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Review

Fire Protection Principles and Recommendations in Disturbed Forest Areas in Central Europe: A Review

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Abstract: Forest fires are becoming a more significant problem in Central Europe, but their danger is not as high as that in Southern Europe. The exception, however, is forest fires occurring in disturbed areas (windthrow and bark beetle outbreak areas), which are comparable in severity and danger to the most serious forest fires. In this study, we describe the current situation in Central European countries in terms of fire protection for disturbed areas in managed forests and forest stands left to spontaneously develop (secondary succession). If a country has regulations and strategies in this area, they are often only published in the local language. In this review, we combine information from all Central European countries and summarize it in a unified international language, provide an opportunity for local authorities to express their own experiences, and integrate data from worldwide scientific research. Thus, this paper may be considered a universal guide for managing fire protection and preparedness in disturbed areas and can serve as a reference for the establishment of strict legislative rules at the state level. These laws must be obligatory for all stakeholders in individual countries. The motivation for this study was two large forest fires in an area left to spontaneously develop in the Bohemian Switzerland National Park in the Czech Republic and Harz Mountains in Germany in the summer of 2022. These incidents revealed that fire prevention legislation was inadequate or nonexistent in these areas. The strategy of the European Union is to increase the size of protected areas and spontaneous development areas. Therefore, we consider it necessary to provide governments with relevant information on this topic to create conditions for better management of these destructive events.

Keywords: fuel load; fire ignition; fire propagation; forest fire prevention; fuel management; spontaneous development; wildfire

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1. Introduction

Ongoing climate change and its manifestations, such as long periods of drought, decreased rainfall or diminishing snow cover, are sometimes accompanied by extreme weather events, such as windstorms that increase the number of disturbance events in Central European forests [1,2].

Forest disturbances have major economic, social, and ecological consequences in Europe and substantial effects on forest productivity and carbon storage [3,4]. The damage caused by windstorms in European forests has increased during the past century [2,5–7], and this trend is expected to continue [1,8]. European forests have become significantly stressed by drought [9]. The combination of a high amount of salvage wood from wind disturbances and long drought periods increases the predisposition to bark beetle infestations [10]. Bark beetle disturbances have greatly increased in conifer forests in the Northern Hemisphere over the last four decades [3]. A large part of Central Europe has been affected by bark beetle outbreaks in recent years, and this can be considered a societal disaster [11]. These outbreaks have significantly changed the structure and appearance of Central European forest stands [12,13].

If the quantity of damaged wood in wind-disturbed areas is too great to be cleaned and processed in a timely manner, the population of bark beetles is likely to increase [12,14]. Damaged trees provide an optimal habitat for developing bark beetle populations, and outbreaks often follow wind disturbance, especially where weather conditions are suitable for the reproduction and survival of beetles. Both types of disturbance often support each other, or one follows the other and leads to cascading disturbance effects on forest ecosystems [15–19]. One example is the bark beetle outbreak in High Tatras National Park (Slovakia) in 2005, after a wind disturbance event in 2004 (called Bora or Elizabeth) [20,21]; another is the outbreak in Bohemian Forest National Park (Czech Republic) in 2008 because of the storm Kyrill that occurred the previous year [22].Even spontaneously developed forest stands have not yet fully recovered from bark beetle outbreaks [23].

A fact that is often overlooked is the greatly increased danger of forest fires in these disturbed areas, e.g., [24–29]. The management and systematic treatment of areas affected by wind disturbances or bark beetle outbreaks should protect them from the occurrence of forest fires. Targeted treatment of the disturbed areas should be carried out to ensure the ability to effectively implement firefighting operations to battle any resulting forest fires.

The aims of this study were as follows: (i) explain the reasons for the increased danger of fire ignition and propagation caused by the fuel loads available after disturbance (windthrow or bark beetle outbreaks); (ii) describe the steps and recommended practices in the field after these disturbances to minimize the fire danger and increase preparedness; and (iii) recommend measures to ensure spontaneous forest development not only for environmental conservations but also for fire protection.

2. Forest Disturbances in Central Europe

Forest disturbances are expected to intensify as Earth's climate changes. Quantifying the vulnerability of forests to disturbances and understanding the underlying mechanisms are crucial for developing mitigation and adaptation [30,31]. Approximately 33.4 billion tons of forest biomass could be seriously affected by these disturbances, with higher relative losses from windthrows (40%) and fires (34%) than from insect outbreaks (26%) [31]. Dominant types of disturbances vary regionally across Europe with forest type, location, climate, the degree of cultural landscape modification, and topography [2]. A long-standing view of European forests has held that large severe disturbances are directly or indirectly caused by human activity, including past forest management practices that simplified forest structures [32–34]. Some authors predict that nearly 100% of timber loss/damage in the future will be caused by wind, fire, and insects [2,31]. Scientists estimate that only a minority of damage is caused by other hazards [35]. For this reason, we focus only on forest fire protection in areas affected by bark beetles and wind disturbances, which are very common in Central Europe [2,10,15,31].

Wind damage related to summer thunderstorms is common but usually results in relatively small areas of wind disturbance [36]. In contrast, winter storm systems in the mountain ranges of central and northwestern Europe affect larger forest areas than any other type of disturbance. Notable examples of these extratropical cyclones include the storm Vivian in February 1990 and storms Lothar and Martin in December 1999, both of which caused damage across large regions of the Alps [37] and Central Europe [18,19]

(Table 1) [38]. Aside from the large storms that Central Europe faced in the previous 35 years, there have been numerous local wind disturbances every, e.g., [39].

Table 1. The largest wind storms damaging forest stands in Central Europe during the last 30 years.

Storm	Year	Country Affected by Storm (•)				
		Czech Republic	Slovakia	Austria	Germany	Poland
Vivian	1990				•	
Lothar and Martin	1999				•	
Elisabeth/Bora	2004		•			
Kyrill	2007	•	•	•	•	•
Klaus	2009				•	
Xynthia	2010				•	•
Nicklas	2015	•	•	•	•	•
Derecho	2017					•
David (Fiederike)	2018	•			•	•
Sabine (Ciara)	2020			•	•	•

Outbreaks of bark beetles and defoliators across Europe affect forests that are dominated by spruce, pine, fir, and other species. However, across the continent, the most significant insect outbreaks are those of European spruce bark beetles (*Ips typographus* L.), which attack Norway spruce (*Picea abies* (L.) Karst.) [15–19,40]. Climate change has a strong amplifying effect on bark beetle population growth [41]: (1) it facilitates bark beetle survival and development (e.g., by reducing winter mortality and allowing the completion of additional beetle generations per year) [42,43]; (2) it increases the size of potential beetle habitat by allowing beetles to spread to higher altitudes and latitudes [44,45]; (3) it increases the probability of extreme, region-wide weather events such as drought, which reduces tree resistance [46,47]. Due to these mechanisms, disturbances caused by bark beetles are projected to increase in Europe in the next decades [2].

3. Increasing Forest Fire Danger after Disturbance

There is an increasing forest fire danger in disturbed forest areas. The forest structure is changed by disturbances, and the amount of flammable material on the forest floor increases [48,49]. Flammable material from trees is transferred to the forest floor immediately (windthrow) or gradually (bark beetle) (Figure 1) [48–50]. After a windthrow event, the structure of the forest stand and the vertical distribution of combustible materials are instantly changed, and the area becomes extremely vulnerable to the uncontrollable spread of a fire. After windthrow, the disturbed area, in contrast to the standing forest cover, is not height-differentiated and is made up of broken, uprooted, standing, and decaying trees, herbaceous cover, and brushwood. The distribution of the biomass of the trees is uneven; timber usually accumulates in several meter layers, and parts of the tree crowns are also found on the forest floor [50] (Figure 2).

Similar to wind disturbance events, bark beetle outbreaks also significantly change the characteristics of the forest environment (Figure 3). During the first phase of a bark beetle outbreak, the infected trees experience drying and shedding of the needles, which is usually accompanied by the shedding of the bark. The surface of the forest floor is therefore covered with a significantly larger amount of flammable material than the floor of a healthy forest stand [51,52]. Then, small twigs break off of dry trees and further increase the amount of flammable material on the forest floor; later, the stronger branches break off and fall to the ground. In addition, there may be uprooted or dry individual trees and a further increase in the amount of flammable material on the surface of the forest floor (Figure 1) [51–54]. The amount of transferred flammable material depends on the period between the destruction of the forest stand by the bark beetles and the salvage logging in the stand. However, even after the relatively quick removal of trees, more combustible material remains on the floor than in the case of harvesting a healthy stand, mainly in the form of bark, broken branches, and the remains of the assimilation apparatus.

