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Review

Managing Wildfire for Whitebark Pine Ecosystem Restoration in western North America

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Abstract: Wildfire in declining whitebark pine forests can be a tool for ecosystem restoration or an ecologically harmful event. This document presents a set of possible wildfire management practices for facilitating the restoration of whitebark pine across its range in Western North America. These management actions are designed to enhance whitebark pine resilience and health, while also being effective wildfire management measures. The actions are presented by the three phases of the wildfire continuum: Before, during, and after a wildfire. Current pre-wildfire restoration actions, such as mechanical thinning's, prescribed burning, and fuel treatments, can also be designed to be fuel treatment activities that allow more effective suppression of wildfires when needed. Three wildfire strategies can be implemented while the wildfire is burning—full suppression, partial suppression, and wildland fire use (letting some fires burn under acceptable conditions)—for protecting valuable whitebark pine trees and for ecosystem restoration. Finally, post-wildfire activities include planting rust-resistant seedlings and monitoring effects of the wildfires. Recommended wildfire management practices for the wildfire continuum are specified by region, site type, and stand type in the last section of this paper.

Keywords: wildland fire use; wildland fire; prescribed fire; controlled wildfires; fire management; five-needle pine ecosystems; restoration

1. Introduction

Wildfires burning in declining whitebark pine (*Pinus albicaulis* Englem.) forests can be both a benefit and a threat [1]. Wildfires can be an effective means of killing encroaching shade tolerant, fire sensitive conifer competition in late seral whitebark pine stands, especially if the pines are declining due to the mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) and white pine blister rust (WPBR; *Cronartium ribicola* J.C.Fisch.) [2]. However, some of the whitebark pine trees that survived MPB and WPBR in these declining stands may be putatively rust-resistant, providing the vital foundation for future whitebark pine restoration efforts [3]; loss of rust-resistant trees from wildfire would severely reduce the chance for successful future whitebark pine regeneration [4,5]. While there is high geographic variability, wildfires are common on many of the high mountain landscapes of Western North America that support whitebark pine [6–8], and they are predicted to increase on high elevation landscapes throughout Western North America because of climate change [9–11]. Therefore, it is vitally important that any whitebark pine restoration strategy include actions to enhance the benefits and reduce the losses from wildfires [12]. Wildfires, in this document, are those unplanned wildland fires that usually start from lightning ignitions and burn across the high mountain landscapes [13]. Wildfires can be actively suppressed (uncontrolled wildfires) or they can be allowed to burn under a prescribed set of weather conditions (controlled wildfires or wildland fire use).

Wildfire management is often described using a circular continuum (Figure 1). There are wildfire planning and proactive activities that are implemented before the wildfire occurs (pre-fire environment) to reduce the impacts of wildfires and to allow firefighters to fight wildfires more safely (e.g., fuel treatments) [14]. Then, there are suppression activities that occur while the wildfire is burning (fire environment), such as backfiring, retardant drops, and fireline construction. Finally, there are those activities that occur after a wildfire has burned to mitigate adverse impacts (post-fire environment), such as erosion control, site stabilization, and planting. Wildfire management for whitebark pine restoration must deal with all fire management activities that occur before, during, and after a wildfire. In this paper, wildland fire management includes both managing wildfires and implementing prescribed fires, while wildfire management includes both uncontrolled wildfires, which are actively suppressed, and controlled wildfires, which are sometimes called wildland fire use (WFU), wildland fire for resource benefit, and prescribed natural fires, where a wildfire is allowed to burn under a set of acceptable weather conditions. In this report, the term "wildfire" will be used to denote uncontrolled wildfires that are actively suppressed and WFU will be used to denote controlled wildfires or those wildfires that are allowed to burn within specific parameters.

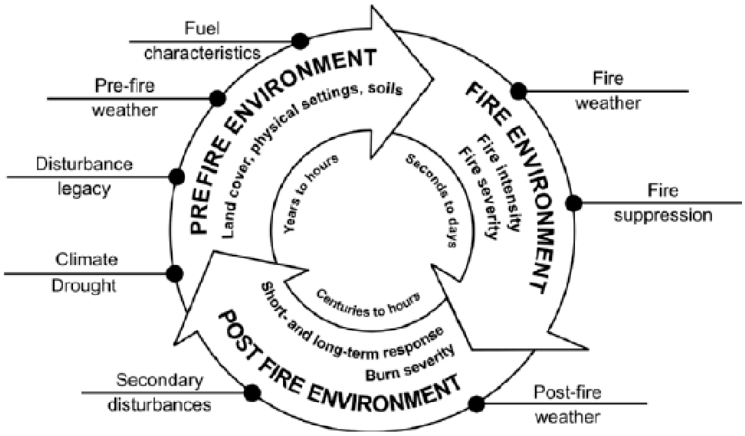

Figure 1. The continuum of wildfire management.

Numerous management guides and strategies have been written to facilitate restoration of declining whitebark pine ecosystems. Keane, Tomback [3] wrote a range-wide strategy for restoring whitebark pine and then Keane, Holsinger [12] wrote a companion guide to the range-wide strategy that discusses how to conduct restoration activities in the context of climate change. Several other restoration strategies were written by land management agencies for implementation at smaller spatial scales such as the Greater Yellowstone Ecosystem [15], the Pacific Northwest [16], and Glacier National Park [17]. However, the management of wildfires in whitebark pine restoration efforts is rarely addressed in most of these documents. There needs to be an explicit strategy and a corresponding set of management practices for how to manage wildfires on high mountain landscapes across the range of whitebark pine. How wildfires are managed may dictate the success or failure of other whitebark pine restoration treatments, and vice versa (many whitebark pine restoration actions can enhance the success of wildfire management).

This report details general management actions for managing wildfire in whitebark pine ecosystems across the geographic range of the species. These actions are specified in Table 1 and the material in the next sections provide context for Table 1. First, objectives for wildfire management in whitebark pine communities are presented to provide a framework for understanding management actions. Then, a set of stratifications are described to link wildfire management actions to specific whitebark pine geographical areas, biophysical settings, and stand conditions. The next section details the management actions that can be used for wildfire management and defines specific terminology. Then, the set of wildfire management practices are presented in Table 1 with several other tables defining terms (Table 2) and tuning Table 1 actions to specific geographic areas (Table 3).

2. Wildfire Management Objectives

Considering that wildfires play important roles in whitebark pine ecology, there are several key objectives identified for the restoration of whitebark pine forests that concern wildfire management [3]:

- Reduce mortality of known high value whitebark pine trees (e.g., plus trees—trees identified by managers to be putatively rust-resistant).
- Reduce competing, shade-tolerant tree species in high elevation whitebark pine communities.
- Increase post-fire whitebark regeneration through the creation of habitat that facilitates caching by the Clark's nutcracker and is also free from shade-tolerant competition so that planted and volunteer rust-resistant whitebark pine seedlings will be able to grow without competition.
- Create heterogeneous landscapes to ensure spatial resilience in the face of climate change [1,18–20].

It is important that all wildfire management strategies, and the actions used to implement these strategies, be implemented at the landscape level, not only at the stand scale, because wildfire is a landscape process. This makes informed wildfire management in whitebark pine forests incredibly important because wildfire treatments are implemented at the most effective scale for the restoration of whitebark pine ecosystems.

