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Effectiveness of pre-fire forest management on post-fire forest conditions in southeastern Arizona

Kira L. Hefty[1*], Jeffrey K. Gillan[2], Jena Trejo[3] and John L. Koprowski[4]

Abstract

Background Western forests in the United States are facing multiple threats that have the potential to permanently alter forest composition and structure. In particular, wildfire can either have beneficial or adverse effects on overall forest health and resilience. Monitoring and assessing the effectiveness of existing forest treatment plans for meeting forest management goals is becoming more critical to increase the capacity for managers to prepare for and accommodate uncertainty associated with changing disturbance regimes. We used a combination of fine-scale vegetation and microclimate surveys on 57 plots, active remotely sensed data (light detection and ranging: LiDAR), and high-resolution satellite imagery to evaluate the effectiveness of an existing management strategy to increase disturbance resistance and resilience of an isolated mixed-conifer forest following a recent large-scale wildfire in southeastern Arizona, USA. We specifically assessed the effectiveness of forest overstory live tree thinning treatments (silviculture) as well as understory fuel reduction treatments (fuel) for influencing post-fire abiotic and biotic conditions, reducing direct post-fire tree mortality, and increasing resilience as compared to untreated forest stands.

Results We found that forest silviculture and fuel reduction treatments implemented prior to a large wildfire had mixed results on post-fire fine-scale vegetation composition and structure, microclimate conditions, tree mortality, and tree resilience. Fine-scale vegetation characteristics within silviculture- and fuel-treated forest units displayed higher herbaceous diversity and decreased density of new tree snags as compared to untreated units post-fire. Relevant to seedling emergence, we found that variance in spring soil moisture content was lower overall in treated units; however, units that received overstory thinning (silviculture) treatments were also associated with higher average summer high soil temperatures as compared to untreated units. Additionally, direct tree mortality and rate of recovery of trees post-fire differed between two treatment types (silviculture and fuel reduction) when compared to untreated units and among contrasting levels of burn severity. Post-fire tree mortality and tree resilience did not differ between control and silviculture units; however, these characteristics did differ between control and fuel units. Unlike control units, probability of tree mortality changed little between burn severity categories in fuel treatments (53.4% of mortality occurring in unburned/low vs. 46.7% in moderate/high severity) and resilience increased an average of 2.04% for trees from unburned/low to moderate/high-severity burn categories.

Conclusions Our methodology could be applied to any forested system experiencing increasing intensity and frequency of wildfire. Our results indicate that post-fire forest conditions and resilience are influenced by forest management strategies, particularly fuel reduction treatments. To accommodate uncertainty associated with changing disturbance regimes and climate change, implementing post-fire and post-treatment assessments and monitoring

*Correspondence:
Kira L. Hefty
Kira.Hefty@usda.gov
Full list of author information is available at the end of the article

as presented in this study will be essential for developing attainable goals and for maintaining desired forest conditions.

Keywords Sky island, Arizona, Fuel treatment, Silviculture treatment, LiDAR, dNBR, Adaptive management

Resumen

Antecedentes Los bosques del Oeste en los EEUU están enfrentando múltiples amenazas que tienen el potencial de alterar permanentemente la composición y estructura de sus rodales. En particular, los incendios pueden tener efectos tanto beneficiales como adversos en la resiliencia y salud de esos bosques. El monitoreo y determinación de la efectividad de los planes de tratamientos para alcanzar objetivos de manejo forestal es cada vez más crítico para incrementar la capacidad de los gestores para prepararse y acomodarse a las incertidumbres asociadas con los cambios en los regímenes de disturbios. Hicimos un relevamiento combinado de vegetación-microclima a escala fina en 57 parcelas, mediante datos tomados con sensores remotos (LIDAR) e imágenes satelitales de alta resolución, para evaluar la efectividad de una estrategia de manejo existente para incrementar la resistencia y resiliencia de un bosque mixto de coníferas aislado luego de un incendio a gran escala en el sudeste de Arizona. Evaluamos específicamente la efectividad de tratamientos silviculturales de raleos y también la reducción del combustible superficial para influenciar las condiciones bióticas y abióticas en el post-fuego, reduciendo la mortalidad directa en el post-fuego e incrementando la resiliencia comparada con rodales no tratados.

Resultados Encontramos que los tratamientos silviculturales y la reducción del combustible superficial implementados antes del incendio de gran escala tuvo resultados mixtos a escala fina tanto en la estructura y composición de la vegetación, en las condiciones micro climáticas, y en la mortalidad y resiliencia de los árboles. Las características de las unidades de vegetación a escala fina dentro de los tratamientos silviculturales y de reducción del combustible mostraron una mayor diversidad de herbáceas y un decrecimiento en la densidad de árboles muertos en pie comparadas con unidades no tratadas en el post fuego. Algo relevante en relación con la emergencia de plántulas, es que encontramos que la variación en el contenido de humedad del suelo en primavera fue menor en general en las unidades tratadas. Sin embargo, las unidades que recibieron los tratamientos silviculturales de raleos, también estuvieron asociadas a mayores temperaturas del suelo durante el verano en comparación con las unidades no tratadas. Adicionalmente, la mortalidad directa de árboles y la tasa de recuperación de los árboles en el post fuego, difirieron entre los dos tipos de tratamientos (raleos y reducción del combustible) cuando se los comparó con las unidades no tratadas o con niveles contrastantes de severidad del fuego. La mortalidad post fuego y la resiliencia de los árboles no difirieron entre el control y las unidades con tratamientos silviculturales. Sin embargo, esas características sí difirieron entre el control y las unidades de tratamiento de combustibles. A diferencia de las unidades de control, la probabilidad de muerte de los árboles cambió muy poco en cuanto a las categorías de severidad en los tratamientos del combustible (53,4% de mortalidad ocurrió en no quemado y baja severidad vs 46,7 en severidad moderada a alta) y la resiliencia se incrementó en promedio un 2,04% para los árboles de las categorías de tratamiento no quemado-baja severidad a quemados a moderada-alta severidad.

Conclusiones Nuestra metodología puede ser aplicada a cualquier sistema de bosque que experimente un incremento en la intensidad y frecuencia de fuegos. Nuestros resultados indican que las condiciones y resiliencia del bosque en el post fuego están influenciadas por las estrategias de manejo de ese bosque, en particular por los tratamientos de reducción del combustible. Para acomodar las incertidumbres asociadas con los cambios en los regímenes de disturbios y el cambio climático, la implementación de determinaciones en el post fuego y en el post tratamiento y monitoreo presentados en este estudio serán esenciales para desarrollar metas alcanzables y mantener las condiciones deseadas en el bosque.

