Sierra Nevada Forest Restoration Works

A Summary of the Fire and Fire Surrogate Study

Photo by Ariel Thompson

Current conditions of many seasonally dry forests in the western United States, especially those that once experienced low- to moderate-intensity fire regimes, leave them uncharacteristically susceptible to high-severity wildfire. Years of fire suppression coupled with increasingly extreme climate conditions have created such a high vulnerability to wildfire and drought that large-scale forest restoration cannot wait. After 20 years of research and over 40 publications, the Fire and Fire Surrogate Study ("Study") has demonstrated that prescribed fire and restoration thinning are successful in meeting fuel reduction objectives to create forest stands more resilient to wildfires. These critical forest health treatments also have a number of co-benefits, such as increased tree vigor, reduced wildfire emissions, and stabilizing forest carbon. The following pages summarize results from the abundance of literature generated by this Study, organizing the work by subject matter and highlighting management implications and other key takeaways.

Over time and with continued maintenance, all the treatments utilized in the Study proved to be effective in increasing resistance and resilience to modeled wildfires. As uncharacteristically high vulnerability to wildfire and drought exists at such a great scale throughout California forests, these findings emphasize how critical it is to begin implementing fire and fire surrogate treatments immediately, and to ensure that there are plans and funding for continued maintenance of these treatments so that their long-term benefits may be realized. High vulnerability to wildfire and drought exists at such great scale throughout California forests that action is warranted today. We know enough from studies like the Fire and Fire Surrogate Study to move forward competently with large-scale forest restoration treatments. This document is available for download at https://forests.berkeley.edu/research/current-projects/fire-and-fire-surrogates-study.

***Principal Investigator:* *Scott Stephens, PhD*,** *sstephens@berkeley.edu*

Professor, Dept. of Environmental Science, Policy and Management

Co-Director, Berkeley Forests

STEPHENS LAB
Research & Education in Wildland Fire Science

Center for Fire Research and Outreach

Berkeley Forests

The Fire and Fire Surrogate Study

Overview

Dry forests throughout the western United States are fire-dependent ecosystems, and much attention has been given to restoring their ecological function. For this reason, land managers often are tasked with reintroducing the fire process via prescribed fire and fire-surrogate treatments (such as thinning and mastication). During planning, managers are expected to anticipate the effects of management actions on forest structure, ecological function, and future fire behavior. In the case of fire surrogate treatments, managers must understand which components or processes are changed or lost, and with what effects, if treatments such as thinning and mastication are used instead of fire or in combination with fire.

As such, a nationwide research effort, The Fire and Fire Surrogate Study, commenced in 2001 to evaluate the impacts of prescribed fire and mechanical fuel reduction treatments. As part of this national effort, UC Berkeley implemented a suite of fuel treatments at its Blodgett Forest Research Station in the northern Sierra Nevada (Figure 1) beginning in 2001. The Fire and Fire Surrogate Study at Blodgett Forest Research Station (Study) is comprised of a network of twelve stands, ranging in size from 35-70 acres, each of which was randomly assigned one of four possible treatments, which represent the basic range of forest restoration and fire hazard reduction options. The treatment options initiated at Blodgett Forest were:

1) **Control**: no active management.
2) **Fire-only**: prescribed fire applied to the forest stand.
3) **Mechanical-only**: Crown thinning followed by commercial thinning from below, which removed mid and larger sized trees, followed by mastication, which chipped/shredded smaller trees in place leaving 10% of them in clumps throughout the forest stand.
4) **Mechanical + fire**: same mechanical treatment described above, followed by prescribed fire.

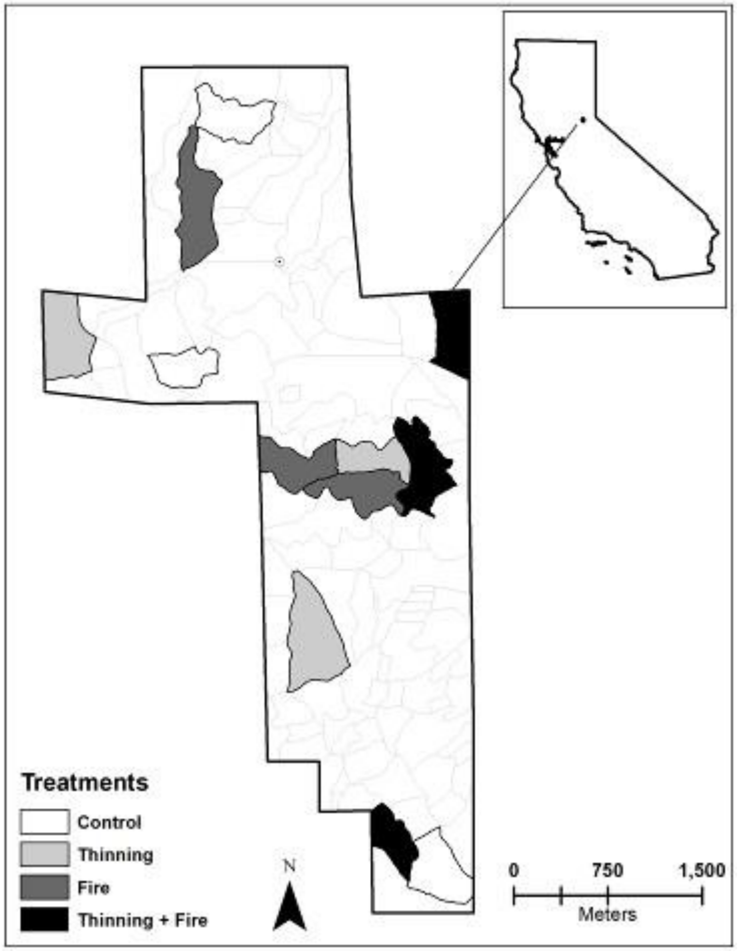


Figure 1. The location, geographic boundary and fire and fire surrogate study unit locations at Blodgett Forest Research Station, Georgetown, CA, USA.

The Fire and Fire Surrogate Study

Overview

Although national funding for the project ended in 2009, Berkeley Forests staff and UC Berkeley faculty and researchers have worked tirelessly to secure additional funds+ and continue the Study. While 20 years is a relatively short time frame relative to the lifespan of trees, the study is one of the longest continuous studies evaluating the impact and effectiveness of fuel management options. As of the summer of 2020, each study plot (with the exception of those in the "Control" areas) had been entered multiple times, with some areas having been treated three times—a number that is unprecedented in fuel treatment studies in California. These subsequent entries maintained the original intent of the three active treatment options from the original Fire and Fire Surrogate Study.

The research conducted as part of this Study explores the impacts of prescribed fire and fire surrogate treatments on forest structure, fire behavior, fuel loads, forest carbon, soil and soil carbon, forest pests, economics, social responses to treatments, and wildlife. These impacts are described in more detail in the pages to follow, but key takeaways about how each treatment impacted the biotic (trees, plants, wildlife, humans) and abiotic (fire, soil, carbon) elements of forested ecosystems are contained in Table 1. As the following pages reveal, the results of these treatments were varied and impacted every aspect of the forest ecosystem. Managers should not solely focus on fire hazard reduction when planning these treatments – many elements must be considered and then prioritized based on the management objectives for a given site.

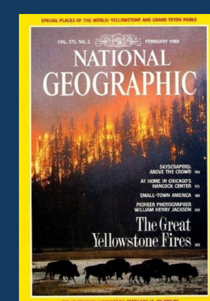
+A complete list of funding sources is included on the last page of this document.

Beyond Academia: National media coverage of the Fire and Fire Surrogate Study

The Fire and Fire Surrogate Study has drawn interest not only from academics, but from a variety of media outlets including national newspapers & radio programs, TED talks, and magazines. In 2019 and 2020, the Study was featured in National Geographic and Wired magazines, respectively.

The National Geographic article highlighted the work experts were doing to implement prescribed fire and fire surrogate treatments at a larger pace and scale across the state. The article notes that much of the science driving the "emerging consensus" on forest management best practices in California is based on the work done at Blodgett Forest as part of the Fire and Fire Surrogate Study. More recently, Wired magazine explored how California's wildfires are changing—becoming more severe and unprecedent with each passing year. The Wired article uses the response of the forest to fire and fire surrogate treatments to set the stage for what California forests should look like under more natural fire regimes.

Both magazines sent journalists to Blodgett Forest, to join Researcher Brandon Collins on a tour through the different treatment areas. Dr. Collins brought researchers to different sites to show them the positive impacts actively treating the land can have, and brought attention to the critical role of fire and fire surrogate treatments in mitigating future mega-fires in California.



The Fire and Fire Surrogate Study

Overview

Table 1: Impacts of fire and fire surrogate treatments to the biotic and abiotic elements of forested ecosystems.

