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Special Feature: Long-Term Ecological Effects Of Forest Fuel And Restoration Treatments

Long-term efficacy of fuel reduction and restoration treatments in Northern Rockies dry forests

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Abstract

Fuel and restoration treatments seeking to mitigate the likelihood of uncharacteristic high-severity wildfires in forests with historically frequent, low-severity fire regimes are increasingly common, but long-term treatment effects on fuels, aboveground carbon, plant community structure, ecosystem resilience, and other ecosystem attributes are understudied. We present 20-year responses to thinning and prescribed burning treatments commonly used in dry, low-elevation forests of the western United States from a long-term study site in the Northern Rockies that is part of the National Fire and Fire Surrogate Study. We provide a comprehensive synthesis of short-term (<4 years) and mid-term (<14 years) results from previous findings. We then place these results in the context of a mountain pine beetle (MPB; *Dendroctonus ponderosae*) outbreak that impacted the site 5–10 years post-treatment and describe 20-year responses to assess the longevity of restoration and fuel reduction treatments in light of the MPB outbreak. Thinning treatments had persistently lower forest density and higher tree growth, but effects were more pronounced when thinning was combined with prescribed fire. The thinning +prescribed fire treatment had the additional benefit of maintaining the highest proportion of ponderosa pine (*Pinus ponderosa*) for overstory and regeneration. No differences in understory native plant cover and richness or exotic species cover remained after 20 years, but exotic species richness, while low relative to native species, was still higher in the thinning+prescribed fire treatment than the control. Aboveground live carbon stocks in thinning treatments recovered to near control and prescribed fire treatment levels by 20 years. The prescribed fire treatment and control had higher fuel loads than thinning treatments due to interactions with the MPB outbreak. The MPB-induced changes to forest structure and fuels increased the fire hazard 20 years post-treatment in the control and prescribed fire treatment. Should a wildfire occur now, the thinning+prescribed fire treatment would likely have the

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lowest intensity fire and highest tree survival and stable carbon stocks. Our findings show broad support that thinning and prescribed fire increase ponderosa pine forest resilience to both wildfire and bark beetles for up to 20 years, but efficacy is waning and additional fuel treatments are needed to maintain resilience.

KEYWORDS
fuel treatment effectiveness, fuel treatment longevity, nonnative plant response, *Pinus ponderosa*, prescribed fire, thinning

INTRODUCTION

Alterations to historical fire disturbance regimes have cascading consequences for ecosystem resilience and stability (Seidl et al., 2016; Turner, 2010). In the western United States (US), more than a century of fire exclusion in low-elevation, dry forests has increased forest density and shade-tolerant species dominance, resulting in higher fire hazard (Hagmann et al., 2021; Prichard et al., 2021). The inland dry forests of the western US historically burned frequently (5–30 years), typically as low-intensity, low-severity fires (i.e., majority of overstory trees survived), fostering low-density forests dominated by shade-intolerant conifer species (Greenberg & Collins, 2021; Hagmann et al., 2021). However, fire regimes in these dry conifer forests now differ vastly from historical conditions, with many forests now susceptible to burning as high-intensity fires that can threaten human communities and further degrade forest ecosystems with uncharacteristically severe fire effects (Hagmann et al., 2021).

Climate change exacerbates the effect of fire exclusion, especially in dry forests. Increasing fuel aridity, longer fire seasons, and a growing number of days of weather conducive to high-intensity fire all favor high-severity fires (Abatzoglou et al., 2019; Abatzoglou & Williams, 2016; Jolly et al., 2015). Furthermore, fire-excluded forests are especially susceptible to tree mortality during drought (Keen et al., 2022; Voelker et al., 2018) and bark beetle outbreaks (Fettig, Runyon, et al., 2022; Kane et al., 2017). As a result, there are widespread efforts on federal, state, tribal, and private lands to restore these forests, with the goals of increasing ecosystem resilience to wildfires and other disturbances, reducing forest density and fuels, and shifting species composition toward more fire-tolerant species (Stephens et al., 2016; USDOI; USDA, 2014).

Fuel reduction treatments and restoration treatments in forests with frequent, low-severity historical fire regimes vary, but often have complementary objectives (Hood et al., 2022; North et al., 2021; Stephens et al., 2021). Restoration-based fuel treatments have broader objectives than only reducing fuel loading. Typically, treatments are also designed to reduce forest density and increase the dominance of larger trees of fire-resistant species, thereby reducing the likelihood of uncharacteristic high-intensity wildfires that are difficult to control, threaten human communities, and often have negative ecological outcomes (e.g., high tree mortality, soil erosion, loss of critical wildlife habitat) (Agee & Skinner, 2005). Mechanical treatments (e.g., thinning, masticating) can remove trees precisely to the exact size, species, and spacing specifications. However, thinning alone temporarily increases surface fuel loads and potential fire intensity if fuels are not reduced by further mechanical treatment or prescribed fire (Fiedler et al., 2010; Prichard et al., 2021). By contrast, prescribed fire alone can consume fine fuels and kill small trees, but often fails to adequately reduce tree density, especially if trees have developed fire-resistant thick bark (Roccaforte et al., 2015; Ryan et al., 2013; Zald et al., 2022). Thus, combined mechanical and burning treatments are typically most effective at both changing forest structure and composition and reducing surface fuels (Fulé et al., 2012; Martinson & Omi, 2013), but the combined effects of thinning and fire also often achieve a number of other ecological objectives (Kalies & Yocom Kent, 2016).

Numerous empirical studies have reported the short-term and medium-term (<10 years) effects of fuel and restoration treatments in fire-dependent forested ecosystems, yet the longer-term (>10 years) effects have only been explored in a handful of sites (Kalies & Yocom Kent, 2016). Given the enormous spatial extent of the wildland fuels problem in the US (USDA Forest Service, 2022), a complete understanding of long-term treatment effects and longevity is essential to planning prescriptions and scheduling additional treatments needed to maintain low fire hazard. Beyond fire hazard, long-term treatment effects on ecological attributes (e.g., tree growth, ecosystem carbon [C] pools, understory plant diversity, resilience to drought and insects) are also important to consider. Results of 20+-year-old studies of fuel treatments show that cutting and prescribed burns can increase long-term tree growth (Fulé et al., 2022; Tepley et al., 2020) and recover aboveground biomass (Clyatt et al., 2017). While fuel treatments can initially reduce torching and crowning probabilities (proxies for fire hazard), this effect wanes over time as biomass recovers to pretreatment levels (Hood et al., 2020). Season of burning may also differentially affect long-term tree mortality patterns (Tepley et al., 2020; Westlind & Kerns, 2021) and resistance to bark beetle outbreaks (Tepley et al., 2020). Together, these studies indicate that mechanical and prescribed fire restoration treatments may have many positive long-term effects, but effects are sometimes inconsistent and important knowledge gaps remain.

Ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.) dominates or is a major component of dry forests in the Northern Rockies, occurring over a large geographic range where historical fire regimes vary from frequent, low-severity surface fires to moderate-frequency, mixed-severity fires (Hood et al., 2021). At all but the driest sites, ponderosa pine is a seral, shade-intolerant species that maintains dominance over co-occurring species because of frequent, low-intensity fires. In the Northern Rockies, ponderosa pine at relatively low-elevation, dry sites typically experienced a low-severity fire regime, with average fire-free intervals of approximately 5–30 years (Arno, 1980; Heyerdahl et al., 2008). Frequent, low-severity surface fires were most common, but small patches of infrequent, high-severity fires also occurred (Arno et al., 1995). Fire exclusion, coupled with past harvesting that removed many of the largest ponderosa pines, has increased the relative dominance of shade-tolerant Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco var. *glauca* [Beissn.] Franco) and other associates (Clyatt et al., 2016; Hood et al., 2021; Naficy et al., 2010). The changes resulting from altering the historical fire regime have reduced ponderosa pine forest resiliency to disturbance through increased susceptibility to mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreaks (Hood et al., 2015, 2016; Tepley et al., 2020) and high-severity wildfire (Hagmann et al., 2021; Prichard et al., 2021). These changes have led to increased efforts to determine appropriate restoration and fuel treatments in the Northern Rockies and other forests dependent on frequent, low-severity fires.

The Northern Rockies Lubrecht Fire and Fire Surrogate (FFS) study is a 20+-year fuel treatment and restoration experimental study in a ponderosa pine-dominated forest. It was established in 2000 as one of 12 sites in the National FFS study network. The goal of the multidisciplinary FFS project was to quantify the short-term (<4 years) effects of fuel reduction treatments in frequent-fire forests across the US (McIver et al., 2013; Stephens et al., 2012). Only Lubrecht and three other sites in the FFS network remain active. Together with another long-term fuel treatment study in western Montana, Lick Creek, the Lubrecht FFS site includes crossed thinning and prescribed burning treatments. At both study sites, treatment effects on vegetation and fuel dynamics (Crotteau et al., 2018, 2020; Fajardo et al., 2007; Fiedler et al., 2010; Hood et al., 2020), understory diversity (Dodson et al., 2007; Jang et al., 2021; Metlen & Fiedler, 2006), aboveground ecosystem biomass and C stocks (Clyatt et al., 2017), tree physiology (Peters & Sala, 2008; Sala et al., 2005), soil nutrient cycling (DeLuca & Zouhar, 2000; Ganzlin et al., 2016; Gundale et al., 2005), forage quality (Ayers et al., 1999), and resilience to drought stress and bark beetles (Crotteau & Keyes, 2020; Hood et al., 2016; Six & Skov, 2009; Tepley et al., 2020) have been studied extensively. Research from these two study areas forms most of the current and comprehensive body of knowledge of long-term restoration fuel treatment effects in the region. Although a slightly younger study, Lubrecht fills knowledge gaps that Lick Creek cannot address because Lubrecht's history includes the compound effects of restoration fuel treatments and a mountain pine beetle outbreak.

Here, our goal was to provide a comprehensive picture of treatment effects over the 20-year post-treatment measurement period at the Lubrecht FFS site. To that end, our specific objectives were to (1) synthesize previously published short-term (1–4 years) and medium-term (5–14 years) mechanical and prescribed burning treatment effects on soil, understory plant communities, and mountain pine beetle dynamics; and (2) report long-term (15–20 years) treatment effects on forest vegetation, fuels, and carbon dynamics. To address objective 2, we compared the immediate (1-year) post-treatment effects on forest structure and composition, understory diversity, fuel loadings, potential fire effects, and aboveground carbon stores to a new set of measurements obtained 20 years after the plots were treated. We then discussed the long-term responses in the context of the short-term and mid-term responses to assess the longevity of restoration and fuel reduction treatments commonly used in dry, low-elevation forests of the western US and to more broadly discuss treatment design and effectiveness in similar forest types.