3. Whitebark Pine Stratifications

In this report, the set of wildfire management actions or practices are reported in Table 1 by three major categories—geographic region within the range of whitebark pine, biophysical site type, and stand type.

3.1. Geographic Region

This report covers the entire range of whitebark pine in western North America, but it is difficult if not impossible to provide one set of detailed wildfire management actions that would be applicable everywhere. For the purposes of this report, the ecological zones map for whitebark pine developed by the US Fish and Wildlife Service was used to divide the area into different ecologically distinct regions (Figure 2). Differences in climate, soils, topography, and ecology are discussed in USFWS (Unitied States Fish and Wildlife Service) [21].

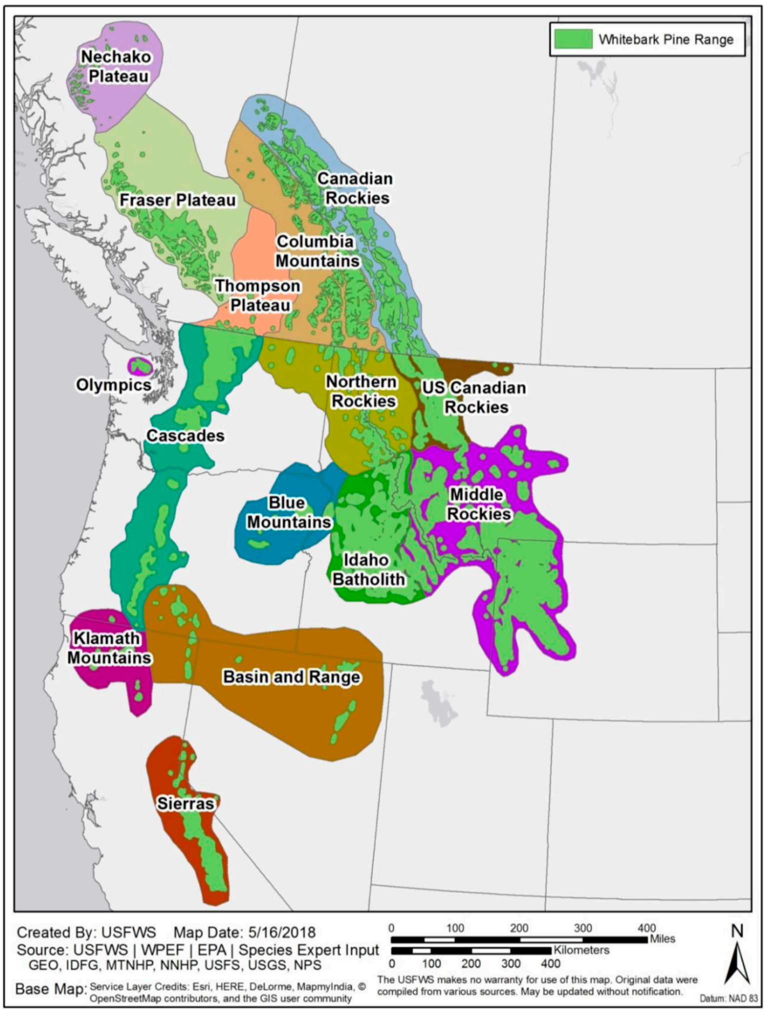

Figure 2. The regions used by the US Fish and Wildlife Service for evaluation whitebark pine for conservation. These regions are used in this paper.

3.2. Site Types

In general, whitebark pine ecosystems occur on three major high mountain biophysical settings [22] (Figure 3). On the productive upper subalpine sites, whitebark pine is the major seral species that is eventually replaced by the more shade-tolerant subalpine fir (*Abies lasiocarpa* (Hooker) Nuttall), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), or mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), depending on geographic region [23]. These sites, referred to as seral whitebark pine sites in this report (SERAL), and support upright, closed-canopy forests in the lower portions of the upper subalpine, just above or overlapping with the elevational limit of the shade-intolerant lodgepole pine (*Pinus contorta* Douglas) (Figure 3a), and the two species can often share dominance. Other minor species found on these sites are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), limber pine (*Pinus flexilis* E.James), and alpine larch (*Larix lyalli* Parl.) [22,24]. It is on these sites where wildfires can kill the shade tolerant competitors of whitebark pine and create competition-free habitat for nutcracker caching that results in whitebark pine regeneration. This is the most common site type and is found mostly in regions in the US and Canadian Rocky Mountains.

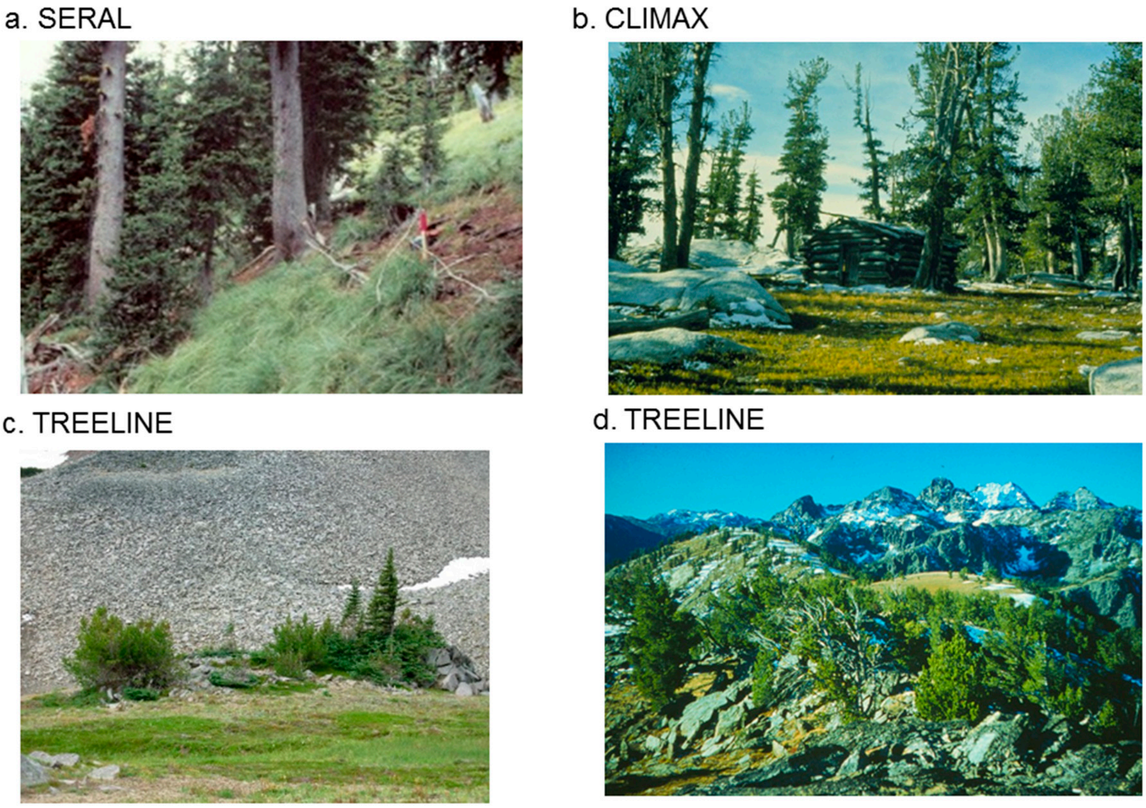

Figure 3. The three site types used in this report to stratify wildfire management actions: (**a**) seral (whitebark pine is seral to fir, spruce, hemlock), (**b**) climax (whitebark pine is the only dominant able to grow into a forest), (**c**), and (**d**) treeline.

