Main manuscript for

Good fire: quantifying the beneficial ecosystem work of western U.S. wildfires (2010-2020)

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This file includes: Main Text, Figures 1 to 2, and Extended Methods

Abstract

Wildfires are doing necessary work for western US forests that have evolved with fire. Here we define “good fire” as areas that burn in an ecologically beneficial way, with a severity that is analogous to their historical fire regimes prior to European settlement. We focus on low-moderate severity wildfire as this type of burning can promote regeneration, even in the context of a warming climate (Davis et al., 2023). We quantify the amount of forested area (i.e., deciduous, conifer, or mixed forest types) burned in low-moderate severity good fire and compare that to the amount of forested area that received prescribed burns (2010-2020). Our results show that 50% of the forested area burned by wildfires in the western US burned as low-moderate severity good fire. Moreover, the total area of this type of good fire was 3.3 million ha for wildfires (N = 18,126 events), compared with 2.7 million ha for forested prescribed burning (N = 25,761 events) over this same period. Lower severity wildfires are doing important work to promote healthy forests, 23% more by area than accomplished through prescribed burning. We also quantified high severity good fire in systems that historically experienced stand replacement, which represents an additional 10% of the forest area burned. Knowing that fires are likely going to increase in frequency and area with warming (Stephens et al., 2023), our key challenge in the future will be promoting good fire while still protecting lives and property.

Introduction

During wildfires we understandably tend to focus on the tragic consequences in the moment, lives lost and homes destroyed, rather than the longer-term beneficial ecosystem outcomes. While extreme wildfires can be disastrous, they can also provide critical nutrients to soils, prevent crowding of trees, and reduce the extent or intensity of future fires. In effect, there is simultaneously good and bad fire (1, 2). This dichotomy forces us to reckon with how we appreciate fire in our landscapes and our lives today, especially across western U.S. forests that have all evolved with fire and need it to maintain healthy structure and function. With a drastic increase in wildfires burning across the western US since the 1980s, particularly in our forest systems (3), we need to count the benefits of burning.

Here, we quantify the amount of "good fire," or ecologically beneficial wildfire, that has occurred across western US forests (2010-2020). More specifically, we quantify the amount of forest area that has burned during wildfires with a severity that matches its historical fire regime (4). We delineate two classes: low-moderate severity wildfire in regions that historically burned this way, hereafter "lower severity regions," and high severity wildfire in regions that historically had stand-replacing fires, hereafter "high severity regions." While this study does not document recovery trajectories, it assumes that burning in congruence with historical fire patterns will have ecological benefits, which has been demonstrated for low-moderate and high severity burns in the appropriate ecosystems (5, 6). Further, we compare this lower severity area with the amount of prescribed burning that has been conducted in forested public lands during the same decade. It is important to note that while we explore severity here, ecological benefits may be compromised when fire intervals, size of high severity patches, or the total size of a fire diverge too far from historical norms. Additional data sources offer opportunities to characterize these other dimensions of fire effects (e.g., (7)). On the other hand, ecological benefits may be conferred by low severity fire in regions with historically high severity fire regimes; the potential for such dynamics is not taken into account here and therefore our estimate is conservative. As we shift our fire management tactics from a focus on suppression to more intentional forest restoration and proactive fuel treatments, we urgently need a recounting of fire to acknowledge the beneficial ecosystem work that wildfire is doing and will continue to do across western U.S. forests.

Results and Discussion

Wildfires have done beneficial ecosystem work across western U.S. forests, and more than what prescribed burning accomplished (2010-2020). The total area of lower severity good fire over this decade was 3.3 million ha for wildfires (N = 18,126 events), compared with 2.7 million ha for prescribed forest burns (N = 25,761 events) (Figure 1). Additionally, across the west (2010-2020), there were 649,000 ha of high severity good fire. This area represents 10% of the total area of forest burned by wildfires over the time frame. If we combine low, moderate, and high severity "good fire," this amounts to 3.9 million ha across the west (2010-2020). This area is 60% of the total forest burned by wildfires, and 47% more than what was accomplished by prescribed forest burning. On average, wildfires did beneficial work in 0.3 million ha per year in lower severity regions, but there was substantial interannual variation (annual minimum = ~40,000 ha; annual maximum = ~600,000 ha), likely due to differences in drought and non-drought years and the climatic controls on burned area (Figure 2) (8). Even in non-drought years, low-moderate severity burning within wildfire perimeters constituted roughly an equivalent amount of burned area to that which occurred under recent prescribed burning efforts. There were substantial differences across states, but in most states the areas of prescribed burning and lower severity good wildfire were roughly equivalent (Figure 2). The one exception was California, which is the largest state in the west by land area and has experienced some record-breaking wildfire years over the past decade. California had over a million ha of lower severity good fire during this time period, which was 2.8 times