METHODS

Treatments and experimental design

The University of Montana's Lubrecht Experimental Forest was selected as the Northern Rockies' site for the

National FFS study (McIver et al., 2013; Stephens et al., 2012). The study area was heavily logged in the late 1800s and early 1900s and, at the time of treatment implementation, the site was dominated by 80–90-year-old second-growth ponderosa pine and Douglas-fir, with occasional trees up to 200 years old, and a minor component of western larch (*Larix occidentalis* Nutt.) and lodgepole pine (*Pinus contorta* Douglas ex Louden). Small Douglas-fir trees were abundant throughout the understory, while similarly sized ponderosa pines were less numerous and in scattered patches (Fiedler et al., 2010; Metlen & Fiedler, 2006). Historically, the mean fire return interval was 7 years (2–14 year range), but fire frequency greatly declined after 1871 and the study site had not burned since the late 1800s (Grissino-Mayer et al., 2006). Moderate grazing was prevalent throughout the 1900s (Gundale et al., 2005).

Treatments were implemented in each of the three blocks using a randomized, full-factorial design: two levels of mechanical (Mech) treatment (thinned + unthinned) by two levels of prescribed fire (burned + unburned), for a total of four treatment levels (untreated control, Fire, Mech, and Mech+Fire). Previous publications for the Lubrecht FFS study refer to the treatments as the control, Thin-only, Burn-only, and Thin–Burn, while the national-level FFS publications use control, Fire, Mech, and Mech+Fire. Here, we opted to follow the national-level treatment naming convention for consistency across the remaining active FFS sites. The prescription intensity was intended to maintain 80% overstory tree survival given a wildfire in 80th percentile weather conditions (see Fiedler et al., 2010 for site and treatment prescription details).

Stands were mechanically treated in 2001 and burned in 2002, creating twelve, 9 ha experimental units (three, 36 ha blocks each including four treatments). The cutting prescription was a combined low thinning and improvement cut with a targeted residual basal area of 11 m^2 ha^{-1}, favoring retention of large ponderosa pine and western larch over Douglas-fir. Broadcast burns were conducted in May and June. At the time of the burns, temperatures ranged from 9 to 29°C, relative humidity ranged from 20% to 48%, and wind speeds ranged from 2 to 13 km h^{-1}. Fires were generally low intensity to maintain operational control, resulting in low-severity burns that consumed much of the forest floor and surface fuels and killed many small-diameter trees, but with pockets of moderate-to-high severity in two of the Mech+Fire treatment units. The study area was subsequently affected by a severe regional MPB outbreak that began approximately 5 years after treatment and lasted until 2012 (Gannon & Scott Sontag, 2010; Hood et al., 2016).

Vegetation sampling

We measured all live aboveground forest vegetation at Lubrecht except for bryophytes. We divided lifeforms into two broad classes for measurement and analysis: tree and nontree (hereafter, "understory") vegetation. The tree class was then subdivided by size into overstory (diameter at breast height [dbh; 1.37 m] ≥10.16 cm) and regeneration (height ≥10 cm and dbh <10.16 cm), the latter comprised of five subclasses (small seedling: 10 cm ≤ height <50 cm; large seedling: 50 cm ≤ height <137 cm; small sapling: 0.1 cm ≤ dbh <3 cm; medium sapling: 3 cm ≤ dbh <6 cm; large sapling: 6 cm ≤ dbh <10.16 cm). We characterized understory vegetation as either native or exotic using the PLANTS database (USDA; NRCS, 2023).

The full suite of vegetation data was sampled on permanently monumented 0.10 ha (20 m × 50 m) modified-Whittaker plots (see Metlen & Fiedler, 2006 for plot diagram and details). The Whittaker plots were randomly selected plot locations from 36 systematically located grid points within each of the 12 treatment units, 10 plots per treatment unit, for a total of 120 plots. Overstory trees in each of the Whittaker plots were permanently tagged and status (e.g., alive, dead), species identity, dbh, total height, and crown length were recorded. Saplings were tallied by diameter class on five, 100 m^2 subplots per plot; seedlings were tallied by height class on 20, 1 m^2 subplots per plot. Understory vegetation was identified by species (or by genus for difficult-to-identify species) and the cover was estimated on twelve, 1 m^2 subplots per plot.

Overstory trees were measured prior to treatment in 2000 and immediately after harvest in 2001. All trees were assessed annually from 2002 to 2005 for changes in status. In 2005, 2012, and 2020, we conducted a complete remeasurement of trees following the initial protocol, including tagging and measuring new trees as they grew into the tree class. Regeneration was measured in 2002 and 2022. Understory vegetation was measured in 2002, 2004, 2016, and 2022. Hereafter, we refer to the earliest data (2001, 2002) as "2002" to represent the collective immediate post-treatment data, and the most recent data (2020, 2022) as "2022" to represent the collective long-term (20-year) post-treatment data.

Surface fuels sampling

Dead surface fuel loading was first measured 1 year after treatment (2000 for Cont, 2001 for Mech, 2002 for Fire and Mech+Fire) using planar intersect sampling. A modified Brown's (1974) protocol was used to quantify 1-h (woody material <0.64 cm diameter), 10-h (0.64 cm ≤ diameter <2.54 cm), 100-h (2.54 cm ≤ diameter <7.62 cm), and 1000-h+ (diameter ≥7.62 cm) timelag classes. On each of the 36 grid points, two, 15.2 m transects were established; 1-h and 10-h fuels were tallied for 1.8 m of the length, 100-h fuels were tallied for 3.7 m, and 1000-h+ fuel diameters were recorded along the entire transect lengths. Duff and litter depths were each measured along transects at 4.6 and 10.7 m from the plot center.

Potential fire effects and aboveground live carbon stock calculations

Surface fuels data and measured tree data were input into the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; Dixon, 2018; Reinhardt et al., 2009) to calculate plot-scale canopy fuel characteristics and potential fire behavior for our two measurement years (2002, 2022). Potential fire behavior was modeled using FFE-FVS, whereby measured dead fuel loadings were keyed to the Anderson (1982) 13 original fire behavior fuel models, and the FFE-FVS algorithm selects and weights predicted fire behavior from 1 to 2 most similar models (Rebain, 2010; revised 1 February 2022). FFE-FVS selected combinations of fuel models 8, 10, 12, and 13; fuel model 10 was most dominant in control and Fire, while fuel model 8 was most dominant in Mech and Mech+Fire. This default FFE-FVS method produces consistent results to predictions based entirely on user-inputted, customized fire behavior fuel models in FFE-FVS (Noonan-Wright et al., 2014). Potential fire behavior was based on FFE-FVS's default "severe" fire weather scenario (4% 10-h fuel moisture, 21.1°C ambient temperature, and 32.2 km h^{-1} wind speed at 6.1 m) instead of percentile (e.g., 80th, 97th) fire weather conditions to provide standardized analysis. To relate the default weather scenario to local weather conditions, we obtained average daily temperature, relative humidity (RH), and wind speeds using FireFamilyPlus (Bradshaw & McCormick, 2000). Weather data during the primary fire season of 15 July through 15 September were available from 2001 to 2020 from two nearby Remote Automated Weather Stations (242,513 and 241,518). Local temperatures under 97th percentile weather conditions were 5.3°C hotter than the FFE-FVS "severe" weather scenario used to estimate the probability of torching but less windy (10.5 km h^{-1} vs. 32.2 km h^{-1}). The local weather stations are sheltered and do not provide good estimates for windspeeds, but alternative stations are lacking in the area with long-term records. Based on these comparisons, we expected the potential fire behavior and effects reported to be conservative, best-case outcomes in the event of a wildfire. Output generated from FFE-FVS POTFIRE and CARBON reports included the probability of torching (pTorch; in percentage), the probability of mortality by overstory basal area (pMort; in percentage), and total aboveground live carbon estimates (includes live seedlings, saplings, and trees, including stems, branches, and foliage; totC; in megagrams per hectare) (see Rebain, 2010 for further variable descriptions).

Statistical analyses

To explore the long-term effects of fuel reduction and restoration treatments on overstory structure and composition, we first examined the effects of treatments on tree diameter distribution. We subsequently tested forest structure and composition using treatment-level basal area, stem density, quadratic mean diameter (QMD), and stand density index (SDI). QMD was calculated as the dbh of the overstory tree average basal area. SDI is a unitless density metric that incorporates overstory tree size and density (Reineke, 1933). SDI was scaled by an *a priori* maximum stocking value for ponderosa pine of 1111 to determine relative SDI for estimates of site occupancy levels (Long & Shaw, 2005).

We analyzed understory native and exotic vegetation total percent cover and richness. Richness was the count of total genera present; we used genus instead of species to avoid identification inconsistencies because the different field crews sampling vegetation varied between time points.

We calculated dead, downed woody debris loading (in megagrams per hectare) according to Brown (1974), and used local depth-to-loading regressions to calculate litter and duff loading (in megagrams per hectare; D. Lutes & US Forest Service, personal communication and unpublished data, 9 August 2023). Dead, downed woody fuel loadings were grouped into two pools for analysis: fine woody debris (FWD) comprised fuel less than 7.62 cm diameter (1, 10, and 100-h); coarse woody debris (CWD) comprised sound fuel greater than or equal to 7.62 cm diameter (1000-h). Litter and duff loadings were combined for a forest floor (FF) analysis.

We calculated the carbon stable to potential fire under severe fire weather conditions. Whereas the totC metric is naive to tree species composition, size, and forest fuel arrangement, the stableC metric takes these stand characteristics into consideration to form a metric of live tree resilience to wildfire. Stable carbon (stableC) was calculated using pMort and totC from FFE-FVS as $(1 - \text{pMort}) \times \text{totC}$. Thus, stableC ranged from 0 Mg ha^{-1} (where pMort was 100%) to equal to totC (where pMort was 0%).

