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To cite this article: Lucas B Harris *et al* 2024 *Environ. Res. Lett.* **19** 114070

View the article online for updates and enhancements.

IOP Publishing Environ. Res. Lett. 19 (2024) 114070 https://doi.org/10.1088/1748-9326/ad8462

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
19 July 2024

REVISED
1 October 2024

ACCEPTED FOR PUBLICATION
8 October 2024

PUBLISHED
17 October 2024

LETTER

Severity of a megafire reduced by interactions of wildland fire suppression operations and previous burns

Lucas B Harris[1,*], Calvin A Farris[2], Dani Niziolek[3,4] and Alan H Taylor[3]

[1] Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405, United States of America
[2] National Park Service Fire Management, Pacific West Region, Klamath Falls, OR 97601, United States of America
[3] Department of Geography and Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, PA 16802, United States of America
[4] Current address: Great Basin Institute, 16750 Mt. Rose Highway, Reno, NV 89511, United States of America.
[*] Author to whom any correspondence should be addressed.

E-mail: lucas.harris@uvm.edu

Keywords: fire severity, fire management, forest resilience, fire suppression, fire exclusion, reburns

Supplementary material for this article is available online

Abstract

Burned area and proportion of high severity fire have been increasing in the western USA, and reducing wildfire severity with fuel treatments or other means is key for maintaining fire-prone dry forests and avoiding fire-catalyzed forest loss. Despite the unprecedented scope of firefighting operations in recent years, their contribution to patterns of wildfire severity is rarely quantified. Here we investigate how wildland fire suppression operations and past fire severity interacted to affect severity patterns of the northern third of the 374 000 ha Dixie Fire, the largest single fire in California history. We developed a map of the intensity and type of suppression operations and a statistical model of the Composite Burn Index (CBI) including weather, fuels, and terrain variables during the fire to quantify the importance of operations and prior fires on wildfire severity. Wildfire severity was estimated without operations and previous fires and then compared with modeled severity under observed conditions. Previous low and moderate-severity fire without operations decreased CBI by 38% and 19% respectively. Heavy operations and offensive firing in the footprint of past fires lowered fire severity even more compared to prior fire alone. Medium operations and defensive firing reduced but did not eliminate the moderating effects of past fires. This analysis demonstrates important interactions between suppression operations and previous burns that drive patterns of fire severity and vegetation dynamics in post-fire landscapes. Given the need to reduce wildfire severity to maintain forest resilience, particularly with a warming climate, increased attention to using operations and severity patterns of previous fires known to reduce wildfire severity in megafires are likely to increase forest resilience and improve ecological outcomes.

1. Introduction

Burned area and the proportion of high-severity fire have increased since the mid-1980's in forests of the western USA (Westerling 2016, Parks and Abatzoglou 2020), creating widespread potential for fire-driven conversion of forests to non-forest (Coop *et al* 2020, Guiterman *et al* 2022) with profound long-term negative consequences for wildlife habitat (Ayars *et al* 2023), water quality (Raoelison *et al* 2023) and carbon stocks and sequestration (Peeler *et al* 2023). Consequently, reducing the severity of future wildfires is a key management goal and an impetus to scale-up fuel treatments in forests that historically burned frequently (Kalies and Yocom Kent 2016, Williams *et al* 2024).

As fire occurrence and area burned increases in forests of the western USA, fire regimes are transitioning from being mainly controlled by fuels, fire weather, and terrain in long unburned landscapes to a fire regime controlled by initial fire severity and rates of fuel recovery in reburns (Buma *et al* 2020, Taylor *et al* 2021). High-severity wildfire can lead to forest loss in dry pine and mixed-conifer forest and when these areas reburn they tend to burn at high-severity again (figure 1(A)), while initial low-severity wildfire

fire reduces fuels and reburns tend to be low in severity (Harris and Taylor 2017, Coop *et al* 2020). The self-reinforcing nature of fire severity in reburn landscapes is most evident with fire return intervals of 10–20 years for dry pine and mixed-conifer forests and likely longer for higher elevation fir-dominated forests (Parks *et al* 2014, Harvey *et al* 2016, Harris and Taylor 2017), and fire severity can drift upward with longer periods between reburns (Taylor *et al* 2021). Low and moderate-severity wildfires are becoming more widespread in dry pine and mixed-conifer forest and can be considered treatments that reduce potential for undesirable high severity fire effects across landscapes and regions (Hessburg *et al* 2019, Taylor *et al* 2022, Davis *et al* 2024). Furthermore, low and moderate severity fire effects buffer the negative effects of climate change on tree regeneration compared to areas that burn at high severity, at least for climate projections spanning the next 50 years (Davis *et al* 2023).

Fire management plays a strong role in shaping fire extent and severity in the western USA and globally (Parks *et al* 2023, Kreider *et al* 2024). Effective fire suppression tends to increase fire extent and severity by promoting long term fuel buildup, and by extinguishing most ignitions. Fires that do escape initial attack are usually burning under extreme weather or terrain conditions (Calkin *et al* 2015) and this 'suppression bias' has a strong effect and increases proportions of high-severity fire (Kreider *et al* 2024). Similarly, wildland fire suppression operations (e.g. the suite of ground- and aerial-based firefighting tactics used to suppress fires, hereafter 'suppression operations') on wildfires that escape initial attack are likely to have pervasive effects on fire severity but they are poorly known and understood.

Suppression operations may either increase or decrease fire severity depending on the interactions between (a) the specific tactics used within the broader context of concern for lives, property, and resources; and (b) fuel, terrain and weather. A common narrative is that firing operations (i.e. backfires or burn outs) used to consume fuel in advance of a fire-front lead to undesirable high-severity fire effects (Backer *et al* 2004, Driscoll *et al* 2010, Stephens *et al* 2013). Yet, well-timed and strategically located firing operations may also reduce wildfire fire severity by reducing head fire formation or delaying fire spread until weather is more favorable, as was found in an analysis of the severity patterns of California's Reading Fire in 2012 (Harris *et al* 2021a).

