18), Bhattacharyya coefficient (10), chi-square test (18), sequential F-test (32), OLS-based CUSUM test (32), Fisher's exact test (36)	Low reliance on fire suppression data	Difficult to control multiple sources of spatial and temporal variation in wildfire data
	Regression analysis	Quantify the extent to which fire suppression variables explain wildfire data	Logistic regression (6, 21), regression tree analysis (11), ordinary least-squares regression (19), random forest (21), boosted classification trees (21), random effects panel model (34)	Clarification of the relative contribution of fire suppression	High dependence on fire suppression data
Experimental study	Scenario modeling	Comparison of wildfire simulation data for different suppression scenarios	MEDFIRE model (2), LANDIS model (4, 37), ALFRESCO model (5), RHESSys-WMFIre framework (13), iLand model (14), LANDIS PRO 7.0 model (15), boosted regression tree model (25), logistic regression model (28), Burn-P3 small-frei containment model (29), SCRPPLE model (33), BP model (35), FBP model (35)	Elucidating the mechanism of fire suppression effects on wildfire characteristics	Research processes are complex

Note: Code numbers refer to the study ID values in Table 1.

Additionally, a few observational studies used regression analysis to explore the quantitative dependence between wildfire characteristics and fire suppression (Table 2). In these analyses, variables for fire suppression activities were established, including quantitative measures of fire suppression resources (e.g., number of firefighters, fire engines, fire breaks, and water power) and quantitative and qualitative measures of fire suppression efficiency (e.g., fire suppression efficiency factor, probability and spread of wildfires, threshold for the rate of spread of extinguishable wildfires, average return period of wildfires, fire suppression tools used per unit burned area, number and proportion of large wildfires, initial firefighting success, and response time). The literature employed regression methods such as logistic regression [43,66], regression tree [71], ordinary least-squares regression [77], boosted classification trees [43], random forest regression [43], and random effects panel model [90].

Approximately 55% of the studies used different models to simulate wildfire regimes under various scenarios, and half did not use hypothesis testing to rigorously compare the simulated values across scenarios (Table 2). The models used in these studies included the MEDFIRE model [40], LANDIS model [37,93], ALFRESCO model [65], RHESSys-WMFIre framework [73], iLand model [74], LANDIS PRO 7.0 model [75], boosted regression tree BRT model [81], logistic regression model [84], Burn-P3 small-fire containment model [85], SCRPPLE model [89], BP model [91], and FBP model [91]. Experimental studies constructed simulation models of fire dynamics using empirical data and knowledge of fire behavior mechanisms. They identified cause-and-effect relationships between variables by manipulating one or more variables in the model and observing corresponding changes in fire variables. Of the experimental studies, 55% statistically analyzed significant differences between the simulated results, whereas 45% attributed the fire changes solely to observations.

3.3. Study Findings

Academic disagreement is reflected in the conflicting conclusions of studies on how fire suppression alters wildfire regimes. However, there is less disagreement among studies on changes in fire number, frequency, and burned area of wildfires due to fire suppression than there is on alterations in fire size, intensity, and ELF due to fire suppression (Figure 5). Statistically, the findings reveal two patterns: (1) around two-thirds of the studies reported that fire suppression reduced the fire number, burned area, or fire frequency, while nearly one-third concluded that the effect was not significant, and only a few studies reported that fire suppression had a negative effect; (2) approximately 50% of the studies observed that fire suppression leads to increased fire size, intensity, burned area, and large wildfires, while almost 30% reported the opposite, and 20% concluded that the effect was not significant.