We evaluated the effects of treatment and time on plot-scale responses using generalized linear mixed effects models using the *glmmTMB* package for R (Brooks et al., 2017; R Core Team, 2022). The responses (and error distribution for each) were: tree density (Gaussian), basal area (Gaussian), QMD (Gaussian), SDI (Gaussian), proportion of ponderosa pine (Beta), seedling density (Tweedie), sapling density (Tweedie), FWD (Tweedie), CWD (Tweedie), FF (Tweedie), pTorch (Beta), pMort (Beta), totC (Tweedie), and stableC (Tweedie). Beta error distributions were assigned to proportion data where responses ranged from 0 to 1; we added 0.001 to actual 0 s and subtracted 0.001 to actual 1 s to satisfy the mathematical limits of the Beta distribution. Tweedie error distributions were assigned to responses that either had long tails, skewness, or both, and did not satisfy the more restrictive Gaussian, Poisson, or Negative Binomial distributions. Each model was fitted with interacting fixed effects of treatment (four levels: Cont, Fire, Mech, Mech+Fire) and year (two levels: 2002 and 2022), plus a random effect of experimental unit nested within the block, with model hypothesis tests determining whether the Cont effect (i.e., intercept) was significantly different from 0 and whether each treatment was significantly different from Cont. Models also included fixed effects of treatment and year on the dispersion parameter to account for heterogeneous variances across treatments. These models were followed up with Tukey–Kramer simultaneous pairwise testing to determine treatment differences within the year. All tests of statistical significance were evaluated at $\alpha = 0.05$. Model validation was performed using the *dharma* package for R (Hartig, 2022), which provided visual (Q–Q plot and boxplots) and statistical validation of dispersion, homoscedasticity, and appropriateness of error distribution. Despite parameterization of flexible distributions and treatment-scale dispersion terms, percent ponderosa pine and native cover residuals showed evidence of heteroscedasticity, pMort and stableC poorly fit error distributions, and stableC may inadequately account for dispersion. However, linear mixed effects models are generally robust to minor violations of assumptions (Schielzeth et al., 2020), and we are confident these models are improvements over simpler alternatives.

The short-term and mid-term results of treatment effects on soils, vegetation, and fuels at the Lubrecht FFS study have been previously published (Crotteau & Keyes, 2020; Dodson et al., 2007; Dodson & Fiedler, 2006; Fiedler et al., 2010; Ganzlin et al., 2016; Gundale et al., 2005; Metlen & Fiedler, 2006; Six & Skov, 2009), including treatment interactions with the MPB outbreak (Crotteau et al., 2018, 2020; Hood et al., 2016). The initial 4 years of data collected from all sites in the FFS network were archived (McIver et al., 2016), and mid-term vegetation and fuel data from Lubrecht were also archived (Crotteau et al., 2019; Hood, 2016). We refer readers to these primary publications for details on methods and results for the first 15 years of the study but synthesize the main findings below to provide context for the previously unpublished, long-term results reported here.

SYNTHESIS OF SHORT-TERM AND MID-TERM RESULTS

Soil responses

Research at Lubrecht broadly explored the effects of treatments on soil physical, chemical, and biological properties. Overall, treatments had only temporary effects on most variables. Gundale et al. (2005) measured a brief (4–5 week) increase in mineral soil inorganic nitrogen (N) concentrations, but there were no changes in mineral soil C, non-N nutrients (e.g., calcium, magnesium, potassium, phosphorus), or soil microbial properties (e.g., microbial biomass or community composition) (Appendix S1: Table S1). This is perhaps not surprising. While fire has been shown to drive short-term increases in nutrients, most non-N nutrients are not typically volatilized during fire (Neary et al., 1999). Burning did increase the area of bare mineral soil, but that did not translate to changes in mineral soil bulk density or other physical properties. Gundale et al. (2005) posited that the lack of mineral soil responses likely reflected the effects of heterogeneous fire conditions, uneven fuel consumption, and/or low fire severity in some areas of the Fire and Mech+Fire treatments.

Gundale et al. (2005) also observed short-term declines in O-horizon depth and C stock, and parallel increases in O-horizon C:N ratios in the Fire treatment. The Fire and Mech+Fire treatments also showed temporary (<3 year) increases in total O-horizon inorganic N concentrations, rates of N cycling processes, and organic matter decomposition rates (Appendix S1: Table S1). In most cases, however, the measurable, significant effects of treatments on soil C and N pools and N fluxes were ephemeral. For example, Gundale et al. (2005) measured declines in O-horizon C capital in the Fire treatment, and those changes corresponded to a short-term decline in O-horizon C:N ratios. The Fire treatment also showed elevated NH_4^+ concentrations in the O-horizon, but the increases were only detectable at 1 and 4 weeks following treatments. Rates of nitrification increased in the Mech+Fire in year 1, and net nitrification increased in the Mech+Fire for 3 years. There was also a strong correlation between fine fuels consumed and both net nitrification and net N mineralization, perhaps reflecting the effects of fire severity or variations in microclimate that varied with fire severity (Gundale et al., 2005).

Over the mid-term, there were few measurable treatment-driven differences in soil C and N cycling metrics. At 11 years after treatment, the total soil C pool in the Mech+Fire plots was still significantly lower than in the other treatments, and net nitrification rates were still slightly elevated above other treatments (Ganzlin et al., 2016). The short-term increases in inorganic N observed by Gundale et al. (2005) were not detectable at year 11. However, while absolute rates of N mineralization and nitrification were lower in all treatments in 2013 than in 2001 or 2004, rates of both processes still strongly correlated with fine fuels consumed in the burned plots, even after 11 years (Ganzlin et al., 2016). Thus, although treatments had some lasting effects, for most soil variables the longevity of treatment effects in this ecosystem was <10 years. From a nutrient cycling perspective, the relatively short longevity of the treatments suggests that repeated treatments (e.g., with fire) are necessary to maintain the relatively N-rich soil conditions that the initial Fire and Mech+Fire treatments created.

Short-term vegetation responses

Immediate treatment effects on vegetation communities are reported in Metlen and Fiedler (2006), Dodson and Fiedler (2006), and Dodson et al. (2007). Metlen and Fiedler (2006) found that burning treatments initially reduced understory cover and richness, but both thinning and burning treatments increased cover and richness (especially of forbs) over pretreatment conditions after 3 years. Treatments increased exotic plant cover relative to the control in the first 4 years, and increases were greatest in the Mech+Fire treatment (Dodson & Fiedler, 2006). Dodson et al. (2007) also showed that all active treatments (especially Mech+Fire) reduced the abundance of common species, benefiting uncommon native plant species and species assemblages. Fiedler et al. (2010) explored short-term (4 years) treatment effects on stand structure and tree growth, demonstrating an immediate beneficial effect of thinning (i.e., Mech and Mech+Fire) on overstory growth rates and the stand-out benefits of the Mech+Fire treatment which further reduced crown fire hazard by raising crown base height, increasing mean diameter, and increasing proportion of fire-tolerant species. Six and Skov (2009) reported short-term bark beetle activity and emphasized the short pulse of activity associated with burning, wherein some tree-killing beetle species responded positively and killed fire-injured trees but successful attacks did not expand to healthy trees.

Schwilk et al. (2009) and (McIver et al., 2013) compared vegetation and fuel responses at Lubrecht with results from other sites in the National FFS study. In these short-term multisite syntheses, Lubrecht showed similar responses to other sites in the network; mechanical treatment was most effective at quickly attaining a desirable stand structure and composition but was not a complete surrogate for fire. Thus, the combination Mech+Fire treatment was highlighted as the best option for increasing forest resilience to disturbance. Short-term treatment effects on fire hazard and probability of mortality in the event of a wildfire were compared across the FFS sites by Stephens et al. (2009). While the likelihood of crown fires was low across all treatments and weather scenarios, the torching index was only high (i.e., harder for torching to occur) in the Mech+Fire treatment, followed by the Fire treatment. The Mech treatment greatly increased surface fuels, which caused a short-term increase in hazard and potential fire severity (i.e., tree mortality) relative to the other treatments, including the control.

Interaction with mountain pine beetle outbreak

After the short-term (4-year) treatment responses were measured, Lubrecht was affected by a regional MPB outbreak. MPB-driven overstory ponderosa pine mortality levels were highest in the control and Fire treatments, with approximately 50% and 39%, respectively, killed during the outbreak, compared with almost no mortality in the Mech and Mech+Fire, leading to similar live ponderosa pine basal area and overstory density across all treatments by the end of the outbreak (Hood et al., 2016). The mortality event slightly reduced ponderosa pine QMD in the control, as MPB-killed larger trees, while QMD increased during the same time period in the Mech and Mech+Fire (Hood et al., 2016). The increased growth associated with mechanical treatments also increased resin ducts relative to control and Fire treatments, and prescribed burning changed resin chemistry in a way that may have negatively affected MPB communication (Hood et al., 2016). In concert these two treatment modes of thinning and burning likely maximized individual tree resistance to MPB, while reduced density in the mechanical treatments also bolstered stand-level resistance. Following the MPB outbreak, changes in vegetation dynamics reflect the combined effects of the fuel reduction treatments and the outbreak. Crotteau et al. (2018) quantified the effects of MPB-caused mortality on forest fuels within the context of the experiment, characterizing the sources and lasting effects of treatment and outbreak on fire hazard. Likewise, (Crotteau et al., 2020) assessed the joint effects of treatment and outbreak on vegetation structure and composition, wherein they found that the combined Mech+Fire treatment had the most enduring and beneficial effect on ecosystem resiliency.

LONG-TERM RESULTS

Forest structure and composition

Immediately after treatment, the mechanical treatments reduced tree density, basal area, and SDI relative to the control and Fire treatments (Table 1, Figure 1), with post-treatment basal area values close to the prescription target of 11 m^2 ha^{-1} (Mech = 10.8 m^2 ha^{-1}, Mech+Fire = 9.5 m^2 ha^{-1}). By contrast, the prescribed burns only slightly reduced tree basal area and had no measurable effects on forest structure compared with the control (Table 1, Figure 1). Relative SDI was 40% in the control, 38% in Fire, 18% in Mech, and 15% in Mech +Fire. While there were no statistical differences in ponderosa pine dominance among treatments, the control tended to have less ponderosa pine (55%) compared with the Mech (79%) and Mech+Fire (78%) treatments, where the thinning prescriptions preferentially retained ponderosa pine.

At 20 years post-treatment, only the Mech+Fire treatment maintained lower tree density, basal area, and SDI relative to the control (Table 1, Figure 1, Appendix S1: Table S2). The Mech treatment was intermediate; it maintained lower tree density than the control but, statistically, basal area and SDI in the Mech treatment were similar to control values. Relative SDI declined over time in the control (33%) and Fire (32%) due to MPB-caused mortality and increased in the Mech (27%) and Mech+Fire (20%). Trees in the mechanical treatments (especially Mech+Fire) grew faster (QMD difference: Mech = 2.8 cm, Mech+Fire = 5.5 cm vs. Cont = 0 cm, Fire = 0.8 cm) and were larger (QMD: Mech = 33.9 cm, Mech+Fire = 38.5 cm vs. Cont = 28.3 cm, Fire = 27.7 cm) than the control and Fire treatments (Table 1). All treatments showed a decline in ponderosa pine dominance over the 20 years, but the decline was subtle in the Mech+Fire treatments (−3%) compared with the other treatments (Fire = −19%; Mech = −16%) and control (−25%). The MPB outbreak drove much of the decline in ponderosa pine in the control and Fire (Figures 1 and 2), whereas there was a gradual increase in the relative abundance of Douglas-fir growing into the tree class in the Mech treatment (Figure 2).

