Initial attack wildfire suppression selects for extreme burning conditions

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Executive summary (to become abstract)

Most wildfires in the western U.S. are managed for suppression. This is usually effective at keeping fires small. It is often assumed that the fires that grow large do so because they burn under extreme fuel and climate conditions. We quantify this "selection" effect using an evolutionary ecology framework and discuss implications for management.

Abstract

Wildfires typically undergo active suppression efforts in forests of the western U.S.A. A vast majority of these wildfires are extinguished during "initial attack" suppression within the first few days after their discovery, which constrains the area of vegetation that they effect. In the long run, the reduced footprint of fire in the drier, lower elevation forests of the western U.S. has led to a dramatic buildup of fuel such that

In the short run, this reduces the footprint of fire in these forests. In the long run, buildup of fuel in the drier, lower elevation forests of the region

A century of such a policy has enabled dramatic densification of low- to mid-elevation dry and mesic forests in the west, with yellow pine/mixed-conifer forests of California's Sierra Nevada range being a prime example.

The dominant management approach for wildfires in yellow pine/mixed-conifer forests of the Sierra Nevada mountain range, as it is for many western U.S. forests, is full suppression. "Initial attack" efforts within the first few days of discovering a new ignition prioritized extinguishing

Thus "large" modern fires in this system are often considered "bad" fires with respect to forest health.

However, this correlation may be confounded by the extreme conditions under which “large” fires grow large. Ideally, there’d be a more extensive fire footprint

Introduction

Fire suppression is an oft-cited root cause of the modern trend of larger, more severe wildfires in the yellow pine/mixed-conifer forests of California’s Sierra Nevada mountain range (Miller and Thode 2007; Calkin *et al.* 2015; Safford and Stevens 2017). While most of this ecosystem would experience frequent, low- to moderate-severity wildfire every 8 to 15 years in the several centuries prior to Euroamerican settlement, suppression management has largely eliminated fire effects from much of western dry forested land in the past 100 years (Steel *et al.* 2015; Safford and Stevens 2017; Miller and Safford 2017). A lack of frequent fire has led to densification of Sierra yellow pine/mixed-conifer, which increases fuel loading and homogenizes forest structure (Collins *et al.* 2016; Stephens *et al.* 2018). Synergistic alignment of these extreme fuel conditions with earlier snowmelt, longer fire seasons, and hotter droughts (aka “climate change droughts”) (Westerling 2006, 2016; Abatzoglou and Kolden 2013; Abatzoglou and Williams 2016) increases the probability that fires will generate self-propagating behavior (Coen *et al.* 2018) and kill all (or nearly all) overstory vegetation (Koontz *et al.* 2019b) in large, contiguous patches of mortality (Stevens *et al.* 2017). The Sierra yellow pine/mixed-conifer community is ill-adapted to regenerate in the centers of these large patches, which are far from seed sources (Welch *et al.* 2016), and thus the modern trend of atypically large, contiguous, stand-replacing fires in this system compromise forest health and increase the potential for long-term shifts in vegetation type to shrub- or grasslands (Millar and Stephenson 2015; Stevens *et al.* 2017; Steel *et al.* 2018).

Despite the long-term effects of fire suppression on wildfire trends, fire suppression generally is very effective at its immediate goal of extinguishing fires. Between 1970 and 2002, over 97% of fires burning on U.S. Forest Service land were contained during before they reached 120 hectares in size (Calkin *et al.* 2005, 2015).

In the western U.S., including the Sierra yellow pine/mixed-conifer system, the vast majority of fires are managed for suppression (Calkin *et al.* 2015). The “10 a.m. policy”, which dictated that fires should be put out before 10 a.m. of the day following their discovery, was established in the 1930’s and has since been modified, but its aggressive spirit in managing fire persists in today’s modern firefighting apparatus (Dale 2006; Johnson *et al.* 2009).

Wildfire effects to forest vegetation are outcomes of a complex social-ecological system dynamic (Calkin *et al.* 2015). Direct causes of fire effects to vegetation arise from fire behavior and intensity (Keeley 2009), which are coupled to fuel, weather, and topography (McKenzie and Hessl 2008). Wildfire effects are indirectly related to resource availability, legacies of management policy, and incentive structures that prioritized short term loss of timber resources over long-term benefits of wildfire (Houtman *et al.* 2013; Calkin *et al.* 2014, 2015).

The fires that remained small are often assumed to have burned under mild or moderate vegetation and climate conditions, facilitating initial suppression efforts. The fires that escape initial attack and grow large account for 97.5% of the total burned area of fires managed by the U.S. Forest Service (Calkin *et al.* 2005), and are often assumed to have grown to these sizes because they were burning under more extreme conditions (Calkin *et al.* 2014).

"Essentially, through our management efforts we have changed the distribution of fire behavior to only the most extreme." (Calkin *et al.* 2015).

Thus, the general short-term success of fire suppression policy paired with its long-term cumulative effect has led to a management paradox with respect to maintaining forest health: *we shouldn't put out the fires that we can, but we can't put out the fires that we should.*

Many studies have suggested that adding more fire to the landscape is a way to return forests to pre-Euroamerican settlement resilient conditions (Mallek *et al.* 2013; Meyer 2015; North *et al.* 2015; Collins *et al.* 2017; Stevens *et al.* 2017) and some efforts are underway though barriers remain (Doane *et al.* 2006; Calkin *et al.* 2015).