Sites where whitebark pine is the only major tree species able to successfully dominate high-elevation settings are called climax whitebark pine sites (CLIMAX) in this report and often occur on harsh sites in the upper subalpine forests and at treeline on relatively dry, cold slopes [23,25] (Figure 3b). Other species, such as subalpine fir, spruce, and lodgepole pine, can occur on these sites, but as scattered individuals with truncated growth forms [26] Alpine larch is often found on north-facing climax whitebark pine sites, often in association with sub-surface water [27]. Whitebark pine is mostly self-replacing in these open communities. These site types are often found in the Sierra, Kalamath, Cascades, and Basin and Range regions (Figure 2).

The last site type is the alpine treeline ecotone (TREELINE) where whitebark pine can also occur as krummholz, elfin forests, clusters, groves, tree islands, and timber atolls (Figure 3c,d) [26,28,29]. There are some sites where whitebark pine occurs as a minor seral in lower subalpine sites [24,30], but these are not addressed in this report.

3.3. Stand Types

Several stand conditions are recognized in this report and used in the wildfire management practices guide in Table 1 (Figure 4). There is no definitive key to uniquely identify each stand type on the ground so there may be some overlap across stand type categories. The recently burned or treated stands in whitebark pine habitat (BURNED) (Figure 4a). Here, seedlings are sparse and widely scattered and the ground surface may still have char present. In general, these stand types occur from 1–20 years after a burn and tree regeneration is so limited that the stand cannot be categorized as a seedling stand.

The next set of stand types are seral stages of whitebark pine dominated forests (Figure 4b–d) [31]. First are the early seral stands dominated by whitebark pine seedlings and saplings (EARLY). In these stands, whitebark pine trees less than 10 cm or (4.5 inches) DBH (diameter breast height) have the plurality of canopy cover and density over all other tree species. In general, seedlings are below 1.37 m (4.5 ft) tall and saplings are below 10 cm DBH (4.5 inches). Following EARLY stands along the successional trajectory are the mid-seral (pole, mature) stands dominated by whitebark pine (MID). These trees are above 10 cm DBH but below 40 cm (16 inches) DBH. Finally, in the successional cycle are the late seral stands dominated by the whitebark pine on lands that could support whitebark pine, but also contain substantial amounts of the shade-tolerant competitors (LATE), which are trees above the 40 cm DBH threshold.

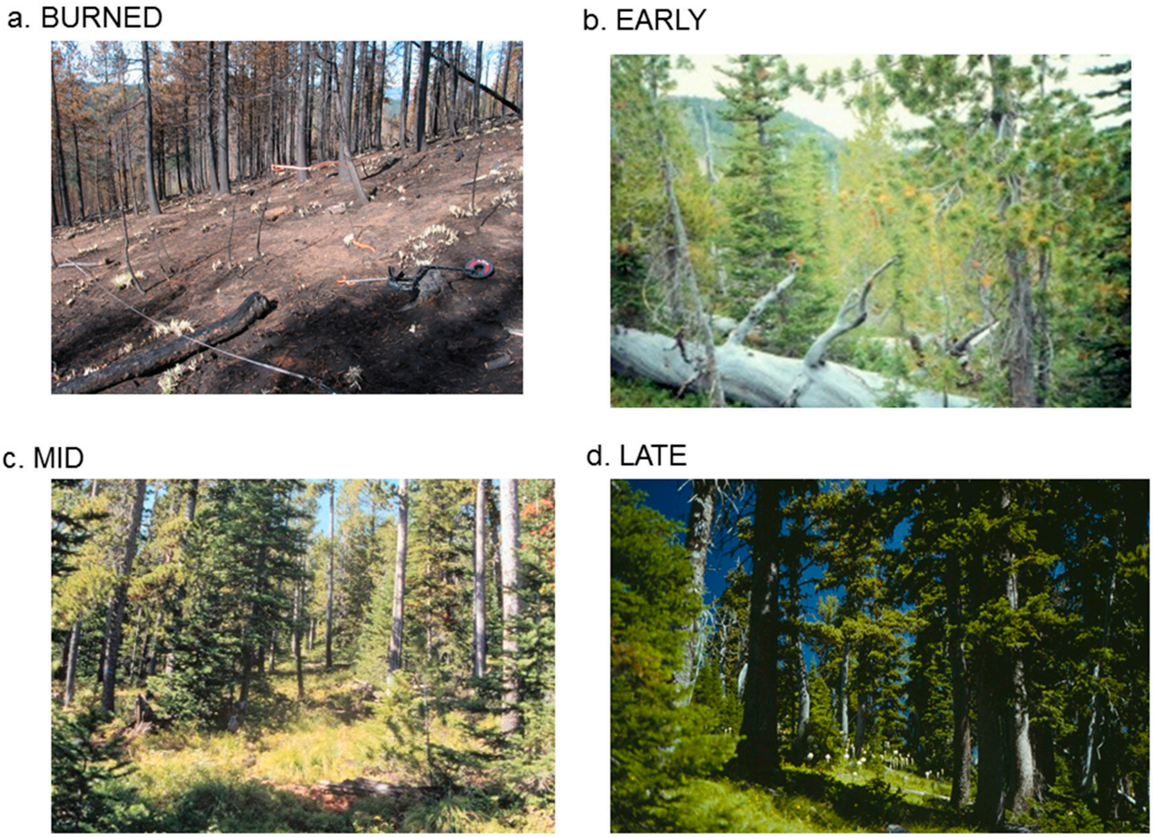

Figure 4. Four of the eight stand types used to stratify wildfire management actions. (**a**) recently burned stands, (**b**) early seral stands, (**c**) mid-seral stands, and (**d**) late seral stands that contain significant fir, spruce, mountain hemlock.

Stands of any seral stage that are dominated by the competitors of whitebark pine such as subalpine fir, spruce, and hemlock are considered as one stand type (FIR) because all of these stands may need treatments to promote whitebark pine dominance [32]. These FIR stands have relatively heathy whitebark pine component, but those FIR stands with high whitebark pine mortality (>50%) and evidence of rust-resistant, cone-producing whitebark pine trees are considered as a separate stand type (MORT). These stands have high levels of rust and beetle mortality and the FIR trees may be any size.

The last set of stand types are those stands that have recently been treated (TREAT) (<10 years since treatment), but not with wildfire (i.e., those stands are BURNED). These are high value stands that must be protected because of the high investment by land management agencies. This includes plantations, cutting units, and research areas. Then, we have grouped all possible stand conditions (ALL) for SERAL, CLIMAX, and TREELINE sites for brevity in Table 1.

4. Wildfire Management Actions

4.1. General Terminology

Reductions in surface and canopy fuels to lessen fire intensity, burn severity, and adverse ecological impacts on whitebark pine landscapes are fundamental goals in wildfire management [12]. Surface fuels are the live and dead biomass within 2.0 m of the ground and consist of fine fuels that facilitate fire spread and coarse fuels that contribute to higher fire intensities that usually result in higher tree mortality [33]. Eight fuel components are often used to describe surface fuelbeds: litter, duff, shrub, herb, and four downed woody components (1 h = 0–0.25 inch diameter; 10 h = 0.25–1.0 inch; 100 h = 1–3 inch; 1000 h = 3+ inch) [33]. In general, the treatment of surface fuels usually involves actions that reduce fine and coarse woody fuels to lower wildfire fireline intensities to fight the fire more effectively and increase firefighter safety, and related to whitebark pine restoration, this fuel reduction will also decrease fire-caused whitebark pine mortality as the species is somewhat resistant to fire because of its deep roots, high and sparse crowns, and moderately thick bark [34].

