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Review

Refining Ecological Techniques for Forest Fire Prevention and Evaluating Their Diverse Benefits

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Abstract: In this study, an ecological framework was developed to sort out the existing forest fire prevention techniques. The subsequent analysis involved comparing the ecological values and application prospects of these techniques developed in different time periods. As ecological applications, fire regimes reflect vegetation response to wildfires, providing valuable insights for shaping the fire risk and behaviors in forests through fuel treatment and vegetation modification. Fuel treatment and the construction of green fire barriers are both rooted in existing ecosystems and possess ecological characteristics. While fuel thinning focuses on reducing the potential fire intensity and severity, green fire barriers have been more targeted for fire prevention purposes. Among these techniques, green fire barriers demonstrate unique sustainability and have the potential to generate long-term ecological and environmental benefits. Through the comprehensive utilization of several fuel management formulas, we can effectively combine the fire prevention demands with ecological maintenance and environment protection. This integrated approach promotes the development of fire-resilient ecosystems and desirable living environments in a more realistic and sustainable manner.

Keywords: fire regime; fuel treatment; shaded fuelbreak; green fire barrier; ecological fire prevention; fire-resilient ecosystem

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1. Introduction

Forest fire is a common phenomenon across the globe. As a natural hazard, it has profound impacts on human lives and the built environment. Such impacts are evident through the altered state of wildland ecosystems and can be linked to the climate change trends observed in recent decades [1–4]. Fire prevention and management have always been the main focus of forestry workers. Over time, various fire prevention techniques have been developed and utilized to meet the evolving demands of fire management [2,5–10]. Fuel treatment serves as the central theme in this series of innovative techniques, encompassing nonfuel engineering fuelbreaks in earlier times, fuel thinning tactics popularized in the 1960s, and the later adoption of shaded fuelbreaks [2,5,11,12]. In China, starting from the late 1960s, evergreen broad-leaved forest stands with high moisture content in the foliage were densely grown in designed areas, called the construction of green fire barriers. After their construction and maintenance over several "five-year plans", their total length now exceeds one million kilometers across the nation [10,13–16].

Initiated in the early part of last century, forest fire ecology is dedicated to exploring the ecological consequences and related issues of forest fires, with the emphasis placed on understanding the relationships and interactions among forest fires, forest ecosystems, and the environment [17–19]. Following the advancement of forest fire ecology, ecologists have tracked the pattens of fire characteristics and behaviors, return time, and the frequency of occurrence in the forests. The ecological and economic roles of the fire ecological factors have been evaluated [1,20–22]. To date, the concept of fire regimes has been extended to describe fire and its role in the ecosystem, allowing us to coordinate the relationship between fire and the ecological environment [21–23]. For forests with different vegetation distributions and those undergoing certain types of fuel treatment, quantifications were also made to the fire occurrence frequency, burning areas, and intensities, as well as fire severity, highlighting the dynamic nature of forest fire ecology [21,22,24–26].

At present, the technological advancements in forest fire prevention and management exhibit limited integration with research in forest fire ecology and fire regimes [5–10,20–23]. This discrepancy can be attributed to the diverse backgrounds of researchers and the goals set for engineering-based work. Evidently, there is a lack of basic concepts to link the research contents from two distinct disciplines [8–10,20–23]. Understanding the existing fire prevention techniques and their progress from the perspective of ecology and then evaluating their ecological benefits and advantages systematically are impending issues to build upon previous achievements in parallel fields. Combining forest fire management with ecological maintenance directly has the potential to enhance the overall economical, ecological, and social benefits derived from such management activities, leading to a considerable reduction in the costs spent on fire-fighting and the ecological recovery of burnt areas after fire incidents.

The objective of this study is to classify and systematically elucidate forest fire prevention techniques by introducing a conceptual ecological system. The interrelationship between the diversity of vegetation and fire behavior was examined in terms of fire regimes through an extensive literature survey. The ecological features of the fire management measures through fuel treatment were then analyzed, and the ecological nature of green fire barriers and their modifications was also revealed. Establishment of a framework for ecological forest fire prevention techniques allowed for comparisons to be made of the ecological benefits and other consequences arising from the use of these fire protection measures. From the perspective of ecological sustainable development, understanding the mechanism and ecological consequences of different fire prevention techniques can provide a solid foundation for further planning the application scenarios of vegetation communities with different management measures, thus promoting the balance and integration of forest fire management with ecosystem maintenance and sustainable development.

2. Understanding of Fire Regimes as a Guide for Fire Prevention

Plant communities show distinctions in their regional distributions. They are typically sorted into four types of grasslands and six types of forests in general, and a variety of mixed forests are often involved, including coniferous mixed forests, broad-leaved mixed forests, and coniferous broad-leaved mixed forests. Their potential fire behaviors are habitually characterized by fire regime parameters. It is well known that the regions dominated by grass and herbaceous vegetation are more prone to frequent, but low-severity fires [27]. Once the herbaceous layer is dry and continuously distributed, it supports the rapid spread of surface fires. Among the different types of grasslands, meadow steppe can reach the highest fire intensity, followed by typical steppe and desert steppe [28].

Shrub-dominated plant communities are prone to fires due to the dense growth and dry environment [29]. Once a fire is maintained by the burning of a herbaceous layer only, the fire front typically spans 5–8 m. However, if the herbage and the understory burn together, then more intense fire can occur, with the fire front often exceeding 15 m in length. In coniferous forests with loose surface fuels, fires can easily ignite and spread at low to moderate burning intensities. The historical fire interval in coniferous forests ranges widely, from 2 to 23 years [30,31]. Fire occurrence in the northern hemisphere exhibits a clear seasonality pattern, with periods of frequent fire activity predominately observed in spring and autumn [1].

The water content of forest fuels directly affects their proneness to catching fire and subsequently alters the fire spread rate, burning intensity, and potential environmental harm [26]. The surface fuels with water content above 35% are almost nonflammable, and those with water contents between 25% and 35% have low flammability. Fuels with water content ranging from 17% to 25% become flammable, and fuels with moisture contents between 10% and 16% are highly flammable; when the moisture content drops below 10%, fuels become extremely flammable [32]. Newly germinated coniferous leaves can reach water contents of 200–300%, and once the moisture content falls below 100%, crown fires can occur under certain conditions [33]. Environmental humidity has a significant impact on the water content of fuels, especially in fine fuels, which turns to be the primary reason why forest and grassland fires are seldom to occur in perennial humid areas [34,35].

