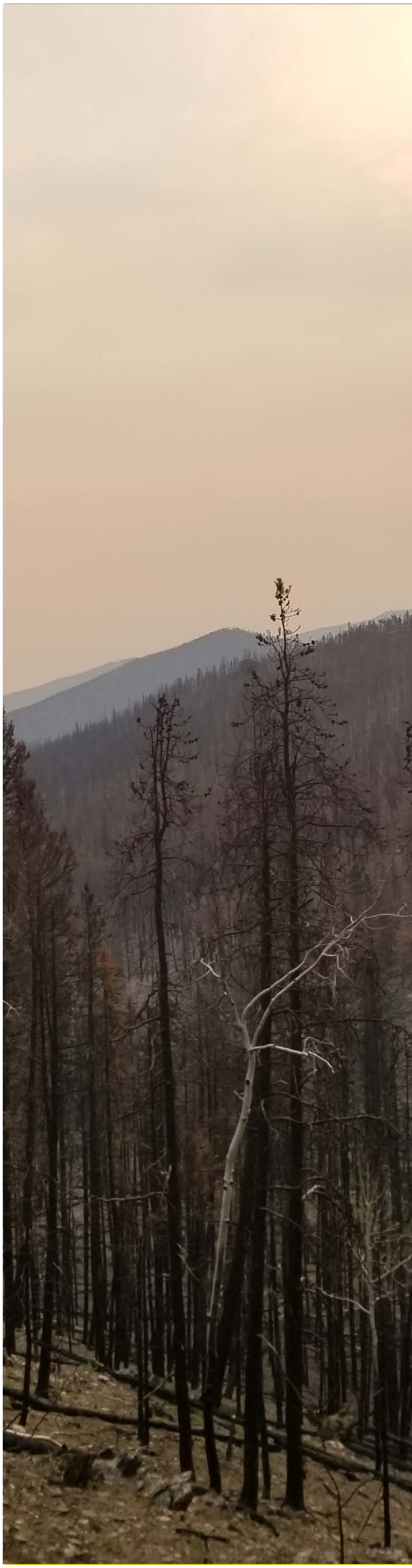

The historic 2020 fire year in northern Colorado and southern Wyoming

A LANDSCAPE ASSESSMENT TO INFORM POST-FIRE FOREST MANAGEMENT

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SWERI Southwest Ecological Restoration Institutes
Northern Arizona University | Colorado State University | New Mexico Highlands University

Colorado Forest Restoration Institute, Colorado State University
Northern Arizona University Ecological Restoration Institute
New Mexico Forest and Watershed Restoration Institute

Document Development: This development of this technical document was motivated by discussions with employees of the U.S. Department of Agriculture (USDA) and non-government organizations (NGOs), as well as knowledge gained from two management workshops focused on post-fire landscape management (April 2022 "Wildfire Resilience Roundtable" in Boulder, CO, and June 2022 "Reforestation Summit" in Washington, D.C.). In the wake of the 2020 wildfires in northern Colorado and southern Wyoming, we identified an urgent need for new tools and knowledge focusing on the management of these newly burned landscapes. This report is a collaboration of researchers from academic institutions, NGOs, and government entities. The development and publication of this report are a joint effort of two of the three Southwest Ecological Restoration Institutes, including the Ecological Restoration Institute and the Colorado Forest Restoration Institute. Together with other collaborators on this report, staff at the Ecological Restoration Institute led analyses and developed spatial datasets, while staff at the Colorado Forest Restoration Institute led information exchange efforts with managers as well as document production and outreach activities.

Southwest Ecological Restoration Institutes (SWERI)
The Southwest Ecological Restoration Institutes include three university-based restoration institutes: the New Mexico Forest and Watershed Restoration Institute (NMFWRI), the Colorado Forest Restoration Institute (CFRI), and the Ecological Restoration Institute (ERI) in Arizona. These institutes were congressionally appointed in 2004 by the Southwest Forest Health and Wildfire Prevention Act (H.R.2696), and the Institutes work together to develop a program of applied research and service to help create healthy forests, prevent wildfires, sustain the resiliency of water supplies to wildfires, and create jobs.

Ecological Restoration Institute (ERI), Northern Arizona University
The Ecological Restoration Institute is nationally recognized for mobilizing the unique assets of a university to help solve the problem of unnaturally severe wildfire and degraded forest health throughout the American West. ERI serves diverse audiences with objective science and implementation strategies that support ecological restoration and climate adaptation on Western forest landscapes.

Colorado Forest Restoration Institute, Colorado State University
The Colorado Forest Restoration Institute is a science-based outreach and engagement organization hosted by the Department of Forest and Rangeland Stewardship and the Warner College of Natural Resources at Colorado State University. Colorado State University (CSU) is a land-grant university with a mission to provide teaching, research, public service, and engagement that CFRI strives to uphold. CFRI was established by Congress as part of the Southwest Ecological Restoration Institutes to serve as a bridge between researchers, managers, and stakeholders working to restore and enhance the resilience of forest ecosystems to wildfires in Colorado, the Southern Rocky Mountains, and the Intermountain West. CFRI leads collaborations between researchers, managers, and stakeholders to generate and apply locally relevant, actionable knowledge to inform forest management strategies. CFRI's work informs forest conditions assessments, management goals and objectives, monitoring plans, and adaptive management processes.

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CSU Land Acknowledgment
Colorado State University acknowledges, with respect, that the land that the university is on today is the traditional and ancestral homelands of the Arapaho, Cheyenne, and Ute Nations and peoples. This was also a site of trade, gathering, and healing for numerous other Native tribes. We recognize the Indigenous peoples as original stewards of this land and all the relatives within it. As these words of acknowledgment are spoken and heard, the ties Nations have to their traditional homelands are renewed and reaffirmed.

CSU is founded as a land-grant institution, and we accept that our mission must encompass access to education and inclusion. And, significantly, that our founding came at a dire cost to Native Nations and peoples whose land this University was built upon. This acknowledgment is the education and inclusion we must practice in recognizing our institutional history, responsibility, and commitment.

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Cover photo credit: A high severity burn area in the 2020 Cameron Peak Fire. (Photo credit: Kate Weimer, Colorado Forest Restoration Institute, Colorado State University)

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Executive Summary

Wildfire activity is increasing throughout forests of the western United States, in large part due to the effects of a warming climate. The 2020 fire year in northern Colorado and southern Wyoming is a particularly striking example – several of the largest fires on record in this region (i.e., since the early 1900s) occurred in 2020. Many of these fires burned in high-elevation forests, an uncommon occurrence over the past century, and several burned well into the fall and winter due to atypically warm, dry conditions. Like the 2002 Hayman Fire and other recent events in the region, the 2020 fires may drive conversions from forests to grasslands or shrublands, and cause associated changes to ecosystem services. Such changes in ecosystems may not be desirable for landowners, land managers, or other stakeholders, motivating potential management intervention. After fire, reforestation is a key management strategy that can help to accelerate forest recovery. However, reforestation is expensive and time-consuming, and may not be feasible, successful, or desirable everywhere. Assessments of post-fire landscape conditions may help to plan management efforts and allocate reforestation resources following the 2020 wildfires. To address this need, we used spatial data, together with statistical models developed from west-wide surveys of post-fire tree regeneration, to conduct a post-fire landscape assessment for areas affected by five 2020 wildfires – the Calwood, Cameron Peak, East Troublesome, Mullen, and Williams Fork. This assessment was guided by the Resist-Accept-Direct (RAD) framework, an emerging paradigm that helps to navigate uncertainties and potential management approaches across diverse landscapes.

For each fire, we quantified spatial patterns of live trees, the effects of pre-fire bark beetle outbreaks, the potential for natural post-fire recruitment of the dominant conifer species, and climate suitability (a proxy for reforestation suitability). Post-fire conditions and predicted post-fire trajectories varied widely within and across the five burned landscapes. Overall, 604,550 ac burned with 55% of the total area burning at high severity. Approximately 28% of this high-severity area (15% of the total area) was > 650 ft from live trees, suggesting that limited recovery may occur for species that require live trees for post-fire seed dispersal. However, these landscapes also contained tree species such as aspen (*Populus tremuloides*) and lodgepole pine (*Pinus contorta* var. *latifolia*) which are capable of resprouting from established root systems or regenerating from canopy-stored seeds following fire, respectively. Aspen (> 50%) and lodgepole pine (> 90%) were present prior to fire occurrence across most high-severity areas that were > 650 ft from live trees, suggesting that continued monitoring of natural recovery processes will be critical in many areas prior to management intervention. Indeed, predictions of post-fire recruitment indicated that lodgepole pine would regenerate well across many intermediate to high-elevation sites, while species dependent on seed dispersal from the unburned edge would be limited to sites near live trees and in wetter areas. Where planting is considered necessary to meet management goals, our newly developed maps of climate suitability for the dominant conifers help to identify where such actions might be most successful. The 2020 wildfires are likely to present social and ecological challenges that will last decades. This report presents new information to aid in prioritizing post-fire management activities following these wildfires but is intended to be used as a part of a broader decision framework incorporating expert knowledge, policy mandates, and local site assessments.

1. Introduction and Background

The 2020 fire year brought extreme wildfire activity to nearly every continent on the planet. Over 9.5 million acres burned in the western continental US alone (*National Interagency Coordination Center* 2020), with wildfires primarily driven by dry weather patterns over the preceding months, high winds, and above-average temperatures (Higuera and Abatzoglou 2021). In northern Colorado and southern Wyoming, the 2020 wildfire season included many of the largest fire events since the early 1900s. For example, three wildfires in northern Colorado and southern Wyoming – the Cameron Peak (208,663 ac), East Troublesome (193,812 ac), and Mullen (176,878 ac) – eclipsed Colorado's previously largest recorded wildfire (2002 Hayman Fire [138,114 ac]) (National Interagency Fire Center 2022). The wind-driven nature of these fires led to dramatic fire behavior, which tested both containment and structure protection efforts. For example, the East Troublesome Fire burned nearly 100,000 ac in a single day and crossed over the Continental Divide in Rocky Mountain National Park, spotting over alpine tundra (Coop et al. 2022, *National Interagency Coordination Center* 2020). Overall, the 2020 wildfires in northern Colorado and southern Wyoming (hereafter, the 2020 wildfires) cost nearly $300 million to suppress, destroyed over 1,000 structures, killed countless trees, and spurred massive debris flows (*National Interagency Coordination Center* 2020). These wildfires are likely to reshape the social and ecological landscape of the northern Colorado and southern Wyoming region for decades to come.

Patterns of post-fire tree regeneration will influence the longer-term ecosystem structure and function of areas burned by the 2020 wildfires, with implications for land management planning. Most coniferous tree species in the western United States require seed dispersal from live trees to successfully regenerate in severely burned areas (Burns and Honkala 1990). For these species, the majority of seed dispersal, and therefore post-fire regeneration, is limited to <300-650 feet from live trees that survived fire (McCaughey et al. 1986, Kemp et al. 2016). Therefore, areas in the center of large, high-severity patches can take long periods to recover as conifer forests or may remain as persistent treeless meadows for decades to centuries (Kaufmann et al. 2000, Chambers et al. 2016, Stevens-Rumann and Morgan 2019). However, the pre-fire composition of the forest plays an important role in ecosystem response; some Rocky Mountain species such as lodgepole pine (*Pinus contorta* var. *latifolia*) and aspen (*Populus tremuloides*) have fire-adaptive traits like serotiny (cones that open following heating) or resprouting (the ability to reproduce from belowground root tissues after burning), respectively, that can facilitate rapid post-fire recovery of large high-severity burn patches (Tinker et al. 1994, Turner et al. 2007, Kreider and Yocom 2021). Temperature, precipitation, and topography also influence patterns of post-fire tree regeneration for most species, with cooler, wetter sites often having more rapid or abundant tree establishment in comparison to warm, dry areas (Harvey et al. 2016, Davis et al. 2019, Rodman et al. 2020a).

Notably, many forests that burned in the 2020 wildfires experienced pre-fire tree mortality as a result of mountain pine beetle (*Dendroctonus ponderosae*), spruce beetle (*Dendroctonus rufipennis*), or western balsam bark beetle (*Dryocoetes confusus*) outbreaks since the early 2000s (Hicke et al. 2020), leading to altered structure and composition (Andrus et al. 2020a, Rodman et al. 2022a). Because bark beetle outbreaks often kill large, seed-bearing trees (Hart et al. 2014, Johnson et al. 2014) and the viability of even serotinous cones can decline with time since tree mortality (Teste et al. 2011, Rhoades et al. 2022), prior bark beetle outbreaks have the potential to hinder forest recovery following wildfire. Still, studies of such effects report mixed results. Prior bark beetle outbreaks can limit forest recovery potential following some wildfires (Carlson et al. 2017, Andrus et al. 2021), whereas post-fire recovery following other wildfires may be relatively unaffected (Harvey et al. 2014, Schapira et al. 2021). In general, species that rely on post-fire seed dispersal from live trees are likely to be most vulnerable to the combined effects of bark beetle outbreaks and wildfire. The complex nature of the 2020 wildfires – with a mosaic of fire severities, pre-fire forest communities, pre-fire management, environmental conditions, and severity of pre-fire insect outbreaks – suggests that post-fire forest trajectories will vary substantially across each landscape, requiring site-specific management planning.

In complex post-fire landscapes such as those of the 2020 wildfires, managers may benefit from partitioning the landscape into operational units defined by different expected states, conditions, or likely trajectories, which can then be addressed using a range of management strategies (Aplet and Mckinley 2017). The Resist-Accept-Direct (RAD) framework provides a powerful tool to navigate uncertainties and apply a diversity of management approaches across such landscapes (Lynch et al. 2021, Magness et al. 2022). '*Resist*' strategies seek to maintain ecosystem function over time within a range of acceptable variation based on historic patterns. However, not all historic patterns are likely to be adaptive under future climate conditions (Millar et al. 2007, Dudney et al. 2018). In such cases, '*Accept*' strategies seek to acknowledge change in ecosystem function both within and beyond historical patterns, allowing landscapes to transform into a new state without intervention. Acceptance may be most appropriate when active management is infeasible, or where the expected trajectory of a site is well-aligned with desired conditions. Finally, '*Direct*' strategies rely on active management to target a specific desired state or condition which may not be met under the expected trajectory of a site. Applying RAD in the management of post-fire landscapes begins with a detailed assessment of likely ecosystem trajectories, their overlap with desired conditions, and the feasibility of adaptive management. Based on these criteria, strategies can then be developed to resist, accept, and/or direct change following wildfire depending on social values and local context, such as the size and severity of the area affected, and environmental conditions such as climate and topography (Fig. 1; Stevens-Rumann and Morgan 2019, Stevens et al. 2021).