greater than what was accomplished through prescribed burning. Importantly, good fire is distributed in patches across individual fire events (e.g., the million acre August Complex wildfire burned in a patchwork of low-high severities, Figure 1C). Of the forested prescribed burns included in our west-wide analysis, 85% by area occurred in lower severity regions and further only 28% of that area was designated as broadcast burns, i.e., intentional, controlled fire that burns through a predetermined landscape.

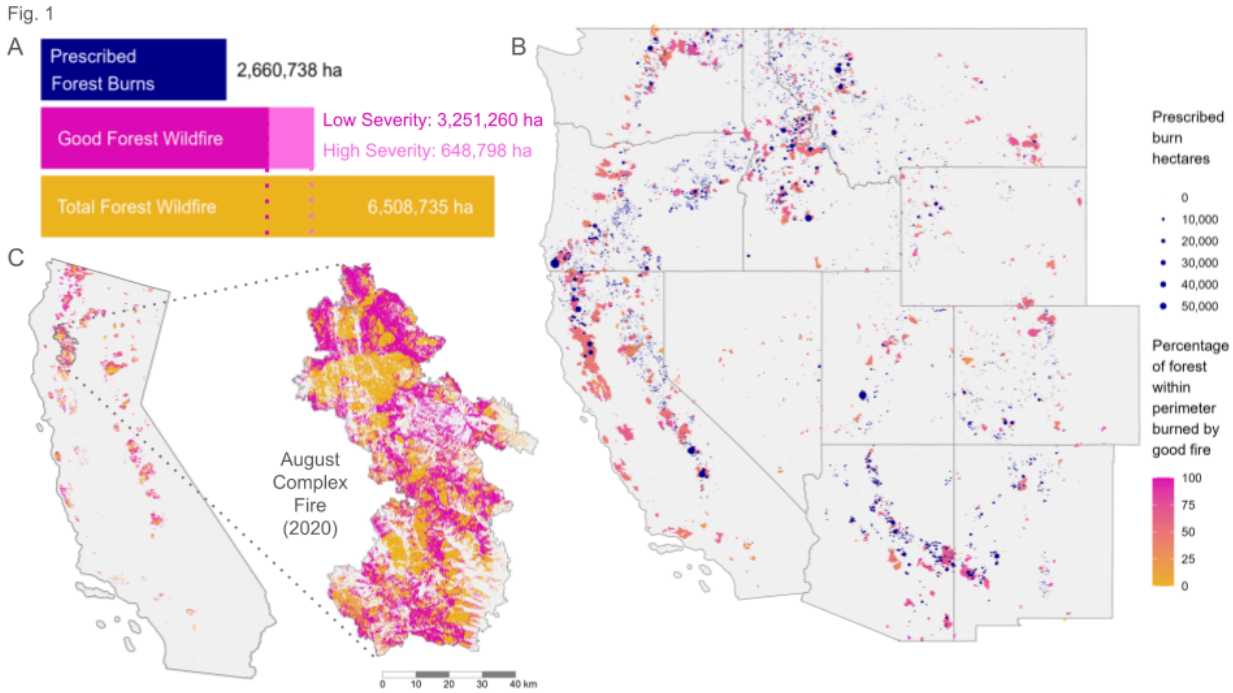


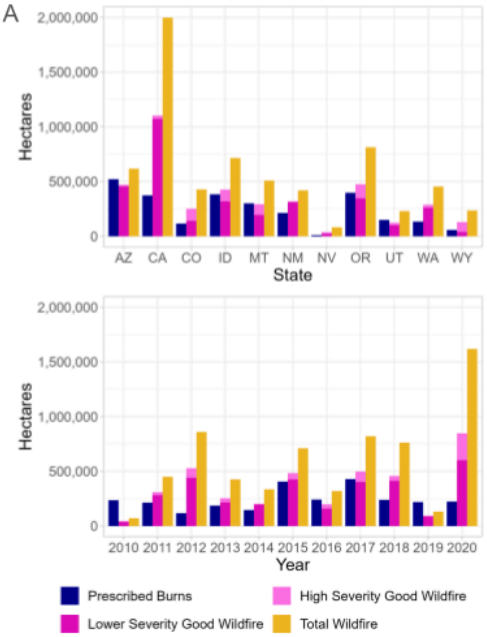
Figure 1. *Good fire in western U.S. forests (2010-2020) (A) Area of prescribed fire, low-moderate and high severity good fire, and total wildfire. Good fire is a subset of total wildfire; prescribed fire is not. (B) The extent of good fire and proportion within individual fire perimeters (gradation from yellow (0%) to pink (100%)), compared with prescribed forest fires (blue). Fire perimeters contained >10% forest in the year before burn. (C) The extent of good fire in California and the August Complex fire showing the extent and patterning of good fire (pink) and all other forest fire (yellow).*

We need a drastic reframing of wildfire to include the ecological benefits. Good fire constitutes cultural fire, prescribed fire, and managed wildfire. Indigenous communities around the world practice forms of patch mosaic burning to manage ecosystems (9, 10). We need to shift (back) to a more holistic approach of land stewardship that honors the intent and traditional knowledges around cultural fire (11). In addition to supporting indigenous burning, we need to enact more prescribed burning (12). The recent $4.4B federal investment in the U.S. for prescribed fire by the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) (13) is an important step in the right direction. States are accomplishing significant amounts of prescribed burning (Figure 2), but need to treat more acres. One underrecognized way is through promoting good wildfire. Fire suppression teams should get credit for the hard work that actually contributes to wildfires burning at lower severities. And