We use a new dataset of fire severity (Koontz *et al.* 2019a) to measure this "selection by suppression" effect and ask:

1) What is the strength of "selection" on wildfire burning conditions (regional climate, vegetation density, vegetation continuity, concurrently burning fires) imposed by initial attack suppression efforts?

2) What are the consequences of these varying conditions for wildfire effects (burn duration, fire event size, severity configurations)?

3) To what extent might prematurely extinguished suppression wildfires exhibit desireable fire effects, were they to be allowed to burn for longer? That is, are small suppression fires behaving like small wildfire use fires (and thus they should perhaps be left to burn and cover more area)?

A small number of natural ignitions are allowed to burn under moderate conditions in "resource benefit", "resource objective", or "wildland fire use" fires in recognition of the important role that fire plays in many healthy forest systems (Davis 1979; Meyer 2015).

Fuels are of particular interest because they can be modified (Agee and Skinner 2005)

Coarse-scale influence of management on fire effects (Meyer 2015; Harris and Taylor 2015; Lydersen *et al.* 2017; Stevens *et al.* 2017; Steel *et al.* 2018)

Methods

Study system

The Sierra Nevada yellow pine/mixed-conifer (hereafter Sierra YPMC) is a disturbance-prone forest system in the Sierra Nevada mountain range of California, U.S.A. It spans the full 628 kilometer latitudinal length of the Sierra Nevada, and 2,500 meters of elevation (300 meters to 2800 meters), primarily on the western slope of the mountain range (Safford and Stevens 2017). The forest is dominated by ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), and incense cedar (*Calocedrus decurrens*) in varying mixes. Prior to Euroamerican settlement, the ecosystem experienced frequent, low- to moderate-severity wildfire every 8 to 15 years on average (Steel *et al.* 2015; Safford and Stevens 2017), which consumed surface fuels but generally had minimal effects on large, established trees. This fire regime generated heterogeneous horizontal forest structure, with groups of relatively even-aged trees having interlocking crowns, individual trees with distinct crowns, and variably-sized gaps between these tree clump and individual tree structural features (Lydersen *et al.* 2013). A century of fire suppression has led to infill of these gaps, homogenizing the horizontal forest structure and compromising forest resilience in an era of climate change-induced hotter droughts (North *et al.* 2009; Millar and Stephenson 2015; Collins *et al.* 2016).

For our study, we compiled the Sierra YPMC type using the U.S. Forest Service Fire Return Interval Departure (FRID) dataset and included "dry mixed-conifier", "moist mixed-conifer", and "yellow pine" vegetation types following Steel *et al.* (2018) and Koontz *et al.* (2019b). These classifications represent "potential vegetation" given the climate of the area, such that there is no influence of recent disturbance events (Harvey *et al.* 2016; Steel *et al.* 2018; Koontz *et al.* 2019b).

Context of Sierra YPMC wildfire

To describe the modern context of wildfire activity in the Sierra Nevada yellow pine/mixed-conifer system, we used geospatial records contained in Short (2017) (U.S. Forest Service Fire Program Analysis Fire Occurrence Database; FPAFOD), the most comprehensive database of wildfire occurance for the United States representing 1.88 million wildfire records from 1992 to 2015.

The FPAFOD contains point locations for the centroids of each fire's footprint, rather than the perimeter of each fire as in some other databases (Eidenshink *et al.* 2007). We spatially subsetted the FOD data to fire events whose centroids occurred within the Sierra Nevada mountain range, as defined by the Jepson geographic subdivisions (north, central, and south Sierra Nevada Foothills and High Sierra Nevada, as well as the Tehachapi Mountain Area) (Project 2016). For each fire record, we approximated its footprint by creating a circular buffer around the centroid with an area equivalent to the reported area of the fire. Using this footprint approximation, we calculated the proportion of area that intersected with the our compilation of Sierra YPMC from the FRID dataset. We retained all fires with greater than zero area of the approximate footprint covering the Sierra YPMC extent. We calculated burn duration as the number of days between the containment date and the alarm date, and retained all fires with a burn duration of greater than 0 and less than 364 days to eliminate likely errors in reporting of alarm and containment dates.

At the centroid of each fire, we used the gridMET product (Abatzoglou 2013) to calculate the median windspeed for the first three days of the fire. We also calculated the energy release component, a modeled estimate of expected fire behavior in conifer forest, for the three days prior to the fire's discovery date. The gridMET product has a daily temporal resolution and a 4 kilometer spatial resolution, so our climate variables capture regional conditions over time periods of several days, but not very local weather events that might occur over the span of hours. Each of these variables has a strong impact on wildfire behavior at macroscales (Abatzoglou and Kolden 2013).

