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REVIEW **Open Access**

Effectiveness of firebreaks: a review

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Abstract

Background Firebreaks—areas where fuels are removed—are widely implemented to reduce wildfire spread and support suppression efforts. Despite their global use, concerns remain about their effectiveness, particularly under extreme fire weather, and the ecological trade-offs associated with their construction and maintenance. This review synthesizes current knowledge on firebreak design, application, and performance, focusing on the mechanisms driving breaches and identifying priorities for improving their effectiveness.

Results Firebreak effectiveness depends on a combination of environmental, structural, and operational factors, including width, placement, maintenance, fuel conditions, and suppression capacity. Historical observations and modeling studies indicate that strategically placed and well-maintained firebreaks can reduce wildfire spread and risk; however, breaches remain common during extreme fire events. Firebrand transport, or spotting, is the primary mechanism by which wildfires circumvent firebreaks, with firebrands capable of traveling distances that exceed typical firebreak widths. However, existing empirical and fire simulation models often inadequately represent spotting, limiting evaluation of firebreak effectiveness. The ecological consequences of firebreaks, including habitat fragmentation, edge effects, and invasive species colonization, add further complexity to their implementation.

Conclusions While firebreaks remain an important tool in wildfire management, their reliability is constrained under extreme fire conditions. Future research should prioritize the development of spatially explicit, predictive models that integrate fire weather, fuel continuity, topography, and suppression efforts; the expansion of standardized, georeferenced databases on firebreak breaches; and assessments of ecological and social trade-offs. Advances in remote sensing and high-resolution fire monitoring offer opportunities to better evaluate performance and anticipate breaches. Integrating firebreaks into broader, adaptive wildfire management strategies—including fuel reduction, land-use planning, and community preparedness—will be critical to enhancing landscape resilience and maximizing the protective benefits of these structures.

Keywords Fire behavior, Firebreak effectiveness, Spotting, Wildfire management, Wildfire risk

Resumen

Antecedentes Las barreras (o fajas) contra incendios (áreas donde el combustible vegetal es removido), son implementadas de manera amplia para reducir la propagación y aportar a los esfuerzos de supresión. A pesar de su uso de manera global, existen dudas acerca de su efectividad, en especial bajo condiciones ambientales y de fuego extremas, y los costos y/o beneficios ecológicos asociados con su construcción y mantenimiento. Esta revisión sintetiza el conocimiento actual sobre el diseño, aplicación y performance de estas barreras, enfocando en los mecanismos que producen brechas e identificando prioridades para mejorar su efectividad.

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Resultados La efectividad de las barreras contra el fuego depende de una combinación de factores ambientales, estructurales, y operacionales, incluyendo el ancho de las fajas, su ubicación, mantenimiento, condiciones del combustible y la capacidad de supresión. Observaciones históricas y estudios del modelado indican que estas barreras estratégicamente ubicadas y bien mantenidas pueden reducir la propagación y el riesgo de incendios; sin embargo, algunas brechas aparecen como comunes en caso de eventos de fuegos extremos. El transporte de pavesas, o "*spotting*", es el mecanismo primario por el cual los incendios sobrepasan estas barreras, con pavesas encendidas capaces de cubrir distancias que sobrepasan el ancho de estas fajas. Sin embargo, existen modelos empíricos y de simulación que representan inadecuadamente este transporte de pavesas, limitando así la evaluación de la efectividad real de las fajas o barreras cortafuegos. Las consecuencias ecológicas de estas fajas/barreras, incluyendo la fragmentación del hábitat, los efectos de borde, y la colonización de especies invasoras, le agregan un poco más de complejidad a su implementación.

Conclusiones Aunque las fajas/barreras cortafuegos siguen siendo una herramienta importante en el manejo de fuegos de vegetación, su confiabilidad está limitada bajo condiciones de fuego extremas. Investigaciones futuras deberán priorizar el desarrollo de modelos espaciales explícitos y predictivos que integren el tiempo meteorológico al momento del incendio, la continuidad del combustible, la topografía, y los esfuerzos de supresión; la expansión de bases de datos geo-referenciadas sobre las brechas en las fajas, y la determinación de costos y beneficios tanto ecológicos como sociales. Los avances en sensores remotos y el monitoreo de incendios a altas resoluciones espaciales ofrecen oportunidades para evaluar la performance y anticipar estas brechas. El integrar las barreras cortafuegos en estrategias más amplias de manejo de incendios, estrategias de manejo adaptativas, incluyendo la reducción de combustibles, el planeamiento en el uso del suelo, y la preparación de la comunidad, son aspectos críticos para aumentar la resiliencia del paisaje y maximizar los beneficios protectores de esas estructuras.

Introduction

Although wildfires play an important role in shaping the evolution of plant and animal species (Keeley et al. 2011; Juli and Dylan 2012) and biogeochemical processes (Schlesinger et al. 2016; Dove et al. 2020), they have drawn global concern due to their increasingly severe impacts on natural and human systems. For instance, recent severe wildfire events include Australia's 2019–2020 mega-fires (Ward et al. 2020), the unprecedented 2020 wildfire season in the United States (Li et al. 2021), the extreme 2022 wildfire season in Southwest Europe (Rodrigues et al. 2023), and the record-breaking 2023 fire season in Canada (Jain et al. 2024). Between 2003 and 2023, the global frequency of extreme wildfires—those exceeding the 99.99th percentile of daily summed fire radiative power—has more than doubled (Cunningham et al. 2024). Projections indicate that global wildfires will become increasingly frequent and severe under climate change, amplifying threats to ecosystems, human lives, and infrastructure (Senande-Rivera et al. 2022; Yu et al. 2022). Such increasing wildfire risk demands an assessment of current mitigation strategies, particularly those focused on fuel management, which remains one of the few controllable factors in wildfire risk mitigation.

Among the natural factors influencing wildfire activity, including fuel, weather/climate, and topography, fuel is the only factor that can be directly modified through human intervention. As a result, fuel treatment has become a cornerstone of wildfire management via clearing fuel loads and reducing flammability (Finney 2001; Agee and Skinner 2005). These strategies ultimately seek to create fire-resistant conditions that manage the risk, costs, and benefits of wildfire in support of land management goals. Treated areas are referred to as either fuelbreaks or firebreaks, depending on whether fuels are cleared (Ascoli et al. 2020). Fuelbreaks are parcels of land, linear or in blocks, covered by vegetation where fuels are reduced strategically, in both loads and flammability, so that fires burning into them can be controlled more effectively and safely (Shinneman et al. 2019). Firebreaks, on the other hand, are often referred to as linear or block-shaped areas where fuels are removed and cannot support fire ignition or spread. They are designed to be completely non-flammable and serve as direct containment lines during wildfires. Certain natural features, such as water bodies, rocky outcrops, and cliffs also serve as firebreaks in fire management, as they are non-combustible and can act as barriers to fire spread (Price et al. 2007; Fisher et al. 2022). Firebreak implementation varies widely across different fire-prone regions and is often integrated into broader fuel reduction strategies alongside prescribed burning, mechanical thinning, and planned ignitions (Price et al. 2007; Ascoli et al. 2020; Fisher et al. 2022; Tyburski and Szczygieł 2023).

Given the escalating frequency and intensity of wildfires, firebreaks have been widely implemented to enhance the resilience of ecosystems and save resources (e.g., water) during wildfire suppression (Hansen 2012).

For example, the U.S. Department of Agriculture launched the "Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests" to address the nation's growing wildfire crisis (U.S. Department of Agriculture 2022). Under this strategy, approximately 1.57 million acres of forests were treated between 2023 and 2024 (https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/WCS-making-difference.pdf). In China, the catastrophic 'Great Black Dragon Fire' of 1987 in the Daxing'anling region spurred significant reforms in wildfire management (Zong et al. 2022b), including the annual construction of firebreaks and the use of prescribed burning to reduce wildfire occurrence (Zong et al. 2021, 2024). Moreover, integrated, multi-purpose, and cross-agency approaches have also been developed to improve firebreak construction and maintenance worldwide (Clark et al. 2023).