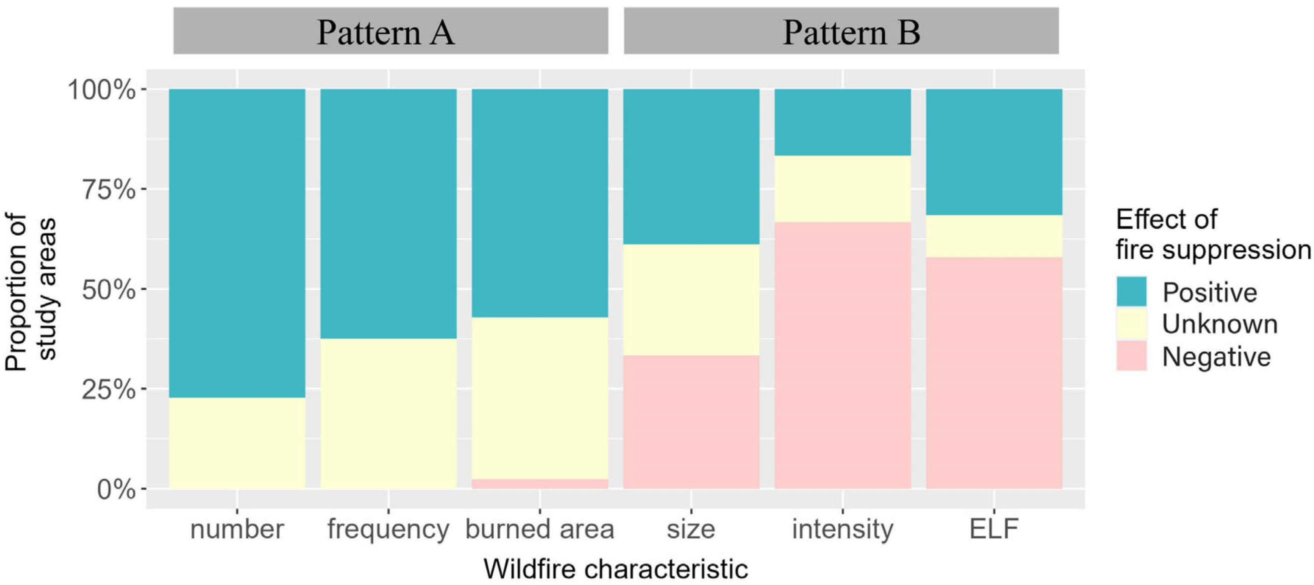

Figure 5. Proportion of study areas exhibiting positive, negative, or unknown effects of fire suppression across all wildfire characteristics. The suppression effect was counted in both categories because it could simultaneously alter fire characteristics. Positive effect indicates that fire suppression decreases fire characteristics. Negative effect indicates the opposite. Pattern A indicates that the proportion of research areas showing positive effects is much larger than that of research areas showing negative effects. Pattern B indicates the opposite.

Only a small fraction of the study areas exhibited a completely positive effect of fire suppression (Figure 6). Among the 50 study areas, investigations were conducted in 15 of them on changes in variables for both Pattern A and Pattern B under the influence of fire suppression. Approximately 50% exhibited the opposite effect of fire suppression on variables for two patterns, indicating a decrease in the number (or frequency) of fires and an increase in fire size (or intensity). Another approximately 30% showed an insignificant effect of fire suppression on both variables. Only three study areas showed that fire suppression activities reduced both the number (or frequency) and size (or intensity).

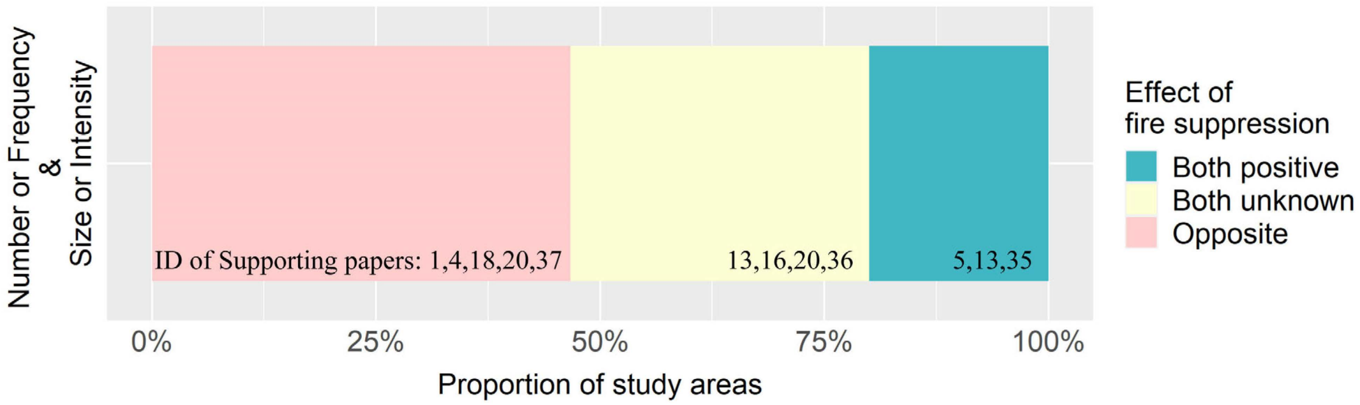

Figure 6. Proportion of study areas simultaneously exhibiting both positive, both unknown, or opposite effects of fire suppression on fire number (or frequency) and fire size (or intensity). "Both positive" indicates that fire suppression reduces both fire number (or frequency) and size (or intensity). "Opposite" indicates opposite effects of fire suppression on fire number (or frequency) and fire size (or intensity). Code numbers refer to the study ID values (Table 1).