Biotic	
Initial Subsequent Long-term*	The treatments implemented were successful in altering **forest structure** and fuel in ways that reduce overall fire hazards. All treatments had impacts beyond fuel load reduction, which generated results that were consistent with forest restoration objectives and improved forest resilience.
Initial	**Public perception** of fire and fire surrogate treatments were overwhelmingly positive. When asked, over 80% of individuals who took tours of the treatments founds fire only and mechanical + fire to be acceptable treatments, and well over half ranking mechanical treatments similarly. An individual's group association was the greatest predictor of response variability.
Initial	Overall **understory plant** species richness increased after treatments, particularly fire-adapted plants in fire or fire + mechanical treatment areas. In some cases, especially in areas with mechanical + fire treatments, exotic annual plants tended to increase as well, but maintained low overall levels.
Initial	**Wildlife** studies, which focused primarily on song birds and small mammals, found that in the short term and at the stand scale, fire-surrogate forest-thinning treatments effectively mimic low-severity fire.
Initial	**Bark beetles** did take advantage of treated areas – especially those with fire damaged or dead / downed trees – but on a small scale with a focus on trees with small to medium diameters. In the longer term, thinning effects (improved vigor, etc.) reduced stand susceptibility to bark beetle attacks.
Abiotic	
Initial Subsequent Long-term	**Fire Behavior** varied between treatment types and time frames, but over time and with continued maintenance, all three treatments proved to be effective in increasing resistance and resilience to modeled wildfires
Initial Subsequent Long-term	All treatments reduced total **carbon** stocks and live tree carbon when carbon storage was considered in a context that does not incorporate wildfire probability. Mechanical only and controls maximized expected total carbon stocks when accounting for wildfire probability and offsite wood uses, although our wildfire modeling may underestimate C losses, particularly in the control stands. Treatments that included fire produced conditions that were most insensitive to increased wildfire probability but at lowers levels of forest carbon.
Initial Subsequent Long-term	**Soil** conditions were affected by treatments, but reverted to pre-treatment states after only a few years. Initial changes in mineral soil exposure, pH, and exchangeable cations tended to disappear quickly. Other variables, including bulk density, soil carbon, dead-wood carbon, and soil nitrogen exhibited only very subtle responses to treatments.

****Initial, Subsequent and Long-term** indicate the timeframes during which research was conducted for the specific element noted. Initial = 1-3 years after the first treatments; Subsequent = 4-8 years after the first treatments; Long-term = 9-18 years after the first treatments.*

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

The prescribed fire and fire surrogate treatments implemented as part of this Study have been successful in altering forest structure and fuels in ways that reduce overall fire hazards. While these treatments were effective in achieving this one objective, there were additional impacts from each treatment on forest structure, which generated results that could be tied to specific management objectives.

All three treatments shared the following results:

- Basal area, tree density, live tree volume, canopy cover, and tree seedling density were all significantly reduced relative to untreated controls immediately following mechanical and fire + mechanical treatments. After 3 prescribed fires, the fire-only treatments also produced these outcomes.
- Live vegetation was considerably reduced in the sub-canopy (i.e. smaller trees that can be ladder fuels) and in the forest understory (seedlings, plants, and shrubs).
- The total abundance of native herbaceous plant species was not significantly affected when compared to untreated controls, however, species richness (i.e. the variety of species in a given area) was negatively impacted (Figure 3).
- By all metrics (density, percent cover, volume), coarse woody debris in decay classes 1 and 2 (i.e. not rotten) was not significantly altered by any of the treatments when aggregated across all diameter classes. Total volume of coarse woody debris in decay classes 1–3 (i.e. sound to just slightly rotten) with a large end diameter of 5” or more was also unchanged by all three treatments.

Fire-only treatments left live tree density and live tree biomass relatively unchanged initially, but did reduce surface fuels and coarse woody debris more than mechanical-only (Figure 2). By 2009, however, tree density had significantly decreased, as many of the trees that were damaged after the first burn (Figure 2) died and fell to the ground. As a result, surface fuel loads increased, necessitating a second prescribed burn (Figure 2). Although this may seem to be a negative impact, it had a positive effect for second and third-entry (2017) prescribed burns, as areas with higher initial fuel loads experienced a higher percentage of consumption of those fuels. This effect was even more pronounced in stands that had higher percentages of basal area in pine species. Fire-only treatments also significantly reduce coarse woody debris in decay classes 3 to 5 (slightly to very rotten), bringing levels of coarse woody debris closer to historical levels.

After the second burn an interesting phenomenon became apparent: The fire-only stands were developing a “patchy” pattern of tree clumps, openings with shrubs, and large isolated individual trees. This pattern appears to be a common characteristic of historical forests that experienced frequent fire. Treatments that included fire also resulted in better recruitment of large snags. These structural characteristics are thought to provide a suite of habitat types for wildlife species that are adapted to distinct structural and compositional environments. Recent research also suggests there may be additional benefits of this patchy pattern tied to snow retention and water yield.

The fire-only treatments also had some interesting effects on forest stand species composition, seedlings, and herbaceous plants. When projecting future mortality rates in fire-only treatment areas, fire-only stands appeared to result in a much higher projected mortality rate for Douglas-fir than any of the other treatments – which would impact long-term stand structure and composition. Although seedling densities for all species were initially reduced after treatments, fire-only treatments significantly increased Douglas-fir seedling density over time, which may balance out projected mortality in the long-term. California black oak and sugar pine seedlings decreased when the fire only treatment was applied, as did the number of native plant species in the understory (also referred to as “species richness”). This impact on seedling regeneration and native species richness could be concerning, as retention and recruitment of California black oak and native plant species is often a desired management goal on public lands in the Sierra Nevada.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Fire-only treatments consisted of prescribed fires conducted in 2002, 2009 and 2017. The photos below show the same study plot prior to the initial treatment and in the 16 years following, highlighting how this treatment series impacted forest structure and fuel loads over time. The orange dot identifies the same tree through the sequence.

Stand in 2002, before treatment.

Stand one year following the first prescribed fire.

Regrowth seven years after the first prescribed fire.

Following the second prescribed fire in 2009.

Eight years after the second prescribed fire.

Following the third prescribed fire in 2017.

Figure 2. Photo series of a typical fire-only treatment plot over the course of the study period, both before and after treatments.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Mechanical + fire treatments changed forest stand structure most drastically after the initial entry, as they reduced both live tree biomass (via mechanical thinning) and consumed fuel on the forest floor via the prescribed fire that followed the mechanical treatment (Figure 4). This treatment was effective at reducing fuel loads and shrub cover initially and 7-years post treatment, but by 2015 it was apparent that the increased light to the forest floor, coupled with seed stimulation from prescribed burning, were creating a surprisingly vigorous understory shrub response (Figure 4). Thus, another mastication and prescribed fire were required in 2018 in order to maintain the treatment's benefits. As with the fire-only treatments, mechanical + fire treatments resulted in a higher large-snag recruitment as well as higher consumption of coarse woody debris in decay class 4 (rotten) than treatments without fire.

Another interesting impact of the mechanical + fire treatments on forest structure was the high rate of observed mortality in overstory trees in the years following the initial treatment. As with the fire-only treatments, mechanical + fire saw increased tree mortality 7-year post treatment, as fire does not always immediately kill the trees it impacts. Overstory tree mortality was highest in this treatment option, as the additional surface fuel inputs generated from mechanical entries (i.e., tree tops and limbs from harvests, and mastication of sub-canopy trees and shrubs), resulted in additional fuel inputs for the follow up prescribed burns. The increased fine fuel loads and total fuel depth likely resulted in greater fire residence time when burned, and thus longer potential exposure to lethal temperatures.

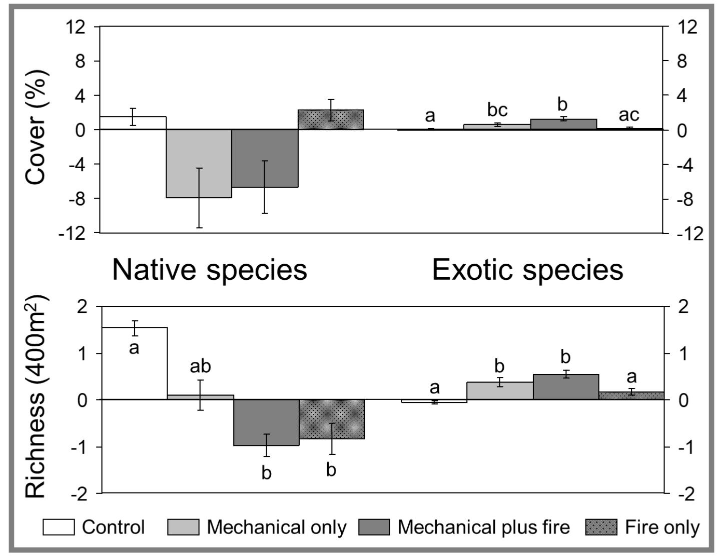


Figure 3. The differences in native and exotic plant species cover and richness following initial treatments (measured in 2003). Impacts to species cover were short-lived, and native plant species regained abundance in the years following the initial treatment.

The mechanical + fire treatments also had unique impacts on certain tree species, seedling regeneration and on understory plant species that are important to consider in terms of their long-term effects on forest vegetation composition. This treatment method resulted in higher observed mortality among white fir and sugar pine species, specifically. It also significantly increased ponderosa pine seedling densities, but reduced California black oak and sugar pine seedlings. Finally, it resulted in an increase in exotic herbaceous species cover and richness (Figure 3), while decreasing the native species richness. Operationally this treatment has been the most difficult to implement and maintain, a product of the shrub response and reduced tree growth from fire injuries.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Mechanical + fire treatments included a commercial harvest and mastication in 2002, followed by a prescribed burn that same year. A second mastication followed by a second prescribed burn was conducted in 2018. The photos below show the same study plot prior to the initial treatment and in the 17 years following, highlighting how this treatment series impacted forest structure and fuel loads over time. The orange dot identifies the same tree through the sequence.