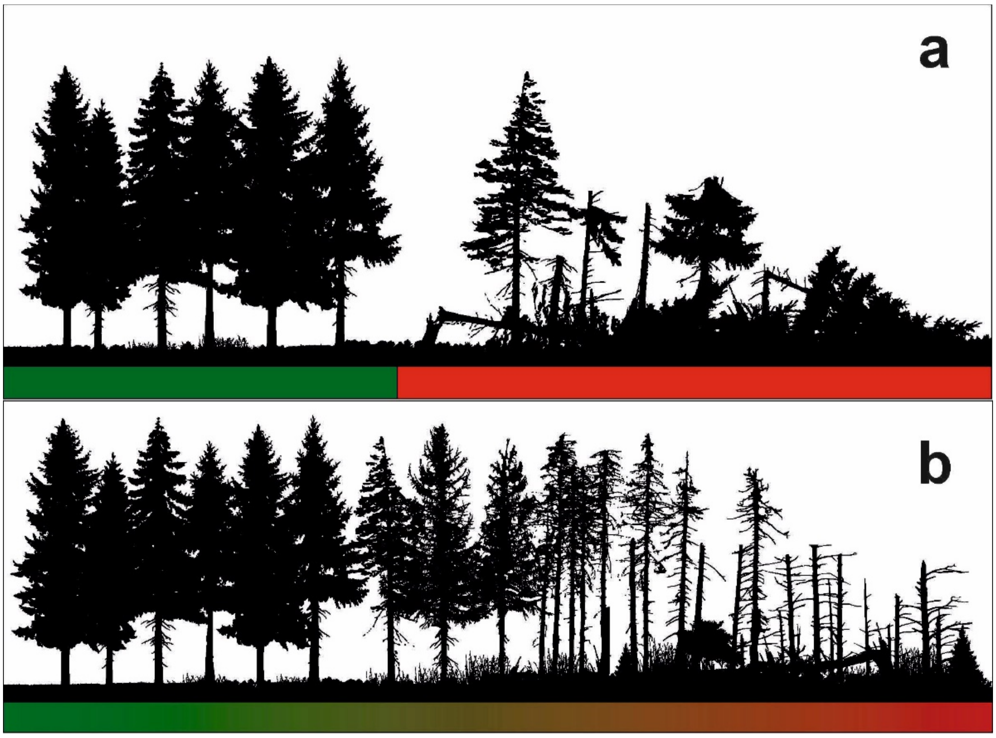

Figure 1. Transfer of fuel from crowns to forest floor: (**a**) wind disturbance; (**b**) bark beetle outbreak.

Figure 2. Forest stands damaged by bark beetle outbreaks in High Tatras National Park.

Figure 3. Windthrow outbreak in High Tatras National Park in Slovakia in 2004.

These transfers of flammable material increase the value of potential heat energy, which can be released during a fire [26,55]. More heat energy released during a fire means quicker loss of moisture content of flammable material in the path of the spreading fire, usually accompanied by increasing speed of the fire front [55]. Additionally, when the fire produces more heat, there is a higher probability of spot fires, and in the worst scenario, a convection column is formed [56]. More intense fires are also able to consume more solid pieces of flammable material [57–59].

The second problem is increasing sunlight on the forest surface because of the disturbance (especially after the bark beetle outbreak) [60], and depending on the characteristics of the habitat, grasses and herbs begin to dominate sooner or later [61] and dry up in the late summer or autumn months, creating an easily ignitable fuel. The effect of grasses on fire behavior has previously been published many times, see e.g., [62–64].

Together with an increasing amount of flammable material, the environment supports the intense and rapid spread of forest fires once ignited [65]. If a fire occurs in such a forest, under favorable weather conditions, it will have a very high burning intensity [66], with a rapid fire front, which may lead the fire to spread over a large area, favored by the limited availability of the forest [67,68].

These ignitable and high-intensity fire conditions of the environment can be accompanied (especially windthrows) by a destroyed forest road network and thus the impossibility of getting to a possible fire site with fire vehicles or having access to water supply points, which, in the event of a fire, may increase the losses [67].

4. Managed Forest Stands after Disturbance

4.1. Salvage Logging

From a forest fire perspective, the basic principle for decreasing the fire danger is the reduction in the fuel load in the area affected by the disturbance by removing the damaged timber as quickly as possible [28]. We recommend the following procedures to reduce the risk of injuries to workers during salvage logging, significantly reduce the fire danger, and increase preparedness for a possible forest fire (Figure 4).

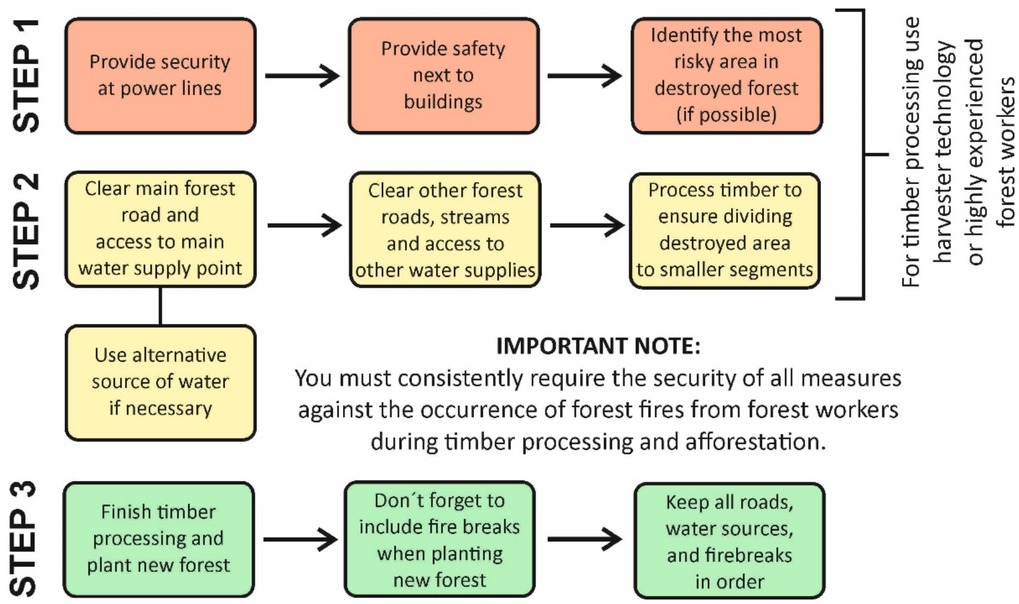

Figure 4. How to address windthrow areas step by step in relation to fire protection.

- Provide security at power lines in cooperation with the relevant services.
- Provide safety next to buildings (removal of trees hanging next to buildings).

- Process timber from disturbed areas starting in the places with the greatest fire danger, depending on the natural conditions, the composition of tree species, or the volume of the damaged timber.
- Ensure that all forest roads are passible in the entire disturbed area and verify access to and cleaning of all water courses and other water supply points.
    - If there is a "main" water supply point nearby that could be used as a source of water for suppression, focus primarily on making (most important) the forest road network to this supply point passable; immediately afterward, make other water supply points in the disturbed area available.
    - For critical locations with inaccessible or remote water supply points, it is appropriate to secure an alternative source of water for potential suppression (temporary small dams on waterways in the area of the disturbance and in its vicinity or portable water supply points such as tanks).
- Process timber in the disturbed area once all forest roads are made available and all streams and water supply points are clear.

By loosening the road network, the disturbed area is divided into smaller parts, and timber processing should then proceed so that, in the event of a fire, the ability of flames to jump between individual segments of the disturbed area is minimized [50]. In the vicinity of a disturbed area with undamaged forest stands, the main priority should be to prevent fires from spreading beyond the damaged forests and to stop fires within the disturbed forest. The main protection of the area will be the isolation of the areas of disturbed forests from the complex of managed forests with special fire protection strips.

These steps are mostly suited to windthrow disturbances; during bark beetle outbreaks, there is no destroyed forest road network or access to water supply points. However, we must still periodically check if the forest road network is passible and whether the water supply points are accessible, as decaying or dead individual trees can more easily uproot or break. Removing these trees during fire suppression can cause unnecessary delays, which increases the time for the fire to develop freely or the time needed to transport water for suppression, if necessary. Otherwise, bark beetle outbreak timber processing is similar to that for windthrow disturbance.