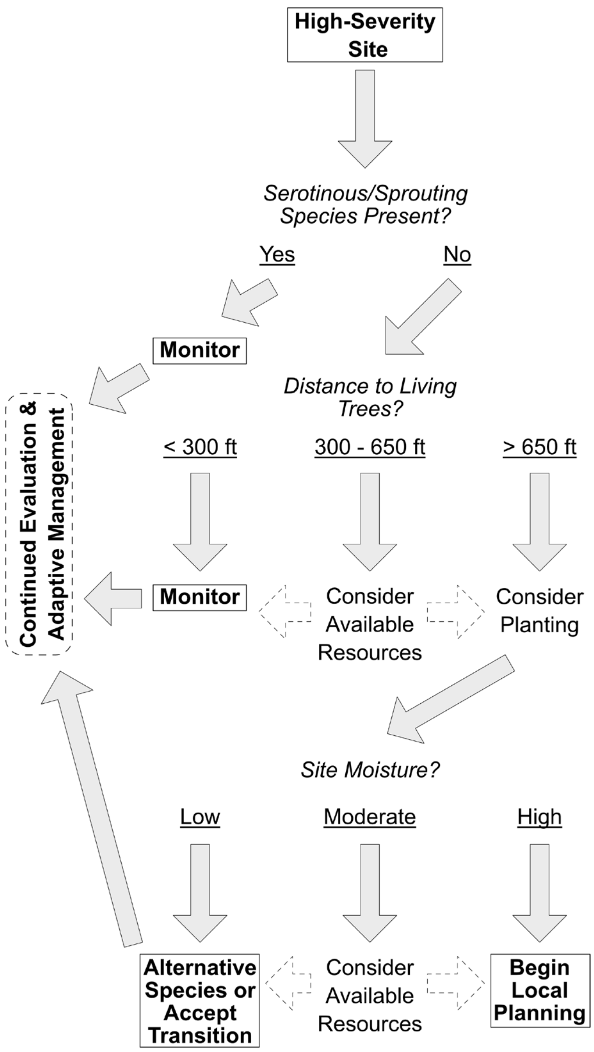

Figure 1: Flowchart with landscape-scale considerations for post-fire reforestation activities. Adapted from Stevens-Rumann and Morgan (2019).

Currently, post-fire landscape management occurs at different intervals following fire, depending on the resource being managed and the condition of the landscape. Immediately after fire, landowners or managers typically perform an initial site evaluation and implement treatments focused on soil stability, flood risk, and water retention (Robichaud et al. 2009). Over intermediate time scales (e.g., 1-10 years following fire), vegetation conditions (e.g., forest and non-forest cover) are typically compared to desired conditions for a landscape to determine the need for subsequent intervention (Guiterman et al. 2022). If early post-fire regeneration is deemed insufficient to return forest cover to desired levels and active management is feasible, reforestation (e.g., planting tree seedlings) is a common post-fire management strategy aimed at increasing the rate of forest recovery (North et al. 2019). Reforestation may be particularly valuable in large treeless patches where severe fire has eliminated seed sources, where resprouting and serotinous species are absent, and there is a low probability of natural establishment (Kemp et al. 2016, Stevens et al. 2021). Such plantings may help to accelerate forest recovery while maintaining key ecosystem services (e.g., nutrient retention and water quality; Rhoades et al. 2019).

However, reforestation is both costly and time-consuming, and success can vary widely (Ouzts et al. 2015, Kolb et al. 2019). In addition, operational bottlenecks of seed collection, nursery infrastructure for production, and the availability of skilled labor currently limit the ability to keep pace with the total burned acreage in need of intervention (Dumroese et al. 2019, Fargione et al. 2021). These barriers to implementation are reflected in the 2021 Infrastructure Investment and Jobs Act, which provides $200 million in funding for seed collection, planning, and reforestation on federal lands (H.R.3684). Notwithstanding increases in funding for reforestation, assessments of post-fire landscapes may help to effectively target management resources by identifying where active intervention is feasible, where forests are least likely to recover naturally, and where planting success is likely to be highest. Because natural tree regeneration is typically more rapid and abundant at wetter, more productive sites, it follows that planting success may be higher in relatively wet sites where recovery is solely limited by distance to live trees or seed availability (Fig. 1; Stevens-Rumann and Morgan 2019). Although assisted migration (moving species beyond current ranges) and assisted gene flow (moving genotypes within species ranges) hold promise in promoting forest adaptation to a warming climate (i.e., "Direct" strategies; Millar et al. 2007, Aitken and Bemmels 2016), they are not widely applied strategies in reforestation on public lands. This reflects both policy limitations and the need for research to reduce uncertainties about the effectiveness of such strategies in the context of uncertain future rates of change (Williams and Dumroese 2013, North et al. 2019, Young et al. 2020). Thus, most reforestation activities are currently applied as '*Resist*' strategies, which are most appropriate when historical forest communities are well-aligned with the current and future environmental conditions of a site. An understanding of where natural forest recovery is unlikely and where environmental conditions are suitable for the pre-fire forest community will help to prioritize reforestation activities in the landscapes burned by the 2020 wildfires.

Our primary objective in this report is to describe landscape conditions following five major fire events that occurred in the fall of 2020 throughout northern Colorado and southern Wyoming – the Calwood, Cameron Peak, East Troublesome, Mullen, and Williams Fork Fires (Fig.

2, Table 1). These fires are notable because of their large extents (i.e., some of the largest in this area since the early 1900s), their proximity to development, and the dominant forest types burned (i.e., many high-elevation forests), which present difficult challenges to managers. For each wildfire, we assess the post-fire distances to live trees, the effects of pre-fire bark beetle outbreaks, and the potential for the dominant conifer species to naturally recover post-fire. We also assess spatial patterns of climate suitability for the dominant conifer species to help inform broad-scale reforestation planning, which is ongoing and will continue for many years. We make the findings and spatial data described in this report publicly available but recognize that such information is only one small piece of the decision-making framework that necessarily incorporates policy mandates, local site visits, and expert knowledge.

Table 1: Incident name, fire size, and percentage high-severity fire within five major fires in northern Colorado and southern Wyoming that occurred during the 2020 fire season.

Fire Name	Size (ac)	High Severity (%)
Calwood	10,113.9	42.8
Cameron Peak	208,913.0	54.3
East Troublesome	193,811.9	57.4
Mullen	176,877.5	48.7
Williams Fork	14,833.4	58.5

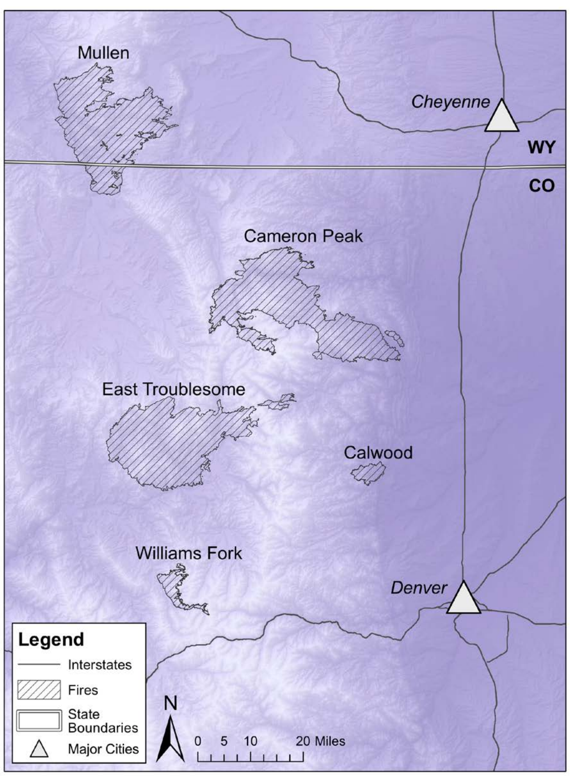

Figure 2: The locations of five major fires in northern Colorado and southern Wyoming that occurred during the 2020 fire season. Landscape conditions following these five fires are the focus of this report.

2. Study Area

To define the study area, we used Calwood, Cameron Peak, East Troublesome, Mullen, and Williams Fork Fire perimeter data from the National Interagency Fire Center (*National Interagency Fire Center* 2022). Together, these five wildfires (Fig. 2, Table 1) burned 604,550 ac between August and November 2020. On days of greatest fire spread, the Severe Fire Danger Index, a derived weather variable that represents the combined effects of wind speed, humidity, temperature, and fuel moisture (Jolly et al. 2019), typically exceeded the 95th percentile relative to longer-term (i.e., 1979-2020) daily weather conditions. In other words, fuel preconditioning from a year of severe drought, combined with dry, windy weather during burning, played a key role in the extreme fire behavior of these fires.

The area burned spanned a wide range of elevations (ca, 5,300 to 12,000 ft) which drives variation in typical climatic conditions. For example, mean annual temperatures range from 29.7 to 42.5°F, and total annual precipitation ranges from 13.8 to 43.0 inches across the five fires (1991-2020 climate normal; *PRISM Climate Group 2022*). This climatic variation leads to a broad range of forest communities across the study area (Peet 1981), which are adapted to a wide range of typical disturbance regimes and have a range of regeneration strategies. Thus, while the fire behavior in the 2020 wildfires was extreme relative to recorded conditions in the region, it may or may not align with the natural disturbance regimes (Veblen and Donnegan 2005, Addington et al. 2018) and fire-adaptive traits (Davis et al. 2018, Rodman et al. 2021) of a given forest community. For example, forests with traits such as resprouting or serotiny, which facilitate recovery following high-severity fire, may be less vulnerable to fire-driven forest loss.

Common forest types in the study area include both lower montane (roughly 5,500 to 8,000 ft) and upper montane (centered on 8,000 to 9,000 ft but variable with latitude and topography) forests (Kaufmann et al. 2006). Lower montane forests, typically dominated by ponderosa pine (*Pinus ponderosa* var. *scopulorum*), experienced historical (prior to 20th-century fire suppression) fires that were typically frequent and of low-moderate severity; their extent was fuel-limited so that years of most widespread fire followed years of cool-moist conditions favorable to the understory growth and increased surface fuels connectivity (Veblen et al. 2000, Gartner et al. 2012). Frequent fires were lethal to tree seedlings and saplings but rarely killed mature ponderosa pine due to its thick bark and self-pruning habit (Sherriff et al. 2014, Brown et al. 2015).

In contrast, upper montane forests were characterized by a much more complex fire regime, including low-, moderate-, and high-severity patches which created a heterogeneous mosaic of tree ages, species, and densities across the landscape reflecting the interplay of topography, fuels, and climate (Kaufmann et al. 2000, Huckaby et al. 2001, Sherriff et al. 2014). In upper montane forests, thick-barked ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) often survived fire, and the post-fire seedbed conditions were favorable to the rapid and abundant establishment of these two species (Sherriff and Veblen 2006, Schoennagel et al. 2011). Infrequent occurrences of large and severe fires in the upper montane zone, associated with extreme drought, also contributed to landscape heterogeneity by creating large, long-lasting non-forest openings (Kaufmann et al. 2000). Tree-ring reconstructions of fire history across the montane zone show a marked reduction in fire frequency during the 20th century compared to the 19th century and earlier (but varying in timing by site) reflecting both modern fire suppression and land use changes (Veblen et al. 2000, Schoennagel et al. 2011). Recent (since ca. 2000) increases in fire activity, in combination with limited post-fire recovery, raise concerns about fire-driven forest losses across the montane zone (Chambers et al. 2016, Rother and Veblen 2016, Rodman et al. 2020b, 2020a).

At the highest elevations of our study area, subalpine forests (c. 9,000–11,500 ft) are primarily composed of Engelmann spruce (*Picea engelmannii* var. *engelmannii*), subalpine fir (*Abies lasiocarpa* var. *lasiocarpa*), and lodgepole pine, with the latter often forming even-aged postfire stands at the transition to the upper montane zone (Sibold et al. 2006). All three subalpine conifer species are thin-barked and easily killed by fire (Baker 2009). Fire in the subalpine zone is limited primarily by climate and fire weather rather than the availability of fuels. Historically, fires in the subalpine zone were often large (i.e., > 2,500 ac), severe, and burned at intervals of 200-500 years or more during exceptionally dry years (Sibold and Veblen 2006). Following past subalpine fires, lodgepole pine typically recovered quickly whereas recovery of Engelmann spruce and subalpine fir was sometimes protracted for 100 years or more depending on seed availability and site conditions (Coop et al. 2010, Rodman et al. 2019). Rates of burning in Rocky Mountain subalpine forests are now greater than any seen in the last 2,000 years (Higuera et al. 2021). Following recent fires in the subalpine zone of Colorado and Wyoming, a limited availability of live trees and observations of low initial post-fire tree regeneration densities raise concerns about the efficacy of natural regeneration on management-relevant timescales (Guz et al. 2021, Schapira et al. 2021).

