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). 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).

Wildfire effects to forests are outcomes of a complex social-ecological system dynamic (Calkin *et al.* 2015). Proximate causes of fire effects to vegetation arise from fire intensity and fire behavior (Keeley 2009), which are coupled to fuel, weather, and topography (McKenzie and Hessl 2008)

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)

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", "resource objective", or "wildland fire use" fires in recognition of the important role that fire plays in many healthy forest systems (Davis 1979; Calkin *et al.* 2015; Meyer 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.*

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) What is the strength of "selection" on wildfire burning conditions (regional climate, vegetation density, vegetation continuity) 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)?

MethodsK

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 (**???**; 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).

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.

Results

Context of Sierra YPMC

We found 16219 fire events burning at least partially in Sierra Nevada yellow pine/mixed-conifer, and 14873 fires burning in majority Sierra yellow pine/mixed-conifer in the FPAFOD database (Short 2017).

Some summary stats of the Sierra Nevada yellow pine/mixed-conifer subset of the Short (2017) fire occurrence dataset. (0.61% of fires are 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). The MTBS dataset (Eidenshink *et al.* 2007), with a lower fire size threshold of 400 hectares, accounts for 0.01% of fires; the USFS Region 5 geospatial dataset, with a lower fire size threshold of 80 hectares, accounts for 0.02% of fires; the Koontz *et al.* (2019a) dataset, which is derived from FRAP and has a lower fire size threshold of 4 hectares, accounts for 0.05% of fires.

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.

