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FIELD NOTE

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How forest management changed the course of the Washburn fire and the fate of Yosemite's giant sequoias (*Sequoiadendron giganteum*)

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Abstract

Background The Washburn fire started on July 7, 2022 in the lower Mariposa Grove in Yosemite National Park, posing immediate threats to the iconic giant sequoias (*Sequoiadendron giganteum*), critical Pacific fisher (*Pekania pennanti*) habitat, and the community of Wawona. The wildfire quickly gained national attention and the public followed Yosemite's firefighting efforts closely. In the aftermath of the Washburn fire, we evaluate how decades of fire management and recent roadside thinning in the Park shaped the tactics and outcomes of this wildfire. Fuels reduction and prescribed fire have been at the core of Yosemite's fire management program since the 1970s and much of this activity has been concentrated in the two areas where firefighting operations were most successful in protecting key resources. We use long-term fire effects monitoring data, airborne light detection and ranging data, and operational perspectives to link together science, management, and fire operations.

Results Successful initial attack and suppression efforts kept fire out of the Mariposa Grove and the community, where topography and the distribution of heavy fuels largely drove fire behavior throughout the course of the fire. We demonstrate the cumulative effects of decades of fuels treatments in reducing two major drivers of fire behavior – tree density and fuel load – and highlight substantially lower ladder fuels and fire severity in treatment units compared to untreated areas within the Washburn fire footprint.

Conclusions We show how repeated prescribed fire and fuels treatments can promote forest structure indicative of frequent-fire regimes, moderate extreme fire behavior, improve the ability to protect key resources of concern, and increase human safety in the face of unplanned wildfire. Strategically placed prescribed fire and fuels treatments surrounding the Washburn fire were key considerations in wildfire suppression tactics and were instrumental in protecting the Mariposa Grove.

Keywords Prescribed fire, Fuels treatments, Thinning, Wildfire, Suppression, Washburn fire, Mariposa Grove, Yosemite National Park, Mixed conifer

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Resumen

Antecedentes El incendio de Washburn comenzó el 7 de julio de 2022 en la llamada baja arboleda Mariposa en el Parque Nacional Yosemite, poniendo en riesgo inmediato a las icónicas sequoias gigantes (*Sequoiadendron giganteum*), al mamífero carnívoro marta pescadora, y a la comunidad de Wawona. Este incendio ganó rápidamente la atención a nivel nacional, y el público en general siguió con atención y cercanía los esfuerzos del combate de este incendio. En las postrimerías del incendio de Washburn, evaluamos cómo décadas de manejo del fuego y el raleo en las banquinas de las rutas del parque modelaron las tácticas y resultados de este incendio. La reducción de los combustibles y las quemas prescriptas han estado en el corazón de los programas de manejo del fuego en el parque Yosemite desde los años ´70 s, y mucha de esta actividad fue concentrada en dos áreas donde las operaciones de combate fueron más exitosas en proteger recursos clave. Usamos datos de monitoreo de efectos del fuego en el largo plazo, datos obtenidos por la tecnología LIDAR (*airborne light detection and ranging data*), y perspectivas operacionales para ligar en conjunto la ciencia, el manejo y las operaciones en incendios.

Resultados El ataque inicial exitoso y los esfuerzos en la supresión, impidieron que el fuego llegue a la arboleda Mariposa y a la comunidad, donde la topografía y la distribución de los combustibles pesados condujo mayoritariamente el comportamiento del fuego durante el transcurso del incendio. Demostramos los efectos acumulativos de décadas de tratamientos que buscaban reducir los mayores conductores del comportamiento del fuego (la densidad de los rodales y la carga de combustible), subrayando especialmente las menores escaleras de combustible y baja severidad del fuego en las unidades tratadas relacionadas con las no tratadas dentro de la huella que dejó el incendio de Washburn.

Conclusiones Mostramos cómo quemas prescriptas repetidas y tratamientos de combustibles, pueden promover una estructura forestal indicativa de regímenes de fuegos frecuentes, moderar fuegos extremos, mejorar la posibilidad de proteger recursos de importancia, e incrementar la seguridad humana en caso de un incendio no planificado. Las quemas prescriptas estratégicamente planificadas y el tratamiento de combustibles que rodearon al incendio de Washburn fueron consideraciones clave en las tácticas de supresión y fueron instrumentales para proteger la arboleda Mariposa.

Background

Hotter temperatures, prolonged drought and the abundance of dead and downed wood across the Sierra Nevada have led to uncharacteristically large, intense wildfires in recent decades (McKelvey et al. 1996; Hagmann et al. 2021). These fires displace and threaten communities and can exceed the resistance and resilience mechanisms of wildlife and plant populations (e.g. Jones et al. 2021; Shive et al. 2022). During the past five years, approximately 20 percent of the entire population of endemic mature giant sequoias (*Sequoiadendron giganteum*) in the Sierra Nevada have been lost (Shive et al. 2022; Stephenson et al. 2021). A century of fire suppression in the Sierra Nevada has led to forest conditions with greater tree densities, fuel loads, and proportion of shade-tolerant tree species than pre-settlement conditions (Collins et al. 2011; Knapp et al. 2013; Stephens et al. 2015). These forest conditions can increase rates and size of high-severity fire (Steel et al. 2015; Stephens et al. 2015; Boisramé et al. 2017). Higher tree densities have also been associated with reduced forest health (Hankin and Anderson 2022) and widespread bark beetle-induced tree mortality (Fettig et al. 2007). Historical forest structure created and maintained by frequent lightning ignitions and Indigenous burning promoted ecosystem resilience by minimizing competition and resisting high-severity wildfire (North et al. 2022). Active fuels management, primarily thinning and prescribed fire, are effective tools to restore forest conditions that limit the spread of large, high-severity wildfires and maintain natural ecosystem processes (Fulé et al. 2012; Restaino et al. 2019; North et al. 2021).

