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 system 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). Fortuitous 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 "initial attack" suppression 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, though a small number of natural ignitions are allowed to burn under moderate conditions in "resource benefit" or "wildland fire use" fires in recognition of the important role that fire plays in many healthy forest systems (Calkin *et al.* 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.

"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.*

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).

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; 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) How do burning conditions (regional climate, vegetation density, vegetation continuity) vary between suppression and wildfire use fires?

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)?

Methods

and 98.5% remain smaller than 80 hectares (Short 2017).

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 over 2,750 meters of elevation (229 meters to 3053 meters; 95% interval = (679, 2516) meters; IQR = (1273, 1945) meters), primarily on the western slope of the mountain range. 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 (Collins *et al.* 2016) and compromising forest resilience (North 2012) in an era of climate change-induced hotter droughts (Millar and Stephenson 2015).

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).

Measuring wildfire burning conditions

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 so long as it didn’t threaten lives or property. 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).

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 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 median 100-hour fuel moisture, energy release component, and vapor pressure deficit for the 3 days prior to each fire's discovery date, which captures regional climate 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).

Aggregating burning conditions to the fire event level

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 (100-hour fuel moisture, energy release component, vapor pressure deficit) values within each fire perimeter.

Designating "survivorship" of suppression fires

For each wildfire with a suppression management objective, we determined whether it "survived" initial attack by whether it's 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) as wildfire "phenotypes" with some distribution, and measured the extent to which wildfire suppression "selected" for particular phenotypes using the survivorship of each fire to initial attack as our fitness metric. Given the binomial response of the data, we used a logistic regression framework in an evolutionary ecology framework (Lande and Arnold 1983; Janzen and Stern 1998).

Implications of selection for wildfire responses

We fit models using the same prefire fuel and climate conditions to wildfire effects responses including fire event size, proportion high severity, and the stand-replacing decay coefficient (Collins *et al.* 2017; Stevens *et al.* 2017).

Comparing to the "wildland fire use" fires in some way?

Future work?

Took the Short (2017) dataset and subsetted to (approximately) Sierra YPMC. (took centroid and fire area, assumed circular fire, assessed how much of it fell across the Sierra YPMC raster image; super small fires that intersected no centroids of the raster image were converted back to points and we "extracted" the Sierra YPMC raster value (either 0 or 1) based on the point location instead). Uploaded to Earth Engine and got the regional climate values for the centroids. (Also got the fuel values for the centroids, but these aren't that meaningful because they should vary quite a bit across the fires. Could still calculate across the assumed circular fires?)

Some summary stats of the Sierra Nevada yellow pine/mixed-conifer subset of the Short (2017) fire occurrence dataset. (65% of fires less than a Landsat pixel; 5.2% of fires in Koontz *et al.* (2019a) dataset; 1.5% in USFS Region 5 dataset; 0.5% in MTBS dataset)

Subset Short (2017) into suppression/managed wildfire based on where it burns, using method of Steel *et al.* (2018).

Use the expanded set of fires, and the relationships between fire size/SDC and covariates to extrapolate the potential added "good fire area" that might have burned if the Short (2017) suppression fires weren't extinguished.

Results

Selection by suppression

We found a sizeable effect of phenotypic selection of initial attack suppression on the heterogeneity of NDVI and the prefire energy release component. Wildfires that survived initial attack were more likely to be burning in more extreme, homogenous fuels (lower heterogeneity of NDVI) and more extreme, hotter/drier climate conditions (higher energy release component) compared to wildfires that succumbed to the initial attack.

Table 1:

	Dependent variable:
	survived_ia
scale(prefire_ndvi)	-0.045
	(0.084)
scale(nbhd_sd_ndvi_1)	-0.269^{***}
	(0.079)
scale(prefire_erc)	0.190^{**}
	(0.077)
Constant	0.920^{***}
	(0.079)
Observations	812
Log Likelihood	-478.293
Akaike Inf. Crit.	964.585
Note:	*p<0.1; **p<0.05; ***p<0.01

Implications of selection by suppression

Comparison to wildland fire use fires by treating these fires as the “wild type” in the evolutionary ecology framing.