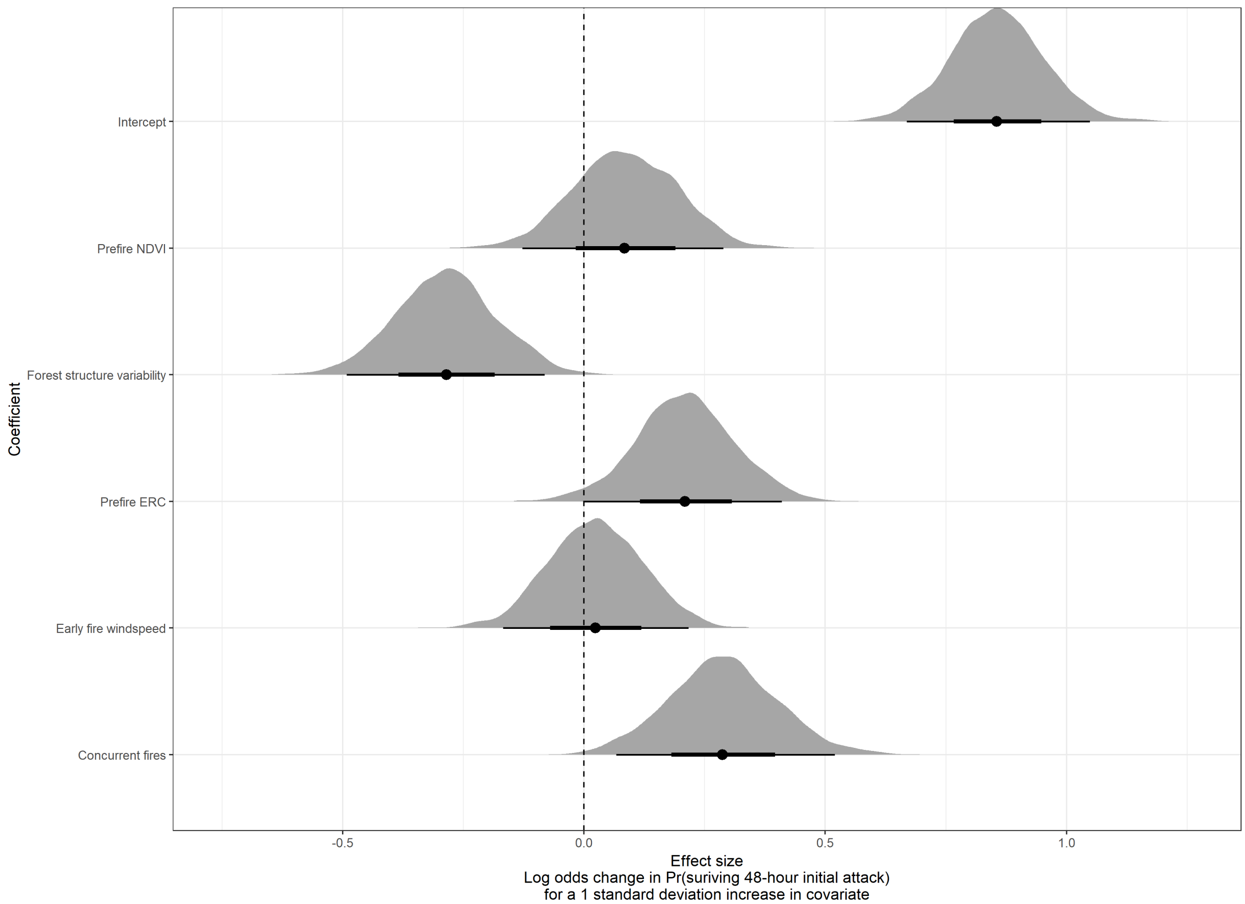
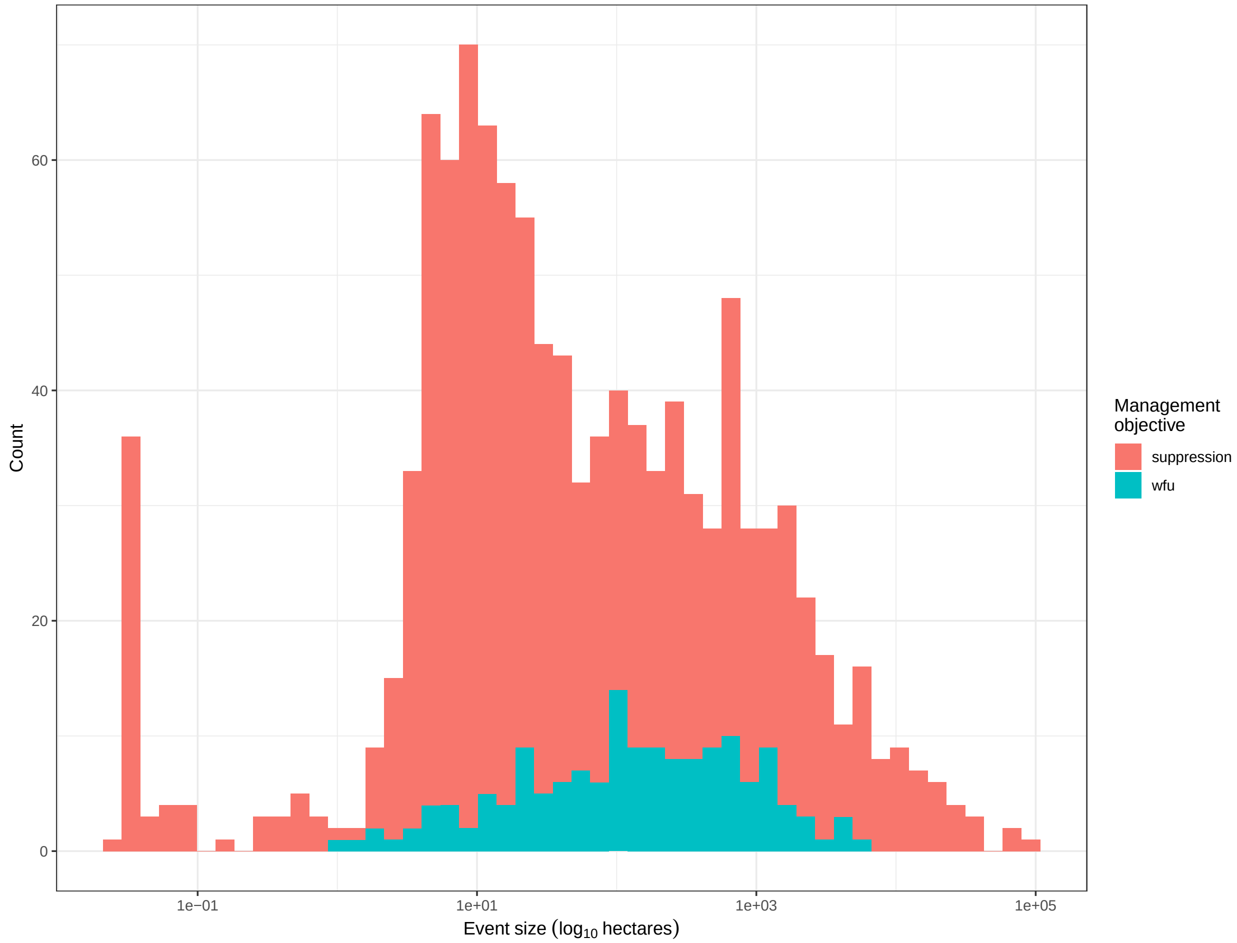