For forests with historically frequent fire regimes (e.g. mixed-conifer, giant sequoia, ponderosa pine (*Pinus ponderosa*)), reducing forest density through mechanical fuel treatments and prescribed fire can prevent high-severity fire and restore natural ecosystem processes (Stephens et al. 2013). Fuel treatments and previous burn footprints are effective barriers to the spread and probability of high-severity fire (Collins et al. 2010; Lydersen et al. 2017; Cansler et al. 2022). Mechanical thinning treatments followed by prescribed fire effectively reduce surface fuel loads, fireline intensities, the likelihood of passive and active crown fire, and retain larger trees through increased stand resistance (Pollet and Omi 2002, Stephens and Moghaddas 2005, Stephens et al. 2009, Fule et al. 2012). For example, the largest fire in Yosemite National Park history, the 2013 Rim Fire, had significantly lower proportions of high-severity fire in areas with previous fuels treatments or were burned by

low- to moderate-severity fire (Lydersen et al. 2017), limiting negative impacts of plume-dominated wildfire. These reductions in fire intensity increase human safety and allow for more effective firefighting in the wildland-urban interface. Beyond moderating fire behavior, restoration thinning and prescribed fire treatments provide numerous co-benefits (Stephens et al. 2020). Associated increases in soil moisture have been shown to significantly increase dead woody debris fuel moisture content and shorten fire seasons (Rakhmatulina et al. 2021). Furthermore, treatments have been shown to enhance biodiversity, increase water availability, increase long-term carbon storage stability (Krofcheck et al. 2017), and improve forest resilience to beetles, and drought (Churchill et al. 2013; Young et al. 2017).

Like much of the Sierra Nevada, Yosemite's mixed-conifer forests are dense with ladder fuels and dead biomass after a century of fire suppression and the recent severe drought and bark beetle outbreaks. These fuel conditions pose significant risks to the Park's communities and numerous natural resources. Strategically-placed prescribed fire and other fuels reduction treatments have been implemented in Yosemite to achieve protection and resource objectives, particularly in the wildland-urban interface and surrounding the Park's giant sequoia groves. By reducing heavy fuel loads and removing abundant dead biomass, the Park can create more resilient communities and landscapes to ongoing climatic change and increasing fire activity. Prescribed fire is the primary tool for reducing fire risk, however, fuel conditions in some areas of the Park require significant preparation prior to first-entry burning to meet objectives of firefighter safety and ecological benefit. This need has increased with expanding drought- and bark beetle-caused tree mortality. Thinning and brush removal are therefore important components to the fire management program to allow for safe prescribed burning implementation. Recent roadside thinning projects using mechanical biomass removal have greatly increased the Park's capacity for prescribed burn projects. Furthermore, reducing tree densities and surface fuel loads along roadways maintain safe evacuation routes, increase firefighter safety by creating significant fuel breaks, and allow for suppression tactics such as backfire operations. This proactive management strategy facilitates more effective resource management and wildfire suppression in the face of longer fire seasons, hotter temperatures and associated drought, and rapidly changing fuel conditions.

While research has demonstrated the effectiveness of fuels treatments such as thinning and prescribed fire in moderating fire behavior and reducing the risk of large, catastrophic fire, there are few opportunities to directly link historical and contemporary fuels treatments to unplanned wildfire operations and outcomes (but see Moghaddas and Craggs 2007). In July 2022, the Washburn fire started in Yosemite National Park in a location immediately threatening the Park's largest giant sequoia grove, critical habitat for the threatened Pacific fisher (*Pekania pennanti*), and the community of Wawona. It was also an area with a rich history of fuels treatments and prescribed fire surrounding these highly valued natural resources, therefore the Washburn fire presented an opportunity to evaluate the direct impact of a long-term fire management program. Here, we join together historical fuels treatments, recent biomass removal operations, and an unplanned wildfire in Yosemite National Park to highlight how fuels treatments influenced decisions and tactics for the Washburn fire—a wildfire with a full suppression response, and significantly impacted successful protection of the Mariposa Grove of Giant Sequoias and the community of Wawona. We addressed the following questions: a) did forest conditions vary between forested areas with historical and contemporary fuels treatments compared to untreated areas of southern Yosemite National Park? b) did fuels treatments alter fire behavior and fire severity? and c) how did fuels treatments influence operational decisions and firefighting tactics on the Washburn fire? First, we provide background and data on the use of prescribed fire and thinning treatments in the areas surrounding the Washburn fire, second, we use airborne LiDAR data to highlight forest structure differences between these treatment areas and the footprint of the Washburn fire, and third, we discuss how this treatment history influenced the outcome of the Washburn fire.

Methods

Study area

Yosemite National Park is located in the central Sierra Nevada of California and encompasses over 307,156 hectares, 94% of which is designated Wilderness. The Park extends from low-elevation dry forests and chaparral to high-elevation subalpine forests and granitic peaks. The climate is Mediterranean, with hot, dry summers and cold, snowy winters. Numerous natural and cultural resources exist within the Park, including habitat for the threatened Pacific fisher, spotted owl (*Strix occidentalis*) and Great gray owl (*Strix nebulosa*), and sensitive amphibians, giant sequoias, and abundant archaeological sites. Fire has a strong influence on these Park resources and shapes the configuration and composition of Yosemite's forests. Lightning strikes are pervasive throughout the Park and ignite numerous fires each year (Van Wagtendonk 1994, van Wagtendonk and Davis 2010). Both from lightning and cultural burning, fire has historically occurred in all vegetation types in the Park (excluding the

high-elevation alpine zone), however fire was excluded from much of the Park from the late 19th to mid-twentieth century. Consequently, early researchers in the Park identified an issue of abundant fuels and unnaturally dense forests within Yosemite, posing risks to valued resources such as the Mariposa Grove of Giant Sequoias, and nearby communities (Kilgore 1972; Biswell 1999; Van Wagtendonk 2007).