3. Methods

3a. Mapping Fire Severity and Distance to Live Trees

To quantify distances to live trees throughout each fire perimeter, a proxy for post-fire seed availability in non-serotinous conifers, we calculated the Relativized Burn Ratio (RBR) following Parks et al. (2018) and overlaid these data with a tree canopy height model (CHM) from 2019 (Potapov et al. 2021), the year immediately before fire occurrence. We assumed that all 100-ft pixels with RBR ≥ 283 burned at high severity and were devoid of live trees (based on Parks et al. 2018). To account for areas that had previously burned, were harvested, or were persistent treeless meadows but may have had RBR values < 283, we also required that pixels with live trees had canopy height values ≥ 16.4 ft (5 m) in 2019. This is a height above which the CHM is more reliable in detecting tree cover (Potapov et al. 2021), and the approximate size at which the non-serotinous conifer species in our study area reach reproductive maturity (Andrus et al. 2020b, Rodman et al. 2021). Finally, we overlaid the RBR and CHM data to map the distances from each 100-ft pixel within a fire perimeter to the closest live tree. Because high-severity areas are the most likely targets for reforestation activities, we visualized the overall distribution of distances to live trees within the high-severity portion of each fire (i.e., where RBR ≥ 283), and calculated the proportion of the high-severity area that was < 300 ft from a live tree, 300-650 ft from a tree, and > 650 ft from a tree, based on numbers in the decision support framework of Stevens-Rumann and Morgan (2019) and Fig. 1.

3b. Mapping Recruitment Probabilities Throughout Each Fire

To better understand the potential for natural forest recovery in each fire event, we mapped the probability of post-fire recruitment for each of the dominant coniferous tree species – Douglas-fir, Engelmann spruce, lodgepole pine, ponderosa pine, and subalpine fir – using statistical models from Davis et al. (*In Review*). Briefly, these models were developed through a broad-scale synthesis of post-fire conifer regeneration data throughout the western United States, which included 10,230 field plots and 334 sampled fire events across the West. Many of these plots and fire events were within the southern Rocky Mountains, which gives additional confidence to our predictions (Table 2). Statistical models were fit for each species using spatial data related to climate, topography, fire severity, distance to live trees, post-fire canopy cover, and pre-fire disturbance (e.g., bark beetle outbreaks) to predict the presence of post-fire seedlings in sampled field plots. We used the statistical models from Davis et al. (*In Review*) to predict the probability of natural recruitment for each conifer species throughout each fire at a 100-foot resolution. Climate data, obtained from GridMET (Abatzoglou 2013), represent the average conditions from 2001-2020 at a 2.5-mile resolution. Topography was described at a 300-ft resolution using the continuous heat insolation load index, which combines slope angle, aspect, and latitude to estimate terrain-driven solar heating (Theobald et al. 2015). Post-fire canopy cover (i.e., the mean tree cover within a 1,000-ft radius around each 100-ft pixel) was calculated using 2021 canopy cover data from the Rangeland Analysis Platform (Jones et al. 2018). Fire severity (RBR) and distances to live trees, as described in *subsection 3a*, were also included as predictors of natural recruitment in these models. Prior to making predictive maps of post-fire recruitment, we resampled climatic and topographic layers to match the 100-ft resolution of other data using methods that only minimally altered data values.

For subalpine fir and Engelmann spruce, the tree species that are most likely to be influenced by the combined effects of bark beetle outbreaks and wildfire (Carlson et al. 2017, Andrus et al. 2021), we identified areas affected by species-specific insects and pathogens before the 2020 fires. Specifically, we identified the presence of western balsam bark beetle (*Dryocoetes confuses*) and/or subalpine fir decline (a morality complex including western balsam bark beetle and fungal pathogens; Harvey et al. 2021) as inputs into fir recruitment predictions, and spruce beetle (*Dendroctonus rufipennis*) as an input into spruce recruitment predictions using US Forest Service Aerial Detection Survey (ADS) data from 1997 to 2019 (Forest Health Protection 2021). We defined forest areas as "affected" by prior decline or bark beetle outbreaks if they were within 1,650 ft of moderate or high-severity mortality (i.e., moderate/high-severity codes and/or ≥ 10 trees/ac) from 1997 to 2019. We used a 1,650-ft buffer around individual polygons to improve detection accuracy and account for locational error in ADS data (Coleman et al. 2018). We then included the presence or absence of prior bark beetle disturbances in models of Davis et al. (*In Review*) to predict post-fire recruitment for spruce and fir across each fire.

We excluded bark beetle terms from lodgepole pine predictions as results of prior bark beetle outbreaks on post-fire regeneration and seed viability for this species are mixed in the literature (Teste et al. 2010, Harvey et al. 2014b) and because the recruitment models of Davis et al. (*In Review*) showed no major effects of prior bark beetle outbreaks on post-fire recruitment for this species. Still, seed viability is low in long dead serotinous trees in this area, and the effects of past mountain pine beetle outbreaks on lodgepole pine regeneration throughout these fires is a key area of future research and a source of uncertainty in these fires (Rhoades et al. 2022). Lastly, we excluded bark beetle terms in ponderosa pine and Douglas-fir predictions because bark beetle outbreaks affecting these species have been relatively limited in the region (Chapman et al. 2012, Hicke et al. 2020, USFS 2020). To qualitatively describe the amount and timing of pre-fire tree mortality due to bark beetle outbreaks, we summarized tree mortality area data from Hicke et al. (2020) for important beetle agent and host tree combinations – i.e., Douglas-fir beetle (*Dendroctonus pseudotsugae*) and Douglas-fir, spruce beetle and Engelmann spruce, mountain pine beetle (*Dendroctonus ponderosae*) and lodgepole pine, mountain pine beetle and ponderosa pine, western balsam bark beetle/subalpine fir decline and subalpine fir. These summaries were restricted to areas within each fire perimeter.

Table 2. Sample size and model performance metrics for each model of post-fire recruitment probability. "Plots" and "fires" refer to the sample sizes used to develop predictive models across the western United States, while numbers in parentheses give the sample sizes within the southern Rocky Mountains (i.e., Colorado, southern Wyoming, and northern New Mexico, USA). "AUC" refers to the area under the receiver operating characteristic curve, a measure of predictive performance ranging 0 – 1, where 1 indicates perfect model predictions. "CV AUC" is the mean AUC from 10-fold cross validation (predictions made to data not used to build the model). "Thresholdss" refers to the species-specific probability threshold used to categorize regeneration as likely or unlikely which maximized the sum of sensitivity and specificity (i.e., the True Skill Statistic).

Species Name	Species Code	Plots	Fires	AUC	CV AUC	Threshold^{ss}
Subalpine fir (Abies lasiocarpa)	ABLA	2,268 (274)	139 (15)	0.81	0.78	0.16
Lodgepole pine (Pinus contorta)	PICO	3,232 (264)	178 (15)	0.79	0.77	0.59
Engelmann spruce (Picea engelmannii)	PIEN	1,535 (194)	138 (19)	0.73	0.71	0.49
Ponderosa pine (Pinus ponderosa)	PIPO	7,719 (1,707)	276 (36)	0.70	0.69	0.22
Douglas-fir (Pseudotsuga menziesii)	PSME	6,018 (1,213)	274 (40)	0.74	0.75	0.39

In our predictions of recruitment probability (i.e., 'P(Recruit)'), P(Recruit) represents the probability that at least 40 trees ac-1 of the focal species will establish within 10 years of fire occurrence. Because the 2020 fires burned across a range of ownership designations, all of which may have different management goals, we did not test our predictions against national forest- and forest type-specific stocking levels; we used a single number of 40 trees ac-1 for simplicity and a more consistent comparison across species. We limited predictions of natural recovery to areas with ≥ 5 ft2 of pre-fire live basal area acre-1 of the corresponding tree species based on species basal area maps from the 2000s (Wilson et al. 2013). We restricted recruitment maps to each fire perimeter, and reclassified them into four categories of 'low', 'low/moderate', 'moderate/high', and 'high' using breaks centered around species-specific classification thresholds from Davis et al. (*In Review*) (Thresholdss; Table S1).

3c. Mapping Climate Suitability in High-Severity Areas

We mapped climate suitability for each species using similar methods to those in *subsection 3b*, but with a few small changes. First, RBR was set to a constant value of 100 (i.e., low/moderate severity), tree cover was set to 30%, distance to live trees was set to 30 ft, and prior disturbance was set to "none" throughout each fire. In other words, we held the effects of fire severity, distance to live trees, and forest canopy cover constant to isolate the effects of climate and topography on recruitment potential for each species. Data for Engelmann spruce, lodgepole pine, and subalpine fir were derived from models of Davis et al. (*In Review*) using 2001-2020 climatic conditions. Because some land owners and managers are already using the Southern Rockies Reforestation Tool (SRRT; Rodman et al. 2022b) to aid in reforestation planning of ponderosa pine and Douglas-fir, climate suitability for these species was obtained using SRRT for the 1981-2010 climate period. As in *subsection 3b*, we limited predictions to areas that had ≥ 5 ft2 of live basal area acre-1 for a given species in the early 2000s. However, climate suitability maps were further restricted to high-severity areas within each fire perimeter where reforestation is more likely to occur. For visualization, we classified climate suitability maps into five equal-interval categories, ranging from low to high.

4. Results

4a. Calwood Fire

The Calwood Fire ignited on October 17th, 2020, near Jamestown, Colorado, and was contained on November 14th, 2020. During this one-month period, the fire burned 10,114 ac of montane forest ranging from 5,545-8,580 ft (Fig. 3). Calwood primarily affected forests composed of ponderosa pine, with Douglas-fir and lodgepole pine present at higher elevations and on wetter sites. Of the total fire area, 42.8% burned at high severity. However, 40.7% of this high-severity area was within 300 ft of a live tree, as compared to 29.9% of the area within 300-650 ft, and 29.4% beyond 650 ft. Only a small amount of the pre-fire forest area was impacted by bark beetle outbreaks (3.2% cumulative tree mortality from 1997 to 2018), with the majority of this mortality attributed to mountain pine beetle colonization of ponderosa pine between 2010 and 2012.

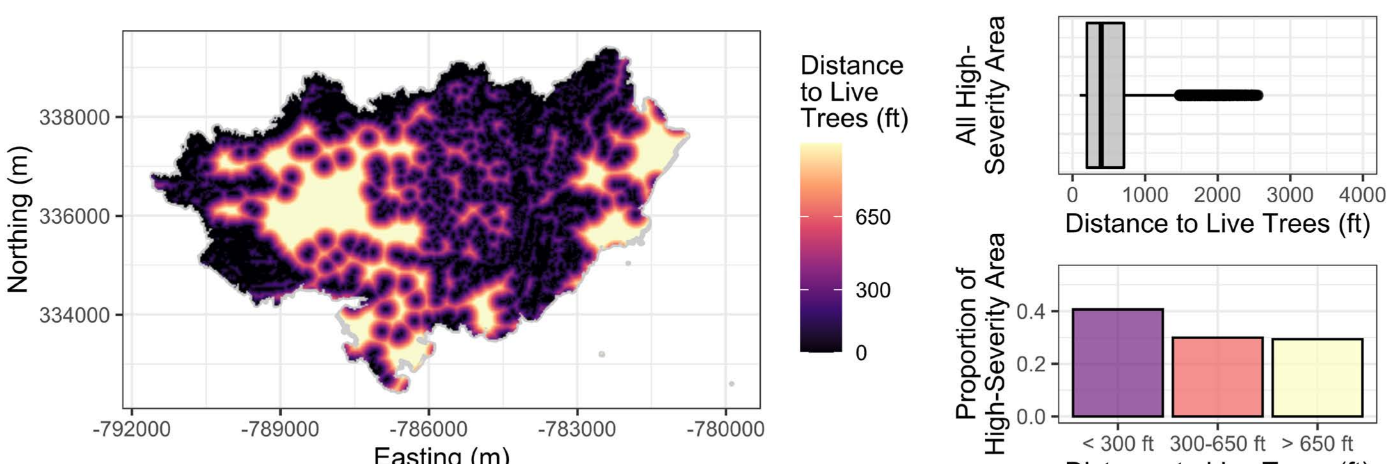

Figure 3: Map of distances to live trees in the Calwood Fire (left), as well as the range of distances to live trees within high-severity areas (right). White areas in the map are outside of the final fire perimeter (shown in grey).

Post-fire recruitment probabilities in the Calwood Fire varied by species and location (Fig. 4). Where present at higher elevations, lodgepole pine had the highest probabilities of natural recruitment within 10 years of fire occurrence. Ponderosa pine had low to moderate probabilities of natural recruitment in many portions of the fire, with the highest probabilities near live trees. Recruitment probabilities for Douglas-fir were relatively low in most areas but were high in locations with abundant surviving tree cover, near the edge of the fire, and on northeast-facing slopes. Across all species, 49.0% of the total fire area was predicted to have low to moderate recruitment potential.

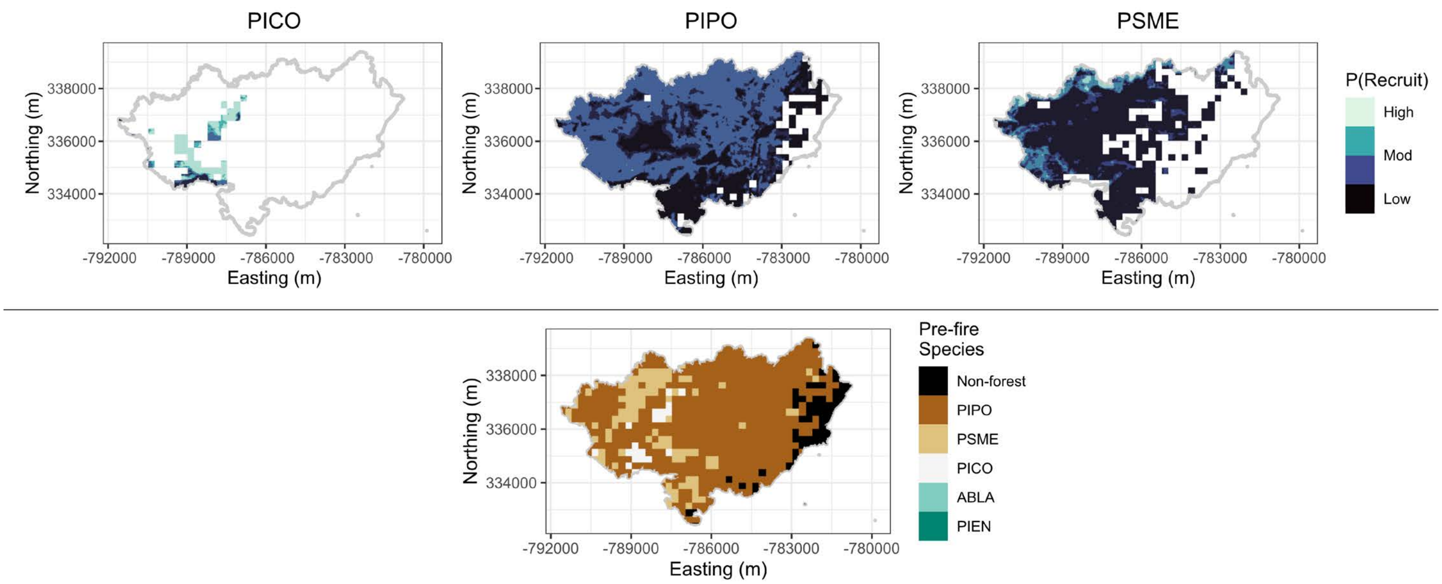

Figure 4: Probabilities of natural recruitment for each dominant coniferous tree species in the Calwood Fire. White areas in each map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. PICO: lodgepole pine, PIPO: ponderosa pine, PSME: Douglas-fir.