The range of suppression options is greater within areas of past low to moderate-severity fire where fuels and fire hazard are reduced. This may create a positive feedback between operational flexibility and previous low–moderate-severity fire (Agee *et al* 2000, Moghaddas and Craggs 2007, Vorster *et al* 2023) that encourages forest persistence (figure 1(B)) and aids efforts to scale-up use of low-severity fire as a fuel treatment. For example, the combination of low and moderate-severity fire with operations in one study reduced severity by two-fold compared to either operations or severity alone (Harris *et al* 2021a). Suppression operations that reduce severity in reburns could also facilitate forest recovery following a previous moderate–high-severity wildfire by allowing some vegetation including tree regeneration to persist (figure 1(C)).

Recent large fires have necessitated an unprecedented scope of suppression operations (i.e. funds, equipment and personnel). For example, national federal suppression costs in the USA topped $4 billion for the first time in 2021 (www.nifc.gov/fire-information/statistics). That year, California's Dixie Fire cost >$600 million to suppress and had >6000 personnel assigned to the fire at its peak (McDonald *et al* 2021). Quantitative estimates of the effects of these operations on fire severity are rare for two reasons. First, there is a need to counterfactually assess what fire severity would have been in the absence of operations (Harris *et al* 2021a). Second, relying on archival incident data alone to develop a spatially explicit reconstruction of fire operations is problematic because these data are typically incomplete and inconsistent, and may require interpretation by experienced fireline personnel who were managing the fire (Harris *et al* 2021a).

Here, we investigate how interactions between suppression operations and prior fires influenced fire severity within California's 2021 Dixie Fire, the largest recorded individual wildfire to date in California at 374 000 ha. To our knowledge, this is the first study to quantify the effects of suppression operations and previous fires on fire severity patterns of a megafire. We selected the Dixie Fire opportunistically based on the feasibility of reconstructing fire suppression operations, yet it is a compelling case study that is emblematic of broader fire management challenges in western USA forests in the following ways: (1) it was a megafire burning under extreme weather with high rates of spread (Coop *et al* 2022, Taylor *et al* 2022, Cova *et al* 2023), (2) it burned over a mosaic of long-unburned and recently-burned areas, and (3) it necessitated a strong and complex suppression response including the implementation of large fire tactics. We used a recently-developed methodological framework to predict fire severity under observed conditions and counterfactual scenarios representing conditions in the absence of suppression operations and/or past fires (Harris *et al* 2021a). A map of operational categories was developed across 133 000 ha of the northern arm of the Dixie Fire centered around Lassen Volcanic National Park (LVNP), using incident maps, documents, and consultation with fire management personnel directly involved with managing the northern section of the Dixie Fire (figure 2).

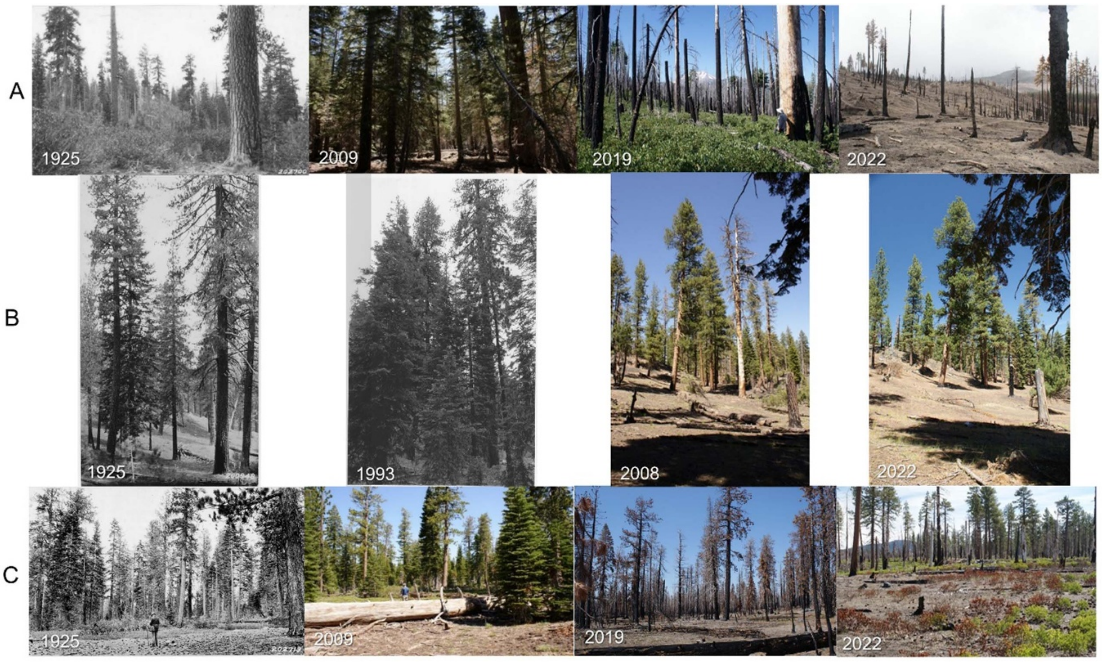

Figure 1. The effects of fire suppression, suppression operations and initial fires on severity as seen in repeat photographs in the footprint of the 2021 Dixie Fire: (A) mixed conifer forest showing infilling due to fire suppression, the effects of a severe 2012 wildfire that killed the forest canopy and switched vegetation to fire dependent shrubs which was reburned at high severity by the Dixie fire in a location where operations were minimal; (B) Jeffrey pine forest showing infilling caused by fire suppression, the effects of two prescribed fires (1998, 2004) and low-severity effects from the Dixie Fire where operations were offensive firing; (C) mixed conifer forest showing infilling due to fire suppression, the effects of a severe wildfire in 2012, and low-severity effects from the Dixie Fire in a location where operations were heavy.

This allowed us to quantify and map how suppression operations interacted with past low, moderate and high-severity fire to affect fire severity outcomes.