Managing natural lightning ignitions for multiple objectives and prescribed fire have been a part of the fire management program since the early 1970s (Stephens et al. 2021). In many areas, abundant high elevation granite, the lack of access, and minimal threats to human infrastructure allow for fire management strategies such as confine and contain or monitor with no direct suppression. Much of the forest remains departed from natural fire return intervals, however, resulting in abundant fuels across the landscape (Scholl and Taylor 2010, NPS [National Park Service] 2022). Management interventions are therefore necessary to reduce fire hazard and the threat of large, catastrophic wildfire, protect life and property, and prevent negative ecological outcomes that result from fire behavior outside of the natural range of variability.

The Mariposa Grove of Giant Sequoias is the largest sequoia grove within Yosemite National Park and is home to over 500 mature giant sequoias. The Mariposa Grove holds significance for the origins of natural land protection. The Grove was at the center of the national park idea as the first natural area protected in perpetuity for its scenic and recreational value, designated by President Lincoln in 1864. The Mariposa Grove has a rich history of natural and prescribed fire, with fires dating back to 450 C.E. (Biswell 1961) and occurring frequently (every 1–15 years, Swetnam et al. 1990). The Mariposa Grove was one of the first areas of Yosemite to be treated as part of its prescribed fire program (Figs. 1 and 2) and remains a focal area for Yosemite fire and fuels management. Over 1,821 hectares have been treated by prescribed fire in the Mariposa Grove and surrounding areas near the community of Wawona since 1970, targeting small-diameter shade-tolerant trees and heavy dead and downed fuels to promote healthy forest conditions and giant sequoia regeneration (Kilgore 1972; Shive et al. 2018).

The Washburn fire

The Washburn fire started on July 7, 2022, in the lower Mariposa Grove in Yosemite National Park (Fig. 1) posing immediate threats to the iconic giant sequoias and the community of Wawona. The fire quickly gained national attention. Successful initial attack and suppression efforts kept fire out of the Mariposa Grove and the community of Wawona, but the surrounding topography and distribution of heavy fuels drove intense fire behavior and rapid fire spread. Regional fire activity was low, therefore, abundant resources were available for suppression efforts. A Type II Incident Management Team transitioned onto the Washburn fire on July 9th. In the first two days, the Washburn fire grew to 737 hectares and increased to 1846 hectares by July 14th. There was limited fire spread throughout the next two weeks, with total fire size reported as 1977 hectares.

Operational objectives included keeping the fire to as small a footprint as possible and limiting fire spread towards the community of Wawona, Wawona Road, Yosemite's southern entrance station, the Mariposa

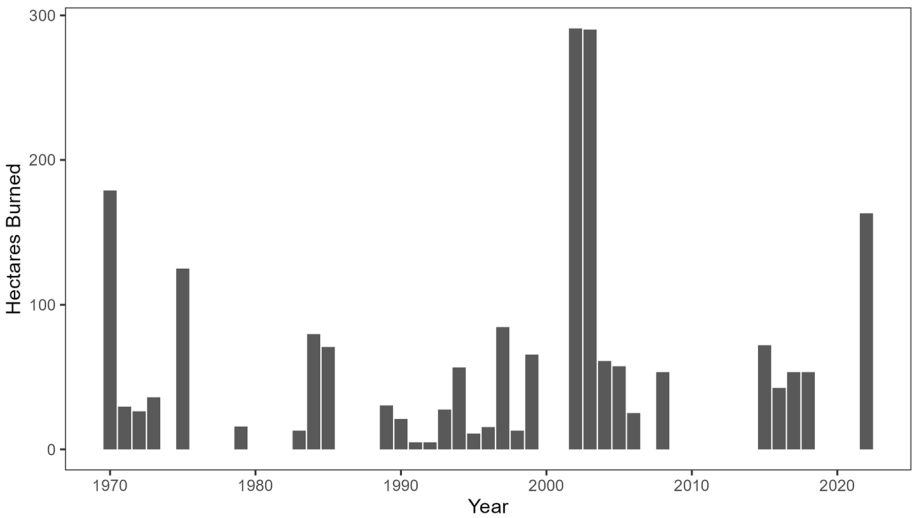

Fig. 1 History of prescribed fire treatments in the Mariposa Grove and surrounding the community of Wawona from NPS fire history records (NPS Datastore). Treatments typically included handpiling and burning, jackpot burning, or broadcast burning under favorable weather conditions