TABLE 1 Forest structural characteristics by treatment 1-year post-treatment (2002) and 20 years post-treatment (2020 for trees [≥10.16 cm dbh]; 2022 for saplings [0.1–10.16 cm dbh] and seedlings [10–137 cm tall]).

Year	Treatment	Density (trees ha^{-1})	BA (m^2 ha^{-1})	QMD (cm)	SDI (metric)	Proportion ponderosa pine	Density (seedlings ha^{-1})	Density (saplings ha^{-1})
2002	Control	397b	23.8b	28.3ab	447b	0.55a	6102c	2164b
		(340, 454)	(20.3, 27.2)	(26, 30.7)	(387, 507)	(0.27, 0.8)	(3854, 9661)	(1118, 4186)
	Fire	410b	21.6b	26.9a	418b	0.65a	3139b	1415b
		(349, 470)	(18.4, 24.8)	(24.5, 29.3)	(361, 474)	(0.36, 0.86)	(1918, 5139)	(743, 2695)
	Mech	147a	10.8a	31.1ab	196a	0.79a	4535bc	990b
		(118, 176)	(8.3, 13.4)	(28.5, 33.7)	(156, 236)	(0.52, 0.92)	(2826, 7276)	(512, 1915)
	Mech+Fire	123a	9.5a	33b	169a	0.78a	1339a	139a
		(96, 151)	(6.7, 12.2)	(29.5, 36.4)	(125, 213)	(0.51, 0.92)	(710, 2525)	(68, 284)
2022	Control	318c	19.9b	28.3a	372b	0.3a	3738a	2363b
		(261, 375)	(16.5, 23.4)	(26, 30.7)	(312, 433)	(0.12, 0.59)	(2317, 6031)	(1225, 4558)
	Fire	320c	19.1b	27.7a	360b	0.46ab	2903a	1070ab
		(259, 380)	(15.9, 22.4)	(25.3, 30.1)	(303, 416)	(0.2, 0.74)	(1762, 4781)	(560, 2046)
	Mech	202b	17.2ab	33.9b	301b	0.63ab	4004a	2098b
		(173, 231)	(14.6, 19.7)	(31.3, 36.5)	(261, 341)	(0.34, 0.85)	(2483, 6457)	(1105, 3984)
	Mech+Fire	122a	13a	38.5b	217a	0.75b	3084a	380a
		(94, 149)	(10.2, 15.7)	(35.1, 41.9)	(173, 261)	(0.47, 0.91)	(1774, 5359)	(192, 755)

Note: Only the tree class was used to calculate basal area (BA), quadratic mean diameter (QMD), stand density index (SDI), and proportion of ponderosa pine. Values are modeled means and 95% confidence intervals. Lowercase letters indicate pairwise differences between treatments within a measurement year. Only live tree trees were included. For reference, maximum SDI for ponderosa pine is 1111.

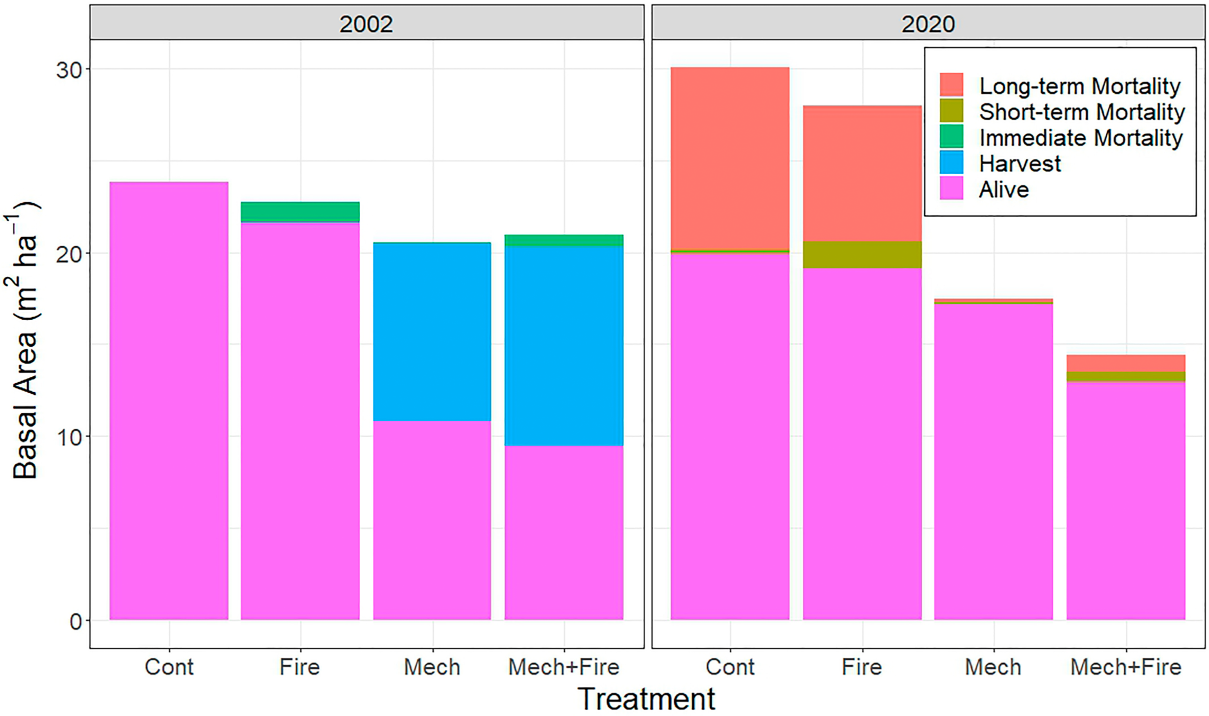

FIGURE 1 Overstory basal area (trees ≥10.16 cm dbh) immediately post-treatment (2002) and 18 years later (2020), showing live, harvested, and dead basal area. Immediate mortality includes trees that died between the pretreatment and 1-year post-treatment measurements. Short-term mortality includes trees dying 2–4 years post-treatment. Long-term mortality includes trees dying 5–18 years post-treatment (mostly from mountain pine beetle; see Hood et al. (2016) for details on long-term mortality and beetle outbreak).

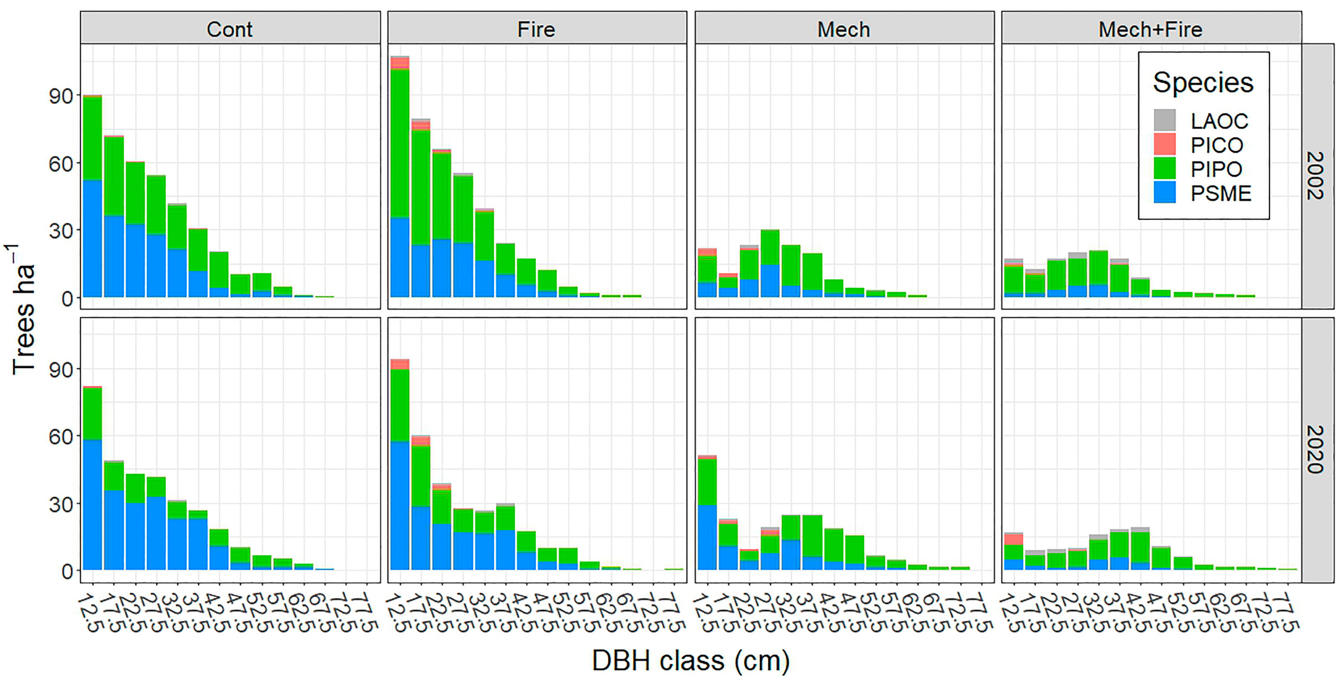

FIGURE 2 Overstory (trees ≥10.16 cm dbh) diameter distributions by treatment in 2002 (immediately following treatment) and in 2020 (18 years post-treatment) by 5-cm diameter classes. Stacked bars illustrate density by species, where LAOC, *Larix occidentalis*; PICO, *Pinus contorta*; PIPO, *Pinus ponderosa*; and PSME, *Pseudotsuga menziesii*.

Immediately after treatment, sapling and seedling density were lowest in Mech+Fire (Table 1, Figure 3). The majority of seedlings were Douglas-fir (Figure 3A). The Fire treatment had intermediate levels of seedling density between the highest densities in the control and Mech (no difference) and the lowest in the Mech+Fire. The few saplings remaining in the Mech+Fire were almost all Douglas-fir, whereas ponderosa pine sapling relative density was much higher in the other treatments (Figure 3B).

At 20 years post-treatment, while there were no statistical differences in seedling density among treatments (Table 1), seedling composition had changed in the control and Mech+Fire (Figure 3A). Ponderosa pine seedling dominance declined markedly in the control from 32% to 14% but more than doubled from 19% to 50% in the Mech+Fire. Sapling density was still much lower in the Mech+Fire (380 saplings ha^{-1}) compared with the control and Mech treatments (over 2000 saplings ha^{-1}), while sapling density in the Fire treatment was intermediate (1070 saplings ha^{-1}). Douglas-fir saplings were dominant across all treatments, especially in the smallest diameter sapling class (Figure 3B).