It is highly recommended to use harvester technology for processing disturbed areas. If it is not possible to use this technology, we recommend employing the most experienced forest workers [69,70]. Many forest workers will be working in the disturbed area during processing. Due to the large number of people in the area, the likelihood of fire ignition due to negligence also increases [71]. Discarded cigarettes (despite the prohibition of smoking in the forest) or a forgotten fuel canister can become the initiator of a forest fire. It is necessary to increase the intensity of training and follow-up inspections and to consistently require the security of all measures against the occurrence of forest fires [50]. Many tractors, harvesters, and forwarders are also usually involved in the timber processing of disturbed areas, so it is necessary to check their technical conditions and supplement them with fire extinguishers if they are missing.

4.2. After Salvage Logging

Processing timber in disturbed areas decreases the amount of flammable material on the forest floor, thus reducing the fuel load of the given area [50]. Although all the flammable material is concentrated near or on the forest floor in a wind-disturbed area, a smaller amount of flammable material is released from the drying trees if the timber is rapidly processed, compared to leaving the disturbed area untouched long-term [28]. The processing of timber in bark beetle outbreak areas does not further increase the amount of flammable material on the forest floor caused by the gradual decay of individual trees [72]. Generally, the more immediate the response is, the less flammable material is released from the decaying trees.

From the point of view of fire protection, it is preferable that there be as little flammable material as possible on the forest floor [73,74]. However, regarding the current trends of leaving material such as dead wood to maintain biodiversity, there are tradeoffs to be made between nature conservation and fire management. It is necessary, especially in areas with high fire danger, to leave a quantity of dead wood in the forest that will not unnecessarily increase the fuel load but, on the other hand, allow enough living space for organisms bound to dead wood [75].

Importantly, the vulnerability of a disturbed area to the occurrence of a forest fire is still high even after processing. This vulnerability stems from the relatively rapid increase in easily ignited grasses and herbs caused by a drastic change in light conditions on the forest floor [76], supported by the amount of flammable material released from trees before and during timber processing. The amount of flammable material released from the destroyed tree stands affects the intensity of the fire in the first years after disturbance until this released combustible material decomposes [26,28,72]. The time required for decomposition of flammable material is highly dependent on the characteristics of the habitat [77].

However, a fire in these areas is less dangerous and easier to control and suppress due to the completed processing of timber (Figure 5a) [28]. Access and movement around the fire during suppression are also easier in the case of cleared areas.

Figure 5. Succession of a new generation of the forest after completion of salvage logging in the disturbed area: (**a**) grasses still dominate the area; (**b**) almost full cover of the forest surface by tree crowns—grasses mostly disappear.

4.3. Planting a New Forest

When planting new forest stands in disturbed areas, care must be taken in the selection of tree species to reduce the predisposition to disturbances recurring in the future as much as possible; additionally, the selection of tree species should correspond to the habitat conditions in response to current climate change [12]. It is also important to use local tree genotypes during afforestation, which may be best adapted to local natural conditions [78].

To minimize fire spread in afforested areas after large disturbances, it is appropriate to divide the areas with a system of fire breaks when planning afforestation [79]. An example can be taken from the division of a large complex of pine stands after a large-scale forest fire on the Polish–German border near the German village of Forst (51.7434406° N, 14.6949142° E) (Figure 6). Fire breaks slow down and can even stop forest fires from spreading and increase accessibility for fire suppression to some parts of the forest stands [28,74,79–81]. Additionally, the forest road infrastructure built for timber processing and as a fire break must be maintained in the postdisturbance phase (operable water supply points, places for water fulfilling of aircraft, water supply points from watercourses, forest road network passable for firefighting equipment, forest road network useable like fire breaks) [67].

Figure 6. Firebreak in coeval pine stands.

Fire protection in these newly planted forest stands is also important in view of the high costs of reforesting these areas [82]. In the event of a fire, these seedlings of the newly planted forest will be destroyed, and new tree planting will be necessary, which increases economic demand [82–84].

4.4. After Planting a New Forest

The increased vulnerability of the emerging forest to forest fires lasts until the tree crowns fully cover the forest surface. As a result of the cover, light conditions on the forest floor change, easily ignitable grasses and herbs mostly disappear, and there is an increase in soil moisture due to shading and reduced evaporation (Figure 5b). These forest stands are, therefore, more difficult to set on fire [85,86]. However, if they catch fire, they can be very dangerous. These forest stands restored in disturbed areas are characterized by an unfavorable age structure (only slightly differentiated) and sometimes also species. In large postdisturbance areas, where one-age coniferous young trees dominate in large areas, flames covering the entire height of the trees can be expected [87]. This situation can also threaten the surrounding mature forest stands and facilitate the formation of crown fires in mature forest stands [88,89].

5. Spontaneously Developing (Unmanaged) Forests after Disturbance

5.1. Prolonging Fire Danger

The principles of spontaneously developing forest stands (nonintervention forest management) are currently most often applied in protected areas, primarily in national parks [90]. These areas are usually visited much more often by the public [91], which is also the reason why the vulnerability of these areas to the occurrence of forest fires is continuously significantly higher. Humans cause up to 98% of forest fires in Central Europe, as well as almost the rest of the world [56,92].

In normal situations in spontaneously developing forest stands, the natural processes of tree death and the growth of a new generation are very slow [90]. If there is currently no damage to the forest stand by strong winds or gradations of insects, dying (standing) trees do not pose a high fire danger [93]. In natural and slow processes, trees die gradually, and the processes of biomass decomposition by fungi take place at the same time, meaning that biomass does not undergo very large accumulation and drying [61,94].

However, these areas are also sometimes fatally damaged by wind events or bark beetle outbreaks [90], which leads to a sharp increase in the fuel load of these areas [26,66]. The role that the application of spontaneous development has in this process should be discussed in the context of the elaboration of strategy documents, e.g., [95]. It is important to realize that, due to spontaneous development, timber is not processed in these disturbed areas [90], which prolongs and deepens the problems in the field of fire protection [96]. In spontaneously developing forests that were affected by a disturbance, the flammability of the area caused by the accumulation of flammable material from thousands of decaying trees on the forest floor is much higher and decreases slowly [26,28,89,97] (Figure 7).

Figure 7. Fuel load in a spontaneously developing forest a few years after a bark beetle outbreak.

Depending on the type of habitat, natural regeneration processes, and thus the rate of decomposition of the most flammable material, it can take 5 to 10 years and occasionally much longer [26,61]. Many studies have indicated that lying deadwood from wind disturbance can reduce browsing pressure on young seedlings due to the barrier effect [98]. On the other hand, in bark beetle-destroyed forest stands, due to increased sunshine and decreased shadow, there is a decrease in natural humidity in the area, which affects various organisms and leads to a slowing of the decomposition processes of the accumulated flammable material [99]. Another problem in relation to forest fires lies in the gradual drying out of standing dead trees due to alternating precipitation, sunshine, frost cracks, or partial breaks (breaking off of branches and tree tops). The integrity of the tree trunk is gradually weakened, and the area of surfaces suitable for heating and burning increases (principle of woodchips). In the case of a forest fire, the entire standing trunk can gradually burn, as demonstrated in Bohemian Switzerland National Park (Figure 8). Research carried out in the Polish complex of the Białowieża Forest damaged by bark beetles showed that approximately 10 years after dying, dead spruces were practically devoid of branches. Some of the dead trees were lying, and some were still standing; however, they did not pose a significant threat to the spread of fires. The same research years before showed that in the first 3 years after dying, the trees were mostly standing and had most of their branches. As a result of the systematic falling of trees and branches, a loose spatial structure is created that allows grass-like vegetation to develop on the ground. Grass cover poses a serious danger for fire ignition and rapid spread. When analyzing the decay of the spruce stand over time, researchers found that the susceptibility of potentially combustible material to ignition and fire spread was highest in the initial phase and reached a maximum in the 2nd to 3rd year. (This chapter is supported by long-term research in Bialowieza Forest see, [100–103]).

This is the biggest difference with managed forest properties; there is a significant reduction in the flammability of the area much quicker after timber processing after a given disturbance [104]. It is evident from the above that the riskiest period for the occurrence and intensive spread of forest fire in these spontaneously developing forests is within five years of the disturbance event [26].