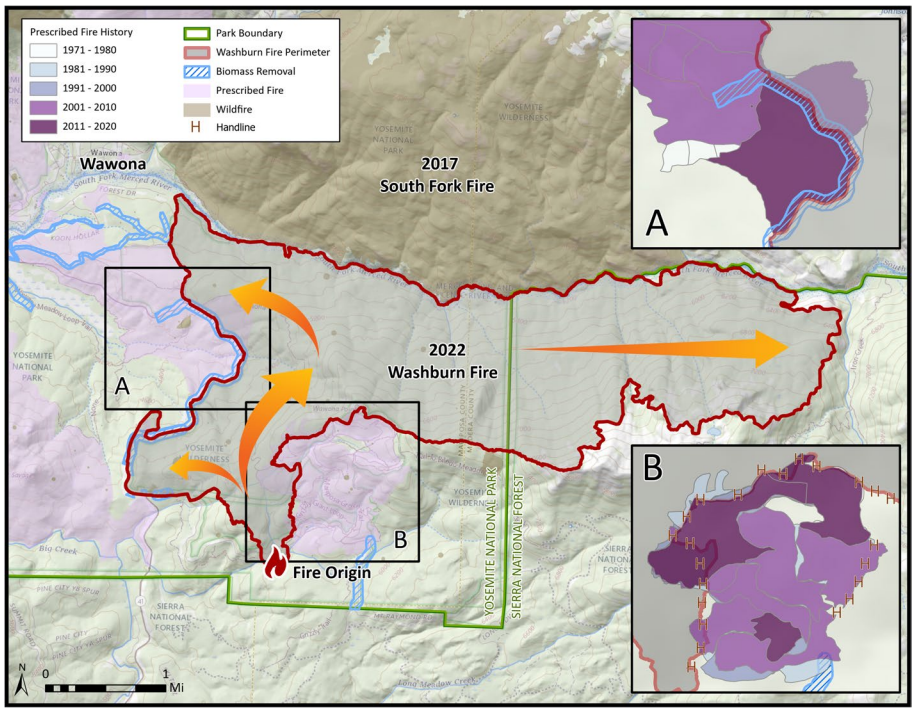

Fig. 2 Washburn Fire perimeter with origin and arrows showing fire progression. Purple graduated shading shows prescribed fire history in the Wawona area (inset A) and Mariposa Grove (inset B). The fire was also bounded by the 2017 South Fork wildfire along its north perimeter and historical prescribed fires along the western perimeter

Grove, and the administrative boundary with Sierra National Forest. Numerous values were at risk as the Washburn fire progressed. The fire started at the southwest corner of the Mariposa Grove, where it could move uphill rapidly into the grove and threaten its hundreds of mature trees. The Grove is also home to numerous wildlife species, the Galen Clark historical cabin, and significant cultural sites. The Washburn fire burned entirely within critical habitat for the threatened Pacific fisher. Furthermore, dense and steep forested terrain stood between the Mariposa Grove and the community of Wawona, prompting evacuations of employees and private residents. Power and communications infrastructure were in close proximity to the fire.

The Washburn fire burned rapidly through steep terrain without any known fire history, characterized by abundant dead and downed fuels and dense ladder fuels. These forest conditions are the legacy of almost a century of fire suppression and the horizontal and vertical fuel continuity facilitated rapid fire spread, intense fire behavior, and high resistance to control. Furthermore, conditions were already hot and dry relatively early in the fire season, with Energy Release Components ranging (ERC) from the 90th to 97th percentile in the first two weeks of July. The combination of abundant fuels and conducive weather (approx. 30 °C at 1524 m elevation and 19–31% humidity, Wawona RAWS station) led to a few days of explosive fire growth and continued active burning overnight with little humidity recovery.

Fire and fuels management

As part of the Yosemite prescribed fire and fuels management program, fire effects monitoring data has been collected surrounding treatment events in the Mariposa Grove and the community of Wawona since 1990. The fire effects monitoring program has followed protocols established by the National Park Service Fire Monitoring Handbook (USDI National Park Service 2003) and collects data such as forest structure and composition, fuel load, and burn severity to track long-term treatment effects and facilitate adaptive management. This decades-long record of forest conditions highlights important changes facilitated by prescribed fire and demonstrates the effectiveness of these fuel treatments in achieving management objectives such as fire hazard reduction and forest health.

We used long-term fire effects data maintained in the FEAT-FIREMON database from 15 plots in the Mariposa Grove and 16 plots in the area surrounding Wawona. Some aspects of the sampling protocols have been changed over the period of record, therefore, we selected

tree density, basal area (i.e. cross-sectional area of live trees), and fuel load as informative and consistent metrics of forest condition and metrics frequently targeted by managers for treatment objectives. We used linear models to evaluate the relationship between these metrics and time. All analyses were performed in R (R Core Team 2021).

We used high-density return airborne LiDAR to compare forest structure between the forests within the Washburn fire footprint and those with a history of prescribed fire (i.e. Mariposa Grove and Wawona area). LiDAR-derived data layers were produced for Yosemite National Park as part of the California LiDAR project's southwest pilot area in collaboration with the U.S. Geological Survey's 3DEP program (collected 10/07/2019 – 10/23/2019). LiDAR metrics were developed according to methods outlined in Chamberlin et al. (2021), and here, we use post-processed canopy cover metrics and tree approximate objects ("TAOs", hereafter, "tree density"). TAOs may not represent true individual trees but rather include one dominant tree as well as several subdominant trees due to detection of interlocking crowns during the LiDAR point cloud segmentation process (Jeronimo et al. 2018). TAOs considered here represent both live and dead canopy. We tested differences in canopy cover by each height stratum between the Washburn fire and surrounding fuels treatment areas with t-tests ($\alpha = 0.05$).

To assist in wildfire preparedness and facilitate protection of human life, property, and natural and cultural resources, Yosemite has implemented roadside biomass removal along its major road corridors in 2021 and 2022. The roadside biomass removal projects aim to reduce horizontal and vertical fuel continuity within 61 m (200 feet) of roads to strengthen important fuel breaks and moderate fire behavior along roads, thus increasing firefighter safety and facilitating safer evacuation procedures should a wildfire occur (Fig. 2). These projects mechanically remove trees up to 0.51 m in diameter and hazard trees killed by fire, insects, and drought. The biomass removal projects have treated 185 ha and removed approximately 4851 metric tons of fuel since its start in 2020.

Fire behavior and operations

We conducted informal interviews with fire operations personnel on the Washburn fire and consulted published decisions from the Wildland Fire Decision Support System (WFDSS) to evaluate protection priorities, values at risk, tactical and strategic decisions, and fire behavior. Operations personnel described fire behavior in treated areas where suppression resources were placed and shifts in fire behavior upon reaching untreated areas. WFDSS decisions were published weekly during the incident and address considerations for incident management, such as weather, fire behavior, natural and cultural resource and socioeconomic values, and resource availability for suppression tactics.

We evaluated change in vegetation as a proxy for fire severity within and outside treated areas using pre- and post-fire satellite imagery (Planet Labs PBC). We calculated the difference in normalized difference vegetation index values (dNDVI) before (October 17, 2021) and after (October 16, 2022) the Washburn fire. We then compared dNVDI between treated and untreated areas using a Student's t-test.