The continuity of vegetation plays an important role in potential fire behavior. Fuel continuity is divided into vertical and horizontal continuity, referring to the continuity of fuel in the vertical and horizontal directions, respectively [5,36]. Better vertical fuel continuity increases the likelihood of surface fires transitioning into crown fires. Horizontal fuel continuity determines the potential for fire spread at the same level [33,37]. Coniferous forests exhibit high continuity to support crown fire spread. By contrast, coniferous broad-leaved mixed forests and broad-leaved forests have low crown continuity, making it difficult for crown fires to propagate. As stated in the literature [38], when the gap between trees exceeds 100 m, crown fire transitions to surface fire, and intermittent crown fires occur when the fuel distribution is intermittent.

Fuel moisture content, load, and spatial distribution of fuels in different forests constitute diverse fire regimes and behaviors at each spatial level, as illustrated in Figure 1. By adjusting the fuel's physical properties, quantities, and distribution patterns, existing vegetation types and structures in forests or grasslands can be maintained in a more sustainable way [22,39–43]. It has been recognized that, the reduction in potential spread rate and burning intensity of wildfires implies lessened fire impact to the local landscapes and the built environment, allowing for positive feedback to the atmospheric circulation that both plants and human beings rely on [22,39].

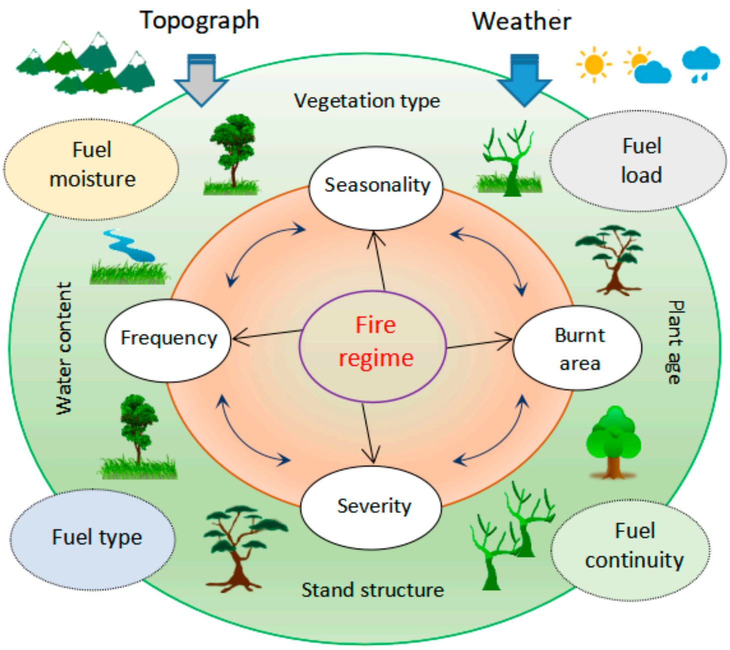

Figure 1. Relationship between the vegetation characteristics and fire regimes.

3. Fuel Treatment as a Fire Prevention and Management Measure

Fuel treatment is a common way to mitigate wildfires in forest areas, and the establishment of nonfuel zones can be regarded as a typical fuel treatment measure in early times. Fire spread is mitigated by simultaneously reducing surface and crown fuels, and the occurrence of destructive active crown fires can be prevented [5,21,33,37,40]. Existing fuel treatment techniques can be classified into three types: prescribed burning, mechanical treatment, and biochemical treatment, as illustrated in Figure 2.

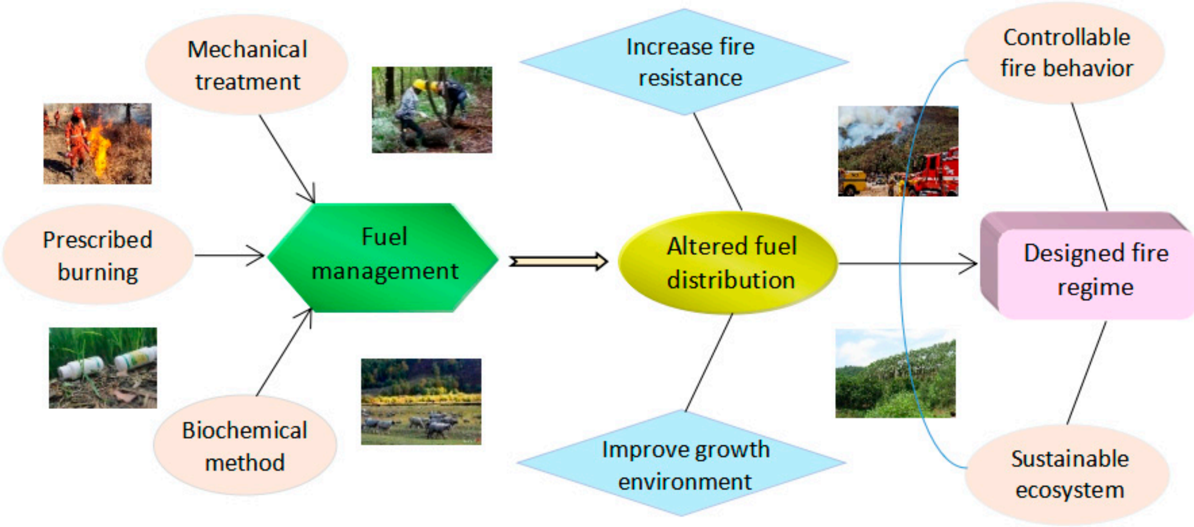

Figure 2. An illustration of fuel treatment methods and their ecological impact.

Prescribed burning involves deliberate fires set in the forest and grassland to reduce the amounts of surface fuels, especially fine ones. In addition to the intentional ones, prescribed burning also includes wildfires under permitted conditions [6,44]. As an ecological process, a prescribed fire can be designed and set at a controlled level to ensure an acceptable environmental impact. Mechanical treatment mainly relies on manual or machine work to remove the fuels in localized forests and grasslands to the desired levels [40]. Biochemical methods involve inhibiting the growth of specific herbs through grazing or the application of chemical herbicides in targeted areas.

An important feature of fuel treatment is to conduct the fuel thinning according to the fuel types and distribution patterns. The creation of shaded fuelbreaks is a representative prescription of forest thinning, which is to basically remove the fine fuels on the ground or change their highly-combustible characteristics within the fuelbreaks, cut the trees with small diameters, retain the trees with fire resistance, and increase the height of the crown base from the ground [2,8,45,46]. Typical indicators for implementation include reducing the surface fuel load below 4.5 t/hm^2, removing trees with small diameters (usually <15 cm), and maintaining crown density by up to 40%. Meanwhile, there is a requirement to maintain crown height above 2 m and crown gaps of >3 m [8,9,45].