Canopy fuel is the burnable biomass above 2 m from the ground that is less than 6 mm in diameter and are usually described by four characteristics in wildfire management [35,36]. Canopy bulk density (CBD; kg m^{-3}) is the amount of canopy fuel per unit volume of the thickest canopy layer above surface fuels [37]. Canopy cover (CC; %) is the percent of the sky that is occupied by canopy fuels [38]. Canopy base height (CBH; m) is the height at which the CBD exceeds 0.037 kg m^{-3} and canopy height (CH; m) is the height at which the CBD goes below 0.037 kg m^{-3} [37]. CBD and CC dictate rate of spread and fire intensity in the canopy, and CBH dictates whether a surface fire will transition to a crown fire [36]. In general, most fuel treatments attempt to minimize crown fire potential by reducing CBD below 0.037–0.100 kg m^{-3} and increasing CBH to well above any flame height generated by a surface fire [39]. Tools that can be used to plan pre-wildfire treatments to reduce CBD and increase CBH are FuelCalc [40], FOFEM [41], and FVS-FFE [42], all of which can be accessed from https://www.firelab.org/applications.

The general actions available for wildfire management in whitebark pine forests are discussed next for each of the three phases of wildfire management, as shown in Figure 1—before, during, and after a wildfire. There are major overlaps between wildfire management activities and general proactive whitebark pine restoration actions. The primary objective of most wildfire actions is to reduce fuels to fight fires safely and this also may serve to protect valuable whitebark pine resources because these actions may also enhance health, vigor, cone production, and resilience of whitebark pine ecosystems. In this paper, all wildfire management actions before, during, and after a wildfire can also be *de facto* restoration treatments as well as accomplishing the primary objectives of wildfire management. Restoration treatments, conversely, can act as important fuel treatments that modify fire growth, provide safe zones to protect firefighters, and provide attack points for fire suppression activities.

4.2. Before a Wildfire

All wildfire management actions that reduce fuels before a wildfire has occurred can also be designed to simultaneously protect and enhance existing whitebark pine trees from damage or mortality. The Keane, Tomback [3] range-wide strategy, and most of the other regional restoration strategies, detail important restoration actions and treatments that create conditions that facilitate whitebark pine regeneration, improve tree vigor and resilience, conserve rust-resistant seed sources, and promote rust resistance [15–17]. These tactics include creating nutcracker caching habitat, reducing competing vegetation by manipulating forest structure and composition, and diversifying age class structure. However, for a restoration action to aid in wildfire management, it is critical that pre-wildfire actions also reduce surface and canopy fuels, which allow safe and effective firefighting while simultaneously protecting rust-resistant whitebark pine trees.

Reductions in surface and canopy fuels are important because, besides reducing crown fire potential, they also eliminate competition to improve tree vigor, which is increasingly important as climate warms [43,44]. Improved vigor often results in greater ecosystem resilience because the vigorous trees are now able to allocate more resources to defenses against disturbances, which may intensify under climate change [12]. Improved vigor may also increase cone crop production in frequency and quantity because trees may allocate resources to reproduction [45]. Finally, increased vigor will contribute to longevity and allow trees to remain on the landscape for a long time [46].

The tools needed to reduce pre-wildfire fuels are described in detail next. Mechanical cuttings and prescribed burning are the primary tools for implementing treatments in the context of the wildfire management objectives, and the most effective treatments usually involve some combination of silvicultural cuttings, prescribed burning, and planting rust-resistant seedlings [12]. These treatments should be designed to improve landscape heterogeneity while also facilitating whitebark pine resilience, rust-resistance, and sustainable cone crops. Since climate change may result in significant increases in subalpine productivity [12,43,45], it is important to remove as many shade-tolerant competitors as possible to reduce canopy fuels, and also to retard succession and make restoration treatments last longer [2]. Cutting trees smaller than merchantable size or removing advanced regeneration may increase treatment effectiveness and longevity in the future, but this also may be costly and time-consuming. Again, it is vitally important that any mechanical cutting to improve whitebark pine growing conditions should also treat the fuels surrounding apparent rust-resistant trees to reduce the chance that they are lost from wildfire. Additionally, to make any mechanical treatment last longer and become more effective, it is vital that prescribed burning be combined with mechanical cuttings where possible.

4.2.1. Mechanical Cuttings

Mechanical cuttings are treatments that manipulate the stand by cutting trees to reduce CBD and increase CBH. Novel silvicultural strategies for whitebark pine are needed to address both restoration and wildfire concerns because normal silvicultural approaches have had limited success [47,48]. In general, most cuttings should eliminate subalpine fir trees and other shade-tolerant competitors while retaining living whitebark pine trees that are still somewhat healthy [32]. Mechanical cuttings are mostly done with a chainsaw but can be done with other mechanical treatments [14]. The cuttings should start with the smaller shade tolerant trees (>2.5 cm DBH) and move to the larger trees until CBH is above 5 m (15 ft) and CBD is below 0.01 kg m^{-3} at least. These cuttings are also silvicultural thinnings that can improve the health of potential cone-producing whitebark pine. It is strongly advised that cut trees be removed from the site or treated by pile burning, or the slash lopped and scattered to avoid a buildup of surface fuels. However, if the site is to be burned with a prescribed fire, then it may be advantageous to leave some of the fine fuels to support prescribed burning activities [32]. Usually, mechanical cuttings are only effective when treated stands are in close proximity to roads and are easily accessed (e.g., gentle slopes, non-rocky, and few wet areas).

Several types of mechanical cuttings are being used in restoration treatments for whitebark pine and they could also be adapted to be pre-wildfire fuel treatments. Silvicultural thinning (THIN) is used to reduce competitors, which also reduces CBD and increases CBH. Keane and Parsons [32] created nutcracker openings (NO in Table 1) in successionally advanced subalpine fir stands with both healthy and dying, rust-infected whitebark pine; nutcracker openings are a cutting treatment that attempts to mimic patchy, mixed severity fires where all trees except whitebark pine are cut in openings. The size and shape of these openings may vary, but they can be anywhere from 1–40 acres (1–20 ha). These openings may provide a means to stop a crown fire because of the lack of crown fuels; Keane and Parsons [32] report that the Gash Fire did not burn one of the research sites because of the lack of canopy and surface fuels. Another cutting treatment is selection cuts (SEL in Table 1) where all trees except whitebark pine are sawn down (group selections can be small nutcracker openings). The primary purpose of both NO and SEL are to both reduce competition and to enhance regeneration opportunities for whitebark pine by creating desirable caching habitat for the Clark's nutcracker. Daylighting (DAY) or the cutting of shade-tolerant competing species in a circular area around selected whitebark pine trees (area radius roughly equal to the height of the canopy) has been gaining favor among managers because it is cheap and easy, but there is little research on its effectiveness. In general, DAY is an effective pre-wildfire treatment when the area around the target tree is at least equal to the overall canopy height and the activity fuels are removed or reduced via pile and burning.