Although there is a broad consensus on the need to expand firebreak construction and maintenance as part of proactive wildfire risk reduction strategies (Prichard et al. 2021; McKinney et al. 2022), concerns remain about their effectiveness—particularly as fire regimes intensify under climate change (Dennis 2003). Increasing reports of firebreak breaches in recent years have raised questions about the reliability of these structures in extreme conditions. For example, during Canada's record-breaking 2023 wildfire season, an intense fire breached Okanagan Lake—a natural firebreak nearly 3 km wide—and advanced toward the city of Kelowna (Jain et al. 2024). Such events underscore the urgent need to re-evaluate the conditions under which firebreaks succeed or fail, and to improve strategies for their placement, design, and maintenance.

To address these issues, this review synthesizes a growing body of research on the design, application, and performance of firebreaks in wildfire-prone landscapes. We focus on firebreaks, rather than fuelbreaks, given the relatively limited research in this area. Specifically, we aim to (1) discuss the global use of firebreaks, including their construction, implementation, maintenance, and associated ecological trade-offs; (2) examine research on firebreak effectiveness, drawing on evidence from investigation and modeling studies; (3) highlight the role of firebrand transport ("spotting") as the primary mechanism of firebreak breaches; and (4) identify knowledge gaps and future research directions to enhance firebreak effectiveness under increasingly challenging fire conditions.

Introduction to firebreaks in global wildfire management

Firebreaks have long been used in wildfire prevention and control. For example, indigenous communities in both North and South America—such as Brazil (Mistry et al. 2016) and Canada (Christianson et al. 2012)—have historically used firebreaks to protect settlements and valuable resources from wildfire. Today, firebreaks remain a frontline tool for wildfire mitigation and suppression worldwide. However, their construction and implementation vary globally, reflecting variations in local environmental conditions, vegetation, and fire management practices (Ascoli et al. 2020).

Firebreak implementation

Prescribed burning is a widely used method to create and maintain firebreaks by reducing vegetation and surface fuels. It involves the controlled use of low-intensity fire to achieve specific management objectives outlined in predefined prescriptions. This technique has proven effective in many forested regions, including those in North America (Faivre et al. 2016), Australia (Price et al. 2007; Penman et al. 2013), and the Mediterranean (Salis et al. 2016). Timing is a critical factor in firebreak planning and construction using prescribed burning, which typically requires weeks or months of preparation prior to the fire season (Chung 2015). For example, in the western United States, prescribed burning is often conducted in spring or autumn, when weather and vegetation conditions are more favorable for achieving the desired fire behavior while maintaining control (Swain et al. 2023).

Firebreak width is an important factor in firebreak construction, and varies depending on local fire regimes, landscape features, vegetation types, and management objectives. In regions prone to high-intensity fires or extreme fire weather, firebreaks are generally constructed wider. In China, mechanical firebreaks, created via plowing, slashing, or prescribed burning typically range from 30 to 90 m wide, depending on vegetation type and terrain (Zong et al. 2021). In the United States, the Conservation Practice Standard for firebreaks (CODE 394) recommends the minimum firebreak widths between 10 and 500 ft (3–152 m), depending on burn unit position (upwind or downwind) and vegetation type (Natural Resources Conservation Service 2021). These guidelines also advise aligning firebreaks with topographic contours to reduce erosion and removing dead or hollow trees within 100 ft (approximately 30.5 m) of firebreaks to facilitate maintenance. In Canada, recommended firebreak widths typically range from 30 to 200 m, with wider firebreaks advised on steeper slopes to help reduce the occurrence of crown fires (Partners in Protection 2003). A summary of firebreak width guidelines in various fire-prone areas, spanning both countries and broader regions, is shown in Table 1.

Both natural and artificial features, such as lakes and roads, are often incorporated into firebreak networks because they provide non-flammable barriers that

Table 1 Examples of recommended firebreak width and construction guidelines for fire-prone countries and broader regions

Country or region	Width (m)	landscape	Purposes	Sources
USA	3–152	All land where protection from wildfire or facilitation of firebreak is needed	Stopping or significantly reducing the spread of wildfire resulting from excessive biomass accumulations	Conservation Practice Standard: Firebreak (Code 394) (Natural Resources Conservation Service 2021)
Canada	30–200	Wildland-urban interface	Helping individuals and communities mitigate the risk of loss from wildfires	FireSmart: Protecting Your Community from Wildfire (Partners in Protection 2003)
Australia	2–10	All vegetated areas	Minimizing the spread of fire and allowing access by emergency vehicles	Firebreak Notice Requirements and Bushfire Information 2025–26 (Shire of Augusta Margaret River 2025)
China	30–90	Forested areas	Wildfire risk mitigation	National Forest Fire Prevention Plan (2016) for 2016–2025 (National Forestry and Grassland Administration 2016)
Europe	20–30	Forested areas	Increasing the safety and efficiency of ground fighting maneuvers, and enabling the implementation of backfires	Forest Fire (CFPA-E Guideline No 6:2016 N) (European fire protection associations 2016)

require minimal additional treatment (e.g., Price et al. 2007; Narayanaraj and Wimberly 2011). For example, in Poland, regulations require Type A firebreaks—30-m-wide strips adjacent to public roads—to be cleared of dead trees, branches, and other flammable material to prevent roadside ignitions (Tyburski and Szczygieł 2023). Forest roads widely use linear firebreaks in China, Australia, and the USA (Narayanaraj and Wimberly 2012; Zong et al. 2021; Fisher et al. 2022).

Firebreak application

Once constructed, firebreaks serve multiple purposes in wildfire management. They are used in pre-suppression planning to divide landscapes into compartments, limiting the area affected by a single wildfire and facilitating suppression operations (Aparício et al. 2022). During wildfire events, firebreaks can act as anchor points for suppression activities, including burnout operations, where controlled fires are ignited along a break to remove fuels ahead of an advancing wildfire (Thompson et al. 2021). Firebreaks also help protect human communities, critical infrastructure, and high-value ecological assets, such as old-growth forests and endangered species habitat (Schoennagel et al. 2009; Zong et al. 2022a; Ganteaume et al. 2023).

Given these varied roles, integrating firebreaks into broader landscape-level fire planning is essential. This includes evaluating their spatial distribution, connectivity with other fuel reduction methods, and alignment with natural barriers to maximize their effectiveness (Pollet and Omi 2002; Reinhardt et al. 2008; Zong et al. 2024). Strategic placement of firebreaks along roads, ridgetops, and streams can enhance their ability to halt or redirect fire spread. In Portugal, firebreak networks are linked with mosaics of varying fuel treatments, while in Chile, extensive firebreaks are constructed in and around forest plantations to shield adjacent communities (Úbeda and Sarricolea 2016; Aparício et al. 2022).

Importantly, firebreaks also require regular maintenance to remain effective, as vegetation regrowth—especially in productive ecosystems—can quickly restore fuel continuity (Chung et al. 2013). For example, invasive species like cheatgrass (*Bromus tectorum*) can colonize firebreaks and create new fire hazards unless actively managed (Gundale et al. 2008; Fenesi et al. 2017). Maintenance practices vary by region but commonly include mechanical clearing, herbicide application, and prescribed burning. In central Italy, livestock grazing has also been used as a complementary strategy to maintain firebreaks by keeping grass short, potentially reducing long-term costs (Pardini et al. 2007). Herbicides are also applied in areas, such as the United States and Australia, to suppress shrub and grass regrowth and reduce long-term maintenance costs (Ellsworth et al. 2022). Despite these strategies, firebreak maintenance faces several challenges, including inconsistent funding and limited operational capacity during peak wildfire periods.

Firebreak's ecological impacts

While firebreak construction and maintenance are essential for controlling wildfire spread, it is equally important to consider their ecological consequences, as the design and placement of these structures can profoundly affect habitats, biodiversity, and ecosystem processes (Suárez-Esteban et al. 2013; van Aardt et al. 2024). Poorly designed or excessively wide firebreaks can fragment habitats, disrupt wildlife movement, and alter key ecosystem functions. For instance, when firebreaks are placed in sensitive areas such as riparian zones, they may degrade water quality or reduce biodiversity (Akbarimehr et al. 2016; Laudon et al. 2016; Arjmand et al. 2023). Firebreaks can also create edge effects, expose forest interiors to wind and solar radiation, and facilitate the spread of invasive species (O'Reilly-Nugent et al. 2016; Lemke et al. 2019), all of which may undermine long-term ecological resilience. These trade-offs are especially concerning in ecologically sensitive or high-conservation-value landscapes, where even limited disturbance can have outsized impacts.