Within high-severity areas of the Calwood Fire, climate suitability was primarily moderate to high for each species (Fig. 5). For lodgepole pine, higher elevations were predicted to have high climate suitability irrespective of aspect or topographic setting. Likewise, areas with high suitability for ponderosa pine and Douglas-fir seedlings were at the highest elevations in the fire, though these species also had high-suitability sites in valley bottoms and on northeast-facing slopes. Overall, planting of ponderosa pine and Douglas-fir, focusing on intermediate to high-elevations throughout the fire and protected topographic settings, may best align with the current and projected future climate of this area.

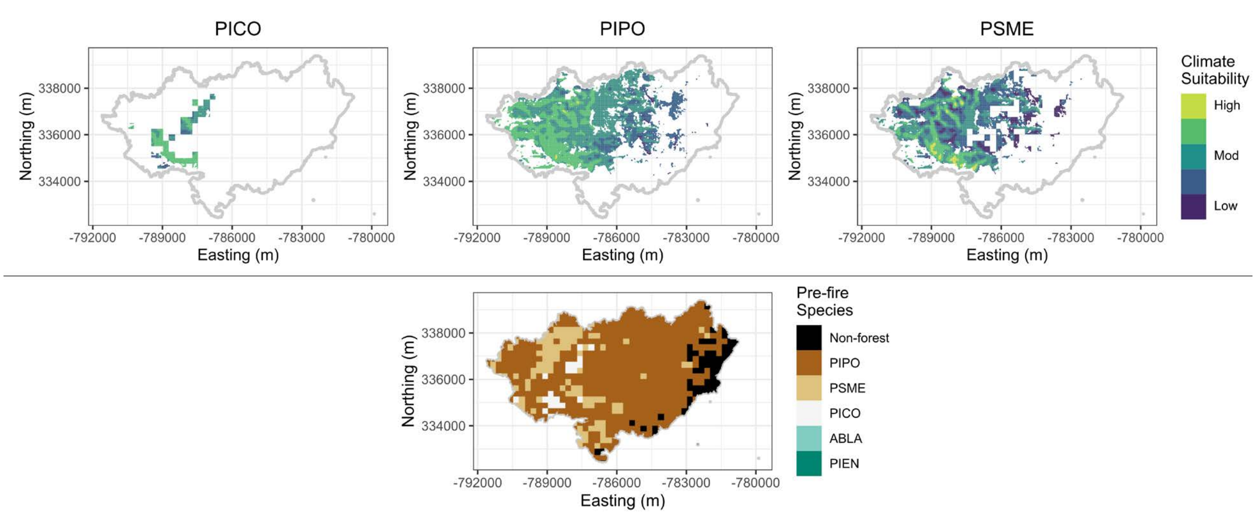

Figure 5: Climate suitability based on recent climate (ca., 1981-2020) and topography for each dominant coniferous tree species in the Calwood Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. PICO: lodgepole pine, PIPO: ponderosa pine, PSME: Douglas-fir.

4b. Cameron Peak Fire

The Cameron Peak Fire began on August 13th, 2020, near Cameron Pass, Colorado, and was declared contained on December 2nd, 2020. During several distinct phases of activity and spread, Cameron Peak burned 208,913 ac, becoming the largest fire in Colorado's recorded (i.e., since the early 1900s) history (Fig. 6). The fire spanned a wide range of elevations (5,308-11,897 ft) and forest types, affecting lower montane forests dominated by ponderosa pine and Douglas-fir on the eastern side, upper montane and subalpine forests with lodgepole pine in the center of the fire, and subalpine forests with Engelmann spruce and subalpine fir at the western end. Of the total fire area, 54.3% burned at high severity. Overall, 38.5% of this high-severity area was within 300 ft of a live tree, as compared to 28.8% of the area within 300-650 ft, and 32.8% beyond 650 ft. Cameron Peak had substantial pre-fire bark beetle activity with 40.6% cumulative tree mortality from 1997 to 2018. Mountain pine beetle was active in ponderosa pine (1.4% tree mortality) from 2010 to 2013 and lodgepole pine (28.9% tree mortality) from 2007 to 2013, while background levels of other beetles (e.g., 2.4% mortality from spruce beetle) were present throughout the 2000s and 2010s (Fig. S1)..

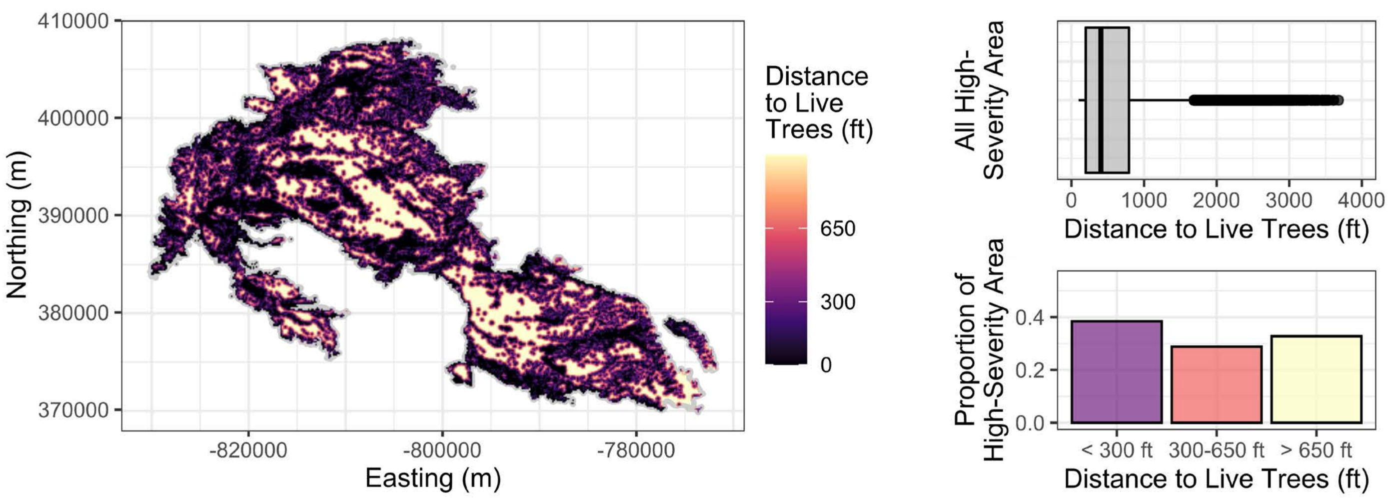

Figure 6: Map of distances to live trees in the Cameron Peak Fire (left), as well as the range of distances to live trees within high-severity areas (right). White areas in the map are outside of the final fire perimeter (shown in grey).

Because the Cameron Peak Fire was large and spanned a broad range of elevations, 10-year post-fire recruitment was predicted to vary within and among species throughout the fire (Fig. 7). Lodgepole pine had high probabilities of recruitment throughout much of the fire, particularly at intermediate to high elevations. Subalpine fir and Engelmann spruce had relatively low recruitment probabilities overall, but had moderate (fir) or moderate to high (spruce) values at high elevations, in areas with abundant surviving canopy cover, and on northeast-facing slopes. Ponderosa pine recruitment probabilities were relatively low throughout the fire but were moderate in areas near live trees. Douglas-fir had high recruitment probabilities in areas with abundant surviving canopy cover and on northeast-facing slopes. Of the total fire area, 24.1% was predicted to have low to moderate recruitment potential of all species.

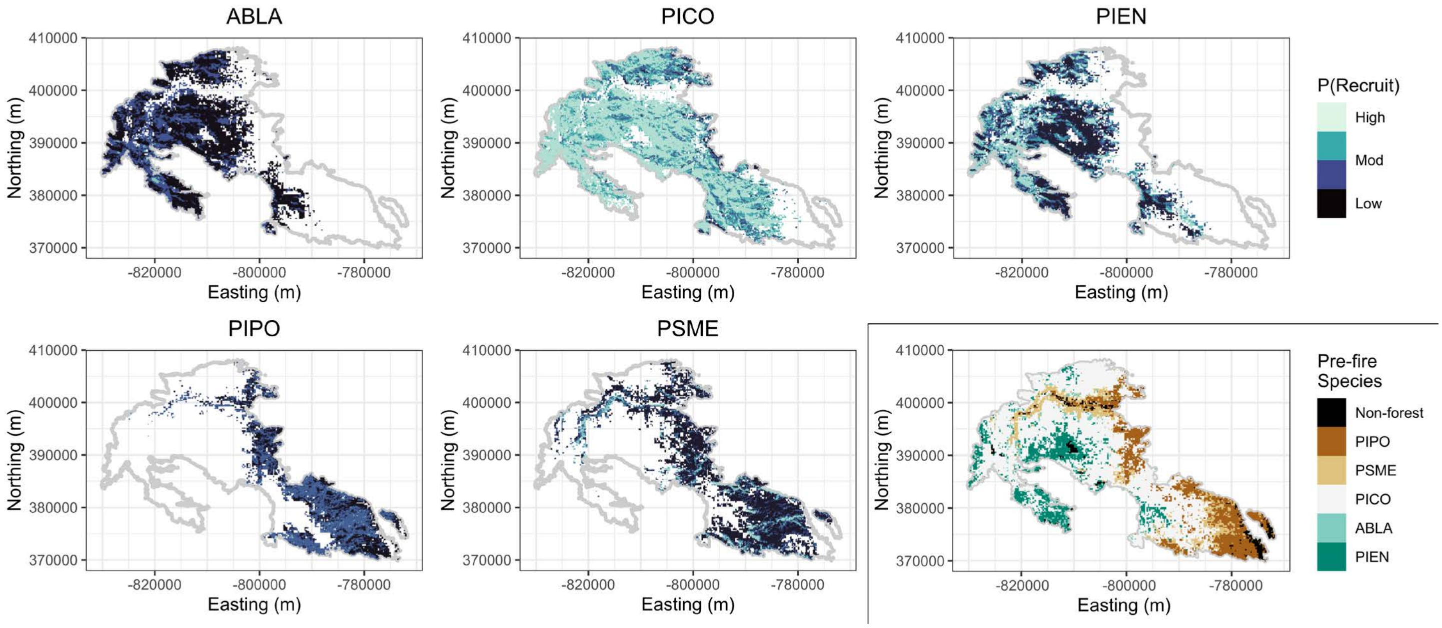

Figure 7: Probabilities of natural recruitment for each dominant coniferous tree species in the Cameron Peak Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

Climate suitability also varied substantially for each species throughout the Cameron Peak Fire (Fig. 8). Suitability for subalpine fir was relatively low in most areas but was moderate at the highest elevations and on northeast-facing slopes. Likewise, higher elevations and more sheltered topographic locations had high suitability for Engelmann spruce and lodgepole pine. In contrast, ponderosa pine and Douglas-fir had high moisture availability at low to intermediate elevations in the fire, particularly in valley bottoms and northeast-facing slopes. Overall, plantings of ponderosa pine and Douglas-fir at intermediate elevations in the fire, and plantings of lodgepole pine and Engelmann spruce at higher elevations, would best align with current and future climate conditions. For all species and most parts of the Cameron Peak Fire, planting on northeast-facing slopes and valley bottoms may lead to greater success.