Based on previous knowledge, we consider the period with the greatest danger for fire ignition to be from the second to third year after the disturbance due to the spontaneously developing vegetation and shrub layer, when herbs and grasses appear on the newly light-exposed forest floor [102]. In combination with flammable material that reaches the forest surface due to disturbance and is not yet largely decomposed, it creates ideal conditions for dangerous and very difficult-to-suppress forest fires [26,72]. The extremely difficult and demanding movement of firefighters and the transport of water in these disturbed areas during the suppression of a potential forest fire cannot be ignored (Figure 7) [50,102].

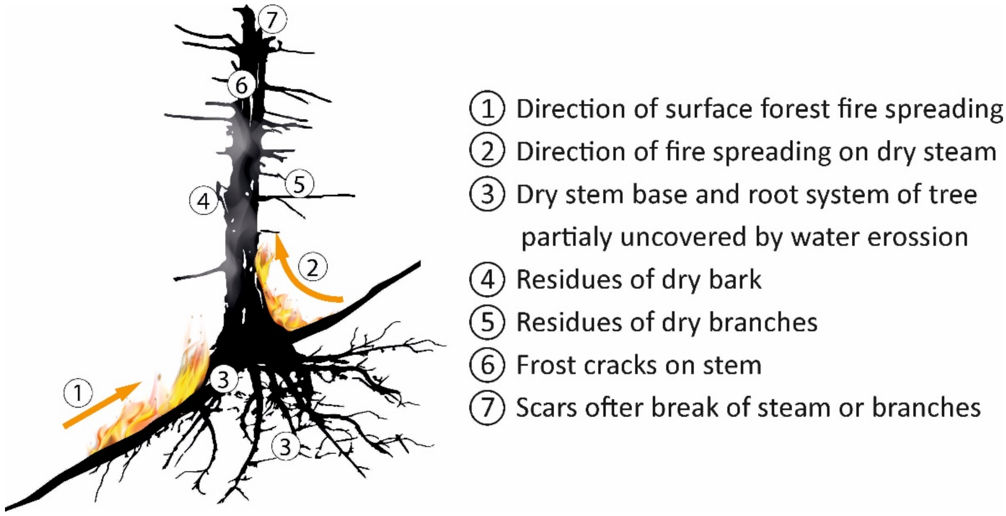

Figure 8. Degradation of standing trees killed by bark beetles in relation to fire.

5.2. Recommendations for Decreasing Fire Danger in Spontaneously Developed Forests

We recommend leaving a maximum of 30% of the biomass in spontaneously developing forest stands. It is necessary for all disturbed areas to be clear, all forest roads to be maintained in operable conditions, and all waterways and water supply points to remain accessible and usable. These measures are necessary, above all, for the possible passage of firefighting vehicles or the use of water supply points to suppress forest fires [50].

Furthermore, it is highly recommended that certain sections be completely cleared of all destroyed timber for the building of partial fire breaks, namely, along the main forest roads and in places that are easily accessible to fire brigades; this will also make disturbed areas less complex. These cleared areas must be wide enough (at least 30 to 50 m, ideally even more); sufficient width should ensure a momentary reduction in fire intensity, which can be advantageous when trying to suppress a forest fire [28,74,80,81]. Cleaning up the surroundings of these main forest roads in spontaneously developing forests will also ensure greater safety for future visitors [94,101]. To make this beneficial for stopping the spreading of fire, a small effort must be expanded to build firebreaks.

6. Fire Protection of Spontaneously Developed Forests in Central Europe

As previously mentioned, when a disturbance occurs, there is a significant increase in the probability of a forest fire and possibly increased burning intensity. Central European forests have already faced forest fires in disturbed areas. The pattern of these fires thus far has indicated a small-burned area. The situation clearly changed in the 2022 fire season. In Bohemian Switzerland National Park, most of the fire burned the forest stands destroyed by bark beetles. The fire reached a size of 1060 hectares [105], and another approximately 500 hectares were burned on the German side of the national park [106]. Another large forest fire occurred in Harz Mountain National Park, where approximately 300 hectares of the area were burned [107]. During this fire, for the first time, firefighting aircraft from the RescEU fleet launched in Germany [108].

The aforementioned forest fires took place in an environment that was left to spontaneously develop, and disturbance occurred. Nature protection strategies often neglect fire protection and measures for fuel load reduction in these places despite disturbances, perhaps not fully accounting for the danger of the situation, as in the aforementioned Bohemian Switzerland National Park and Harz Mountains National Park. Moreover, the current trends and plans of the European Union indicate that protected areas, potentially even forest areas with spontaneous development, will increase [109]. Required rules and procedures must be established for the purposes of fire protection in these areas regarding the population, biodiversity, and property. There are no specific regulations or laws ensuring fire protection in these spontaneously developed forest stands in Central European countries. If any guidelines are in place, they are not legally enforceable (Supplementary Material Table S1).

6.1. Poland

In Polish national parks, issues related to fire protection are similar to those in managed forests administered by the State Forests. In the event of a disturbance that disrupts the spatial system of the stand, local actions are taken based on forest management principles and expert knowledge. Local expertise and recommendations are developed for these types of areas to reconcile various forest functions. That is, for example, the case of fire protection guidelines in areas affected by wind disturbance [110]. Nevertheless, detailed laws or regulations do not exist.

6.2. Czech Republic

Within the framework of the legislation of the Czech Republic, there are currently no obligations in the field of fire prevention in disturbed areas, even in the management of spontaneously developing forests. The need to change the legislation after the fire in Bohemian Switzerland National Park has already been pointed out by some; for example, as stated by the Director General of the Fire and Rescue Service of the Czech Republic, "Legislative steps consist in the fact that, in some provisions, we will probably have to adjust the performance of state fire supervision and the duties of administrators, especially of national parks, in the area with spontaneous development of forest, in order to ensure the arrival of fire technic and equipment, to build fire breaks and to ensure enough water supply points". He further stated that, "the firemen had to cut through many original but overgrown roads in Bohemian Switzerland National Park in order to reach the fire and start suppression" [111].

6.3. Slovakia

Slovakia does not have established rules within the legislation that addresses the principle of fire protection of forests being allowed to spontaneously develop or having very limited forest management. Some fire protection guidelines have been developed, for example, in the High Tatras after the wind disaster in 2004 [50,67]. However, these procedures and principles are not part of the legislation, and it is very difficult to apply guidelines due to conflicts with nature conservation, and even partial application requires much effort from interested parties.

6.4. Austria

Austria does not have a specific law regarding how to minimize the probability of fire ignition in areas of spontaneously developing forest stands. There are several regulations or management principles now worked out [112,113].

6.5. Germany

The same case as in Austria or the Czech Republic is in Germany. There are no specific regulations or laws on how to address disturbed areas in relation to fire protection in spontaneously developed forest stands. For further information, see Table S1.

7. Maximize Prevention and Preparedness

Regardless of the applied management, further points are recommended to minimize the forest fire danger and maximize the effectiveness of fire suppression in these areas. The following steps should be processed by forest owners in close cooperation with local fire brigades:

- Develop or apply existing systems for monitoring fire danger in disturbed areas.
- Limit the access of people to the forest and ensure the safety of bystanders.
- Evaluate the coverage of the disturbance area by communication signals.

- Protect particularly endangered fragments by making additional firebreaks.
- Notify the territorial competent fire units of the fire hazard.
- Re-evaluate the number of technical means intended for fire protection and their numerical increase in the disturbed area.
- Equip members of the fire brigade with maps of forest roads and water supply points or ensure GIS data of these roads and water supply points.
- Analyze the possibility of using aerial firefighting (determination of landing and handling areas)

Ideally, during the timber processing of the disturbance, ensure that there are regular ground and aerial fire patrols [50,67].

8. When Forest Fire Occurred

The occurrence of a forest fire in a disturbed area leads, in most cases, to only a partial burnout of the available fuel; therefore, there is a high probability that additional forest fires will occur in these areas [114].

In the event of forest fires in wind-disturbed areas, a significant amount of flammable material will usually burn out. In wind-disturbed areas, the amount of fuel on the forest floor is greater due to the immediate movement of combustible material from the crown layer to the forest floor caused by the breakage and uprooting of trees (Figure 1). Burned wind-disturbed areas are, therefore, "less" dangerous for future wildfires than bark beetle outbreak areas.