Figure 1: Halfeye plot showing posterior distributions of coefficient estimates for model predicting the probability of wildfire survivorship in the first 48 hours of initial attack. The effect sizes are proportional to the 'strength of selection' of initial attack on the burning conditions of wildfire. 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.



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

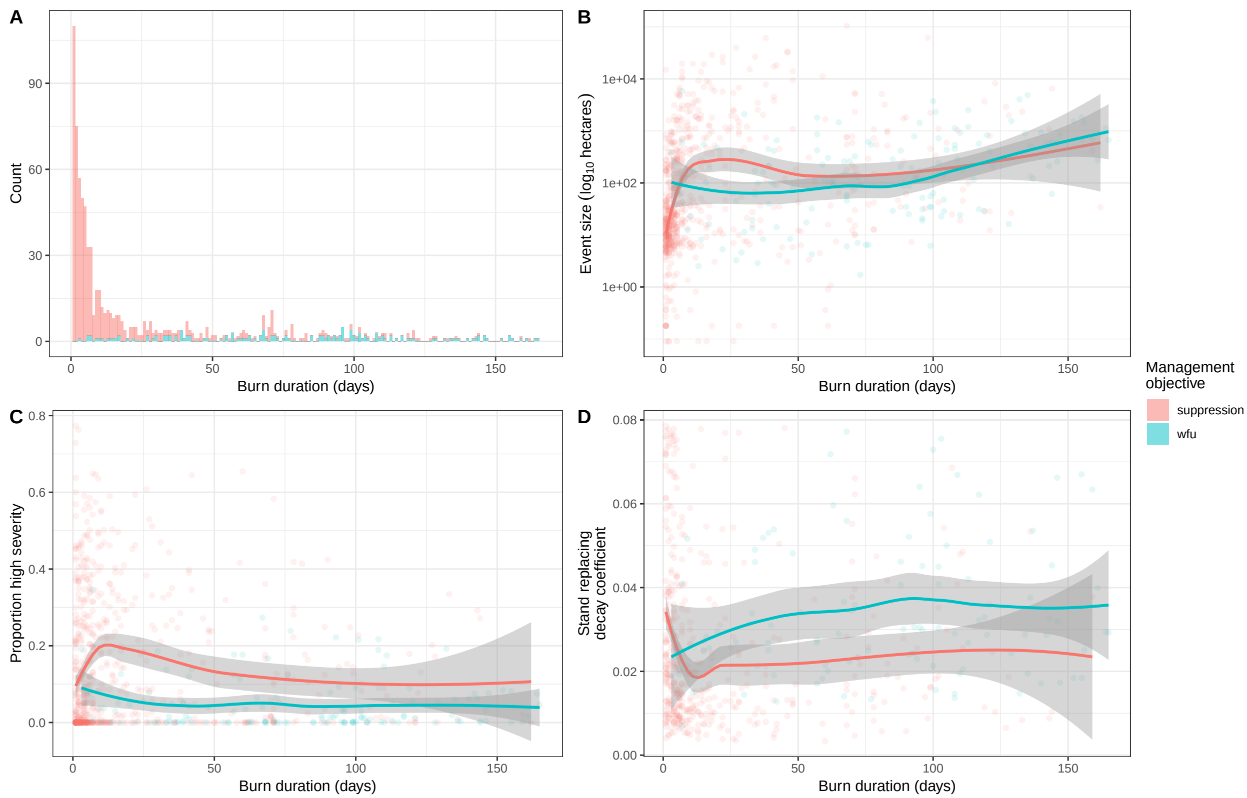
Implications of selection by suppression