Results

Fire and fuels management

We found that in the Mariposa Grove, live tree density (> 10 cm diameter at breast height) and basal area per hectare decreased over three decades of prescribed fire treatments (Fig. 3), although these trends were not statistically significant ($p > 0.05$, Table 1). Live tree density in the Wawona area decreased significantly over time ($p = 0.01$), yet basal area per acre remained constant over the same treatment history ($p = 0.83$). Prescribed fire treatments were effective at significantly reducing fine woody debris over shorter timescales ($p = 0.002$, $p = 0.044$ for 1- and 2-year post-fire, respectively), however recovery of pre-treatment fine woody debris occurs within five years of a treatment ($p > 0.05$, Fig. 4).

LiDAR-derived canopy cover data indicate that the untreated Washburn fire footprint and surrounding treated areas did not differ significantly in overstory tree cover or surface cover ($p > 0.05$), but canopy cover from 2 to 16 m in height (i.e. ladder fuels) were significantly different between the two areas ($p < 0.05$ for each height stratum, Fig. 5). Ladder fuels were substantially lower in the treated areas, where decades of fuels treatments have been implemented. In contrast, the majority of the Washburn fire footprint had no recent fire history, and thus substantially denser forest conditions. Lidar-derived tree density was also much higher within the Washburn footprint, with an average of 135 trees per hectare compared to 104 and 99 trees per hectare in the treated Mariposa Grove and the Wawona area, respectively.

Fire behavior and operations

Fire operations personnel witnessed extreme fire behavior during initial attack (pers. comm. P. Bevington). In the first operational period, tree torching from the point of ignition was casting embers long distances to ignite spot fires mid-slope, deep within an untreated forested area with limited fire history. These spot fires quickly developed into head fire running upslope and exhibited extreme fire behavior, with short crown runs and flame

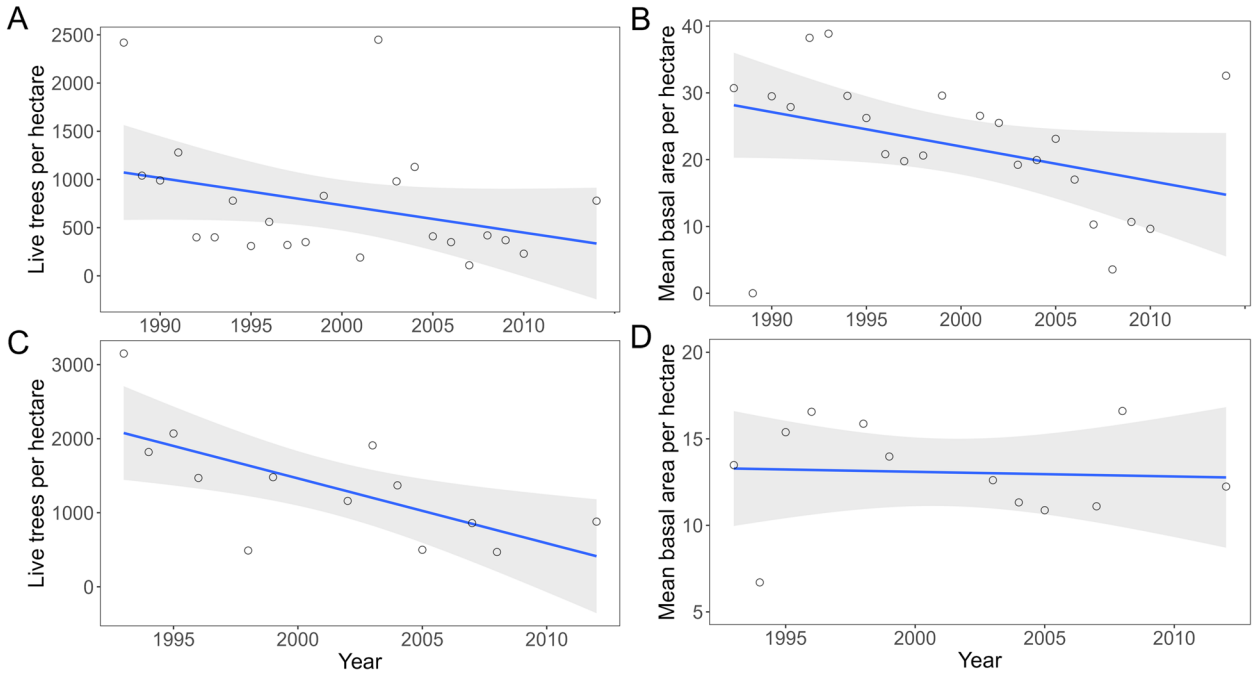

Fig. 3 Live trees per hectare (**a**, **c**) and basal area (cross-sectional area of a tree, in square meters) per hectare (**b**, **d**) over time in Mariposa grove (**a**, **b**) and the Wawona area (**c**, **d**), where decades of fuels and fire management (primarily prescribed fire) have occurred. Larger trees contribute more basal area, thus the Wawona area highlights the focus on removal of small-diameter trees. Data are from long-term monitoring plots as part of the Yosemite fire effects monitoring program

Table 1 Model results from linear models predicting live tree density (per hectare) and basal area (square meters per hectare) as a function of year. Individual models were specified for data from the Mariposa grove and Wawona

Model	Slope	t-value	*p*-value	R-squared
Mariposa Grove				
Live tree density ~ Year	-28.34	-1.64	0.12	0.11
Basal area ~ Year	-0.52	-1.87	0.08	0.14
Wawona				
Live tree density ~ Year	-87.59	-3.06	0.01	0.46
Basal area ~ Year	-0.05	-0.22	0.83	0.00

lengths exceeding 60 m (pers. comm. P. Bevington, Fig. 6). Even backing fire downslope from these spot fires exhibited intense fire behavior, with long residence times due to heavy dead and downed wood and high scorch heights.