Shaded fuelbreaks have proven to be effective in lessening fire severity during wildfires. Field observations of a fire occurring in Washington state demonstrated a substantial shift in fire behavior when high-intensity crown fires encountered fuelbreaks, resulting in the survival of trees within the fuelbreaks [2]. Agee and Skinner [8] also reported a fire in the national forest area of Larsen, CA, USA, in 2002, predominately a *Pinus ponderosa* crown fire, which affected an area of over 800 hm^2. The fire was automatically extinguished in the fuelbreaks after thinning and surface prescribed burning. An on-site photo taken after the fire showed minimal impact on vegetation within the fuelbreaks (Figure 3). Extensive studies have shown that constructing a network of fuelbreaks in high-risk areas, such as residential and important facilities near forested areas, can reduce the frequency of forest fires in the region and prevent the occurrence of large-scale severe fires that are difficult to control [2,8,21,46,47].

Forest thinning can also promote the production of commercial wood and yield greater economic returns. Long-term observations of tree growth within shaded fuelbreaks have revealed positive impacts on forest health and tree output resulting from the removal of weeds, dead trees, and diseased trees [9,48]. As reported by Grah and Long [48], fuelbreaks located in central and northern California, consisting mainly of mixed *P. ponderosa* and *Pinus lambertiana*, along with other coniferous mixed forests, showed 5-year growth rates of 6.5 and 6.6 m^3/hm, respectively, which were 0.9–1.2 m^3/hm higher than the untreated forest area. The 5-year growth of other mixed forests within the fuelbreaks was 7.3 m^3/hm, similar to the untreated forest areas. The annual incomes from the two mixed pine forests within the fuelbreaks reached 6.4% and 4.0%, respectively, surpassing those of the untreated forest area by 1.6% and 1.8% [48].

(**a**) (**b**)

Figure 3. A comparison of the status of *Pinus ponderosa* forests in Laren National Park, California, after the fire in 2002; the left-hand side photo (**a**) reflects serious damage in the untreated areas and the right-hand side photo (**b**) demonstrates that the pine trees in the shaded fuelbreaks were almost untouched during the fire [8].

4. Green Fire Barriers and Their Modifications

Green fire barriers are characterized by the planting of evergreen broad-leaved tree species within flammable plant communities to prevent the spread of surface fires and crown fires. The width of the planted area usually ranges from 15 m to 30 m, with the ultimate goal of achieving a canopy coverage exceeding 90% [13–15]. The selected tree species have lush foliage with high leaf water content, allowing them to retain an ample water supply within the planted stands. Existing studies and on-site observations have shown that the fire protection function of biological fire prevention forest zones originates from the unique canopy structure formed by dense plantations of evergreen broad-leaved trees. Surface fire is alleviated due to the inhibition of the growth of surface fuels in the banded areas, whereas the crown fire is weakened and finally blocked through continuously reducing the heat transfer efficiency within the developed stands [14–16].

Standardized methods exist to identify suitable tree species for constructing green fire barriers with commonly used representative tree species, including *Schima superba Gardn. et Champ*, *Ilex latifolia Thunb*, *Michelia macclurei Dandy*, and *Mytilaria laosensis Lec.* [13,15,49]. Extensive practical experience with the planting of these tree species has shown a survival rate of over 91% and a preservation rate of afforestation reaching higher than 88% after three years. The average tree height after 20 years exceeds 14 m, meeting the criteria for fast-growing tree species [13,50]. Detailed parameters for constructing the green fire barriers can be found in Table 1. The diversity in plant species expands the flexibility of the forest belts to be developed in specific landscapes [10,13,49].

Biological fire prevention forest belts often exhibit compound structures, incorporating a diverse mix of plant species, such as evergreen tree species and evergreen herbs or shrubs located outside or within the designated areas (Figure 4). This diversification expands the effective width of the barriers, enhancing their efficiency in blocking thermal radiation and absorbing burning fuel debris (firebrands) originating from adjacent wildfires [13–15,49]. Similar to shaded fuelbreaks, green fire barriers act as thermal shields, facilitating the access of firefighting teams to the fire site and enabling the organization of fire response activities with greater efficacy (refer to Figure 5). Extensive field surveys have indicated that the widespread use of such management measures in fire-prone areas reduces the occurrence of wildfires and their potential impact on the local environment, and has a moderating effect on local meteorology, including the adjustment of wind patterns to a certain extent [8,13,47].

The cultivation of evergreen broad-leaved trees requires long construction cycles and entails a substantial workload (see Table 1). However, the combination of green fire barriers with shaded fuelbreaks can compensate for these limitations. Given the relative convenience of constructing shaded fuelbreaks, they can be seamlessly integrated into existing biological fire barriers, enhancing their joint capacity to block flame radiation and absorb firebrands from adjacent forest fires [15]. In addition, the fusion of the two major techniques has yielded a variety of cost-effective treatment recipes suitable for landscapes with specific vegetation distributions and varying levels of fire risk [10].

Table 1. General information on the construction and maintenance of green fire barriers [9,10,13,49].

Item	Major option and Practice	Principal Role and Function
Tree species selection	Evergreen broad-leaved tree species featuring luxuriant foliage, high water content, and rapid growth capacity were often adopted; typical species included *Schima superba Gardn. et Champ, llex chinensis Sims, Michelia macclurei Dandy, Camellia Chekiangoleosa Hu, Camellia sinensis*, etc.	The growth habits and dense canopy distribution of evergreen broad-leaved trees made it possible to form unique stands which were identified to be effective in mitigating the spread of surface fires and crown fires.
Plantation	The selected evergreen broad-leaved trees were planted into flammable plant communities in band areas. The row spacing was controlled between 1 and 2 m, and the bandwidth was in the range between 20 and 35 m; the grown canopy density was expected to be higher than 0.7.	Dense plantation and the shadow effect of forest canopy prevented the growth of surface fuels; high water content was retained by the luxuriant foliage.
Typical structure	Mixed forest stands can be developed with evergreen large arbors, small arbors, or shrubs in order to increase the canopy density of the stand and the bandwidth.	Composited structures can increase the canopy density and avoid the growth of flammable vegetation on the stand floor, thus increasing the capacity of the structure to resist external thermal radiation and to absorb firebrands.
Distribution area	Planation is usually located within the high-flammable stands and the junction of forest and farmland. In valley and mountain areas, evergreen tree species are planted along the hillside, with the bandwidth parallel to the usual wind direction.	Green fire barriers can prevent and mitigate surface fire spread from adjacent wildland and residential houses. They are built in the modified form in northern China, owing to the local weather conditions. Wide use in fire-prone areas also brings long-term benefits for the local environment, especially for humidity and wind moderation.
Period for construction and maintenance	Self-maintenance can be expected after 3–5 years of forest fostering, but the surface litters of the stand should be regularly cleaned over the years.	Missing plants need to be replenished in a timely manner, and the surface litters should be removed from time to time to ensure the stability of the fire prevention functions.