Balancing fire management goals with ecological integrity is therefore crucial. Strategic planning should consider not only fire behavior and suppression logistics, but also ecological constraints and values. For example, minimizing firebreak width, avoiding sensitive habitats, and integrating firebreaks with less intrusive fuel reductions (e.g., prescribed burning or grazing) can help reduce adverse effects (Valor et al. 2015). As firebreaks become more widespread in response to intensifying wildfire risks due to climate change, efforts to harmonize their protective function with ecosystem conservation will be increasingly important.

Overall, while firebreak guidelines differ across regions, they are consistently adapted to local fire regimes, vegetation patterns, and terrain. The widespread incorporation of natural features and variation in construction approaches reflects a shared recognition that firebreak design must be tailored to the biophysical context rather than follow fixed-width standards. At the same time, the multifunctional use of firebreaks—from operational suppression to long-term landscape planning—underscores their central role in wildfire management, as well as the need to balance protection goals with environmental and social considerations.

Firebreak effectiveness assessment

Literature on firebreak effectiveness has increased substantially in recent decades, encompassing anecdotal evidence, experiments, and modeling. This section updates the current understanding of how firebreaks mitigate wildfire risk, excluding studies that focus only on post-treatment fuel loading or fuel structures without fire behavior data. Because any non-fuel areas can be served as firebreaks (Ascoli et al. 2020), we included not only studies explicitly addressing firebreaks, but also those evaluating the effectiveness of water, forest roads, and other artificial non-fuels where fuels have been completely removed (e.g., Aparício et al. 2022) in mitigating wildfires.

Drivers for firebreak failure

Observations of historical fires serve as a benchmark for assessing firebreak efficacy and factors at both plot and regional scales. Key variables, such as firebreak density, width, type, and prevailing fire weather conditions, have been found to significantly affect effectiveness (Wilson 1988; Price et al. 2007; Syphard et al. 2011b; McKinney et al. 2022). Wider firebreaks are generally more effective at limiting fire spread by reducing adjacent fuel continuity (Agee and Skinner 2005). For example, in the tropical savannas of northern Australia, wider stream corridors proved more effective than roads or other non-fuel types at halting fires (Price et al. 2007; Fisher et al. 2022). In WUI areas, studies in central Washington have shown that denser road networks reduce fuel loading and connectivity, slowing fire spread and reducing burned area (Narayanaraj and Wimberly 2013).

Under extreme fire weather conditions, post-fire investigations have shown that firebreaks are often breached (Price et al. 2007; Fisher et al. 2022). In western Arnhem Land, Northern Territory of Australia, for instance, approximately 73% of wildfires between 1998 and 2001 fully or partially breached firebreaks (Price et al. 2007). Such breaches have also been reported in Canada (Hassan et al. 2021; Jain et al. 2024), the USA (Syphard et al. 2011a; Gannon et al. 2023), and Spain (Ortega et al. 2024).

Some studies attempted to evaluate the effectiveness of firebreaks using a broader suite of factors, including fire behavior and suppression conditions (Table 2). In southern California, Syphard et al. (2011b) used historical wildfire data from 1980 to 2007 to identify key factors influencing firebreak performance in limiting large fire spread. They found that firefighting activities, fire weather, and firebreak maintenance were consistently important, but also noted that these regional statistical models did not generalize well to other geographic areas. A follow-up study in the same region analyzed wildfires between 2017 and 2020 and reported that firebreaks successfully stopped only 28% of large fires (>200 ha), with outcomes largely influenced by suppression, fire intensity, and weather conditions (Gannon et al. 2023). Comparable findings have been reported in the sagebrush biome of the western U.S. (Weise et al. 2023) and in southern Spain (Ortega et al. 2024), where statistical models indicated that suppression capacity and fire behavior were the primary drivers of firebreak success.

Overall, the effectiveness of firebreaks is influenced by a complex interplay of design attributes (e.g., width, density, and type), environmental conditions (e.g., fire weather and fuel moisture), and operational factors. While firebreaks can slow or halt fire spread under moderate conditions, their reliability diminishes under

Table 2 Empirical studies and modeling approaches evaluating firebreak effectiveness. This table highlights recent studies that used empirical data and/or statistical modeling to evaluate the effectiveness of firebreaks. Each study identifies key environmental, fire behavioral, or management factors influencing firebreak performance in different ecosystems and geographic regions

Authors	Year	Study area	Contribution
Syphard et al.	2011	Southern California	Identified key factors affecting firebreak effectiveness in controlling large fires, including fire-fighting activities, fire weather, and maintenance
Gannon et al.	2023	Southern California	Used statistical models incorporating suppression, fire behavior, weather, topography, and fire-break characteristics to evaluate effectiveness
Weise et al.	2023	Sagebrush biome, Western U.S.	Found that firebreak effectiveness was influenced by fuel types, topography, and seasonally hot, dry conditions
Ortega et al.	2024	Southern Spain	Developed predictive models based on suppression, fire behavior, weather, topography, and firebreak features to assess potential effectiveness

extreme fire weather, when breaches become more likely. Empirical studies highlight the need to move beyond static design prescriptions and instead account for dynamic variables, including suppression capacity and real-time fire behavior. Statistical and process-based modeling, when grounded in historical fire data, can improve understanding of these interactions and help inform adaptive strategies. Ultimately, firebreak performance must be evaluated not only by their physical presence, but also by their role within a broader landscape of fire management practices.

Firebreak effectiveness assessment based on process-based models

To quantify firebreak effectiveness and support wildfire management from fire behavior perspectives, most studies have employed process-based burn probability (BP) models and scenario analysis (Suffling et al. 2008; Zong et al. 2021; Carrasco et al. 2023; Yemshanov et al. 2025) (Fig. 1). These models simulate wildfires ignition and spread across heterogeneous landscapes, often incorporating simplified representations of spotting processes and firebreak breaching rules (Finney 1998; Tymstra et al. 2010). For example, the Prometheus fire growth model used in the Burn-P3 system determines firebreak breaches based on the relationship between firebreak width and simulated flame length (Alexander 2006; Tymstra et al. 2010). A firebreak is considered breached if its width is narrower than the simulated flame length. Using this approach, a study in northeast China (Zong et al. 2021) found that increasing firebreak density and width significantly reduced burn probability, particularly in high-risk areas.

Evaluations of firebreak effectiveness have also extended to fire-related losses and risk mitigation (Carrasco et al. 2023; Zong et al. 2024), and optimization of firebreak configurations for management outcomes (Mollocana-Lara et al. 2025; Murray et al. 2025; Yemshanov et al. 2025). Mollocana-Lara et al. (2025), for example, found that implementing firebreaks based on major fire paths and connect with other barriers offered greater protection than construction in remote wildlands.

Few studies have assessed firebreak effectiveness at the national scale. An evaluation in Portugal demonstrated the potential of a national firebreak network (FBN) to support fire management goals (Aparício et al. 2022). Full implementation of the FBN, which cost between €550 and €21,000 per km, was projected to reduce large fire (> 500 ha) occurrences by 13%, cut suppression costs by €11 million annually, lower residential losses by 8%, and reduce burned area within protected zones by 14%. However, simulations also indicated that over 35% of large fires would still breach the planned FBN, highlighting potential gaps in early-stage containment capacity.

Several simulations also caution that firebreaks alone may be insufficient to halt intense wildfires under extreme fire weather (Penman et al. 2013), as breach rates increase with fire weather severity (Zong et al. 2024). Nevertheless, there is a broad scientific agreement that wider firebreaks, particularly those strategically placed, can improve effectiveness across diverse environments (Syphard et al. 2011a; Fisher et al. 2022; Gannon et al. 2023). However, many fire simulation models lack robust spotting mechanisms, which can lead to overestimations of firebreak effectiveness (Wang et al. 2024). Importantly, extensive interventions may also have unintended consequences. Overly wide firebreaks can lead to drier, windier conditions and increase the availability of fine fuels, thereby intensifying fire behavior (Millikin et al. 2024). For example, in Alberta's black spruce (*Picea mariana*) forests, simulations showed that firebreaks reduced wind drag relative to untreated stands, resulting in higher near-surface wind speeds and faster fire spread through surface and canopy fuels (Beverly et al. 2020; Marshall et al. 2020).