2. Methods

2.1. Study area

We limited our analysis to the northern arm of the Dixie Fire (133 000 ha) because this area contained a rich history and mosaic of previous fires on National Park Service and United States Forest Service lands, and because consultation with fire managers indicated there was sufficient data in this part of the fire to develop a map of variation in suppression operations (figure 2). The Dixie Fire began on 13 July 2021, and the northern arm of the fire which comprised our study area burned between 2 August and 6 September. This period included days of atmospheric instability and plume-dominated fire behavior that saw rapid fire growth (Taylor *et al* 2022), including the top five days of growth across the entire Dixie Fire and four days with >15 000 ha burned in the study area (mean daily burned area = 3619 ± 6076 ha within the study area). Most of the fire's northern arm was on federal land including 54% on the Lassen National Forest and 21% within LVNP. Mid-montane, fir-dominated forest was the main vegetation type within the study area (64% according to CALVEG vegetation types) (Keeler-Wolf 2007) including locally abundant areas of white fir (*Abies concolor*) and red fir (*Abies magnifica*). Another 20% of the study area was dominated by either ponderosa pine (*Pinus ponderosa*) or Jeffrey pine (*Pinus jeffreyi*) forest, and lodgepole pine (5%) forest was common within LVNP in particular. Prior to Euro-American settlement, these pine forests would have commonly experienced fire return intervals of <20 years whereas cooler more mesic fir-dominated forests would have burned at intervals ranging from 20 years to >100 years (Taylor 2000, van de Water and Safford 2011). Exclusion of fire since the early 20th century by federal agencies dramatically increased forest fuel load and fuel continuity increasing potential for high severity fire (figure 1).

2.2. Fire severity and predictors

The severity of the Dixie Fire was quantified using estimates of Composite Burn Index (CBI) values estimated from Landsat imagery following Parks *et al* (2019). CBI is a field-derived index of fire effects on vegetation across vegetation strata, and ranges from 0 to 3 with values <1.25 commonly considered low-severity (limited vegetation mortality) and values >2.25 representing high-severity effects (near-total vegetation mortality) (Key and Benson 2006).

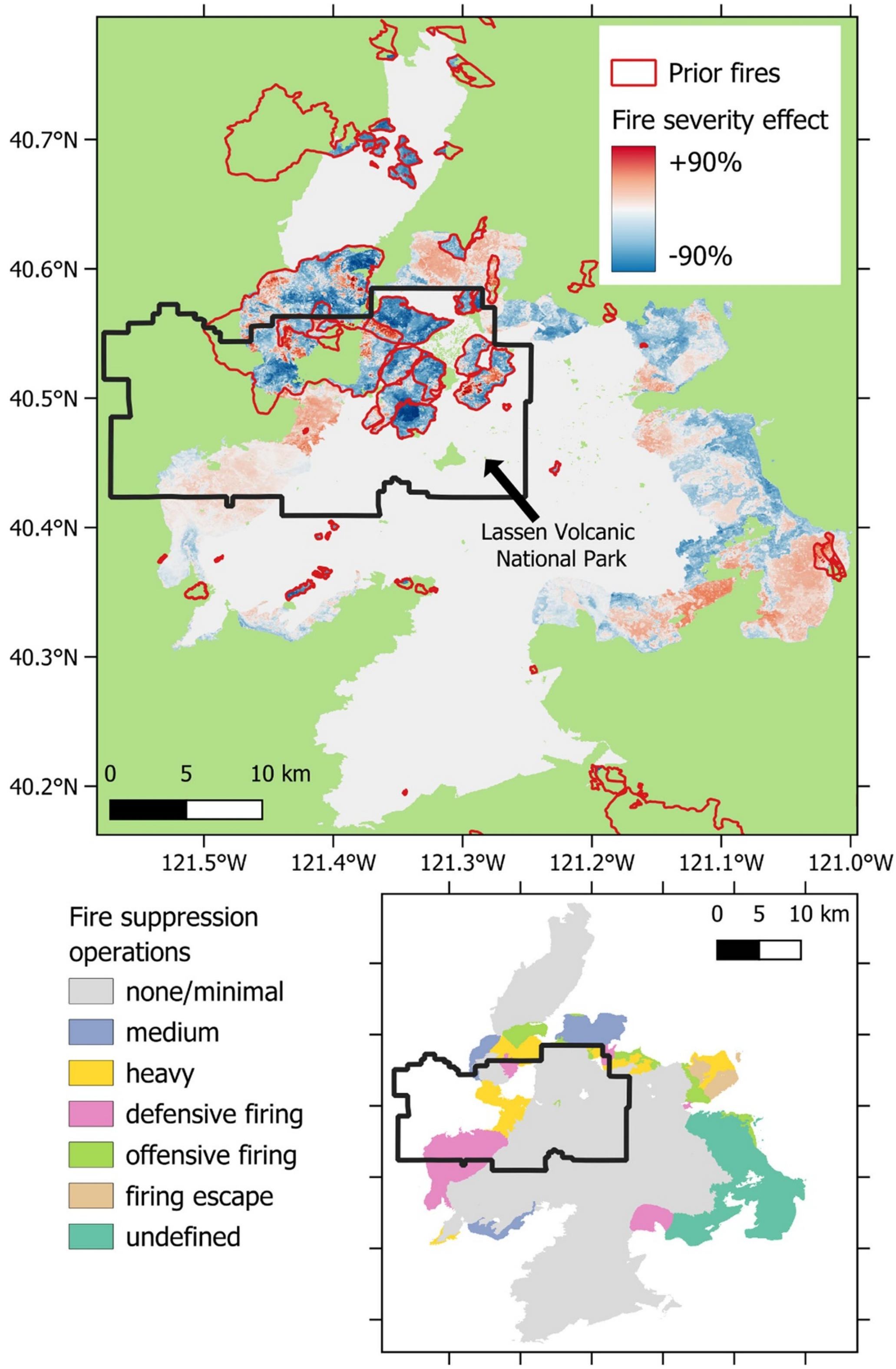

Figure 2. The effect of operations and prior fire severity on severity within the northern arm of the Dixie Fire based on a comparison of predicted fire severity values under observed conditions against predicted values under a 'no operations or prior fire' scenario. Reds (blues) indicate that operations and prior fires increased (decreased) severity. Inset shows categories of wildland fire suppression operations that took place during the Dixie Fire.