Most studies agreed that fire suppression can control burned areas; however, researchers had different views on whether it creates a wildfire paradox (Figure 7), with 38% of the studies supporting the wildfire paradox and 40% not supporting it. A few researchers believed that there was an increase in fire size, intensity, or ELF due to suppression. However, no increase was observed in the burned area due to a decreased number or frequency of fires e.g., [35,36,76]. Others concluded that suppression decreases wildfire size, intensity, or ELF, further decreasing the total burned area e.g., [40,73]. Although these studies agreed that firefighting controls the burned area, they offered contrasting assessments of its ecological significance. The former concluded that firefighting activities cause catastrophic fires. In contrast, the latter argued that it has the desired effect of controlling fire risks. The debate revolves around whether fire suppression increases wildfire size, intensity, or ELF, reflecting the wildfire paradox. Classifying the literature based on this debate (Figure 7) revealed that 38% of the studies supported the wildfire paradox (11 papers, 19 study areas), 40% showed no evidence of it (18 papers, 20 study areas), and 22% lacked sufficient evidence to judge the ecological significance of fire suppression (for example, wildfire area and frequency were discussed, but there was no discussion on change in fire size).

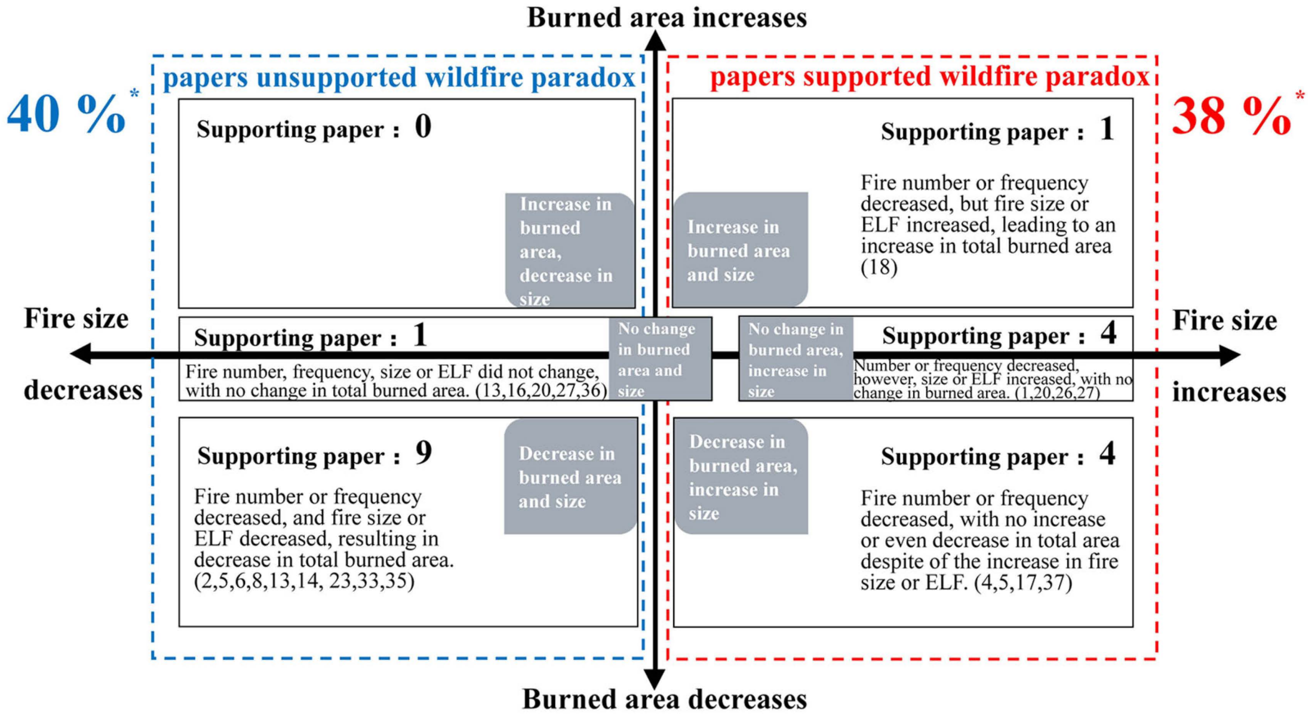

Figure 7. Summary of trends in multiple wildfire characteristics under the influence of fire suppression. The asterisk denotes that the proportion is not restricted to the papers mentioned in the figure and includes the papers that discuss only fire size (22) or ELF (11, 21, 24, 30, and 31). Code numbers refer to the study ID values (Table 1).