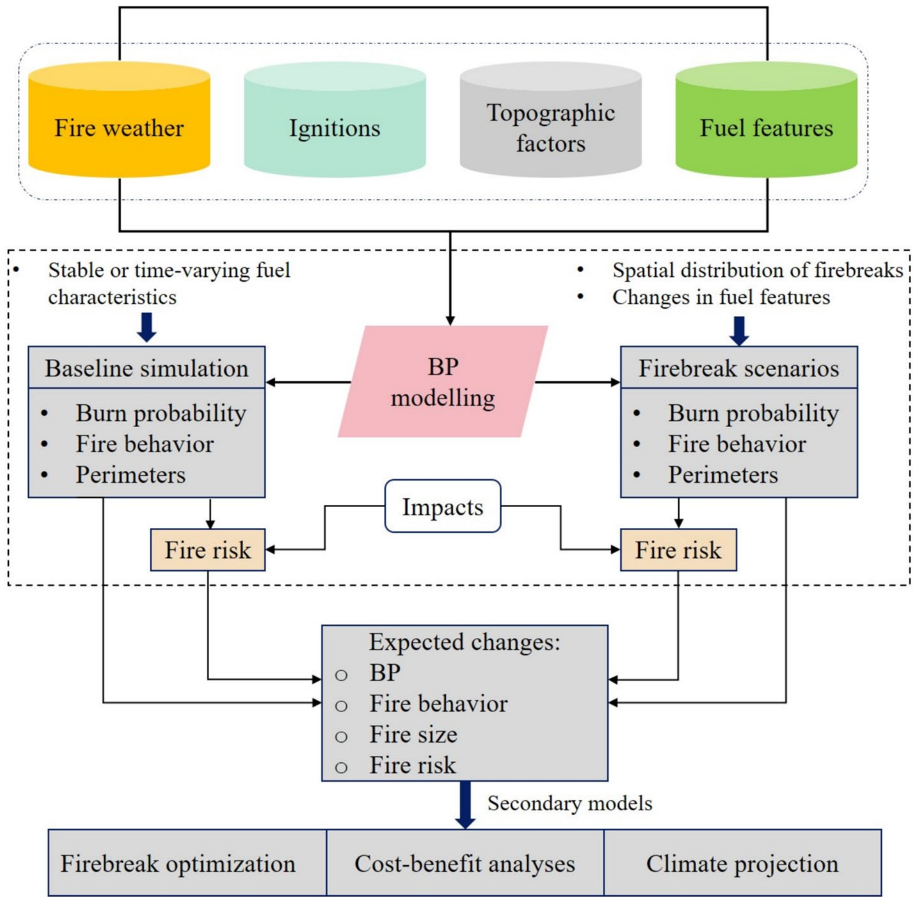

Fig. 1 Conceptual framework illustrating how burn probability (BP) models can be used to evaluate firebreak effectiveness at landscape scales

Spotting: the primary mechanism of firebreak failure

Spotting—the lofting and transport of burning plant material (firebrands) by strong convection columns—is the primary pathway through which wildfires breach firebreaks (Koo et al. 2010; Wadhwani et al. 2022; Martin and Hillen 2016). Firebrands can travel downwind, land on receptive fuels, and ignite new fires, allowing wildfires to bypass fuel gaps and continue spreading (Fig. 2). This process involves three interrelated stages: generation, transport, and ignition.

Firebrand generation is influenced by vegetation type, fuel moisture and structure, fire intensity, and wind speed (Suzuki and Manzello 2016; Caton-Kerr et al. 2019; Adusumilli et al. 2021). Certain species, such as Douglas-fir (*Pseudotsuga menziesii*) and grand fir (*Abies grandis*), produce more firebrands due to needle structure and resin content (Hudson et al. 2020), while shrubs like sagebrush (*Artemisia* spp.) generate large numbers of hot firebrands relative to dry mass when compared to ponderosa pine (*Pinus ponderosa*) (Adusumilli et al. 2021). Taller trees and drier fuels increase production, and stronger winds and higher heat release rates produce more numerous, hotter, and longer-traveling firebrands (Manzello et al. 2012a; Tohidi et al. 2015; Fernandez-Pello 2017; Adusumilli et al. 2021).

Once lofted, firebrand transport is governed by aerodynamic forces, thermal properties, and wind dynamics (Fernandez-Pello 2017; Wadhwani et al. 2022). Distance depends on mass, shape, terminal velocity, and wind structure. Smaller, lighter firebrands can travel long distances under extreme fire weather conditions, often exceeding typical firebreak widths, reducing barrier effectiveness (Pereira et al. 2015). For instance, average spotting distances in southeastern Australia were 0.9 km between 2002 and 2018, with extremes up to 13.9 km (Storey et al. 2020). During the 2017 fire season in the Northern Rockies, USA, the maximum spotting distances reached 2.7 km (Page et al. 2019).

Predicting the maximum spotting distance is therefore crucial for determining the effective width of firebreaks. Many empirical and mathematical models have been developed by incorporating key parameters including wind field, firebrand dynamics, combustion behavior, and flow structures around the fire. However,

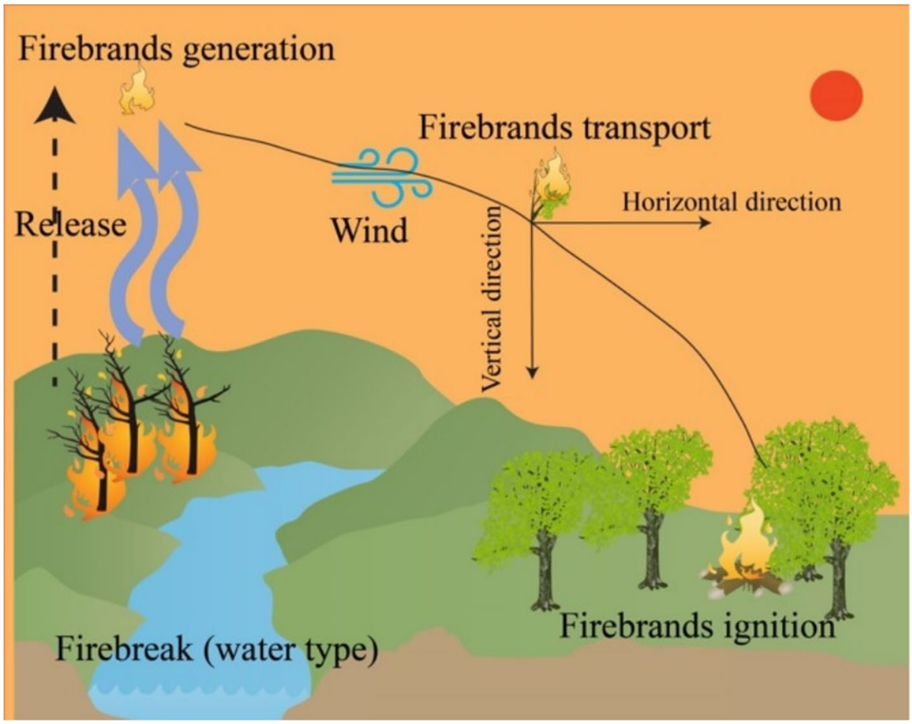

Fig. 2 Conceptual diagram of spotting and firebreak breaching based on the Okanagan Lake breaching event during Canada's 2023 wildfire season (Jain et al. 2024) generalized to represent a typical process

most are based on low- to moderate-intensity events and lack calibration from observations of high-intensity wildfires (Storey et al. 2020). For example, Page et al. (2019) found that Albini's (1979) model consistently underestimated observed spotting distances in the Northern Rockies during the 2017 fire season by an average of 186 m. This underscores a pressing management challenge: firebrands can traverse firebreaks over considerable distances, a process not well captured by current modeling tools.