Stand in 2001, before treatment.

Stand following the mechanical treatment, prior to the prescribed fire.

One-year after the completion of the first treatment, including the prescribed fire.

Regrowth 13 years after the initial mechanical + fire treatment .

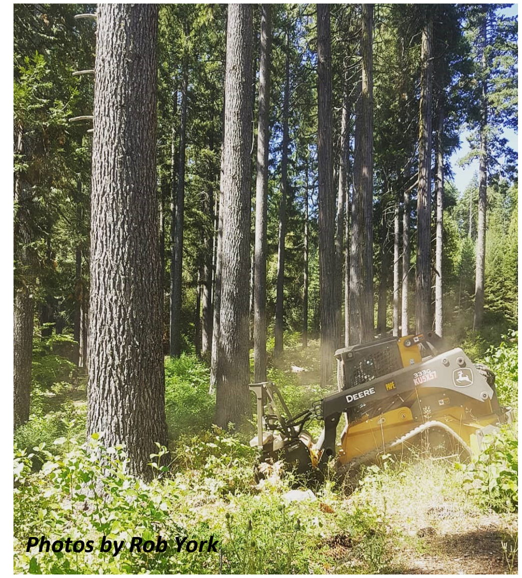
Stand following a second mastication treatment, prior to the second prescribed fire.

Stand following the second prescribed fire.

Figure 4. Photo series of a typical mechanical + fire treatment plot over the course of the study period, both before and after treatments.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads



Mechanical-only treatments, although initially effective in reducing ladder fuel and understory shrub cover, caused a pulse in surface fuels after the first treatment, as much of the biomass removed from the overstory and understory laid on the ground after mastication (Figure 5). Over time, the initial pulse of surface fuels broke down, and by 2009 they had almost totally decomposed. Further, in this time period, measured live tree biomass in the mechanical-only treatment areas exceeded pre-treatment levels – but with a much lower tree density conducive to more vigorous individual tree growth that was more likely to be resilient to disturbance (Figure 5).

By 2015, it was evident that tree growth – both diameter and crown expansion – was accelerated in the mechanical-only stands, more so than in the fire-only and mechanical + fire treatment areas. Further, the improved tree vigor from thinning kept observed and future projected mortality rates consistently low across all tree species, while in the treatments with fire, mortality rates were higher. Mechanical-only treatments also maintained low-density overstory structure more than a decade after the first treatment. As with all treatments, the mechanical-only treatments did require re-entry to maintain the benefits of the initial treatment, and another mastication was implemented in 2017 to maintain treatment effectiveness. The vigorous individual tree growth seen in the trees remaining after the initial treatment also allowed for a second commercial harvest in 2019, again offsetting the costs of mastication (which did not generate any income).

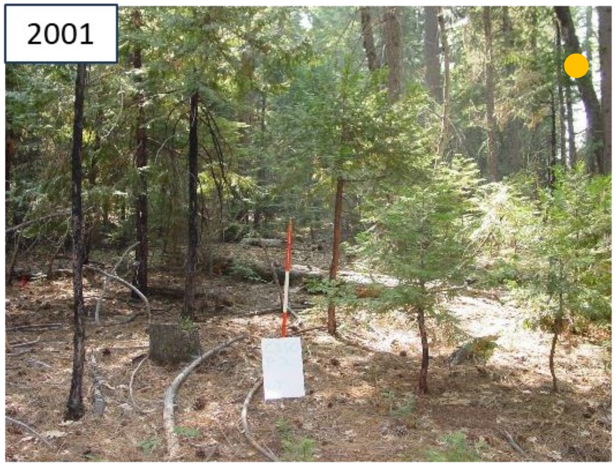
The mechanical-only treatments lacked some structural elements that were present in the two fire treatments: (1) recruitment of large snags and (2) low shrub cover, both of which contribute to the overall heterogeneity of habitat – an important consideration for wildlife species in the treated areas. This was due to the lack of fire which would kill mature trees but leave them standing, and would stimulate seed germination and expose bare mineral soil, both of which are critical for regenerating certain tree and shrub species. Mechanical-only treatments were also not impactful at reducing coarse woody debris compared to the treatments which included fire. This highlights the fact that while mechanical treatments can serve as a proxy for fire, certain ecosystem processes cannot be fully replicated by these treatments.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Mechanical-only treatments included mastication in 2002 and 2017, as well as commercial harvest in 2002 and 2019. The treatment was designed to remove ladder fuels and provide more growing space to mature trees. The photos below show the same study plot prior to the initial treatment and in the 19 years following, highlighting how this treatment series impacted forest structure and fuel loads over time. The orange dot identifies the same tree through the sequence.

2001



Stand in 2001, before treatment.

2003

Post first mechanical treatment - mastication and harvest.

2015

Stand 13 years of after the first treatment.

2019

Post second mechanical treatment - mastication and harvest.

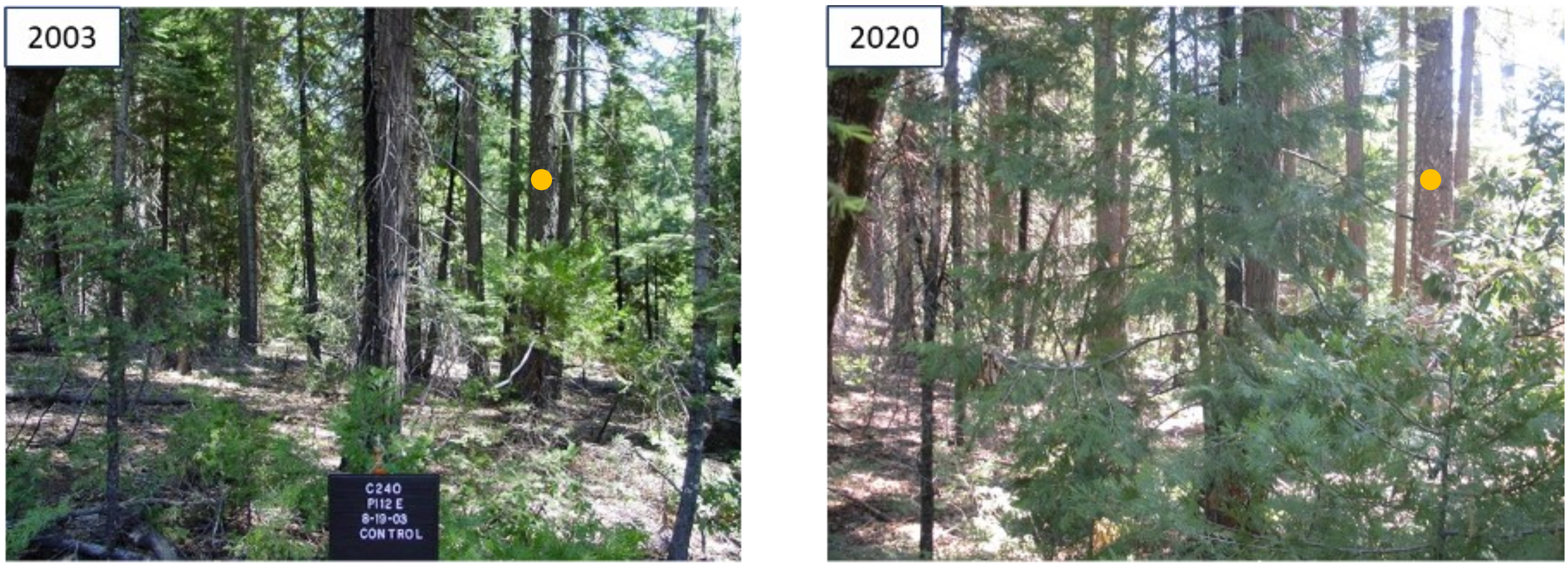
Figure 5. A photo series of a typical mechanical-only treatment plot over the course of the study period, both before and after treatments.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Control "treatments", or a lack of active management, consistently reported the highest amounts of live tree biomass over the course of this study, but this biomass was distributed throughout many small-diameter trees that did not have the same vigorous growth rates or lower densities as was observed in other treatments (Figure 6). There was also little change in understory vegetation as seen in the other treatments. The projected vulnerability for trees in the control is likely to result in comparatively high mortality rates compared to the mechanical treatment.

As the control treatments did not have any active management, the photos below show the same control plot two years after the start of the study (2003) and 17 years later in 2020—providing a good sense of how stands in the Sierra Nevada will continue to develop if left untreated. The orange dot identifies the same tree through the sequence.



Control stand in 2003 two years after the onset of the study.

Control stand in 2020 with no management activity, 17 years after the first photo (same photo point).

Figure 6. Photo series of a typical control plot over the course of the study period.

The Fire and Fire Surrogate Study

Forest Structure and Fuel Loads

Publications summarized in this section

Collins, B. M., Das, A. J., Battles, J. J., Fry, D. L., Krasnow, K. D., & Stephens, S. L. (2014). Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival. *Ecological Applications*, *24*(8), 1879-1886.

Collins, B. M., Moghaddas, J. J., & Stephens, S. L. (2007). Initial changes in forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management*, *239*(1-3), 102-111.