while we only consider fire severity here, there are many types of good wildfire that should be considered in future work (see SI Appendix), such as slower and cooler fires, which will be easier to manage. There is a key need to develop a framework for measuring multiple dimensions of beneficial fire that enables managing for ecological benefits.

Fundamentally, we need to recognize that wildfires themselves are doing beneficial work at broad scales, both reducing future fire risk and sustaining healthy ecosystems that need it.

Fig. 2

A



B

Good fire in the western U.S. by year, state, and overall (2010-2020)

Group	Prescribed burn forest ha	Lower severity good forest wildfire ha	High severity good forest wildfire ha	Total good forest wildfire ha	Total forest wildfire ha	All good forest wildfire as a percentage of total forest wildfire	All good forest wildfire as a percentage of total forest
Arizona	521,512	455,869	15,111	470,980	618,602	76%	13.3%
California	373,682	1,073,626	30,152	1,103,778	1,999,146	55%	12.3%
Colorado	116,182	142,141	109,488	251,629	428,379	59%	3.7%
Idaho	384,102	318,746	108,481	427,227	715,328	60%	6.6%
Montana	301,283	195,446	97,242	292,687	509,645	57%	3.8%
Nevada	11,065	23,759	13,352	37,111	82,061	45%	1.8%
New Mexico	213,539	312,938	6,507	319,444	420,149	76%	7.8%
Oregon	397,789	347,993	127,274	475,268	813,717	58%	5.2%
Utah	149,633	100,776	22,669	123,445	230,698	54%	3.1%
Washington	133,914	261,455	26,742	288,197	454,741	63%	3.9%
Wyoming	58,038	38,510	91,771	130,281	236,270	55%	4.5%
2010	236,633	39,894	4,701	44,596	71,532	62%	0.1%
2011	213,596	282,715	26,921	309,636	449,842	69%	0.5%
2012	117,740	441,921	86,482	528,403	860,439	61%	0.8%
2013	186,641	216,244	38,273	254,517	426,233	60%	0.4%
2014	146,270	197,690	5,970	203,661	335,449	61%	0.3%
2015	406,186	425,199	58,479	483,678	711,386	68%	0.8%
2016	241,780	159,196	39,534	198,729	319,869	62%	0.3%
2017	429,431	403,449	93,506	496,955	820,891	61%	0.8%
2018	239,595	413,674	44,614	458,288	762,084	60%	0.7%
2019	219,365	88,422	5,701	94,123	131,847	71%	0.2%
2020	223,500	602,855	244,609	847,464	1,619,162	52%	1.4%
All Years	2,660,738	3,271,260	648,789	3,920,049	6,508,735	60%	6.2%