Background

High-intensity natural disturbances are increasingly causing landscape-scale shifts in ecosystem composition and structure (Koprowski et al. 2005; Hudak et al. 2011; Johnstone et al. 2016). Maintaining ecosystem resilience in the face of high-intensity disturbance, such as wildfire, continues to be particularly challenging given climate change projections, invasive species encroachment, and direct anthropogenic activity (Peters 1990; Folke et al. 2004; Allen et al. 2010; Chmura et al. 2011). Traditional management practices used to ensure long-term ecosystem function are becoming insufficient to address changing disturbance regimes (Folke et al. 2004; Schwartz et al. 2012). It is therefore essential to innovate and adapt management strategies to minimize ecosystem vulnerability and to accommodate uncertainty regarding future events and outcomes. Several management techniques have been proposed in response to these critical issues, many of which employ an iterative process that involves designing and implementation of management actions with consideration given to anticipated environmental change, monitoring the sufficiency of actions to maintain ecosystem resilience, and adjusting future actions dependent on outcomes (Stein et al. 2013). Such adaptive management strategies are gaining traction as tools to address threats of climate change; however, currently few case studies adhere to the crucial step that defines adaptive management: monitoring the impacts of management actions on ecosystem resiliency (Allan and Curtis 2005; Hagerman and Pelai 2018). Ecological resilience, or the ability of natural communities or community properties to persist through and recover from disturbance, has emerged as a critical topic of concern given climate change projections (Holling 1973; Nikinmaa et al. 2020). Current lack of monitoring and assessment hinders the ability of managers to prepare for or potentially reduce the prevalence of rapid biotic and abiotic shifts in natural communities (Mawdsley et al. 2009; Nagel et al. 2017).

Silviculture treatments are active manipulations of forest stand structure or composition used to achieve various management goals and improve overall forest health (Lezberg et al. 2008; Prichard et al. 2010; Dodge et al. 2019). Two dominant treatment strategies exist: mechanical forest thinning, including overstory removal treatments, and prescribed burn or understory fuel reduction treatments. Silviculture treatments are often implemented to decrease overstory canopy cover, increase the structural height of live tree crowns, and reduce understory dead and decaying organic material (Agee and Skinner 2005). Rearrangement and reduction of fuels is often the primary objective of silviculture treatments. Fuel treatments, including thinning and prescribed fire, are commonly implemented to reduce the probability of high-severity, stand-replacing wildfire by influencing wildfire behavior and potential (Agee and Skinner 2005; Hudak et al. 2011). Nevertheless, the effectiveness of treatments to promote forest stand resistance or resilience to wildfire have had mixed results dependent on type of prescription used or if a combination of strategies were used (Prichard et al. 2010; Hudak et al. 2011; Stephens et al. 2012; Dodge et al. 2019). Manipulative experimentation is often the strongest method of inference when determining the effectiveness of forest treatments; however, it is costly and time-consuming to implement at a relevant spatial scale (Haddad 2012; Watts et al. 2016). With rapidly changing systems, large-scale and timely assessments are needed to support management decisions. Acute, high-intensity disturbances associated with natural events present opportunities for managers and researchers to explore how pre-disturbance treatments may impact ecosystem resiliency. Natural experiments provide information necessary to identify potential shortcomings of current strategies and better prepare for future uncertainty (McGarigal and Cushman 2002).

Forested systems in the southwestern United States are subject to multiple direct anthropogenic and climate-related threats that have impacted stand resiliency (Koprowski et al. 2005; Hatten 2014; Merrick et al. 2021). Most forests in this region are geographically isolated from each other, restricted to high elevation mountain tops separated by vast expanses of desert. The Pinaleño Mountains in the Madrean Sky Island Complex of southeastern Arizona are experiencing heightened wildfire intensity as a result of combined effects of historical wildfire suppression, increased drought, and increased temperatures (Hatten 2014). Subsequently, individual high-intensity fire events have caused landscape-level changes in vegetation community composition and structure (Cunningham et al. 2006; Goforth and Minnich 2008; Barton and Poulos 2018). Due to the isolated nature of sky islands, these drastic changes could be detrimental for wildlife species with limited dispersal capability across large stretches of highly disturbed habitat or non-habitat (Leonard and Koprowski 2010; Kostyack et al. 2011; Lawler and Olden 2011; Merrick and Koprowski 2017). To address these challenges, managers and researchers designed the Pinaleño Ecosystem Restoration Project (PERP). Signed in 2011, the objective of the PERP is to improve ecosystem sustainability by maintaining and restoring habitat for wildlife (U.S. Department of Agriculture, Forest Service 2010). Specifically, the PERP guides forest fuels treatments that will both improve habitat quality while reducing wildfire intensity potential, disease, and beetle infestation. Special management consideration is given to sensitive species in the Pinaleños, such as the Mount Graham red squirrel (*Tamiasciurus fremonti grahamensis*) and the Mexican spotted owl (*Strix occidentalis*). As part of the PERP, managers outlined mechanical thinning and fuel reduction treatments intended to improve overall forest health and resilience to natural disturbances; however, no monitoring protocols or post-action assessment guidelines have been established to determine the effectiveness of specific actions. Recent large-scale wildfires in Pinaleños provided an opportunity for researchers to assess the effectiveness of specific forest treatments for promoting forest resistance and resilience to disturbance, thereby preserving habitat for at-risk species.

In 2017, the Frye Fire burned approximately 19,000 ha of forest in the Pinaleño Mountains, including 60%

spruce-fir forest, causing drastic and widespread changes to vegetation composition and structure (Merrick et al. 2021). Within 4 years prior to the Frye Fire, managers had completed a series of mechanical overstory thinning (herein silviculture treatment) and understory fuel reduction (herein fuel treatment) treatments on 137 ha of mixed spruce-fir forest as part of the PERP. The area treated fell entirely within the perimeter of the Frye Fire. We used this as an opportunity to assess the influence of silviculture and fuel treatments made as part of the PERP on post-fire vegetation and abiotic conditions with the goal to inform future treatments pursued as part of the PERP. Specifically, we used fine-scale field measurements combined with high-resolution satellite data and light detection and ranging (LiDAR) data to assess how pre-fire forest treatments may have impacted the extent of microclimate and vegetation change by addressing three questions: (1) Do post-fire, fine-scale vegetation characteristics and microclimate conditions most associated with treated units differ from untreated forest units?, (2) Did direct post-fire tree mortality differ among treated and untreated forest units?, (3) Did treated forest units display higher post-fire resilience as compared to untreated units?

Methods

Study area

The Pinaleño Mountains are part of the Madrean Sky Island Complex in southern Arizona, USA, which includes the tallest peak in southern Arizona, Mount Graham (3270 m). Vegetation changes drastically along an abrupt elevation gradient, from low-elevation thornscrub and grassland scrub transitioning to mid-elevation Madrean evergreen woodland and high-elevation conifer forest. The high elevation zone is dominated by trembling aspen (*Populus tremuloides*), corkbark fir (*Abies lasiocarpa*), white fir (*Abies concolor*), Douglas fir (*Pseudotsuga menziesii)*, Engelmann spruce (*Picea engelmannii*), and Ponderosa and southwestern white pine (*Pinus ponderosa* and *P. strobiformis*) (Brown and Lowe 1982). Elevation within our study area ranged from 2630 to 3000 m in the high elevation zone.