Native and nonnative understory plant species responses

After 20 years, there were few detectable differences in native species cover and genus richness across treatments (Figure 4A,C). However, we observed an increase in average native cover across all treatments over the duration of the experiment from 16% to 42% (Appendix S1: Table S3). In 2002, average native vegetation cover was greatest in the Mech and control treatments, and lowest in Fire and Mech+Fire; on average, native plant cover was 41% lower in the treatments with prescribed burning than the unburned treatments. Yet, there were no treatment differences 20 years later. While native plant cover increased over time, average native plant richness decreased from 8.2 to 6.0 genera in the time since initial treatment (Appendix S1: Table S3). Native plant species richness was 25% lower in the Fire treatment than the Mech and Cont in 2002 but, by 2022, there were no differences among treatments. We observed the greatest increases in *Calamagrostis*, *Symphoricarpos*, *Spiraea*, and *Arnica* cover across the treatments (ranging from an average of 3%–7% point increases), while *Penstemon*, *Stipa*, and *Balsamorhiza* genera had slight decreases in cover (<1% point). Interestingly, the same genera showed gains across all treatments.

Exotic plant species cover and richness were very low across the study over time, although both spiked ~4 years post-treatment (Figure 4B,D). Exotic cover was highest in Mech+Fire in 2002, where it was 2.7 times higher than Fire but, by 2022, there were no differences among treatments (Appendix S1: Table S3). Exotic richness was also highest in the Mech+Fire in 2002, 2.3 times more than the Fire treatment. By 2022, the only remaining

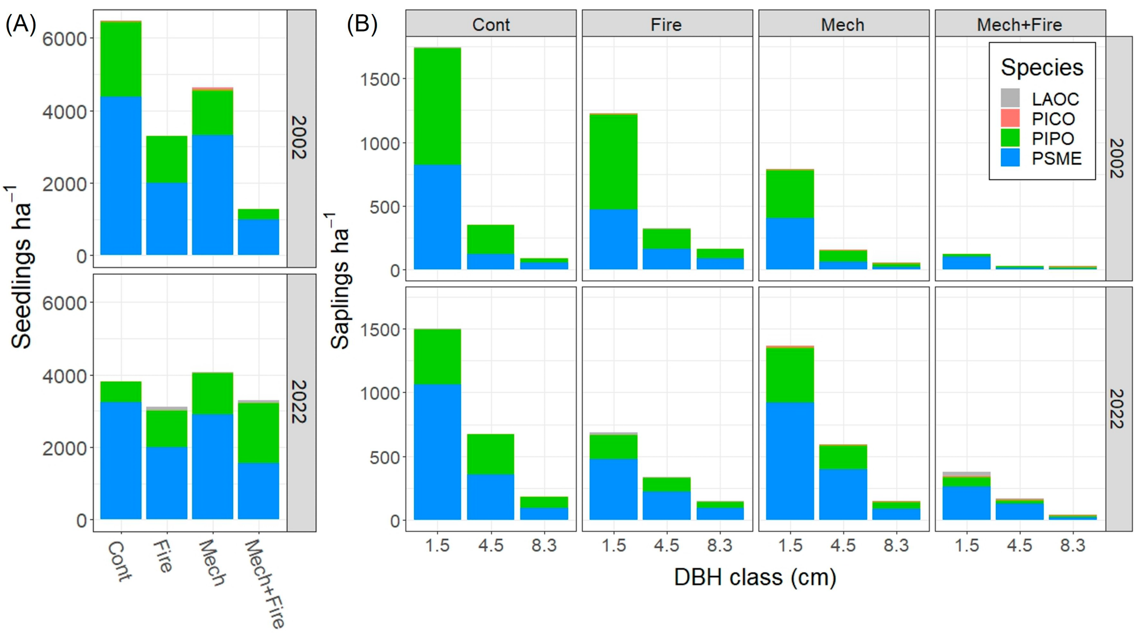

FIGURE 3 (A) Seedling (10 cm ≤ height <137 cm) density and (B) sapling (0.1–10.16 cm dbh) diameter distributions by treatment in 2002 (immediately following treatment) and 2022 (20 years post-treatment). Sapling diameter classes: 1.5 = 0.1–3.0 cm dbh; 4.5 = 3.1–6.0 cm dbh; 8.0 = 6.10–10.16 cm dbh. Stacked bars illustrate density by species, where LAOC, *Larix occidentalis*; PICO, *Pinus contorta*; PIPO, *Pinus ponderosa*; and PSME, *Pseudotsuga menziesii*.

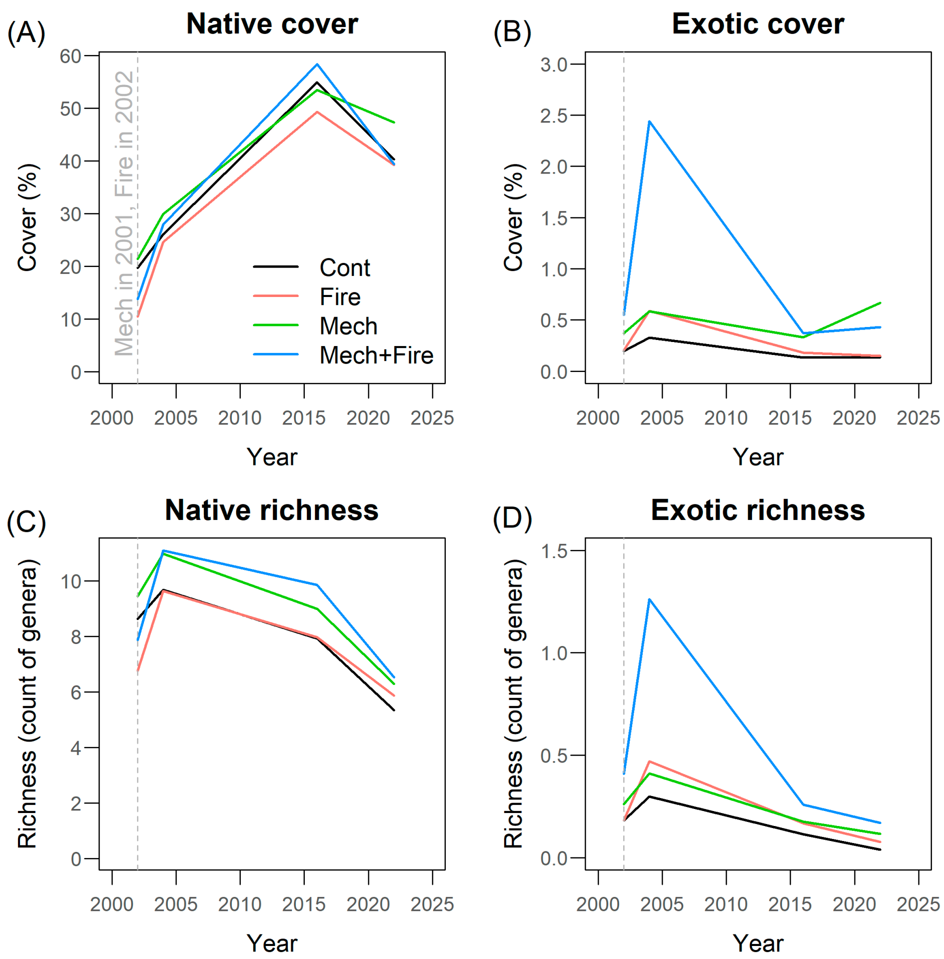

FIGURE 4 Average native and exotic (A, B) understory percentage cover and (C, D) richness (count of genera) on 1 m^2 quadrats over time by treatment. Measurement years were 2002, 2004, 2016, and 2022; only 2002 and 2022 were used for testing.

differences were between the Mech+Fire and Cont, with exotic richness in the Mech+Fire 4.3 times higher than the control, which had only 0.04 exotic genera per quadrat (i.e., one instance of an exotic per 25 quadrats). *Cirsium* gained the most cover in control and Fire treatments (0.02% to 0.05% points), whereas *Trifolium* gained the most in Mech and Mech+Fire treatments (0.06% to 0.16% points). The greatest cover losses were in the *Taraxacum* genus across all treatments (up to 1.1% points).

Surface fuels and potential fire effects

Surface fuel loads varied by treatment and year, as treatments directly influenced fuels and developmental trajectory in 2002 but were then indirectly affected by the MPB outbreak (Figure 5). Fine woody debris (1-, 10-, and 100-h fuels) was different across all treatment levels in 2002 (Appendix S1: Table S4; Figure 5A), with the highest fuel load in the Mech treatment due to activity fuels from the harvest. Loading was second highest in the Mech+Fire treatment after the prescribed burn consumed much of the activity fuels, followed by the control, and lowest in the Fire treatment. By 2022, short-term differences between Mech and Mech+Fire and between control and Fire were no longer apparent (Figure 5A). While these two groups remained different from each other, average FWD loading in the thinned treatments declined over time and was twice (1.9×) as low as the Fire and control where FWD increased because of bark beetle-caused tree mortality that transferred fuels from the overstory to the surface (Figure 5A). Sound CWD (1000-h fuels) loading patterns were similar to FWD patterns, but even more pronounced (Figure 5B). After burning in 2002, CWD loading in Fire was less than loading in both control and Mech (Appendix S1: Table S4). Following the trend observed for FWD, CWD loads in the control and Fire increased over time because of bark beetle-caused overstory mortality. In 2022 Fire and control were no different from each other, and Mech and Mech+Fire were no different from each other, but the

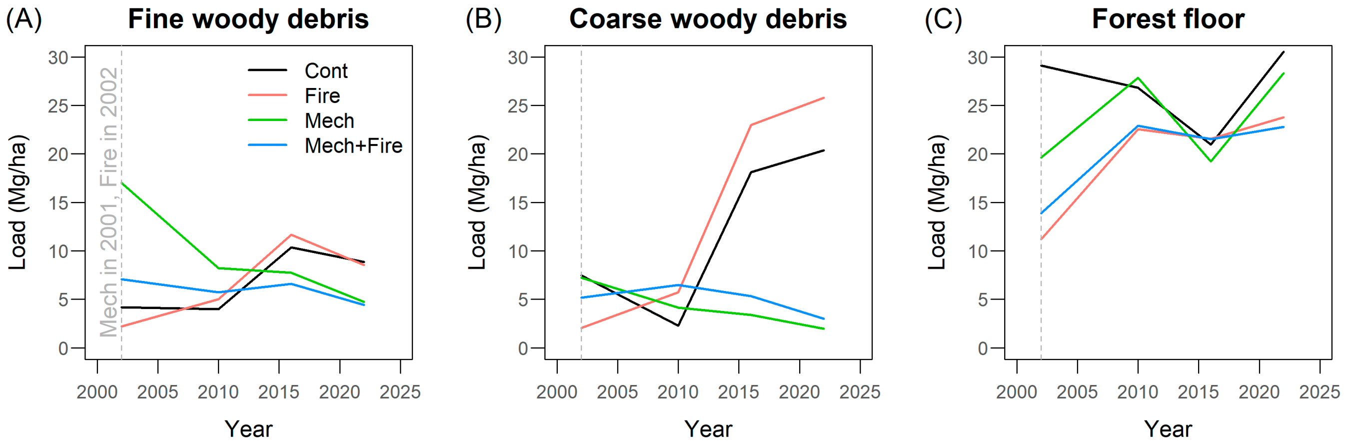

FIGURE 5 (A) Fine woody debris, (B) coarse woody debris, and (C) forest floor surface fuel loads over time by treatment. Measurement years were 2002, 2010, 2016, and 2022; only 2002 and 2022 were used for testing. The study area was affected by a regional mountain pine beetle outbreak between 2005 and 2012, especially in the Cont and Fire treatment.

averaged unthinned treatments had nine times (9.3×) higher loading compared with the thinned treatments. Finally, FF loads (litter and duff) showed a persistent effect of burning across the two measurement periods (Appendix S1: Table S4; Figure 5C). Forest floor loads were highest in control, reduced in Mech, and lowest in both the Fire and Mech+Fire in 2002. At 20 years later there was still no difference between Fire and Mech+Fire, and average loads were 1.3 times higher in control and Mech than Mech+Fire.