Figure 8 shows the significant differences in the literature supporting and not supporting the wildfire paradox regarding study setting and design. Studies opposing the paradox mostly occurred in the RIL pyrome (Figure 8C). In contrast, those supporting it covered all pyromes (Figure 8C), and studies supporting the paradox had smaller spatial and longer temporal scales than those opposing it (Figure 8D,E). Regarding the regional context, the most striking difference was the proportion of fire regime pyrome composition (Figure 8C). A total of 80% of the studies that opposed the paradox were in the RIL pyrome, which was significantly higher than the proportion of studies that supported the paradox. The remaining 20% were in the RCS pyrome, whereas the literature supporting this conclusion covered all five fire zones. Although the differences in climate and biome composition ratios were relatively insignificant, notable patterns emerged (Figure 8A,B). For example, subtropical humid (Cwa, with a distinct dry season) and subtropical mountain (Cwb, with a distinct dry season) climates were only observed in the literature supporting the paradox. The former accounted for 30% of the literature. In contrast, temperate continental humid (Dfa) climates were only reported in the literature opposing it (Figure 8A). Similarly, temperate grassland, savannah, and shrubland biome only appeared in the studies against the paradox, accounting for 30% of the studies. In contrast, tropical and subtropical moist broadleaf forest biome only appeared in the studies that supported the paradox (Figure 8B). Regarding study design, clear distinctions existed within the literature at the spatial and temporal scales (Figure 8D,E). Approximately 70% of the study areas supporting the wildfire paradox were concentrated at the smallest spatial scale (0–1000 km^2), whereas only 10% opposed it. The spatial scale of the opposing literature was evenly distributed across all scales (Figure 8D). Almost 50% of the supporting studies were at the longest timescales (>100 y), while only 10% were at the shortest timescales (0–25 y). For opposing studies, 40% were at the shortest timescales (Figure 8E). The type of research design (Figure 8G) showed little difference, with slightly more observational research supporting the wildfire paradox.