Output from this method correlates well with field-measured CBI ($R^2 = 0.73$) in California forests (Parks *et al* 2019). Prior to analysis, the LANDFIRE Fire Behavior Fuel Model layer representing conditions in 2020 (https://landfire.cr.usgs.gov/fbfm13.php) was used to screen out developed and agricultural areas, snow and ice, water and barren land from the analysis (Reeves *et al* 2009).

Table 1. Variables considered for random forest model of Dixie Fire severity.

Category	Variable	Source/Details
Response	Composite Burn Index (CBI) from the Dixie Fire	Parks *et al* (2019)
Vegetation/fuels	Bare ground cover	Rigge *et al* (2022)
Vegetation/fuels	Herbaceous cover	Rigge *et al* (2022)
Vegetation/fuels	Litter cover	Rigge *et al* (2022)
Vegetation/fuels	Shrub cover	Rigge *et al* (2022)
Vegetation/fuels	Tree cover	Rigge *et al* (2022)
Vegetation/fuels	Normalized Differenced Vegetation Index	Maximum April–June value from Landsat imagery
Terrain	Elevation	30-m Digital Elevation Model
Terrain	Slope	30-m Digital Elevation Model
Terrain	Aspect (cosine-transformed)	Beers *et al* (1966)
Terrain	Topographic Position Index	Weiss (2001); using a circular 500-m window
Terrain	Roughness	Standard deviation of elevation in a circular 500-m window
Terrain	Surface Relief Ratio	Wood and Snell (1960); using a circular 500-m window
Water balance	Actual Evapotranspiration	Flint *et al* (2021); 2010–2020 means
Water balance	Climatic Water Deficit	Flint *et al* (2021); 2010–2020 means
Weather	Maximum temperature	Abatzoglou (2013)
Weather	Minimum relative humidity	Abatzoglou (2013)
Weather	Maximum relative humidity	Abatzoglou (2013)
Weather	Vapor pressure deficit	Abatzoglou (2013)
Weather	Average wind speed	Abatzoglou (2013)
Weather	Energy Release Component	Bradshaw *et al* (1983), Abatzoglou (2013)
Operations	Operations category	See table 2
Fire/treatment history	Prior fire severity	Parks *et al* (2019); classified into no fire, low, moderate or high-severity
Fire/treatment history	Time since last fire	Taylor *et al* (2022): none, <10 years, 10–20 years, 20–30 years, >30 years
Fire/treatment history	Time since last mechanical treatment	Taylor *et al* (2022): none, <10 years, $\geqslant 10$ years-152
Land ownership	Land ownership type	CAL FIRE's California Land Ownership layer (https://gis.data.ca.gov/datasets/CALFIRE-Forestry::california-land-ownership): other, Bureau of Land Management, Forest Service, National Park Service, California Department of Fish and Wildlife

A suite of vegetation and fuel, terrain, weather, and fire/treatment history rasters were used as potential predictors of Dixie Fire severity (table 1). Six terrain variables were calculated from a 30 m Digital Elevation Model (table 1). Daily weather was quantified by matching a previously-developed daily progression map of the Dixie Fire (Taylor *et al* 2022) to gridded weather from GridMET (Abatzoglou 2013). Perimeters of prior fire and fuel treatments were obtained from a prior analysis of the Dixie Fire (Taylor *et al* 2022). Severity of the most recent prior fire (1986–2020) was also calculated following Parks *et al* (2019) and classified into low (CBI $<$ 1.25), moderate and high (CBI $>$ 2.25), with an additional 'no prior fire' category for areas that did not burn from 1986 to 2020. Severity was only calculated for fires from 1986 to 2020 because pre-fire layers were needed to construct counterfactual 'no prior fire' scenarios (see *Quantifying influences of operations and prior fire*) and the vegetation cover data that we used began in 1985 (Rigge *et al* 2022). Note that we did consider mechanical treatment (table 1) but this variable was removed during the variable selection process, in line with Taylor *et al* (2022) who found that mechanical treatment alone did not substantially reduce the severity of the Dixie Fire.

2.3. Operations

Building on the methods of Harris *et al* (2021a), we used a combination of interagency incident data and firsthand observations by fire management personnel assigned to the incident to map seven categories of suppression operations (table 2). These categories represent a gradient between areas where operations were absent to areas where intensive ground and aerial operations dictated the fire growth patterns. Terminology follows definitions in the National Wildfire Coordinating Group (NWCG)

Table 2. Categories of wildland fire suppression operations.

Operations Class	Description
None/minimal	Areas where no suppression occurred, or only minor and spatially restricted activities that would have had no influence on overall fire spread or behavior (such as point protection around structures)
Medium	Areas where various direct or indirect suppression activities occurred (NWCG 2024), but were not intensive or widespread enough, or were not sustained long enough to have more than a localized influence on the fire. These may include helicopter bucket drops or fix-winged retardant drops, construction of contingency fire line, improvement of fuel breaks along roads or trails, and mop-up of hot spots near lines or roads.
Heavy	Areas with a combination of widespread tactics that exerted a direct and clear influence on overall fire growth and behavior. These consisted primarily of areas where crews performed offensive backfiring (often road systems) to check fire spread toward the line, and to prevent the formation of a head fire (i.e. 'staying even' with the fire). This often occurred over a series of several days and burn periods, often during favorable conditions. Also includes areas where ground and aerial resources aggressively extinguished or confined (with fire line) sections of the fire to prevent future growth.
Defensive firing	Areas burned directly by an emergency firing operation, whereby backfires were set from roads or bulldozer lines to "stop, delay, or split a fire front, or to steer a fire" (NWCG 2024). These represent emergency situations where urgency dictated the timing and implementation strategy of the firing. The entire polygon was burned by the firing (in contrast to incremental firing in the Heavy category where firing and natural spread were intertwined).
Offensive firing	Areas burned by burnout operations from indirect fire lines used to preemptively widen the lines and create blackened areas ahead of the main fire. These were often implemented under more moderate conditions than emergency firing because crews had more time and options (including ignition patterns).
Firing escape	Offensive firing that burned longer duration and larger extent than originally planned. However, these areas were indirectly influenced by surrounding suppression operations.
Undefined:	Areas that experienced a combination of direct and indirect suppression activities, but the specific timing, scale, and scope of the activities, and their subsequent impact on fire growth, could not be definitively resolved spatially. or differentiated between other categories.