Q1: Influence of forest treatment on fine-scale vegetation and microclimate conditions

The PERP designated two categories of treatment strategies: silviculture and fuel. According to the PERP, silviculture treatments included treatment of live and dead standing trees whereas fuel treatments referred to treatment of downed woody fuel (U.S. Department of Agriculture, Forest Service 2010). All silviculture treatments were accompanied by fuel treatments; however, some forest stands only received fuel treatments. Silviculture treatments included thinning of live trees < 18″ DBH or to achieve a basal area density of 150 ft^2/acre. Debris, or fuel, created by silviculture treatments was then subject to lop-and-scatter, hand cutting and piling followed by burning, or mastication and broadcasting through the understory. Whole tree removal was conducted by outside contracts; however, removal was not completed in several units prior to the Frye Fire. Fuel treatments in the absence of silviculture treatments included mortality thinning in snag pockets or live understory tree thinning < 9″ DBH. Lop-and-scatter or hand cutting and piling accompanied by burning was completed to dispose of downed woody material and debris following fuel treatments. No large live trees were cut or removed in fuel treatments. No broadcast burning was used in either treatment category prior to the Frye Fire. Silviculture treatments began in the fall of 2014 and fuel treatments began in the fall of 2012. The Frye Fire ignited in June of 2017, approximately 4 years after the first set of fuel treatments were completed.

To assess how treatment type may influence post-fire vegetation characteristics and seedling establishment, we measured fine-scale biotic and abiotic features within 30-m-diameter circular plots within the Frye Fire burn perimeter and randomly stratified among three treatment categories: (1) silviculture treatment, (2) fuel treatment, and (3) control or no prescribed treatment (Fig. 1). We measured plots in June-July 2020, 3 years post-fire. Control units included areas that fell within the planned treatment zone of the PERP but were areas that had not been treated at least 10 years prior to the Frye Fire and had not been treated following the Frye Fire. Treatments > 10 years in age display fuel loads and conditions similar to untreated units in montane conifer forests in the western U.S. (Keifer et al. 2006; Battaglia et al. 2008; Martinson and Omi 2013; Dodge et al. 2019). Consequentially, treated forest units are predicted to become less effective at reducing burn severity, or the measure of soil and organic matter loss or alteration related to fire intensity (Keeley 2009), after an estimated 10 years (Agee and Skinner 2005).

We divided plots among three categories: 18 in silviculture treatments, 19 in fuel treatments, and 20 in control units (57 total plots). Treatment and control units encompassed approximately 212 ha: 62 ha received silviculture treatments, 75 ha received fuel treatments, and 75 ha were designated as untreated (control). We placed all plots at least 60 m apart and 50 m from the nearest major road. Due to size constraints of our candidate sample area, our limited ability to sample a large number of plots at random, and potential confounding effects that may influence fire behavior and post-fire recovery, we chose to control for aspect and slope in

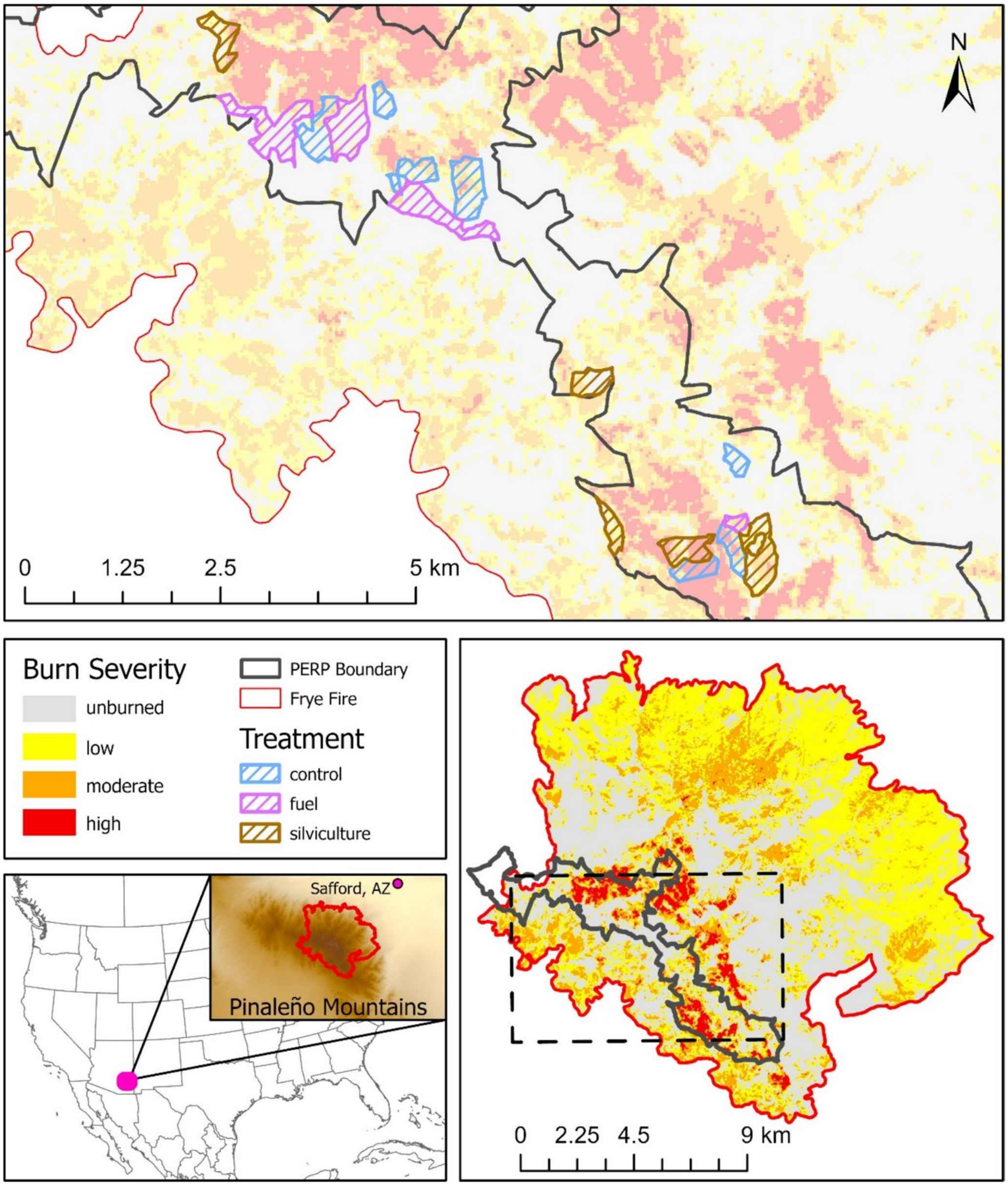

Fig. 1 Study area used in an analysis of post-fire forest composition, structure, and resilience in the Pinaleño Mountains of southeastern Arizona, USA. The bottom left image shows the location of the Pinaleño Mountains and the full perimeter of the Frye Fire (2017). The bottom right image shows the burn severity categories encompassed within the Frye Fire perimeter and the planned treatment perimeter for the Pinaleño Ecosystem Restoration Plan (PERP). The top image displays a close-up of a portion of the PERP planning area and the specific treatment zones selected for study in 2020

our plot site placement. We used 30-m resolution differenced normalized burn ratio (dNBR) indices calculated from pre- and post-fire Landsat 8 Operational Land Manager (OLI) data to classify low, moderate, and high burn severity pixels (Escuin et al. 2007). Additionally, we validated burn severity in the field using guidance from Parson et al. (2010) on char height present on tree stems and tree canopy char. We stratified sample points according to the proportional coverage of each burn severity class within our study region. Proportionately, fuel treatments received the greatest number of plots in low severity (57.9%) and silviculture treatments received the fewest (44.4%). Silviculture treatments received the greatest number of plots in moderate severity (38.9%) and fuel treatments received the fewest (21.1%). Control units received the greatest number plots in high severity