Collins, B. M., Stephens, S. L., & York, R. A. (2019). Perspectives from a long-term study of fuel reduction and forest restoration in the Sierra Nevada. *Tree Rings. 29: 7-9*, *29*, 7-9.

Knapp, E. E., Stephens, S. L., McIver, J. D., Moghaddas, J. J., & Keeley, J. E. (2004). Fire and fire surrogate study in the Sierra Nevada: evaluating restoration treatments at Blodgett Forest and Sequoia National Park. In *In: Murphy, Dennis D. and Stine, Peter A., editors. Proceedings of the Sierra Nevada Science Symposium. Gen. Tech. Rep. PSW-GTR-193. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture: 79-85* (Vol. 193).

Kobziar, L., Moghaddas, J., & Stephens, S. L. (2006). Tree mortality patterns following prescribed fires in a mixed conifer forest. *Canadian Journal of Forest Research*, *36*(12), 3222-3238.

McIver, J. D., & Fettig, C. J. (2010). Ecological consequences of alternative fuel reduction treatments in seasonally dry forests: the national fire and fire surrogate study. *Forest Science 56: 2-3*, *56*, 2-3.

McIver, J. D., Stephens, S. L., Agee, J. K., Barbour, J., Boerner, R. E., Edminster, C. B., ... & Haase, S. (2013). Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). *International Journal of Wildland Fire*, *22*(1), 63-82.

McIver, J. D., & Weatherspoon, C. P. (2010). On conducting a multisite, multidisciplinary forestry research project: lessons from the national Fire and Fire Surrogate study. *Forest Science*, *56*(1), 4-17.

McIver, J., Youngblood, A., & Stephens, S. L. (2009). The national Fire and Fire Surrogate study: ecological consequences of fuel reduction methods in seasonally dry forests. *Ecological Applications*, *19* (2), 283-284.

Management Considerations

- All active treatments required routine maintenance (re-burning, a second mastication, etc.) to maintain their benefits over time.
- While mechanical treatments allow for a higher degree of control over types of trees removed, there are ecosystem processes associated with fire that they cannot fully recreate.
- With fire alone, it takes multiple prescribed burns to entirely remove unwanted trees, while with mechanical methods they can be removed immediately.
- Mechanical removal of small-diameter trees is critical to creating fire-adapted forest structures , but may not generate enough income to offset costs. Both mechanical treatments at Blodgett Forest, however, did produced positive revenues.
- When relying on natural seedling regeneration, treatments must be intensive enough to create conditions that will facilitate germination of shade intolerant seedlings, such as pines and oaks.
- The loss of decayed coarse woody debris and snags may be an undesirable forest management outcome in some cases (particularly for wildlife habitat). Altering these elements should be analyzed in the context of long-term forest management goals.
- California black oaks were negatively impacted by treatments that included fire. Decades of fire suppression had increased duff loads (ground fuels) that top-killed many of these trees during burning.

Publications summarized in this section (*continued*)

Moghaddas, J. J., York, R. A., & Stephens, S. L. (2008). Initial response of conifer and California black oak seedlings following fuel reduction activities in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management*, *255*(8-9), 3141-3150.

Stephens, S. L., & Moghaddas, J. J. (2005). Fuel treatment effects on snags and coarse woody debris in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management*, *214*(1-3), 53-64.

Stephens, S. L., McIver, J. D., Boerner, R. E., Fettig, C. J., Fontaine, J. B., Hartsough, B. R., ... & Schwilk, D. W. (2012). The effects of forest fuel-reduction treatments in the United States. *BioScience*, *62*(6), 549-560.

Schwilk, D. W., Keeley, J. E., Knapp, E. E., McIver, J., Bailey, J. D., Fettig, C. J., ... & Skinner, C. N. (2009). The national Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. *Ecological applications*, *19*(2), 285-304.

Stephens, S. L., Moghaddas, J. J., Edminster, C., Fiedler, C. E., Haase, S., Harrington, M., ... & Skinner, C. N. (2009). Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. *Ecological Applications*, *19*(2), 305-320.

Waldrop, T. A., & McIver, J. (2006). The National Fire and Fire Surrogate Study: early results and future challenges. *Gen. Tech. Rep. SRS-92. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station. pp. 526-530.*

Youngblood, A., Metlen, K. L., Knapp, E. E., Outcalt, K. W., Stephens, S. L., Waldrop, T. A., & Yaussy, D. (2005). Implementation of the fire and fire surrogate study-a national research effort to evaluate the consequences of fuel reduction treatments. *USDA Forest Service General Technical Report PNW, 635*, 315.

The Fire and Fire Surrogate Study

Fire Behavior

While all three treatments implemented for this study were all successful in altering forest structure and fuels in ways that reduce overall fuel loads, their impact on **modeled wildfire behavior** varied by treatment and timeframe (Table 2).

Table 2: A summary of the positive and negative impacts of each treatment type over the course of the treatment study, organized by time periods in which these effects were realized.

	Timeframe		
	2001-2002	**2009**	**2015-2017***
Mechanical-only	- No impact on wildfire behavior	+ Decreased wildfire hazard due to surface fuel decomposition	- Vigorous understory growth increased fire hazard, but not a very high levels
Fire-only	+ Reduced modeled wildfire behavior	- Increased surface fuel inputs increased modeled wildfire behavior, but was still low overall	+ Reduced modeled wildfire behavior + Development of a fire-resilient landscape
Mechanical + fire	+ Reduced modeled wildfire behavior	+ Continued efficacy in reducing modeled wildfire behavior	- Vigorous shrub growth increased fire hazard

**Another set of treatments were conducted between 2017-2019, likely reducing modeled wildfire behavior and hazard, however, research about the impacts of these treatments is still underway and has not yet been published.*

Mechanical-only treatments did not have an obvious impact on reducing wildfire hazard initially. These treatments largely eliminated ladder fuels after the first treatment, but did so at the expense of augmenting surface fuels (from the masticated material left on site), thus, little change to wildfire hazard was realized. Crown thinning alone also did not reduce fire hazards. It should be noted that the effectiveness of mechanical-only treatments to reduce certain aspects of wildfire hazard was largely dependent upon the type of harvest system used. Those systems that did not leave harvest residuals (treetops, limbs, etc.) on site would be more likely to reduce crown fire potential.

Six-years post treatment, the surface fuel left behind by initial treatments had largely decomposed, and the modeled wildfire hazard decreased significantly. This decrease in wildfire hazard was bolstered by improved vigor in individual trees, which made them more resilient to wildfires and drought. The mechanical only treatment also opened up a great deal of growing space for new trees, and by 2017, regeneration (i.e. young tree growth) was so strong that another mastication treatment was needed to maintain the fuel-reduction benefits. A second commercial harvest was conducted the following year.

Fire-only treatments were effective at reducing modeled wildfire hazard initially, even under fairly extreme weather conditions. This was due to the high consumption of surface fuel (live and dead vegetation on the forest floor), and to the considerable reduction in ladder fuel (small trees and low branches) reported. It should also be noted that the success of fire-only treatments could be impacted by the time of year and conditions during prescribed burns. Specifically, spring burns were less likely to remove as much fuel as those burns that took place in the fall under drier conditions (all fires at Blodgett Forest were conducted in the fall). As the small to mid-sized trees killed by the initial prescribed fire began to fall to the forest floor, fire-only treatment areas began to accumulate surface fuels. Surface fuel accumulation would have a negative impact on modeled wildfire behavior, so a second prescribed burn was implemented seven years after the first burn to maintain the treatment's benefits.

The Fire and Fire Surrogate Study

Fire Behavior

While fire-only stands continued to recruit dead trees into the surface fuels after 2009, a patchy pattern of tree clumps, openings with shrubs, and large isolated individual trees often associated with more natural fire regimes emerged. When a third burn was conducted in 2017, researchers found that it experienced considerably lower fuel-consumption – a phenomenon they attributed to the patchy pattern noted above. This is an important finding for understanding wildfire hazard as well, because regardless of pre-burn fuel loads, the decreased fuel continuity meant that fire had a more difficult time traveling across the landscape.

Management Considerations

- Managers who are concerned about wildfire risks associated with the pulse of surface fuel following mechanical treatments may want to consider whole whole-tree removal systems.
- There will not be a one-size fits all solution, each treatment will be unique to the landscapes to which it is applied and the objectives it aims to achieve.

Mechanical + fire treatments were shown to be the most effective at reducing residual overstory tree mortality in modeled wildfires, likelihood of passive crown fire, and overall modeled wildfire hazard. Like the fire-only treatments, the mechanical + fire treatments also consumed much of the surface fuels and in reduced ladder fuels. However, this treatment also reported greater observed mortality and future vulnerability of overstory trees, which suggests a tradeoff between reduction in wildfire hazard and reduced tree vigor. As time passed, this treatment also experienced the most vigorous understory shrub response, which compromised the reductions to wildfire hazard realized by the initial mechanical + fire treatment. To maintain the benefits of this treatment, another mastication and prescribed burn were conducted in 2018.

Control areas produced the most severe modeled fire behavior and tree mortality, and were the most susceptible to crown fires. Further, fire behavior modeling demonstrated increasing hazardous fire potential over time to a level which exceeded all other treatment types.

Publications summarized in this section

Collins, B. M., Moghaddas, J. J., & Stephens, S. L. (2007). Initial changes in forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management*, *239*(1-3), 102-111.