Ultimately, firebreaks are most vulnerable when firebrand generation, transport, and ignition align under a combination of very favorable conditions. Dry fuels, tall or resin-rich vegetation, strong winds, and intense fires increase firebrand numbers and energy, raising the chance they cross barriers (Ganteaume et al. 2009; Wang et al. 2016). Wildland-urban interface surfaces such as mulch, rooftops, and decks are also vulnerable. High winds, low humidity, and steep slopes increase ignition potential (Manzello et al. 2012a, b; Suzuki and Manzello 2016; Song et al. 2017; Storey et al. 2021). Together, these factors highlight that firebreaks are less effective whenever firebrand production is high, transport distances are long, and environmental conditions favor ignition, emphasizing the need to consider spotting dynamics in fire management.

Key challenges in assessing firebreak effectiveness and future research directions

Our review of the literature on firebreaks and their role in wildfire mitigation highlights several critical knowledge gaps across physical processes, modeling approaches, and effectiveness evaluations.

Statistical analyses of historical wildfire data have identified factors influencing firebreak effectiveness (Syphard et al. 2011b; Fisher et al. 2022; Gannon et al. 2023; Weise et al. 2023; Ortega et al. 2024), but these studies are typically confined to local scales or individual case studies. There is also a need for more completeness and consistent records of firebreak breaching events, to improve model performance and real-world scenarios.

To date, no spatially explicit models currently exist to assist fire managers in predicting firebreak breaches across landscapes. Although recent studies have developed empirical models to evaluate firebreak effectiveness (Syphard et al. 2011b; Gannon et al. 2023; Weise et al. 2023; Ortega et al. 2024), these models have limited practical applicability. They rely on predictor variables that do not fully reflect real-time field conditions associated with fire spread, and some metrics such as burned area or fire intensity remain difficult to obtain due to the lack of reliable, safe-distance fire behavior monitoring equipment (Filkov et al. 2018). Furthermore, the drivers of firebreak effectiveness at broader spatial scales remain highly variable and uncertain due to heterogeneity in fuels, topography, weather, spatial patterns, treatment designs, and fire behavior (McKinney et al. 2022). Further research into the drivers of firebreak failure is therefore a priority for future studies.

Firebrand transport models are primarily developed using data from experimental burns (Albini et al. 2012; Pereira et al. 2015; Martin and Hillen 2016; Page et al. 2019; Storey et al. 2020), which do not fully capture real-world complexity, including variable fire weather, topography, and firebreak characteristics. Key drivers of long-distance spotting, such as highly convective plumes or large aerodynamic firebrands under extreme conditions, are often excluded from these models for practical and safety reasons (Page et al. 2019; Storey et al. 2020; Wadhwani et al. 2022). Currently, no study has clearly identified the conditions that facilitate spotting and lead to firebreak failure.

Although recent simulations focus on changes in overall fire likelihood and risk under different firebreak scenarios, they often lack detail on the specific conditions under which fires are successfully contained. Moreover, the effectiveness of different firebreak types varies (Price et al. 2007; Fisher et al. 2022), yet these distinctions are seldom incorporated into the fire growth model (e.g., Tymstra et al. 2010).

Understanding spotting is critical for assessing firebreak effectiveness, but challenges remain due to difficulties observing spotting processes, inadequately representing extreme fire behaviors, and the complexity of incorporating firebreaks into experimental burns. Given documented firebreak breaches and their impacts on ecosystems and infrastructure, there is a pressing need for reliable predictive methods. From the perspective of fire suppression, identifying firebreak breaches after a fire event (e.g., Syphard et al. 2011b; Gannon et al. 2023; Weise et al. 2023; Ortega et al. 2024) is far less important than predicting such a breach in advance. Identifying conditions that increase the likelihood of breaches is essential for developing robust, scalable, and practical models. Such models can inform strategic decisions on the placement, design, and management of firebreaks, ultimately enhancing their effectiveness in mitigating wildfire spread.

Conclusion

Firebreaks are widely used to reduce wildfire spread and impacts, but their effectiveness is shaped by a complex interplay of environmental, structural, and operational factors. Our review highlights that, while firebreaks can be effective under certain conditions—particularly when strategically placed or combined with suppression efforts—they are often breached during extreme fire weather, raising concerns about their reliability.

Modeling approaches, including burn probability simulations and empirical statistical models, have improved our ability to evaluate firebreak performance at landscape scales. However, many existing models simplify or omit critical processes such as long-distance spotting, limiting their predictive accuracy. Experimental studies often fail to capture real-world variability, and post-fire assessments remain constrained by scale, scope, and data quality.

A key challenge is the development of predictive tools capable of anticipating firebreak breaches under diverse fire conditions. Achieving this will require better integration of empirical fire behavior data, improved representation of spotting processes in simulations, and consistent documentation of firebreak performance during wildfires. Advances in remote sensing and high-resolution fire monitoring offer promising avenues to address some of these limitations.

To enhance the utility of firebreaks in wildfire risk mitigation, future research should focus on (1) developing spatially explicit models that account for fire weather, fuel continuity, terrain, and fire suppression efforts; (2) expanding databases on firebreak breaches with georeferenced, standardized observations; and (3) investigating the ecological and social trade-offs associated with firebreak construction and maintenance.

Ultimately, firebreaks should be viewed as one component of a broader, adaptive fire management strategy that also includes fuel reduction, community preparedness, and land-use planning. Recognizing and addressing their limitations is essential for maximizing their effectiveness in increasing landscape resilience to wildfire.

Authors' contributions
XZZ: conceptualization, literature collection and review, and writing the manuscript. XLW: conceptualization, supervision, reviewing and editing the manuscript. SCPC: literature collection, writing and reviewing the manuscript. MDF: conceptualization, supervision, coordination of project and funding, reviewing and editing the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
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References

Adusumilli, S., J. E. Chaplen, and D. L. Blunck. 2021. Firebrand generation rates at the source for trees and a shrub. *Frontiers in Mechanical Engineering* 7 : 655593. https://doi.org/10.3389/fmech.2021.655593.

Agee, J., K., and C. Skinner N. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211: 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Akbarimehr, M., S. A. Hosseini, F. Shariati, and S. M. Hodjati. 2016. Impact of season and road on stream crossings and river water quality in Darabkola, hyrcanian forest. *Water Resources* 43:369–376. https://doi.org/10.1134/S009780781602007X.

Albini, F.A. 1979. Spot fire distance from burning trees: a predictive model[M]. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Albini, F., A., M. Alexander E., and M. Cruz G. 2012. A mathematical model for predicting the maximum potential spotting distance from a crown fire. *International Journal of Wildland Fire* 21: 609–627. https://doi.org/10.1071/WF11020.

Alexander, ME. 2006. Models for predicting crown fire behavior-a review. *V short course on fire behaviour modelling; association for the development of industrial aerodynamics*. pp. 173–255. Coimbra, Portugal: Forest Fire Research Centre.

Aparício, B., A., F. Alcasena, A. Ager, W. Chung, J.M.C. Pereira, and A.C.L. Sá. 2022. Evaluating priority locations and potential benefits for building a nation-wide fuel break network in Portugal. *Journal of Environmental Management* 320: 115920. https://doi.org/10.1016/j.jenvman.2022.115920.

Arjmand, A., H. Kiadaliri, F. Kazemnezhad, and M. Eshagh Nimvari. 2023. Effects of forest roads on vegetation biodiversity and soil characteristics in Hyrcanian forests. *Nordic Journal of Botany* 2023 : e04039. https://doi.org/10.1111/njb.04039.

Ascoli, D., L. Russo, F. Giannino, C. Siettos, and F. Moreira. 2020. Firebreak and Fuelbreak. In *"Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires.,"* ed. S.L. Manzello, 444–452. Cham: Springer International Publishing.

Beverly, J., L., S.E.R. Leverkus, H. Cameron, and D. Schroeder. 2020. Stand-level fuel reduction treatments and fire behaviour in Canadian boreal conifer forests. *Fire* 3: 35. https://doi.org/10.3390/fire3030035.

Carrasco, J., R. Mahaluf, F. Lisón, C. Pais, A. Miranda, F. de la Barra, and A. Weintraub. 2023. A firebreak placement model for optimizing biodiversity protection at landscape scale. *Journal of Environmental Management* 342: 118087. https://doi.org/10.1016/j.jenvman.2023.118087.