Potential fire effects varied by treatment and year, tracking the effects of treatment on fuels, subsequent stand dynamics, and bark beetle-caused overstory mortality (Figure 6). The probability of torching values reflect the initial reduction in surface fuels by burning and elevated activity fuels after thinning in the 2002 measurement (Appendix S1: Table S5). Specifically, the average probability of torching was six times (6.1×) higher in control and Mech than Mech+Fire, and three times (2.9×) higher in Mech than Fire. However, by 2022, the treatment ranking changed because of the indirect effect of treatment on fuel loads via the bark beetle-caused overstory mortality (Figure 6A). Here, a high range of variability in the control and Fire treatment muddied contrasts, but the average probability of torching was still four times (4.0×) higher in the control than in Mech+Fire. The probability of mortality accentuated some of the differences and trends from the probability of torching estimates, as the two are mechanistically linked (Appendix S1: Table S5; Figure 6B). The average probability of mortality was 1.8 times greater in control, Fire, and Mech than in Mech+Fire in 2002. By 2022, the average probability was 2.9 times greater in control and Fire than Mech+Fire and was 1.8 times greater in control

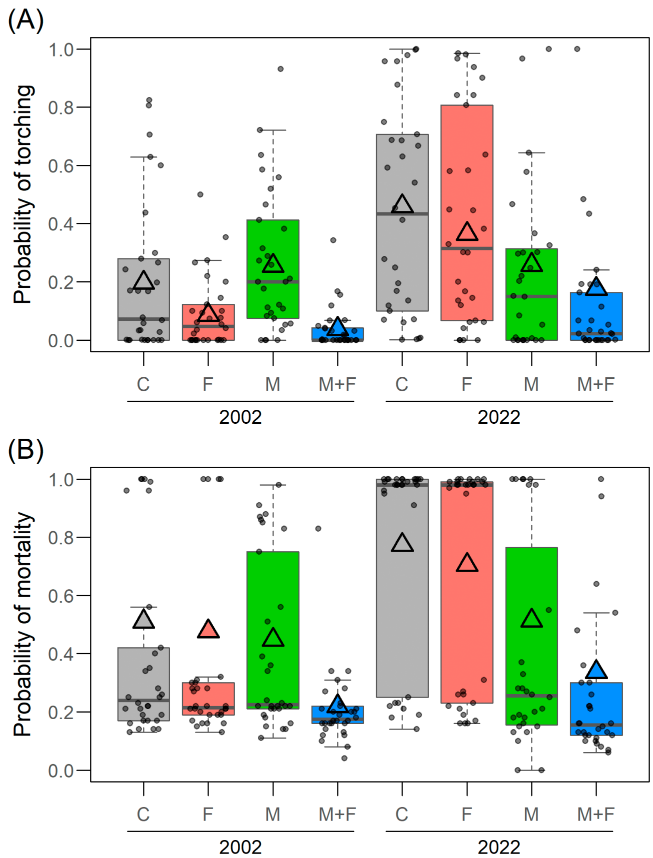

FIGURE 6 (A) Probability of torching and (B) overstory mortality (by basal area) boxplots by treatment from modeled fire in 2002, immediately following treatment, and 2022, 20-years post-treatment. Fire was modeled with the Fire and Fuels Extension to the Forest Vegetation Simulator under "severe" fire weather conditions. Treatment levels: C, Cont; F, Fire; M, Mech; M+F, Mech+Fire. Boxplots illustrate median, first and third quartiles, and range of plot-scale data; triangles are treatment-scale means; circles are jittered plot-level values.

than Mech. The median probability of tree mortality in the control and Fire approached 1.0, compared with 0.25 in Mech and 0.15 in Mech+Fire.

Aboveground live carbon stocks

Immediately after treatment in 2002, the mean totC in the control was 50.6 Mg ha^{-1} and ranged from 14.4 to 94.5 Mg ha^{-1} (Figure 7A). TotC did not differ between the control and Fire, but both had an average of 2.1 times more C than Mech and Mech+Fire, which were also no different from each other (Appendix S1: Table S6). By 2022, totC across treatments had somewhat equilibrated due to periodic growth and mortality over the 20 years (Figure 1), but the control still had 1.5 times the carbon than Mech+Fire (Figure 7A).

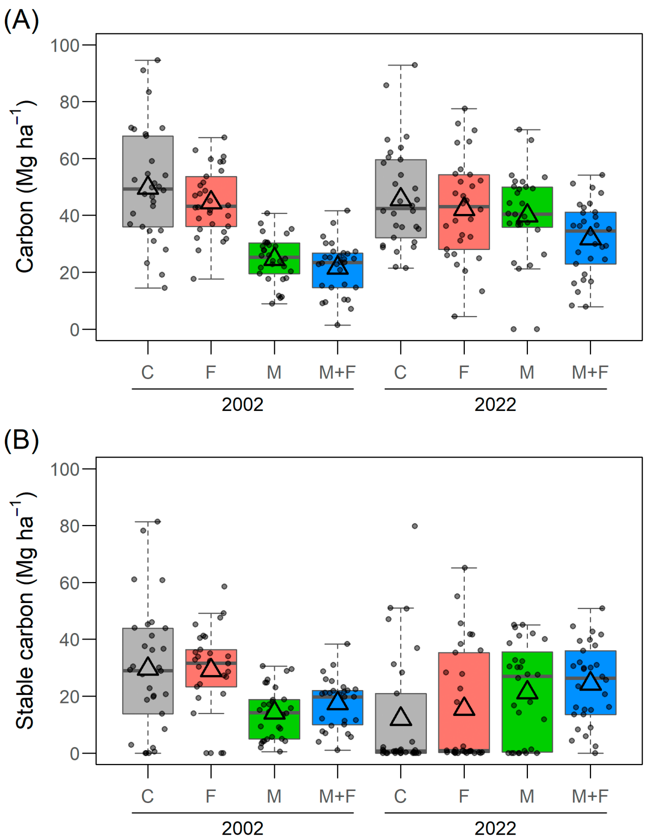

FIGURE 7 (A) Total aboveground live carbon and (B) stable aboveground live carbon boxplots by treatment in 2002, immediately following treatment, and 2022, 20-years post-treatment. Stable aboveground live carbon was calculated as that remaining after modeled fire. Fire was modeled with the Fire and Fuels Extension of the Forest Vegetation Simulator under "severe" fire weather conditions. Treatment levels: C, Cont; F, Fire; M, Mech; M+F, Mech+Fire. Boxplots illustrate median, first and third quartiles, and range of plot-scale data; triangles treatment-scale means; circles are jittered plot-level values.

In 2002, mean stableC, a metric of live tree resilience to wildfire, in the control was 29.6 Mg ha^{-1} and 1.6 times higher than Mech+Fire. If a wildfire were to have occurred in 2002 in the control, we estimated that 21.0 Mg ha^{-1} or 42% was unstable and subject to loss from burning under severe fire weather conditions (Figure 7B; Appendix S1: Table S6). At 20 years later there were no statistical pairwise differences in stableC treatment means, despite significant model interaction terms between treatment and year, likely due to high variability within the plots and only three replicates that limited statistical power (Figure 7B). Nevertheless, the median values of control and Fire showed that 50% of observed plots had stableC below 1 Mg ha^{-1}, whereas the median value of Mech and Mech+Fire were 26–27 Mg ha^{-1} (Figure 7B). These estimates imply that if a wildfire were to occur today, tree mortality would be nearly 100% in most areas of the control and Fire units, resetting stableC to near 0 Mg ha^{-1} in those areas, whereas higher tree survival in Mech and Mech+Fire would allow higher stableC.

DISCUSSION

Long-term study sites provide invaluable insight into temporal responses of forested ecosystems in the Northern Rockies to restoration treatments. The 20-year Lubrecht FFS study is unique among other long-term studies in that it allowed us to assess not only the effects of forest fuel and restoration treatments on the ecosystem, but also to explore the interactions between forest restoration, a mountain pine beetle outbreak, and ecosystem resilience. Our study demonstrates that fuel and restoration treatments can increase forest resilience to both wildfire and mountain pine beetle outbreaks, with the mechanical + prescribed burning treatment providing the longest term benefits.

Fire hazard

The primary objective at Lubrecht (and for all the National FFS study sites) was to reduce the likelihood of high-severity wildfire, such that 80% of the dominant and co-dominant trees would survive a wildfire burning under 80th percentile weather conditions (i.e., the 80–80 rule). Both burning and thinning followed by burning initially reduced fire hazard and probability of tree mortality in the event of a wildfire relative to the control, while thinning without burning caused an ephemeral increase in torching probability (but reduced crowning probability) and potential tree mortality due to the slash generated from the harvest (Table 2; Figure 6) (Crotteau et al., 2018; Stephens et al., 2009). Twenty years post-treatment and approximately 10 years post MPB outbreak, the probability of torching and tree mortality had greatly increased in the control and Fire treatments to such a degree that, should a wildfire occur, the tree mortality would likely approach 100% throughout much of these units (Figure 6B, median values). In contrast, fire hazard and probability of mortality changed little over the 20 years in the thinned treatments, although variability was greater in the Mech compared with the Mech+Fire (Figure 6A). Predicted patches of elevated torching and mortality potentials in the Mech treatments in 2020 were driven by dense Douglas-fir regeneration contributing to ladder fuels (Tables 1 and 2).