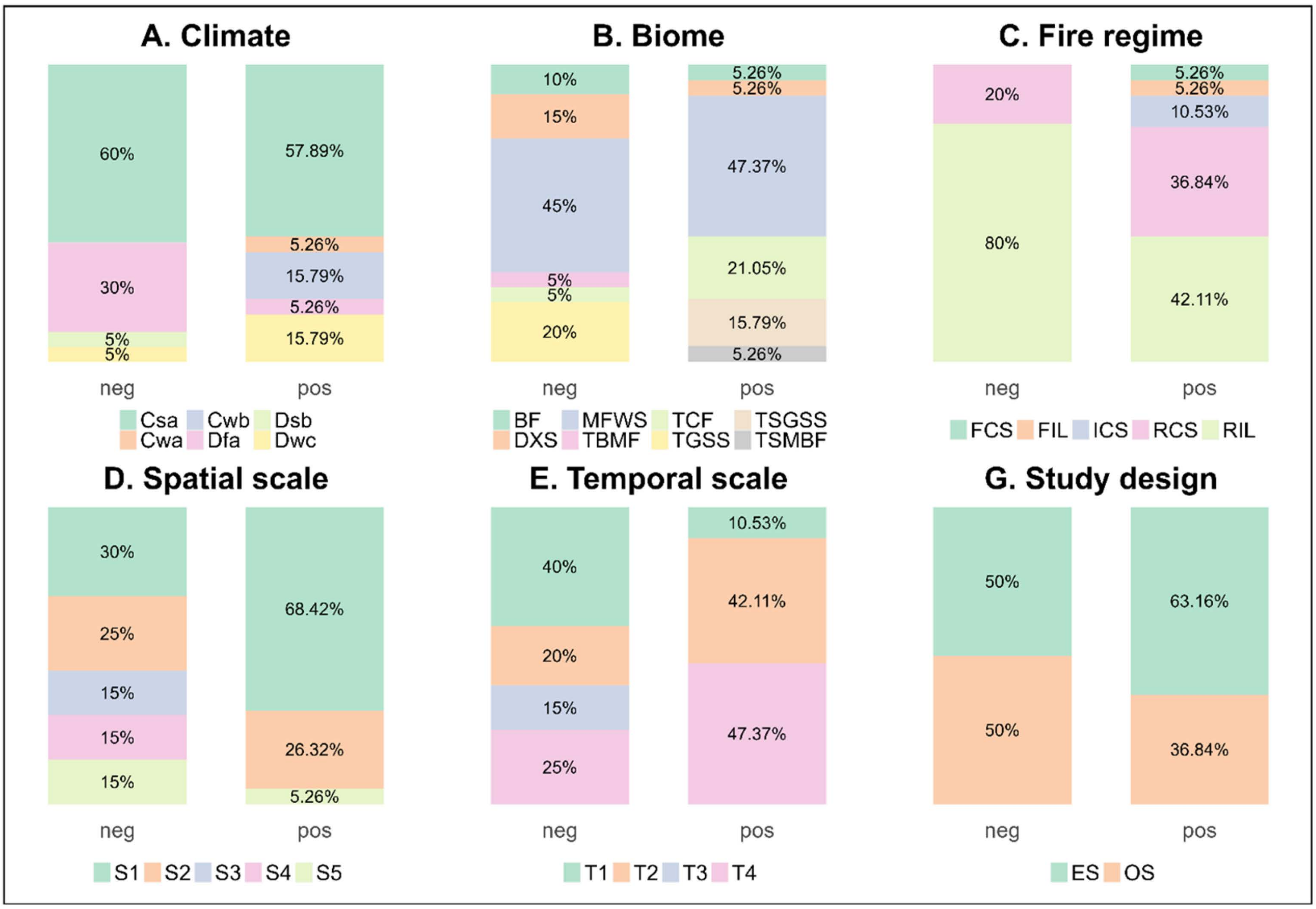

Figure 8. Comparison of two groups of literature reviewed in terms of geographical background and research design. "neg" indicates the literature that does not support the paradox and "pos" indicates the literature that supports the paradox. The value indicates the proportion of papers with the same type for each characteristic. "Csa" is Mediterranean hot summer climate. "Cwb" is dry winter subtropical highland climate. "Dsb" is warm summer hemiboreal climate. "Cwa" is dry winter humid subtropical climate. "Dfa" is hot summer continental climate. "Dwc" is subarctic or boreal climate. "S1" is 0–10^3 km^2. "S2" is 10^3–10^4 km^2. "S3" is 10^4–5×10^4 km^2. "S4" is 5×10^4–10^5 km^2. "S5" is >10^5 km^2. "T1" is 0~25 yr. "T2" is 25~50 years. "T3" is 50~100 years. "T4" is more than 100 years. "ES" is experimental study. "OS" is observational study design.

4. Discussion

4.1. Where Are the Study Areas in the Existing Research?

The literature shows a clear clustering of spatial distribution and lack of discussion on tropical savannas. Mediterranean forests, woodlands, and shrublands in the western United States and Europe have been studied extensively. In these areas, the fire regime is dominated by the RIL pyrome, with high-intensity and large wildfires [59]. These economically developed and resource-rich regions prioritize fire suppression activities to mitigate wildfire hazards [95]. Boreal forests, temperate conifer forests, temperate broadleaf and mixed forests, and temperate grasslands in the USA, Canada, and China have received attention. These areas include the RIL and RCS pyromes. Although fires in the RCS pyrome are not severe, their occurrence in boreal forests can significantly impact global ecosystems through carbon release [9]. Therefore, the prevention of forest fires is crucial in this region, resulting in more attention from researchers. However, little attention has been given to the effects of fire suppression policies on wildfires in the FIL pyrome, primarily located in tropical savannas [59]. Further research is required to investigate the effects of anthropogenic fire suppression on wildfire dynamics in tropical savannas across Africa, South America, and Australia.