(20%) and silviculture units received the fewest (16.7%). We controlled for potential effects of aspect and slope by placing plots on similar southerly aspects (140°–242°) and lower angle slopes (5.5°–15.5°). By constraining sampling to specific aspects and slopes and by stratifying by burn severity category, we hoped to isolate features of interest (ex: forest treatment type), reduce confounding effects and make within-strata samples more homogeneous, increase statistical precision, and reduce sampling error. These methods have been used for many forest applications, including forest inventory, forest change monitoring, and burn severity analyses (Scott 1998; Miller and Quayle 2015; Gharun et al. 2017).

To examine abiotic and biotic features, we used the same circular sample plot and understory quadrat structure as Hudak et al. (2011) and Dodge et al. (2019). Each circular plot included three 10-m long transects at 45°, 165°, and 285° (adjusted for declination), two smaller interior subplots, and five 1-m^2 quadrat locations (Fig. 2). Inventoried variables included coarse woody debris, DBH of all trees ≥ 10 cm, tree regeneration, understory vegetation and abiotic composition, and microclimate conditions including soil moisture content (mV) and soil temperature. We chose these features to encompass vegetation and microclimate features thought to be important to forest resilience and wildlife species of concern as indicated within the PERP (Merrick et al. 2007; U.S. Department of Agriculture, Forest Service 2010; Singleton et al. 2021).

Presence of coarse woody debris (CWD), particularly larger downed logs, is associated with midden

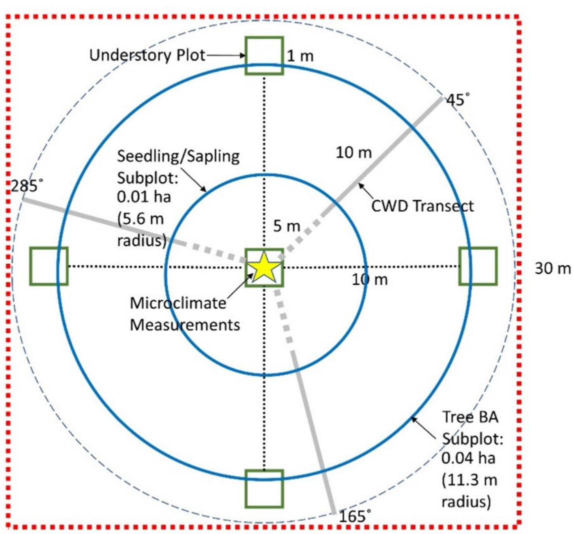

Fig. 2 Diagram of plot used to sample fine-scale forest vegetation and microclimate conditions in a study of post-fire forest resilience in the Pinaleño Mountains, Arizona, USA, 2020

occurrence for the federally endangered Mount Graham red squirrel (Smith and Mannan 1994). Nevertheless, a large amount of CWD may also be associated with overstory damage or tree die-off following extreme events (Roccaforte et al. 2012; Dodge et al. 2019). We measured CWD along three 10-m long transects (45°, 165°, and 285°) and buffered 5 m from plot center. We classified CWD as any downed log with at least 7.6 cm DBH where it crossed the transect (Woodall et al. 2010). We collected four measurements for each piece of CWD: DBH at transect intersection, DBH of both terminal ends of the same stem, and length (cm). If one piece of CWD branched or split and crossed the transect twice (example: a branching stem), we measured both branches if each met minimum size requirements. We used the equation for a truncated cone to measure volume of each CWD segment crossing a transect:

$$ {}_1 * DBH_2 + DBH_2{}^2) $$

DBH_1 and DBH_2 are the DBH of the small and large end measurements of each CWD segment, and L is the length (Ulyshen et al. 2018).

We calculated tree basal area for all live and dead standing trees ≥ 10 cm DBH within a 11.3 m radius (0.04 ha) subplot surrounding plot center. We assigned three unique snag classes to standing dead trees based on stem and canopy structure. If a snag was standing with bark mostly intact and canopy showing < 10% damage, we classified the snag as snag class 1 (later referred to as “fresh” snag). If a snag was missing large chunks of bark but still maintained structural integrity and retained some canopy structure, we assigned it to snag class 2. If a snag was leaning or otherwise lacking structural integrity or had been broken along the stem, we assigned it to snag class 3. We counted all saplings and seedlings within a smaller 5.3 m radius (0.01 ha) subplot. We defined saplings as trees on which a DBH < 10 cm could be measured. We classified any tree lacking a DBH (i.e., tree was shorter than breast height) as a seedling. We counted young aspen as true seedlings because we were unable to assess whether aspen regeneration was clonal or from seed.

We measured understory vegetation within five 1-m^2 quadrats placed in the four cardinal directions 10 m from plot center as well as at plot center. Within quadrats, we measured percent cover of all vegetation and abiotic features (woody debris, herbaceous litter, and exposed soil). If plants were dead but still rooted, we classified each by their functional group and species codes. If unrooted, we denoted plants as litter. We summarized percent cover of plants by their corresponding functional group (annual vs. perennial forbs and grasses/sedges, shrubs, and trees) rather than by unique species to avoid model overparameterization and improve model convergence. We additionally retained individual species codes to calculate Shannon diversity for both annual and perennial herbaceous plants.

We measured soil moisture and soil temperature on each plot at plot center from the date the plot was monumented through May 2021. We used HOBO MX2201 temperature sensor loggers (Onset Computer Corporation, Bourne, MA, USA) to measure soil temperature. The loggers recorded temperature every eight hours beginning at 02:00 h each day. We manually measured soil moisture once/week July–October 2020 and March–May 2021 with a SM150T soil moisture sensor (Delta-T Devices Ltd, Cambridge, England). We measured soil temperature and volumetric water content 5–7 cm below the soil surface to capture conditions relevant to tree seed germination. We calculated seasonal (spring, summer, fall, winter) averages and standard deviations from final soil temperature and moisture readings for analysis.