glossary (NWCG 2024). We considered collectively the extent of firing and burnout operations, fire lines, ground attack efforts by engines and hand crews, aerial attack efforts such as helicopter drops and fix-wing retardants, and mop-up. The eastern portion of the study area was mapped as 'undefined' because operations known to have taken place could not be categorized or mapped with high confidence, although we believe the impacts were most likely high due to efforts to hold the fire along a major road.

We first examined official incident data as obtained from the National Interagency Fire Center (NIFC) archive (https://ftp.wildfire.gov/), the Wildland Fire Decision Support System (WFDSS) incident page (https://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml), and National Park Service documents (on file at LVNP). We evaluated incident maps and narratives from Incident Action Plans (IAP) and WFDSS to identify features like fire lines, burnouts, and in some cases retardant drops (where available). We used daily growth perimeters compiled by Taylor *et al* (2022) to identify corresponding spatial polygons and identify spatially and temporally anomalous burn patterns that would indicate firing operations (as indicated by separated and/or oddly shaped fingers or patches). These daily growth perimeters, which were derived from aircraft infrared mapping, were used to delineate operations boundaries in most cases. Narratives from daily IAPs and ICS-209 reports and recorded incident briefings were then evaluated to verify mapped observations and to identify additional information about operational tactics and strategies and crew assignments that would help to further resolve spatial patterns of operations that were not initially clear.

Then, we consulted with fire management personnel assigned to the Dixie Fire in various operational or planning roles (table S1) to improve the spatial resolution and delineation of operations and their impacts on fire growth by: (a) independently corroborating the initial mapping, (b) identifying gaps and areas of uncertainty, and (c) combining firsthand observations and incident data to refine and finalize the maps. We consulted personnel independently and in groups to arrive at a consensus. The author who performed the consultations (C.A. Farris) was a manager assigned to the Dixie Fire and served a vital role as a bridge between science and management. These sessions consisted of reviewing the fire day by day with personnel, and merging their firsthand observations with incident data and daily growth perimeters to arrive at a consensus on what types of operations were occurring on particular days and locations. This consultation process occurred independently of and prior to analyzing fire severity. In some cases, only one or two individuals had firsthand knowledge needed to verify the type and spatial location of activities on a given day (e.g. an individual present at a defensive firing, or an individual monitoring a portion of the fire via ground or air who could delineate approximately where firing merged with a fire front). In most cases multiple individuals were able to corroborate the spatial locations of different suppression operations.

2.4. Fire severity model

We developed a Random Forest (Breiman 2001) model to quantify factors contributing to variation in CBI in the Dixie Fire following the approach of Harris *et al* (2021a). Individual 30 m pixels were sampled from rasters of the predictor variables (table 1) at grid points spaced 450 m apart ($n = 6358$ samples) to address the potential influence of spatial autocorrelation. Sampling pixels is a common technique to address issues of spatial autocorrelation when modeling influences on fire severity (Dillon *et al* 2011, Birch *et al* 2015, Parks *et al* 2018), although an alternative technique is to explicitly incorporate spatial autocorrelation (Wimberly *et al* 2009, Povak *et al* 2020). The choice of spacing between samples is important in analyses of fire severity because using distances that are too short for a given dataset may inflate model accuracy and lead to overfitting (van Mantgem *et al* 2001, Kane *et al* 2015). Harris *et al* (2021a) found that closer spacing of 120 m was sufficient to reduce the influence of spatial autocorrelation, but given the greater size of our study area we found that a more conservative, wider spacing still yielded an adequate sample size for analysis. An examination of model residuals (figure S1) confirmed that spatial autocorrelation did not have a substantial impact on the model or its interpretation. Next, multicollinearity was addressed by identifying pairs of variables with Spearman rank correlation coefficients ($|r_s|$) > 0.7 and retaining the variable with greater importance (measured by the Model Improvement Ratio [MIR], Murphy *et al* 2010). Then, variables were selected using the interpretation procedure of the VSURF algorithm (Genuer *et al* 2015) to remove variables that did not contribute significantly to the accuracy of the model. For a given variable to be included, its removal had to increase out-of-bag (OOB) error to more than the previous OOB error plus its standard deviation (Genuer *et al* 2010). Finally, a final model was run with the selected variables ($n = 13$) using 2000 trees and otherwise default values from the 'randomForest' R package (v 4.7–1.1, Liaw and Wiener 2002). The relative importance and relationships of individual variables to Dixie Fire severity were assessed using variable importance (MIR) and partial dependence plots (Friedman 2001) implemented with the 'pdp' R package (Greenwell 2017).

2.5. Developing counterfactual scenarios for operations and previous fires

We quantified and mapped the influence of suppression operations and prior fires on the severity of the Dixie Fire by using counterfactual scenarios representing conditions in the absence of operations and prior fire. To assess fire severity in the absence of operations, a 'no operations' layer was created in which all values were set to 'no/minimal' operations. To assess fire severity in the absence of prior fire, prior fire severity was set to 'no prior fire' and vegetation/fuels layers were developed representing the conditions prior to the most recent fire for a given pixel. For the Normalized Differenced Vegetation Index (NDVI), the April–June maximum was calculated as for the Dixie Fire but for the year of each prior fire rather than 2021. For vegetation cover, values from the year preceding each fire were used (e.g. 2011 tree cover within a 2012 wildfire footprint). The model of Dixie Fire severity was then used to generate predicted CBI values (30 m grain size) under two sets of conditions: observed and conditions without operations or prior fires. These two sets of predicted CBI values were compared to quantify the magnitude of the effect of operations and prior fire on severity within each 30 m pixel of the study area. Effect size was calculated as:

$$\text{Effect size } (\%) = \frac{\text{CBI}_{\text{observed}} - \text{CBI}_{\text{none}}}{\text{CBI}_{\text{none}}} * 100$$

where $\text{CBI}_{\text{observed}}$ is predicted CBI under observed conditions and CBI_{none} is predicted CBI under the counterfactual scenario assuming no prior fire or operations. Percentage effects on fire severity were calculated for each combination of operations category and prior fire severity (mean ± standard deviation, area within each category is shown in table S2).