All the above treatments may also be fuel treatments to reduce crown fires, but some past restoration treatments left abundant fuel on the site [32]. It is important that competing shade-tolerant conifers be cut, including the regeneration, because any residual competing trees, even small seedlings, will compromise the efficiency of the mechanical treatment for both reducing canopy fuels and restoring whitebark pine. This is why many cuttings are followed by prescribed burning to kill most of the small and large shade-tolerant tree competitors and leave the more fire-tolerant whitebark pine individuals [49–51]. Girdling subalpine fir trees has also been effective in some restoration efforts because it is a cheap, rapid means of killing competing subalpine fir, as long as the girdling is done below the live branches [52]. However, girdling is not recommended as a pre-wildfire fuel treatment because it leaves a large portion of the tree biomass on the site which could provide the fuel to foster high severity wildfires that might kill whitebark pine trees being restored. The reduction or removal of slash generated from the treatment is vital to reduce the severity of future unplanned wildfires [47], but also to allow nutcrackers access to the ground for caching [2] and reduce potential mortality from *Ips* spp. beetles [53]. This may be accomplished by (1) piling slash and then burning the piles, (2) whole tree skidding to a designated landing, or (3) augmenting cuttings with a prescribed fire.

4.2.2. Prescribed Burning

Prescribed burning alone is not as straightforward as mechanical cuttings because prescribed fire effects are highly variable across space; parts of the treated stand may be lightly burned leaving many competing fir and spruce trees alive [32]. It can also severely burn parts of the stand resulting in high mortality in valuable cone-bearing whitebark pine trees [32]. However, if done correctly, prescribed fires can kill most of the smaller shade-tolerant understory trees that mechanical cuttings often miss. Prescribed burns can also effectively reduce fuels for wildfire mitigation. Prescribed burns kill trees from the "bottom up" so the smaller trees, especially the shade-tolerant, fire sensitive species, usually have highest mortalities thereby effectively raising the CBH, but the prescribed burn has to be somewhat intense to kill some overstory trees to reduce CBD, and this is difficult because the valuable living rust-resistant whitebark pine trees may be compromised.

In this document, we define three kinds of prescribed fires to use for pre-wildfire management activities. Prescribed fires at low intensity (PFLI in Tables 1 and 2) are planned fires meant to mimic the non-lethal surface fire regime [32,54]. The primary goal of this fire is to remove competing fir, spruce, and hemlock seedlings, saplings, and pole trees to reduce CBD and heighten CBH, and also to increase the vigor of remaining mature cone-bearing whitebark pine trees. Prescribed fires at moderate intensities (PFMI) are implemented to emulate mixed severity fire regimes where small to large holes in the canopy are created by crowning and torching while the fire burns at lower intensities throughout the rest of the stand. PFMIs will hopefully create effective firebreaks while generating potential nutcracker caching habitat to facilitate regeneration and removing competition from other shade-tolerant trees. Last there are prescribed fires at high intensities (PFHI) that are meant to mimic a stand-replacement fire [32]. In PFHI, the fires essentially kill all trees and leaves large burned areas that are fuel-breaks, which are also a competition-free area for whitebark pine natural regeneration and an ideal area for planting rust-resistant whitebark pine seedlings. Both PFMIs and PFHIs can act as effective pre-wildfire actions by removing the canopy and surface fuels to stop crown fires and provide potential lookouts, safe zones, and escape routes [32].

To enhance effectiveness of prescribed fire, Keane and Parsons [32] found that fuel augmentation (FA in Tables 1 and 2) is a viable pre-fire action. FA is the process of changing the surface fuelbed to facilitate a wider prescribed burning window and a more comprehensive and consistent burn once the fire is ignited. Usually FA involves directional felling the shade-tolerant, fire susceptible competing trees in areas where surface fuels are insufficient to achieve the prescribed burning objective. Fortunately, this action also increases CBH and reduces CBD. The red needles and small twigs of the felled trees create additional fine surface fuels that allow prescribed burners to light hotter burns under cooler and moister conditions thereby creating a wider burn "window" allowing fire specialists the ability to ignite a prescribed burn when fuel moistures are higher, such as towards the end of the autumn burning season [32]. Keane and Parsons [32] also found that those stands that were treated with prescribed fire after FA acted as effective fuelbreaks against wildfires that occurred after the prescribed burn.

4.3. During a Wildfire

There are basically three options for wildfire management while the fire is burning on whitebark pine landscapes: (1) Full suppression (FS), (2) partial suppression (PS), and (3) allowing wildfires to burn under an acceptable set of conditions (WFU; wildland fire use). In general, wildfire suppression involves attempting to contain any wildfire using various firefighting tactics such as fireline construction, retardant and water drops, and ignition operations. The FS tactics that are usually employed can be stratified into two types: initial attack and incident management. In initial attack, crews are sent to extinguish fires when they are small (<40 ha) using various wildfire suppression tactics to prevent them from becoming large. Initial attack tactics are usually quite effective and most land management agencies report that initial attack usually suppresses around 92% to 98% of all fires, even though it is estimated that around 70% of these fires may have probably stayed small [55]. Incident management, however, is when escaped small fires become large (>40 ha) and large-scale suppression activities must be used to contain the wildfire. Usually, wildfire suppression activities become less effective when fires get large; it is usually weather that eventually contains large fires [56]. Partial suppression (PS) is a term used only in this report, and it represents a strategy where suppression tactics are used on small areas to protect values at risk, sometimes called "spot" suppression. In this report, it often involves retardant or water drops to protect high value, rust-resistant whitebark pine trees.

The last wildfire management action, which is perhaps the most important tool for all landscape level restoration, is controlled wildfires or WFU [57]. WFUs are lightning-started fires that are allowed to burn under acceptable weather and site conditions, which are specified in a local fire plan [58]. Aggressive use of WFU has the potential to be an efficient, economical, and ecologically viable method of restoring whitebark pine in many areas, especially wilderness areas [3]. Landscapes where WFU might be contra-indicated are those with few whitebark pine seed sources both near and distant, but only if planting is an impossibility. Otherwise, most WFU will probably improve whitebark pine's status and health if the fires are carefully monitored to avoid high mortality of potentially rust-resistant trees (i.e., linked with partial suppression actions).

4.4. After a Wildfire

Basically, there are two primary management actions that can take place after wildfire for whitebark pine restoration—planting and monitoring. There may be other post-wildfire mitigation efforts to reduce erosion or stabilize the burned area, but these are not included in this paper.

4.4.1. Planting

Facilitating natural whitebark pine regeneration using management treatments and wildfires may be undependable in the near-future, especially with changing climates and continued losses of cone-bearing whitebark pine from MPB and WPBR. Relying on natural regeneration is a risky business considering that many areas may have insufficient populations of mature, cone-bearing whitebark pine to sustain viable regeneration. Keane and Parsons [32] found little natural whitebark pine regeneration after 10 years in their treated study sites, probably because the nutcracker reclaimed most of the cached seed in areas of low seed-producing trees. Even if natural regeneration does occur, the majority of the nutcracker cached seeds may be from whitebark pine trees susceptible to rust. Therefore, a critical action after wildfires on whitebark pine sites, especially when stands with high rust mortality are burned, should include the successful planting of rust-resistant seedlings. This may be the best option under changing climates, especially in those stands decimated by MPB and WPBR [12].