Measuring wildfire severity

The CalFire Fire Resource and Protection Program (FRAP; http://frap.fire.ca.gov/) maintains the most comprehensive datset of wildfire perimeters in the state of California, including attribute data for each fire such as its discovery date, its containment date, and the management objective. The management objective represents the approach taken by the management unit overseeing the wildfire– either "suppression", with a goal of extinguishing the fire, or "wildland fire use", with a goal of allowing the fire to burn to benefit forest resources so long as it didn't threaten lives or property (Meyer 2015). This dichotomy is somewhat simplistic, as each wildfire can be managed for multiple objectives, but it is a generally useful framework for understanding the primary management goal (Meyer 2015). This dataset contains all fires >4 hectares, and thus has greater representation of fire events compared to other wildfire events datasets, though it lacks severity information. For instance, the Monitoring Trends in Burn Severity (MTBS) database only contains wildires in the western U.S. that are larger than 400 hectares (Eidenshink *et al.* 2007) and the U.S. Forest Service Region 5 geospatial database contains wildfires in the Sierra Nevada that are larger than 80 hectares (Steel *et al.* 2018), though both of these datasets contain information on wildfire severity.

Koontz *et al.* (2019a) used the expanded FRAP dataset of over 1,000 wildfire perimeters to calculate wildfire severity and calibrate satellite-derived measures using ground-based overstory composite burn index (CBI) (Koontz *et al.* 2019b), which is an integrated measure of the effect of a wildfire on the forest overstory one year after the burn (Key and Benson 2006). CBI correlates well with direct measures of fire impact to vegetation in Sierra YPMC, such as percent of overstory mortality (Miller and Thode 2007). Thresholds of wildfire severity (unchanged, low, moderate, and high) calibrated to the full dataset (Koontz *et al.* 2019b) were imposed on each fire and then contiguous pixels of each category were vectorized into polygons to form patches of each severity category.

Burning conditions per fire event

In addition to mapping wildfire severity across each fire in the FRAP perimeter database, Koontz *et al.* (2019b) also calculated fuel and regional climate variables within the burn perimeter. The prefire Normalized Difference Vegetation Index (NDVI; Rouse *et al.* (1973)]) was found to correlate strongly with local wildfire severity, as was the standard deviation of NDVI within the 90m x 90m window surrounding each pixel, which represents a measure of horizontal forest structure and fuel continuity (Koontz *et al.* 2019b). The gridMET product (Abatzoglou 2013) was used to calculate the energy release component for the 3 days prior to each fire's discovery date as well as the wind speed for the first three days of the fire. For this study, we assigned prefire burning conditions for each fire as the mean fuel (prefire NDVI, prefire standard deviation of NDVI within 90m x 90m moving windows) and regional climate (energy release component for 3 days prior to the fire, wind speed for first 3 days of the fire) values within each fire perimeter.

For each fire, we calculated the total number of fires burning on that fire's alarm date, the proportion of area represented by each severity category, as well as the maximum patch size of each severity category. Finally, we calculated the stand replacing decay coefficient (SDC) (Collins *et al.* 2017; Stevens *et al.* 2017), a single metric that integrates high severity patch size and shape such that a lower SDC corresponds to a larger, more circular high severity patches with effectively more area within those patches far from the patch edges.

Designating "survivorship" of suppression fires

For each wildfire in the Koontz *et al.* (2019b) dataset with a suppression management objective, we determined whether it "survived" initial attack by whether its burn duration (discovery date subtracted from the containment date) was greater than 1 day. Following Abatzoglou *et al.* (2018), we assumed that fires under a suppression management objective that burned for more than one day would require different firefighting tactics than direct attack and thus represented a reconfiguration of firefighting personnel and resource allocation.

Quantifying the selection effect of fire suppression

We treated the prefire fuel (prefire NDVI, heterogeneity of NDVI) and climate conditions (prefire energy release component, early fire wind speed) as wildfire "phenotypes" having some distribution, and used logistic regression to measure the extent to which wildfire suppression "selected" for particular burning condition phenotypes using the survivorship of each fire to initial attack as a binary response fitness metric in an evolutionary ecology framework (Lande and Arnold 1983; Janzen and Stern 1998).

Results

Fire event size and burn duration context of Sierra YPMC wildfire

We found that 16219 fire events burned at least partially in Sierra Nevada yellow pine/mixed-conifer between 1992 and 2015 covering 2.19 million total hectares and 1.18 million hectares of this forest type. A total of 14873 fires burned in greater than 50% Sierra yellow pine/mixed-conifer in the same period. The vast majority of these fire events were very small. Comparing the distribution of fire sizes in this system between 1992 and 2015 to relevant reference sizes:

- 61.46% of fires were smaller than 0.09 hectares– the size of a single pixel from Landsat which is a USGS satellite product often used to measure fire effects by comparing imagery just before the fire to imagery one year after the fire (Miller and Thode 2007).
- 98.87% of fires were smaller than 400 hectares– the minimum fire size for inclusion in the MTBS dataset for the western U.S. (Eidenshink *et al.* 2007), meaning that MTBS would include approximately 1.13% of fires in this system.
- 97.93% of fires were smaller than 80 hectares– the minimum fire size for inclusion in the USFS Region 5 geospatial dataset (Steel *et al.* 2018), meaning that the USFS Region 5 data accounts for approximately 2.07% of fires in this system.
- 94.88% of fires were smaller than 4 hectares– the minimum fire size for inclusion in the CalFire FRAP fire perimeter dataset which was used to derive the Koontz *et al.* (2019a) severity dataset. Thus, the Koontz *et al.* (2019a) dataset includes approximately 5.12% of fires in this system during its timespan of 1984 to 2017.