The open spaces within shaded fuelbreaks can be used for growing evergreen broad-leaved trees, effectively inhibiting the growth of combustible grasses and herbaceous shrubs, as well as preventing the invasion of species within or outside forest boundaries. There is no doubt that, with the current technical knowledge and expertise, various types of wildfire separation networks can be extensively built in specific forest areas, establishing fire-resilient landscapes and green living environments with tolerable fire risk and negligible fire losses under the usual weather conditions.

Figure 4. Typical layout of green fire barriers with the integration of evergreen big arbor species and a small arbor species. The green belts are located on the ridge of Wuziling, Tianmu Mountain, Zhejiang Province, and the strip with dark green color (labeled by blue star) is a *S. superba* stand, which was built in the late 1980s. This fire separation facility was expanded in recent years by densely growing *Photinia* × *fraseri Dress* in the open space at a width of about 15 m (labeled by a red and green star).

Figure 5. The unique stand of *S. superba* species has not only been used for preventing forest fires due to human faults, but also serves as scenery in Menggutang Cultural Park, Qiandao Lake Town, Chun'an County, Zhejiang Province. Stone steps were built inside the stand as a path for tourists and a passage for firefighters to approach the annex forest in a state of emergency. An evergreen species of grass, *Ophiopogon bodinieri H. Lév.*, was planted along the stone steps (shown in the zoomed-in window). This species contains high water content in all seasons and is able to trap fine surface fuels. Because of its loose structure and high water content, it can effectively prevent fires caused by dropped cigarette butts.

In a monograph of the former State Forestry Administration [13], examples are provided to exhibit the effectiveness in using green fire barriers to block wildfires. On March 28, 2000, a wildfire broke out in Yuchi Village, Youxi County, Sanming City, Fujian Province due to an electric powerline failure. After a sweep of 32 hm^2 of highly-flammable forests, the fire was then blocked by the *Schima superba* stands, avoiding its further spread. The photo taken on site shows that the *Schima superba* forest belt suffered a slight burn at the side facing the fire [13]. As pointed out in another work [10], the effective mitigation of large-scale fire cases in recent decades in China can be somehow attributed to the long-term construction and maintenance of green fire barriers across the nation.

5. Appraisals of Fire Prevention Measures from Ecological Perspectives

Apart from all-removed fuelbreaks and natural fuelbreaks, such as roads and rivers, the remaining fire prevention techniques can be collectively referred to as the development of fire-resilient ecosystems. These techniques involve fuel treatment and the rearrangement of plant distribution structures to create modified fire regimes that favor the mitigation of fire hazards. Conceptually, these techniques can be classified as ecological techniques with two main objectives: reducing forest combustibles and promoting the growth of fire-resistant trees rather than flammable trees [8,10,51,52]. One notable example is the standard green fire barriers and their modified versions, although their ecological effects require long-term observation and testing across different regions and spatial and temporal scales [10,25].

Mechanical treatment involves activities such as pruning dead branches and removing trees to achieve the desired stand density, distribution patterns, and species composition, resulting in a reduction in tree competition. This enhances forest regeneration, as supported by field observations and simulations of tree growth [53]. However, mechanical treatment can generate smoke and pose risks of burning nearby vegetation during operation. In addition, the removal of organic materials leads to a decrease in carbon stocks and nutrient content stored within the stands.

Data obtained from forest harvesting activities indicate that carbon stocks in temperate forests decrease by an average of 30% after treatment, with hardwood forests experiencing higher carbon stock losses (36%) compared with coniferous forests or coniferous broad-leaved mixed forests (20%) [54]. After fuel treatment, increased sunlight exposure and elevated microclimate temperatures within the forest can stimulate microorganism respiration, resulting in reduced litter input and faster decomposition and leading to a loss of carbon stocks in the topsoil. A comprehensive study by James and Harrison [55], focusing on publications between 2008 and 2016, revealed an average soil stock reduction of 11.2% due to forest harvesting. Specifically, the largest loss was observed in the organic layer at 30.2%. Surface soil carbon stocks (0–15 cm) decreased by 3.3% and deep soil (60–100 cm) decreased by 17.7%.

The use of herbicides in biochemical methods can effectively control weed growth and reduce surface fuel loads, thereby decreasing the frequency of fire incidents. The use of herbicides has been increasing year by year to meet the demands of modernized forestry production. However, herbicides are organic pollutants with toxicity, and their long-term use over large areas leads to concerns regarding drug-related issues [56]. Jayasumana et al. [57] investigated the link between a mysterious kidney disease in rural Sri Lanka and glyphosate contamination. Their study found that the overuse of glyphosate, particularly when combined with hard water or toxic elements, such as arsenic and cadmium, can result in the pollution of drinking water sources, leading to severe health problems for local residents. From a land use effectiveness perspective, relying on herbicides to halt vegetation growth in specific areas in the long term is not a sustainable approach and has detrimental effects on local water and soil conservation. The frequent use of glyphosate over large areas negatively impacts the sustainable development of the local ecological environment, owing to its incapacity to coordinate and stabilize the local ecosystem.

Grazing as a fuel management measure has certain constraints. The grazing area and the number of grazing herbivores in a specific grassland need to be carefully planned by considering the seasonal growth of grassland vegetation and the energy, nutrition, and mineral needs of the grazing herbivores [58]. Moderate grazing can effectively remove fine fuels, reduce fuel quantity, and alter the composition and structure of forests. Compared with other fuel management measures, grazing can bring substantial economic profits with minimal pollution to the local ecosystem [59]. However, overgrazing leads to soil desertification, soil erosion, and nutrient loss, which are detrimental to plant growth. Moreover, overgrazing forces plant species to adapt to degraded soil and biological environments, resulting in xeric and salinized conditions [60]. The ecological effects of different fuel management techniques are compared in Table 2, highlighting their diversity and trade-offs.