Collins, B. M., Stephens, S. L., & York, R. A. (2019). Perspectives from a long-term study of fuel reduction and forest restoration in the Sierra Nevada. *Tree Rings. 29: 7-9*, *29*, 7-9.

Levine, J. I., Collins, B. M., York, R. A., Foster, D. E., Fry, D. L., & Stephens, S. L. (2020). Forest stand and site characteristics influence fuel consumption in repeat prescribed burns. *International Journal of Wildland Fire*, *29*(2), 148-159.

McIver, J. D., & Fettig, C. J. (2010). Ecological consequences of alternative fuel reduction treatments in seasonally dry forests: the national fire and fire surrogate study. *Forest Science 56: 2-3*, *56*, 2-3.

Stephens, S. L., Moghaddas, J. J., Edminster, C., Fiedler, C. E., Haase, S., Harrington, M., ... & Skinner, C. N. (2009). Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. *Ecological Applications*, *19*(2), 305-320.

York R.A., Levine J.I., Foster D.E., Stephens S.L., Collins B.M. (2020) Silviculture can facilitate repeat prescribed burn programs. *California Agriculture* . In Press.

The Fire and Fire Surrogate Study

Forest Carbon

Photo by Ariel Roughton

All active treatments resulted in significantly reduced total carbon stocks; however when considering losses from wildfire and likelihood of fire occurrence the story is more complex.

Mechanical-only treatments significantly reduced above ground carbon (i.e. all of the carbon in aboveground live and dead biomass) and reduced live tree carbon stocks (i.e. the carbon in aboveground stem, branches and boles of live trees) immediately following treatment. This was primarily accomplished through the removal of live trees in the form of tree boles ("trunks") harvested or masticated during treatment. (It should be noted that a great deal of the carbon "lost" via mechanical harvesting actually was stored as wood products following processing.) Mechanical-only treatments also emitted C02 through the combustion engines of the equipment conducting the thinning, harvesting and mastication, but these emissions were very small.

Mechanical-only treatments showed a weak positive effect on *stable* live tree carbon (i.e. the carbon in trees predicted to survive a wildfire) in the immediate years post treatment, with this effect increasing over time. Seven years post treatment, the mechanical-only treatments showed a stronger carbon sink strength and reached higher biomass levels than treatments that included fire. Further, live tree biomass in the mechanical-only areas exceeded pre-treatment levels, while maintaining a much lower live-tree density. This finding indicates that it is possible to achieve higher live tree carbon levels (like those found in untreated forests) in a lower-density structure that is more resilient to disturbance. Mechanical-only treatments also maximized expected total carbon stocks when incorporating wildfire risk and the carbon stability of live biomass, dead biomass, and offsite forest products.

The **fire-only** treatments also reduced carbon stocks, particularly those stocks contained within the litter, duff and dead wood found on the forest floor via combustion. Thus, treatments involving fire emitted significantly more C02 than did mechanical treatments, and the carbon lost during burns was immediately released into the atmosphere. The loss of carbon stored in more persistent duff layers was unique to treatments which utilized fire, as were the large reductions in litter – which was reduced by 40% by fire-only treatments. Fire treatments also appeared to have negative impacts on live tree carbon stocks, reducing post-treatment radial growth by 12% in the seven years following the initial treatment. Fire-only treatments also significantly increased carbon storage in dead wood, which is a less stable storage medium for carbon stocks. As with the mechanical treatments, however, in the years following the initial treatment, tree biomass carbon stock levels returned to pre-treatment levels while still maintaining a lower fire hazard because of the removal of surface and ladder fuels. When the probability of wildfire was considered, fire-only treatments were shown to have a strongly positive and durable effects on stable live tree carbon.

The **mechanical + fire** treatments lost more carbon and emitted significantly more CO2 than either the mechanical or fire-only treatments. This is expected, as this treatment lost carbon via both live-tree removal and surface and ground fuel consumption and emitted CO2 through combustion engines and prescribed fire. As with other mechanical treatments, both above ground carbon and live tree carbon stocks were significantly reduced in this treatment, however trees in this treatment did not experience the same levels of increased growth as those in the mechanical-only treatment and did not reach pre-treatment biomass levels after 17 years. Mechanical + fire treatments did result in the least loss from tree mortality when wildfire probability was considered. Potential wildfire emissions were also lowest for this treatment.

The Fire and Fire Surrogate Study

Forest Carbon

Modeling results for the **control** demonstrated that 90% of the live tree carbon had a high (>75%) chance of being killed in a wildfire; in contrast, all three active treatments had low vulnerabilities to carbon loss. As the annual probability of wildfire increased, risk-adjusted expected live tree carbon begins to decline steeply in control units. In contrast, the risk-adjusted expected live tree carbon of treated stands is relatively insensitive to wildfire probability increases. Based on levels of annual wildfire probabilities from 2000-2015, controls maximize expected total carbon stocks although wildfire modeling may underestimate carbon losses in the control stands and current wildfire probabilities are likely higher. Mechanical only stands had the second highest carbon stocks when annual wildfire probability is considered.

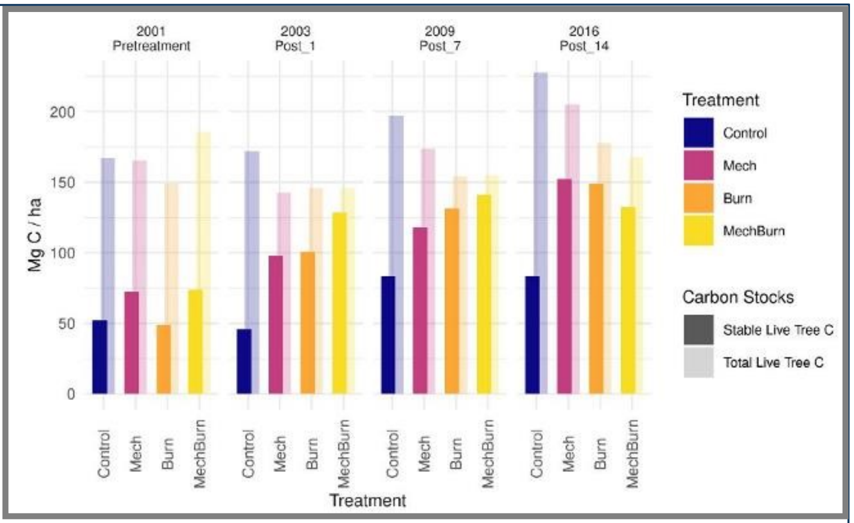


Figure 7. *Stability of live tree carbon stocks. Bar heights are treatment means for a given measurement year. Faded bars indicate observed live tree carbon stocks, while solid bars indicate stable live tree carbon stocks. Stable live tree carbon is the amount of carbon which in trees expected to survive at least three years after a modeled wildfire.*

Although all three active treatments decreased carbon stocks initially, when wildfire probability is considered, all three active treatments *increased* stable live tree carbon (Figure 7). The upfront carbon costs incurred by reducing fuel loads and improving wildfire hazard can only have realized benefits if a wildfire occurs during the treatments' effective lifespan, the probability of which is increasing, as we have seen in the western United States in the last decade. Thus, it seems that removing some carbon using the treatments described above, thereby reducing total carbon in the short term but increasing fire resistance in the long-term, is a more prudent approach to forest carbon management.

Publications summarized in this section

Boerner, R. E., Huang, J., & Hart, S. C. (2008). Fire, thinning, and the carbon economy: effects of fire and fire surrogate treatments on estimated carbon storage and sequestration rate. *Forest Ecology and Management*, *255*(8-9), 3081-3097.

Boerner, R. E. J., Huang, J., & Hart, S. C. (2008). Impacts of fire and fire surrogate treatments on ecosystem nitrogen storage patterns: similarities and differences between forests of eastern and western North America. *Canadian Journal of Forest Research*, *38*(12), 3056-3070.

Foster, D. E., Battles, J. J., Collins, B. M., York, R. A., & Stephens, S. L. (2020). Potential wildfire and carbon stability in frequent-fire forests in the Sierra Nevada: trade-offs from a long-term study. *Ecosphere*, *11*(8), e03198.

Hatch, L.E., C.N. Jen, N.M. Kreisberg, V. Selimovic,k R.J. Yokelson, C. Stamatis, R.A. York, D. Foster, S.L. Stephens, A.H. Goldstein, and K.C. Barsanti. 2019. Highly speciated measurements of terpenoids emitted from laboratory and mixed-conifer forest prescribed fires. Environmental Science and Technology 53: 9418-9428.

Jen, C., L. Yutong, L. Hatch, N. Kreisberg, C. Stamatis, K. Kristensen, J. Battles, S. Stephens, R. York, K. Barsanti, and A. Goldstein. 2018. High hydroquinone emissions from burning manzanita. Environmental Science and Technology Letters 5(6): 309–314.

Stephens, S. L., Boerner, R. E., Moghaddas, J. J., Moghaddas, E. E., Collins, B. M., Dow, C. B., ... & Keeley, J. E. (2012). Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. *Ecosphere*, *3*(5), 1-17.

Stephens, S. L., Moghaddas, J. J., Hartsough, B. R., Moghaddas, E. E., & Clinton, N. E. (2009). Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Canadian Journal of Forest Research*, *39*(8), 1538-1547.