Context of suppression fires compared to wildfire use fires

There is a clear multimodality in the fire event size between fires that are managed for suppression versus fires that are managed for resource benefit (i.e., wildfire use fires) (Figure 1.

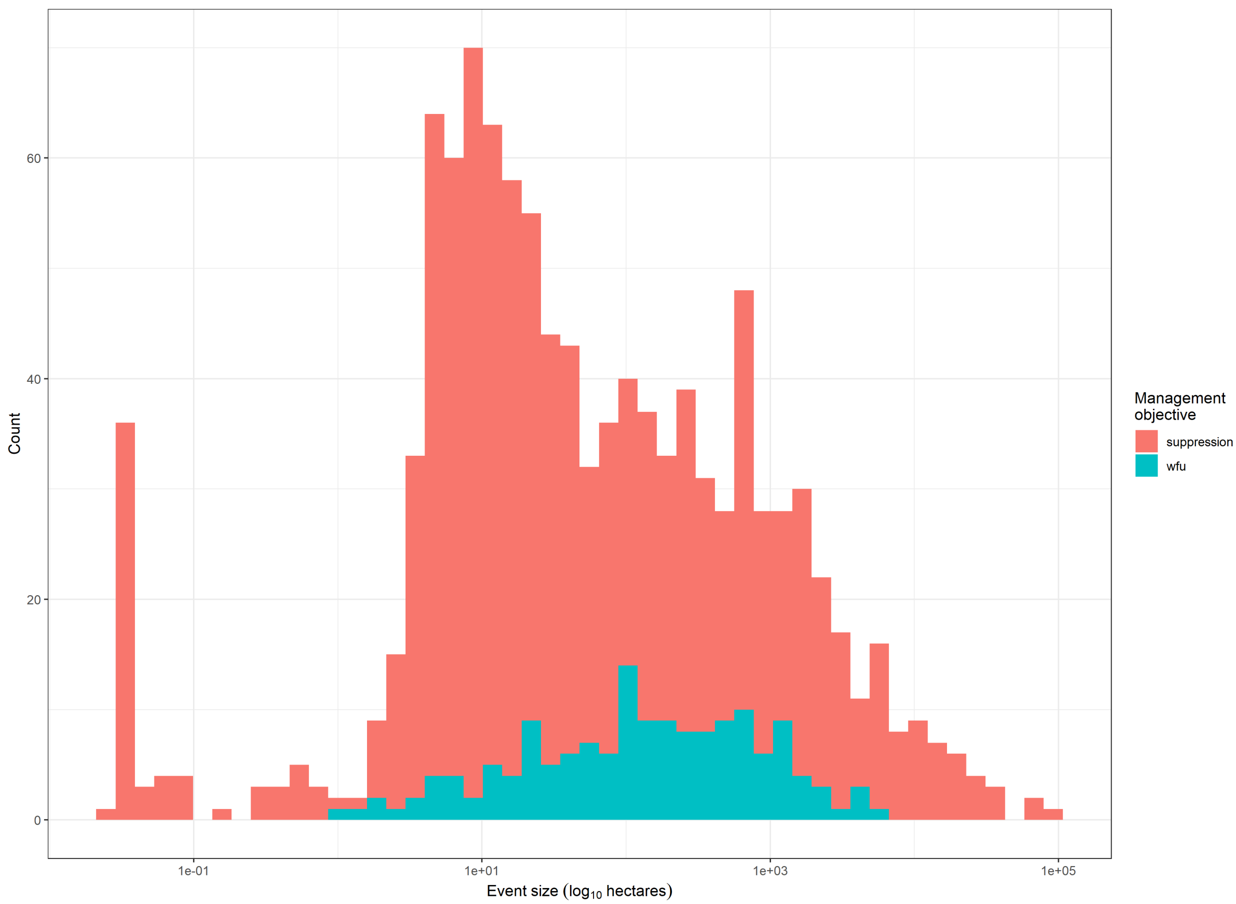

Figure 1: Distribution of log fire event size by management objective. While wildfire use fires exhibit a lognormal distribution in size, suppression fires exhibit clear multimodality with many fires extinguished when they are very small.