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.

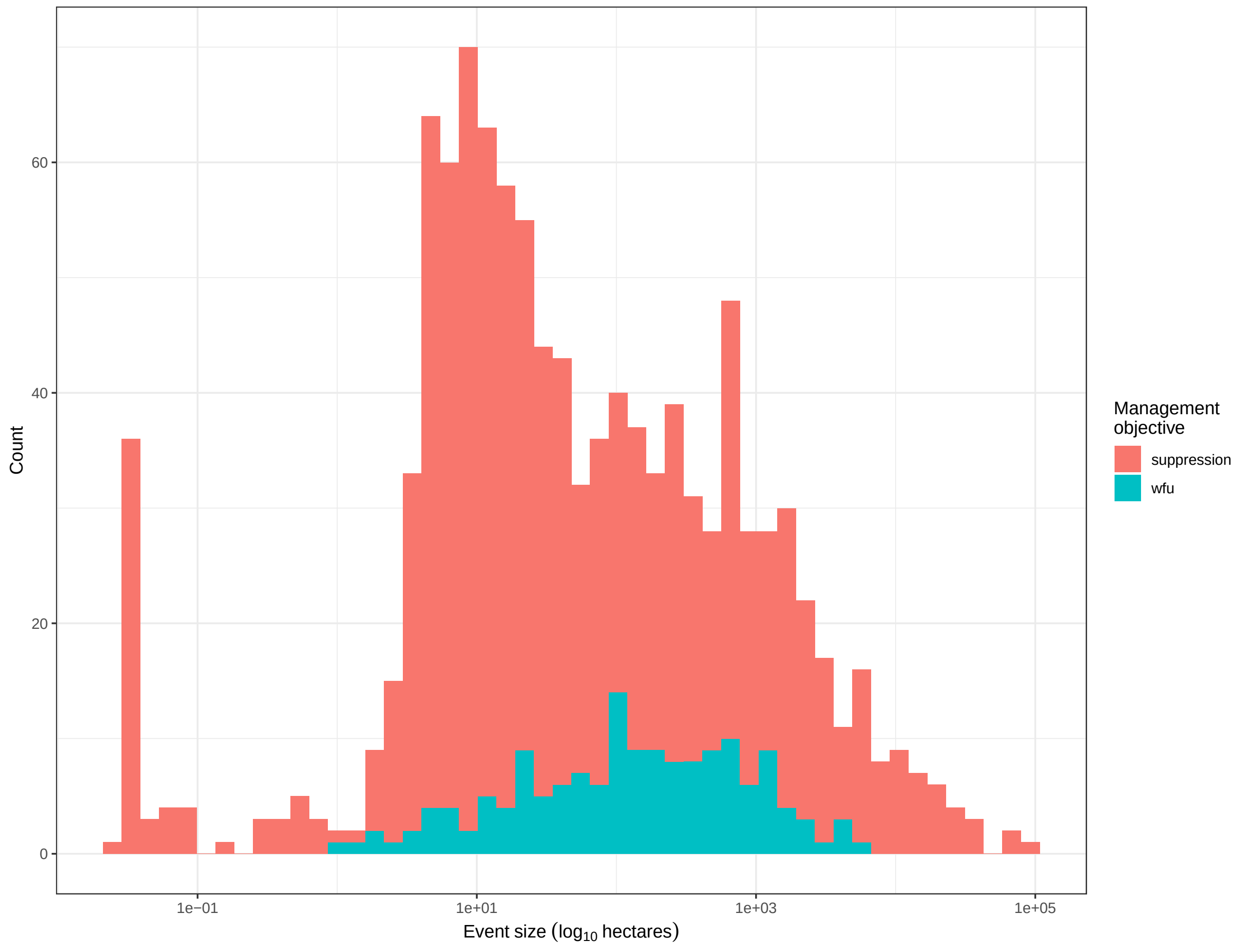

Figure 1: Distribution of log fire event size by management objective. While wildfire use fires exhibit a lognormal distribution in size, suppression fires exhibit clear multimodality.