Prescribed fire is widely used as a tactic to prevent large-scale and high-intensity fires by implementing controlled small-scale fires (Table 2). Using data on fire emissions from previous fires, Wiedinmyer and Hurteau [61] utilized the Regional Fire Emission Model to estimate the reduction in CO_2 emissions resulting from prescribed fires in dry, temperate forest systems in the western United States. Observations from the period between 2001 and 2008 indicated that prescribed fires can reduce CO_2 emissions by 18–25%, and in particular forests, the reduction can be as high as 30%. Additionally, surface burning during prescribed fires can increase the content of nutrients, such as N, P, K, and Mg, facilitating soil amendment [1,5,6]. Through the examination of heat shock and seed germination of 57 species, Luna et al. [62] found that prescribed fires or high summer temperatures, with soil temperatures reaching 80 °C, can promote seed germination. Prescribed fires can also reduce the density of forest insects, improve forest stand conditions, and provide a better habitat for wildlife [38]. However, considerable debate and disagreement still remain regarding the ecological effects of prescribed fires, particularly concerning the potential environmental pollution they may generate and their long-term effects on ecosystems (Table 2). Further research and exploration are needed in the future to gain a more comprehensive understanding of these impacts.

As listed in Table 2, both shaded fuelbreaks and green fire barriers offer multiple benefits, including the protection of the natural ecological environment, promotion of forest health, and increased forest product output. Also, they contribute to the conservation of local soil and water resources [63]. As stated previously, green fire barriers feature complex structures with unique landscape patterns that enhance their benefits for forest landscapes. Furthermore, under the usual weather conditions, these barriers provide long-term advantages, as they can sustain themselves for centuries with minimal maintenance owing to their living plant components [10,13].

Table 2. Comparisons of the ecological and environmental benefits obtained from different techniques.

Item	Ecological Benefit	Environmental Benefit	Sustainability
Prescribed burning	① Promotes the nutrient return and the establishment of the dominant species to enhance the ecosystem's stability; ② Stimulates species which have exhibited resistance to heat to grow, and controls or removes non-native species [62]; ③ Reduces forest insect density [38].	① A large amount of smoke is released during the action, resulting in local air pollution; ② Inconducive to soil and water conservation after long-term practice; ③ Inconducive to local carbon reserves.	① Due to the plants' nature, the prescribed fire needs to be repeated after several years; ② Long-term effects of prescribed burning on ecosystems have been controversial for a rather long time.

Table 2. *Cont.*

Item	Ecological Benefit	Environmental Benefit	Sustainability
Mechanical treatment	① High sunlight exposure and high temperature microclimate in the forest can stimulate microorganism breath and the decomposition of litters, as well as promote the reproduction of trees [53]; ② Economic returns and extension of fire intervals are conducive to the accumulation of commercial wood products.	① Generates smoke to cause air pollution and creates the risk of burning plants nearby; ② Removal of surface organics reduces the amount of carbon storage and nutrient content in the stand, leading to topsoil carbon loss [54].	① Through regularly repeated treatment, the ecosystem can be maintained at the desired fuel distribution status.
Biochemical treatment	① It can effectively protect the forests and maintain the forest ecology; ② The inhibition of herbaceous plants can effectively promote tree growth [56].	① No cumulative pollution problems with short-term use; ② Long-term use may result in drug harm problems and water pollution [57].	① Herbicides have a strong inhibitory effect on surface plants and microorganisms; ② Large-scale use will break the dynamic balance of the ecosystem.
Grazing	① Flammable fine plants and the surface fuel loads are reduced; ② Long-term grazing may alter the forest composition and structure; ③ Less pollution to the ecosystem with more additional economic output to be expected.	① Overgrazing leads to soil desertification and soil erosion; ② Breaks the balance between soil salt accumulation and desalination, and accordingly aggravates soil salinization [60].	① Moderate grazing can establish a dynamic balance between forest and stockbreeding, leading to sustainable development of forest ecology.
Shaded fuelbreak	① Maintains the original ecological environment, promotes forest health and productivity [48]; ② Regulates the local temperature and humidity; ③ Provides landscape benefits and establishes wildlife habitats or corridors.	① Causes certain environmental pollution during implementation either by mechanical or biochemical treatment; ② Conducive to water and soil conservation to a certain extent.	① Because of the creation of an unstable ecosystem, it demands regular maintenance; ② Generation of forest windows results in the invasion of alien plants.
Green fire barrier	① Increases the land utilization rate and forest productivity; ② Promotes additional economic outputs [13]; ③ Regulates the temperature and air humidity within the forest [13]; ④ Generates landscape benefits and establishes wildlife habitats or corridors.	① Conducive to water and soil conservation; ② Improves the nutrition of the surface soil; ③ Provides long-term positive effects on environmental humidity and wind patterns; ④ Conducive to local carbon reserves.	① Automatically establishes a dynamic balance for long-term self-maintenance and sustainable development of the built ecosystems [15].

The combination of green fire barriers with various crops, such as fruits, tea trees, soybeans, herbal medicine, vegetables, and edible fungi, is worthy of mentioning as it has been proven effective [13]. This integration improves landscape utilization and enhances the production of nontimber forest-based products. Successful examples of this practice have been documented in the Chinese forestry sector, as highlighted in a monograph published in 2003 [13]. A holistic approach can be achieved by popularizing green fire barriers in fire-prone areas, encompassing accidental forest fire prevention, forest health promotion, ecological maintenance, and environmental protection (Table 2). This integration of fire management engineering and ecological development maximizes the synergy of ecological, landscape, economic, and social benefits [10]. Figure 6 shows the growth of tea trees (*Camellia sinensis (L.) O. Ktze*) within the originally all-removed fuelbreaks for fire protection along power transmission lines, showcasing attractive features in land use, local water conservation, and additional economic profits.

Figure 6. Evergreen broad-leaved tree species, *Camellia sinensis (L.) O. Ktze.*, densely grew in the band areas along the power transmission line. Located in the Jieshou Forest Farm, Chun'an County, Zhejiang Province, which was a replacement of the previous all-removed fuelbreaks built for preventing fires caused by faulty power lines. The reuse of the open land by planting a fire-resistant species represents the integration of the demand for forest fire prevention with economic output and ecological conservation.