Planting (PLANT in Tables 1 and 2) is one of the main actions in the range-wide restoration strategy [3]. Reforestation with rust-resistant seedlings will increase the representation of blister rust-resistant genotypes in the next generation of whitebark pine forests and hopefully create resilient whitebark pine forests of diverse age structures that are more likely to withstand frequent wildfires, MPB outbreaks, and the spread of WPBR [1]. Sowing seeds from rust-resistant sources in treated or burned areas, if shown to be efficacious, may be another cost-efficient alternative to planting. As mentioned, areas with declining whitebark pine seed sources are unlikely to produce enough seeds to attract and support nutcrackers, so natural seed dispersal is unlikely [59]. Additionally, because WPBR is at the northern limit of whitebark pine's range, as well as the upper elevational limits in North America, both important climate change fronts, the seedlings from rust-resistant parent trees may be planted at both limits. Most other restoration actions will be ineffective without the planting of rust-resistant seedlings.

Several suggestions for planting seedlings are important to mitigate the effects of climate change and ensure high seedling survival. First, planting probably should be prioritized for the higher portions of whitebark pine seral sites based on results of a simulation experiment that found sapling survival highest in the colder portions of whitebark pine's range [1]. Given the high costs of growing rust-resistant seedlings and planting of them in remote settings, planting should start at the higher regions in burned areas where they are most likely to survive in the future, and then planting should progress downwards in elevation. Second, seedlings should be planted in microsites that best mitigate harsh site conditions and provide protection from sun and wind [60]; seedlings or seeds should be placed near rocks, stumps, or other objects that provides some protection from sun and snow. Microsites may moderate seasonally arid conditions when the planted seedling is most susceptible to drought effects, or protect against hard frosts, deep snow packs, prolonged insolation, drought, and soil erosion during the critical time of seedling establishment [61]. Planting sites may need to be selected based on whether they might contain important mycorrhizae needed to ensure seedling survival [62]. Seedlings planted in proximity to sapling or mature whitebark pine trees, or perhaps near *Vaccinium* spp., plants have a chance to be colonized by the appropriate mycorrhizae [63,64]. It may be advantageous to wait for undergrowth vegetation, particularly shrubs, to develop before planting whitebark pine seedlings on burned sites, although this could require a number of years for extreme sites; there may be excessive erosion and soil movement during the years directly after a burn that may dislodge planted seedlings, and undergrowth shrubs may provide partial shade that is favorable to seedling survival [32].

4.4.2. Monitoring

It is critical that proactive and reactive wildfire management actions be monitored to ensure that the restoration and wildfire control objectives were successfully met, and more importantly, to provide a means for others to design and adjust various wildfire actions to increase success and efficiency. Without pre and post-treatment data, ineffective treatments could be continually repeated throughout the range of whitebark pine [3]. There are many methods, systems, and protocols for post-wildland fire monitoring. First however, people should check with their land management agency to see if there are already a set of inventory and monitoring protocols in place that might be required. These should be followed and modified to ensure a comprehensive monitoring approach. If no monitoring protocols are required, then there are a number of systems that might help with monitoring actions.

All monitoring (MON in Table 1) activities must be designed around the objectives of the treatment. However, there are some generalities that can be detailed here that are generally required for each monitoring project. First, a comprehensive description of the tree population must be conducted by inventorying all trees in a fixed area plot and measuring species, DBH, height, height to base of crown, and some health assessment (e.g., percent of crown killed by rust, an assessment of beetle, rust, or some other insect/disease presence). Sampling protocols such as FIREMON [65], FFI [66], and FS-VEG can be used. Canopy fuels can be computed from the sampled tree data using a wide variety of programs such as FVS [67], FuelCalc [40], or FOFEM [41]. Next, an assessment of the surface fuels is needed by measuring the loading of the eight surface fuel components using a wide variety of measurement techniques, such as planar intercept [68], photo series [69], photoloads [70], and destructive sampling [33]. The tree and fuel sampling should be done before and after the wildfire if possible, especially if pre-wildfire treatments are implemented. However, monitoring can take place after a wildfire has burned an area and pre-wildfire conditions can often be recreated from the sampled data.

5. Wildfire Management Actions in Whitebark Pine Forests

The set of wildfire management practices for the restoration of whitebark pine ecosystems is synthesized into an easy-to-use table for land managers (Table 1). These actions were specifically designed to be implemented in high mountain landscapes that contain whitebark pine ecosystems, but it is fully recognized that each land management agency has its own set of policies and protocols for implementing a specific fire management plan. As a result, these guidelines can easily be expanded, modified, and amended at a later date. Table 1 below describes the set of possible wildfire management practices for the whitebark pine sites and stands, along with any associated actions that fire or land managers might want to employ before and after a wildfire that may reduce the impacts of the wildfire and restore whitebark pine ecosystems. Table 2 contains definitions and descriptions of the codes used in Table 1. Since many of the actions suggested in Table 1 may not be relevant or possible in all lands across the range of whitebark pine, an ancillary table (Table 3) was developed to provide caveats, cautions, and suggestions for implementing the wildfire actions for each geographic region (Figure 2). There are four columns in Table 1 that denote management and restoration actions that promote efficient wildfire management and facilitate the restoration and maintenance of whitebark pine forests on North American landscapes stratified by site type, stand type, and time (before, during, and after wildfire).

Table 1. The set of wildfire management practices and companion restoration treatments that can be implemented before, during, and after the wildfire for all geographical regions (Figure 2) by site type (Figure 3) and stand type (Figure 4). These wildfire management practices are listed in order of preference and their acronyms are defined and detailed in Table 2 along with a complete description of other concerns and the definitions of the acronyms. There are subtle differences in the implementation of these actions across geographic regions which are discussed in Table 3.

Site Type	Stand Type	Possible Prescribed Burning Actions Before Wildfire	Possible Mechanical Restoration Actions Before Wildfire	Possible Practices to Implement During a Wildfire	Possible Restoration Actions After Wildfire or Treatment	Other Concerns (Notes)
SERAL	BURNED	None	None	None	PLANT, MON	RR, CC
	EARLY	None	SFT, DAY	None	PLANT, MON	RR, CC
	MID	PFLI	THIN, FA, SFT, DAY	PS, WFU	PLANT, MON	FR, RR, PT, PILE, SCV, CC
	LATE	PFMI, PFLI, PFHI	THIN, FA, SEL, NO, SFT, DAY	WFU, PS	PLANT, MON	FR, RR, PT, PILE, SCV, SCR
	FIR	PFHI, PFMI	NO, SEL, THIN, DAY	WFU, PS	PLANT, MON	FR, RR, PT, PILE, SCV, SCR
	MORT	PFLI, PFMI	SEL, NO, THIN, SFT, DAY, FA	WFU, PS	PLANT, MON	FR, RR, PT, PILE, SCV, SCR
	TREAT	None	None	FS	PLANT, MON	RR, CC
CLIMAX	ALL	None	SFT, DAY	PS, WFU	PLANT, MON	RR, PT, CC
TREELINE	ALL	None	None	None	PLANT, MON	CC, RR, PT

Site type: SERAL-Areas where whitebark pine is seral to other shade-tolerant conifers; CLIMAX-Areas where whitebark pine is the major climax species; TREELINE: Areas where whitebark pine occurs in timber atolls, krummholz, elfin forests, or treeline communities. Stand type; BURNED: Recently burned or treated stands in whitebark pine habitat; EARLY: Early seral (seedling, sapling) stands dominated by whitebark pine in seral site type; MID: Mid-seral (pole, mature) stands dominated by whitebark pine in seral site type; LATE: Late seral stands dominated by the competitors of whitebark pine on lands that could support whitebark pine in seral site type and there are still living whitebark pine in stand; FIR: Any early or mid-seral stand that is dominated by the competitors of whitebark pine; MORT: Any stand in in the seral site type with high whitebark pine mortality (>70%) and evidence of rust-resistant, cone-producing whitebark pine trees; TREAT: Previously treated stands or landscapes that have received a fuel treatment or restoration action; ALL: Any stand on whitebark pine climax and seral sites of any seral stage.