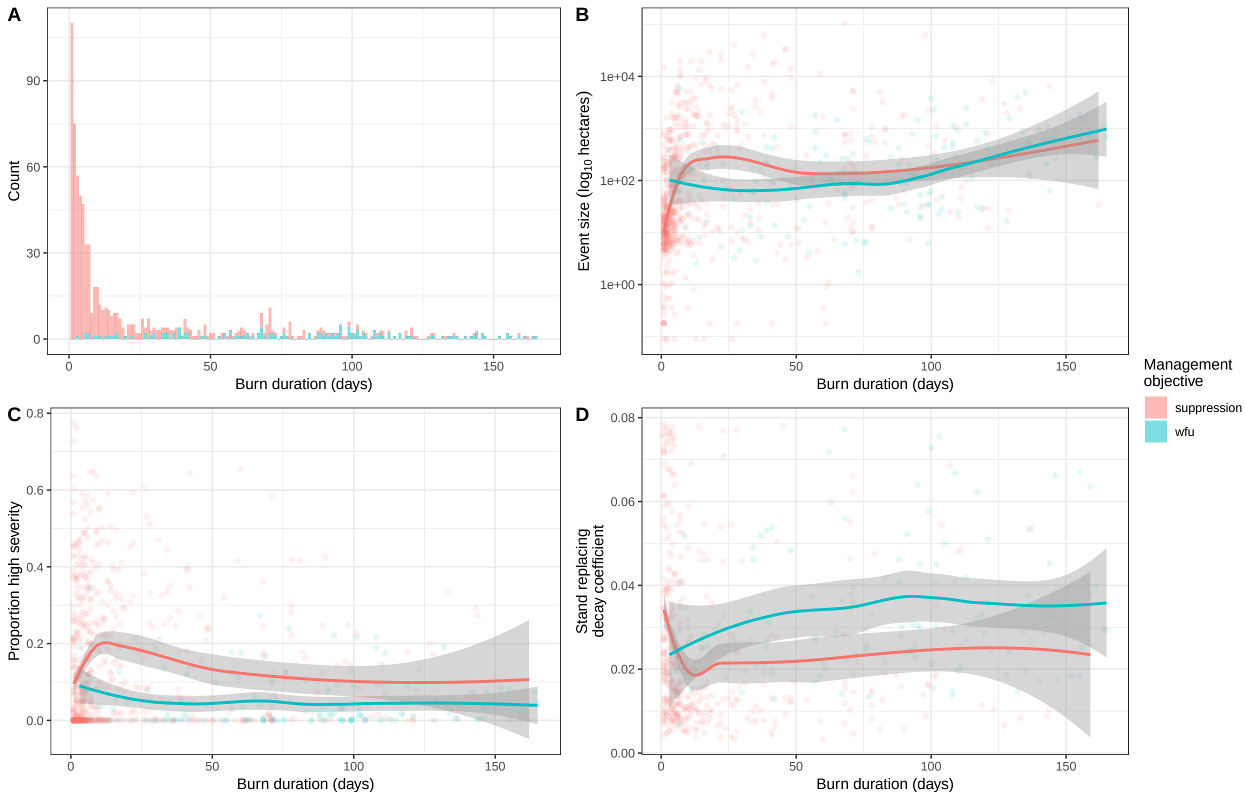

Figure 2: A) Distribution of burn duration by management objective. Most suppression fires are quickly extinguished. B) Effect of burn duration on fire event size shows that there's a similar trajectory between suppressed and wildfire use fires except early in the burning period when suppression fires 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.