Figure 2. *(A) The area (ha) of good wildfire in the western U.S. by state and year, compared with the total forest area that burned and the amount of prescribed fire conducted. Good fire is a subset of total wildfire; prescribed fire is not. (B) Area (ha) of total burned areas and good forest wildfire as a percentage of total forest wildfire and as a percentage of total forest. Total forest area for each state and 'All Years' is averaged over 2010-2020.*

Knowing that wildfires are going to occur, we need to fundamentally shift our management approach. We need to better cultivate good wildfires that will be less intense and more restorative, while at the same time protecting people and homes. There may be fire management tactics that could accomplish this, such as promoting lower intensities at the interior area of wildfires, rather than just focusing suppression on fire edges. Moreover, we should capitalize better on recent wildfire footprints as places to prioritize future prescribed and cultural burning and use wildfire boundaries as spatial breaks for future burns that restore adjacent fire-excluded ecosystems. Capitalizing on wildfires in these and other ways offers promise for hastening the recovery of fire-prone landscapes across the western US. We also need to consider that in a warming climate with more wildfires projected (14) the window is shrinking for less intense and lower severity fires. If we imagine that every square inch of the west will burn, as a question of *when*, rather than *if*, how can we manage our landscapes for that eventuality? Seeing wildfires for the positive work they generate allows land managers and society to better sustain fire-prone landscapes, which is where we call home across the west.

Materials and Methods

In order to quantify the area burned by “good fire” in western U.S. forests (2010-2020) we estimate the area burned that matches in severity with what that region experienced historically prior to European settlement (15). We estimated the Composite Burn Index (16), a measure of the degree of ecosystem response or severity, across 18,126 wildfire perimeters (event size range: 1-432,000 ha) collected from the “combined wildland fire polygons” dataset (17) and the Monitoring Trends in Burn Severity (MTBS) program (18). We compare with the area of prescribed burning across western U.S. forests (N = 26,813), which mostly occurs in low-moderate severity regions (85% by area; see Extended Methods). See Extended Methods.

Extended methods

We analyzed wildfires from 2010-2020 within 11 states in the western United States: Washington, Oregon, California, Idaho, Montana, Nevada, Utah, Colorado, Wyoming, New Mexico, and Arizona. In order to capture wildfires of all sizes we integrated wildfire perimeters from multiple sources. Our source for large wildfires was the Monitoring Trends in Burn Severity (MTBS) fire perimeters, which comprise all wildfires ≥ 405 ha in the western U.S. starting in 1984 (Eidenshink et al. 2007). Our source for data on wildfires < 405 ha was the “combined wildland fire polygons" dataset (Welty and Jeffries 2021). This dataset integrates 40 different data layers and is designed to be a comprehensive collection of wildfire boundaries within the United States. In total, our dataset included a total of 3,197 large (≥ 405 ha) and 14,929 small (< 405 ha) wildfire perimeters for the western U.S. (total N = 18,126).

Within fire perimeters and at prescribed burn event locations, we focused exclusively on areas that were forested one year before the fire. We used two land cover products to calculate forested area: the Landscape Change Monitoring System (LCMS) Land Cover Class v2022.8 (19) and the Land Change Monitoring, Assessment, and Projection (LCMAP) Primary Land Cover v1.3 (20). Areas were considered forested only if both land cover products classified them as “tree cover” (i.e., deciduous, evergreen, and mixed forest trees; woodlands were excluded) the year prior to the wildfire or prescribed fire event. Combining the two land cover maps produced a more conservative estimate of forest cover, and reduced the ‘false positive’ forest present in either individual product. Utilizing the combined dataset, the total forested area across the 11 western U.S. states was 62 million ha in 2020.