In bark beetle outbreak areas, fuel is gradually released from treetops to the forest floor (Figure 1). In the event of a fire, a significant amount of the flammable material on the forest floor is burned [89]. However, depending on fire severity, the degree of decomposition, or the degree of timber processing completed after the bark beetle outbreak, a significant amount of flammable material remains in the disturbed area due to standing dead trees. Due to the degradation of these dead trees, additional flammable material will gradually appear on the surface of the forest floor (breaking off of branches and tops of crowns and uprooting of individuals). Therefore, soon after, another available fuel appears after the original forest fire [114]. An example of this is the fire in Bohemian Switzerland National Park. The photographs were taken three months after the forest fire and show an increasing amount of flammable material on the forest floor (Figure 9a,c) and in places that were not affected by the first fire (Figure 9b).

Figure 9. Ongoing fuel load in Bohemian Switzerland National Park despite a fire in the summer of 2022. (**a**) fallen trees in the burned area (black zone) after fire; (**b**) edge of unburned young forest destroyed by bark-beetles; (**c**) partially burned death trees.

The processes of regeneration of the forest floor after a forest fire are identical to those caused by the fall of needles during bark beetle outbreaks. A disturbance area provides enough space, light, and nutrients for the rapid onset of vegetation growth. This vegetation dries up in the autumn of the first or second year after the fire (depending on the time of the forest fire event) and thus creates an area that is easily ignited [76] with a large amount of flammable material, which has fallen on the forest floor due to degradation or has remained unburnt on the forest floor after the original fire [61,114].

Another consideration is that after a fire in the disturbed area is partially burned, standing and dead downed trees remain in the area. As a result of the burning, the surface of these partially burned trees became charred. The charred layer provides nutrients to soil during decomposition [115,116] but also becomes a natural inhibitor of decomposition and prolongs the presence of these partially charred individuals in the disturbed area. For that reason, the amount of flammable material remains in the areas affected by fire for a significantly longer time.

It is evident that these abovementioned phenomena take place, especially in forest stands left to spontaneously develop. Bark beetle outbreaks and wind events in stands with regular forest management regimes are usually processed before the regrowth of flammable vegetation occurs. Charred wood is also partially removed from the area.

9. Conclusions

The fact that one disturbance event creates ideal conditions for another disturbance in the form of a forest fire is evident, and these wind or bark beetle-disturbed areas in Central Europe should be a priority for fire protection. These areas quickly become very vulnerable to the occurrence of forest fires, and the burning of these areas tends to be intense, difficult to suppress, and affects people from a wide area, either through smoke, the necessity of evacuation, or, in the worst-case, damage or destruction of their property. To date, human losses due to forest fires have been rather rare in Central Europe.

It is necessary to acknowledge the connections between disturbances, forest management, and forest fires to understand the processes that influence vulnerability to forest fires and their intensity. The importance of forest fires in Central Europe is on the rise, and it is necessary to pay great attention to this issue and be prepared to manage these destructive events better. More fires are expected to burn in landscapes with a legacy of disturbance [117].

The European Union envisages an increase in protected areas and areas managed as spontaneous development, which will certainly also include forest stands. Therefore, we consider it necessary that when applying these principles, great emphasis is placed on fire protection and the existence of suitable technical and personnel equipment nearby in the event of a fire.

This article provides a basic overview of what happens after disturbance in relation to fire vulnerability and potential fire intensity. It also provides simple steps to reduce fire danger and increase preparedness for potential forest fires in disturbed areas. This paper aims to help foresters and policymakers better understand forest fire problems in these areas. The introduced principles and methods of securing fire protection in disturbed areas of managed and unmanaged forest stands should be further developed in detail at the level of individual states and should be included in legislation to be enforceable.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fire6080310/s1, Table S1: Fire protection situations in disturbed areas or spontaneously developed forests in Central Europe based on questions addressed to the coauthors representing respected local authorities in forest fire protection.

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References

1. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402. [PubMed]
2. Patacca, M.; Lindner, M.; Lucas-Borja, M.E.; Cordonnier, T.; Fidej, G.; Gardiner, B.; Hauf, Y.; Jasinevičius, G.; Labonne, S.; Linkevičius, E.; et al. Significant increase in natural disturbance impacts on European forests since 1950. *Glob. Chang. Biol.* **2023**, *29*, 1359–1376. [CrossRef]
3. Seidl, R.; Schelhaas, M.-J.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806–810. [PubMed]
4. Reyer, C.P.; Bathgate, S.; Blennow, K.; Borges, J.G.; Bugmann, H.; Delzon, S.; Faias, S.P.; Garcia-Gonzalo, J.; Gardiner, B.; Gonzalez-Olabarria, J.R.; et al. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environ. Res. Lett.* **2017**, *12*, 034027. [CrossRef]
5. Schelhaas, M.-J.; Nabuurs, G.-J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries: Natural disturbances in the European forests. *Glob. Chang. Biol.* **2003**, *9*, 1620–1633. [CrossRef]
6. Seidl, R.; Schelhaas, M.-J.; Lexer, M.J. Unraveling the drivers of intensifying forest disturbance regimes in Europe. *Glob. Chang. Biol.* **2011**, *17*, 2842–2852. [CrossRef]
7. Gregow, H.; Laaksonen, A.; Alper, M.E. Increasing large scale windstorm damage in Western, central and northern European forests, 1951–2010. *Sci. Rep.* **2017**, *7*, 46397. [CrossRef]
8. Ikonen, V.-P.; Kilpeläinen, A.; Zubizarreta-Gerendiain, A.; Strandman, H.; Asikainen, A.; Venäläinen, A.; Kaurola, J.; Kangas, J.; Peltola, H. Regional risks of wind damage in boreal forests under changing management and climate projections. *Can. J. For. Res.* **2017**, *47*, 1632–1645.
9. Senf, C.; Buras, A.; Zang, C.S.; Rammig, A.; Seidl, R. Excess forest mortality is consistently linked to drought across Europe. *Nat. Commun.* **2020**, *11*, 6200. [CrossRef]
10. Hlásny, T.; König, L.; Krokene, P.; Lindner, M.; Montagné-Huck, C.; Müller, J.; Seidl, R. Bark beetle outbreaks in Europe: State of knowledge and ways forward for management. *Curr. For. Rep.* **2021**, *7*, 138–165. [CrossRef]
11. Hlásny, T.; Zimová, S.; Merganičová, K.; Štěpánek, P.; Modlinger, R.; Turčáni, M. Devastating outbreak of bark beetles in the Czech Republic: Drivers, impacts, and management implications. *For. Ecol. Manag.* **2021**, *490*, 119075. [CrossRef]
12. Hlásny, T.; Krokene, P.; Liebhold, A.; Montagné-Huck, C.; Müller, J.; Qin, H.; Raffa, K.; Schelhaas, M.J.; Seidl, R.; Svoboda, M.; et al. *Living with Bark Beetles: Impacts, Outlook and Management Options From Science to Policy 8*; European Forest Institute: Joensuu, Finland, 2019.
13. Sommerfeld, A.; Rammer, W.; Heurich, M.; Hilmers, T.; Müller, J.; Seidl, R. Do bark beetle outbreaks amplify or dampen future bark beetle disturbances in Central Europe? *J. Ecol.* **2021**, *109*, 737–749. [CrossRef]
14. Zatloukal, V. Historical and current factors of the bark beetle calamity in the Šumava National Park. *Silva Gabreta* **1998**, *2*, 327–357.
15. Thom, D.; Seidl, R.; Steyrer, G.; Krehan, H.; Formayer, H. Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems. *For. Ecol. Manag.* **2013**, *307*, 293–302. [CrossRef]
16. Stadelmann, G.; Bugmann, H.; Meier, F.; Wermelinger, B.; Bigler, C. Effects of salvage logging and sanitation felling on bark beetle (*Ips typographus* L.) infestations. *For. Ecol. Manag.* **2013**, *305*, 273–281. [CrossRef]
17. Panayotov, M.; Bebi, P.; Tsvetanov, N.; Alexandrov, N.; Laranjeiro, L.; Kulakowski, D. The disturbance regime of Norway spruce forests in Bulgaria. *Can. J. For. Res.* **2015**, *45*, 1143–1153. [CrossRef]
18. Holeksa, J.; Jaloviar, P.; Kucbel, S.; Saniga, M.; Svoboda, M.; Szewczyk, J.; Szwagrzyk, J.; Zielonka, T.; Żywiec, M. Models of disturbance driven dynamics in the West Carpathian spruce forests. *For. Ecol. Manag.* **2017**, *388*, 79–89. [CrossRef]
19. Janda, P.; Trotsiuk, V.; Mikoláš, M.; Bače, R.; Nagel, T.A.; Seidl, R.; Seedre, M.; Morrissey, R.C.; Kucbel, S.; Jaloviar, P.; et al. The historical disturbance regime of mountain Norway spruce forests in the Western Carpathians and its influence on current forest structure and composition. *For. Ecol. Manag.* **2017**, *388*, 67–78. [CrossRef]
20. Don, A.; Bärwolff, M.; Kalbitz, K.; Andruschkewitsch, R.; Jungkunst, H.F.; Schulze, E.-D. No rapid soil carbon loss after a windthrow event in the High Tatra. *For. Ecol. Manag.* **2012**, *276*, 239–246. [CrossRef]
21. Vanická, H.; Holuša, J.; Resnerová, K.; Ferenčík, J.; Potterf, M.; Véle, A.; Grodzki, W. Interventions have limited effects on the population dynamics of Ips typographus and its natural enemies in the Western Carpathians (Central Europe). *For. Ecol. Manag.* **2020**, *470*, 118209. [CrossRef]
22. Fink, A.H.; Brücher, T.; Ermert, V.; Krüger, A.; Pinto, J.G. The European storm Kyrill in January 2007: Synoptic evolution, meteorological impacts and some considerations with respect to climate change. *Nat. Hazards Earth Syst. Sci.* **2009**, *9*, 405–423. [CrossRef]
23. Nikolov, C.; Konôpka, B.; Kajba, M.; Galko, J.; Kunca, A.; Janský, L. Post-disaster Forest Management and Bark Beetle Outbreak in Tatra National Park, Slovakia. *Mt. Res. Dev.* **2014**, *34*, 326–335. [CrossRef]
24. Cohen, J. Preventing disaster—Home ignitability in the wildland-urban interface. *J. For.* **2000**, *98*, 15–21.