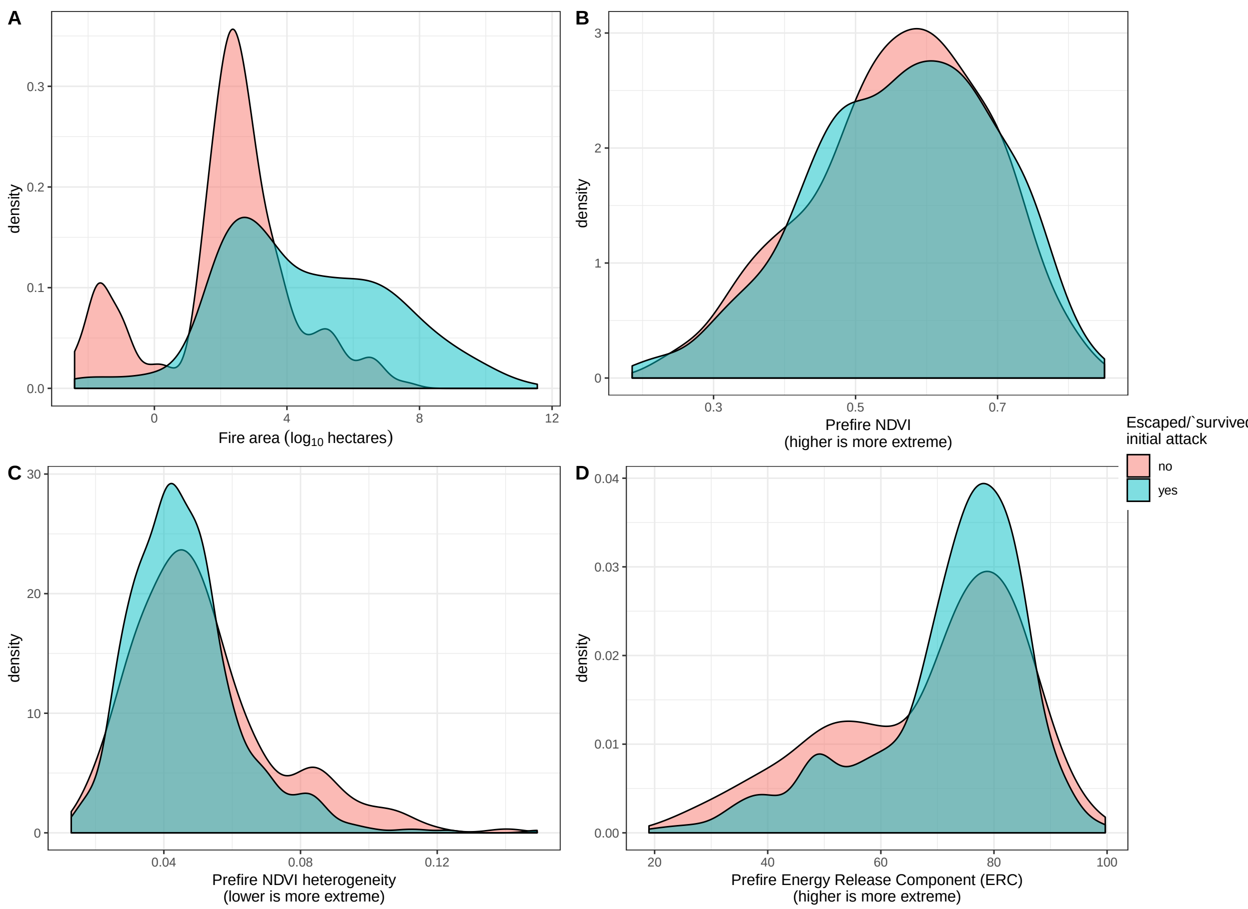

Figure 3: The selection effect on the vegetation and climate burning conditions of suppressed wildfires.