We used R v3.6.2 statistical software (R Core Team 2019) to complete all statistical analyses. We assessed all abiotic and biotic features measured on each plot for correlation in a correlation matrix. If the Pearson correlation coefficient between pairs was > 0.5, we retained one variable of each correlated pair for further analysis. We found three correlated pairs, including fresh snags (i.e., class 1 snags) and basal area cover of all snags, seedlings and saplings, and litter and bare ground. Of these correlated pairs, we retained fresh snags, seedlings, and bare ground. We used multinomial logistic regression to determine whether the three different treatment categories (control/no treatment, silviculture, and fuel) could be distinguished by post-fire vegetation and abiotic conditions. We used forwards and backwards stepwise variable selection to initially determine which independent variables were represented in top performing models based upon Akaike's information criteria adjusted for small sample size (Akaike 1974; Zhang 2016). We examined independent variables individually and eliminated if their 95% confidence intervals overlapped zero. We used the McFadden pseudo-R^2 approach and the Hosmer–Lemeshow goodness-of-fit test to assess model fit of our final model candidate set (McFadden 1974; Fagerland and Hosmer 2012). We additionally used leave-one-out cross-validation to assess the predictive accuracy of our models.

Q2: Influence of forest treatment on post-fire tree mortality

We used a combination of passive and active remote sensing data to assess rate of change of tree health immediately following the Frye Fire as well as 1, 2, and 3 years post-fire. We calculated the normalized difference vegetation index (NDVI) from 3-m resolution, 4-band Planetscope imagery to assess tree health (Planet Team 2021). We calculated NDVI pre-fire in October 2016 and March 2017 as well as annually post-fire in October 2017, 2018, 2019, and 2020. All analyses were conducted at the spatial scale of each delineated treatment zone (control, fuel, and silviculture), meaning we analyzed all individual trees within the bounds of all delineated treatment units.

To identify individual trees and understand tree mortality, we used airborne discrete-return light detection and ranging (LiDAR) data collected by Watershed Sciences Inc. in September 2008 pre-fire (Laes et al. 2009). The LiDAR dataset was collected using fixed wing aircraft and met the minimum recommended specifications for forest analyses, including an average point density of 7.36 points/m^2 (approximately 37 cm point spacing), sidelap greater than 50%, and a scan angle within 14° of nadir (Laes et al. 2009; Mitchell et al. 2012). We clipped and analyzed all point cloud data to the extent of the boundaries of each treatment zone as well as our pre-delineated control zones (Fig. 1). We used methods described by Dalponte and Coomes (2016) to delineate individual tree crowns. We processed all point cloud in the lidR package in program R (Roussel et al. 2020; Roussel and Auty 2021). Due to the time lag between 2008 LiDAR data collection, tree thinning treatments, and the Frye Fire in 2017, we used spatial analyses and ocular examination of pre- and post-fire satellite imagery to eliminate individual trees from analysis that may have been naturally or purposefully removed through prescribed treatments pre-fire. Our criteria for elimination included thresholds for canopy hull size, canopy height, and immediate pre-fire NDVI. We generated canopy hulls for each individually identified tree from the 2008 LiDAR dataset to represent canopy area and tree height was indicated by the highest point returns within each canopy hull. We eliminated all trees with a canopy area ≤ 9 m^2 or a height less than 24 m as measured in 2008 from further analysis. We selected these criteria based on characteristics of trees that were removed during prescribed treatments between 2008 and 2017. Additionally, we eliminated individual trees from the 2008 dataset if they had an average NDVI < 0.42 as calculated at the centroid of each canopy hull in spring of 2017 immediately pre-fire (Vanderhoof and Hawbaker 2018). Although trees with a value slightly under 0.42 may still be live trees, we designated this cut-off to reduce the likelihood of including true dead or removed trees in our pre-fire dataset.

To assess immediate post-fire impacts to stand structure, we defined tree mortality based on direct change in NDVI 3 months post-fire, final NDVI after 3 years, and average percent change in NDVI over 3 years. We calculated percent change in NDVI as net growth of NDVI between each time step, which we then averaged at the conclusion of 3 years to determine growth trends in individual trees. To be labeled as dead, trees had to simultaneously meet three criteria: (1) NDVI < 0.43 months post-fire (Brodrick and Asner 2017), (2) an average percent change in NDVI < 0% for 3 years following the fire, and (3) NDVI < 0.43 years following the fire. We considered all other individual trees that did not meet these criteria as alive. We converted these continuous new mortality data to binary by assigning a "1" to trees considered dead and a "0" to live trees. We used binomial logistic regression analysis including tree condition (alive or dead) as a response to evaluate differences in direct tree mortality among treatment categories. To account for possible effects of burn severity on mortality, we used the difference normalized burn ratio index (dNBR) in an interaction with treatment type for model predictors. We used 30-m resolution Landsat 8 OLI satellite imagery collected in March 2017 pre-fire and immediately post-fire in October of 2017 to calculate dNBR. Following guidance by Lutz et al. (2011), we split dNBR into four categories: (1) no change, (2) low severity, (3) moderate severity, and (4) high severity. Due to small sample sizes of trees within some burn severity*treatment type groupings, we consolidated burn severity levels into two groups: unburned/low severity and moderate/high severity (Dodge et al. 2019).

Q3: Influence of forest treatment on tree resilience

Forest resilience, or the ability of a forest or forest properties to persist following disturbance, can be measured in many different ways (Nikinmaa et al. 2020). In addition to measuring seedling and sapling recruitment as described above, we chose to measure forest resilience by assessing multi-year trends in post-fire canopy greenness. Using trees considered alive from our previous mortality analysis, we estimated rate of change of canopy greenness among all time steps by calculating percent growth or loss from one time step to the next. We used this calculation to summarize resilience of trees among the three treatment categories. We used rate of change in NDVI as a response variable in a linear model with treatment type, burn severity category, and time since fire as predictors. We treated treatment type, burn severity, and time since fire as a three-way interaction to compare differences in trends in NDVI as associated with groupings of these variables. We examined potential violations of model assumptions such linearity, normality of residuals, and homogeneity of residual variance by using diagnostic plots. To correct for heteroskedasticity, we log-transformed NDVI prior to analysis. Additionally, we used Cohen's *D* pairwise effect size calculations to determine if NDVI differed among treatment categories prior to the Frye Fire.