While the Lubrecht treatments were designed to meet the 80–80 rule, fuel treatments are now typically designed to be effective under more extreme weather conditions (e.g., 90th or 97th percentile weather; Stephens et al., 2009). Based on this more stringent objective, after 20 years only the Mech+Fire treatment was close to meeting the primary study objective of at least 80% likelihood of tree survival under severe wildfire conditions, with median and mean predicted survival rates of 85% and 66%, respectively (Figure 6). Compared with similar treatments at Lick Creek (also in western MT), the Mech and Mech+Fire treatments at Lubrecht generally lasted longer as a fire hazard reduction treatment (Hood et al., 2020). The differences in treatment longevity may be due to the slightly higher initial post-treatment average basal

TABLE 2 Summary of short-term (1–4 years) treatment effects compared with pretreatment measurements, except for soils data that are compared with control values.

Attribute	Short-term treatment effect				Mid-term treatment trend				Long-term treatment trend			
	C	F	M	M+F	C	F	M	M+F	C	F	M	M+F
Overstory density	→	→	↓	↓	↓	↓	↑	↑	↓	↓	↑	↑
Overstory tree diameter	→	↑	↑	↑	↑	↑	↑	↑	→	→	↑	↑
Overstory pine composition	→	→	↑	↑	↓	↓	↓	→	↓	↓	→	→
Regeneration density	↑	↓	→	↓	↓	↓	↑	↑	↓	↓	↑	↑
Regeneration pine composition	→	↑	→	↑	↓	↓	→	↑	↓	↓	↓	↑
Native understory cover	→	↓	→	↓	↑	↑	↑	↑	↑	↑	↑	↑
Native understory richness	→	↓	↑	↓	↓	↑	↓	→	↓	↓	↓	↓
Exotic understory cover	→	↑	↑	↑	→	→	→	→	→	→	↑	→
Exotic understory richness	→	↑	↑	↑					↓	↓	↓	↓
Fine woody debris load	→	↓	↑	→	↑	↑	↓	→	↑	↑	↓	→
Coarse woody debris load	→	↓	→	↓	↑	↑	↓	→	↑	↑	↓	→
Forest floor load	→	↓	↓	↓	↓	↑	→	↑	→	↑	↑	↑
Fire hazard	→	↓	→[b]	↓	↑	↑	↑	→[b]	↑	↑	↑	↑
Predicted tree mortality	→	↓	↑	↓	↑	↑	↓↑	→↑	↑	↑	↑	↑
Total aboveground carbon	→	↓	↓	↓	↓↑	↓↑	↑	↑	→	→	↑	↑
Stable aboveground carbon	→	↓	↓	↓					↓	↓	↑	↑
Total soil carbon	→	↓	↑	↓	→	→	→	↓				
Soil C:N	→	↓	→	↓	→	→	→	→				
Total soil inorganic nitrogen	→	→	↑	↑	→	→	→	→				
Net nitrogen mineralization	→	→	→	↑	→	→	→	→				
Net nitrification	→	→	→	↑	→	→	→	→				
Decomposition	→	↑	→	↑	→	→	→	→				

Note: Treatments: C, Cont; F, Fire; M, Mech; M+F, Mech+Fire. Mid- (5–14 years) and long-term (18–20 years) trends reflect treatment responses compared with 1-year post-treatment measurements. Short- and mid-term changes are based on previously published results[a]; long-term results are reported in this paper. → = no change; ↓ = decrease; ↑ = increase.

[a]Soil and ecosystem data from Gundale et al. (2005) and Ganzlin et al. (2016). No long-term soil responses were measured. Tree, understory vegetation, and fuel data from Crotteau et al. (2020), Crotteau et al., 2018, Dodson and Fiedler (2006), Fiedler et al. (2010), and Stephens et al. (2009). Mid-term richness and stable carbon not reported.

[b]Short-term Torching Index was the same as control, while Crowning Index was higher than control. Mid-term probability of torching increased, while Crowning Index was unchanged from 2002 to 2016.

area at Lick Creek than at Lubrecht and because Lick Creek was not as affected by the MPB outbreak as Lubrecht. The increase in hazard and potential tree mortality in the control and Fire treatment was likely driven by the sharp increase in fine and coarse fuels deposited after MPB-killed trees in these treatments decomposed and fell (MPB-caused mortality was negligible in the Mech and Mech+Fire, Hood et al., 2016). The pulsed increase in fine fuel loads from the MPB outbreak seems to be stabilizing (Figure 5A), but the coarse wood load was still increasing 10 years post-outbreak and was much higher in 2022 in the control and Fire treatment relative to the Mech and Mech+Fire (Figure 5B). Studies of beetle-killed ponderosa pines in the Southwest US and California have indicated low persistence of standing snags beyond 10 years (Chambers & Mast, 2014; Reed et al., 2023), which aligns with our findings of only approximately 21% of dead ponderosa pine still standing in 2020. Therefore, while the main fuel pulse from the outbreak is likely over, we expect that coarse fuel loading in the control and Fire treatment will continue increasing in the near future as many of these remaining snags fall.

Restoration

A second main objective at Lubrecht was to restore the site to a forest structure and composition that more closely resembled historical reference conditions of ponderosa pine-dominated, fire-maintained forests. Specifically, the desired future conditions at the site were uneven-aged, relatively open, spatially complex structure, with basal area ranging from 8 to 20 m^2 ha^{-1}, dominated by large (>40 cm dbh) trees, and 90% ponderosa pine (Fiedler et al., 2010). Both thinning treatments met the target basal area goal immediately, but QMD in Mech+Fire especially was more rapidly approaching the desired condition. Tree growth based on tree ring analysis in the first 10 years post-treatment was very similar in the Mech and Mech+Fire (Hood et al., 2016), but growth seemed to have slowed in the Mech during the second half of this study, probably due to the increase in tree and regeneration density over time (Table 1; Figure 8). This is consistent with Tepley et al. (2020), who reported a sustained increase in 20+ years of growth after fuel treatments, especially in the initial post-treatment years in mechanical treatments without burning. However, heavy Douglas-fir regeneration that developed over time at the Lick Creek site contributed to slowly declining growth in the cut-only treatment, compared with a more sustained increase in growth in the combined cutting and fire treatments (Tepley et al., 2020). It is likely that the decreased density and basal area in the control and Fire from the MPB outbreak will lead to an increase in tree growth, as has been observed in survivors of other bark beetle outbreaks (Jarvis & Kulakowski, 2015; Taylor et al., 2006). Additional research is needed to determine whether a growth release occurred after the outbreak and species-level differences.

None of the treatments met the goal of establishing >90% ponderosa pine dominance at Lubrecht. Immediately post-treatment, the thinning treatments had the highest proportion of ponderosa pine at 78%–79%, but pine dominance waned over time in the Mech to 63% and 75% in the Mech+Fire 20 years post-treatment as Douglas-fir regeneration grew into the overstory class (Figure 2). By contrast, the declines in ponderosa pine dominance in the control and Fire were largely driven by the MPB outbreak such that 20 years post-treatment, Douglas-fir dominates in these units (Table 1). Given higher Douglas-fir sapling densities across all size classes and treatments (Figure 3), we expect pine dominance in all treatments to decline further without maintenance treatments. The ability of maintenance prescribed fire to reduce regeneration will also decline as small trees grow and develop thicker bark to become more fire tolerant. Ponderosa pine regeneration becomes tolerant of surface fires more quickly than Douglas-fir (Rodman et al., 2021), allowing for a window of opportunity to use fire to selectively reduce Douglas-fir regeneration with less impact on small ponderosa pine (Battaglia et al., 2008; Engber & Varner, 2012). These results align with numerous studies (e.g., Hagmann et al., 2021; Hood et al., 2020; North et al., 2007), and highlight how quickly composition can shift to shade-tolerant species in the absence of frequent, low-severity fire in dry conifer forests.

Treatment effects on understory vegetation diversity and nonnative species responses are important considerations for restoration. Native and exotic plant cover and richness in the treatments generally tracked closely with the control across years, with the exception of an ephemeral spike in exotic cover and richness in the Mech+Fire 4 years post-treatment. This spike sharply declined 10 years later and remained higher than the other treatments, but still low at 0.5% cover. These patterns are very similar to Lick Creek, where there was also an increase in exotic cover 5 years post-treatment that was largest in the cut and burned treatments compared with the cut-unburned treatment (Jang et al., 2021). Fuel treatment studies on understory vegetation have reported mixed results on both native and nonnative responses (Kalies & Yocom Kent, 2016), suggesting that responses are likely to be site specific and dependent on the particular treatment. For example, native herb cover initially increased after burning and thinning treatments in California but then declined and became more homogeneous over