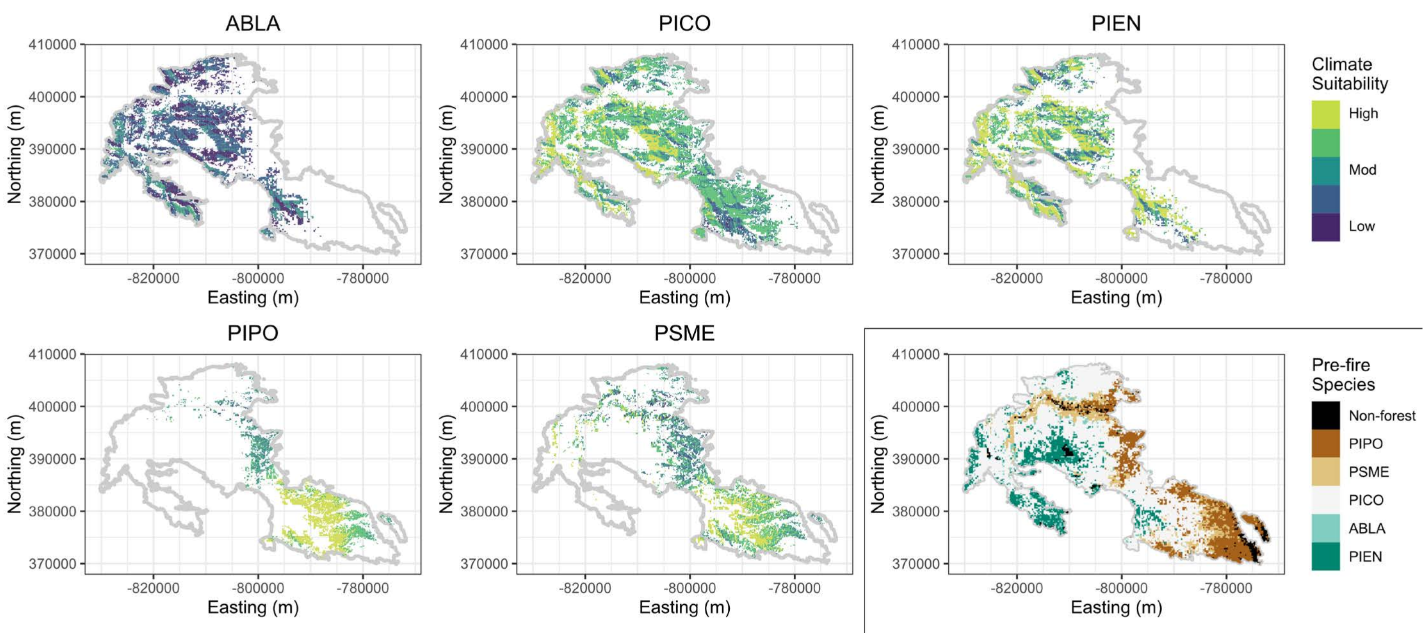

Figure 8: Climate suitability based on recent climate (ca., 1981-2020) and topography for each dominant coniferous tree species in the Cameron Peak Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

4c. East Troublesome Fire

The East Troublesome Fire began on October 14th, 2020, near Kremmling, Colorado, and was declared contained on November 30th, 2020. In that time, East Troublesome burned 193,812 ac, becoming the second-largest fire in Colorado's recorded history (Fig. 9). The fire affected elevations from 7,884 to 12,067 ft, primarily in upper montane and subalpine forests dominated by subalpine fir, Engelmann spruce, and lodgepole pine, with only limited components of ponderosa pine and Douglas-fir at the lowest elevations. Of the total fire area, 57.4% burned at high severity. However, 37.9% of this high-severity area was within 300 ft of a live tree, as compared to 32.2% of the area from 300-650 ft to a live tree, and 29.9% of the area > 650 ft. The East Troublesome landscape had moderate-severity bark beetle outbreaks (23.2% tree mortality across species) from 1997 to 2018, with the greatest effects due to spruce beetle in Engelmann spruce (4.7% tree mortality) from 2013 to 2018 and mountain pine beetle in lodgepole pine (16.6% tree mortality) from 2001 to 2009.

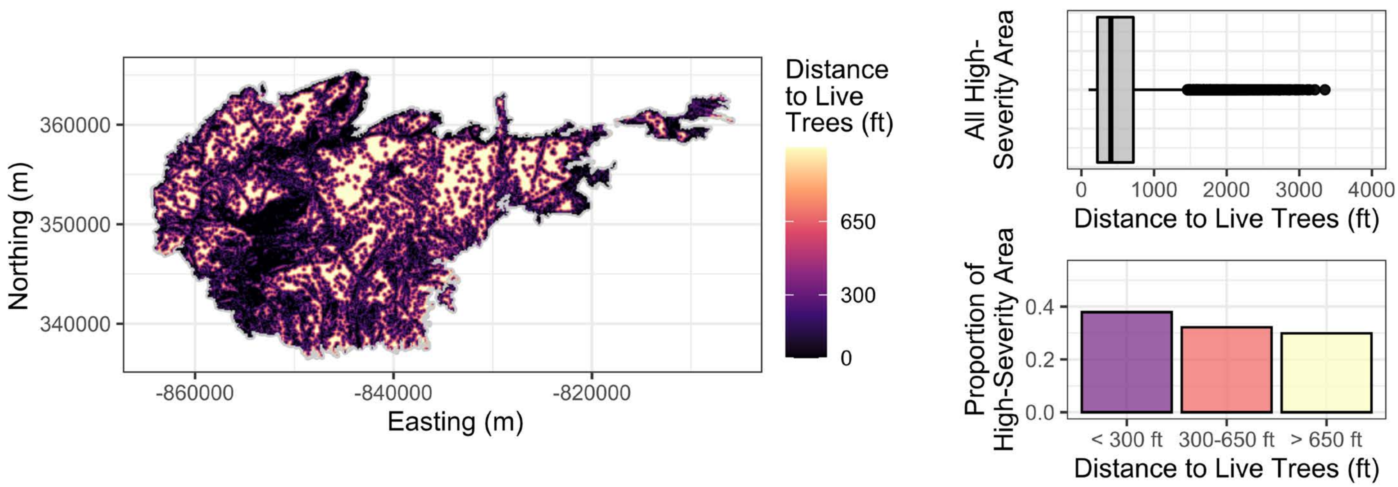

Figure 9: Map of distances to live trees in the East Troublesome Fire (left), as well as the range of distances to live trees within high-severity areas (right). White areas in the map are outside of the final fire perimeter (shown in grey).

Post-fire recruitment probabilities were relatively low for many tree species in the East Troublesome Fire (Fig. 10). However, lodgepole pine had high recruitment probabilities throughout much of the fire, and Engelmann spruce had high probabilities in wet, high-elevation areas. Subalpine fir, ponderosa pine, and Douglas-fir had low predicted recruitment probabilities in most portions of the fire. Of the total fire area, 34.7% was predicted to have low to moderate recruitment potential across all species.

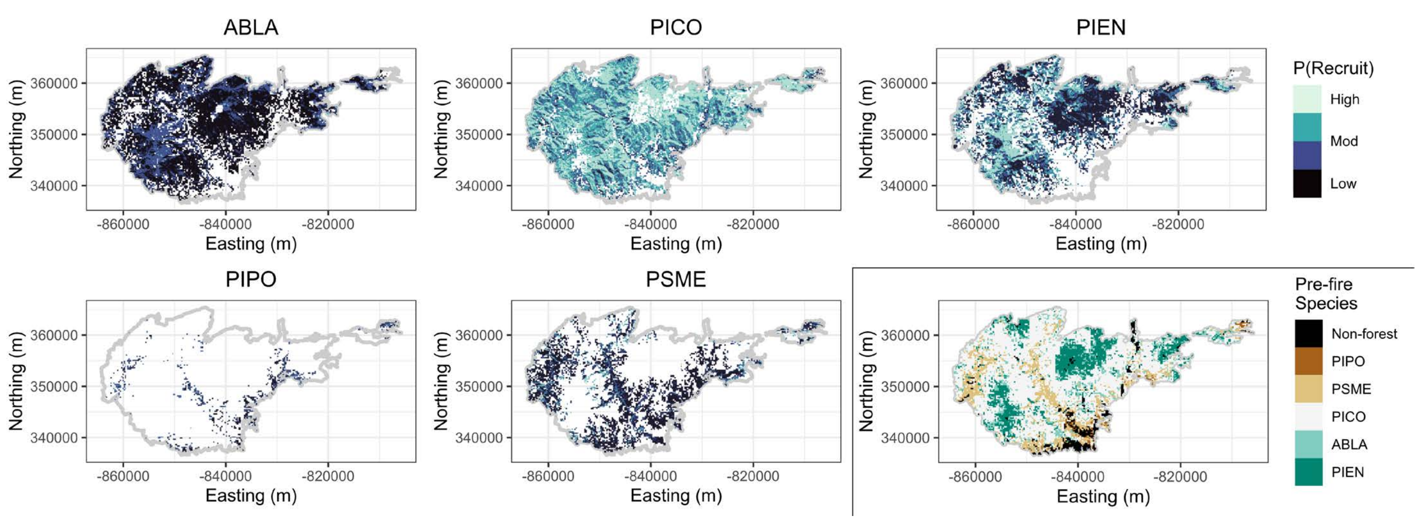

Figure 10: Probabilities of natural recruitment for each dominant coniferous tree species in the East Troublesome Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

While probabilities of natural recruitment were relatively low for most species in the East Troublesome Fire, climate suitability was relatively high (Fig. 11), suggesting that reforestation activities could help supplement natural regeneration as needed. For example, reforestation may be valuable in areas where initial site assessments indicate limited post-fire recruitment of lodgepole pine from serotinous cones. In particular, areas occupied by Engelmann spruce, ponderosa pine, and Douglas-fir before fire occurrence had high climate suitability for each respective species. At lower elevations in the fire (e.g., < 9,000 ft), we expect that limited planting of ponderosa pine and Douglas-fir may be appropriate, whereas planting of lodgepole pine and Engelmann spruce may be more appropriate at higher elevations in the fire, with a particular focus on northeast-facing slopes.

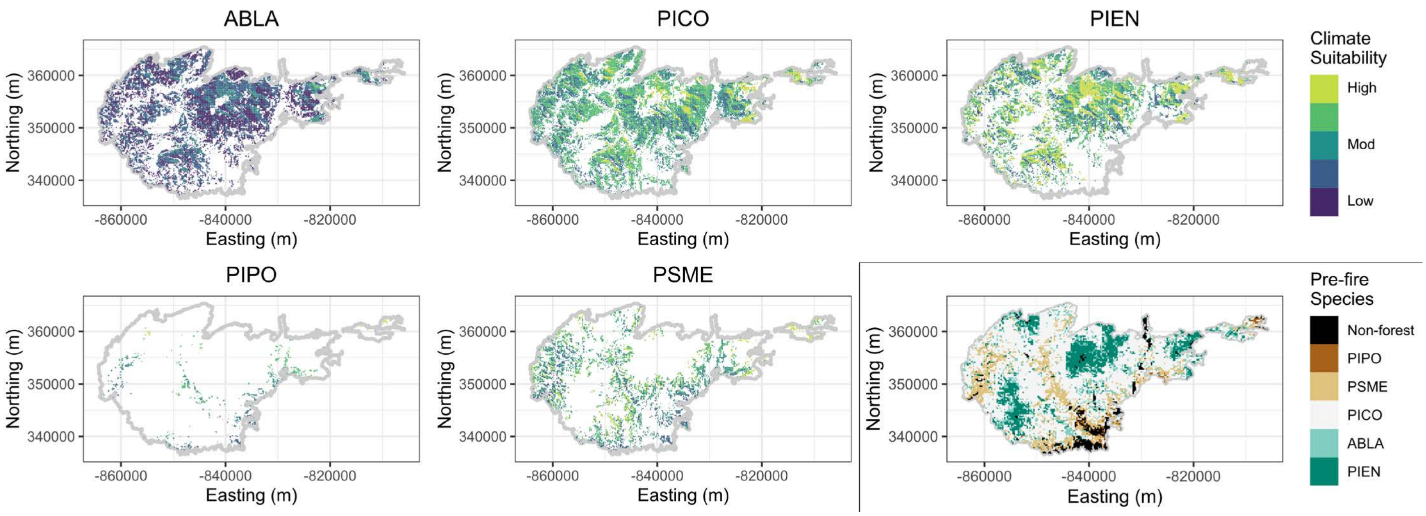

Figure 11: Climate suitability based on recent climate (ca., 1981-2020) and topography for each dominant coniferous tree species in the East Troublesome Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

4d. Mullen Fire

The Mullen Fire began in Savage Run Wilderness, southwest of Centennial, Wyoming, on September 17th, 2020, and was contained on October 24th, 2020. During this time, the fire burned 176,878 ac at elevations from 7,395 to 10,407 ft along the border of southern Wyoming and northern Colorado. Of the total fire area, 48.7% burned at high severity. However, this fire was heterogeneous and spatially complex, with most high-severity areas being near live trees. In fact, 50.4% of the high-severity area was within 300 ft of a live tree, as compared to 31.0% of the area from 300-650 ft to a live tree, and just 18.7% being > 650 ft (Fig. 12). The Mullen Fire had high amounts of pre-fire beetle kill (35.9% tree mortality across species) from 1997 to 2018, primarily driven by mountain pine beetle activity in lodgepole pine (34.2% tree mortality) from 2006 to 2011.

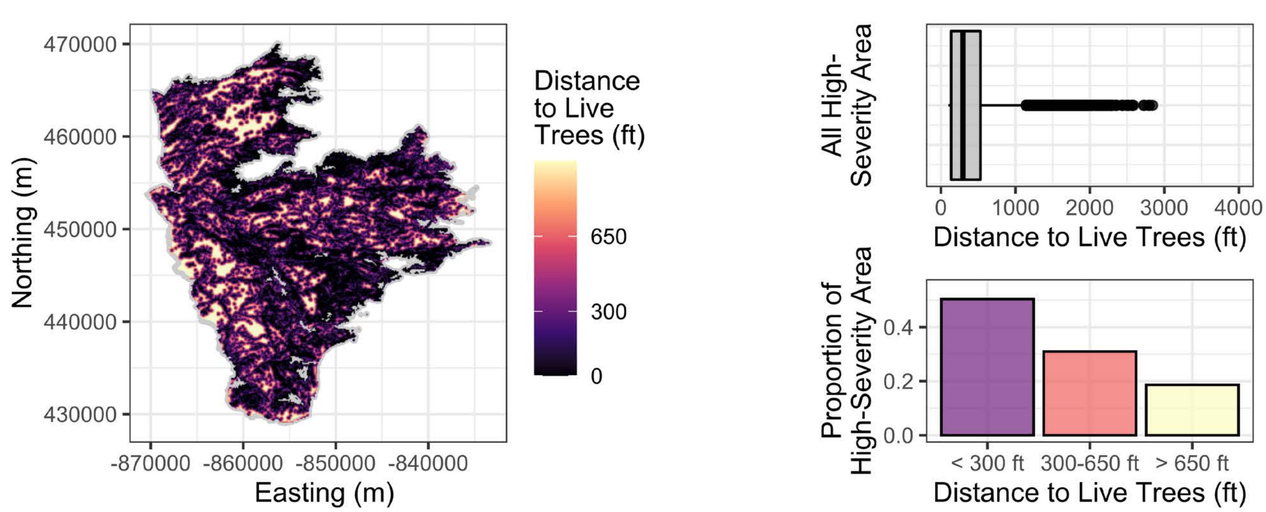

Figure 12: Map of distances to live trees in the Mullen Fire (left), as well as the range of distances to live trees within high-severity areas (right). White areas in the map are outside of the final fire perimeter (shown in grey).