The Fire and Fire Surrogate Study

People

To better understand public perceptions of the different treatments, surveys were given to groups visiting Blodgett Research Forest to view the results of the treatments 1-2 years after they were completed. The survey addressed five basic questions: (1) general acceptability of each treatment method, (2) how the tour changed attendees' opinions about any of the methods (3) the importance of seeing and discussing the treatments, (4) treatment preferences based on land ownership, and (5) what variables were most important for treatment preference. The groups touring these treatment sites were made up of individuals from five distinct groups including foresters, environmentalists, entomologists, the Natural Resource Conservation Service (NRCS), and teachers and high school or undergraduate students.

There was a clear preference for including prescribed fire in treatments, with 89% finding use of **fire-only** somewhat to very acceptable and 83% finding **mechanical + fire** treatments acceptable. Researchers noted that these results were similar to other surveys of the more general public, where roughly 80% of respondents found the use of prescribed fire a somewhat-to-fully acceptable management tool. More than half of respondents in the FFS study survey said that either treatment involving fire was "very acceptable" – the highest preference ranking available. The **mechanical-only** treatments garnered less positive responses (vs. both fire treatments), although was still considered somewhat-to-very acceptable by 69% of respondents. The **control** site reported the lowest support from respondents, with 58% indicating it was not acceptable to completely unacceptable.

The treatments involving fire also fared well when respondents were asked about how the tour changed attendees' viewpoints. For those who said the tour changed their view of the forest health treatments, 44% reported a more positive view of the mechanical + fire treatments, and only 11% had a more negative view. For fire-only treatments, 33% indicated a more positive view and only 6% a more negative view. Touring the treatments did not have a strong positive or negative effect on views related to the mechanical-only treatments, with just over 60% saying the tour did not change their views and roughly equal portions of the remainder saying it had either a positive or negative effect. When asked about the untreated control, tour attendees whose opinions changed did so in a strongly negative manner. Attendees also noted that the ability to see treatments and discuss them with experts was valuable, with seeing the treatments weighted as slightly more important than discussing them.

People

The survey also asked respondents to consider treatment preferences in light of different ownerships and management objectives. Participants seemed to recognize the importance of "place" in treatment selection, as preferences were distinctly different for the three different land ownership options given—National Parks, US Forest Service, and private timber. Overall, respondents preferred mechanical + fire treatments across all land types, but there were significant differences for other treatments. The clearest preferences were for National Parks, where fire-only and mechanical + fire were the first and second-most preferred choices. For both private timber and US Forest Service land, mechanical + fire was the preferred treatment for approximately 50% of respondents with the second-preferred treatment distributed evenly between the three active treatments. Responses also seemed to indicate that survey-takers understood the importance of treatment on these lands, with roughly 80% of respondents ranking "no treatment" as least preferred.

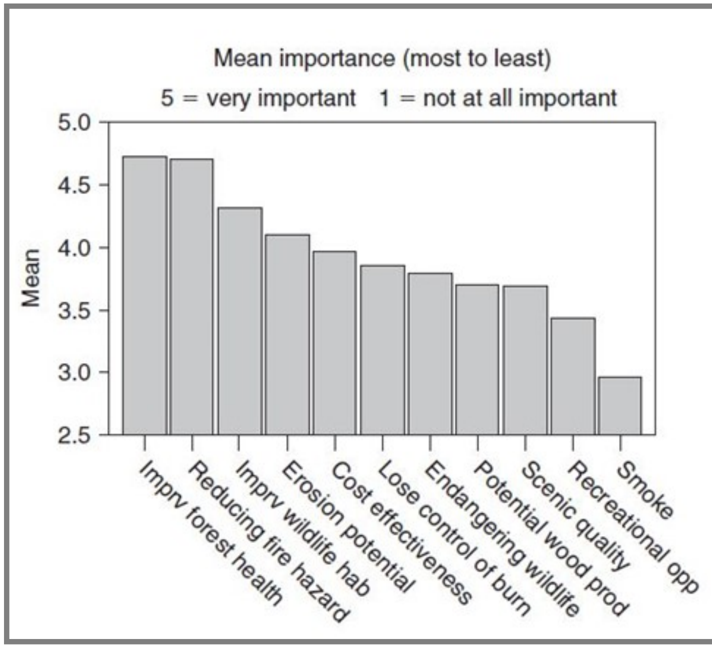


Figure 8. *Importance of issues considered when determining treatment preferences from survey at Blodgett Forest.*

In terms of how different considerations influenced respondents' treatment preferences, forest health and fire hazard reduction were the two most important (Figure 8). Interestingly, least important were the issues of recreation and smoke (Figure 8). The lack of concern arounds smoke is surprising, as many managers assume that smoke is a major issue for most members of the public. This may be explained by the fact that smoke can be dangerous for a small proportion of the population, and thus, these small groups may be more likely to vocalize concerns. Also interesting was the participant response when asked if their rankings would change if the proposed treatment was within a mile of their own home. Only 18% of respondents indicated that it would, which is somewhat unexpected as anecdotal evidence has indicated that the public is less amenable to treatments "in their own backyard."

Analysis of the survey results showed that group membership was the key element in differences in survey responses. The differences found between groups suggest that when objections to a fuel treatment are raised, they are likely due to the views of specific subsets of the public, rather than a general disapproval. While this study does demonstrate that there are clear differences between group preferences, it does not offer much insight into the values shaping these different preferences and recommends further research in this area.

Overall, results indicated that there was good acceptance of all three of the active treatment types across groups. Further, participants' rankings of treatments mirrored the effectiveness of these treatments in reducing fire hazard at the study site. These findings, combined with the fact that concerns about reducing fire hazard and increasing forest health were the key consideration in treatment preference, suggest that participants understand and value the role of different treatments in reducing fire hazard.

The Fire and Fire Surrogate Study

People

Publications summarized in this section

Hartsough, B. R., Abrams, S., Barbour, R. J., Drews, E. S., McIver, J. D., Moghaddas, J. J., ... & Stephens, S. L. (2008). The economics of alternative fuel reduction treatments in western United States dry forests: financial and policy implications from the National Fire and Fire Surrogate Study. *Forest Policy and Economics*, *10*(6), 344-354.

McCaffrey, S., Moghaddas, J. J., & Stephens, S. L. (2008). Different interest group views of fuels treatments: survey results from fire and fire surrogate treatments in a Sierran mixed conifer forest, California, USA. International Journal of Wildland Fire, 17(2), 224-233.

Treatment Economics

The cost of a given treatment is a critical consideration when managers evaluate which treatment options are best suited for the lands they manage. All of the active treatments in this Study required an initial expenditure of funds as well as re-entry treatments to maintain their benefits, but varied in their ability to generate income and in their efficacy both initially and long-term.

The **mechanical-only** treatments showed the greatest return on investment compared to other active treatments, as it had a longer re-entry period when compared to fire-only (~15 years vs. ~7 years) and it generated income during the follow-up treatment (vs. mechanical + fire which did not). **Mechanical + fire treatments** also generated income, which offset the costs of the initial treatment resulting in a net gain, and had a long re-entry interval—only requiring follow up after 15 years. It did not, however, generate income during the follow up treatments, which were limited to mastication and prescribed fire (no commercial harvest). The mechanical + fire treatments were, however, more efficacious at reducing surface fuels than the mechanical-only treatments. **Fire-only** was the least expensive treatment to implement, but generated no income, so all costs were realized. Fire-only treated areas also had the shortest re-entry interval, requiring follow up burns seven and fifteen years after the initial treatment.

A critical factor in evaluating the economics of any treatment is the value of the material removed. The timber market can be highly variable and may not always provide enough revenue to offset treatment costs. Further, if managers are not removing trees that can be made into high value wood products (dimensional lumber, etc.), it is unlikely that they can sell this material for a meaningful amount. There are a number of societal costs and benefits to consider as well (creating less fire-prone forests, dealing with smoke, etc.), although it has been challenging to assign simple dollar values to these.

The Fire and Fire Surrogate Study

Soil

Healthy soils are critical to the proper function of forest ecosystems, as they help regulate important ecosystem process such as nutrient uptake by trees and plants, decomposition, and water availability. Understanding the impacts of treatments on the physical, biological and chemical properties of soil and on soil carbon an important facet of the larger Study. At Blodgett Forest, all three active treatments had some impact on the physical, biological or chemical properties of the soil in the first two years after treatment. Nearly all of these impacts, however, were not found to persist in subsequent study years (3-7 years post-treatment).

Generally, the treatments had limited impacts to the physical properties of soil, and these impacts were concentrated in areas used as skid trails (i.e. temporary roads or trails used by heavy equipment to remove trees from a harvest area stand), which were installed long before this Study took place. Overall, soil bulk density was not significantly different among treatments (including the control), even when comparing only the skid trails. Soil strength of skid trails was significantly increased by the **mechanical + fire** treatments, with mean soil strength in these units 45% greater than the control and 26% greater than the mechanical-only units. It is unknown why the two mechanical treatments had such effects on the soil in skid trails. Mastication equipment did not cause significant increases to soil strength or bulk density over the entire unit, even though they operated off skid trails in both the mechanical-only and mechanical + fire treatments. These results may be explained by the fact that masticated residue was broadcast across the unit, creating a bed of debris over which the equipment traveled, and operations took place in the summer period when soil was drier and more resistant to compaction. On average, none of the treatments exceeded the USFS threshold of detrimental compaction (10%).