Discussion

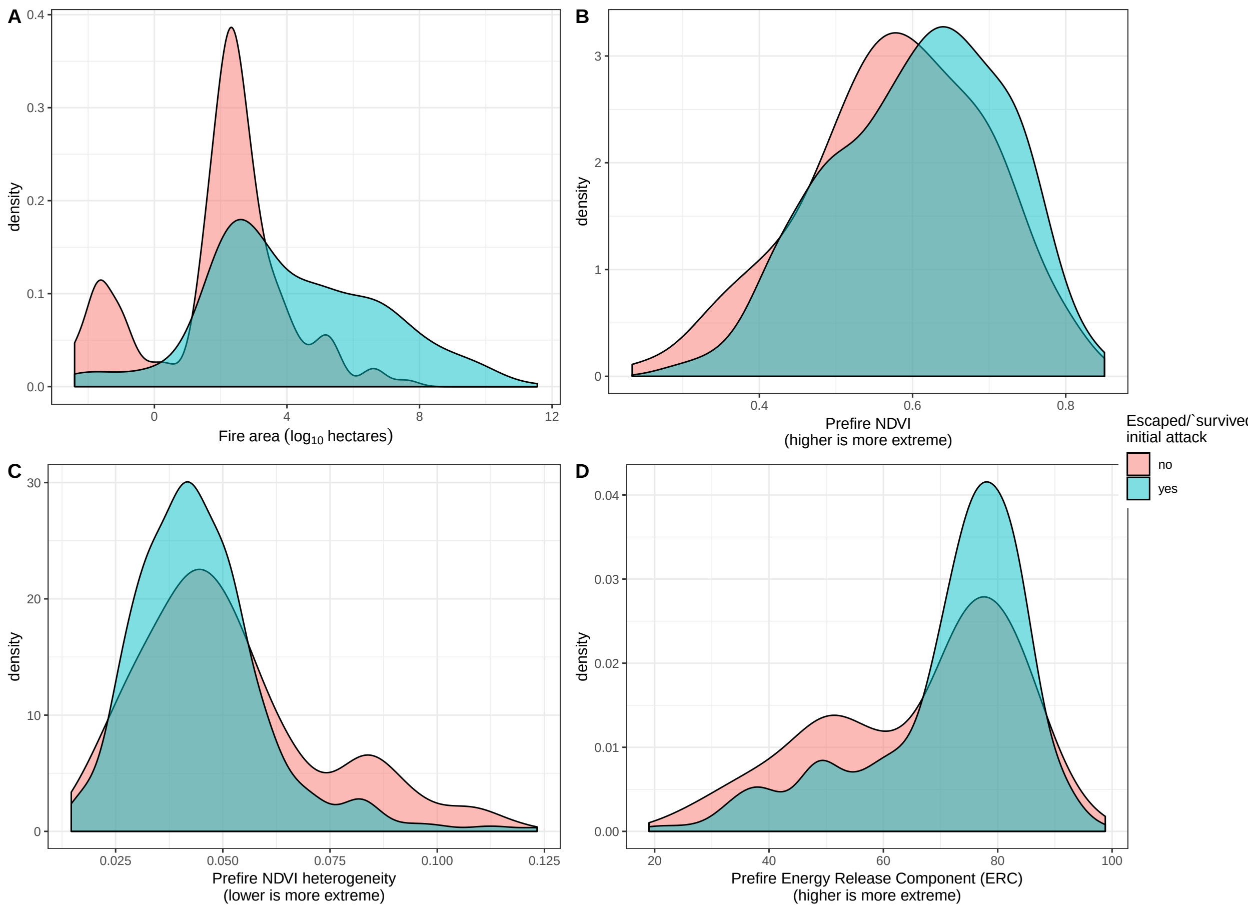
We have demonstrated a clear multi-modality in the fire event size distribution of wildfires managed with a suppression objective, and further measured the effect of this "selection by suppression" on the severity characteristics of these events.