3. Results

3.1. Fire severity model

The northern arm of the Dixie Fire that comprised the study area burned at 48% high severity and 26% each low and moderate severity according to CBI classifications, similar to percentages for the entire Dixie Fire (45% high, 26% low, 29% moderate). The final fire severity model for the study area contained 13 variables and explained 56.0% of variability in CBI. NDVI was the most important variable and was positively related to CBI (figures 3 and S2). Cover of trees and herbs both had unimodal relationships with CBI. Four weather variables were retained: wind speed, temperature and the Energy Release Component had positive relationships with CBI and maximum relative humidity had a unimodal relationship (figures 3 and S2). Suppression operations category was moderately important (8th in importance), and its partial dependence plot indicated that CBI tended to

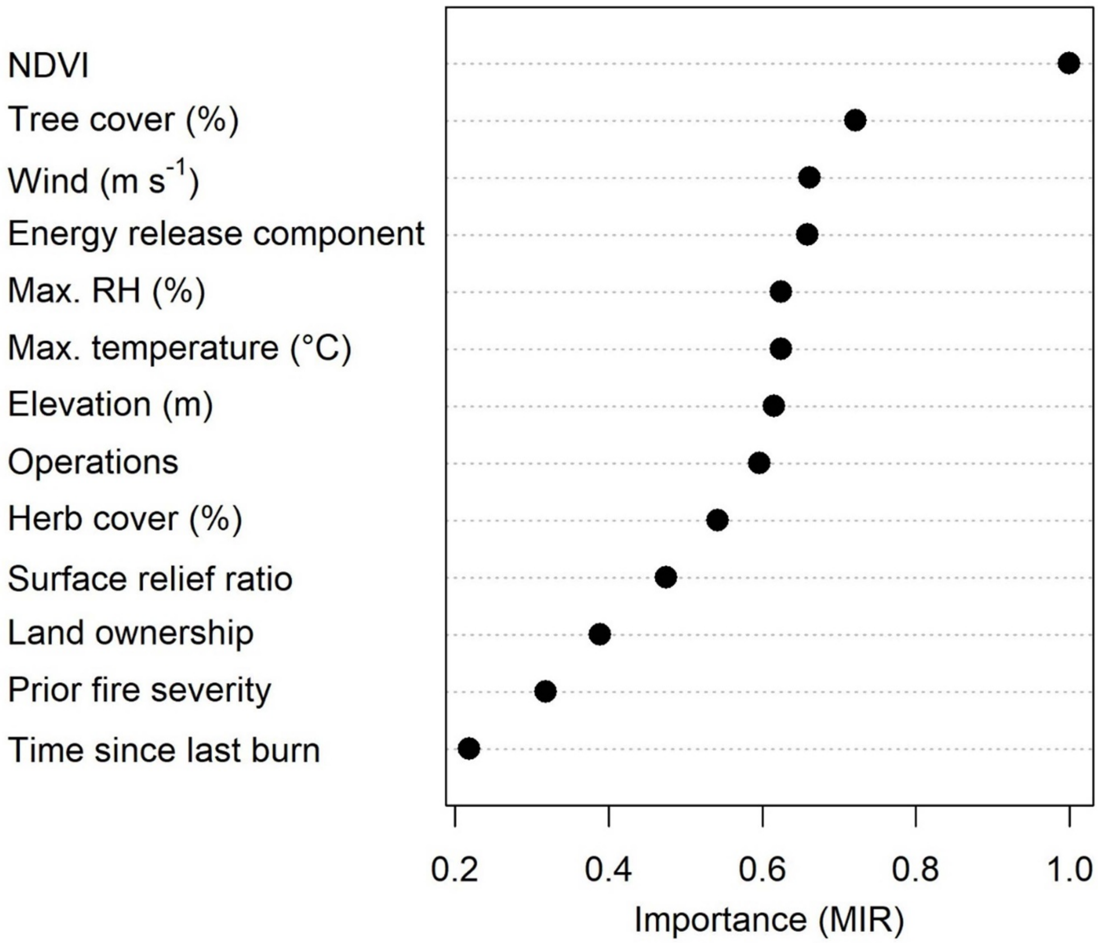

Figure 3. Variable importance (Model Improvement Ratio, MIR) from the Random Forest model of Dixie Fire severity. The most important variable is scaled to 1, whereas 0 indicates no improvement to model accuracy. NDVI is the normalized differenced vegetation index and RH is relative humidity.

be highest in areas with no/minimal operations or defensive firing operations and lowest in areas with offensive firing or heavy operations. Five other variables of low to moderate importance were included: elevation was unimodally related to CBI, the surface relief ratio was positively related to CBI, CBI was slightly higher on federal lands than other lands, the prior fire severity variable indicated that Dixie Fire CBI was highest in areas with no recent fire and lowest in areas with recent low-severity fire, and the time since last burn variable indicated that areas with no prior fire tended to experience higher severity and areas burned <20 years ago tended to experience lower severity (figures 3 and S2).