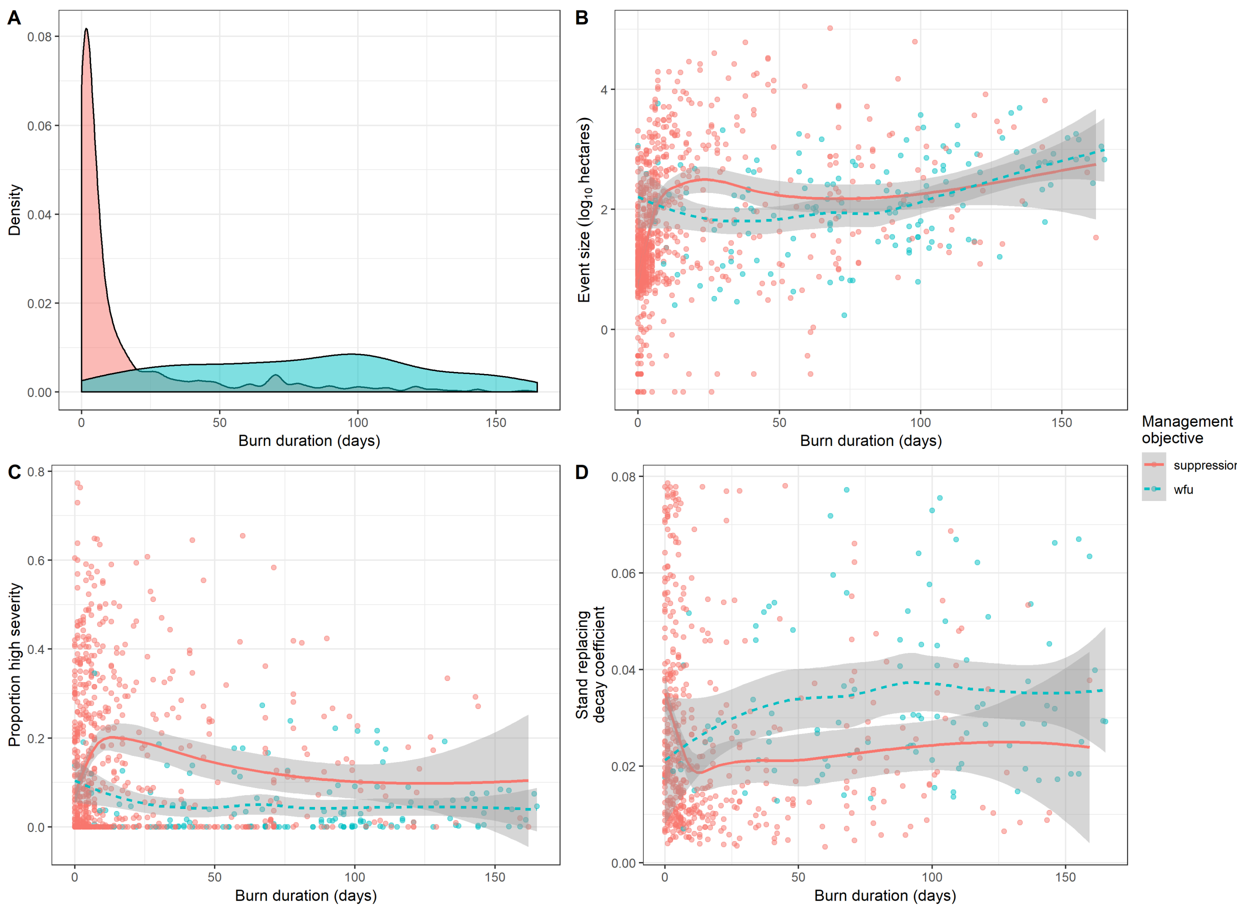

Figure 2: A) Distribution of burn duration by management objective. Most suppression fires are quickly extinguished. B) Effect of burn duration on fire event size shows that there's a similar trajectory between suppressed and wildfire use fires except early in the burning period when suppression fires remain small. C) The high severity portion of the fire tends to increase with shorter-duration suppression fires, but is relatively constant across burn durations for wildfire use fires. D) For fires with a high severity component, the stand replacing decay coefficient sharply declines for short-lived fires indicating that the high severity patches are larger and simpler which may reduce tree propagule pressure in the center of these patches and compromise dry forest regeneration. The SDC tends to increase with the burn duration for wildfire use fires.