Although other studies have shown increases to bulk density as a result of fire, this was not the case for the **fire-only** treatments at Blodgett. Many of the previous studies making this connection were looking at wildfires of higher severity (vs. prescribed burns), which may explain the discrepancy. Treatments that utilized fire did, however, expose more mineral soil than mechanical-only treatments. Exposure of mineral soil can lead to elevated levels of erosion, but this was not found to be the case at Blodgett. In subsequent study years, mineral soil exposure levels were reduced to below 10% with no reports of significant erosion or mass wasting.

What was measured, and why?

Bulk Density: An indicator of soil compaction, and thus an indicator of soil health. The bulk density of a soil can impact the amount of water and nutrients available to plants, soil microorganism activity, root depth and soil porosity—all of which influence soil productivity and thereby the ecosystem above.

Carbon: Soil carbon plays many roles in forested ecosystems. It is critical to maintaining proper nutrient balance (C:N ratio) in soils, which in turn allows for healthy soil microbial activity. Belowground carbon is a substantial and generally stable carbon pool, with the amount of carbon stored in soils often greater than the amount stored in above-ground biomass.

Detrimental Compaction: A regional compaction threshold developed by the US Forest Service to help determine compaction levels detrimental to soil productivity. For the Study area, guidance states that "soil porosity should be at least 90% of total porosity found under natural conditions." Changes in soil porosity are determined based on a threshold of soil bulk density.

Nitrogen: An essential nutrient for all living organisms in forested ecosystems. As with carbon, it plays a critical role in maintaining proper nutrient balance in soils (C:N ratio). Further, it is a vital element for healthy plant growth, however it must often go through some sort of process to convert it into forms that plants can use (such as ammonium, NH_4+, and nitrate,NO_3-).

Phosphatase Activity: An indication of soil microbial activity, phosphatase are produced as long as soil microbes are metabolically active. Proper soil microbe function is critical to forest health, as plants rely on soil microorganisms to mineralize organic nutrients needed for growth and development.

Soil Strength: Measured as "the shear stress that a soil can sustain," soil strength is important because it determines the ability of plant and tree roots to enter and explore the soil. If soils strength is too high, plant roots may not be able to access parts of the soil necessary for healthy growth.

Soil pH—Measure of the acidity or basicity of a soil, pH impacts nutrient availability and the health and vigor of forest plants and trees.

The Fire and Fire Surrogate Study

Soil

Photo by Ariel Roughton

The impacts to the chemical and biological properties of forest soils were more pronounced in the years immediately following treatment, especially for those treatments that utilized fire. Both the **fire-only** and **mechanical** + **fire** treatments reduced forest floor carbon and nitrogen pools by over 80%, significantly decreasing both mass and depth of forest floor materials. Carbon pools in the mineral soil layers, however, were stable and not significantly impacted by any of the treatments—both immediately following treatment and in subsequent studies. Further, it should be noted that the carbon pool in the litter layer usually rapidly returns to its pre-disturbance state if high levels of disturbance are avoided and there are trees and plants to provide litter inputs to this layer. In other words, soil carbon pools did not display any lasting, negative impacts as a result of any of the Study treatments. **Mechanical-only** treatments reduced fire-root biomass, but otherwise had few reported impacts on soil carbon pools.

Nitrogen pools were significantly reduced in the forest floor layer, with reductions of 86% in **fire-only** and 90% in **mechanical + fire** treatments. While these reductions were concerning, it should be noted that the Blodgett study sites reported unusually high levels of forest floor nitrogen in pre-treatment surveys, and thus the remaining forest floor nitrogen levels were not out of line with other western forests following fires. Given that combustion during fire accounts for the bulk of nitrogen losses, these results are even less surprising as the severity of the first entry prescribed fires at Blodgett was among the highest of any of the fires in the nation-wide study. At the expense of the forest floor nitrogen pools, the treatments involving fire resulted in increased nitrogen in the mineral soil layers—specifically to $N0_3$- (nitrate) and NH_4+ (ammonium), both of which are plant-available forms of nitrogen. As most ecosystem nitrogen is contained within the mineral soil layer, treatments generally impacted no more than 10-15% of the *total* ecosystem N, despite their strong effects on the aboveground pools. **Mechanical-only** treatments increased forest floor nitrogen pools—a result that was not unexpected given that harvest residues often have significant quantities of nitrogen stocks.

Treatments involving fire, generally, had greater negative effects on the indicators of soil microbial activity, such as phosphatase levels, in western forests. Researchers note that phosphatase activity is tied to certain environmental factors (temperature, moisture, and available nitrogen), so these results may not be fully attributable to the treatments. Both fire treatments also increased soil pH immediately following treatment, but these impacts were not present when sampled in subsequent years. Soil pH increases have been linked to fire severity, which may explain why increases at Blodgett were higher than at other national study sites.

Although many impacts seem to be transient in nature, most of the soil research conducted as part of this Study was done after only one treatment entry. Further measurements are needed to better understand how repeated treatments impact the physical, biological and chemical properties of soil. Such follow up work could answer questions such as whether repeated prescribed burns of lower severity may have reduced impacts on soil, or if masticators will continue to show no impact on compaction after repeat entries.

The Fire and Fire Surrogate Study

Soil

Publications summarized in this section

Boerner, R. E., Huang, J., & Hart, S. C. (2009). Impacts of Fire and Fire Surrogate treatments on forest soil properties: a meta-analytical approach. *Ecological Applications*, *19*(2), 338-358.

Boerner, R. E., Giai, C., Huang, J., & Miesel, J. R. (2008). Initial effects of fire and mechanical thinning on soil enzyme activity and nitrogen transformations in eight North American forest ecosystems. *Soil Biology and Biochemistry*, *40*(12), 3076-3085.

Dore, S., Fry, D. L., Collins, B. M., Vargas, R., York, R. A., & Stephens, S. L. (2016). Management impacts on carbon dynamics in a Sierra Nevada mixed conifer forest. *PloS one*, *11*(2), e0150256.

Dore, S., Fry, D. L., & Stephens, S. L. (2014). Spatial heterogeneity of soil CO2 efflux after harvest and prescribed fire in a California mixed conifer forest. *Forest Ecology and Management*, *319*, 150-160.

Moghaddas, E. E., & Stephens, S. L. (2008). Mechanized fuel treatment effects on soil compaction in Sierra Nevada mixed-conifer stands. *Forest Ecology and Management*, *255*(8-9), 3098-3106.

Moghaddas, E. E., & Stephens, S. L. (2007). Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest. *Forest Ecology and Management*, *250*(3), 156-166.

Management Considerations

- Managers should re-use skid trails whenever possible, to keep significant compaction limited to small portions of a given unit.
- Mastication equipment may not result in the soil compaction associated with other heavy harvesting equipment if the machines can create and travel over a bed of masticated debris and soils are dry.
- Reuse of skid trails is critical when running heavy logging machinery in a unit if there is a desire to keep compaction confined or below a certain threshold.
- Higher severity fires may have less desirable effects on soil properties, so managers with soil concerns may want to burn during times of year conducive to less severe outcomes (i.e. spring).
- High severity wildfires have far greater impacts to soil than those reported for the fire or fire surrogate treatments, so managers must consider the tradeoffs between leaving fuels untreated vs. the soil disturbance impacts of reducing fuels and restoring forests.

The Fire and Fire Surrogate Study

Wildlife

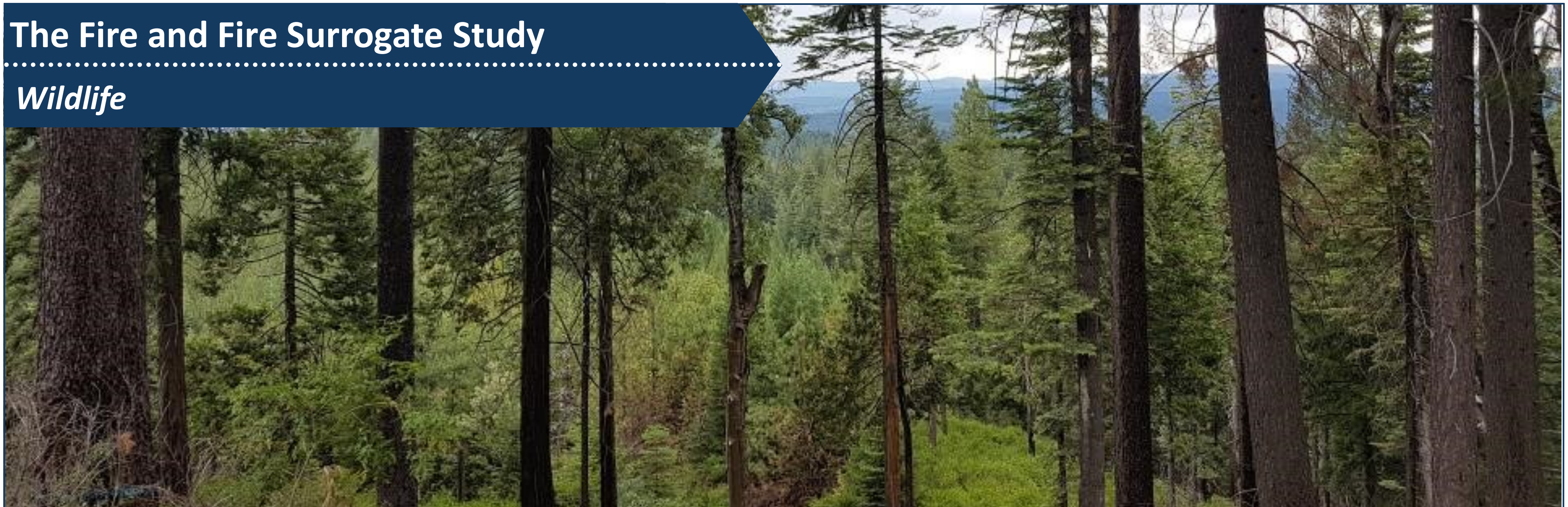
Understanding the impacts of fire and fire surrogate treatments on biodiversity is extremely important to land managers, as they are often tasked with ensuring that such treatments are not negatively impacting the habitat and overall well being of wildlife species found in treatment areas. This Study found that in the short term, and at fine spatial scales, all three active treatments appear to effectively mimic low-to-moderate severity fire, which is beneficial to many wildlife species in the western United States. This was confirmed via specific wildlife-focused research that included avian nesting surveys, small-mammal response to treatments, microhabitat selection of bark foraging birds, and arthropod populations – all of which confirmed that there were little or no negative impacts to the species studied. Further, results from a meta-analysis of avian and small-mammal responses to fire surrogate treatments showed that all the fuel reduction treatments included in the analysis resulted in an increase to the average biomass of small animals.