25. Franklin, J.F.; Agee, J.K. Forging a science-based national forest fire policy. *Issues Sci. Technol.* **2003**, *20*, 59–66.
26. Jenkins, M.J.; Hebertson, E.; Page, W.; Jorgensen, C.A. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *For. Ecol. Manag.* **2008**, *254*, 16–34. [CrossRef]
27. Black, S.H.; Kulakowski, D.; Noon, B.R.; DellaSala, D.A. Do Bark Beetle Outbreaks Increase Wildfire Risks in the Central U.S. Rocky Mountains? Implications from Recent Research. *Nat. Areas J.* **2013**, *33*, 59–65. [CrossRef]
28. Omi, P.N. Theory and Practice of Wildland Fuels Management. *Curr. For. Rep.* **2015**, *1*, 100–117. [CrossRef]
29. Müller, M.M.; Vilà-Vilardell, L.; Vacik, H.; Mayer, C.; Mayr, S.; Carrega, P.; Maier, H. *Forest Fires in the Alps: State of Knowledge, Future Challenges and Options for an Integrated Fire Management*; EUSALP Action Group: Nice, France, 2020.
30. Bruchwald, A.; Dmyterko, E. Zastosowanie modelu ryzyka uszkodzenia drzewostanu przez wiatr do oceny prawdopodobieństwa lokalizacji szkód w lasach Regionalnej Dyrekcji Lasów Państwowych w Białymstoku. *Sylwan* **2019**, *163*, 629–636. [CrossRef]
31. Forzieri, G.; Girardello, M.; Ceccherini, G.; Spinoni, J.; Feyen, L.; Hartmann, H.; Beck, P.S.A.; Camps-Valls, G.; Chirici, G.; Mauri, A.; et al. Emergent vulnerability to climate-driven disturbances in European forests. *Nat. Commun.* **2021**, *12*, 1081. [CrossRef]
32. Klimo, E.; Hager, H.; Kulhavý, J. *Spruce Monocultures in Central Europe: Problems and Prospects*; European Forest Institute: Joensuu, Finland, 2000; Volume 33.
33. Hansen, J.; Spiecker, H. Conversion of Norway spruce (Picea abies [L.] Karst.) forests in Europe. In *Restoration of Boreal and Temperate Forests*; Stanturf, J.A., Ed.; CRC Press: Boca Raton, FL, USA, 2005; pp. 339–347.
34. Sierota, Z.; Grodzki, W.; Szczepkowski, A. Abiotic and Biotic Disturbances Affecting Forest Health in Poland over the past 30 Years: Impacts of Climate and Forest Management. *Forests* **2019**, *10*, 75. [CrossRef]
35. Frolking, S.; Palace, M.W.; Clark, D.B.; Chambers, J.Q.; Shugart, H.H.; Hurtt, G.C. Forest disturbance and recovery: A general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure. *J. Geophys. Res. Biogeosci.* **2009**, *114*, 1–27. [CrossRef]
36. Nagel, T.A.; Mikac, S.; Dolinar, M.; Klopcic, M.; Keren, S.; Svoboda, M.; Diaci, J.; Boncina, A.; Paulic, V. The natural disturbance regime in forests of the Dinaric Mountains: A synthesis of evi-dence. *For. Ecol. Manag.* **2017**, *388*, 29–42. [CrossRef]
37. Bebi, P.S.E.P.; Seidl, R.; Motta, R.; Fuhr, M.; Firm, D.; Krumm, F.; Kulakowski, D. Changes of forest cover and disturbance regimes in the mountain forests of the Alps. *For. Ecol. Manag.* **2017**, *388*, 43–56. [CrossRef]
38. De Cárcer, P.S.; Mederski, P.S.; Magagnotti, N.; Spinelli, R.; Engler, B.; Seidl, R.; Eriksson, A.; Eggers, J.; Bont, L.G.; Schweier, J. The Management Response to Wind Disturbances in European Forests. *Curr. For. Rep.* **2021**, *7*, 167–180. [CrossRef]
39. Křístek, Š.; Holuša, J. Historical abiotic damage to forests in the Moravian-Silesian Beskids (Czech Republic). *For. J.* **2015**, *61*, 196–202. [CrossRef]
40. Ginszt, T.; Laskowska-Ginszt, A. Ten years (2012–2021) of spruce bark beetle *Ips typographus* (L.) activity in the Bi-alowieza Forest District of the Bialowieza Primeval Forest. *Sylwan* **2022**, *166*, 183–193.
41. Raffa, K.F.; Aukema, B.H.; Bentz, B.J.; Carroll, A.L.; Hicke, J.A.; Turner, M.G.; Romme, W.H. Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *BioScience* **2008**, *58*, 501–517. [CrossRef]
42. Baier, P.; Pennerstorfer, J.; Schopf, A. PHENIPS—A comprehensive phenology model of *Ips typographus* (L.) (Col., Scolytinae) as a tool for hazard rating of bark beetle infestation. *For. Ecol. Manag.* **2007**, *249*, 171–186. [CrossRef]
43. Berec, L.; Doležal, P.; Hais, M. Population dynamics of *Ips typographus* in the Bohemian Forest (Czech Republic): Validation of the phenology model PHENIPS and impacts of climate change. *For. Ecol. Manag.* **2013**, *292*, 1–9. [CrossRef]
44. Jönsson, A.M.; Appelberg, G.; Harding, S.; Bärring, L. Spatio-temporal impact of climate change on the activity and voltinism of the spruce bark beetle, Ips typographus. *Glob. Chang. Biol.* **2009**, *15*, 486–499. [CrossRef]
45. Jakoby, O.; Lischke, H.; Wermelinger, B. Climate change alters elevational phenology patterns of the European spruce bark beetle (*Ips typographus*). *Glob. Chang. Biol.* **2019**, *25*, 4048–4063. [CrossRef]
46. Huang, J.; Kautz, M.; Trowbridge, A.M.; Hammerbacher, A.; Raffa, K.F.; Adams, H.D.; Goodsman, D.W.; Xu, C.; Meddens, A.J.H.; Kandasamy, D.; et al. Tree defence and bark beetles in a drying world: Carbon partitioning, functioning and modelling. *N. Phytol.* **2019**, *225*, 26–36. [CrossRef] [PubMed]
47. Matthews, B.; Netherer, S.; Katzensteiner, K.; Pennerstorfer, J.; Blackwell, E.; Henschke, P.; Schopf, A. Transpiration deficits increase host susceptibility to bark beetle attack: Experimental observations and practical outcomes for *Ips typographus* hazard assessment. *Agric. For. Meteorol.* **2018**, *263*, 69–89. [CrossRef]
48. Collins, B.; Rhoades, C.; Battaglia, M.; Hubbard, R. The effects of bark beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage logged and untreated lodgepole pine forests. *For. Ecol. Manag.* **2012**, *284*, 260–268. [CrossRef]
49. Jenkins, M.J.; Runyon, J.B.; Fettig, C.J.; Page, W.G.; Bentz, B.J. Interactions among the Mountain Pine Beetle, Fires, and Fuels. *For. Sci.* **2014**, *60*, 489–501. [CrossRef]
50. Hlaváč, P.; Chromek, I.; Majlingová, A.; Osvald, A. *Projekt Protipožiarnej Ochrany na Území Vysokých Tatier po Vetrovej Kalamite: Realizačný Projekt*; Technical University Zvolen: Zvolen, Slovakia, 2005.
51. Jenkins, M.J.; Hebertson, E.G.; Page, W.G.; Lindquist, W.E. *Resources for Managing the Impact of Bark Beetle Activity on Conifer Fuels and Fire Behavior*; Utah State University: Logan, UT, USA, 2011.
52. Page, W.; Jenkins, M.J. Predicted fire behavior in selected mountain pine beetle–infested lodgepole pine. *For. Sci.* **2007**, *53*, 662–674.
53. Billings, R.F.; Clarke, S.R.; Espino-Mendoza, V.; Cordón Cabrera, P.; Meléndez Figueroa, B.; Ramón Campos, J.; Baeza, G. Bark beetle outbreaks and fire: A devastating combination for Central America's pine forests. *Unasylva* **2004**, *55*, 7.