3.2. Effects of operations and prior fire

Counterfactual scenarios show how prior fire and operations interacted to influence fire severity. While effects on CBI were spatially variable (figure 2), the comparison of areas with different prior fire severity and operations categories revealed distinct effects (figures 4 and S3). In the absence of operations, prior low- and moderate-severity fire reduced Dixie Fire CBI by an average of 38% and 19% respectively (figure 4). In the absence of prior fire, three operations categories reduced CBI by up to 12% on average (heavy operations, offensive firing and escaped offensive firing) whereas defensive firing operations and medium operations increased CBI by 1% and 4% respectively (figure 4). Offensive firing augmented the beneficial effects of past low–moderate severity fire, reducing Dixie Fire CBI by 40%–49% on average. Heavy operations further reduced CBI in areas of past moderate-severity fire but not in areas of past low-severity fire. Meanwhile, medium operations and defensive firing reduced but did not eliminate the beneficial effects of past low–moderate severity fire. Notably, operations also dampened fire severity in areas of past high-severity fire across all categories of operations (figure 4).

4. Discussion

Resources dedicated to suppression operations in the USA have increased over the past several decades and are likely to continue increasing in the future (Calkin *et al* 2015), and accounting for their effects on fire severity is vital because fire severity patterns

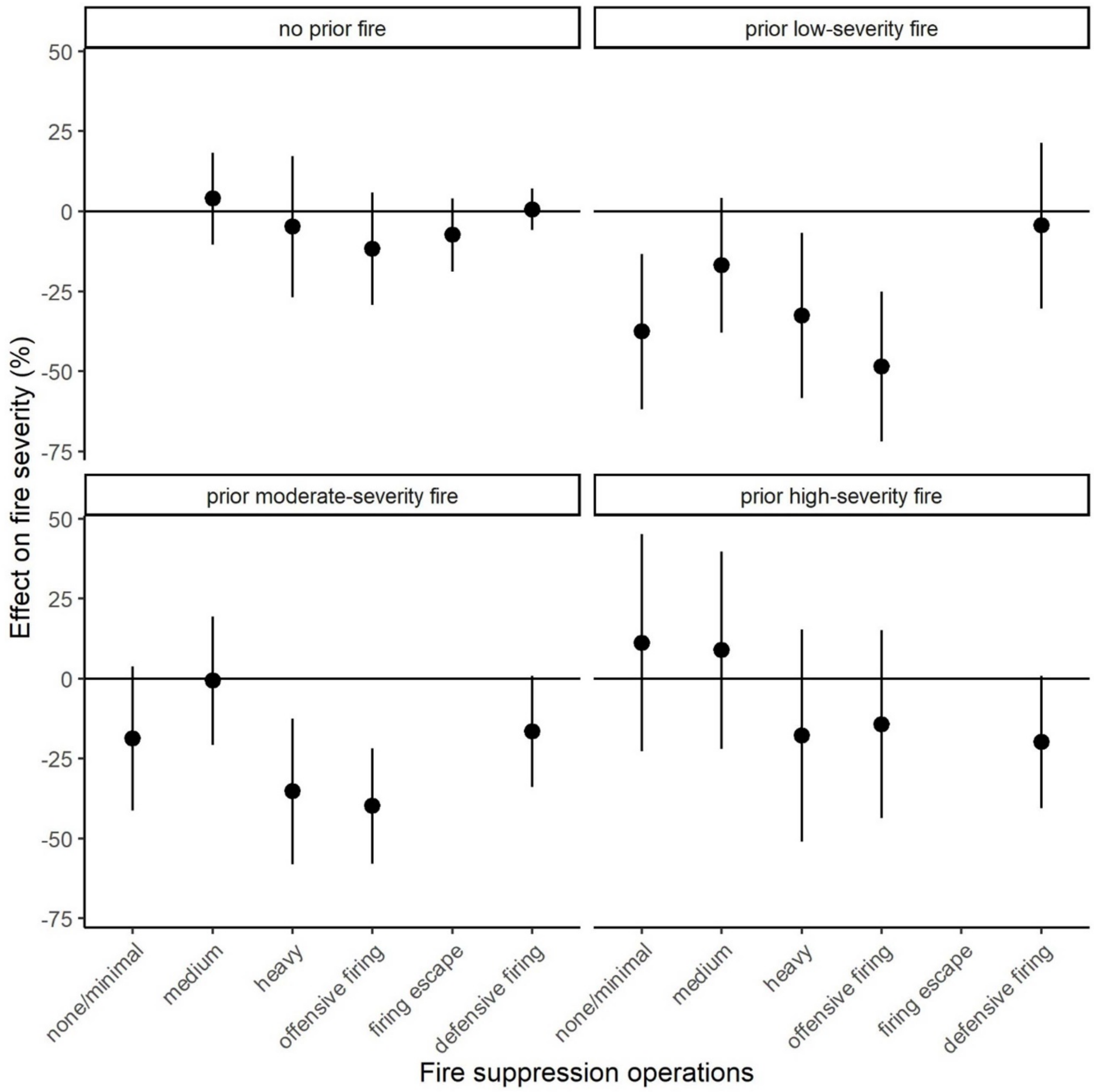

Figure 4. Effects of suppression operations and prior fires on the severity of the Dixie Fire (mean ± standard deviation of percentage change in Composite Burn Index, CBI) based on a comparison of predicted CBI under observed conditions with predicted CBI had operations and prior fires not occurred. Categories representing <100 ha are not shown.

are known to control vegetation dynamics (Johnstone *et al* 2016, Harris *et al* 2021b). One often repeated narrative on firing operations is that defensive firing operations, in particular, tend to produce high-severity effects (Backer *et al* 2004, Driscoll *et al* 2010, Stephens *et al* 2013). However, the modest effect of defensive firing we identified suggests that its potential to increase fire severity may be overstated since this tactic is used at times and locations when extreme fire weather, heavy fuels and rugged terrain already make high-severity fire effects more likely. Suppression operations can also reduce fire severity. Examples include offensive firing conducted under moderate weather conditions, or cases where operations delay fire spread until the weather moderates (Harris *et al* 2021a). Indeed, we found that heavy operations and offensive firing tended to reduce fire severity. Our results suggest that application of particular suppression operations provide a substantial opportunity to increase proportion of area burned at low–moderate severity in wildfires, which is important since annual area burned by wildfire dwarfs the area burned by prescribed fires in western USA forests and efforts to scale-up prescribed fire face substantial barriers (Williams *et al* 2024). A continued focus on training and leadership on large fire tactics, particularly the implementation of complex firing operations, may help to decrease fire severity in the process of suppressing future large fires.