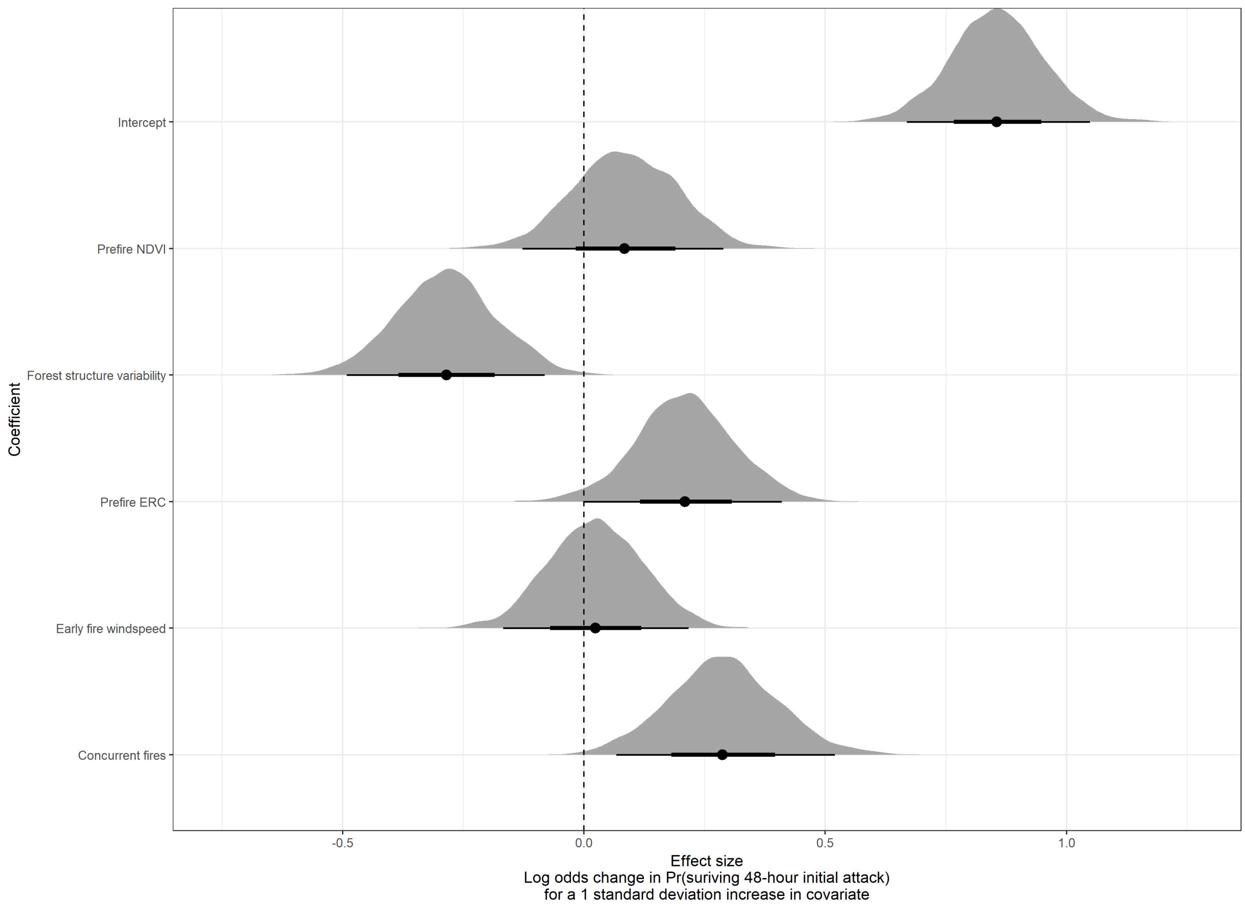

Figure 3: Halfeye plot showing posterior distributions of coefficient estimates for model predicting the probability of wildfire survivorship in the first 48 hours of initial attack. The effect sizes are proportional to the 'strength of selection' of initial attack on the burning conditions of wildfire. Credible intervals are shown below each probability density function with the point representing the mean, the dark line representing the 66% credible interval, and the light line representing the 95% credible interval.

Selection by suppression

We found a sizeable effect of phenotypic selection of initial attack suppression on the heterogeneity of NDVI, prefire energy release component, and number of fires burning concurrent with each fire's discovery date. Wildfires that survived initial attack were more likely to be burning in more extreme, homogenous fuels (lower heterogeneity of NDVI), more extreme, hotter/drier climate conditions (higher energy release component), and with more fires burning concurrently compared to wildfires that succumbed to the initial attack (Figure 3.