Studying the guidelines for the effective use of fire prevention techniques in fire-prone areas, with a focus on maximizing their ecological benefits, is important in addressing the challenges posed by climate change. With a wide range of fire prevention techniques available, fuel management in specific areas should be evaluated in terms of local fire risks, vegetation types, accessibility, and available fire response resources [2,21,25,46,47]. Additionally, the objectives of fire prevention targets may vary in different areas, and achieving them requires proper technological preparation and practical implementation [5,20,22,25,43,46,64]. By developing a multifaceted management tool, all the essentials can be taken into account, including wildfire management, natural resource protection, and ecological and environmental maintenance (needs). Fuel management and fire protection are then integrated into the overall development of sustainable ecosystems, enabling the diversification of outputs from limited resources and human efforts.

Given that climate warming produces longer, drier fire seasons with more extensive burning, a more practical option is necessary for some states under the present fire situations. As an intermediate management policy, fuel management should strive to promote adaptive resilience to wildfires in response to changing climate and fire regimes [64,65]. Rather than aiming to return ecosystems to previous, pre-fire, or historical conditions, such management actions can be designed to help communities adapt to the changing climate, fuel, and land-use conditions by directly shaping the human and natural prototypes in a way that acknowledges the present and future inevitability of fires [64]. Understanding vegetation characteristics is essential to determining the management strategies that most effectively coexist sustainably with wildfires [64,65]. There is no doubt that the adaptability and resilience of vegetation depend on the specific ecological environment [64].

Another area of research interest is reducing the impact of potential wildfires on urban structures and facilities in adjacent areas. Safety separation distances are usually applied to maintain coexistence between human society and nearby forests [66,67], which may cause ineffective land use and raise ecological and environmental issues, such as water and soil erosion in certain areas. The wide application of ecological fire prevention techniques at the wildland and urban interface (WUI) is an option to greatly reduce the probability of occurrence and potential burning intensities of wildfires near residential areas [10,15,16,26,63]. Thus, the safe distance necessary for the separation of residential areas from the adjacent forests or grassland can be remarkably reduced, leading to more effective land use at the WUI. As documented in another review paper [10], a variety of techniques are available and effective for mitigating wildfire hazards at the WUI. An alternative method is to make use of the existing shrubs in landscapes around homes by maintaining them with light watering in fire seasons [26]. This approach has advantages over many standard greenbelt designs given that the conservation of native shrubs is most attractive to native fauna, with the addition to the wildland–urban experience. As a result, it has been utilized in a number of landscaping projects in southern California so far [26].

6. Conclusions

A series of fire prevention techniques are proposed to achieve the mitigation of fire hazards through intervening with the material basis for fire initiation and development in certain landscapes. These techniques focus on fuel management, including altering surface fuel quantities, moisture content, and plant distribution patterns. Among these techniques are all-removed fuelbreaks, mechanical fuel thinning, prescribed burning, biochemical methods, shaded fuelbreaks, green fire barriers, and their variations. Implementing these techniques has resulted in favorable outcomes by establishing fire regimes in targeted areas. Fuelbreaks, which involve fuel thinning or plantation, serve as modified or reconstructed localized ecosystems that retain substantial ecological features. Within the conceptual framework of ecology, these fuel management techniques can be categorized as ecological fire prevention techniques.

Fuel thinning techniques, including all-removed fuelbreaks, offer limited ecological benefits, whereas the normal shaded fuelbreak technique does have a positive impact on promoting forest health and wood productivity. From an ecological maintenance perspective, the development of green fire barriers offers greater advantages. The presence of a dense tree population in green fire barriers has a beneficial impact on soil and water conservation and the regulation of local humidity and wind patterns. In addition, as microecosystems developed with the capacity of fire resilience, green fire barriers possess the unique feature of long-term self-maintenance as fire protection facilities and exhibit diverse ecological performances and additional economic benefits through their flexibility.

The existing knowledge base and available techniques can be effectively applied to design fire mitigation strategies for plant communities and the WUI. The development of landscapes in a sustainable and ecologically responsible manner can also be achieved by integrating ecological maintenance and landscape effects in line with environmental demands. As a result, it is necessary to conduct further studies on the quantification of the fire prevention efficacy of different fire prevention prescriptions and the ecological benefits to be achieved. Algorithms and evaluation platforms that consider multiple factors are then developed to serve as convenient engineering tools highlighting the integration of fire prevention and control management with the sustainable development of built environment ecosystems. This approach will promote the development of fire-resilient ecosystems and safe living environments in a cost-effective way.