Within the forested pixels of each fire perimeter, we calculated the Composite Burn Index (CBI), a commonly used and ecologically meaningful measure of fire severity. CBI was estimated using the method described in Parks et al. (2019), which uses random forest regression to calculate CBI based on Relativized Burn Ratio (RBR), latitude, climatic water deficit, and other factors. RBR was calculated using pre- and post-fire image composites of Landsat 4-9 imagery (Collection 2) during the growing season. A correction was applied to the CBI estimates to prevent overprediction at low values (16). We applied commonly used CBI thresholds to identify low-moderate (CBI >= .1 and <2.25) and high severity burned areas (CBI >= 2.25), e.g., see (21). High severity CBI is associated with complete vegetation mortality, while low-moderate CBI is associated with lower levels of vegetation cover change and mortality (21). In fire-adapted forested ecosystems, “good fire” burns at a severity level that is aligned with its historical fire severity prior to European settlement. To estimate historical fire severity characteristics, we used the Landfire Fire Regime Groups (FRG) dataset v1.2.0 , which models presumed fire regime classes based on vegetation dynamics, fire behavior and effects, and biophysical context (15) to distinguish between areas of historical “low and mixed severity” (FRG classes 1 and 3) and “replacement severity” (FRG classes 2 and 4) of any return interval. We then identified two classes of “good fire” in forested

ecosystems: low-moderate severity and high severity. “Lower severity good fire,” (the focus of this research) was defined as low-moderate severity pixels within historically “Low and Mixed Severity” regimes. “High severity good fire” was defined as high severity pixels within historically “Replacement Severity” regimes.

To compare estimates of good forest fire to the forested area impacted by prescribed burning in the western U.S. we used data on 25,761 prescribed burn events in forest systems on national public lands from the National Fire Plan Operations and Reporting System (NFPORS) (22), represented as spatial points. While there are extensive private lands across the western United States not represented in this database, prescribed burning of forested private lands is uncommon across the 11 states analyzed (23). While alternative datasets exist to represent prescribed fire, our data exploration revealed the NFPORS database to be the most comprehensive; additionally, the use of polygons and calculated CBI would not be appropriate for analyzing prescribed fire given the diverse set of forest treatments included in this analysis. We extracted LCMS, LCMAP, and Landfire Fire Regime Group data at each NFPORS data point in Google Earth Engine and processed the data under the assumption that the land cover and historic fire severity characteristics at the datapoint was representative of conditions across the entire burn area. Prescribed burns were only included in our analysis if treatments had an accomplishment date and both land cover datasets identified forested cover at their location in the year prior to treatment. We defined prescribed burning as inclusive of the following treatment types: broadcast burning, machine pile burning, jackpot burning, hand pile burning, and general fire use. Of all the forested prescribed burn events 22,508/25,761 (87.4%) were in low-moderate severity regions. The total area of all prescribed burns that was co-located with these same regions was 2,268,488 ha/2,660,738 ha (85.8%). When comparing the amount of good wildfire with the area of prescribed burns in low-moderate severity regions, wildfires accomplished 44% more low-moderate severity burning by area than that which was accomplished through prescribed burning.

While we explore one aspect of good fire, severity, there are many characteristics that are worth exploring in future work. For example, good fires may also be longer-interval, slower, smaller, patchy, and/or easier to manage during suppression. We will need future research to understand how we can better promote ecologically beneficial patches during a wildfire, such as through autonomous aircraft being used to cool and slow fires or other technological solutions. Good fires may have more specific ecological benefits, such as removing invasive species, reducing competition among native trees, or promoting re-sprouting of grasses for livestock or hunting. We may also define good fires with a combined social-ecological emphasis, such as by ecological benefits in tandem with minimized direct impacts on society and infrastructure, such as reducing homes destroyed, lives lost, or population impacted by smoke.

All code used for analyses described in this article are publicly available at: https://github.com/TylerLMcIntosh/a-number-on-good-fire.

Author Contributions

Conceptualization: J.K.B., W.D.H., K.D.M., R.V.P., C.L.R., B.J.H.; Methodology: J.K.B., T.L.M., R.V.P., Investigation: J.K.B., T.L.M., R.V.P.; Formal analysis: T.L.M., R.V.P.; Visualization: J.K.B., T.L.M., N.T.I., R.V.P.; Data curation: T.L.M., K.C.; Funding acquisition: J.K.B., W.D.H., B.J.H.; Project administration: T.L.M., J.K.B.; Resources: J.K.B.; Supervision: J.K.B.; Validation: T.L.M.; Writing - original draft: J.K.B., T.L.M., R.V.P., K.D.M.; Writing - review & editing: All authors.