Predictions of post-fire recruitment by species in the Mullen Fire suggest that lodgepole pine and Engelmann spruce are likely to recover well throughout much of the fire (Fig. 13). In the low- to mid-elevation areas where ponderosa pine and Douglas-fir were present before the fire, these species have low to moderate recruitment probabilities. Across the fire, 34.2% of the total area was predicted to have low to moderate recruitment for all species..

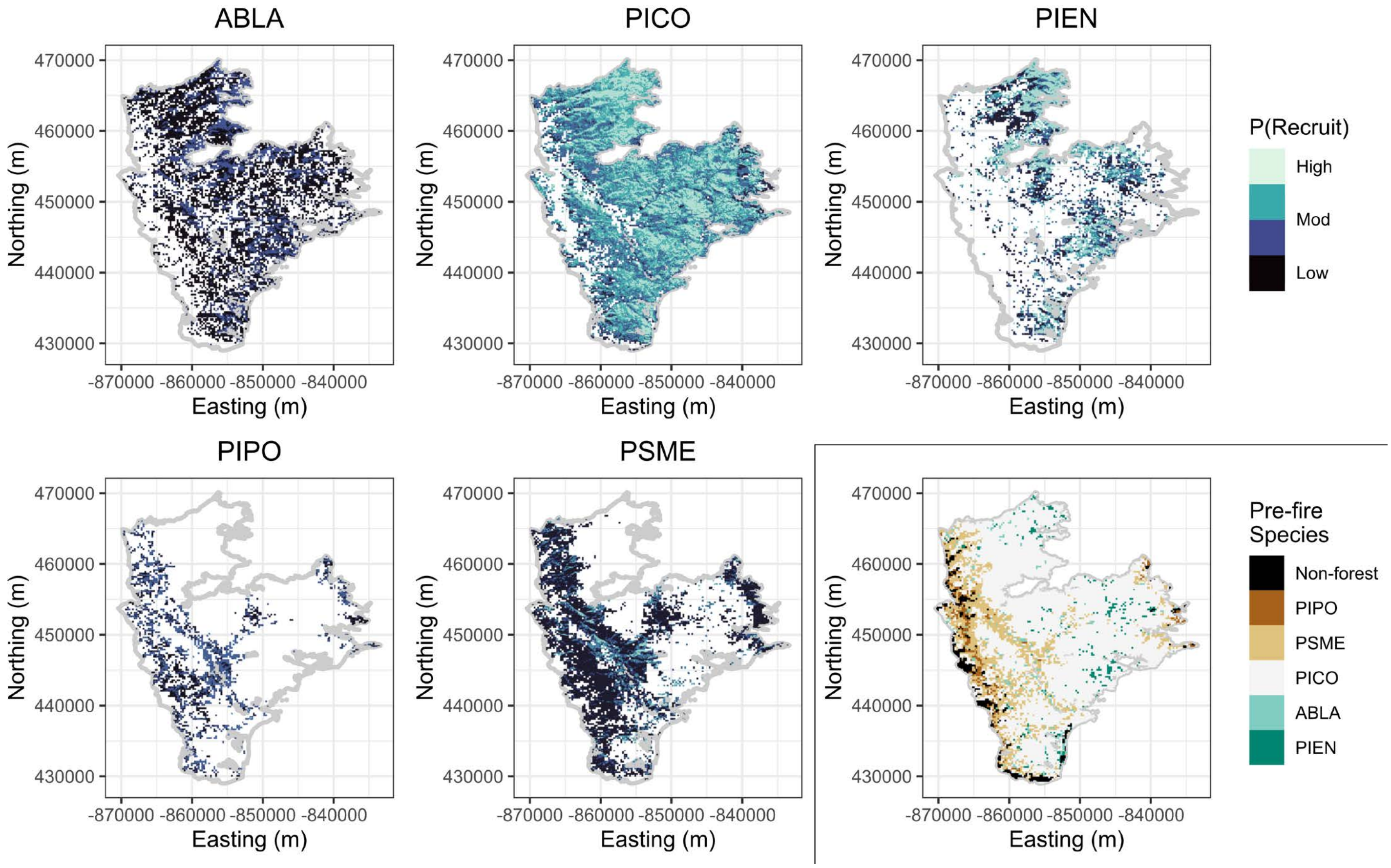

Figure 13: Probabilities of natural recruitment for each dominant coniferous tree species in the Mullen Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

Overall, climate suitability was high for many of the coniferous tree species present in the Mullen Fire, which may increase the success of reforestation activities conducted in areas where seed availability is limiting natural recovery (Fig. 14). Lodgepole pine had moderate to high climate suitability in many areas, particularly at intermediate to high elevations. High-elevation areas throughout the fire had high climate suitability for Engelmann spruce, whereas ponderosa pine and Douglas-fir had some isolated areas with high climate suitability in protected topographic settings. Planting of of Engelmann spruce and lodgepole pine may be most appropriate at high elevations and on northeast-facing slopes, and planting of ponderosa pine and Douglas-fir is appropriate at some lower-elevation sites within the fire.

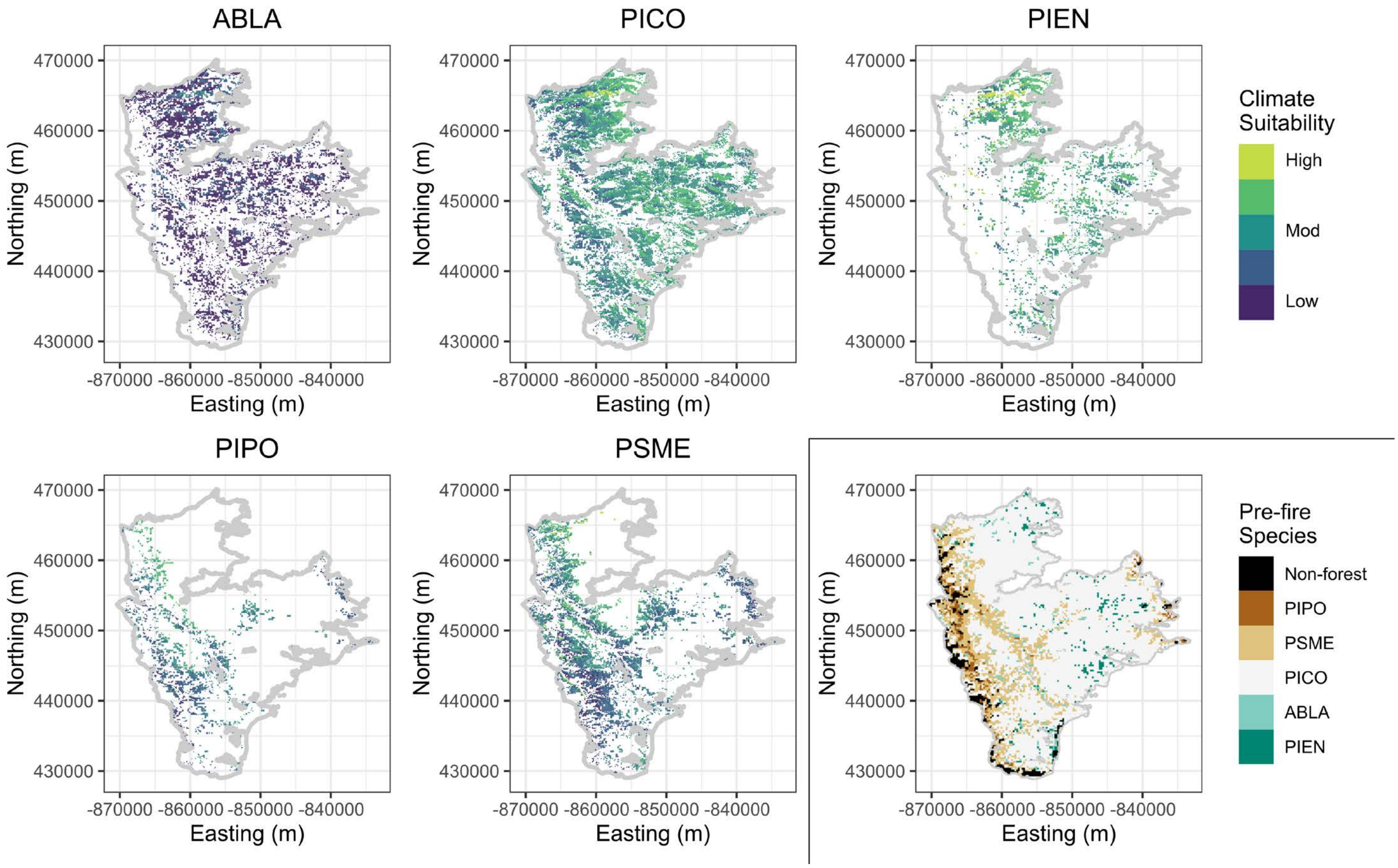

Figure 14: Climate suitability based on recent climate (ca., 1981-2020) and topography for each dominant coniferous tree species in the Mullen Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

4e. Williams Fork Fire

The Williams Fork Fire began in Arapaho National Forest, southwest of Fraser, Colorado, on August 14th, 2020, and was contained on November 30th, 2020 (Fig. 15). The fire burned 14,833 ac from 8,636 to 11,851 ft, primarily in forests dominated by lodgepole pine, Engelmann spruce, and subalpine fir, with minor components of ponderosa pine and Douglas-fir at lower elevations. In comparison to other fires, Williams Fork had the highest proportion of high-severity fire (58.5% of the total area). Still, 49.2% of the high-severity area was within 300 ft of live trees, 27.8% was between 300 and 650 ft, and only 23.0% was beyond 650 ft. Williams Fork had moderate levels of pre-fire beetle kill (24.1% tree mortality across species) from 1997 to 2018, which was mainly driven by mountain pine beetle activity in lodgepole pine (22.4% tree mortality) from 2001 to 2009.

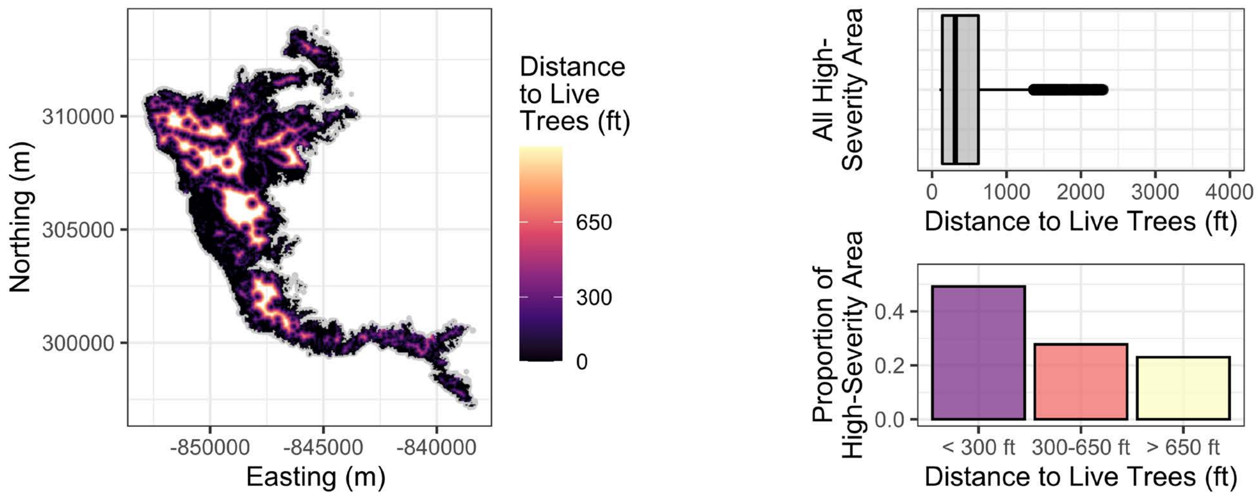

Figure 15: Map of distances to live trees in the Williams Fork Fire (left), as well as the range of distances to live trees within high-severity areas (right). White areas in the map are outside of the final fire perimeter (shown in grey).

The dominant pre-fire species in much of the Williams Fork Fire was lodgepole pine, with spruce being dominant at higher elevations. Our models of post-fire recruitment suggest that abundant lodgepole pine recruitment is likely in the eastern half of the fire (Fig. 16). Engelmann spruce and subalpine fir had high recruitment probabilities in low-severity portions of the fire, particularly at high elevations. In contrast, ponderosa pine and Douglas-fir are unlikely to recruit in many portions of the fire because of low pre-fire abundances. In the Williams Fork Fire, 38.1% of the total area was predicted to have low to moderate recruitment potential for all species.