Incident management identified recent fuels treatments and existing roads as primary holding features to accomplish holding objectives following initial attack of the Washburn fire. While abundant dry fuels largely drove fire progression, reduced fuel continuity in the Mariposa Grove moderated fire behavior and allowed for fewer resources in those areas and safer firefighter entry. Treated areas were critical entry points for crews due to reduced heat and risk from falling snags. Handline construction from the lower grove to Wawona Point was fast and effective, requiring only two shifts of two to three hotshot crews (pers. comm. Parker Bevington). Only one handline from the grove was abandoned due to increases in fire activity the second day of the fire. As crews were initially trying to hold the fire west of the grove, conditions worsened and made it clear that holding in that location would be impossible given heavy fuel loads outside of the grove.

The biomass thinning projects along Wawona Road also facilitated quick and effective holding operations with limited resources. As fire reached thinned areas, flame lengths were reduced and fire intensity decreased significantly (pers. comm. P. Bevington). There was no crown fire in the treatment areas and only limited tree torching where abundant ladder fuels were present. Furthermore, limited ember cast from fire moving through the understory presented little threat of spotting. Gently backing fire within the thinned zone allowed for fire crews to complete active burning operations and tend to the fire without substantial resources (Figs. 6 and 7). Fire severity (dNDVI) in these treatment areas was significantly lower than in untreated areas

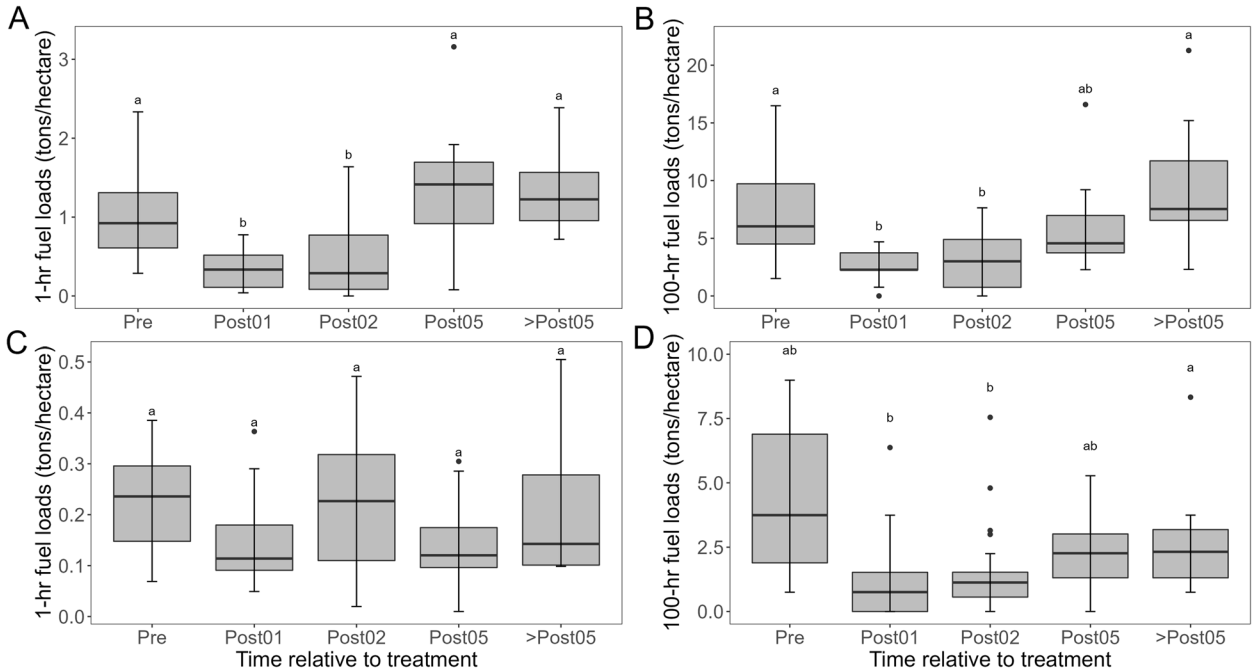

Fig. 4. 1-h (a, c) and 100-h (b, d) fuel loads (metric tons/hectare) over time relative to treatment implementation in Mariposa Grove (a, b) and Wawona area (c, d), respectively, where decades of fuels and fire management (primarily prescribed fire) have occurred. The Mariposa Grove, in particular, highlights the timeline for fuels recovery following treatment, and approach pre-treatment levels in five years. Data are from long-term monitoring plots as part of the Yosemite fire effects monitoring program. Letters represent significant differences in fuel loads ($\alpha = 0.05$)