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Competing Interest Statement

Authors have no competing interests to disclose**.**

References

1. S. J. Pyne, Fire in the mind: changing understandings of fire in Western civilization. *Philos. Trans. R. Soc. B Biol. Sci.* **371**, 20150166 (2016).
2. A. Fidelis, Is fire always the “bad guy”? *Flora* **268**, 151611 (2020).
3. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci.* **113**, 11770–11775 (2016).
4. P. Krebs, G. B. Pezzatti, S. Mazzoleni, L. M. Talbot, M. Conedera, Fire regime: history and definition of a key concept in disturbance ecology. *Theory Biosci.* **129**, 53–69 (2010).
5. M. Bond, R. Siegel, R. Hutto, V. Saab, S. Shunk, A New Forest Fire Paradigm: The Need for High-Severity Fires. *Wildl. Prof.* 46–49 (2012).
6. K. T. Davis, *et al.*, Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proc. Natl. Acad. Sci.* **120**, e2208120120 (2023).
7. B. J. Harvey, M. S. Buonanduci, M. G. Turner, Spatial interactions among short-interval fires reshape forest landscapes. *Glob. Ecol. Biogeogr.* **32**, 586–602 (2023).
8. A. P. Williams, *et al.*, Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earths Future* **7**, 892–910 (2019).
9. C. Eisenberg, *et al.*, Out of the Ashes: Ecological Resilience to Extreme Wildfire, Prescribed Burns, and Indigenous Burning in Ecosystems. *Front. Ecol. Evol.* **7**, 436 (2019).
10. M. Adams, “Storytelling through Fire: The Socio-Ecological and Cultural Reclamation of Indigenous Cultural Fire in Northern California,” UC Davis. (2023).
11. F. K. Lake, *et al.*, Returning Fire to the Land: Celebrating Traditional Knowledge and Fire. *J. For.* **115**, 343–353 (2017).
12. C. A. Kolden, We’re not doing enough prescribed fire in the western United States to mitigate wildfire risk. *Fire* **2**, 30 (2019).
13. E. Goldman, A. Wu, K. Kohn, A. Bartuska, Visualizing Federal Funding For Wildfire Management And Response. (2022).
14. J. J. Stephens, *et al.*, Fires of Unusual Size: Future of Extreme and Emerging Wildfires in a Warming United States (2020-2060). [Preprint] (2023). Available at: https://essopenarchive.org/users/705887/articles/691394--fires-of-unusual-size-future-of-extreme-and-emerging-wildfires-in-a-warming-united-states-2020-2060?commit=d621f99431dbe73fb610b95dfabb07540e56c4ec [Accessed 2 December 2024].
15. Landfire, U.S. Department of Agriculture, U.S. Department of the Interior, U.S. Geological Survey, The Nature Conservancy, Landfire FRG (Fire Regime Groups) Layer. Google Earth Engine. Deposited 2016.

16. Parks, *et al.*, Giving Ecological Meaning to Satellite-Derived Fire Severity Metrics across North American Forests. *Remote Sens.* **11**, 1735 (2019).
17. J. Welty, M. Jeffries, Combined wildland fire datasets for the United States and certain territories, 1800s-Present. U.S. Geological Survey. https://doi.org/10.5066/P9ZXGFY3. Deposited 2021.
18. J. Eidenshink, *et al.*, A Project for Monitoring Trends in Burn Severity. *Fire Ecol.* **3**, 3–21 (2007).
19. USDA Forest Service, USFS Landscape Change Monitoring System (Conterminous United States and Southeastern Alaska). Deposited 2023.
20. J. F. Brown, *et al.*, Lessons learned implementing an operational continuous United States national land change monitoring capability: The Land Change Monitoring, Assessment, and Projection (LCMAP) approach. *Remote Sens. Environ.* **238**, 111356 (2020).
21. J. D. Miller, A. E. Thode, Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sens. Environ.* **109**, 66–80 (2007).
22. U.S. Department of Agriculture, U.S. Department of the Interior, National Fire Plan Operations and Reporting System (NFPORS).
23. J. Wood, M. Varner, “Burn Back Better” (2023).