Results

Q1: Influence of forest treatment on fine-scale vegetation and microclimate conditions

We considered top-ranked models to be models that explained the greatest amount of variation using the least number of independent abiotic and biotic variables (Table 1). Four top-ranked models with a ΔAICc < 6 emerged from our analyses and included the following variables: coarse woody debris, fresh snags, herbaceous diversity, total tree seedling count, average summer soil temperature, average spring soil moisture content, and the deviation of spring soil moisture content. The highest ranked, best-fitting model included all variables except for average spring soil moisture content (Pearson's $\chi^2 = 51.38$, $p < 0.0001$; McFadden's pseudo-$R^2 = 0.51$; Table 2). Fuel and silviculture units were more likely to have higher coarse woody debris cover and higher understory herbaceous diversity as compared to control units (β: 1.99, SE: 0.77, $p = 0.01$; β: 1.87, SE: 0.93, $p = 0.04$, respectively). On average, control plots had an average of 3.81% cover of coarse woody material, whereas fuel plots had 9.34% and silviculture plots had 7.13%. Silviculture units were associated with increased total

Table 1 AICc ranked top models from a study of abiotic and biotic conditions among three different forest treatment scenarios (control/untreated, fuel, and silviculture) in the Pinaleño Mountains of southeastern Arizona 3 years following the 2017 Frye Fire. Forest treatment type was used a categorical response to understand how post-fire features differentiated among treatment categories

Model	*K*	AICc	ΔAICc	AICc Wght	Log-likelihood	McFadden pseudo R^2
CWD + fresh snags + herb diversity + seedlings + AVG summer soil temp + SD spring soil moisture	14	98.95	0	0.44	− 30.47	0.51
CWD + fresh snags + herb diversity + AVG summer soil temp + SD spring soil moisture	12	99.41	0.46	0.35	− 34.16	0.45
CWD + fresh snags + herb diversity + seedlings + AVG summer soil temp + AVG spring soil moisture	14	100.92	1.97	0.17	− 31.46	0.5
CWD + fresh snags + herb diversity + seedlings + AVG summer soil temp + SD spring soil moisture + AVG spring soil moisture	16	103.85	4.91	0.04	− 29.13	0.53

Table 2 Best fitting model describing abiotic and biotic conditions most associated with fuel and silviculture forest treatment units and in reference to control/untreated units in the Pinaleño Mountains of southeastern Arizona in the 3 years following the 2017 Frye Fire

	Fuel					Silviculture				
	Coefficient	SE	95% LL	95% UL	*p*-value	Coefficient	SE	95% LL	95% UL	*p*-value
Intercept	1.50	0.80	−0.07	3.06	0.06	0.60	0.89	−1.15	2.36	0.50
Coarse woody debris	1.99	0.78	0.46	3.51	0.01	1.87	0.93	0.05	3.68	0.04
Fresh snags	−2.24	0.94	−4.09	−0.39	0.02	−3.64	1.11	−5.80	−1.47	0.00
Herbaceous diversity	1.74	0.78	0.22	3.27	0.03	2.41	0.92	0.61	4.20	0.01
Seedling count	1.00	0.87	−0.71	2.72	0.25	2.59	1.09	0.45	4.73	0.02
AVG summer soil temp	1.31	0.78	−0.22	2.84	0.09	3.11	1.01	1.13	5.08	0.00
SD spring soil moisture	−2.21	0.87	−3.92	−0.49	0.01	−2.20	1.07	−4.29	−0.11	0.04

seedling cover (187 total across plots as compared to 133 for control plots) and higher average summer soil temperature (18.32 ± 1.71 as compared to 15.45 ± 1.90 for control plots; β: 2.59, SE: 1.09, $p = 0.02$; β: 3.11, SE: 1.01, $p = 0.002$, respectively). Although treatment type did not influence species of seedlings present, the majority of seedlings identified were aspen across our study area (percent of seedlings identified as aspen in control, fuel, and silviculture treatments, respectively: 80.45%, 78.79%, 79.21%). In total across plots, control units were associated with significantly higher basal area coverage of fresh snags (305.93 m^2/ha), whereas fuel plots contained 233.30 m^2/ha of fresh snags and silviculture plots 161.04 m^2/ha (β: −2.24, SE: 0.94, $p = 0.02$, β: −3.64, SE: 1.11 $p = 0.001$, fuel and silviculture respectively). Fuel and silviculture units also had reduced variation in spring soil moisture content as compared to control units (β: −2.21, SE: 0.87, $p = 0.01$, β: −2.2, SE: 1.07, $p = 0.04$, respectively). Results from leave-one-out cross validation indicated that the top model performed moderately well (LOOCV accuracy = 0.75, 95% CI: 0.6224–0.8587; LOOCV Kappa = 0.6306). Sensitivity (true positive rate of classification) as well as specificity (true negative rate of classification) was highest for classifying control plots (sensitivity: 0.95; specificity: 0.92), followed by silviculture plots (sensitivity: 0.67; specificity: 0.90). Fuel plots were correctly classified the least, both in terms of sensitivity and specificity (Table 3). Fuel plots were most frequently misclassified as silviculture plots ($n = 6$).

Table 3 Sensitivity, specificity, and accuracy of our top model composed of abiotic and biotic predictors to classify forest treatment type (control/untreated, fuel, and silviculture) in the Pinaleño Mountains of southeastern Arizona, USA, three years following the 2017 Frye Fire. Overall accuracy was 0.75 (95% CI: 0.62-0.86)

	Control	Fuel	Silviculture
Sensitivity	0.95	0.63	0.67
Specificity	0.92	0.82	0.90
Accuracy	0.94	0.72	0.78

Q2: Influence of forest treatment on post-fire tree mortality

Forest stands in control units had the highest overall NDVI both in October of 2016, approximately 1 year pre-fire, and in May of 2017, approximately 2 months pre-fire (mean NDVI 0.55 ± 0.04 SD); however, differences in NDVI among treatment types were not particularly strong as evidenced by pairwise effect size calculations (average Cohen's d: 0.159 ± 0.080 SD). Three months post-fire, change in NDVI as compared to exactly 1 year prior was negative for all treatment types among all levels of burn severity (unburned/low severity mean Δ NDVI: − 0.092 ± 0.070 SD; moderate/high severity mean Δ NDVI: − 0.248 ± 0.080 SD).

Fuel treatments contained the lowest percent of direct post-fire tree mortality (3.38%; Fig. 3) as compared to both silviculture (5.81%) and control units (6.40%). Additionally, increase in probability of direct mortality progressing from unburned/low burn severity to moderate/high burn severity for trees within fuel treatments was lower as compared to trees within control units (β: − 2.137, SE: 0.799, $p = 0.008$). 54.3% of post-fire tree mortality within fuel treatments occurred in unburned/low burn severity areas and 46.7% occurred in moderate/high burn severity areas. In comparison, 97.7% of post-fire tree mortality within control units occurred in moderate/high burn severity areas. As a result, control units experienced the largest positive change in probability of direct mortality progressing from unburned/low burn severity to moderate/high burn severity areas. Probability of tree mortality for silviculture treatments also experienced a positive trend moving from unburned/low burn severity to moderate/high burn severity, although this