Table 2. Definitions, descriptions and related restoration objectives for all wildfire management options in Table 1. CBH-canopy base height and CBD-canopy bulk density.

	Action	Description	Restoration Objective
		Pre-Wildfire management actions	
THIN	Thinning	Mechanically cut trees that impede growth and vitality of whitebark pine in both overstory and understory; attempt to mimic a non-lethal surface fire regime; thin competitors first from largest to smallest	Reduce whitebark pine competition while also reducing canopy fuels to decrease potential for crown fire; create thrifty living cone-producing whitebark pine trees, especially in stands where rust-resistance may be high
SEL	Selection cutting	Mechanically cut competing trees in clumps to improve whitebark pine tree health and vigor while also mimicking a mixed severity fire regime; create open areas for nutcracker caching to facilitate natural regeneration	Create whitebark pine seed caching habitat for the Clark's nutcracker; reduce whitebark pine competition while also removing canopy fuels to decrease potential for crown fire; create thrifty living cone-producing whitebark pine trees, especially in stands where rust-resistance may be high
NO	Nutcracker openings	Cut all trees but whitebark pine in patches of 10–30 ha to mimic mixed severity fire or patches greater than 50 ha to mimic stand-replacement fires	Create whitebark pine seed caching habitat for the Clark's nutcracker; reduce whitebark pine competition to improve regeneration potential and living tree vigor while also removing canopy fuels to decrease potential for crown fire; create thrifty living cone-producing whitebark pine trees, especially in stands where rust-resistance may be high
DAY	Day-lighting	Remove competition and fuels around putative or phenotypic rust-resistant whitebark pine trees at a diameter equal to canopy height	Improve the vigor of living whitebark pine trees; reduce potential for mountain pine beetle infection by putting more sunlight on bole; reduce WPBR infection by decreasing local humidity; reduce fire hazard by removing canopy and surface fuels
SFT	Spot fuels treatments	Remove canopy fuels near healthy whitebark pine trees; reduce surface fuels around trees by piling, scattering, and clipping	Reduce canopy bulk density; increase canopy base height; remove competition and improve vigor.
FA	Fuel Aug-mentation	Add fine woody and foliar fuel to the surface fuelbed by cutting live and dead competing trees in a pattern to facilitate fire spread in a prescribed fire	Cut trees of whitebark pine competitors and arrange the fallen trees so they are distant from living whitebark pine while attempting to create a continuous surface fuelbed and reduce canopy fuels

Table 2. *Cont.*

	Action	Description	Restoration Objective
PFLI	Low intensity prescribed fire	Implement a controlled burn in a treatment unit using prescribed fire to mimic effects of a non-lethal surface fire; may be paired with a fuel augmentation treatment (FA)	Ensure survival of living, cone-producing whitebark pine trees while killing all sizes of its competitors thereby maintaining cone production and slowing successional advance; reduce crown fire potential by decreasing CBD and increasing CBH
PFMI	Moderate intensity prescribed fire	Implement a controlled burn in a treatment using prescribed fire to mimic effects of a mixed severity fire; may be paired with a fuel augmentation treatment (FA)	Create caching or planting sites for whitebark pine regeneration; remove or reduce competitors of whitebark pine; mimic natural fire processes
PFHI	High intensity prescribed fire	Implement a controlled burn in a treatment using prescribed fire to mimic effects of a stand-replacement severity fire; may be paired with a fuel augmentation treatment (R)	Create caching or planting sites for whitebark pine regeneration; remove or reduce competitors of whitebark pine; mimic natural fire processes; create large burned areas where only the bird-dispersed whitebark pine can regenerate
		Management actions during a wildfire	
FS	Full suppres-sion	Fight all fires in the area; emphasize initial attack; keep fires out of high value whitebark pine stands	Protect living whitebark pine trees, especially those trees that are known to be rust-resistant or have the potential to be rust-resistant by eliminating fire; Protect early seral stands dominated by whitebark pine to allow future seed production; accept minor losses from retardant drop damage
PS	Partial suppres-sion	Fight all fires in the area and emphasize initial attack BUT do not use aircraft retardant drops because they may harm valuable trees	Protect living whitebark pine trees, especially those trees that are known to be rust-resistant or have the potential to be rust-resistant by eliminating fire; Protect early seral stands dominated by whitebark pine to allow future seed production
WFU	Wildland fire use	Allow fires to burn under prescribed conditions; mimic native fire regimes while also increasing fuel heterogeneity	Implement a restoration treatment that mimics natural processes: see PFLI if WFU fire is low intensity, see PFMI if WFU fire is moderate intensity and PFHI if high intensity WFU fire
		Post-wildfire management actions	
PLANT	Plant seedlings or seed	Plant rust-resistant seedlings in treatment units where competition has been removed, or plant in recently burned areas where tree and grass competition is minimal	Ensure disturbed stands will regenerate to whitebark pine, and hopefully to rust-resistant whitebark pine; augment the natural dispersal process to ensure whitebark pine regeneration; provide whitebark pine regeneration in those areas where whitebark pine mortality is high
MON	Monitor	Monitor the effects of the treatment(s) or wildfire using agency or published methodologies	Document effects of treatment or wildfire using multiple scale sampling strategies to ensure treatment is effective and to improve future management strategies

Table 2. *Cont.*

	Action	Description	Restoration Objective
		Important concerns for all management actions	
RR	Rust-resistance	Plant rust-resistant seedlings; plant in places that are rich in mycorrhizae (near *Vaccinium* spp.); plant only in places that lack any tree competition with the seedlings (all of whitebark pine's associates will outgrow the species)	Follow planting guidelines including those detailed in McCaughey et al. (2009), Scott and McCaughey (2006); plant in spacings that are about 20 ft by 20 ft but be sure to adjust for potential losses from WPBR;
PT	Plus-trees	Protect all identified whitebark pine plus trees first then protect all trees that have the obvious potential to be rust resistant	Retain rust-resistant trees on the landscape for pollination and cone-collection
FR	Frost	Try to wait for the first hard frost in the fall before attempting a prescribed burn; shrubs and herbs will carry the fire in most circumstances	If in doubt, take fuel moisture measurements of herb and shrub to see if dry enough to burn;
PILE	Piles	If mechanical treatments result in slash piles, try to remove or burn the piles relatively quickly	Prevent *Ips* spp. Caused pine mortality; reduce fuel hazard; allow for greater nutcracker caching
SCV	Silvi-cultural cuttings to improve vigor	Competition removal treatments for reducing fuels in order effectiveness: THIN, DAY, SFT, FA; all of these are less effective with late seral stand types	Cuttings should remove shade-tolerant conifers first, from the highest to lowest DBH; DAY and SFT treatments are often the same an differ only because SFT treat surface fuels as well as canopy fuels
SCR	Silvi-cultural cuttings to improve regeneration	Regeneration removal treatments for reducing fuels in order effectiveness: NO then SEL	Emphasize long linear shapes to create long fuelbreaks; follow treatment with PFLI to remove competing advanced regeneration;
CC	Climate change	Possible future climates may change biophysical conditions and impact proposed actions	Avoid planting in areas without whitebark pine; prioritize actions so that the higher elevation areas within stands or sites are treated first; craft silvicultural and prescribed fire prescriptions to remove more fuels and competitors to anticipate changes in disturbance regimes.