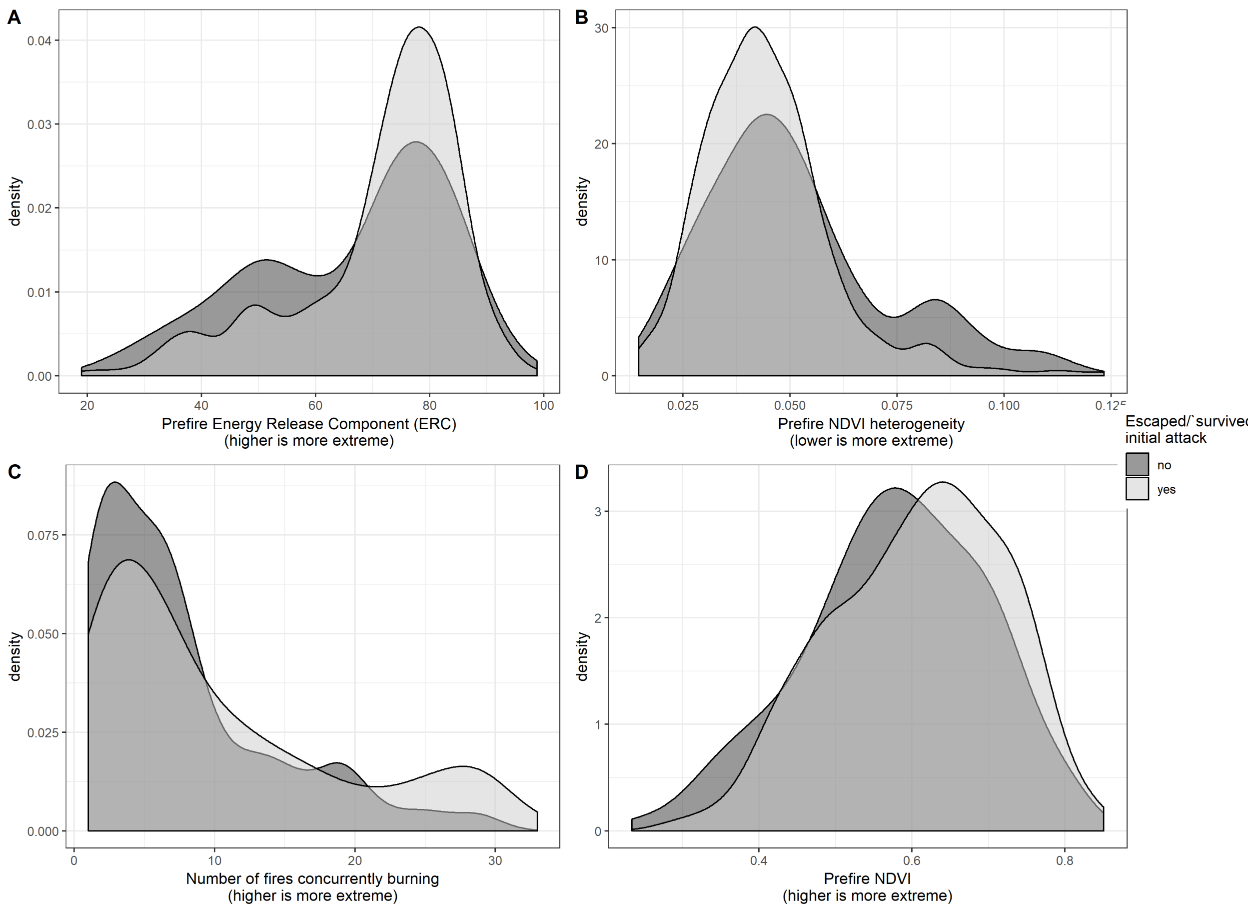

Figure 4: The selection effect on the vegetation and climate burning conditions of suppressed wildfires.

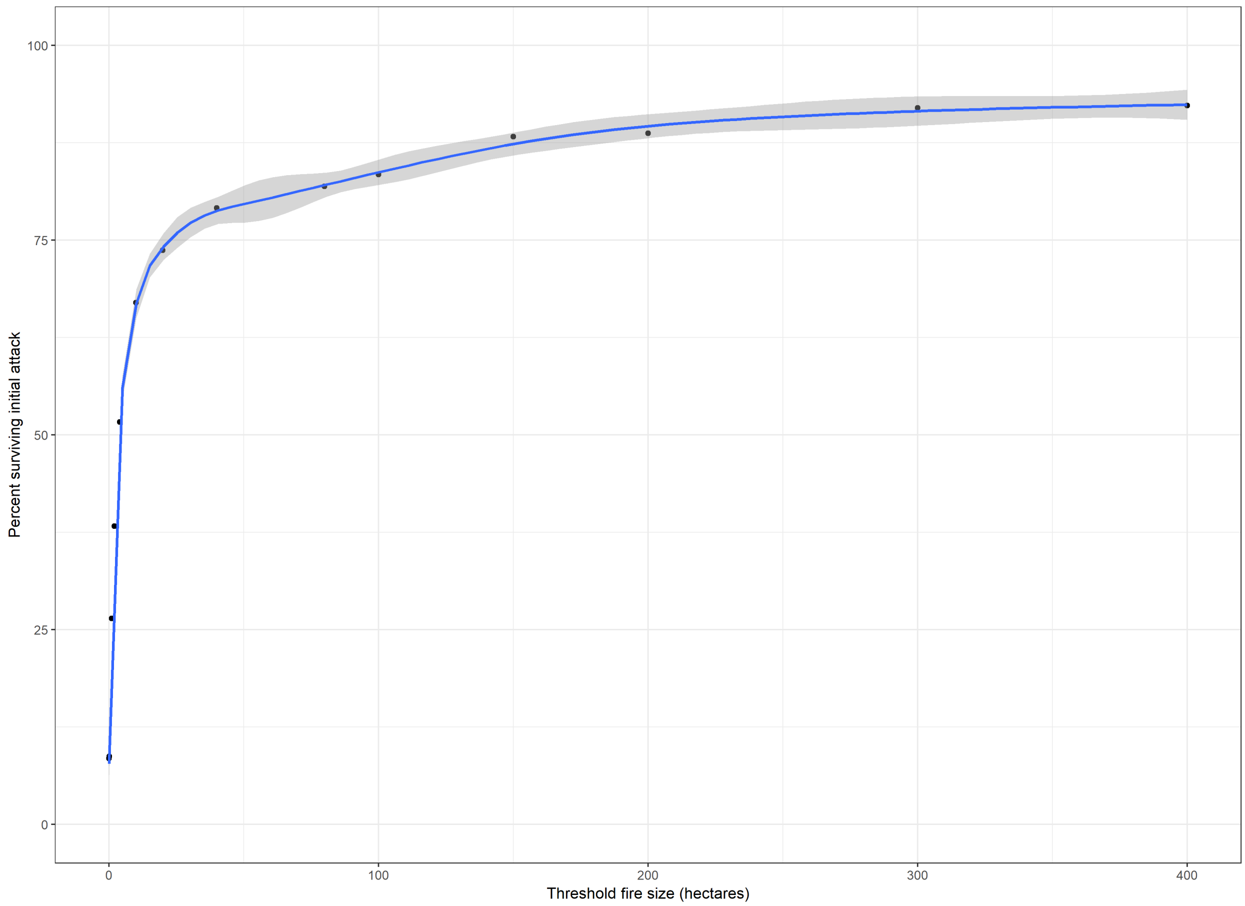

Figure 5: As the minimum fire event size of a dataset increases, a greater proportion of those fire events survived initial attack suppression efforts and burned on average under more extreme conditions. Thus databases with larger minimum fire sizes exhibit a stronger bias towards fires that burned in extreme conditions as a result of selection by suppression.