It should be noted that this Study also found that low-to-moderate severity fire is not a substitute for high severity fires, and thus, prescribed fire and mechanical surrogate treatments are not the best treatment in every scenario or for every wildlife species. To maintain a full complement of vertebrate species, including fire-sensitive taxa, a range of fire severity or disturbances that replicate the natural range of fire severity are critical. This is especially true for small patches of high-severity fire, where positive responses from many avian taxa suggest that this disturbance (either as wildfire or prescribed fire) should be included in management plans where it is consistent with historic fire regimes and where maintenance of regional vertebrate biodiversity is a goal.

Bark Beetles

As many of the treatments in the Study killed or damaged trees, there were understandable concerns that treatments may draw unwanted bark beetle activity. A study examining the mortality attributed to bark beetle species following fire and fire surrogate treatments reported that across all treatments and tree species, the percentage of trees killed by bark beetles was under 7%. It both fire-only and mechanical + fire treatments, bark beetle mortality of small and medium white firs was higher than in other treatments. Additionally, medium sized sugar pines experienced higher rates of mortality from bark beetles with the fire-only treatment. Both of these are important to consider as managers prioritize treatment outcomes, such as desired species composition.

Photos by (counter clockwise from top): David Turgeon, Craig Johnson, D. Manastirski, Colorado State University, Mark Chappell, John F Gatchet, Blalonde / Wikimedia.



Publications summarized in this section

Amacher, A. J., Barrett, R. H., Moghaddas, J. J., & Stephens, S. L. (2008). Preliminary effects of fire and mechanical fuel treatments on the abundance of small mammals in the mixed-conifer forest of the Sierra Nevada. *Forest Ecology and Management*, *255*(8-9), 3193-3202.

Apigian, K. O., Dahlsten, D. L., & Stephens, S. L. (2006). Biodiversity of Coleoptera and the importance of habitat structural features in a Sierra Nevada mixed-conifer forest. *Environmental Entomology*, *35*(4), 964-975.

Apigian, K. O., Dahlsten, D. L., & Stephens, S. L. (2006). Fire and fire surrogate treatment effects on leaf litter arthropods in a western Sierra Nevada mixed-conifer forest. *Forest Ecology and Management*, *221*(1-3), 110-122

Converse, S. J., White, G. C., Farris, K. L., & Zack, S. (2006). Small mammals and forest fuel reduction: national-scale responses to fire and fire surrogates. *Ecological Applications*, *16*(5), 1717-1729.

Farris, K. L., Converse, S., Zack, S., Douglas Robinson, W.D., Amacher, A.J., Contreras, T., ... & Rompre, G. (2010). Short-term effects of fire and fire-surrogate treatments on avian nest survival: a national-scale analysis. *Open Environmental Sciences*, *4*(1).

Farris, K. L., Zack, S., Amacher, A. J., & Pierson, J. C. (2010). Microhabitat selection of bark-foraging birds in response to fire and fire surrogate treatments. *Forest Science*, *56*(1), 100-111.

Fontaine, J. B., & Kennedy, P. L. (2012). Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in US fire-prone forests. *Ecological Applications*, *22*(5), 1547-1561.

Kennedy, P. L., & Fontaine, J. B. (2009). Synthesis of knowledge on the effects of fire and fire surrogates on wildlife in US dry forests. Extension and Experiment Station Communications, Oregon State University. Special Report 1096.

Stark, D. T., Wood, D. L., Storer, A. J., & Stephens, S. L. (2013). Prescribed fire and mechanical thinning effects on bark beetle caused tree mortality in a mid-elevation Sierran mixed-conifer forest. *Forest ecology and management*, *306*, 61-67.

The Fire and Fire Surrogate Study

Recognition

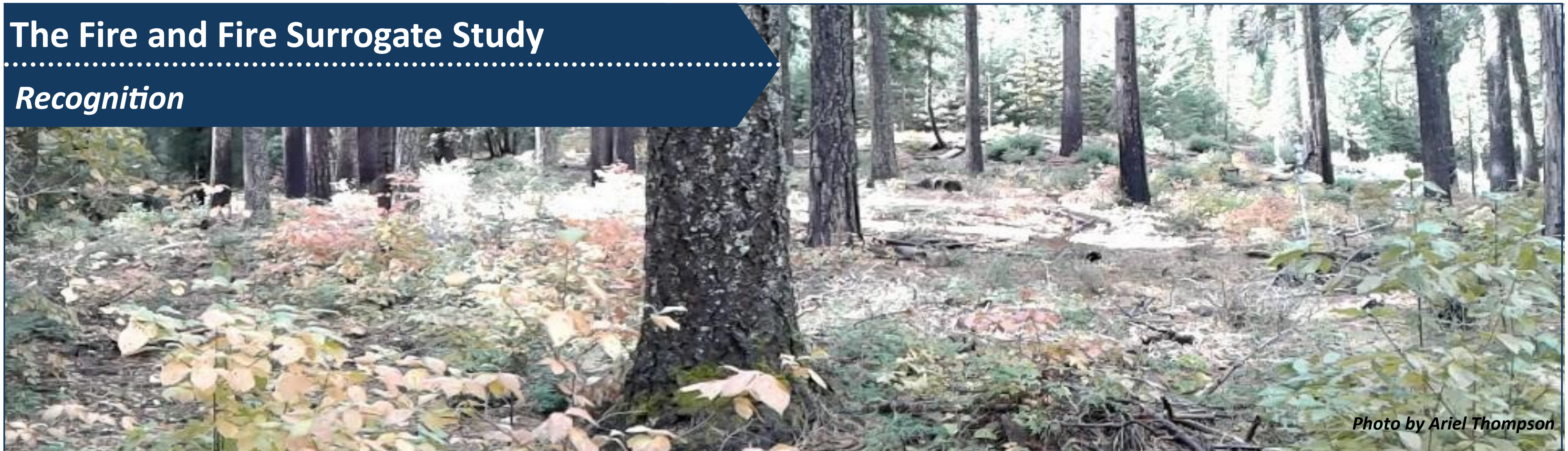


Photo by Ariel Thompson

Berkeley Forests staff and UC Berkeley faculty and researchers have worked tirelessly to continue the Fire and Fire Surrogate Study at Blodgett Forest Research Station for twenty years, and appreciate the many funding sources that have made this work possible (Table 3). Not only has this work been critical in our understanding of how prescribed fire and mechanical forest health treatments impact our forested ecosystems in California, but it has provided dozens of research and field based jobs for undergraduate and graduate students at California universities.

Table 3: Funding sources which contributed to the Fire and Fire Surrogate Study at Blodget Forest Research Station.

Granting Agency	Grant Number and Title	Years
University of California Office of the President via the UC Lab Fees Research Program	Grant No. LFR-20-653572; Transforming prescribed fire practices for California	2019-2022
California Department of Forestry and Fire Protection	Grant No. 8GG18802; Keeping Fire on the Landscape: Consequences for Carbon Balance and Forest Resil-ience	2019-2021-
California Department of Forestry and Fire Protection	Grant No. 14-GHG-FMP-01-0139-DSFR-AEU . Do, Document, and Disseminate Project for GHG Benefits of Fuels and Forest Health Treatments in California.	2017-2019
CA Natural Resources Agency	Grant No. CCCA4-CNRA-2018-014; Innovations in Measuring and Managing Forest Carbon Stocks in Cali-fornia	2015-2018
US Department of Agriculture–US Department of the Interior	USDA-USDI Joint Fire Sciences Program	2010-2013
US Department of Agriculture–US Department of the Interior	USDA-USDI Joint Fire Sciences Program	2001-2008

This document was compiled by Rachelle Hedges, Project and Policy Analyst for Berkeley Forests. Questions may be directed to rachelle.hedges@berkeley.edu.