4.2. How Did Existing Research Quantify the Relationship between Fire Suppression and Fire Regimes?

The most used study design in the literature was difference analysis in wildfire regimes between groups based on empirical data. Further research should focus on controlling other sources of variations in fire regime data for more rigorous difference analysis. In this study design, researchers tested the difference between fire data based on whether fire suppression was used. This approach considers the spatial and temporal extents of fire suppression activities in the study area and avoids relying on quantitative data of fire suppression activities, which are not readily available (Table 2). The accuracy of conclusions inferred from this approach depends on controlling other variables that contribute to the spatial and temporal variability of wildfire regime data between samples, such as climate [96,97], vegetation cover [98], fuel resources [27,99], topography [100], land use change [101], population density [102], and GDP [103]. However, finding two regions or periods that meet these idealistic requirements can be challenging. Studies included in this review that fully controlled for other variables were rare, which may have introduced errors in the results. For example, a study concluded that fire suppression increased the total burned area by selecting a treatment group with features like prescribed fires and dense roads, which could effectively reduce the fuel load and increase fragmentation, thereby greatly reducing the fire size and resulting in a decrease in the total burned area [76]. However, comparing the control group to natural wildfire dynamics may not increase the total burned area. In summary, using difference analysis methods based on empirical data could make it difficult to control for other variables, potentially biasing the conclusions. Studies should aim for rigorous analysis by controlling for multiple sources of spatial and temporal variation in the data [66,104] by using, for example, pre-regression matching to control for differences in other geographic features [90].

Regression analysis quantifies the relative contribution of fire suppression based on multiple regression; however, it has the disadvantage of relying on quantitative data of fire suppression that are not readily available (Table 2). Firefighting resources are the most used variables to measure firefighting levels. However, dispatching difficulties lead to varying actual levels [105]. Therefore, there is a discrepancy between theoretical and actual firefighting efficiency, and subsequent studies need to pay attention to selecting quantitative indicators that represent actual firefighting. Compared to the other two approaches, the experimental research design utilizes qualitative and quantitative modeling, offers the most accurate assessment of fire suppression's impact on wildfire dynamics, and can provide rigorous decision support for wildfire management. However, it requires a deep understanding of the mechanisms within the fire suppression–wildfire regime interaction process in the study area, thus adding complexity to the research. In conclusion, each of the three methods has its advantages and disadvantages, and researchers should choose the one that best suits the purpose of the survey, the available dataset, and the geographical characteristics of the study area.

4.3. What Are the Responses in the Literature to the Research Question? Why Are the Conclusions Opposed?

Existing studies have reached two contradictory conclusions: a few studies suggest that aggressive fire suppression, while controlling the burned area and number of fires, increases the risk of ELF and ultimately harms forests and human society, supporting the wildfire paradox e.g., [39,73,75], while others suggest that fire suppression effectively reduces the risk of wildfire without increasing the size of fires or ELF, and thus are against the wildfire paradox e.g., [68,92]. An equal number of studies supporting each conclusion shows no consensus on this issue, which occurred for several reasons.

The relationship between wildfire suppression and wildfire regimes depends on the relative importance of fuel and climate for wildfires [73,106]. Studies supporting the wildfire paradox hypothesis confirm that long-term fire suppression causes negative wildfire feedback by altering fuel characteristics, increasing the load and continuity of combustible biomass [36,75,78,93], and reducing natural fire patches that would provide opportunistic fire suppression as natural firebreaks, eventually resulting in increased wildfire size or extreme wildfire risk. Moreover, from a management perspective [107], the emphasis on fire suppression expenditure has diminished the prevention budget, resulting in more intense fires. However, this negative feedback occurs only when fuel is the dominant factor driving the wildfire regime. Otherwise, in theory, fire suppression activities cannot significantly alter wildfire dynamics, even if they can change fuel characteristics. For example, in fuel-rich areas with suitable climates, high humidity limits fire spread, and intense wildland fires are rare and only occur during abnormally dry periods [73,106,108]. The climate is a modulator of the occurrence of fires in these regions, with fuel characteristics providing a weak explanation of forest fire dynamics and natural fire patches having a less limiting effect on fire size, negating the wildfire paradox. However, the climate in arid regions is conducive to fire, and the extent of wildfires depends on the fuel and natural fire patches [27]. Therefore, in such fuel-limited systems, fire suppression activities can further induce a shift from frequent and low-intensity wildfires to infrequent and intense ones by altering the main drivers of the fire regime. However, fuel accumulation following fire suppression is not always guaranteed and relies on sufficient moisture levels to support vegetation growth [109]. For example, long-term fire suppression in the fire-limited Watershed Trail in the southwest USA did not significantly affect wildfire occurrence due to moisture deficits [73]. The wildfire paradox is more likely to occur in fuel-limited fire zones. This pattern was reflected in the background information of 37 studies, with most of the areas not supporting the wildfire paradox being in the fuel-limited RIL pyrome, such as most boreal forests, far more than in study areas that supported the wildfire paradox (Figure 8C). The wildfire paradox is rarely observed in temperate continental humid climate areas (Figure 8A,B).