Caton-Kerr, S.E., A. Tohidi, and M.J. Gollner. 2019. Firebrand generation from thermally-degraded cylindrical wooden dowels. *Frontiers in Mechanical Engineering* 5: 32. https://doi.org/10.3389/fmech.2019.00032.

Christianson, A, K., MT, and L'Hirondelle, L. 2012. Community support for wildfire mitigation at Peavine Métis Settlement, Alberta, Canada. *Environmental Hazards* 11: 177–193. https://doi.org/10.1080/17477891.2011.649710.

Chung, W. 2015. Optimizing fuel treatments to reduce wildland fire risk. *Current Forestry Reports* 1:44–51. https://doi.org/10.1007/s40725-015-0005-9.

Chung, W., G. Jones, K. Krueger, J. Bramel, and M. Contreras. 2013. Optimising fuel treatments over time and space. *International Journal of Wildland Fire* 22:1118–1133. https://doi.org/10.1071/WF12138.

Clark, P.E., B.A. Porter, M. Pellant, K. Dyer, and T.P. Norton. 2023. Evaluating the efficacy of targeted cattle grazing for fuel break creation and maintenance. *Rangeland Ecology & Management* 89: 69–86. https://doi.org/10.1016/j.rama.2023.02.005.

Cunningham, C.X., G.J. Williamson, and D.M.J.S. Bowman. 2024. Increasing frequency and intensity of the most extreme wildfires on Earth. *Nature Ecology & Evolution* 8: 1420–1425. https://doi.org/10.1038/s41559-024-02452-2.

Dennis, C. 2003. Burning issues. *Nature* 421:204–206. https://doi.org/10.1038/421204a.

Dove, N.C., H.D. Safford, G.N. Bohlman, B.L. Estes, and S.C. Hart. 2020. High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. *Ecological Applications* 30: e02072. https://doi.org/10.1002/eap.2072.

Ellsworth, L.M., B.A. Newingham, S.E. Shaff, C.L. Williams, E.K. Strand, M. Reeves, D.A. Pyke, E.W. Schupp, and J.C. Chambers. 2022. Fuel reduction treatments reduce modeled fire intensity in the sagebrush steppe. *Ecosphere* 13: e4064. https://doi.org/10.1002/ecs2.4064.

European fire protection associations. 2016. Fire protection in offices-CFPA-E Guideline No 16: 2016 F. https://cfpa-e.eu/app/uploads/2022/04/CFPA_E_Guideline_No_16_2016_F.pdf

Faivre, N., C. Boudreault, S. Renard, N.J. Fenton, S. Gauthier, and Y. Bergeron. 2016. Prescribed burning of harvested boreal black spruce forests in eastern Canada: Effect on understory vegetation. *Canadian Journal of Forest Research* 46: 876–884. https://doi.org/10.1139/cjfr-2015-0439.

Fenesi, A., S. Saura-Mas, R.R. Blank, A. Kozma, B.-M. Lózer, and E. Ruprecht. 2017. Enhanced fire-related traits may contribute to the invasiveness of downy brome (*Bromus tectorum*). *Invasive Plant Science and Management* 9: 182–194. https://doi.org/10.1614/IPSM-D-16-00006.1.

Fernandez-Pello, A.C. 2017. Wildland fire spot ignition by sparks and firebrands. *Fire Safety Journal* 91: 2–10. https://doi.org/10.1016/j.firesaf.2017.04.040.

Filkov, A.I., T.J. Duff, and T.D. Penman. 2018. Improving fire behaviour data obtained from wildfires. *Forests* 9: 81. https://doi.org/10.3390/f9020081.

Finney, M., A. 1998. FARSITE: Fire area simulator – model development and evaluation. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-4,

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* 47: 219–228. https://doi.org/10.1093/forestscience/47.2.219.

Fisher, R., B. Lewis, O. Price, and A. Pickford. 2022. Barriers to fire spread in northern Australian tropical savannas, deriving fire edge metrics from long term high-frequency fire histories. *Journal of Environmental Management* 301 : 113864. https://doi.org/10.1016/j.jenvman.2021.113864.

Gannon, B., Y. Wei, E. Belval, J. Young, M. Thompson, C. O'Connor, and C. Dunn. 2023. A quantitative analysis of fuel break effectiveness drivers in Southern California National Forests. *Fire* 6 : 104. https://doi.org/10.3390/fire6030104.

Ganteaume, A., C. Lampin-Maillet, M. Guijarro, C. Hernando, M. Jappiot, T. Fonturbel, P. Pérez-Gorostiaga, and J.A. Vega. 2009. Spot fires: Fuel bed flammability and capability of firebrands to ignite fuel beds. *International Journal of Wildland Fire* 18: 951–969. https://doi.org/10.1071/WF07111.

Ganteaume, A., B. Guillaume, B. Girardin, and F. Guerra. 2023. CFD modelling of WUI fire behaviour in historical fire cases according to different fuel management scenarios. *International Journal of Wildland Fire* 32:363–379. https://doi.org/10.1071/WF22162.

Gundale, M.J., S. Sutherland, and T.H. DeLuca. 2008. Fire, native species, and soil resource interactions influence the spatio-temporal invasion pattern of *Bromus tectorum*. *Ecography* 31: 201–210. https://doi.org/10.1111/j.0906-7590.2008.5303.x.

Hansen, R. 2012. Estimating the amount of water required to extinguish wildfires under different conditions and in various fuel types. *International Journal of Wildland Fire* 21:525–536. https://doi.org/10.1071/WF11022.

Hassan, Q.K., K.R. Rahaman, M.R. Ahmed, and S.M. Hossain. 2021. Examining post-fire perceptions of selected mitigation strategies after the 2016 Horse River Wildland Fire in Alberta, Canada. *Applied Sciences* 11: 10155. https://doi.org/10.3390/app112110155.

Hudson, T.R., R.B. Bray, D.L. Blunck, W. Page, and B. Butler. 2020. Effects of fuel morphology on ember generation characteristics at the tree scale. *International Journal of Wildland Fire* 29: 1042–1051. https://doi.org/10.1071/WF19182.

Jain, P., Q.E. Barber, S.W. Taylor, E. Whitman, D. Castellanos Acuna, Y. Boulanger, R.D. Chavardès, J. Chen, P. Englefield, M. Flannigan, M.P. Girardin, C.C. Hanes, J. Little, K. Morrison, R.S. Skakun, D.K. Thompson, X. Wang, and M.-A. Parisien. 2024. Drivers and impacts of the record-breaking 2023 Wildfire Season in Canada. *Nature Communications* 15: 6764. https://doi.org/10.1038/s41467-024-51154-7.