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.

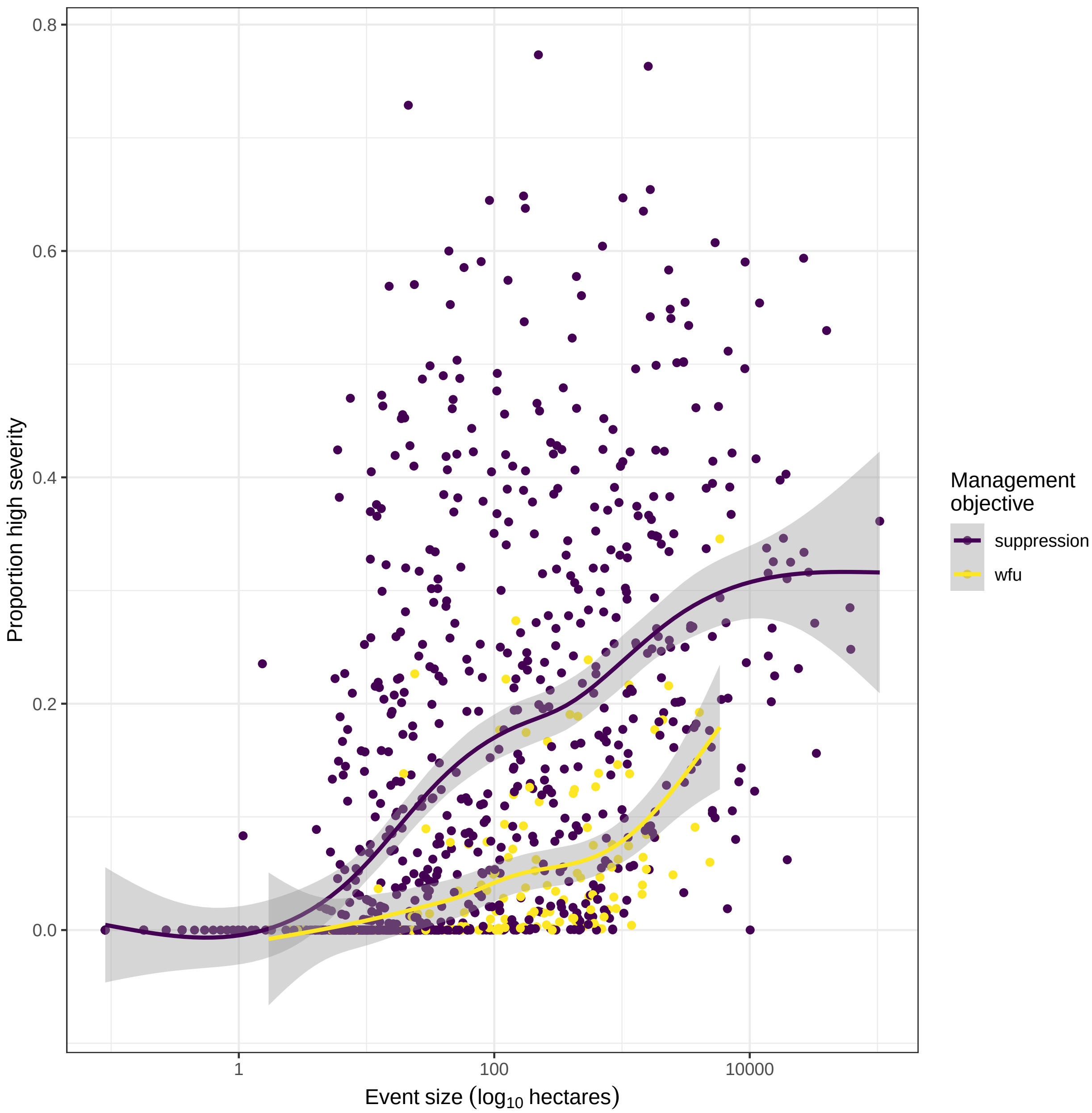
Two implications:



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.



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



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.

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.

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) did a good job of including small fires when measuring fire effects.

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)

References

Abatzoglou JT. 2013. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* **33**: 121–31.

Abatzoglou JT and Kolden CA. 2013. Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire* **22**: 1003.

Abatzoglou JT and Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**: 11770–5.

Abatzoglou JT, Balch JK, Bradley BA, and Kolden CA. 2018. Human-related ignitions concurrent with high winds promote large wildfires across the USA. *International Journal of Wildland Fire* **27**: 377–86.

Agee JK and Skinner CN. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**: 83–96.

Calkin DE, Cohen JD, Finney MA, and Thompson MP. 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences* **111**: 746–51.

Calkin DE, Gebert KM, Jones JG, and Neilson RP. 2005. Forest Service Large Fire Area Burned and Suppression Expenditure Trends, 19702002. *Journal of Forestry* **103**: 179–83.

Calkin DE, Thompson MP, and Finney MA. 2015. Negative consequences of positive feedbacks in US wildfire management. *Forest Ecosystems 2:9 doi: 101186/s40663-015-0033-8* **2**.

Cansler CA and McKenzie D. 2014. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecological Applications* **24**: 1037–56.

Coen JL, Stavros EN, and Fites-Kaufman JA. 2018. Deconstructing the King megafire. *Ecological Applications* **28**: 1565–80.

Collins BM, Lydersen JM, and Fry DL *et al.* 2016. Variability in vegetation and surface fuels across mixed-conifer-dominated landscapes with over 40 years of natural fire. *Forest Ecology and Management* **381**: 74–83.

Collins BM, Stevens JT, and Miller JD *et al.* 2017. Alternative characterization of forest fire regimes:

Incorporating spatial patterns. *Landscape Ecology* **32**: 1543–52.

Davis JB. 1979. A new fire management policy on Forest Service lands. *Fire Technology* **15**: 43–50.

Doane D, O'Laughlin J, Morgan P, and Miller C. 2006. Barriers to wildland fire use. **12**: 3.

Eidenshink J, Schwind B, and Brewer K *et al.* 2007. A Project for Monitoring Trends in Burn Severity. *Fire Ecology* **3**: 3–21.

Harris L and Taylor AH. 2015. Topography, Fuels, and Fire Exclusion Drive Fire Severity of the Rim Fire in an Old-Growth Mixed-Conifer Forest, Yosemite National Park, USA. *Ecosystems* **18**: 1192–208.

Harvey BJ, Donato DC, and Turner MG. 2016. Drivers and trends in landscape patterns of stand-replacing fire in forests of the US Northern Rocky Mountains (1984-2010). *Landscape Ecology* **31**: 2367–83.

Janzen FJ and Stern HS. 1998. Logistic Regression for Empirical Studies of Multivariate Selection. *Evolution* **52**: 1564–71.