54. Schoennagel, T.; Veblen, T.T.; Negron, J.F.; Smith, J.M. Effects of Mountain Pine Beetle on Fuels and Expected Fire Behavior in Lodgepole Pine Forests, Colorado, USA. *PLoS ONE* **2012**, *7*, e30002. [CrossRef] [PubMed]
55. Anderson, H.E. Heat transfer and fire spread. In *Intermountain Forest and Range Experiment Station*; Forest Service, US Department of Agriculture: Washington, DC, USA, 1969; Volume 69.
56. Thomas, P.A.; McAlpine, R.S.; Hobson, P. *Fire in the Forest*; Cambridge University Press: Cambridge, UK, 2010.
57. Byram, G.M. Combustion of forest fuels. In *Forest fire: Control and Use*; McGraw-Hill: NewYork, NK, USA, 1959; pp. 61–89.
58. Alexander, M.E.; Cruz, M.G. Fireline intensity. In *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 1–8.
59. Rossi, J.L.; Chatelon, F.J.; Marcelli, T. Fire intensity. In *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*; Springer International Publishing: Cham, Switzerland, 2020; pp. 391–397.
60. Fischer, A.; Fischer, H.S.; Kopecký, M.; Macek, M.; Wild, J. Small changes in species composition despite stand-replacing bark beetle outbreak in *Picea abies* mountain forests. *Can. J. For. Res.* **2015**, *45*, 1164–1171. [CrossRef]
61. Kéérik, A.A. Decomposition of wood. In *Biology of Plant Litter Decomposition*; Dickinson, C.H., Pugh, G.J.F., Eds.; Academic Press: New York, NY, USA, 2012; pp. 129–174.
62. Platt, W.J.; Gottschalk, R.M. Effects of exotic grasses on potential fine fuel loads in the groundcover of south Florida slash pine savannas. *Int. J. Wildland Fire* **2001**, *10*, 155–159. [CrossRef]
63. Brooks, M.L.; D'Antonio, C.M.; Richardson, D.M.; Grace, J.B.; Keeley, J.E.; DiTomaso, J.M.; Hobbs, R.J.; Pellant, M.; Pyke, D. Effects of Invasive Alien Plants on Fire Regimes. *Bioscience* **2004**, *54*, 677–688. [CrossRef]
64. McDonald, C.J.; McPherson, G.R. Creating Hotter Fires in the Sonoran Desert: Buffelgrass Produces Copious Fuels and High Fire Temperatures. *Fire Ecol.* **2013**, *9*, 26–39. [CrossRef]
65. Wilson, J.B.; Agnew, A.D. Positive-feedback Switches in Plant Communities. In *Advances in Ecological Research*; Academic Press: New York, NY, USA, 1992; pp. 263–336.
66. Cannon, J.B.; O'brien, J.J.; Loudermilk, E.L.; Dickinson, M.B.; Peterson, C.J. The influence of experimental wind disturbance on forest fuels and fire characteristics. *For. Ecol. Manag.* **2014**, *330*, 294–303. [CrossRef]
67. Hlaváč, P.; Chromek, I.; Majlingová, A.; Osvald, A. *Od Projektu Protipožiarnej Ochrany Lesa vo Vysokých Tatrách po Vetrovej Kalamite po Zmenu Legislatívy v Oblasti Ochrany Lesa pred Požiarmi v Podmienkach Slovenskej Republiky*; Technical University Zvolen: Zvolen, Slovakia, 2009.
68. Hlásny, T.; Augustynczik, A.L.; Dobor, L. Time matters: Resilience of a post-disturbance forest landscape. *Sci. Total. Environ.* **2021**, *799*, 149377. [CrossRef]
69. Dvořák, J.; Bystrický, R.; Hošková, P.; Hrib, M.; Jarkovská, M.; Kováč, J.; Krilek, J.; Natov, P.; Natovová, L. *The Use of Harvester Technology in Production Forests*; Lesnická práce: Kostelec nad Černými lesy, Czech Republic, 2011.
70. Szewczyk, G.; Sowa, J.M.; Grzebieniowski, W.; Kormanek, M.; Kulak, D.; Stańczykiewicz, A. Sequencing of har-vester work during standard cuttings and in areas with windbreaks. *Silva Fenn.* **2014**, *48*, 1159. [CrossRef]
71. Ganteaume, A.; Camia, A.; Jappiot, M.; San-Miguel-Ayanz, J.; Long-Fournel, M.; Lampin, C. A Review of the Main Driving Factors of Forest Fire Ignition Over Europe. *Environ. Manag.* **2012**, *51*, 651–662. [CrossRef]
72. Crotteau, J.S.; Keyes, C.R.; Hood, S.M.; Affleck, D.L.R.; Sala, A. Fuel dynamics after a bark beetle outbreak impacts experimental fuel treatments. *Fire Ecol.* **2018**, *14*, 13. [CrossRef]
73. Fernandes, P.M.; Botelho, H.S. A review of prescribed burning effectiveness in fire hazard reduction. *Int. J. Wildland Fire* **2003**, *12*, 117–128. [CrossRef]
74. Loehle, C. Applying landscape principles to fire hazard reduction. *For. Ecol. Manag.* **2004**, *198*, 261–267. [CrossRef]
75. Rummer, R.B. *A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States*; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2005.
76. Knapp, E.E.; Varner, J.M.; Busse, M.D.; Skinner, C.N.; Shestak, C.J. Behaviour and effects of prescribed fire in mas-ticated fuelbeds. *Int. J. Wildland Fire* **2011**, *20*, 932–945. [CrossRef]
77. Swift, M.J.; Healey, I.N.; Hibberd, J.K.; Sykes, J.M.; Bampoe, V.; Nesbitt, M.E. The decomposition of branch-wood in the canopy and floor of a mixed deciduous woodland. *Oecologia* **1976**, *26*, 139–149. [CrossRef]
78. McKeand, S.E.; Abt, R.C.; Allen, H.L.; Li, B.; Catts, G.P. What are the best loblolly pine genotypes worth to landowners? *J. For.* **2006**, *104*, 352–358.
79. 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]
80. Jones, J.G.; Chew, J.D. Applying simulation and optimization to evaluate the effectiveness of fuel treatments for different fuel conditions at landscape scales. In Proceedings of the Joint Fire Science Conference and Workshop, San Diego, CA, USA, 5–9 April 1999; pp. 89–95.
81. Finney, M.A. Landscape fire simulation and fuel treatment optimization. In *Methods for Integrating Modeling of Landscape Change: Interior Northwest Landscape Analysis System*; Gen. Tech. Rep. PNW-GTR-610; US Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2004; pp. 117–131.
82. Fargione, J.; Haase, D.L.; Burney, O.T.; Kildisheva, O.A.; Edge, G.; Cook-Patton, S.C.; Chapman, T.; Rempel, A.; Hurteau, M.D.; Davis, K.T.; et al. Challenges to the Reforestation Pipeline in the United States. *Front. For. Glob. Chang.* **2021**, *4*, 629198. [CrossRef]