Table 3. Modifications and notes of wildfire management actions for whitebark pine restoration presented in Table 1 for each geographic region (Figure 2).

Geographic Region	Category	Modifications
North Rockies, US-Canadian Rockies	WFU	This action is particularly effective in this region because of the abundance of high elevation wilderness areas with ample whitebark pine habitat, especially SERAL site types; has the potential to be a primary restoration action; best used in LATE, FIR, and MORT stand types; needs to be augmented with planting
	THIN	Mountain hemlock is an especially aggressive competitor so remove these trees first, and DAY and SFT often are ineffective when hemlock is present.
	CLIMAX, TREELINE	Most treatments are not needed in these site types because areas are remote and some stands are still healthy; DAY and SFT will be useful around plus trees and potential plus trees
	PFLI-PFHI	This region usually has the best chance of successful implementation, but needs a FA to increase efficiency
	BURNED	The most effective restoration option is to plant old burns which does NOT affect their efficacy for fuelbreaks.
	MORT	Often, competition removal treatments to favor whitebark pine advanced regeneration may fail and regeneration treatments (NO, SEL) are more effective, especially when planting rust-resistant seedlings.
	FS	Full suppression is suggested for treatment units, but it probably won't be needed as most treated areas were fuelbreaks for many north Rockies wildfires
Middle Rockies	WFU	This action is particularly effective in this region because of the abundance of high elevation wilderness areas with whitebark pine habitat; has the potential to be a primary restoration action; best used in LATE, FIR, and MORT stand types
	PFLI-PFHI	Low surface fuel loadings in this region makes prescribed fire difficult and FA might often be needed
	NO, SEL	Most fires were severe fires in this ecosystem so it is important to highlight the regeneration treatments (NO, SEL) and use the competition removal treatments (THIN, DAY, SFT) in those limited areas where appropriate
Idaho Batholith	WFU	A high proportion of this area is designated wilderness so this option may be the only viable restoration treatment
	PFLI-PFHI	Low surface fuel loadings in this region makes prescribed fire difficult and FA might often be needed
	NO, SEL, THIN	Many whitebark pine stands are in the climax site type in this region making most silvicultural options inappropriate with the absence of fir and spruce
Blue Mountains	WFU	May not always be possible in this region when whitebark pine communities are confined to tops of mountains where there are limited SERAL types and remote locations; large WFU might severely depress resident widely scattered whitebark pine populations
	NO, SEL, THIN, PFLI, PFMI	Isolated populations of whitebark pine may make mechanical treatments and perhaps prescribed fire treatments the best option; prescribed fires may need to be kept at low severity to avoid losses in cone-bearing whitebark pine

Table 3. *Cont.*

Geographic Region	Category	Modifications
Sierras; Klamath Mountains; Basin and Range	SERAL	These site types are rare in these regions so most pre-wildfire treatments are not going to be effective restoration or fuel treatments; the CLIMAX and TREELINE sites will naturally provide fuelbreaks except in severe wind-driven fires;
	WFU	Implementing WFU for whitebark pine restoration may be inappropriate in this region because of limited areas with whitebark pine and if these areas burn, it might compromise local populations of the species
	NO, SEL, THIN, PFLI, PFMI	Proactive treatments both silvicultural and prescribed fire, may be inappropriate here because most whitebark pine are in the CLIMAX site type;
Cascades and Olympics	WFU	Whitebark pine stands are mostly found in small isolated populations remote from roads so it is important to evaluate the appropriateness of WFU in areas with small populations of key rust-resistant pine
Canadian Rockies	WFU	Care should be exercised to ensure wildfires aren't burning isolated whitebark pine populations; has the potential to be a primary restoration action; best used in LATE, FIR, and MORT stand types; needs to be augmented with planting, although many areas are very inaccessible
	THIN	Subalpine fir is an especially aggressive competitor so remove these trees first.
	CLIMAX, TREELINE	Most treatments are not needed in these site types because most stands are still healthy; DAY and SFT will be useful around plus trees and potential plus trees
	PFLI-PFHI	This region usually has the best chance of successful implementation, but needs a FA to increase efficiency
	BURNED	The most effective restoration option is to plant old burns which does NOT affect their efficacy for fuelbreaks.
	MORT	Often, competition removal treatments to favor whitebark pine advanced regeneration may fail and regeneration treatments (NO, SEL) are more effective, especially when planting rust-resistant seedlings.
	FS	Full suppression is suggested for treatment units.
Columbia Mountains	THIN	Mountain hemlock is an especially aggressive competitor so remove these trees first, and DAY and SFT often are ineffective when hemlock is present.
Fraser and Thompson Plateau	WFU	May not be possible in the northern regions but maybe in the TO Plateau;
Nechako Plateau	WFU	May not be possible in the northern regions

6. Summary

Wildfires have been and will continue to be major agents of change on the high mountain landscapes of North America. As restoration attempts are being implemented to stem the decline of whitebark pine populations because of major losses from MPB and WPBR, it is important to consider the role of wildfires in whitebark pine forest restoration efforts, and vice versa, it is important to consider the role that restoration can take in wildfire management. This paper presents possible restoration actions that can be implemented before, during, and after a wildfire that would enhance both whitebark pine restoration and wildfire management (Table 1). These actions should be considered holistically in the context of a wildland fire plan and local whitebark pine restoration strategies.

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Abbreviations

ALL	Any stand on whitebark pine climax and seral sites of any seral stage.
BURNED	Recently burned or treated stands in whitebark pine habitat
CBD	Canopy bulk density
CBH	Canopy base height
CC	Canopy cover
CH	Canopy height
CLIMAX	sites where whitebark pine is the indicated climax species
EARLY	Early seral (seedling, sapling) stands dominated by whitebark pine in seral site type
FIR	Any early or mid-seral stand that is dominated by the competitors of whitebark pine
FS	Full suppression
LATE	Late seral stands dominated by the competitors of whitebark pine on lands that could support whitebark pine in seral site type and there are still living whitebark pine in stand
MID	Mid-seral (pole, mature) stands dominated by whitebark pine in seral site type;
MORT	Any stand in in the seral site type with high whitebark pine mortality (>70%) and evidence of rust-resistant, cone-producing whitebark pine trees
MPB	Mountain pine beetle
PS	Partial suppression
SERAL	Sites where whitebark pine is seral to subalpine fir and other shade-tolerant species
TREAT	Previously treated stands or landscapes that have received a fuel treatment or restoration action
TREELINE	Sites where whitebark pine occurs in timber atolls, krummholz, elfin forests, or treeline communities
WPBR	White pine blister rust
WFU	Wildland fire use, or prescribed natural fire or controlled wildfire—wildfires allowed to burn under prescribed circumstances.

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