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References

1. Pyne, S.J.; Andrews, P.J.; Laven, R.D. *Introduction to Wildland Fire*; John Wiley & Sons: New York, NY, USA, 1996; pp. 725–752.
2. Agee, J.K.; Bahro, B.; Finney, M.A.; Omi, P.H.; Sapsis, D.B.; Skinner, C.N.; van Wagtendonk, J.W.; Weatherspoon, C.P. The use of shaded fuelbreaks in landscape fire management. *For. Ecol. Manag.* **2000**, *127*, 55–66. [CrossRef]
3. Glasspool, I.J.; Edwards, D.; Axe, L. Charcoal in the Silurian as evidence for the earliest wildfire. *Geology* **2004**, *32*, 381–383. [CrossRef]
4. Stephens, S.L.; Agee, J.K.; Fulé, P.Z.; North, M.P.; Rommet, W.H.; Swetnam, T.W.; Turner, M.G. Managing forests and fire in changing climates. *Science* **2013**, *342*, 41–42. [CrossRef] [PubMed]
5. Green, L.R. *Fuelbreaks and Other Fuel Modification for Wildland Fire Control: USDA Agricultural Handbook 499*; US Government Printing Office: Washington, DC, USA, 1977.
6. Pyne, S.J. *Fire in America: A Cultural History of Wildland and Rural Fire*; Princeton University Press: Princeton, NJ, USA, 1982.
7. Arno, S.F.; Brown, J.K. *Overcoming the Paradox in Managing Wildland Fire. Western Wildlands*; Montana Forest and Conservation Experiment Station: Missoula, MT, USA, 1991; pp. 40–46.
8. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96. [CrossRef]
9. Wang, H.-H. Scientific basis and prospects of biological-fire-prevention-belt technique. *For. Res.* **2015**, *28*, 731–738. (In Chinese)
10. Wang, H.-H.; Finney, M.A.; Song, Z.-L.; Wang, Z.-S.; Li, X.-C. Ecological techniques for wildfire mitigation: Two distinct fuelbreak approaches and their fusion. *For. Ecol. Manag.* **2021**, *495*, 119376. [CrossRef]
11. Weaver, H. Effects of prescribed burning in ponderosa pine. *J. For.* **1957**, *55*, 133–138.
12. Blackhall, M.; Raffaele, E.; Paritsis, J.; Tiribelli, F.; Morales, J.M.; Kitzberger, T.; Gowda, J.H.; Veblen, T.T. Effects of biological legacies and herbivory on fuels and flammability traits: A long-term experimental study of alternative stable states. *J. Ecol.* **2017**, *105*, 1309–1322. [CrossRef]
13. Forest Fire Prevention Office, State Forestry Administration (FFPO, SFA). *The Construction of Fuelbreak in China*; China Forestry Press: Beijing, China, 2003. (In Chinese)
14. Wang, H.-H.; Tao, J.-J.; Sheng, C.-D. Innovation and the associated advantages in forest firebreak techniques. *World For. Res.* **2015**, *28*, 46–52. (In Chinese)
15. Wang, H.-H. The importance of developing biological fire protection technologies under current wildfire situations. *For. Fire Prev.* **2017**, *1*, 47–53. (In Chinese)
16. Cui, X.; Alam, M.A.; Perry, G.L.W.; Paterson, A.M.; Wyse, S.V.; Curran, T.J. Green firebreaks as a management tool for wildfires: Lessons from China. *J. Environ. Manag.* **2019**, *233*, 329–336. [CrossRef]
17. Cooper, C.F. Ecology of fire. *Sci. Am.* **1961**, *204*, 150–160. [CrossRef]
18. Daubenmire, R. Ecology of fire in grassland. *Adv. Ecol. Res.* **1968**, *5*, 209–266.
19. Cochrane, M.A.; Ryan, K.C. Fire and fire ecology: Concepts and principles. In *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics*; Cochrane, M.A., Ed.; Springer: Berlin, Germany, 2009; pp. 25–62.
20. Finney, M.A. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *For. Sci.* **2001**, *47*, 219–228.
21. Ager, A.A.; Vaillant, N.M.; Finney, M.A. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *For. Ecol. Manag.* **2010**, *259*, 1556–1570. [CrossRef]
22. Ager, A.A.; Vaillant, N.M.; McMahan, A. Restoration of fire in managed forests: A model to prioritize landscapes and analyze tradeoffs. *Ecosphere* **2013**, *4*, 29. [CrossRef]

23. Bradstock, R.A. A biogeographic model of fire regimes in Australia: Current and future implications. *Glob. Ecol. Biogeogr.* **2010**, *19*, 145–158. [CrossRef]
24. Hardy, C.C. Wildfire hazard and risk: Problems, definitions, and context. *For. Ecol. Manag.* **2005**, *211*, 73–82. [CrossRef]
25. Butler, B.W.; Otmar, R.D.; Rupp, T.S.; Jandt, R.; Miller, E.; Howard, K.; Schmoll, R.; Theisen, S.; Vihnanek, R.E.; Jimenez, D. Quantifying the effect of fuel reduction treatments on fire behavior in boreal forests. *Can. J. For. Res.* **2013**, *43*, 97–102. [CrossRef]
26. Keeley, J.E. Protecting the WUI in California: Greenbelts vs thinning for wildfire threats to homes. *Bull. South. Calif. Acad. Sci.* **2020**, *119*, 35–47.
27. Johnston, L.M.; Wang, X.; Erni, S.; Taylor, S.W. Wildland fire risk research in Canada. *Environ. Rev.* **2020**, *28*, 164–186. [CrossRef]
28. Archibald, S.; Roy, D.P.; Van Wilgen, B.W.; Scholes, R.J. What limits fire? An examination of drivers of burn area in Southern Africa. *Glob. Change Biol.* **2009**, *15*, 613–630. [CrossRef]
29. Christensen, N.L. Shrubland fire regimes and their evolutionary consequences. *Ecol. Nat. Disturb. Patch Dyn.* **1985**, 86–99. [CrossRef]
30. Kilgore, B.M. The ecological role of fire in Sierran conifer forests: Its application to national park management. *Quat. Res.* **1973**, *3*, 496–513. [CrossRef]
31. Rothermel, R.; Deeming, J.E. *Measuring and Interpreting Fire Behavior for Correlation with Fire Effects*; General Technical Report, INT-93; USDA: Washington, DC, USA, 1980.
32. Chuvieco, E.; Aguado, I.; Dimitrakopoulos, A. Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment. *Can. J. For. Res.* **2004**, *34*, 2284–2293. [CrossRef]
33. Chandler, C.; Cheney, P.; Thomas, P.; Trabaud, L.; Williams, D. *Fire in Forestry. Forest Fire Behavior and Effects*; John Wily & Sons Inc.: Hoboken, NJ, USA, 1983; Volume 1.
34. Fosberg, M.A. Drying rates of heartwood below fiber saturation. *For. Sci.* **1970**, *16*, 57–63.
35. Fosberg, M.A.; Lancaster, J.W.; Schroeder, M.J. Fuel moisture response-drying relationships under standard and field conditions. *For. Sci.* **1970**, *16*, 121–128.
36. Sandberg, D.V.; Riccardi, C.L.; Schaaf, M.D. Fire potential rating for wildland fuel beds using the fuel characteristic classification system. *Can. J. For. Res.* **2007**, *37*, 2456–2463. [CrossRef]
37. Van Wagner, C.E. Conditions for the start and spread of crown fire. *Can. J. For. Res.* **1977**, *7*, 23–34. [CrossRef]
38. McLauchlan, K.K.; Higuera, P.E.; Miesel, J.; Rogers, B.M.; Schweitzer, J.; Shuman, J.K.; Tepley, A.J.; Varner, J.M.; Veblen, T.T.; Adalsteinsson, S.A.; et al. Fire as a fundamental ecological process: Research advances and frontiers. *J. Ecol.* **2020**, *108*, 2047–2069. [CrossRef]
39. Pyne, S.J. *Introduction to Wildland Fire: Fire Management in the United States*; Wiley-Interscience: New York, NY, USA, 1984.
40. Husari, S.; Thomas, H.N.; Neil, G.S.; Sugihara Scott, L.S. Fire and fuel management. In *Fire in California's Ecosystems*; Sugihara, N., Ed.; University of California Press: Oakland, CA, USA, 2006; pp. 444–465.
41. Cochrane, M.A.; Moran, C.J.; Wimberly, M.C.; Baer, A.D.; Finney, M.A.; Beckendorf, K.L.; Eidenshink, J.; Zhu, Z. Estimation of wildfire size and risk changes due to fuels treatments. *Int. J. Wildland Fire* **2012**, *21*, 357–367. [CrossRef]
42. Agee, J.K. The influence of forest structure on fire behavior. In Proceedings of the 17th Annual Forest Vegetation Management Conference, Redding, CA, USA, 16–18 January 1996; pp. 52–68.
43. Wei, Y. Optimize landscape fuel treatment locations to create control opportunities for future fires. *Can. J. For. Res.* **2012**, *42*, 1002–1014. [CrossRef]
44. Knapp, E.E.; Keeley, J.E. Heterogeneity in fire severity with early season and late season prescribed burns in a mixed-conifer forest. *Int. J. Wildland Fire* **2006**, *15*, 37–45. [CrossRef]
45. Dennis, F.C. *Fuelbreak Guidelines for Forested Subdivisions & Communities*; Colorado State Forest Service: Walden, CO, USA, 2005; pp. 2–8.
46. Oliveira, T.M.; Barros, A.M.G.; Ager, A.A.; Fernandes, P.M. Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. *Int. J. Wildland Fire* **2016**, *25*, 619–632. [CrossRef]
47. Syphard, A.D.; Keeley, J.E.; Brennan, T.J. Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California. *Int. J. Wildland Fire* **2011**, *20*, 764–775. [CrossRef]
48. Grah, R.F.; Long, A. Three California fuelbreaks: Costs and benefits. *J. For.* **1971**, *69*, 89–93.
49. State Forestry Administration (SFA). *Technological Standard of Forest Fire Protection Engineering. LYJ 127-2012*; Heilongjiang Academy of Forestry Design and Research: Harbin, China, 2012. (In Chinese)
50. Xu, X.-Y. The influence of different slope positions on the growth of biological fire prevention forest belts with *Mytilaria laosensis* Lec. *Mod. Agric. Sci. Technol.* **2022**, *17*, 123–125. (In Chinese)
51. Ching, F.F.T.; Stewart, W.S. Research with slow burning plants. *J. For.* **1962**, *60*, 796–798.
52. White, R.H.; Zipperer, W.C. Testing and classification of individual plants for fire behaviour: Plant selection for the wildland urban interface. *Int. J. Wildland Fire* **2010**, *19*, 213–227. [CrossRef]
53. Rozendaal, D.M.A.; Soliz-Gamboa, C.C.; Zuidema, P.A. Timber yield projections for tropical tree species: The influence of fast juvenile growth on timber volume recovery. *For. Ecol. Manag.* **2010**, *259*, 2292–2300. [CrossRef]
54. Nave, L.E.; Vance, E.D.; Swanston, C.W.; Curtis, P.S. Harvest impacts on soil carbon storage in temperate forests. *For. Ecol. Manag.* **2010**, *259*, 857–866. [CrossRef]
55. James, J.N.; Harrison, R.B. The effect of harvest on forest soil carbon: A meta-analysis. *Forests* **2016**, *7*, 308. [CrossRef]