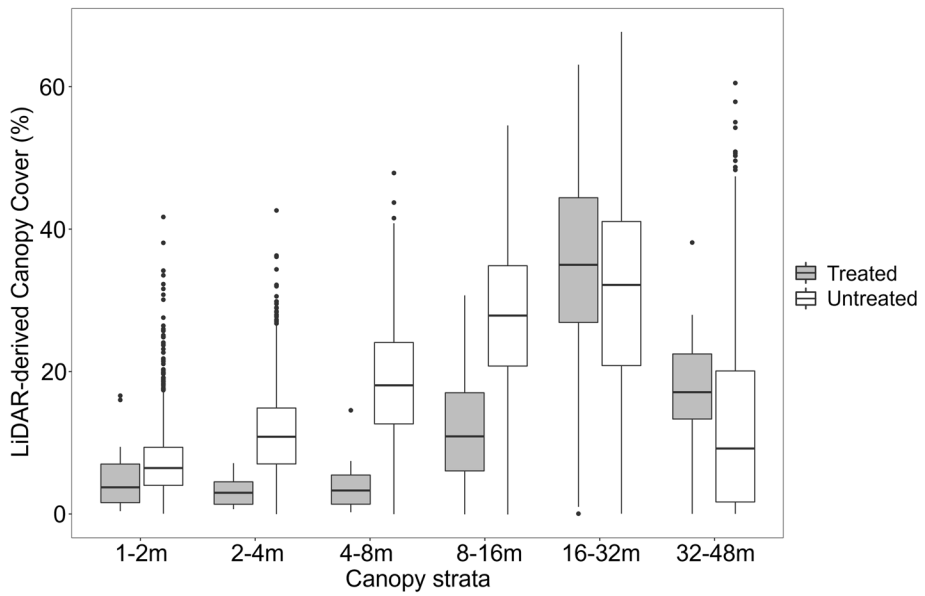

Fig. 5 Lidar-derived canopy cover in different height strata in untreated forests within the Washburn Fire perimeter and treated forests just outside of the perimeter in the Mariposa Grove and Wawona treatment areas. This figure highlights the abundance of mid-canopy fuels (i.e. ladder fuels) in the forests burned in the Washburn compared to treated areas surrounding it, where decades of fuels management has reduced fuels

Fig. 6 Fire behavior in **A** an untreated area above the Mariposa Grove treatment units, and **B** a thinned area near the community of Wawona

Fig. 7 Repeat photo points along Wawona Road, before (**A**) and after (**B**) roadside biomass thinning. **C** Low intensity surface fire during the Washburn Fire, providing safe access for firefighters. **D** Low severity fire effects (i.e. low tree mortality) after the fire has moved through

within the Washburn footprint ($t = -2.016$, $p = 0.048$, Fig. 8), where crown scorch and scorch heights ranged from 75–100% and 10-25 m, respectively, in untreated areas (NPS Fire Effects Data, unpublished).

Discussion

In an era of "mass fires" (Stephens et al. 2022), where devastating impacts of wildfire to human communities, infrastructure, and biological populations are

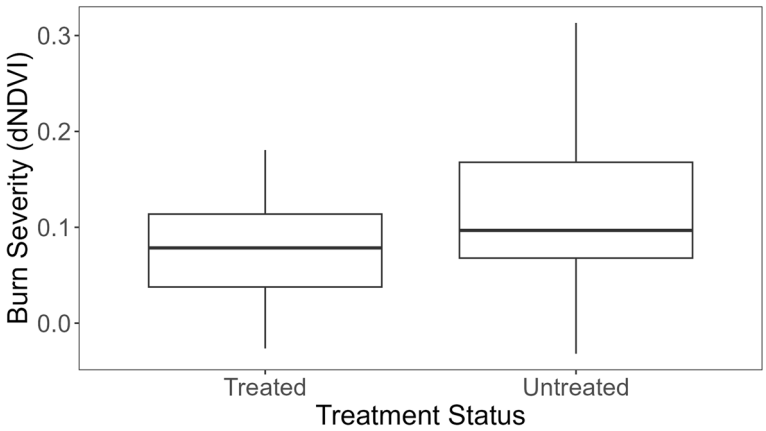

Fig. 8 Burn severity determined by remotely-sensed difference in normalized difference vegetation index in treated and untreated areas of the Washburn fire. Treatments that burned in the Washburn fire were largely roadside biomass thinning completed in 2020 and 2021. Fire severity was significantly different between treated and untreated areas (t = -2.016, $p = 0.048$)

increasingly commonplace (e.g. 2018 Camp Fire, 2021 Dixie Fire, 2021 KNP Complex), strategic and proactive management actions are critical in preventing catastrophic wildfire and facilitating beneficial fire effects. The 2022 Washburn Fire immediately threatened some of Yosemite's most valued resources – the Mariposa Grove of giant sequoias, critical habitat for Pacific fisher, and the community of Wawona, home to many Park employees and private citizens. Despite these threats, no mature giant sequoias and no structures were lost. Areas of the grove that remained unburned also provided refugia for Pacific fishers both during and after the Washburn Fire, including one being monitored by the Park with a GPS collar. Without the rich history of fuels reduction and prescribed fire in and surrounding these highly valued resources, this wildfire could have had a very different outcome for these irreplaceable communities.

Historical and contemporary fuels reduction treatments through prescribed fire and mechanical biomass removal played a substantial role in protecting important values within the Park during the Washburn fire. Through long-term monitoring data and contemporary observations, we highlight how these fuels management actions effectively limited horizontal and vertical fuel continuity, moderating fire behavior and providing important anchor points for suppression tactics. Suppression tactics were effective at minimizing threats to the mature sequoias, requiring additional individual tree protection primarily in trees with pre-existing fire scars. Fire-scarred trees are particularly vulnerable to subsequent fire damage, as exposed wood and thinner bark can lead to greater cambium damage (Shive et al. 2022). Prescribed fire alone typically does not significantly change overstory conditions (Schwilk et al. 2009, Stephens et al. 2012), but the reduction of surface and ladder fuels (Figs. 3 and 4) through repeated small prescribed fires over decades achieved conditions associated with forest resilience. This outcome is highlighted through the trends in tree density and basal area in the Wawona area. While tree density significantly declined over time, basal area remained constant, indicating that prescribed fire treatments targeted removal of small trees that do not contribute greatly to basal area. These data highlight the need for continued and frequent, repeated treatments to maintain lower fuel loads, prevent encroachment of abundant shade-tolerant tree species, and continue to act as effective barriers to fire spread. Reduced tree densities and surface fuels were important considerations in suppression tactics and resource prioritization when the Washburn Fire started.

Operational decisions and firefighting tactics were strongly shaped by the distribution of fuel treatments. Firefighters observed immediate changes in fire behavior shifting from treated to untreated areas, with increased flame lengths and scorch heights, greater heat output, and productive ember cast in untreated forested areas. These changes are consistent with expected shifts in fire behavior after the fuel reduction and decreased fuel continuity resulting from thinning and prescribed burn treatments (e.g. Pollet and Omi 2002, Stephens and Moghaddas 2005, Lydersen et al. 2017). The increase in fire intensity made it difficult for crews to enter untreated areas safely, and effective firefighting operations were ultimately focused on holding and burnout operations anchored into treated areas.