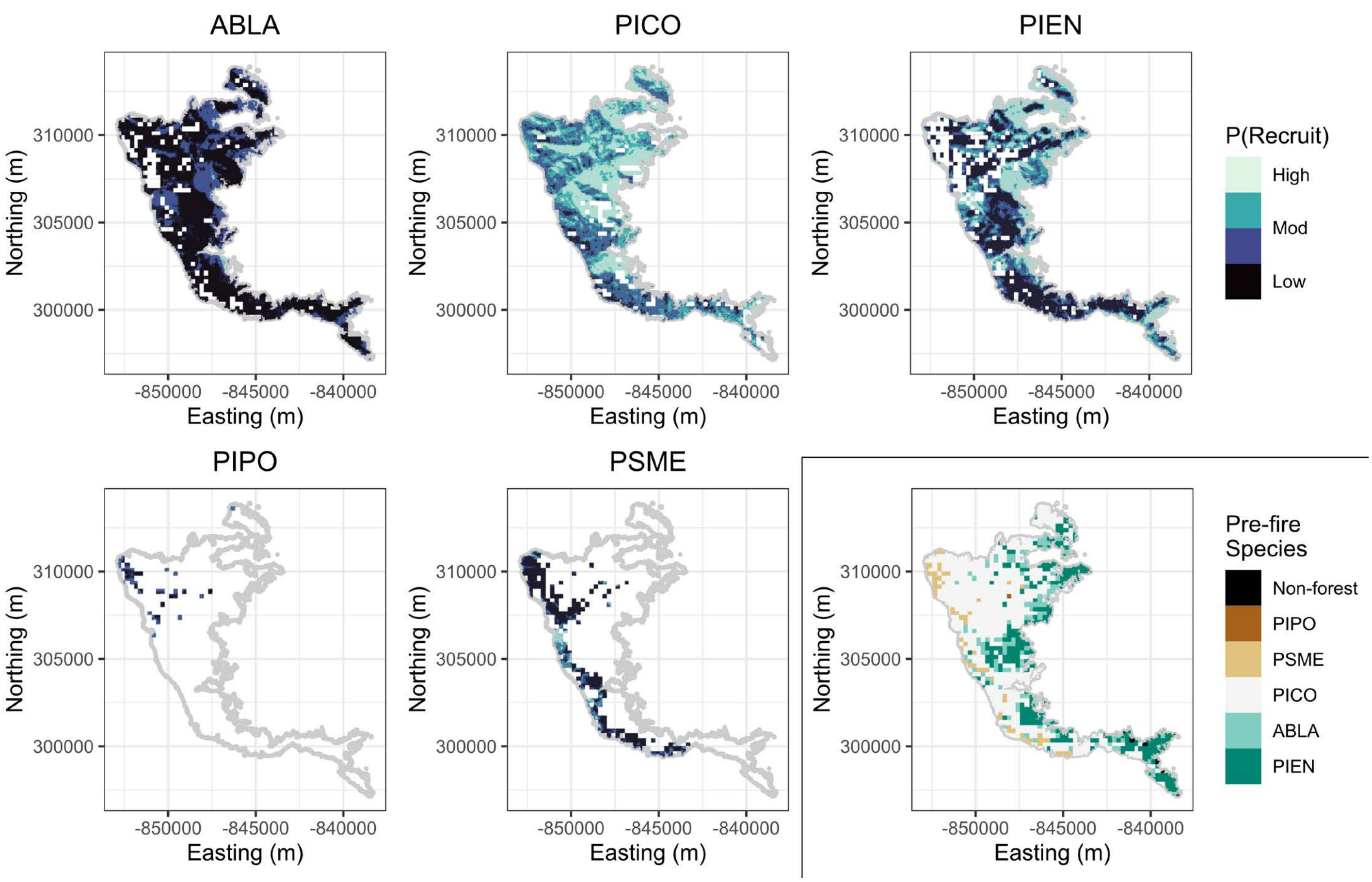

Figure 16: Probabilities of natural recruitment for each dominant coniferous tree species in the Williams Fork Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

Localized areas of moderate or high climate suitability were present for each of the coniferous tree species present in the Williams Fork Fire (Fig. 17). Overall, high elevations and northeast-facing slopes were most suitable for subalpine fir, lodgepole pine, and Engelmann spruce, while low-elevation areas within the fire were considered suitable for ponderosa pine and Douglas-fir. Limited planting of ponderosa pine and Douglas-fir would both be appropriate at the lowest elevations, while Engelmann spruce and lodgepole pine would be appropriate at the highest elevations.

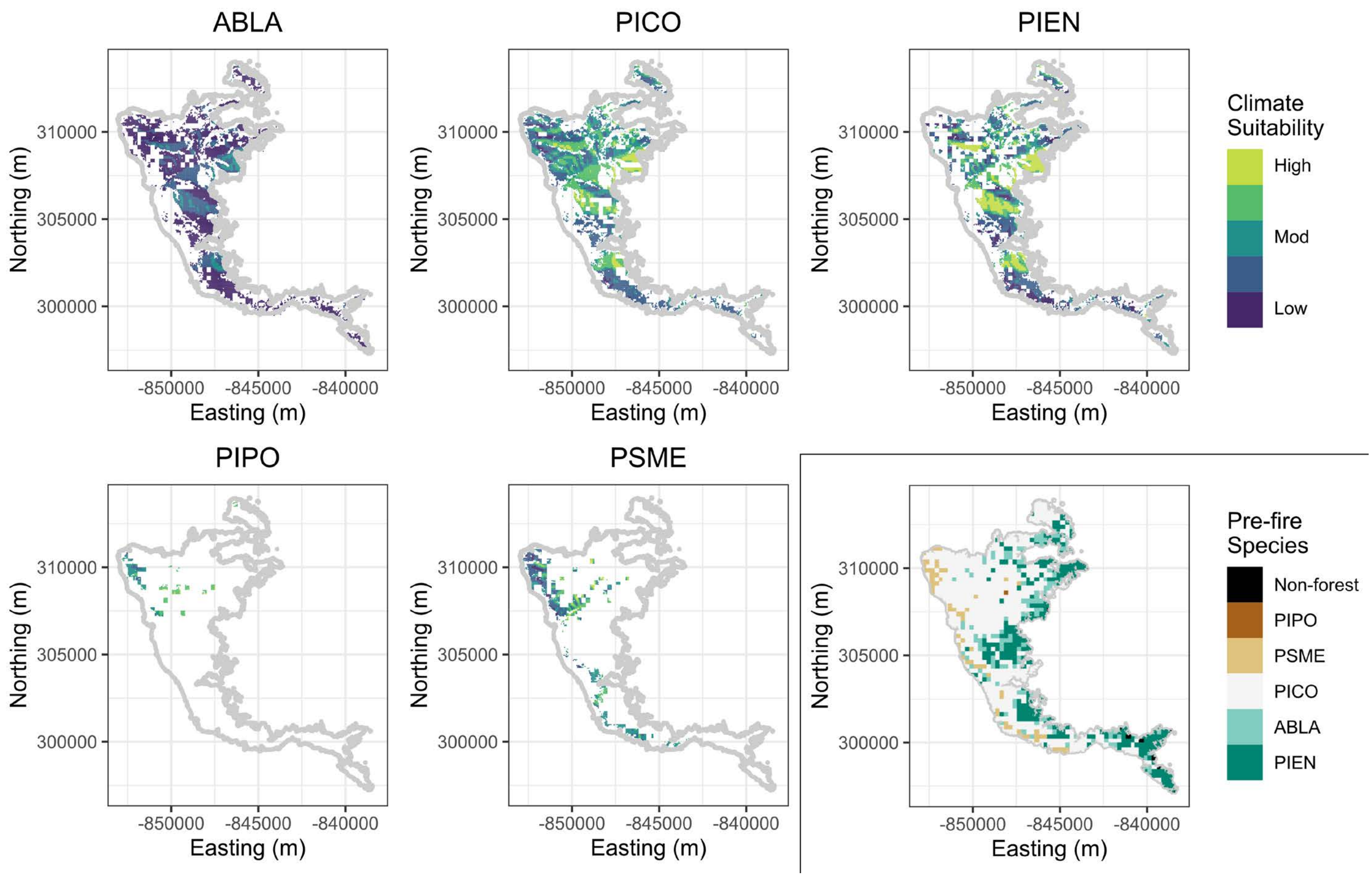

Figure 17: Climate suitability based on recent climate (ca., 1981-2020) and topography for each dominant coniferous tree species in the Williams Fork Fire. White areas in the map are outside of the final fire perimeter (shown in grey) or are in areas with < 5 ft2 of basal area ac-1 of a given species in the early 2000s. The map of pre-fire species (bottom-right) shows nonforest areas and the dominant tree species in forested areas prior to fire occurrence. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir.

5. Discussion and Management Implications

The 2020 wildfire year has accentuated the need for strategic post-fire planning across large, forested landscapes in the western US. As the number of severely burned acres at risk of converting to non-forest continues to expand, there is increased urgency to effectively direct limited funds and expertise to high-priority areas. This urgency is reflected in the 2021 Infrastructure Investment and Jobs Act, which increases funding for seed collection, planning, and reforestation on federal lands (H.R.3684). This analysis provides an initial approach for prioritizing reforestation activities across a range of land ownerships and management designations – using spatially explicit data describing pre-fire beetle outbreaks, fire severity, patterns of live trees, and the potential for natural recovery of the dominant conifer species – to identify those areas most likely to naturally recover to forest in the near-term. Such information may prove useful in delineating operational units across the burned landscapes of the 2020 wildfires, with a range of management strategies aimed to resist, accept, or direct forest change toward desired conditions.

The 2020 wildfire season in northern Colorado and southern Wyoming left behind five landscapes that varied markedly in their total percentage of high-severity fire effects, ranging from 42.8% (Calwood) to 58.5% (Williams Fork) of the total area burned. This variability, in combination with variation in elevations, forest types, land ownerships, and operational conditions (e.g., slope angle, distance to closest road, wilderness designation), suggests that these five landscapes will likely require a range of post-fire management approaches. However, the total percentage of high-severity area is just one facet of fire severity patterns that should be considered when formulating management plans. The contiguity of high-severity patches is also important, as this relates to the spatial patterning of live trees on the landscape. These live trees serve as the necessary seed sources for the recruitment of non-serotinous conifer species, with recruitment often limited to areas < 300-650 ft from live trees, depending on species and local site conditions (McCaughey et al. 1986, Kemp et al. 2016, Stevens-Rumann and Morgan 2019). Based on our maps of distances to live trees, some fires (e.g., Mullen Fire) are well positioned for the recruitment of non-serotinous conifers because a vast majority (i.e., > 80%) of the severely burned area is within 650 ft of surviving forests. In contrast, other fires had larger, more contiguous treeless patches, and a greater area that is distant from live trees (e.g., Cameron Peak with > 30% of high-severity area far from live trees). Across the five fires, sites that burned at high severity and were at least 650 ft from live trees (which might be considered at greatest need of reforestation) are only 27.8% of the high-severity area and 15.3% of the total area burned. Many of these areas may also recover through vegetative reproduction or dispersal of serotinous seed. For example, aspen (54.0%) and lodgepole pine (92.5%) were present prior to fire occurrence in large percentages of the areas with potential reforestation need (Wilson et al. 2013), and are well-adapted to high-severity fire (Tinker et al. 1994, Turner et al. 2007, Kreider and Yocom 2021). Allowing for natural forest recovery processes in areas < 650 ft from live trees and in locations with serotinous or sprouting species makes the seemingly insurmountable task of reforestation following the 2020 wildfires more achievable (Fig. 1).

In addition to seed availability and pre-fire species composition, conifer tree recruitment is limited by climate and topography, which together influence site environmental conditions experienced by plants (Stephenson 1998, Dobrowski 2011). Our models of recruitment probability for each species indicate that while some areas are expected to recover poorly (e.g., low elevations within a species' range and sites far from seed sources), many areas are also predicted to recover well, with variation among and within the five landscapes. Overall, we predicted that lodgepole pine will establish well across intermediate to high elevations in the five landscapes, with moderate to high predicted recruitment across nearly 60% of the total burned area. Likewise, we predicted that Engelmann spruce will establish well across higher elevations, with nearly 20% of the total burned area having moderate to high predicted recruitment. In contrast, subalpine fir, which is often a shade-tolerant and late-seral species in these ecosystems (Aplet et al. 1988, Andrus et al. 2018), was predicted to have more limited recruitment (only ca. 15% of the total fire area having moderate to high recruitment probabilities), primarily in higher elevations and in areas with surviving trees. At lower elevations, ponderosa pine and Douglas-fir recruitment were highly dependent on distance to live trees, local canopy cover, and (in the case of Douglas-fir) aspect. We predicted that these two species would have moderate to high recruitment probability in only 10.5% (ponderosa pine) and 7.3% (Douglas-fir) of the total burned area. Overall, we predicted that 31.2% of the total fire area had low to moderate recruitment probability for all of the dominant conifers, suggestive of protracted conifer forest recovery. However, the remaining 68.2% was predicted to have recovery of at least one species. While maps of distances to live trees provide a rough first filter in defining potential reforestation areas, maps of recruitment probability provide additional insight into the expected ecosystem trajectories throughout each landscape. Knowing which areas are most likely to recover to forested conditions, and which species are likely to dominate initial post-fire communities informs future management decisions because it can help to predict if natural processes are likely to create forest communities that align with the desired conditions.

Should managers desire to use reforestation to help establish forests at a site, the extent to which seedlings match local site conditions will be critical to successful implementation (Dumroese et al. 2016). Climate and topography are two key components of local site conditions that can be incorporated into broad-scale reforestation planning through GIS data (Simeone et al. 2019, Rodman et al. 2022b). Here, we developed maps of climate suitability, which provide an estimate of how the climate and topography of a site compare to other portions of a species' range. While these models were developed using data describing natural tree regeneration following fire (Davis et al. *In Review*), they may also provide an estimate of the potential success of planting for each species, for which existing data are highly limited. Like maps of recruitment probability, maps of climate suitability show broad variation among species and landscapes. However, climate suitability (and potential reforestation suitability) was generally highest at cooler, wetter sites within each species' pre-fire extent. Throughout the five landscapes, areas with moderately high to high climate suitability were widespread for Engelmann spruce (35% of the total high-severity area) and lodgepole pine (44%). Roughly 17% of the high-severity area had moderately high to high suitability for Douglas-fir, with just 9% for ponderosa pine, and < 1%

for subalpine fir. Each conifer species had local areas for which topography and climate suggest high suitability for planting (e.g., upper Calwood and lower Cameron Peak Fires for ponderosa pine). However, the aggregate numbers across fires indicate that Engelmann spruce and lodgepole pine may be the species that are most suitable for reforestation in much of the high-severity area across these fires. Such information may help to prioritize future seed collection efforts and greenhouse use for seedling production of different species in the region.

Our goal in this report was to apply the best available science to assess initial landscape conditions following five large fire events in southern Wyoming and northern Colorado. As part of a broader decision-making framework, this information may prove valuable to land managers, stakeholders, and policymakers in planning future activities. However, we acknowledge that the statistical models and GIS data we used in this assessment are imperfect, and are no substitute for detailed site visits, local operational planning, and expert knowledge. Potential sources of uncertainty in this report include the inherent errors in spatial data (e.g., delayed tree mortality not captured in fire severity maps, a lack of accurate spatial data on lodgepole pine serotiny), unknown effects of pre-fire bark beetle outbreaks on post-fire seed availability and forest recovery, potential interactions with past management and wildfire (e.g., recent clear cuts of fires removing live trees), and weather conditions in initial years following fire. Thus, while our findings provide an initial estimate of landscape conditions, continued monitoring and adaptive management will be critical to successful forest management and planning over the upcoming years.