56. Xu, S.-J.; Li, G.-C.; Li, J.Q.; Shu, Y.-X.; Huang, E. Several theoretical and practical problems in the application of glyphosate. *Guangdong For. Sci. Technol.* **1998**, *14*, 27–33. (In Chinese)
57. Jayasumana, C.; Gunatilake, S.; Senanayake, P. Glyphosate, hard water and nephrotoxic metals: Are they the culprits behind the epidemic of chronic kidney disease of unknown etiology in Sri Lanka. *Int. J. Environ. Res. Public Health* **2014**, *11*, 2125–2147. [CrossRef] [PubMed]
58. Newman, J.A.; Parsons, A.J.; Thornley, J.H.M.; Penning, P.D. Optimal diet selection by generalist grazing herbivore. *Funct. Ecol.* **1995**, *9*, 255–268. [CrossRef]
59. Liu, J.; Feng, C.; Wang, D.-L.; Wang, L.; Wilsey, B.J.; Zhong, Z.-W. Impacts of razing by different large herbivores in grassland depend on plant species diversity. *J. Appl. Ecol.* **2015**, *52*, 1053–1062. [CrossRef]
60. Chang, Q.; Wang, L.; Ding, S.-W.; Xu, T.-T.; Li, Z.-Q.; Song, X.-X.; Zhao, X.; Wang, D.-L.; Pan, D.-F. Grazer effects on soil carbon storage vary by herbivore assemblage in a semi-arid grassland. *J. Appl. Ecol.* **2013**, *55*, 2517–2526. [CrossRef]
61. Wiedinmyer, C.; Hurteau, M.D. Prescribed fire as a means of reducing forest carbon emissions in the Western United States. *Environ. Sci. Technol.* **2010**, *44*, 1926–1932. [CrossRef] [PubMed]
62. Luna, B.; Moreno, J.M.; Cruz, A.; Fernández-González, F. Heat-shock and seed germination of a group of Mediterranean plant species growing in a burned area: An approach based on plant functional types. *Environ. Exp. Bot.* **2007**, *60*, 324–333. [CrossRef]
63. Curran, T.J.; Perry, G.L.W.; Wyse, S.V.; Alam, M.A. Managing fire and biodiversity in the wildland-urban interface: A role for green firebreaks. *Fire* **2018**, *1*, 3. [CrossRef]
64. McWethy, D.B.; Schoennagel, T.; Higuera, P.E.; Krawchuk, M.A.; Harvey, B.J.; Metcalf, E.C.; Schultz, C.A.; Miller, C.; Metcalf, A.L.; Buma, B.J.; et al. Rethinking resilience to wildfire. *Nat. Sustain.* **2019**, *2*, 797–804. [CrossRef]
65. Moritz, M.A.; Batllori, E.; Bradstock, R.A.; Gill, A.M.; Handmer, J.; Hessburg, P.F.; Leonard, J.; McCaffrey, S.; Odion, D.C.; Schoennagel, T.; et al. Learning to coexist with wildfire. *Nature* **2014**, *515*, 58–66. [CrossRef] [PubMed]
66. Cohen, J.D.; Saveland, J. Structure ignition assessment can help reduce fire damages in the W-UI. *Fire Manag. Notes* **1997**, *57*, 19–23.
67. Syphard, A.D.; Brennan, T.J.; Keeley, J.E. The role of defensible space for residential structure protection during wildfires. *Int. J. Wildland Fire* **2014**, *23*, 1165–1175. [CrossRef]