Juli, G.P., and S. Dylan. 2012. Fire and plant evolution. *The New Phytologist* 193: 301–303. https://doi.org/10.1111/j.1469-8137.2011.04010.x.
Keeley, J.E., J.G. Pausas, P.W. Rundel, W.J. Bond, and R.A. Bradstock. 2011. Fire as an evolutionary pressure shaping plant traits. *Trends in Plant Science* 16: 406–411. https://doi.org/10.1016/j.tplants.2011.04.002.
Koo, E., P. J. Pagni, D. R. Weise, and J. P. Woycheese. 2010. Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire* 19:818–843. https://doi.org/10.1071/WF07119.
Laudon, H., L. Kuglerová, R.A. Sponseller, M. Futter, A. Nordin, K. Bishop, T. Lundmark, G. Egnell, and A.M. Ågren. 2016. The role of biogeochemical hotspots, landscape heterogeneity, and hydrological connectivity for minimizing forestry effects on water quality. *Ambio* 45: 152–162. https://doi.org/10.1007/s13280-015-0751-8.
Lemke, A., I. Kowarik, and M. von der Lippe. 2019. How traffic facilitates population expansion of invasive species along roads: The case of common ragweed in Germany. *Journal of Applied Ecology* 56: 413–422. https://doi.org/10.1111/1365-2664.13287.
Li, Y., D. Tong, S. Ma, X. Zhang, S. Kondragunta, F. Li, and R. Saylor. 2021. Dominance of wildfires impact on air quality exceedances during the 2020 record-breaking wildfire season in the United States. *Geophysical Research Letters* 48 : e2021GL094908. https://doi.org/10.1029/2021GL094908.
Manzello, S.L., S. Suzuki, and Y. Hayashi. 2012a. Enabling the study of structure vulnerabilities to ignition from wind driven firebrand showers: A summary of experimental results. *Fire Safety Journal* 54: 181–196. https://doi.org/10.1016/j.firesaf.2012a.06.012.
Manzello, S.L., S. Suzuki, and Y. Hayashi. 2012b. Exposing siding treatments, walls fitted with eaves, and glazing assemblies to firebrand showers. *Fire Safety Journal* 50: 25–34. https://doi.org/10.1016/j.firesaf.2012b.01.006.
Marshall, G., Thompson, D.K., Anderson, K., Simpson, B., Linn, R., Schroeder, D. 2020. The Impact of Fuel Treatments on Wildfire Behavior in North American Boreal Fuels: A Simulation Study Using FIRETEC. *Fire* 3: 18. https://doi.org/10.3390/fire3020018.
Martin, J., and T. Hillen. 2016. The spotting distribution of wildfires. *Applied Sciences* 6 : 177. https://doi.org/10.3390/app6060177.
McKinney, S.T., I. Abrahamson, T. Jain, and N. Anderson. 2022. A systematic review of empirical evidence for landscape-level fuel treatment effectiveness. *Fire Ecology* 18: 21. https://doi.org/10.1186/s42408-022-00146-3.
Millikin, R.L., W.J. Braun, M.E. Alexander, and S. Fani. 2024. The impact of fuel thinning on the microclimate in coastal rainforest stands of southwestern British Columbia, Canada. *Fire* 7: 285. https://doi.org/10.3390/fire7080285.
Mistry, J., B.A. Bilbao, and A. Berardi. 2016. Community owned solutions for fire management in tropical ecosystems: Case studies from Indigenous communities of South America. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371: 20150174. https://doi.org/10.1098/rstb.2015.0174.
Mollocana-Lara, J.G., K.J. Obando-Proaño, and B.G. Córdova-Luspa. 2025. Wildfire mitigation and evaluation of firebreaks through FlamMap simulations in high-susceptibility areas of the Metropolitan District of Quito. *Fire* 8: 189. https://doi.org/10.3390/fire8050189.
Murray, L., T. Castillo, I.M. de Diego, R. Weber, J.R. Gonzalez-Olabarria, J. Garcia-Gonzalo, and J. Carrasco-Barra. 2025. Deep reinforcement learning for optimal firebreak placement in forest fire prevention. *Applied Soft Computing* 175: 113043. https://doi.org/10.1016/j.asoc.2025.113043.
Narayanaraj, G., and M. C. Wimberly. 2011. Influences of forest roads on the spatial pattern of wildfire boundaries. *International Journal of Wildland Fire* 20:792–803. https://doi.org/10.1071/WF10032.
Narayanaraj, G., and M. C. Wimberly. 2012. Influences of forest roads on the spatial patterns of human- and lightning-caused wildfire ignitions. *Applied Geography* 32:878–888. https://doi.org/10.1016/j.apgeog.2011.09.004.
Narayanaraj, G., and M. C. Wimberly. 2013. Influences of forest roads and their edge effects on the spatial pattern of burn severity. *International Journal of Applied Earth Observation and Geoinformation* 23:62–70. https://doi.org/10.1016/j.jag.2012.12.006.
National Forestry and Grassland Administration. 2016. National Forest Fire Prevention Plan (2016) for 2016–2025. https://faolex.fao.org/docs/pdf/chn184464.pdf.
Natural Resources Conservation Service. 2021. Conservation Practice Standard: Firebreak (Code 394). https://efotg.sc.egov.usda.gov/api/CPSFile/15954/394_OK_CPS_Firebreak_2012.
O'Reilly-Nugent, A., R. Palit, A. Lopez-Aldana, M. Medina-Romero, E. Wandrag, and R.P. Duncan. 2016. Landscape effects on the spread of invasive species. *Current Landscape Ecology Reports* 1: 107–114. https://doi.org/10.1007/s40823-016-0012-y.
Ortega, M., F.R.Y. Silva, and J.R. Molina. 2024. Modeling fuel break effectiveness in southern Spain wildfires. *Fire Ecology* 20: 40. https://doi.org/10.1186/s42408-024-00270-2.
Page, W.G., N.S. Wagenbrenner, B.W. Butler, and D.L. Blunck. 2019. An analysis of spotting distances during the 2017 fire season in the Northern Rockies, USA. *Canadian Journal of Forest Research* 49: 317–325. https://doi.org/10.1139/cjfr-2018-0094.
Pardini, A., F. Natali, and R. Tallarico. 2007. Horse grazing in firebreaks sown with *Trifolium brachycalycinum* (Katznl. & Morley) and *Cynodon dactylon* (L.) Pers. *Agroforestry Systems* 70: 17–24. https://doi.org/10.1007/s10457-007-9033-1.
Partners in Protection. 2003. *FireSmart: Protecting Your Community from Wildfire*. 2nd ed. Edmonton, AB, Canada: Partners in Protection.
Penman, T.D., L. Collins, O.F. Price, R.A. Bradstock, S. Metcalf, and D.M.O. Chong. 2013. Examining the relative effects of fire weather, suppression and fuel treatment on fire behaviour – A simulation study. *Journal of Environmental Management* 131: 325–333. https://doi.org/10.1016/j.jenvman.2013.10.007.
Pereira, J. C. F., J. M. C. Pereira, A. L. A. Leite, and D. M. S. Albuquerque. 2015. Calculation of spotting particles maximum distance in Idealised Forest Fire Scenarios. *Journal of Combustion* 2015 : 513576. https://doi.org/10.1155/2015/513576.
Pollet, J., and P. N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* 11:1–10. https://doi.org/10.1071/WF01045.
Price, O.F., A.C. Edwards, and J. Russell-Smith. 2007. Efficacy of permanent firebreaks and aerial prescribed burning in western Arnhem Land, Northern Territory, Australia. *International Journal of Wildland Fire* 16: 295–307. https://doi.org/10.1071/WF06039.
Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, M. North, S.A. Parks, H.D. Safford, J.T. Stevens, L.L. Yocom, D.J. Churchill, R.W. Gray, D.W. Huffman, F.K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31: e02433. https://doi.org/10.1002/eap.2433.
Reinhardt, E.D., R.E. Keane, D.E. Calkin, and J.D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management* 256: 1997–2006. https://doi.org/10.1016/j.foreco.2008.09.016.
Rodrigues, M., À. Cunill Camprubí, R. Balaguer-Romano, C.J. Coco Megía, F. Castañares, J. Ruffault, P.M. Fernandes, and V. de Resco Dios. 2023. Drivers and implications of the extreme 2022 wildfire season in Southwest Europe. *Science of the Total Environment* 859: 160320. https://doi.org/10.1016/j.scitotenv.2022.160320.
Salis, M., M. Laconi, A.A. Ager, F.J. Alcasena, B. Arca, O. Lozano, and D. Spano. 2016. Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area. *Forest Ecology and Management* 368: 207–221. https://doi.org/10.1016/j.foreco.2016.03.009.
Schlesinger, W.H., M.C. Dietze, R.B. Jackson, R.P. Phillips, C.C. Rhoades, L.E. Rustad, and J.M. Vose. 2016. Forest biogeochemistry in response to drought. *Global Change Biology* 22: 2318–2328. https://doi.org/10.1111/gcb.13105.
Schoennagel, T., C.R. Nelson, D.M. Theobald, G.C. Carnwath, and T.B. Chapman. 2009. Implementation of National Fire Plan treatments near the wildland–urban interface in the western United States. *Proceedings of the National Academy of Sciences* 106: 10706–10711. https://doi.org/10.1073/pnas.0900991106.
Senande-Rivera, M., D. Insua-Costa, and G. Miguez-Macho. 2022. Spatial and temporal expansion of global wildland fire activity in response to climate change. *Nature Communications* 13: 1208. https://doi.org/10.1038/s41467-022-28835-2.
Shinneman, D.J., M.J. Germino, D.S. Pilliod, C.L. Aldridge, N.M. Vaillant, and P.S. Coates. 2019. The ecological uncertainty of wildfire fuel breaks:

Examples from the sagebrush steppe. *Frontiers in Ecology and the Environment* 17: 279–288. https://doi.org/10.1002/fee.2045.
Shire of Augusta Margaret River. 2025. Bushfire Information and Firebreak Guide 2025-26. https://www.amrshire.wa.gov.au/residents-community/fire-and-emergency-management/firebreak-notice-and-requirements.
Song, J., X. Huang, N. Liu, H. Li, and L. Zhang. 2017. The wind effect on the transport and burning of firebrands. *Fire Technology* 53:1555–1568. https://doi.org/10.1007/s10694-017-0647-1.
Storey, M.A., O.F. Price, J.J. Sharples, and R.A. Bradstock. 2020. Drivers of long-distance spotting during wildfires in south-eastern Australia. *International Journal of Wildland Fire* 29: 459–472. https://doi.org/10.1071/WF19124.
Storey, M.A., O.F. Price, M. Almeida, C. Ribeiro, R.A. Bradstock, and J.J. Sharples. 2021. Experiments on the influence of spot fire and topography interaction on fire rate of spread. *PLoS One* 16: e0245132. https://doi.org/10.1371/journal.pone.0245132.
Suárez-Esteban, A., M. Delibes, and J.M. Fedriani. 2013. Barriers or corridors? The overlooked role of unpaved roads in endozoochorous seed dispersal. *Journal of Applied Ecology* 50: 767–774. https://doi.org/10.1111/1365-2664.12080.
Suffling, R., A. Grant, and R. Feick. 2008. Modeling prescribed burns to serve as regional firebreaks to allow wildfire activity in protected areas. *Forest Ecology and Management* 256:1815–1824. https://doi.org/10.1016/j.foreco.2008.06.043.
Suzuki, S., and S.L. Manzello. 2016. Firebrand production from building components fitted with siding treatments. *Fire Safety Journal* 80: 64–70. https://doi.org/10.1016/j.firesaf.2016.01.004.
Swain, D.L., J.T. Abatzoglou, C. Kolden, K. Shive, D.A. Kalashnikov, D. Singh, and E. Smith. 2023. Climate change is narrowing and shifting prescribed fire windows in western United States. *Communications Earth & Environment* 4: 340. https://doi.org/10.1038/s43247-023-00993-1.
Syphard, A. D., J. E. Keeley, and T. J. Brennan. 2011a. Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California. *International Journal of Wildland Fire* 20:764–775. https://doi.org/10.1071/WF10065.
Syphard, A. D., J. E. Keeley, and T. J. Brennan. 2011b. Comparing the role of fuel breaks across southern California national forests. *Forest Ecology and Management* 261:2038–2048. https://doi.org/10.1016/j.foreco.2011.02.030.
Thompson, M. P., B. M. Gannon, and M. D. Caggiano. 2021. Forest roads and operational wildfire response planning. *Forests* 12:110. https://doi.org/10.3390/f12020110.
Tohidi, A., N. Kaye, and W. Bridges. 2015. Statistical description of firebrand size and shape distribution from coniferous trees for use in Metropolis Monte Carlo simulations of firebrand flight distance. *Fire Safety Journal* 77:21–35. https://doi.org/10.1016/j.firesaf.2015.07.008.
Tyburski, Ł., and R. Szczygieł. 2023. Rules for the construction of firebreaks along public roads in selected European countries. *Folia Forestalia Polonica* 65:199–209. https://doi.org/10.2478/ffp-2023-0020.
Tymstra, C., R.W. Bryce, B.M. Wotton, S.W. Taylor, and O.B. Armitage. 2010. Development and Structure of Prometheus: The Canadian Wildland Fire Growth Simulation Model Natural Resources Canada. Edmonton, AB: Canadian Forest Service, Northern Forestry Centre, Information Report NOR-X-417.
Úbeda, X., and P. Sarricolea. 2016. Wildfires in Chile: A review. *Global and Planetary Change* 146:152–161. https://doi.org/10.1016/j.gloplacha.2016.10.004.
U.S. Department of Agriculture. 2022. Secretary vilsack announces new 10 year strategy to confront the wildfire crisis. https://www.usda.gov/media/press-releases/2022/01/18/secretary-vilsack-announces-new-10-year-strategy-confront-wildfire.
Valor, T., J. R. González-Olabarria, and M. Piqué. 2015. Assessing the impact of prescribed burning on the growth of European pines. *Forest Ecology and Management* 343:101–109. https://doi.org/10.1016/j.foreco.2015.02.002.
van Aardt, A. C., J. C. L. de Jager, and J. J. van Tol. 2024. Firebreaks and their effect on vegetation composition and diversity in grasslands of Golden Gate Highlands National Park, South Africa. *Diversity* 16 : 373. https://doi.org/10.3390/d16070373.
Wadhwani, R., C. Sullivan, A. Wickramasinghe, M. Kyng, N. Khan, and K. Moinuddin. 2022. A review of firebrand studies on generation and transport. *Fire Safety Journal* 134 : 103674. https://doi.org/10.1016/j.firesaf.2022.103674.
Wang, S., X. Huang, H. Chen, and N. Liu. 2016. Interaction between flaming and smouldering in hot-particle ignition of forest fuels and effects of moisture and wind. *International Journal of Wildland Fire* 26:71–81. https://doi.org/10.1071/WF16096.
Wang, X., Swystun, T., McFayden, C.B., et al. 2024. Mapping the distance between fire hazard and disaster for communities in Canadian forests[J]. *Global change biology* 30(3): e17221.
Ward, M., A. I. T. Tulloch, J. Q. Radford, B. A. Williams, A. E. Reside, S. L. Macdonald, H. J. Mayfield, M. Maron, H. P. Possingham, S. J. Vine, J. L. O'Connor, E. J. Massingham, A. C. Greenville, J. C. Z. Woinarski, S. T. Garnett, M. Lintermans, B. C. Scheele, J. Carwardine, D. G. Nimmo, D. B. Lindenmayer, R. M. Kooyman, J. S. Simmonds, L. J. Sonter, and J. E. M. Watson. 2020. Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution* 4:1321–1326. https://doi.org/10.1038/s41559-020-1251-1.
Weise, C.L., B.E. Brussee, P.S. Coates, D.J. Shinneman, M.R. Crist, C.L. Aldridge, and M.A. Ricca. 2023. A retrospective assessment of fuel break effectiveness for containing rangeland wildfires in the sagebrush biome. *Journal of Environmental Management* 341: 117903. https://doi.org/10.1016/j.jenvman.2023.117903.
Wilson, A.A.G. 1988. Width of firebreak that is necessary to stop grass fires: Some field experiments. *Canadian Journal of Forest Research* 18: 682–687. https://doi.org/10.1139/x88-104.
Yemshanov, D., N. Liu, E.W. Neilson, et al. 2025. Evaluating fuelbreak strategies for compartmentalizing a fire-prone forest landscape in Alberta, Canada. *PLoS One* 20 (5): e0321722.
Yu, Y., J. Mao, S.D. Wullschleger, A. Chen, X. Shi, Y. Wang, F.M. Hoffman, Y. Zhang, and E. Pierce. 2022. Machine learning–based observation-constrained projections reveal elevated global socioeconomic risks from wildfire. *Nature Communications* 13: 1250. https://doi.org/10.1038/s41467-022-28853-0.
Zong, X., X. Tian, and X. Wang. 2021. An optimal firebreak design for the boreal forest of China. *Science of the Total Environment* 781 : 146822. https://doi.org/10.1016/j.scitotenv.2021.146822.
Zong, X., X. Tian, and L. Fang. 2022a. Assessing wildfire risk and mitigation strategies in Qipanshan, China. *International Journal of Disaster Risk Reduction* 80: 103237. https://doi.org/10.1016/j.ijdrr.2022a.103237.
Zong, X., X. Tian, Q. Yao, and P.M. Brown. 2022b. An analysis of fatalities from forest fires in China, 1951–2018. *International Journal of Wildland Fire* 31: 507–517. https://doi.org/10.1071/WF21137.
Zong, X., X. Tian, and X. Wang. 2024. The role of fuel treatments in mitigating wildfire risk. *Landscape and Urban Planning* 242: 104957. https://doi.org/10.1016/j.landurbplan.2023.104957.

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