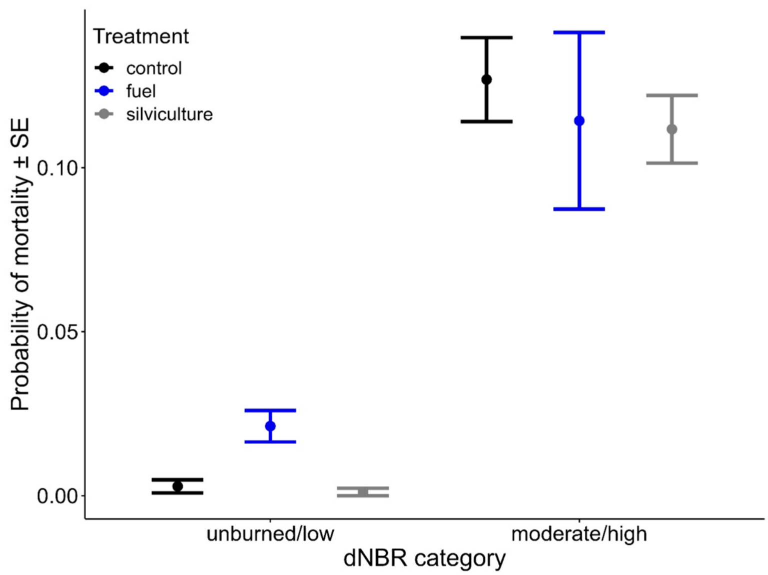

Fig. 3 Probability plus/minus standard error of tree mortality for mature trees within three months following the Frye Fire (2017) in the Pinaleño Mountains in southeastern Arizona, USA. Mortality was calculated using a combination of lidar and remotely sensed satellite imagery

trend was not significantly different from control units (β: 0.779, SE: 1.236, $p = 0.528$, with control units held as the reference category).

Q3: Influence of forest treatment on tree resilience

Fuel treatments had the lowest average percent change in NDVI over 3 years post-fire in all severity categories (5.24% ± 7.13 SD); however, fuel treatments were the only treatment category that exhibited a positive rate of change of NDVI for trees in moderate/high severity regions as compared to trees in unburned/low severity regions (average positive increase of 2.04% moving from unburned/low to moderate/high severity; Fig. 4). The rate of resilience of trees differed strongly between fuel and control treatments moving from unburned/low to moderate/high severity (β: 0.023, SE: 0.011, $p = 0.03$). Nevertheless, fuel and silviculture treatments experienced lower NDVI values overall as compared to control units (β: −0.140, SE: 0.010, $p < 0.001$; β: −0.081, SE: 0.010, $p < 0.001$, respectively). Recovery in silviculture treatments did not differ from control units.

Discussion

Our results demonstrate that current silvicultural and fuel reduction treatments in the Pinaleño Mountains have mixed results in influencing key abiotic and biotic characteristics of forests post-fire as well as reducing post-fire tree mortality and promoting forest resilience. Both fuel and silviculture treatments were associated with increasing coarse woody debris cover, greater herbaceous diversity, and higher variation in spring soil moisture as compared to forest units that did not receive pre-fire treatment. Direct mortality was reduced in fuel treatments as compared to both silviculture and control units. Additionally, fuel treatments displayed a positive rate of change in NDVI moving unburned/low to moderate/high burn severity areas. Silviculture treatments did not differ significantly from control units for either post-fire tree mortality or percent change in NDVI. Prescribed forest management strategies are commonly used to improve forest health and decrease susceptibility to high-intensity wildfire, disease, and pest outbreaks (Hudak et al. 2011). Whether treatments are effective at achieving these goals requires further examination, however, because climate change is altering what we know about the impacts of disturbances on forests and the ability of forests to recover from perturbations (Johnstone et al. 2016; Hörl et al. 2020).

Understory vegetation composition can be a strong signal of healthy functioning forest ecosystems and an early indicator of forest recovery post-disturbance (Zhang et al. 2016). Structurally and compositionally diverse understory vegetation communities can provide cover to facilitate tree seedling growth and provide both forage and shelter for numerous wildlife species (Coppeto et al. 2006). In our study, forest units that received either silviculture or fuel treatments were associated with greater understory herbaceous diversity in comparison to control units. Thinning treatments are known to have a positive effect on understory vegetation richness and diversity by allowing more sunlight to infiltrate to the forest floor (Stephens et al. 2012b). Low-intensity fire or prescribed fire that exposes mineral soil after thinning treatments

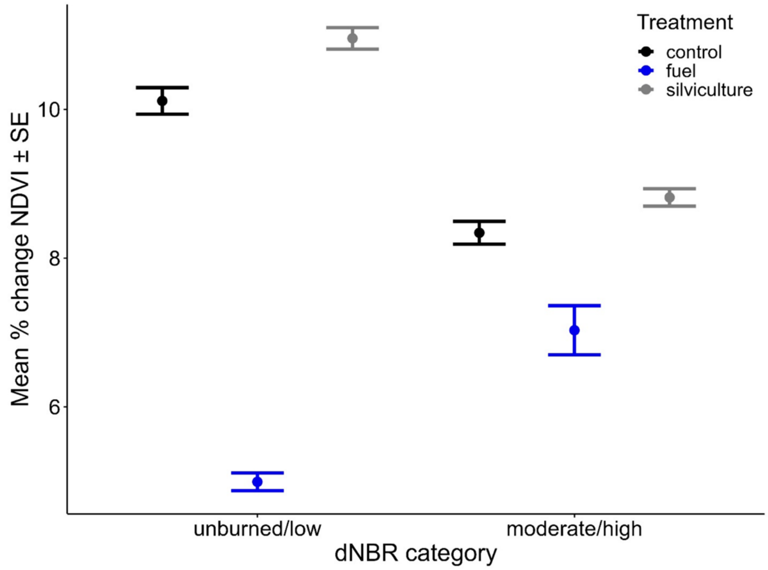

Fig. 4 Mean percent change plus/minus standard error in individual tree greenness (normalized difference vegetation index: NDVI) from October 2017 following the Frye Fire to October 2020 and associated with burn severity in the Pinaleño Mountains in southeastern Arizona, USA. These values were used as measure of forest resilience, with lower rates indicating slower rates of recovery for individual trees

also encourages understory vegetation establishment (Kane et al. 2010). Nevertheless, if fire is too severe or frequent, key physical and biological soil properties may be lost or altered, negatively impacting post-fire herbaceous and tree seedling recruitment (McLauchlan et al. 2014; Agbeshie et al. 2022).