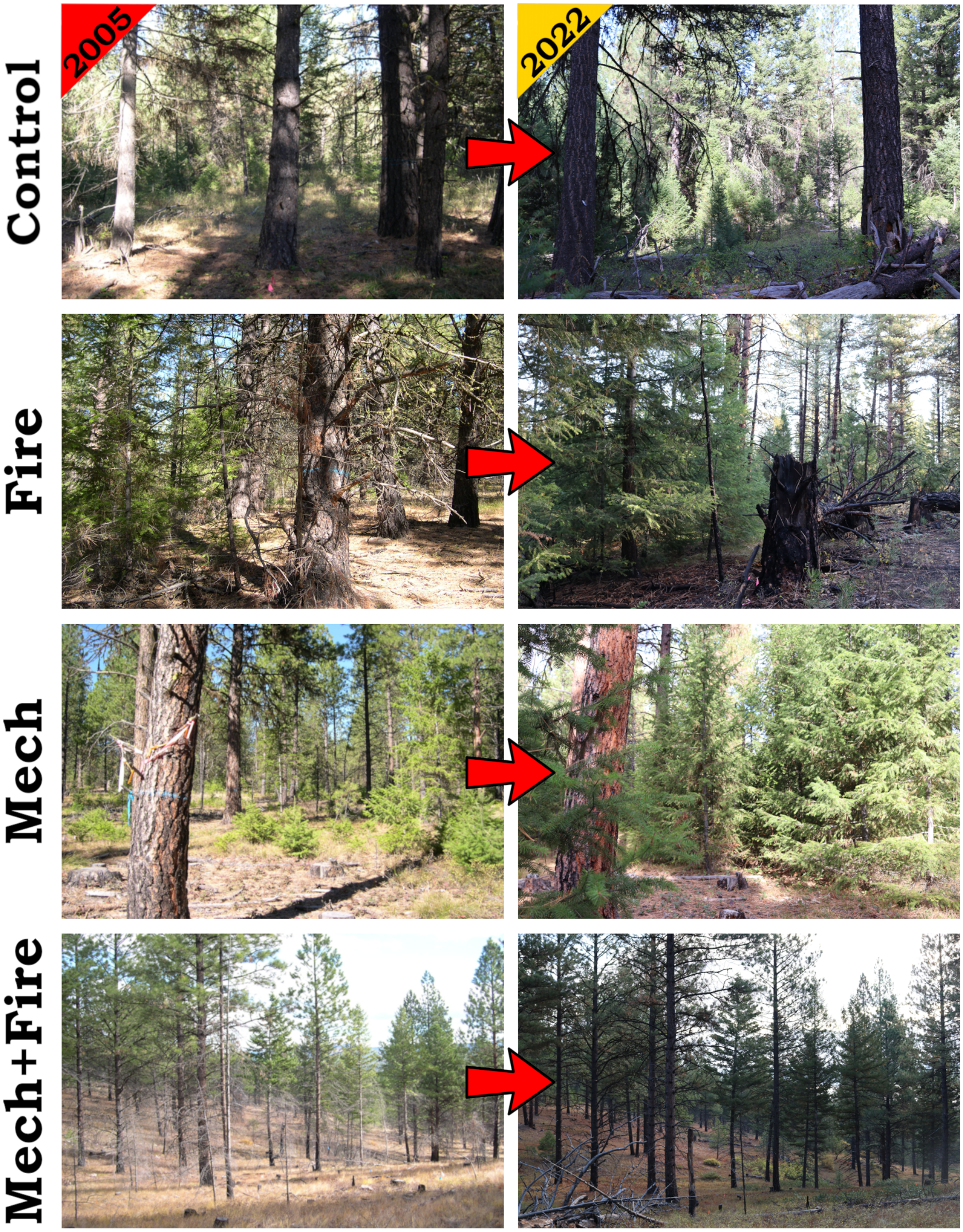

FIGURE 8 Treatment repeat photographs demonstrating change over time from established photopoints: 2005 = 4 years post-harvest and 3 years post-burn; 2022 = 20 years post-treatment. Photographs taken by Justin S. Crotteau.

15 years relative to the control as shrub cover and litter depths increased (Goodwin et al., 2018). This conflicts with the persistent increase in native cover across all treatments that we observed over 20 years and the results of a systematic review showing consistent mid-term and long-term increases in native cover after treatments (Abella & Springer, 2015). While our univariate statistical analysis of 2022 results show no treatment effects on native understory richness compared with the control, using a multivariate approach Crotteau et al. (2020) did find nuanced treatment differences between control and Mech+Fire primarily due to understory richness, overstory density, and shrub cover, suggesting positive long-term treatments effects on native plant species that are in line with broad restoration goals.

Based on the consistency between Lubrecht and Lick Creek, we expect similar understory responses to cutting and burning treatments in ponderosa pine-dominated forests in the Northern Rockies. It is unknown how understory species at Lubrecht may respond to additional maintenance treatments and if the exotic species now present at the site would be able to quickly increase over native species and sustain higher cover than that which occurred from the initial treatment. Kerns and Day (2018) reported an ephemeral increase in exotic cover after initial fall burns (but not spring burns as occurred at Lubrecht); however, repeated burning did not result in additional increases. Emerging threats of new invasive species with life history traits better adapted to forested areas could also affect ecosystem resilience and fire hazard (Kerns et al., 2020). For example, *Ventenata dubia*, an exotic annual grass that can increase fire hazard, has recently been recorded within a few miles of the Lubrecht FFS site (Montana Field Guide, 2023). Continued monitoring will be important to track these responses, especially with future treatments.

Carbon

Managing for low-density forests may effectively meet restoration and fuel treatment objectives in dry conifer forests, but at the potential expense of maximizing aboveground C stores. The thinned treatments (Mech and Mech+Fire) initially reduced aboveground C, but pools recovered over time to approach the control levels in 2022. Aboveground C in the Fire treatment was similar to the control in both 2002 and 2022. The short-term decline in C in the thinned treatments is consistent with numerous other studies (Hurteau et al., 2016; Hurteau & Brooks, 2011; Kalies & Yocom Kent, 2016). However, the long-term patterns at Lubrecht differed from Lick Creek, where live tree C in cut-only and cut-burn treatments were still lower than the control C 23 years post-treatment, although total aboveground live + dead C was not different from the control (Clyatt et al., 2017). These conflicting results likely reflect the compounding effects of the MPB outbreak at Lubrecht that caused high pine mortality and increased CWD in the control and Fire treatment. It is possible that, if the MPB outbreak had not occurred, then the control and Fire treatments would still have higher C 20 years post-treatment than the thinned treatments as Clyatt et al. (2017) observed. We argue that our results are still highly relevant when considering possible treatment effects on C for unmanaged versus managed forests, as bark beetle outbreaks are a widespread disturbance in North America (Raffa et al., 2008) and are projected to increase with climate change, especially in the western US (Kolb et al., 2016).

When considering how possible future disturbances may interact with forest restoration treatments, the timing of the disturbance in relation to treatment is relevant for C stocks. Even accounting for likely tree mortality and fuel consumption, if a wildfire had occurred immediately after treatment, stable C stores were still projected to be higher in the control compared with the Mech+Fire (Figure 7B). However, if a wildfire occurred today (20 years post-treatment), then it is likely that stable C across most of the treatment units would be higher in the Mech and Mech+Fire treatments relative to the control and Fire treatment. In fire-prone forests, it is unrealistic to assume that wildfires will not occur. Managing dry conifer forests at lower density, and therefore lower C, to mitigate the risk of high-severity fire helps maximize C stability against the risk of losing all live biomass to high-severity fire (Hurteau et al., 2019). How additional disturbances, such as insect outbreaks and drought, interact with fuel and restoration treatments to affect C is still poorly understood. Our results suggest that Mech and Mech+Fire treatments can greatly increase resistance to MPB, and maintain lower wildfire hazard, which combine to increase stable C compared with fire-excluded ponderosa pine forests. A study of stable C after a severe drought in California in areas with different intensities of cutting and burning treatments showed that overstory thinning followed by prescribed burning, such as the Mech+Fire treatment at Lubrecht, had similar to slightly lower stable C than the control, while less intense treatments generally had higher stable C than the control (Goodwin et al., 2020). This highlights the challenges of managing resilience to multiple disturbances while also trying to maximize stable C.

CONCLUSION

Since the establishment of the National FFS study, there has been a shift in focus from a strategy that simply reduces fire hazard to one that more broadly strives to increase forest resilience to disturbances and climate stress (Abrams et al., 2021; North et al., 2021, 2022; USDA Forest Service, 2000, 2022). It is also increasingly recognized that recurrent maintenance treatments are necessary in forests with historically frequent, low-severity fire regimes (North et al., 2021; Ryan et al., 2013). The Lubrecht FFS site provides strong evidence that fuel and restoration treatments in ponderosa pine forests in the Northern Rockies that reduce forest density to <150 trees ha^{-1} and below 200 SDI (Table 1) can increase resilience to wildfire (Fiedler et al., 2010; Stephens et al., 2009) and MPB outbreaks (Hood et al., 2016). These SDI values correspond to only 18% relative SDI, well below the recommended range for traditional forest management of 371–618 SDI (Long & Shaw, 2005), and provide empirical support for the suggested values of North et al. (2022) to maximize resilience to multiple disturbances and stressors. The SDI values in the control and Fire treatment were well within the management zone recommended by Long and Shaw (2005), but clearly they were too high to provide resistance to MPB at Lubrecht. In a review of yellow pine studies that had been challenged by severe MPB and other *Dendroctonus* spp. pressure, 30% of plots with SDI values between 150 and 199 had >70% mortality compared with 85% of plots with SDI >400 (Fettig et al., 2022). Together, these results suggest that SDI recommendations to manage forest resilience to disturbances under contemporary and future climates may need to be reconsidered and lowered. Prescribed burning following the thinning treatments had the lowest fire hazard throughout the 20 years of study compared with the control and individual thinning or burning treatments by killing much of the regeneration and consuming activity fuels from the harvest. In areas that have not burned in decades, mechanical + prescribed fire treatments can better meet stand density and fuel reduction objectives than only prescribed fire (Fulé et al., 2012; Kalies & Yocom Kent, 2016). One reason for this is that shade-tolerant species that are easily killed by fire when small have grown to be resistant to surface fires as thick bark develops (Engber & Varner, 2012; Hood et al., 2018; Zald et al., 2022).

Cumulatively, our results suggest that it is time to conduct additional treatments at the Lubrecht FFS study if continued resilience to wildfire, insects, and drought is desired, and if some of the benefits to soil biogeochemical and ecosystem-level processes are to again be restored (Table 2; Figure 8). The Mech+Fire treatment showed long-term resistance to change relative to the other treatments (Table 1), but the longevity of even this treatment is waning. Much of the Douglas-fir regeneration that has occurred post-treatment is still likely to be susceptible to mortality via surface fire, but over time will grow tolerant of fire. Care will also be needed to not kill the majority of ponderosa pine regeneration that has established since treatment. Additional thinning can reduce the basal area and SDI to promote the resilience to fire and bark beetles, as well as provide revenue to offset the cost of treatment. In the mechanical-only treatment, mastication or precommercial thinning of Douglas-fir seedlings and saplings will likely be needed to reduce ladder fuels and compact slash generated from the overstory thinning. These types of treatments are relevant to lands where prescribed burning may not be an option. Future research is needed to examine the effects of maintenance prescribed burns to determine whether it is possible to reduce stand density while increasing ponderosa pine relative dominance without mechanical treatment. Other needs include examining weed responses and a better understanding of how both thinning and burning can be used to maintain low fuel loads but still allow some shade-intolerant species to establish and grow to maturity for sustainable forest dynamics. The Lubrecht FFS study shows that fuel and restoration treatments in ponderosa pine forests of the Northern Rockies can bolster resilience to multiple disturbances, but these benefits are not without potential trade-offs of lower C stocks and the establishment of exotic species.

AUTHOR CONTRIBUTIONS

Sharon M. Hood: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review and Editing, Visualization, Supervision, Project administration, Funding acquisition; **Justin S. Crotteau**: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review and Editing, Visualization, Project administration, Funding acquisition; **Cory C. Cleveland**: Methodology, Resources, Data Curation, Writing—Review and Editing, Visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available in the USDA Forest Service Research Data Archive in the following data sets: Hood and Crotteau (2023), https://doi.org/10.2737/RDS-2023-0063; Crotteau et al. (2019), https://doi.org/10.2737/RDS-2019-0040; Hood et al. (2016), https://doi.org/10.2737/RDS-2016-0010; McIver et al. (2016), https://doi.org/10.2737/RDS-2016-0009.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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