83. King, S.L.; Keeland, B.D. Evaluation of Reforestation in the Lower Mississippi River Alluvial Valley. *Restor. Ecol.* **1999**, *7*, 348–359. [CrossRef]
84. Ouzts, J.; Kolb, T.; Huffman, D.; Meador, A.S. Post-fire ponderosa pine regeneration with and without planting in Arizona and New Mexico. *For. Ecol. Manag.* **2015**, *354*, 281–290. [CrossRef]
85. Omi, P.N.; Martinson, E.J. Effect of fuels treatment on wildfire severity. In *Final Report. Joint Fire Science Program Governing Board, Western Forest Fire Research Center*; Colorado State University: Fort Collins, CO, USA, 2002.
86. Kreye, J.K.; Varner, J.M.; Knapp, E.E. Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory. *Int. J. Wildland Fire* **2011**, *20*, 308–317. [CrossRef]
87. Kilgore, B.M.; Sando, R.W. Crown-fire potential in a sequoia forest after prescribed burning. *For. Sci.* **1975**, *21*, 83–87.
88. Cruz, M.G.; Butler, B.W.; Alexander, M.E.; Forthofer, J.M.; Wakimoto, R.H. Predicting the ignition of crown fuels above a spreading surface fire. Part I: Model idealization. *Int. J. Wildland Fire* **2006**, *15*, 47–60. [CrossRef]
89. Jenkins, M.J.; Page, W.G.; Hebertson, E.G.; Alexander, M.E. Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. *For. Ecol. Manag.* **2012**, *275*, 23–34. [CrossRef]
90. Parviainen, J.; Bücking, W.; Vandekerkhove, K.; Schuck, A.; Päivinen, R. Strict forest reserves in Europe: Efforts to enhance biodiversity and research on forests left for free development in Europe (EU-COST-Action E4). *For. Int. J. For. Res.* **2000**, *73*, 107–118. [CrossRef]
91. Carr, E. "Mission 66": Modernism and the National Park Dilemma in the United States, 1945–1972. Ph.D. Thesis, University of Edinburgh, Edinburgh, Scotland, 2006.
92. FAO. *Fire Management Global Assessment 2006. A Thematic Study Prepared in the Framework of the Global Forest Resources Assessment 2005*; Forestry Paper 151; Food and Agriculture Organization of the United Nations: Rome, Italy, 2007.
93. Peterson, D.L. *Forest Structure and Fire Hazard in Dry Forests of the Western United States*; US Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2005; Volume 628.
94. Snowdon, B.; Nielsen, M.; Thompson, R. *Wildlife/Dangerous Tree Assessor's Course Workbook*; Ministry of Environment and Climate Change Strategy: Victoria, BC, Canada, 2019.
95. Mezei, P.; Blaženec, M.; Grodzki, W.; Škvarenina, J.; Jakuš, R. Influence of different forest protection strategies on spruce tree mortality during a bark beetle outbreak. *Ann. For. Sci.* **2017**, *74*, 65. [CrossRef]
96. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96. [CrossRef]
97. Whigham, D.F.; Olmsted, I.; Cano, E.C.; Harmon, M.E. The Impact of Hurricane Gilbert on Trees, Litterfall, and Woody Debris in a Dry Tropical Forest in the Northeastern Yucatan Peninsula. *Biotropica* **1991**, *23*, 434. [CrossRef]
98. Milne-Rostkowska, F.; Holeksa, J.; Bogdziewicz, M.; Piechnik, Ł.; Seget, B.; Kurek, P.; Buda, J.; Żywiec, M. Where can palatable young trees escape herbivore pressure in a protected forest? *For. Ecol. Manag.* **2020**, *472*, 118221. [CrossRef]
99. Binkley, D.; Fisher, R.F. *Ecology and Management of Forest Soils*; John Wiley & Sons: Hoboken, NJ, USA, 2019.
100. Szczygieł, R.; Kwiatkowski, M.; Kołakowski, B. Forest Fire Risk at Białowieża Primeval Forest. *Bezp. I Tech. Pozar.* **2016**, *43*, 143–160.
101. Szczygieł, R.; Kwiatkowski, M.; Kolakowski, B. Influence of bark beetle infestation on the forest fire risk in the Białowieża Forest. *Sylwan* **2018**, *162*, 955–964.
102. Szczygieł, R.; Kwiatkowski, M.; Tyburski, Ł. *Monitoring of the Fire Hazard of the Białowieża Forest as a Tool for Crisis Management and Regulation*; Fire Protection Laboratory: Raszyn, Poland, 2020.
103. Szczygieł, R.; Kwiatkowski, M.; Tyburski, Ł. *Wpływ Rozpadu Drzewostanów w Wyniku Gradacji Kornika Drukarza (Ips typographus) na Zagrożenie Pożarowe Puszczy Białowieskiej*; Fire Protection Laboratory: Raszyn, Poland, 2023.
104. Omi, P.N. *Forest Fires: A Reference Handbook*; ABC-CLIO: Santa Barbara, CA, USA, 2005.
105. Intellinews. Off-the-Scale Wildfire Devastates Czech Republic's Bohemian Switzerland National Park. 2022. Available online: https://www.intellinews.com/off-the-scale-wildfire-devastates-czech-republic-s-bohemian-switzerland-national-park-251816/ (accessed on 27 July 2022).
106. DW. Fires "Under Control" in Saxony and Brandenburg. 2022. Available online: https://www.dw.com/en/wildfires-in-saxony-and-brandenburg-under-control/a-62613303 (accessed on 27 July 2022).
107. MDR. Waldbrand am Brocken: Streit um Grösse des Feuers. 2022. Available online: https://www.mdr.de/nachrichten/sachsen-anhalt/magdeburg/harz/waldbrand-brocken-streit-betroffene-flaeche-100.html (accessed on 19 September 2022).
108. News in Germany. Forest Fire in the Harz Mountains: Italian Fire-Fighting Aircraft Should Help. 2022. Available online: https://newsingermany.com/forest-fire-in-the-harz-mountains-italian-fire-fighting-aircraft-should-help/ (accessed on 19 September 2022).
109. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. In *Youth Opportunities Initiative*; European Commission: Brussels, Belgium, 2011.
110. Kwiatkowski, M.; Szczygieł, R.; Kołakowski, B. *Opracowanie Programów Zabezpieczenia Przeciwpożarowego Ter-Enów Poklęskowych dla Nadleśnictw: Czersk, Przymuszewo, Rytel i Szubin (Development of Fire Prevention Programmes for the Post-Disaster Areas the Forest Districts in: Czersk, Przymuszewo, Rytel and Szubin.)*; Fire Protection Laboratory: Raszyn, Poland, 2020.
111. Idnes. "Kdo Chce Mít Z Lesa Prales, Potřebuje vyšetřit, řEkl K Požáru v Hřensku Poslanec". 2022. Available online: https://www.idnes.cz/zpravy/domaci/pozar-ceske-svycarsko-zakon-pozarni-ochrana.A220915_124824_domaci_hovo (accessed on 15 September 2022).

112. Bundesministerium. Risikokarte auf Gemeindeebene. 2023. Available online: https://info.bml.gv.at/themen/wald/wald-und-naturgefahren/waldbrand/risikokarte-gemeindeebene.html (accessed on 9 February 2023).
113. Bundesministerum. Brennpunkt Wald. *Land- und Forstwirtschaft Regionen und Wasserwirtschaft.* 2022. Available online: https://info.bml.gv.at/service/publikationen/wald/brennpunkt-wald-aktionsprogramm-waldbrand.html;%20https://www.alpine-region.eu/results/forest-fires-alps-state-knowledge-and-further-challenges (accessed on 15 May 2022).
114. Agee, J.K. Monitoring postfire tree mortality in mixed-conifer forests of Crater Lake. Oregon. *Nat. Areas J.* **2003**, *23*, 114–120.
115. Marañón-Jiménez, S.; Castro, J. Effect of decomposing post-fire coarse woody debris on soil fertility and nutrient availability in a Mediterranean ecosystem. *Biogeochemistry* **2012**, *112*, 519–535. [CrossRef]
116. Marañón-Jiménez, S.; Castro, J.; Fernández-Ondoño, E.; Zamora, R. Charred wood remaining after a wildfire as a reservoir of macro- and micronutrients in a Mediterranean pine forest. *Int. J. Wildland Fire* **2013**, *22*, 681–695. [CrossRef]
117. Talucci, A.C.; Meigs, G.W.; Knudby, A.; Krawchuk, M.A. Fire severity and the legacy of mountain pine beetle outbreak: High-severity fire peaks with mixed live and dead vegetation. *Environ. Res. Lett.* **2022**, *17*, 124010. [CrossRef]