Reduced tree seedling recruitment associated with stand-replacing, high-intensity wildfire can lead to complete shifts in vegetation community composition and structure (Johnstone et al. 2016; Davis et al. 2019; Davis et al. 2020, Singleton et al. 2021). Seedling recruitment was low overall throughout our study area and treated units had mixed results for seedling density as compared to control units. Silviculture units had slightly higher seedling regeneration, whereas fuel and control units did not differ. Additionally, the majority of seedlings were aspen as opposed to the conifer species that dominated the forest canopy pre-fire (Carlson et al. 2020). Aspen resprout readily after fire and may become more prominent in areas experiencing increasing mean high summer temperatures (Elliott and Baker 2004; Kreider and Yocom 2021). In our study area, soil characteristics to support seed germination and seedling establishment differed among treatment types. Both fuel and silviculture treatment units had decreased variability in spring soil moisture content, and average summer soil temperature was higher in silviculture units as compared to control units, indicating overall drier soil conditions in silviculture units. Other studies have demonstrated that increasing soil temperatures, particularly on southerly facing slopes, and decreased growing season soil moisture content negatively impacts the probability of conifer seedling reestablishment (Chambers et al. 2016; Andrus et al. 2018; Carlson et al. 2020). Overtime, severe wildfire coupled with increasing temperatures and decreasing precipitation may result in an overall upslope shift of conifer to more suitable microclimate and habitat conditions (Conlisk et al. 2017; Carlson et al. 2020). In the Pinaleños, however, the isolated and restricted size of the mountain range prohibits either range shifts or expansion of conifer forest in response to changing climate conditions (O'Connor et al. 2014). Aspen regeneration may serve as a structural replacement for conifers in some locations in the Pinaleños; however, they play a very different functional role in forested systems, which could have widespread implications for several wildlife species, particularly conifer-dependent, sensitive wildlife species (Andrus et al. 2021).

In addition to reduced conifer establishment, direct tree mortality associated with wildfire and changing climatic factors remain dominant threats to the persistence of mature conifer forests worldwide (Allen et al. 2010). Results from our study indicate that direct tree mortality was reduced in areas that received understory fuel reduction treatments. Additionally, in fuel treatments, the rate of post-fire recovery of trees increased from unburned/low burn severity to moderate/high burn severity areas. Other studies have also suggested that forest treatments, particularly fuel treatments, can be beneficial for post-fire tree resilience (Prichard et al. 2010; Dodge et al. 2019). Although we found beneficial impacts of fuels treatments, we did not find differences between overstory silviculture treatments and control units for probability of direct mortality nor rate of recovery. This is contrary to other studies that suggest positive impacts of overstory silviculture treatments in buffering trees from direct mortality in the presence of moderate/high severity fires (Prichard et al. 2010; Hudak et al. 2011; Stephens et al. 2012a). One possible explanation may be the residual presence of post-treatment slash and wood chips in the understory prior to the fire that could have contributed to a higher fuel load and therefore higher fire intensity (Dodge et al. 2019). Masticating or mulching and distributing wood chips is often used to accelerate the decomposition of woody debris left over from silviculture treatments (Walker et al. 2011). In sites that are dry or projected to become drier with climate change, however, this decomposition process may no longer be effective and may influence future wildfire behavior by increasing continuous surface fuel loads (Battaglia et al. 2010).

Forest management plans often highlight conservation strategies for sensitive species (Holbrook et al. 2019); however, traditional treatment strategies targeted to reduce forest susceptibility to high-intensity wildfire and other threats may be at odds with habitat requirements for some wildlife species (Stephens et al. 2014; Moriarty et al. 2016). For old growth forest obligate wildlife species, altering certain characteristics of forest structure or composition may negatively impact existing populations by temporarily or permanently reducing the amount of high-quality habitat (Stephens et al. 2014; Tempel et al. 2014). When designing treatment strategies in the Pinaleños, special consideration was given to sensitive wildlife species, in particular the Mount Graham red squirrel (*Tamiasciurus fremonti grahamensis*) and the Mexican spotted owl (*Strix occidentalis*). Mount Graham red squirrels use snags for nesting and downed coarse woody debris to cache cones and build midden structures (Merrick et al. 2007). Our results indicate that both fuel and silviculture treatments were associated with reduced prevalence of fresh snags and increased prevalence of coarse woody debris, suggesting mixed results in terms of potential habitat quality for these sensitive species. Structural features such as snags and coarse woody debris are often associated with mature or old-growth spruce-fir forests, which have long been considered potential areas of refugia from changing climatic and disturbance regimes (Lesmeister et al. 2019). Nevertheless, recent wildfire activity in the Pinaleños has demonstrated that mature forests experiencing increasing temperatures and drought can be vulnerable to high-intensity wildfire (Merrick et al. 2021). Features such as snags and coarse woody debris that may be advantageous to wildlife in mature forests could pose future high-intensity wildfire risk, leading to complete loss of habitat (Passovoy and Fulé 2006; Roccaforte et al. 2012). Conserving old growth forest features important to obligate species while simultaneously reducing potential for large-scale habitat conversion caused by severe disturbance, such as wildfire, is a burgeoning issue in mature forests experiencing drastic change (Holafsky et al. 2020).

Conclusions

Our results suggest that silvicultural and fuel reduction treatments can influence forest vegetation composition, structure, and resilience following wildfire. Differences in coarse woody debris, fresh snags, herbaceous diversity, tree seedling count, average summer soil temperature, and variation in spring soil moisture content were strong plot-level indicators of treatment type post-fire. In particular, fuel treatments had decreased occurrence of fresh snags, greater abundance of coarse woody debris, and greater herbaceous diversity as compared to control plots. Silviculture plots also had decreased prevalence of fresh snags, increased coarse woody debris, increased herbaceous diversity, and increased seedling cover. Our top model had strong predictive accuracy, indicating predictor variables distinguished treatment types well. At the level of individual trees, change in probability of direct mortality was reduced from unburned/low to moderate/high severity categories and recovery rate was higher in fuel treatments as compared to control plots in burned areas. In contrast, change in probability of mortality or rate of recovery did not differ between silviculture and control plots. Although rate of recovery may be higher for fuel treatments, NDVI still remained lower overall in comparison to control units. This extended period of reduced NDVI and decreased prevalence of fresh snags within treated areas may have negative implications for sensitive wildlife species that occur in old-growth forests (Tempel et al. 2014).

Our results demonstrate the effectiveness of forest management strategies, in particular understory fuel reduction treatments, in reducing the direct and short-term impacts of wildfire. Nevertheless, results were mixed, highlighting the importance of consistent monitoring of previous treatments to inform future management decisions (Nagel et al. 2017). Changing disturbance regimes create a moving target which is difficult to plan for and respond to (Stein et al. 2013). Monitoring treatment effectiveness with repeated surveys will be essential to ensure treatments are appropriate to increase resilience in a changing climate and are not negatively impacting occurrence of sensitive species for which they were designed.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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Authors' contributions

K.L. Hefty applied for project funding, designed the research, implemented the research, conducted the analyses, and wrote the final manuscript. J.K. Gillan provided LiDAR analysis support and datasets. J. Trejo provided field access, data, and guidance, J.L. Koprowski provided partial project funding, access permits, field support, mentorship, and editing support.

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Data availability

Data will be made available through Fire Ecology's open-access format with links to our data and code within an open access data repository.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Aldo Leopold Wilderness Research Institute, 790 E. Beckwith Avenue, Missoula, MT 59801, USA. [2]Data Science Institute, University of Arizona, 1657 E Helen St, Tucson, AZ 85719, USA. [3]United States Forest Service, Coronado National Forest, 711 South 14th Ave Suite D, Safford, AZ 85546, USA. [4]Haub School of Environment and Natural Resources, University of Wyoming, 201 Bim Kendall House 804 E Fremont St, Laramie, WY 82072, USA.

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