Discussion

We have demonstrated a clear multi-modality in the fire event size distribution of wildfires managed with a suppression objective, and further measured the effect of this "selection by suppression" on the severity characteristics of these events.

Suppression leads to especially large fires because the ones that grow large are only able to do so because they burn under extreme conditions. We found strong evidence that inital attack "kills" fires that would otherwise burn under more mild and moderate fuel and climate conditions, instead favoring fires that burn under extreme conditions, with concomitant negative consequences for Sierra YPMC forest health.

Two implications:

1) There is "lost work" (in terms of Sierra YPMC area affected positively by wildfire) associated with fires that are extinguished before they have a chance to do that work.

2) Though destructive megaevents are on the rise, their prevalence is highlighted because they are all that burns large.

Essentially all of the suppression fires in Figure 2c that are within or above the confidence interval for the wildfire use fires had beneficial severity characteristics but were suppressed. Each of these fires represents potentially "lost area" of beneficial fire activity.

Bimodal distribution of fire sizes under suppression policy: either the fires were quickly put out and remained very small, or they escaped suppression efforts and grew exceptionally large due to regional climate conspiring with accumulated fuel conditions. Indeed, Miller and Safford (2017) found evidence for this pattern in that the average size of all fires is much smaller under a modern fire suppression management regime compared to pre-Euroamerican settlement fires (as one might intuitively expect given the goal of suppression is to stop fires to protect life and property), but the average size of larger fires (>4 hectares) is, perhaps counter-intuitively, much greater under modern suppression management (Safford and Stevens 2017; Miller and Safford 2017).

Effect of a typical fire versus the typical effect of a fire

Most fires are small, and some are small because they undergo active suppression. We have demonstrated that there is a bias toward extreme burning conditions imposed by suppression that increases with minimum fire size being analyzed. Thus, databases of fire effects that include large fires (e.g., MTBS) have this bias baked in for the Sierra yellow pine/mixed-conifer system.

Cansler and McKenzie (2014) included small fires when measuring fire effects.

Steel *et al.* (2018) found only a small difference in the measure of regional climate during suppression versus wildfire use fires (modeled fuel moisture), which led to the conclusion that an "extreme fuel" effect underlied the differences in the size/configuration of high and unburned severity patches.

But that analysis only included fires greater than 80 hectares in size, which is still pretty big. Analyzing big fires made sense for that paper, because they affect the most area, but if we want to suggest "let fires burn at more moderate weather conditions" as a mitigation strategy for a century of making fuel conditions more extreme, then I think this paper would serve the purpose of measuring the degree to which good work can be done by a fire (even in extreme fuel conditions) in milder weather conditions.

Positive feedback after selection

Forest structure and fuel characteristics link one disturbance event to the next via feedbacks: one wildfire changes the fuel characteristics of the forest as it burns, and those altered fuel characteristics can feedback to influence the behavior and effects of the next wildfire. In Sierra YPMC, severe wildfires with stand-replacing effects, especially large, contiguous stand-replacing effects, tend to homogenize forest spatial structure. In turn, homogenous forest structure increases the probability that a forest will burn at high severity (Koontz *et al.* 2019b). If initial attack suppression selects for wildfires to burn under more homogenous fuel conditions, and those fires are more likely to burn at high severity, then the vegetation within the footprint of those fires will be more likely to regenerate homogeneously, thus "inheriting" the phenotype that was selected for.

On a longer time scale, this is perhaps true for the regional climate trait that suppression also selects for: selection for fires burning under hotter/drier conditions will likely lead to more severe wildfires, with greater release of carbon to the atmosphere, greater climate forcing, and increasingly common hot/dry conditions. In this case, the selection for fires burning under hotter/drier conditions also leads to "inheritance" of the hotter/drier phenotype for future fires.

Case study of many simultaneously burning fires

We subsetted the Koontz *et al.* (2019b) dataset to all fires with greater than or equal to 20 other fires burning on its alarm date. Many of these fires were ignited during the June 21-22, 2008 storms in the Sierra Nevada.

Interdependence on various burning conditions and fire effects

Interacting effects (and directional dependence) of vegetation, regional climate, fire size, and severity patterns: (Cansler and McKenzie 2014; Harvey *et al.* 2016).

"A variety of environmental and social factors influence wildfire growth and whether a fire overcomes initial attack efforts and becomes a large wildfire. However, little is known about how these factors differ between lightning-caused and human-caused wildfires." (Abatzoglou *et al.* 2018)

"As shown by Balch et al. (2017), human-caused fires occupy an environmental niche characterised by lower lightning- frequency and higher fuel moisture than lightning-caused fires. The present work complements those findings by demonstrating the likelihood of human ignitions evolving into large fires when facilitated by strong winds." (Abatzoglou *et al.* 2018)

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