The scale of the 2020 wildfires throughout the western US demands that managers break with post-fire management approaches that are solely centered on restoring pre-fire forest structure and composition across large landscapes. In the face of multiple uncertainties, the RAD framework may assist managers in identifying the best use of finite resources to not only resist but also accept and direct change across a mixture of different patches within a given landscape (Aplet and Mckinley 2017, Stevens et al. 2021). The first step in applying RAD to post-fire landscapes is to conduct a thorough landscape assessment, which identifies current landscape conditions and potential future trajectories. Such information can then be used to develop a range of management plans, to be applied in different zones of the landscape, based on the feasibility of active management as well as how expected natural trajectories align with desired conditions. Here, we present an initial landscape assessment of five recent wildfires that burned at a range of severities, across broad elevational gradients, and in multiple forest types. A range of management approaches is needed in these landscapes based on social values, local site conditions, and expected trajectories. Reforestation of all areas affected by the 2020 wildfires studied here (or even high-severity areas within them) may be challenging over upcoming years due to the time and money required for active reforestation, so targeting areas for reforestation that are far from live trees, had few serotinous or resprouting species before fire, and have high moisture availability for the component species, may help in the initial prioritization of resources.

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7. Supplementary Information

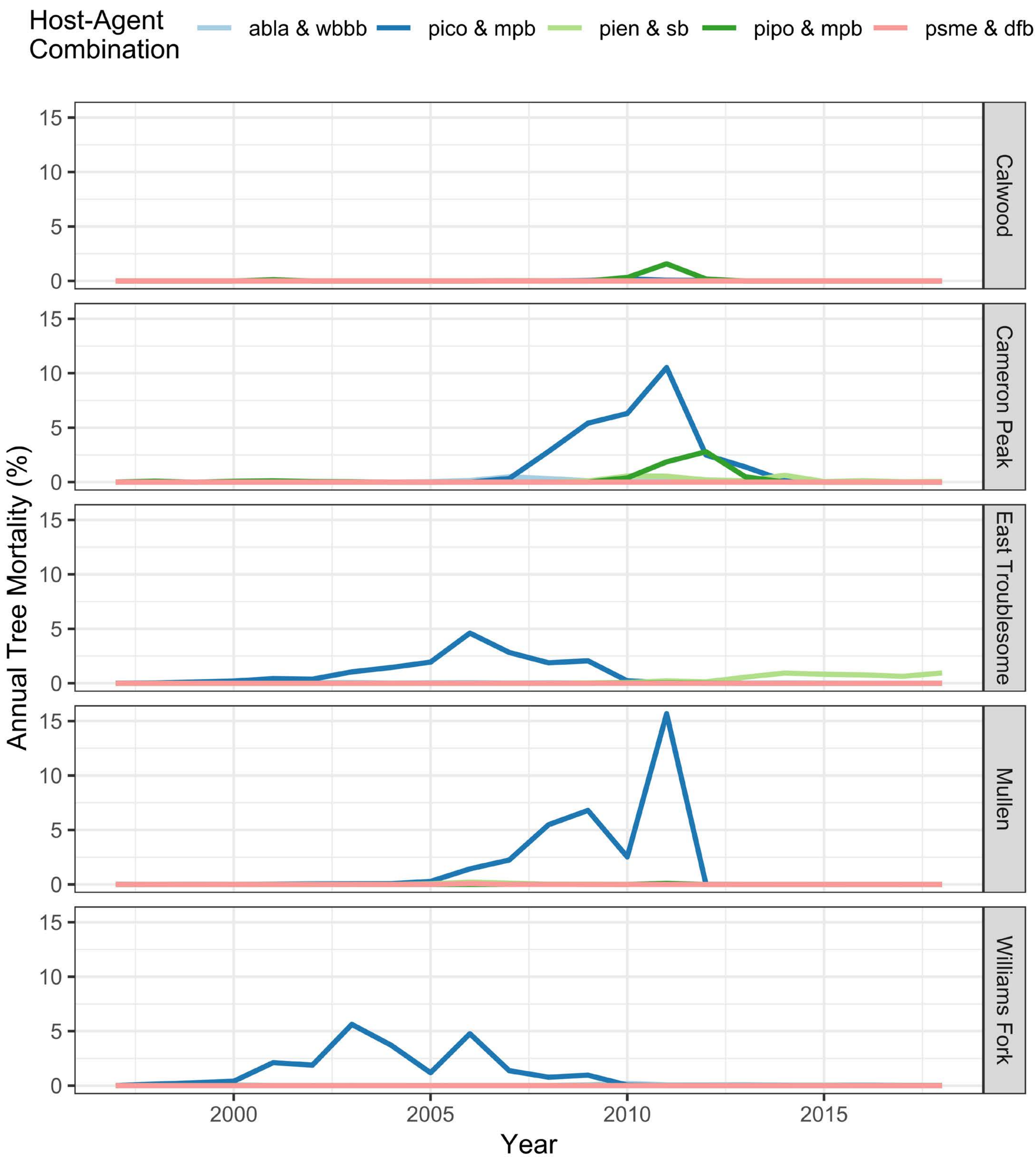

Figure S1: The timing and severity of pre-fire (1997-2018) beetle-caused tree mortality throughout each of five large fires in northern Colorado and southern Wyoming. Data were obtained from Hicke et al. (2020) for each of five common host tree-bark beetle agent combinations. ABLA: subalpine fir, PICO: lodgepole pine, PIEN: Engelmann spruce, PIPO: ponderosa pine, PSME: Douglas-fir. DFB: Douglas-fir beetle, MPB: mountain pine beetle, SB: spruce beetle, WBBB: western balsam bark beetle or subalpine fir decline.

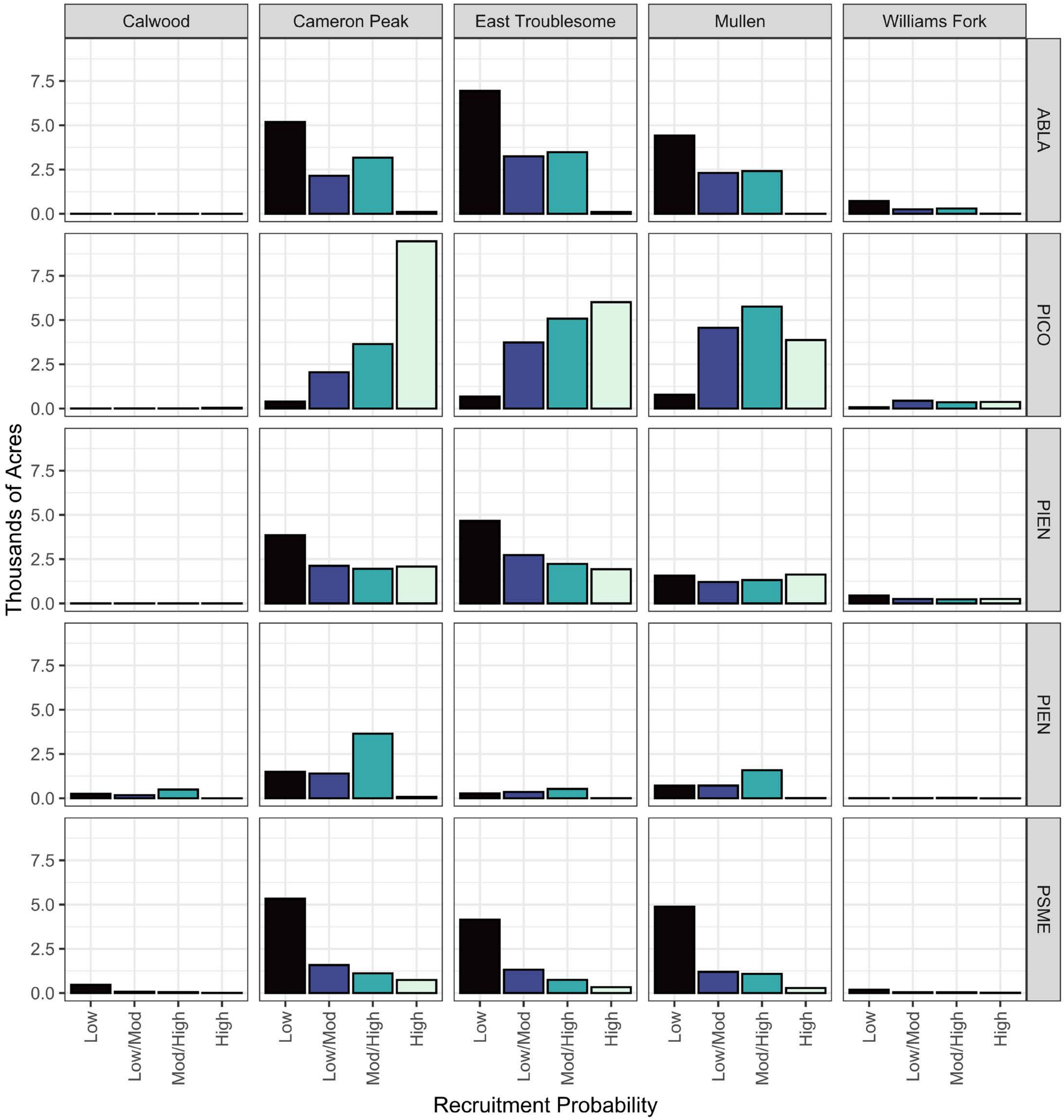

Figure S2: Post-fire recruitment probability across five major fires in northern Colorado and southern Wyoming. Values are summarized within each fire for five dominant coniferous tree species. Bar heights represent the area (thousands of acres) in a given category, with lighter-colored bars representing areas with a greater probability of natural regeneration following fire.

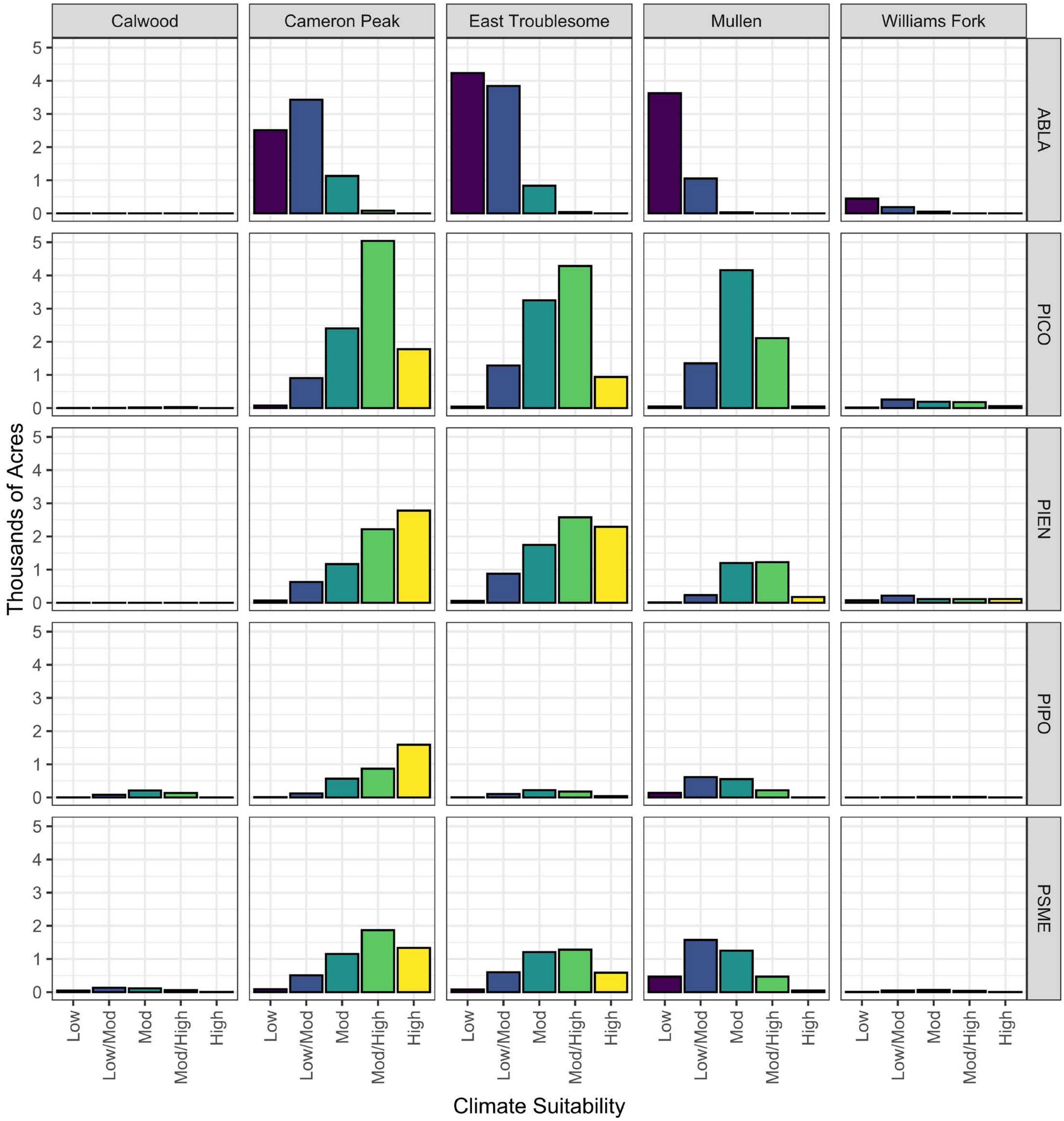

Figure S3: Climate suitability across high-severity areas within five major fires in northern Colorado and southern Wyoming. Values are summarized within each fire for five dominant coniferous tree species. Bar heights represent the area (thousands of acres) in a given category, with lighter-colored bars representing areas with greater climate suitability and a greater potential for reforestation following fire.

8. Additional resources

A summary of this work is represented in the companion ESRI Story Map by Mark Kohn, Kyle Rodman, and Marin Chambers. https://cfri.colostate.edu/2022/11/21/nfr_2020fires_storymap/

Spatial data associated with this report can be found at the following link for planning purposes. https://cfri.app.box.com/folder/182650899411?s=0qqbtfetqpcg5tb5flrtmg8862kh4ahu