We found that suppression operations interacted with prior fire severity to create both positive and negative feedbacks. Offensive firing, and to a lesser extent heavy operations, amplified the beneficial effects of past low–moderate-severity fire. Because fuel treatments such as low-severity fire facilitate suppression efforts and increase the range of available tactics (Agee *et al* 2000, Moghaddas and Craggs 2007, Vorster *et al* 2023), these areas of past low–moderate-severity fire likely enabled certain operations (e.g. offensive firing) that further reduced fire severity. Medium operations, however, did not decrease fire severity. Over some of the area of medium operations that we mapped, crews are known to have begun operations but were diverted or relocated as conditions changed or priorities shifted to other locations of the fire. Such decisions to relocate crews are typically driven by higher-level priorities across the fire or concerns for firefighter safety, and are not uncommon in managing large, dynamic fires. Operations activities that were started but not completed may explain why medium operations were associated with increased fire severity in our analysis. For example, crews that were relocated may have been unable to continue managing firing operations leading to an increase or new configuration of fire activity. Also, because medium operations are less intense and more localized than offensive firing or heavy operations, medium operations may have caused more local and transient effects that are not apparent when examining effects across a broader area. We also found suppression operations reduced fire severity on average within the footprint of past high-severity fire, which are challenging areas from a management perspective due in part to their propensity to reburn at high-severity (Stevens *et al* 2021). Given this propensity, suppression operations within past high-severity patches are unlikely to substantially increase fire severity but may decrease it to the extent that operations cause these patches to burn under more favorable weather. Suppression operations could potentially help to reduce reburn severity and improve prospects for forest recovery in these high-severity patches (figure 1(c)), although safety concerns may dictate tactics due to high hazard to firefighters.

We also note that effects of operations and past fires on the severity of the Dixie Fire were spatially heterogenous, which may reflect the diversity of specific tactics employed within the broad categories of operations. The influence of a given operation is also likely to vary spatially, with direct operations accounting for a small minority of total area burned often close to roads and infrastructure. Spatial heterogeneity in fire severity effects is also likely to arise from differences in vegetation, terrain and weather at specific locations (Harris *et al* 2021a).

Although individual large wildfires can serve as compelling natural experiments to evaluate drivers of fire severity (Thompson *et al* 2007, Povak *et al* 2020, Taylor *et al* 2022), we note that analyzing a population of fires (Dillon *et al* 2011, Taylor *et al* 2021) would allow for a more robust understanding of the fire severity effects discussed here. Moreover our analysis was spatially implicit, so it did not account for the effects of operations and fuel treatments on fire behavior and ultimately fire severity patterns beyond their immediate footprints (Finney 2001, Syphard *et al* 2011). In future work, variables incorporating distance and direction from operations and fuel treatments could potentially be used to address this limitation, which likely results in an underestimate of the impact of operations. Our work does not address how operations influenced the spread and ultimately the final footprint of the Dixie Fire, which are issues likely better suited to process-based fire behavior models. Counterfactual approaches are useful for assessing influences on wildfire severity and intensity for which experimental approaches are not feasible (Arkle *et al* 2012, Wu *et al* 2023), but their estimated effects rely on the underlying statistical model and how accurately it represents these drivers of fire severity (Harris *et al* 2021a). The accuracy of our fire severity model is in line with prior work, (Birch *et al* 2015, Kane *et al* 2015, Harris *et al* 2021a) but still leaves a substantial percentage of variability in fire severity (44%) unexplained. The greatest source of unexplained variability may be fire weather, which was characterized at 4 km and daily resolution but varies considerably hour by hour and kilometer by kilometer in mountainous terrain (Sharples 2009). We considered broad categories of fire suppression operations in this work due to data limitation, but improved characterization of operations (i.e. more types of operations, improved spatial and temporal resolution) would help to more accurately assess their impact.

Estimating the effects of operations using archival incident data alone is likely insufficient for reconstructing operations during large, complex megafires. Problems of incident data quality can arise from staffing turnover throughout long-duration fires (Hand *et al* 2017), swift decisions made in emergency situations which are poorly-documented, inadequate spatial representation of certain tactics such as multi-day firing operations or convergence of multiple fire fronts, and inconsistencies in data documentation and archiving (e.g. data stored offline or in different databases, such as flight logs). Moreover, certain types of information not required for incident reporting might be useful for research and modeling purposes. While data standardization and access are improving rapidly, complete spatial characterization of suppression operations (especially for past fires) requires integration of available data with firsthand observations from fire line personnel and/or real-time tracking of suppression activities. Increased focus on improving documentation perhaps by embedding fire managers and researchers on incident teams during large fires to document tactics would provide the foundation for more completely understanding operation effects on fire severity.

5. Conclusion

Given the urgent need to reduce wildfire severity in dry pine, mixed-conifer and fir forests of the western USA to maintain forest resilience in the face of a warming climate (Davis *et al* 2023), it is important to recognize the influence of suppression operations on fire severity and to identify potential opportunities to reduce fire severity in the process of suppressing wildfires. In a wildfire that burned under extreme weather (Taylor *et al* 2022), we found that the effectiveness of past low–moderate severity fire as a fuel treatment can be enhanced through judicious use of suppression operations (e.g. offensive firing) but diminished in other cases (e.g. defensive firing). We also found that operations tended to reduce fire severity within areas of past high-severity fire, which suggests potential for operations to help move landscapes out of the self-reinforcing trap of high-severity forest fires being followed by high-severity reburns that impede forest recovery. Our results suggest that suppression operations and their interaction with past fires represent an underrecognized opportunity to reduce fire severity in large wildfires.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We thank Alexandra Lister and Finan Turnage-Barney for assistance in compiling geospatial operations data. Financial support for this research was provided by the National Park Service (Cooperative Agreement 18730) and The Pennsylvania State University.

ORCID iD

Lucas B Harris https://orcid.org/0000-0002-1416-5645

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