The heterogeneous response of various vegetation types to fire suppression changes the relationship between fire suppression and wildfire dynamics [110]. In addition to the direct alteration of fire regimes, fire suppression can indirectly impact these regimes. The most typical indirect modification is that fire suppression may alter fire regimes, leading to shifts in the trajectories of vegetation succession and landscape dynamics [111], which could in turn modify fire regimes. For instance, studies have revealed that an increase in fire frequency may result in a decrease in flammability [112]. However, the response of various vegetation types to fire suppression is heterogeneous [110,113], eventually resulting in variations in the effects of fire suppression on fire regimes. For example, in northern Wisconsin, the succession of deciduous trees after suppression has led to negative feedback, with an abundance of dead plant material and higher fire intensity occurring after suppression [114]. However, in western North America, forests are transitioning from pine to less flammable northern hardwoods after fire suppression, resulting in positive feedback [114]. In addition to vegetation species compositions, shifts in structures resulting from changes in vegetation succession trajectories following suppression alter the impact of fire suppression on wildfire regimes. For example, fire suppression in the Great Xing'an Mountains of northeast China has increased the proportion of coniferous forests and decreased the proportion of deciduous forests, thereby increasing canopy density and flammability and the frequency of high-intensity canopy fires [37]. However, it has been suggested [73] that a large increase in canopy density caused by suppression may lead to sub-canopy effects, including reduced sub-canopy evapotranspiration and increased sub-canopy temperature and humidity [115,116], thereby reducing surface fuel accumulation and wildfire frequency [117]. In summary, the differences in wildfire regimes' responses to fire suppression were due to different feedback mechanisms of various vegetation types and structures to fire suppression.

In addition to local climatic and vegetation factors, the quantitative relationship between wildfire regimes and fire suppression is influenced by spatial and temporal scales, data sources, and study methods. Wildfire regimes vary at different scales [28], with fuel and climate playing dominant roles at relatively small and large spatial and temporal scales, respectively [80,118–120]. Thus, extensive fires resulting from fire suppression activities are more observable at a smaller spatial scale and over a longer timescale. Figure 8D shows that nearly 70% of the study areas in the literature supporting the wildfire paradox were within the 0–1000 km^2 scale, which was the smallest spatial scale across the collected studies. This is a significantly higher proportion than that in the literature that did not support the wildfire paradox at this spatial scale. Figure 8E demonstrates that the proportion of research data supporting the wildfire paradox was significantly higher at longer timescales than that which did not support it. Figure 8G does not exhibit significant differences in the proportion of study design types between the two literature sets, possibly due to a general classification. However, the study design and methods affected the results. The impact of fire suppression on wildfires varied depending on whether other natural and human variables were controlled in the difference analysis, whether the assessment indicators were selected to represent the actual level of fire suppression, or whether climate change scenarios were considered.

Other natural and human intervention variables, such as fire prevention measures, land use changes, and climate change, could potentially affect the relationship between fire suppression and fire regimes, leading to variations in the findings of the included studies. Fire prevention measures, such as education and legislative regulations, landscape-scale fuel treatments, and prescribed burning [34,121,122], can effectively reduce ignitions and the accumulation of fuel caused by long-term fire suppression [34,37,74–76,123–125]. Therefore, there has been no escalation of fire regimes, despite aggressive fire suppression, due to these fire prevention measures in regions of the US [95,126], Canada [127], France [88], and Australia [121,123,124]. Land use changes could also interact with fire suppression and alter the fire regimes. Fragmentation caused by roads [121,125,128], grazing land [36], and agricultural fields [39,128] in flammable areas could reduce fuel continuity and the capacity for fire spread, resulting in lower fire frequency and burned area. For example, under the same aggressive fire suppression policy, there was a contrasting alteration in fire regimes between a region with livestock and a region without livestock [36]. Climate change is an additional significant factor that has the potential to worsen the negative effects of aggressive fire suppression on fire regimes. For example, hot dry conditions resulted in a reduction in the length of the fire's self-limiting effect [129]. Through simulation modeling, researchers found that no fire management strategies could fully offset the predicted effects of climate change [39]. Not controlling for other sources of spatiotemporal variability in fire regimes may confound the effect of fire suppression detected in the difference analysis and result in discrepancies between studies.