> *"It became clear that holding the fire on the edge of the grove was going to be the best chance since it's been burned so many times and would need*

less resource commitment in lighter fuels." – Parker Bevington, Duty Officer for Yosemite and Division Supervisor on the Washburn Fire

Local incident management personnel stated that "without the debris removal already completed [along Wawona Road], I do not believe we would have been able to keep fire from crossing the road." Mechanical thinning treatments primarily manipulate and reduce crown connectivity, tree density, and basal area, forest characteristics that strongly influence crown fire potential and long-range spotting (Schwilk et al. 2009, Stephens et al. 2009), which are components of fire behavior that are highly resistant to control. By requiring fewer firefighters in the grove and along Wawona Road, additional firefighters could be committed to structure protection in Wawona and handline construction in heavily fuel-loaded areas that were important for holding (pers. comm. Parker Bevington).

The observed changes in fire behavior on the ground are consistent with remotely-sensed fire severity assessments, determined by the change in NDVI pre- to post-fire. With increased flame lengths, crown scorch, and crown fire observed in untreated areas, fire severity was significantly higher in untreated areas, associated with almost complete canopy scorch and ultimately widespread tree mortality (NPS Fire Effects Data, unpublished). Reduced fire severity in previous fuel treatments also occurred in Yosemite's largest fire to date, the 2013 Rim Fire, resulting from similarly altered fire behavior through reduced surface and ladder fuels (Lydersen et al. 2017). Furthermore, more recent post-fire monitoring in these areas suggest that extended heat residence late into the fall and extensive crown scorch (75–100%) is leading to delayed mortality across much of the interior of the burn (NPS Fire Effects Data, unpublished; pers. comm. P. Bevington). These large patches of mortality will ultimately impact ecological communities and present safety concerns for recreation and subsequent fire management efforts.

It is important to note that the Washburn Fire is not without short-term and long-term ecological impacts. Essential wildfire suppression actions, such as dozer lines and aerial retardant applications, can temporarily or permanently reduce Wilderness character and directly impact native plants (Marshall et al. 2016; Weinberger and Kaczynski 2022). Rare plants and sensitive wildlife species are also directly and indirectly impacted by flame, heat, and noise associated with firefighting operations. Within the dense interior of the fire footprint, large patches of high-severity fire significantly impacted forest communities, removing large contiguous swaths of Pacific fisher habitat and killing numerous mature sugar pines. While these areas may recover to pre-fire vegetation composition and configuration, climatic extremes and seed limitations may direct areas towards alternate post-fire recovery trajectories (Welch et al. 2016; Shive et al. 2018).

The Washburn fire is a valuable demonstration of how fuels treatments are incorporated into wildfire suppression tactics to accomplish incident objectives. Existing fuel treatments greatly increased the ability of firefighting resources to access and successfully implement firefighting tactics under intense fire behavior. Notably, the Washburn fire did not burn under the most extreme fire weather conditions and we would expect that fuel treatments are less effective under extreme fire weather (Safford et al. 2012). However, over 77% of fire starts in this area of the Park occurred below the 80th percentile in energy release component (ERC) in the last five years (NPS Data), highlighting that treating small areas surrounding highly valued resources (Stephens et al. 2016) and strategically placed fuel breaks can be effective barriers in the face of unplanned wildfire (Moghaddas and Craggs 2007, Krofcheck et al. 2018, Tubbesing et al. 2019).

The distribution and magnitude of heavy fuels across the Sierra Nevada will require extensive fuels reduction treatments to prevent the spread of catastrophic fire and ultimately, protect anthropogenic and ecological communities. Managers have several tools available to accomplish these objectives (prescribed fire, thinning, managed wildfire), however the problem remains greater than the capacity of individual fire management programs, particularly in the face of prolonged wildfire seasons. Ongoing efforts to prioritize fuel treatments based on resource values and risk assessments coupled with evaluating the effectiveness of these treatments when disturbances occur will allow managers to have the widest impact and make progress towards accomplishing protection and resource management goals.

Conclusions

The Washburn fire, burning throughout July 2022 in Yosemite National Park, posed immediate threats to the iconic giant sequoias, critical Pacific fisher habitat, and the community of Wawona. The proximity of the fire to two long-term fuels management areas in the Park provided a unique opportunity to evaluate the effect of fuels management on fire behavior and operational decisions on an unplanned wildfire. Successful initial attack and suppression efforts kept fire out of the Mariposa Grove and the community of Wawona, where topography and the distribution of heavy fuels largely drove extreme fire behavior throughout the course of the fire. We demonstrate that

the cumulative effects of decades of fuels treatments, and recent mechanical roadside thinning operations, significantly reduced two major drivers of fire behavior – tree density and fuel load – and highlight substantially lower ladder fuels and ultimately lower fire severity in treatment units compared to untreated areas within the Washburn fire footprint. Together, this study links long-term monitoring data, remote-sensing data, and operational perspectives to show how repeated prescribed fire and fuels treatments moderate extreme fire behavior, improve the ability to protect key resources of concern through suppression tactics, and increase human safety in the face of unplanned wildfire. Strategically placed prescribed fire and fuels treatments surrounding the Washburn fire were key considerations in wildfire suppression tactics and were instrumental in protecting ecological and anthropogenic communities in Yosemite National Park.

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Authors' contributions
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Availability of data and material
Yosemite fire effects data are publicly available on the National Park Service's Data Store (DataStore—Generic Dataset—(Code: 2,239,371) (nps.gov)) and LIDAR is available through the USGS 3DEP program at: LidarExplorer (prd-tnm.s3.amazonaws.com).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
The authors have consent to publish.

Competing interests
The authors declare that they have no competing interests.

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