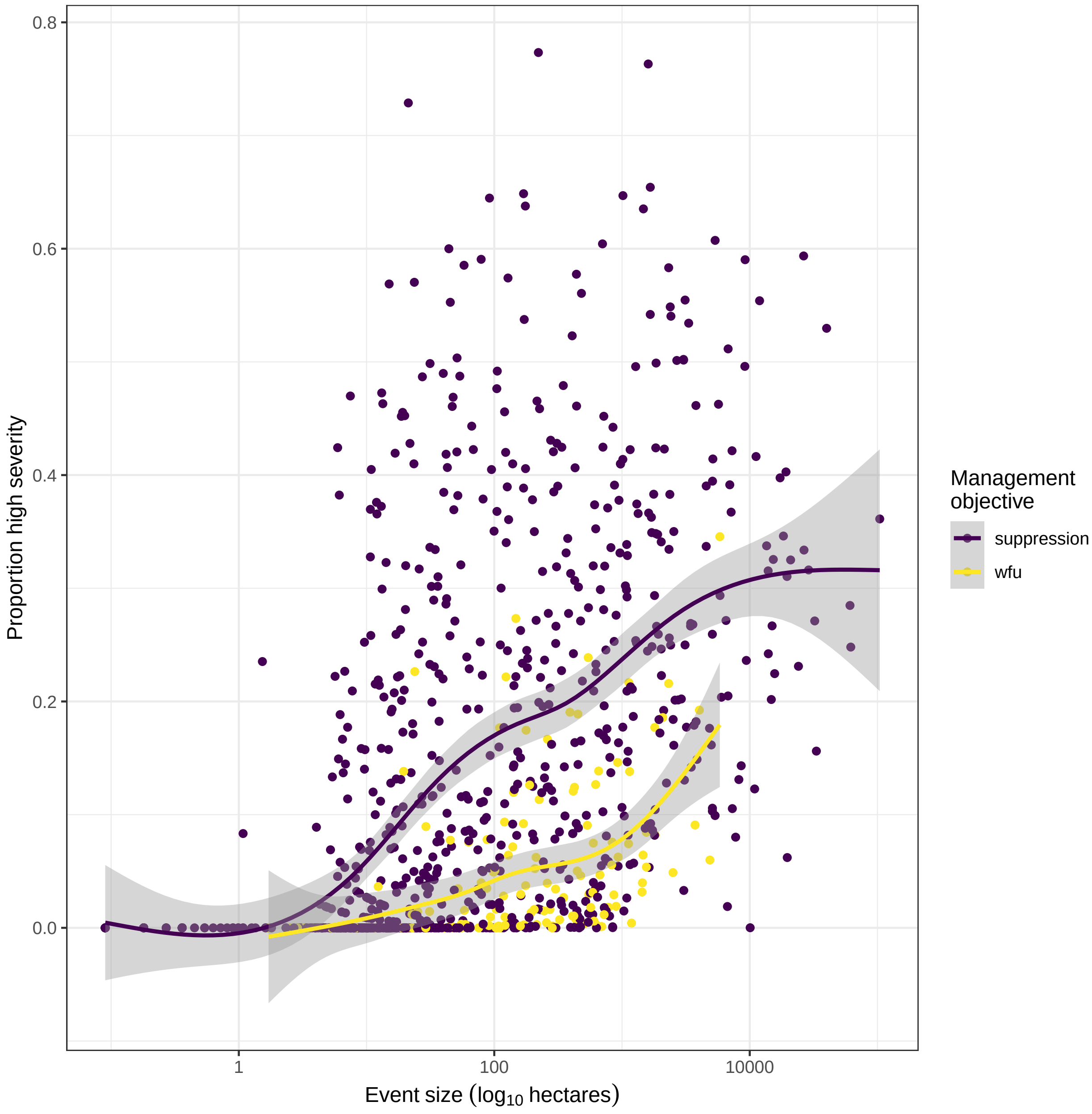

Figure 4: The effect of the fire event size on the proportion of high severity fire by management objective. The effect appears to manifest for suppression fires starting at fires around 40 hectares in size.

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.

Extending the metaphor: a case for an evolutionary response to selection

Evolutionary ecology makes a clear and important distinction between "phenotypic selection"– the differential survivorship or reproduction of individuals with different phenotypes, and "evolutionary response to selection" in which differences in the phenotype distributions are passed on to offspring owing to heritability of the traits under selection (or correlation with heritable traits under selection) (Lande and Arnold 1983). Of course, our "selection" metaphor can only take us so far in exploring the implications of fire suppression on typical wildfire phenotypes in Sierra YPMC as wildfires are not living things, but perhaps we can make one more leap by considering that the fuel conditions are, in a sense, "heritable".

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.

Tying into other studies (need to find a home for these thoughts)

Benefit of having smaller fires to analyze?

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.

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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