Overall, the dominant factors in wildfire regimes, the response of vegetation composition and structure to fire suppression, and the spatial and temporal scales, research objects, and study designs chosen by the researchers all influenced the relationship between fire suppression and wildfire regimes. In addition, it is important to emphasize that the relationship between fire suppression and wildfire regimes is not fixed within a given system. For example, in the context of future climate change, a fuel-limiting system may be transformed into a climate-limiting system [119].

4.4. Limitations and Future Work

This systematic review examines the relationship between fire suppression and wildfire regimes. While the review provides valuable insight into this topic, there are several limitations that can be improved. (1) Selection bias. This review relied on a specific set of studies identified through an existing WOS database search and manually screened based on several criteria. This limited sample (n = 37) may not capture the full spectrum of fire-prone areas, perspectives, methodologies, and findings available in the broader academic landscape. Therefore, there might be other relevant studies in fire-prone areas that were not included, potentially leading to selection bias. Future research would benefit from a more comprehensive review by expanding the database, refining literature search keywords, and increasing the number of researchers involved in literature searching and screening to reduce bias. (2) Scale-effect constraints of global scope. The scope of this review is global and the geographical locations are not limited in the screening criterion. A broad range of ecosystems and climates is considered. Although the global scale contributes to the validation of the premise and principles governing the occurrence of the fire paradox, it does have inherent limitations. A deeper and more comprehensive understanding of why and when the fire paradox does not manifest in regions with fundamental prerequisites is hard to achieve because of the scale effect. It would be highly helpful for sustainable fire management to impose a regional restriction in a future review and investigate whether the fire paradox has occurred in all areas with conditions conducive to its emergence, identify the main factors that could prevent its occurrence, and analyze how these factors interact with fire suppression.

5. Conclusions

To investigate the wildfire paradox across diverse global regions, this study conducted a comprehensive systematic review of existing research on the influence of fire suppression on wildfire regimes, presenting unique findings not available elsewhere. The findings highlight several important points. Firstly, numerous studies have focused on northern mid- and high-latitude biomes, neglecting tropical savannas in Australia, Africa, and South America where wildfires are frequent and intense. Further investigations in these regions are warranted. Secondly, existing studies typically employ difference analysis, regression analysis, and comparison of scenario simulations to explore the impact of fire suppression, with most studies relying on difference analysis. Researchers should choose an appropriate method based on the study area, data availability, and understanding of wildfire regimes. Moreover, there is a necessity for a more robust difference analysis by controlling multiple sources of spatial and temporal variations in fire regimes. Thirdly, while there is general agreement in the literature that fire suppression can reduce the total burned area, the effects of fire suppression activities on wildfire regimes are diverse. The wildfire paradox does not necessarily occur in all ecosystems. This systematic review identifies a pattern that suggests the wildfire paradox is more likely to occur in fuel-limited systems, certain vegetation types, and small-scale and long-term studies. Thus, fuel-limited systems in arid climates are not suitable for aggressive suppression. In contrast, wildfires in climate-limited systems in humid climates can be aggressively suppressed.

Our findings highlight that the complex interactions between fire suppression and various environmental as well as social factors can alter the relationship between wildfire suppression and fire regimes across different ecosystems and scales. Additional research is needed to gain a thorough understanding of the relationship between fire suppression and local wildfire regimes. There is no universal solution to avoid severe fires resulting from coarse fuel build-up resulting from aggressive fire suppression. To establish robust and sustainable wildfire management, wildland fire managers should assess and simulate the unique response of the local wildland ecosystem, implementing management strategies accordingly. The assessment and simulation should be based on different spatiotemporal scales and climate change scenarios. For ecosystems with the potential for the occurrence of the fire paradox, policymakers should not focus solely on short-term reductions in wildfires. Instead, they should incorporate fire prevention measures, such as fuel treatment, and develop fire-resilient infrastructures and communities as part of fire management for long-term benefits.

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