Keeley JE. 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire* **18**: 116.

Key CH and Benson NC. 2006. Landscape Assessment (LA).: 55.

Koontz MJ, Fick SE, and Werner CM *et al.* 2019a. Wildfire severity, vegetation characteristics, and regional climate for fires covering more than 4 hectares burning in yellow pine/mixed-conifer forests of the Sierra Nevada, California, USA from 1984 to 2017. *Open Science Framework*.

Koontz MJ, North MP, and Werner CM *et al.* 2019b. Local variability of vegetation structure increases forest resilience to wildfire. *EcoEvoRxiv*.

Lande R and Arnold SJ. 1983. THE MEASUREMENT OF SELECTION ON CORRELATED CHARACTERS. *Evolution* **37**: 1210–26.

Lydersen JM, Collins BM, and Brooks ML *et al.* 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. *Ecological Applications* **27**: 2013–30.

Lydersen JM, North MP, Knapp EE, and Collins BM. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: Reference conditions and long-term changes following fire suppression and logging. *Forest Ecology and Management* **304**: 370–82.

Mallek C, Safford H, Viers J, and Miller J. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. *Ecosphere* **4**: art153.

McKenzie D and Hessl AE. 2008. A neutral model of low-severity fire regimes. *In: Narog, Marcia G, tech coord 2008 Proceedings of the 2002 Fire Conference: Managing fire and fuels in the remaining wildlands and open spaces of the Southwestern United States Gen Tech Rep PSW-GTR-189 Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station p 139-150* **189**: 139–50.

Meyer MD. 2015. Forest Fire Severity Patterns of Resource Objective Wildfires in the Southern Sierra Nevada. *Journal of Forestry* **113**: 49–56.

Millar CI and Stephenson NL. 2015. Temperate forest health in an era of emerging megadisturbance. *Science* **349**: 823–6.

Miller JD and Safford HD. 2017. Corroborating Evidence of a Pre-Euro-American Low- to Moderate-Severity Fire Regime in Yellow PineMixed Conifer Forests of the Sierra Nevada, California, USA. *Fire Ecology* **13**: 58–90.

Miller JD and Thode AE. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* **109**: 66–80.

North MP, Stephens SL, and Collins BM *et al.* 2015. Reform forest fire management. *Science* **349**: 1280–1.

Project JF (Ed). 2016. Jepson eFlora.

Rouse W, Haas RH, Deering W, and Schell JA. 1973. MONITORING THE VERNAL ADVANCEMENT AND RETROGRADATION (GREEN WAVE EFFECT) OF NATURAL VEGETATION. Greenbelt, MD, USA: Goddard Space Flight Center.

Safford HD and Stevens JT. 2017. Natural Range of Variation for Yellow Pine and Mixed-Conifer Forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA.

Short KC. 2017. Spatial wildfire occurrence data for the United States, 1992-2015 [FPA_FOD_20170508] (4th Edition).

Steel ZL, Koontz MJ, and Safford HD. 2018. The changing landscape of wildfire: Burn pattern trends and implications for California's yellow pine and mixed conifer forests. *Landscape Ecology* **33**: 1159–76.

Steel ZL, Safford HD, and Viers JH. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**: art8.

Stephens SL, Collins BM, and Fettig CJ *et al.* 2018. Drought, Tree Mortality, and Wildfire in Forests

Adapted to Frequent Fire. *BioScience* **68**: 77–88.

Stevens JT, Collins BM, and Miller JD *et al.* 2017. Changing spatial patterns of stand-replacing fire in California conifer forests. *Forest Ecology and Management* **406**: 28–36.

Welch KR, Safford HD, and Young TP. 2016. Predicting conifer establishment post wildfire in mixed conifer forests of the North American Mediterranean-climate zone. *Ecosphere* **7**: e01609.

Westerling AL. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science* **313**: 940–3.

Westerling AL. 2016. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**: 20150178.